JPRS L/9788

11 June 1981

Translation

ASTRONOMICAL OPTICAL SYSTEM PRODUCTION METHODS

By

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JPRS L/9788

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ASTRONOMICAL OPTICAL SYSTEM PRODUCTION METHODS

Moscow METODY IZGOTOVLENIYA ASTRONOMICHESKOY OPTIKI in Russian 1980 (signed to press 14 Nov 80) pp 2-142, 196

["Astronomical Optical System Production Methods", by Eduard Aleksandrovich Vitrichenko, Aleksandr Mikhaylovich Prokhorov and Yevgeniy Vasil'yevich Trushin, research performed under the auspices of the Space Research Institute of the USSR Academy of Sciences, published by Izdatel'stvo "Nauka", 1,000 copies, 196 pages, UDC 522.2]

CONTENTS

ANNOTATION

This book discusses the problem of making astronomical mirrors by the methods of digital and analog control of the shaping process. The American CAOS and CCP automated production systems and the Soviet ZEBRA system are described. Special attention is given to the software for the production systems and communication of the production process with the optical surface shape control procedure. The texts of the programs used in the ZEBRA system are presented.

The book is designed for scientific workers and engineers employed in astronomical instrument making, postgraduates and students at the institutions of higher learning for the indicated specialties.

FOREWORD

In 1974 the largest telescope in the world with a primary mirror diameter of 6 meters was put into operation. With the building of this telescope, a large number of scientific and technical problems were successfully solved. As frequently occurs in practice, during the solution of certain problems new problems arose requiring their solutions in turn. The main one of these problems can be formulated as follows: the creation of an automated "production control" system for the production of high-quality astronomical mirrors. The pioneering article by Brown [1971] on this question begins with the prophetic words: "In the past, the manufacture of mirrors for large telescopes was more an art than a science. However, the role of science is increasing from year to year and, possibly, in the foreseeable future the entire problem as a whole will become understandable and completely controllable."

The problem of the control of astronomical mirrors is the subject of a large number of articles and several monographs, among which is the book by D. T. Puryayev [1976] "Methods of Controlling Aspherical Optical Surfaces" and the book by E. A. Vitrichenko [1980] "Methods of Studying Astronomical Optics"; the problem of automated technology was the subject of only a few articles, and among the books it is possible to mention only the book by N. P. Zakaznov and V. V. Gorelik [1978] "Aspherical Optical System Production." The situation is worse with regard to the procedure for using the results of controlling the shape of an optical surface for giving the processing conditions. Only unrelated information is available on this question in individual articles.

Nevertheless, no one doubts that the production of precision optical surfaces for the needs of astronomy (Gascoigne, 1973] and for other purposes of a practical nature is an urgent problem [Michelson, 1976]. The urgency is so great that it has forced the creation of a special laboratory under the USSR Academy of Sciences which is engaged in the solution of this problem in close connection with industry.

This book sums up many years of activity with respect to the development and introduction of the automated system which the authors call ZEBRA into industry, the basis for which is local control of the force of a small tool. A great deal of attention has been given to the description and analysis of other approaches to the solution of the problem. The principle of the method for control of the local pressure of a tool on a part is discussed, and the software for the ZEBRA automated system is presented.

This system is designed for automated processing of optical surfaces based on measuring the topography of the surfaces. The surface is studied by the control methods, it is stored in an analog or digital unit, and then considering the shape of this surface, the operation of removal of the material in the required amount at the required locations is executed by a program written on the basis of an analysis of the surface topography by specially developed software.

The work on this system was participated in by coworkers whose names the authors consider it their duty to mention: G. I. Amur, A. M. Bogudlov, L. G. Boytsov, L. P. Vasil'yev, V. V. Gorelik, O. A. Yevseyev, V. A. Zverev, V. A. Ivanov, F. K. Katagarov, N. L. Komarov, V. A. Kokotushkin, V. V. Kostin, I. M. Kopylov, Yu. K. Lysyannyy, A. N. Makarov, V. A. Malykhin, S. K. Mamonov, A. A. Savchenko, R. Z. Sagdeyev, S. Ye. Stepanov, G. S. Tsarevskiy.

This book is the first effort to analyze such a complex problem as the automation of optical technology. The authors will be very grateful to the readers for critical remarks.

INTRODUCTION

The manufacture of a large-scale astronomical optical system is connected with overcoming an entire series of difficulties which are caused primarily by the fact that it is necessary to sustain a mathematical surface in the area of an optical surface of several square meters with a precision reckoned in hundredths of a micron.

Recently the ideas have been advanced for the creation of optical telescopes from several mirrors with an equivalent diameter to 25 meters [Pacini, Richter, Wilson, 1977].

The following factors, for example, prevent the solution of the problem: 1) imperfection of the optical machine tool, the effects of adjusting it [Mikhnev, 1973] and wear of the subassembly lead to various types of errors in the optical surface; 2) thermal effects connected with the process of energy release in the contact zone of the tool and the part and nonuniformity of heating of the part and the tool during the surfacing process [Maksutov, 1948, 1979]; 3) nonuniformity of the hardness with respect to grindability over the surface of the billet itself which is unavoidable for large dimensions, leads to different removal of material under equal conditions; 4) nonuniformity of feeding the abrasive suspension to the contact point of the optical part with the tool; 5) imperfection of the tool and its layer introduce their own errors [Tsesnek, 1970].

The existing practice of optical system manufacturers is based on experience and intuition and not on exact information about the production process. This is more a misfortune than a fault, inasmuch as consideration of the numerous production factors without a computer is impossible, and involvement of a computer leads to reexamination of the production process itself. The existing practice is leading to the fact that the process of manufacturing optical surfaces is not converging, that is, during the process of working on the part the practical optician improves the quality of the part, but part of the time is involuntarily spent on its improvement. For this reason the expenditures of time and means on the manufacture of large optical surfaces turns out to be unjustifiably large.

By the accepted operating procedure [Horne, 1972] the quality of the finished optical product depends directly on the qualifications of the practicing optician. This introduces a subjective element into optical technology, it forces long years of training experimental optical personnel, spending large amounts of means on training them. The subjectiveness of classical technology leads to the fact that, for example, one optician "can" manufacture a high-quality part, and another cannot reach this quality in any surfacing time. It is clear that this is entirely unacceptable for the industrial method of production.

The obvious way out of the developed situation can be automation of the shaping process with the application of computer engineering means. In this case the production process becomes strictly converging, that is, in each surfacing session the optical surface will only improve, and this converging process becomes independent of the personal experience of the practicing optician.

The creation of a completely automatic device for the manufacture of optical surfaces could be very enticing. In this case feedback in real time must be organized between the surface shape control and the production process. Unfortunately, the optical surface shape control in real time is not only not implemented, but there are not even any ideas as to how to do this in the near future. There are two basic reasons for this. The contact methods provide insufficient precision, and contactless methods cannot be implemented inasmuch as the optical surface is coated with abrasive suspension. On the other hand, local energy release at the contact spot leads to deformation of the optical surface. It is known that after a production session time is required to remove the local thermal stresses in the part (waiting time). Thus, measurements of the surface shape in real time, even if they can be performed, will pertain to the "current" shape of the optical surface and not to the shape that will be obtained as a result of the waiting period. For the above-indicated reasons the production process can only be automated and not automatic.

The search for ways to create an automatic technological process is possible with basic alteration of the classical technology. Possibly it will be necessary to use ion bombardment methods or vacuum deposition technology (see, for example, [Shapochkin, 1961]). In these methods the optical surface remains free and available for contactless control of its shape in real time. However, along this path there are also characteristic problems that are difficult to resolve.

Recently the paper by Aysin, et al. [1979] appeared in which an effort was made to control (measure) the shape of the optical surface during the surfacing of it and to use the control results in real time to control the shaping process. The experiment demonstrated that when grinding by the contact method precision of 3-5 microns can be achieved. Only the zonal component of the errors was measured; the complete picture of the normal deviations of the entire optical surface was not constructed. The authors draw the conclusion of prospectiveness of the approach.

Another path is possible for obtaining precision surfaces. Classical polishing is reproduced insufficiently precisely. If nonclassical procedures are used [author's certificate No 87504, 1950], and high reproducibility of the process is achieved, then there is no further necessity for controlling the shape of the surface in real time. These nonclassical procedures include ultrasonic polishing in a liquid medium [author's certificate No 85551, 1950] or an abrasive-liquid flow combined with the mask method [author's certificate No 199701, 1967]. The results of studying the reproducibility of these methods are unknown to us.

Soviet projects aimed at shaping the control research can be divided into two basic groups. The first group includes the work on creating equipment with explicit and implicit formers; the second group includes work on a multielement tool and a mask method.

A simple former in the form of a plane was investigated by Agashin and Gorelik [author's certificate No 448119, 1974]. The former creates the possibility of manufacturing complex aspherical surfaces. Line machining of the surface with the application of a complex former was investigated by Alaverdyanets, et al. [author's certificate No 373131, 1973]. The ideas of a parallelogram [author's certificate No 305041, 1971] or various types of levers [author's certificate No 344970, 1972; author's certificate No 87504, 1950; author's certificate No 487750, 1975] are proposed in a number of papers. The rotations of the tool and the billet around various axes permitting manufacture of aspherical surfaces were investigated by Gorelik, et al. [author's certificate No 333017, 1972; author's certificate No 325163, 1972; author's certificate No 217998, 1968]. A knife type tool [author's certificate No 343830, 1972] or a flexible belt on guides [author's certificate No 460987, 1975] are explicit former. A combination of lever mechanisms and a parallelogram permits the manufacture of toruses and barrels [author's certificate No 439380, 1974]. Direct copying to scale was investigated by Granichin and Kaganov [author's certificate No 241254, 1969].

In a number of papers simple tools have been proposed which permit the manufacture of aspherical surfaces [author's certificate No 192651, 1967; author's certificate No 192650, 1967; author's certificate No 151580, 1966; author's certificate No 182549, 1966]. A cam was proposed by Kaplan, et al. as a former [author's certificate No 400443, 1973] and also by Karlin, et al [author's certificate No 147937, 1962]. Complications of the trajectory of motion of the tool over the billet were investigated by Kachkin and Chunin [author's certificate No 129499, 1960], Konyashkin, et al. [author's certificate No 314406, 1972], Skibitskiy [author's certificate No 182019, 1966]. Special attachments and tools permitting aspherical surfaces to be machined were investigated by Khabirov [author's certificate No 427838, 1974], Kuznetsov and Sergeyev [author's certificate No 113952, 1957], Kumanin, et al. [author's certificate No 214328, 1968]. The ideas of creating explicit formers jointly with the ideas of the distribution of operations by zones of the optical surface were studied by Lipovetskiy [author's certificate No 317488, 1971; author's certificate No 325164, 1972], Khusnutdinov and Khabirov [author's certificate No 244142, 1969].

The original kinematics of motion of the tool with respect to the part were investigated by Khusnutdinov [author's certificate No 239071, 1969; author's certificate No 258055, 1969; author's certificate No 463535, 1975; author's certificate No 395238, 1973] and also Chunin and Kachkin [author's certificate No 131632, 1960].

In spite of the great difference in technical solutions, all of the devices indicated above have common advantages and deficiencies. The primary advantage consists in the fact that the application of these methods and devices permits the solution of the problems of manufacturing aspherical surfaces. A common deficiency is low precision of the surfaces obtained, which is unsatisfactory for astronomical optics. The former must be not mechanical device but the normal deviations obtained by precision control methods themselves. Many authors have not given sufficient attention to the methods of controlling the shape of the optical surface. An indirect consequence of this is the almost complete absence in scientific literature of an analysis of these solutions in which the results of quantitative control of optical parts obtained by the proposed method are presented.

Let us discuss the multielement tool. Two tools performing different functions were investigated by Vladimirov and Aref'yev [author's certificate No 103130, 1954]. The combination of the multielement tool with a template was proposed by Gorelik and Denisov [author's certificate No 283846, 1970]. A spring-heel tool developed by Semibratov and his students combines the principles of the multielement tool and the principle of operation distribution by zones [author's certificate No 429931, 1974; author's certificate No 335080, 1972; author's certificate No 427837, 1974]. Split flat springs [author's certificate No 144737, 1962] and simply individual tools on a common base [author's certificate No 595073, 1978; 218687, 1968; author's certificate No 370014, 1973; author's certificate No 360199, 1972] are used as the multielement tool. The multielement tool principle is used in the mask method [author's certificate No 217999, 1968; Tsesnek, 1970].

An analysis of the application of the multielement tool in optical technology leads to the same conclusions as the analysis of the application of methods connected with the template. In the literature we have found no information about the investigation of the shape of the optical surface made by a multielement tool or indications or recommendations for calculating the production processing conditions. Only in the papers by Semibratov and his students were the first steps taken in this direction [Semibratov, 1962; Semibratov, Yefremov, 1976]. Comparisons of new methods described in the author's certificates with classical technology have also not been made, but, nevertheless, this comparison alone can serve as a decisive argument in favor of transition to the new technology.

Excessive criticism of the above-enumerated developments would be improper. Moreover, it is known that many of them are used in industry and provide a large effect. However, most frequently, in our opinion, this effect is achieved for small parts (up to 100 mm in diameter), with large steepness of the surface (more than 10°) and with great asphericalness (more than 0.1 micron/mm). For astronomical mirrors the application of the above-described methods is limited.

American and Soviet automated systems are described in this book in which the actually measured allowance is related one-to-one to the process conditions of subsequent machining of the optical surface.

In the foreign patent literature a great deal of attention is being given to the manufacture of aspherical optical systems using formers and special kinematics of a machine tool. A number of papers in this area were written by Aspden [patent No 3566544, 1971; 3591986, 1971; 1601546, 1970]. The same author was a pioneer in the field of the application of analog and digital engineering for optical technology [patent No 3587195, 1971].

The special tools and machine tools are described in the patents of Bloom, Littlefield and Volk [patent No 3889426, 1974; patent No 3590532, 1971; patent No 1538254, 1968].

Automated polishing of curvilinear optical surfaces was investigated in the patent by anonymous authors [patent No 1284041, 1962].

The most important guarantee of success in the manufacture of optical surfaces is operative quantitative control of the current state of its shape. We shall not discuss this problem here (see [Vitrichenko, 1980], [Puryayev, 1969, 1976]). Our goal is investigation of the production subsystem of the ZEBRA system. An automated technological process was developed for the polishing-finishing operation stage. The same technology can be applied without any alterations to the grinding phase of the part (and even more successfully), inasmuch as the grinding process is reproduced better [Aleksandrov, 1953] than the polishing process. However, control of the ground surfaces is connected with significant difficulties [Bubis, et al., 1974], and therefore it is more convenient to automate the finishing operation inasmuch as the control of the polished surfaces causes no difficulies.

The rapid development of digital and analog engineering in recent times is opening new possibilities for optical technology. It is well known that the application of the computer has undergone a revolution in computer optics [Leonova, 1970]. The digital and analog electronic equipment has had a large influence on the method of investigating the optical elements and systems. In particular, the processing of the measurements of the Hartmann survey is done by computer [Vitrichenko, et al., 1975; Schulte, 1968; Zverev, et al., 1977a, b, c], and the developments with respect to automation of the measurements of the Hartmann photographs have started [Cheban, et al., 1979]. Analogous television equipment has found application for the quantitative Foucault-Philbert Schlieren method [Beskin, et al., 1975; Philbert, 1967; Wilson, 1975]. Modern engineering is also used in the interference method of control [Munnerlyn, Teyssier, 1975; Dutton, et al., 1968].

The problem of the automation of the technological process of manufacturing astronomical mirrors was raised for the first time by the well-known English company "Grebb Parsons." Later two American companies "Aytek" and "Perkin Elmer" presented the results of automated surfacing of astronomical mirrors [Aspden, et al., 1972; Jones, 1977, 1978]. These results demonstrated that automation makes it possible significantly to reduce the surfacing times with simultaneous improvement of the quality of the optical surface. In particular for parts, the diameter of which is on the order of a meter, it is possible to obtain a surface with a mean square error of $\lambda/80$. The achievement of such quality by traditional methods is impossible.

CHAPTER 1. PRINCIPLES OF THE AUTOMATION OF ASTRONOMICAL OPTICAL SYSTEM PRODUCTION

Any optical machine tool is in the simplest case automated, inasmuch as a mechanical or electrical controlled drive unit is used in it. Sometimes by automation we mean improvement of the kinematics of the machine tool to create new possibilities for movement of the tool with respect to the part [Mikhnev, 1973; author's certificate No 460168, 1975]. The next level of automation is the adviser mode. Here the software is organized which recommends the surfacing mode to the practicing optician by certain rules [author's certificate No 244142, 1969]. The highest level of automation can be considered to be the control of surfacing in real time. Inasmuch as, as we have already mentioned, it is still impossible to set up feedback between the process and the control, the mode is calculated by computer, and then this mode is implemented by the computer in real time [Jones, 1977, 1978; Jones, Kadakia, 1968].

In this chapter a study is made of the possible automation means. As it turns out, there are several, and our goal is a comparative analysis to select the one most applicable for practical purposes.

Introduction

Before we become involved in the solution of the engineering problems for the automation of any process it is necessary to construct a mathematical model of this process. For optical technology the mathematical model was constructed more than a half century ago by Preston [Preston, 1927, 1928]. This model has been checked many times experimentally [Krupenkova, et al., 1973; Aspden, et al., 1972], and it has been quite well implemented both for grinding and polishing of the optical surfaces. According to Preston's hypothesis

$$dh=K(a_1,a_2,a_3)PVdt, \qquad (1.1)$$

where dh is the amount of material removed on the optical surface; K is the process constant which depends on the part material (a_1), the tool material (a_2) and the properties of the abrasive material (a_3). In this case the physical parameters of the process are considered to be fixed: the temperature of the medium and part, the method of feeding the contact spot, and so on. The value of P is the specific pressure of the tool on the part. Inasmuch as the size of the tool is a fixed value, P can also be force with which the tool is pressed against the part; V is the speed of the tool with respect to the part; dt is the elemental surfacing time. If at a given point in time the tool is not in contact with a given point of the part, then dt=0.

Integration of (1.1) must be carried out with respect to three variables: with respect to the area of the part, the area of the tool and time. This integral for the classical optical machine tool is not taken in explicit form. The length of the trajectory which the point of the tool describes inside the elemental area on the surface of the part is

$$d\ell = Vdt. \qquad (1.2)$$

Investigation of formulas (1.1) and (1.2) indicates that theoretically we can control four technological functions [Lysyannyy, 1974]: the surfacing time of each elemental area, the speed of the tool with respect to the part, the trajectory of the tool with respect to the optical surface; the pressure (force) of the tool on the part [author's certificate No 384656, 1973]. Here we consider that in any case the size of the tool is less than the dimensions of the part; otherwise none of the control methods can be realized inasmuch as we are talking about elimination of errors in the optical surface of a local nature.

A combined control method is also possible. It is important to note that the control of any of the first three functions is difficult to realize without considering the influence of the remaining functions. Therefore the division investigated in the following items is provisional. The control of the local pressure of a small tool on a part is not related to the other parameters. This gives the most important advantage of the method which we shall mention many times.

The problems of the history of creating controllable shaping processes have been the subject of an article by Shevel'kova and Kuznetsov [1958] and a number of sections of the book by Zakaznov and Gorelik [1978].

The first effort to relate the removal of material from the optical surface and the kinematic parameters of the surfacing process by a calculation procedure was undertaken by Preston in 1924. Preston's work was published in 1927. Tome gave some development to the problem [Tome, 1931]. Among the Soviet papers it is necessary to mention the papers by Titov [1934, 1936]. In Titov's second paper the theoretical possibility of "varying the load on the polisher" is noted, that is, the control principle used in the ZEBRA system is indicated. The papers by Vinokur [1959], who first introduced the concept of the coverage factor [Shevel'kova, Kuznetsov, 1958], which discovered the possibility of numerical solution of the problem of work distribution by zones of the part, played an important role in creating a controlled process of working glass. The papers by Aleksandrov connected with the experimental study of the influence of the kinematic parameters on the precision and speed of surfacing are of interest [Aleksandrov, 1953].

In recent years an analytical approach to the shaping process was developed in the papers by Zakaznov and Gorelik [1978], Semibratov [1958], Semibratov and Yefremov [1976], Tsesnek [1970], Lysyannyy [1972, 1974] and other Soviet researchers. Among the foreign projects it is necessary to note the projects of the English company "Grebb Parsons" [Brown, 1971] and the American company "Aytek] (Aspden, et al., 1971] and "Perkin Elmer" [Jones, 1977, 1978].

Then we shall present a comparative analysis of various methods of controlling the shaping process. Special attention will be given to experiments that have been performed.

1. Surfacing and Time Control

We shall distinguish three methods of controlling the surfacing time: direct control, the mask method and the heel tool method. The last two methods could be called coverage factor control. In some sense all three methods are similar to the tool trajectory control method.

In the paper by Aspden, et al. [Aspden, et al., 1972], two systems are presented which are designed for finishing astronomical mirrors. One of them is based on controlling the surfacing time and is called CAOS/MOD. The acronym CAOS is formed from the first letters of the title of the author's article: "Computer-Assisted Optical Surfacing" -- a computer assists the optical surfacing. In the second model which the authors call CAOS/XY, the tool trajectory control principle is used. The first of the systems is designed only for axisymmetric removal of material, and the second is universal, that is, it permits local removal of the material.

The CAOS/MOD model is based on the following principle. For given adjustment of the tool, the amount of material to be removed at the time the center of the small tool is within the bounds of the annular zone is calculated. Then the surfacing time for various zones is given, and the removal of material is determined as the weighted mean of the removal of material in the various zones. The weighting factor is the surfacing time of each of the zones. In order to explain the indicated principle let us consider an example presented in the paper by Aspden, et al. [1972]. A series of relations for the material removal rate as a function of the part radius are illustrated in Figure 1.1. The parameter is the radius of the annular zone. During the calculations which were performed by a special computer program, it was proposed that the tool and the part rotate with identical angular velocity and in the same direction, and the center of the tool completes oscillations along the radius of the part.

For further analysis of the article by Aspden, et al., an explanation must be offered. In optical technology based on numerical analysis of the technological process it is possible to formulate the following two problems.

The direct problem: to calculate the removal of the material by given parameters of the technological process.

The inverse problem: to determine the parameters of the technological process for the given removal of the material (machining of alloys).

The inverse problem is the basic problem and pertains to the improper Tikhov problems. Therefore a solution is possible only by the iterative methods, and it is inexact. Obviously, if we do not have the solution to the direct problem it is impossible also to solve the inverse problem.

Figure 1.2 gives an example of the solution of the direct problem by the convolution method [Aspden, et al., 1972].

The thickness of the removed material $h(\rho)$ is:

$$h(\rho) = \int_0^R W(\rho - r)\,\tau(r)\,dr, \qquad (1.3)$$

where R is the physical radius of the part, ρ is the current radius of the part, $W(r)$ is the rate of removal of the material on the radius r of the part presented in Figure 1.1, $\tau(r)$ is the surfacing time for a zone with a radius r. Curve 1 of Figure 1.2 is an example of giving the surfacing time in different zones, curve 2 is the thickness of the layer of material which is removed for the surfacing time distribution indicated by curve 1, and with a rate of removal presented in Figure 1.1.

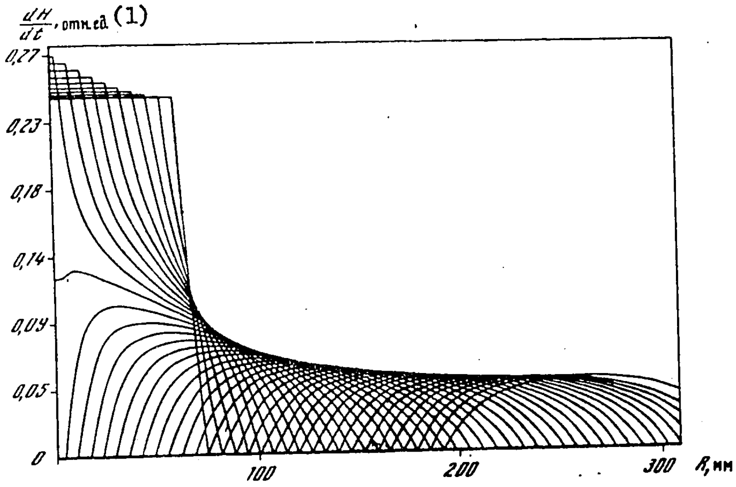
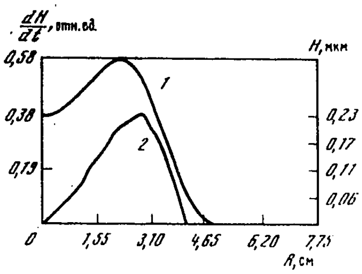


Figure 1.1. Rate of removal of material during movement of a small tool along the radius of an optical part as a function of this radius

Key:
1. relative units

The paper by Aspden, et al., [1972] describes an experiment in which the inverse problem is solved. A part 200 mm in diameter was converted from a sphere to a parabola. The initial part with spherical surface was turned on a spindle. The tool had a diameter of 75 mm and was force-turned in the same direction as the part. The basic difference of the CAOS/MOD system from the ordinary optical machine tool is the presence of a digital control system permitting arbitrary assignment of the surfacing time of each zone of the optical surface. This system is controlled from the punch tape calculated on a computer in accordance with the solution of the inverse problem. The control system permits execution of both simple harmonic oscillations and more complex movements of the tool center.

Figure 1.3 shows the results of the experiment. Curve 1 shows the removal of the material obtained by solving the inverse problem, curve 2 shows the actual removal of material. The horizontal segment indicates the size of the tool. An interferogram indicating the difference in the wave fronts of the parabolic surface and the initial spherical surface is presented in the figure. The part was surfaced by polishing; the removal of material was 8.25 wave lengths at the center of the part (the wave length is 0.63 microns). On comparison of the calculated and experimental removal of material, the calculated curve as multiplied by a coefficient permitting both curves to be matched for the center of the part. This procedure turned out to be necessary as a result of the fact that the absolute rate of removal of the material is unknown. Good agreement of the shape of the curve indicates the effectiveness of numerical simulation of the technological process. A deficiency of the CAOS/MOD system is impossibility of eliminating local errors. The CAOS/XY system which is described in the same paper by Apsden does not have this deficiency.



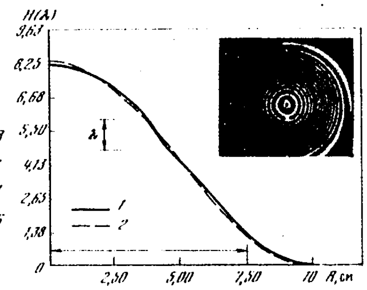


Figure 1.2. Calculation of the thickness H of removed material based on convolution of the curves presented in Figure 1.1 with time distribution of the surfacing by zones.
1 -- surfacing time distribution by zones, 2 -- prediction of the removal of material. The notation is the same as in Figure 1.1.

Key:
1. relative units
2. microns

Figure 1.3. Results of parabolizing an optical surface by polishing using the CAOS/MOD system.
1 -- calculated removal of material in wave lengths, 2 -- actual removal of material.
The horizontal segment indicates the diameter of the tool used, and the vertical segment, the wave length.
An interferogram of the parabolic surface is presented on the right.
The notation is the same as in Figure 1.2.

The Crimean Astrophysics Observatory of the USSR Academy of Sciences has developed a tool, the operating principle of which is based on controlling the surfacing time [Popov, 1972; Popov, Popova, 1970]. A diagram of the tool is shown in Figure 1.4. The tool consists of three guides arranged at an angle of 120° to each other. The guides are fastened to the platform containing the adapter 1 which is connected to the carrier of the grinding and polishing machines (type ShP). The working elements 2 are connected by ball hinges to the shoes located on the guides. The surfaced part, which is a flat mirror 1 meter in diameter, was broken down into annular zones 10 cm wide, and formula (1.1) was used to calculate the surfacing time for each zone. The spindle of the machine tool with the part fastened to it was turned uniformly, the pressure of the tool on the part was constant, and the variation of the absolute velocity along the radius of the part was taken into account.

The number of small tools in the zones can be taken not only equal to three, but greater than or less than, and the control principle does not change from this.

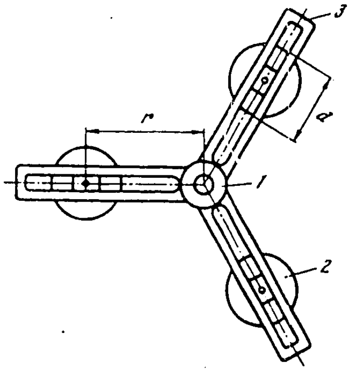
The advantages of the method are simplicity of implementation and the possibility of complete automation. An ordinary optical machine tool without any modification is used, and a relatively simple tool is made. Simple calculations are performed. Both these calculations and the control of the travel of the tool along the zones can be done by computer.

In the given execution there are two significant disadvantages. The first of them is theoretical and consists in the fact that it is impossible to eliminate local errors of the general or local astigmatism type. In other words, only axisymmetric removal of material is possible. This removal permits asphericalization of the optical surface and elimination of the zonal component of the errors. Meanwhile, it is known that on astronomical mirrors local type errors are characteristic [Vitrichenko, 1976]. A cardinal change in the procedure is needed to eliminate them.

Another deficiency of the system is technological. When the tool moves over the annular zone, specific wear of it takes place. This leads to the fact that the center of the annular zone is machined more intensely, and the boundaries of the segment of the annular zone, less intensely. As a result of the machining process, annular grooves are formed in the centers of the zones. The optical surface acquires a "corrugated" shape. Although the amplitude of the errors on the optical surface can be decreased, the dispersion circle increases as a result of an increase in the error gradients of the optical surface. It is very difficult to avoid this effect. In practice we resort to smoothing of the part by a large tool. The oscillating movement of the upper element of the optical machine tool is also used. These measures diminish the indicated effect, but they do not eliminate it.

The programming of the time the tool is in a given annular zone is proposed in the author's certificates of Khusnutdinov and Khabirov [author's certificate No 244142, 1969], Lipovetskiy [author's certificate No 317488, 1971] and the paper by Lysyannyy [1972]. In these author's certificates it is proposed that a cam be used, the shape of which also determines the surfacing time of each of the zones of the optical surface. The basic deficiency of such devices is the necessity for each surfacing session with finishing operations to make the special cam. The idea can be successfully used only for mass asphericalization of parts with low precision requirements. The cam principle is used in the Sabostin machine [1972] developed at Moscow Higher Technical School imeni N. E. Bauman.

The machine tool developed by Zakaznov and Savostin [author's certificate No 427837, 1974] in which the tools are moved from zone to zone as a result of centrifugal forces acting on weights connected to the tool, is of interest. A detailed description of the cam and centrifugal systems can be found both in the original papers and in a book by Zakaznov and Gorelik [1978].



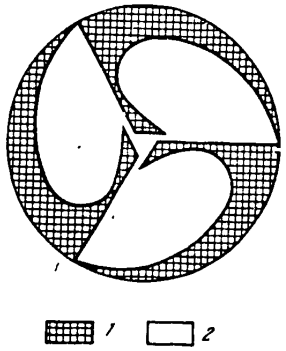


Figure 1.4. Tool with movable polishers.
1 -- adapter, 2 -- polisher, 3 -- guides, r -- radius of the surfaced zone, d -- tool diameter

Figure 1.5. Schematic representation of a tool mask.
1 -- surface filled with resin, 2 -- surface free of resin (does not touch the optical surface)

The mask method is based on the application of a full-sized tool, the diameter of which is comparable to the diameter of the part. The working surface of the tool is made in the form of lobes, the shape of which is calculated to insure required removal of material in the defined zone. An example of the type of working surface is presented in Figure 1.5.

The mask procedure was used by the French PEOCK company when surfacing the mirror 3.65 meters in diameter [Bayle, Espiardu, 1972]. In Soviet practice the method was developed by the Tsesnek group [Leushina, 1975; Lysyannyy, Tsesnek, 1973; Golovanova, 1968], and it was used to make a second parabolic mirror 6 meters in diameter designed to replace the first BTA mirror. The removal is regulated by regulating the contact diameter of the tool with the part. In order to decrease the "corrugation" effect the tool makes oscillating movements of small amplitude.

The most important advantage of the method is the small influence of the boundary effect on the tool, characteristic of methods in which a small tool is used. The basic deficiency of the method is the theoretical difficulty of eliminating local errors. The technical deficiency is the necessity for making a complex tool for each surfacing session. Only the process of calculating the shape of the tool is subject to automation, and there is no necessity for controlling the machine tool in real time.

A prospective approach to the problem of making aspherical surfaces was developed by the Semibratov school [Semibratov, 1970; Semibratov, Yefremov, 1976]. It consists in using the spring-heel tool which has a number of universal properties.

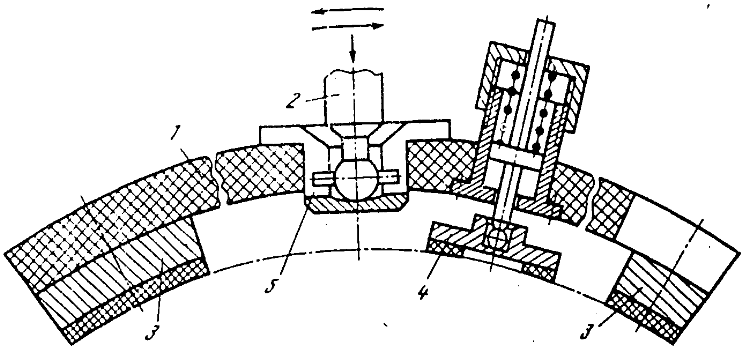


Figure 1.6. Spring-heel tool.
1 -- tool housing, 2 -- carrier of the optical machine tool, 3 -- segmented heels, 4 -- annular heels, 5 -- adapter

The structure of the spring-heel tool is shown in Figure 1.6. The convex surface of the surfaced part is provisionally illustrated by the dash-dot line. The part is rotated on a spindle of the optical machine tool. In the tool housing 1, the operating heel elements of two types are installed: segmented heels 3, the purpose of which is to reduce the bulwark of the optical surfaces to a minimum and the annular heels 4 which are the basic working tools. The number of heels, their arrangement and diameter determine the magnitude and the shape of the removed machining allowance. The housing 1 is made of elastic material,and the external part of the housing is weakened by radial slits. The annular heels are spring loaded as shown in Figure 1.6. All of these measures provide for good strong contact of the optical surface and the working tool. The housing of the tool 1 is connected through the adapter 5 to the carrier of the machine tool 2. During surfacing the tool is force-rotated and undergoes oscillating movements of small amplitude.

The spring-heel tool theoretically makes it possible to solve any problems of axisymmetric removal of material: to apply any form of asphericalness and eliminate zonal errors.

The practice of application of the tool has demonstrated that a part 40 mm in diameter with a maximum machining allowance of 25 microns can be made with precision of 0.2-0.5 of the ring [Semibratov, 1970].

The American company "Perkin Elmer" has developed an automated system designed for polishing and grinding optical surfaces using small tool surfacing time control [Jones, 1977, 1978]. The system is called the Computer Controlled Polisher (CCP). The tool moves over the optical surface along a defined trajectory which is either a twisting or untwisting Archimedes spiral. The shifting takes place at a rate less than the rotation rate of the small tool. The shift rate of the tool along the trajectory is variable, and it is selected so as to insure the required removal of material. The shifting of the tool and its velocity are controlled by a small computer. The pressure of the tool on the part remains constant.

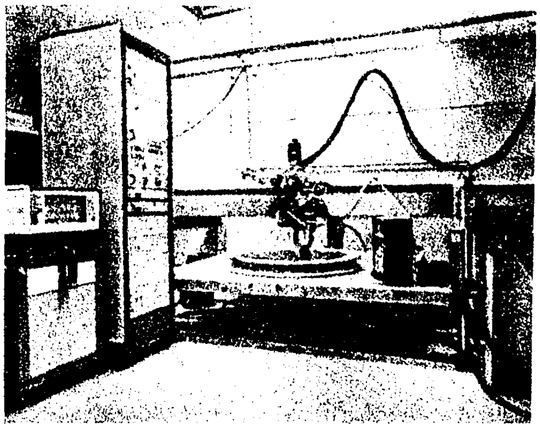


Figure 1.7. Polishing tool controlled from an electronic device (CCP system)

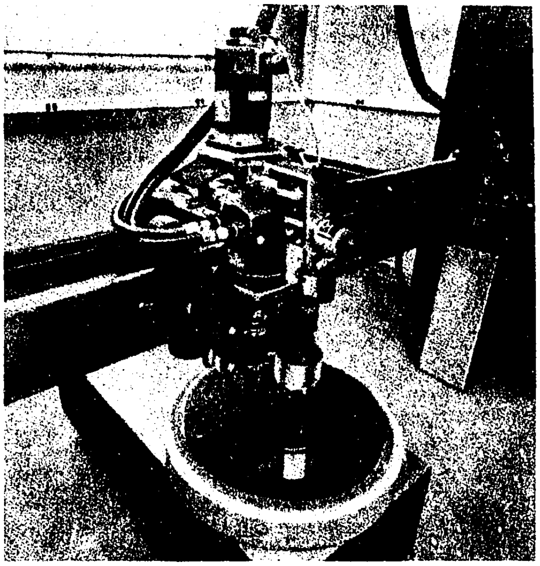


Figure 1.8. Polishing head of an electronically controlled machine tool

Figure 1.9. Flow chart for the production cycle in the CCP system

Key:

1. Information about the required surface
2. Information about the speed restrictions
3. Obtaining an interferogram
4. Analysis of the interferogram
5. Chart of normal deviations
6. Speed calculation
7. Punch tape with speeds
8. Surface polishing

Figure 1.7 shows the general view of the CCP device. The computer is connected through interfaces to two servodrives providing for shifting of the carriage bearing the tool along two mutually perpendicular X and Y axes. The information about the position of the carriage is reckoned by the position gauges and reaches the computer which provides feedback with respect to the carriage position and its rate of displacement.

Figure 1.8 shows the polishing head of a machine tool consisting of two operating elements, each of which is suspended on an individual hinge. The entire tool rotates using a hydraulic servomotor. The abrasive material is sprayed on the optical surface using an atomizer.

The production cycle of the finishing operation is set up as follows (see Figure 1.9). The first step is to obtain an interferogram of the machined surface. The interferogram either is scanned by a high-speed scanner or it is measured on a comparator. The interferogram scans jointly with the information about the required shape of the optical surface are processed by the algorithms described in the paper by Jones and Kadakia [1968]. A result of machining is the normal deviation chart. In turn, the normal deviation chart is the initial file for determining the displacement rate of the tools along the trajectory. During these calculations, the range of possible speeds is taken into account. The file of speeds is output on magnetic tape which is read by a minicomputer realizing the surfacing session. After completion of the surfacing session the part again goes to control .

In the paper by Jones [1977] special attention is given to the shape of the tool. This most important problem has been studied insufficiently; therefore a more detailed discussion is presented of the results of the author of the article. The operation of a small tool is studied both by simulation on a computer and in full-scale experiments. The machine simulation of the operation of the small tool was based on the following principles:

Removal of the material takes place only as a result of rotation of the tool around its axis in the process of moving over the optical surface;

The removal of the material is a function of the distance from the center of the tool;

The tool moves over the surface of the part along a unit trajectory, and control of the removal of the material is achieved as a result of variable speed of this displacement.

According to Semibratov's terminology, the control of the removal of the material takes place as a result of the variable coverage factor which the author calls the dwell function. If the tool makes N passes over the surface, then the total material removed can be described by the equation

$$F(x,y) = S(x,y) - N\iint PT(u,v)R(x-u,y-v)\,du\,dv, \qquad (1.4)$$

where R is the material removal profile which is related to the operation of the small tool; T is the coverage factor; S(x,y) is the chart of the normal deviations of the optical surface before the beginning of finishing operations; F(x,y) is the chart of the normal deviations with respect to completion of the finishing operation.

Simulation consists in the fact that an arbitrary initial chart of normal deviations is input to the computer memory, the program computes the process conditions and calculates a new chart of normal deviations which will occur after realization of the process conditions. The new chart of deviations is initial for the next cycle, and so on. The separate program described in the paper by Wagner and Shannon [1974] defines the material removal profile for a different structure of the small rotating tool.

In formula (1.4) the value of P denotes the product of the constant pressure times the process constant connected with the materials of the tool, the part and the abrasive. This value can be taken from under the integral sign, but it can be considered as a function of the radius of the tool for nonuniform pressure distribution.

The simulation program executed on the IBM-370 computer has been used for many purposes. One of them is the effect of the number of elementary polishers on convergence of the technological process. The results of this simulation are presented in Figure 1.10 where the configuration of two types of tools is also illustrated (see Figure 1.10, a). One of them consists of two elements 2.5 cm in diameter with spacing between centers of 3.8 cm, and the other consists of four elements of the same diameter, but with a spacing between centers of 6.4 and 3.8 cm. Profiles of the removal of material for these types of tools are presented in Figure 1.10, b. The distance from the center of the tool is plottted along the x-axis, and the amount of material removed, along the y-axis. From the figure it is obvious that increasing the number of tool elements increases the removal of material, but the removal profile changes insignificantly.

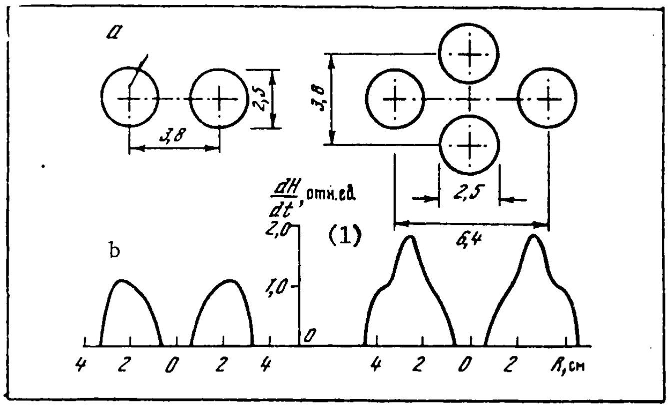


Figure 1.10. Rotating tools.
a -- geometric configurations of two types of tools, b -- rate of removal of material under the tool platform. All dimensions in the figure are given in cm.

Key:
1. relative units

The following model experiment was conducted for two types of tools presented in Figure 1.10, the results of which are presented in Figure 1.11. The order number of the production session is plotted along the x-axis; the mean square deviation of the optical surface expressed in fractions of a wave length is plotted along the y-axis. In the paper by Jones, the wave length is taken as 0.6328 micron. Curve 1 pertains to a rotating tool having four elements; curve 2 indicates convergence of the finishing process for a two-element tool; curve 3 is the convergence for an ideal tool, the removal profile of which is described by an equilateral triangle and the apex of the triangle coincides with the center of the tool. From the figure it is obvious that this ideal tool permits achievement of the best quality of optical surfaces. If a real tool permits a surface to be obtained with mean square deviation of 1/20 of the wave length in 6-8 cycles, an ideal tool leads to a surface with an error of 1/50 of the wave length in 10 cycles, and further improvement of the surface is possible.

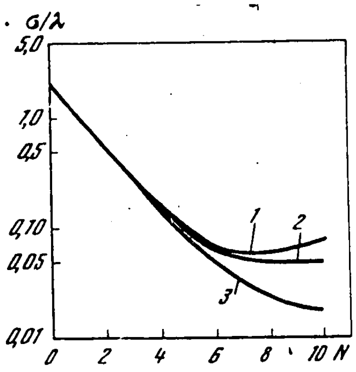


Figure 1.11. Results of model calculations of the convergence of the technological process for different structural designs of tools.
1, 2 -- rotating tool with four and two working elements, respectively; 3 -- model tool having the function of removing material in the form of a triangle

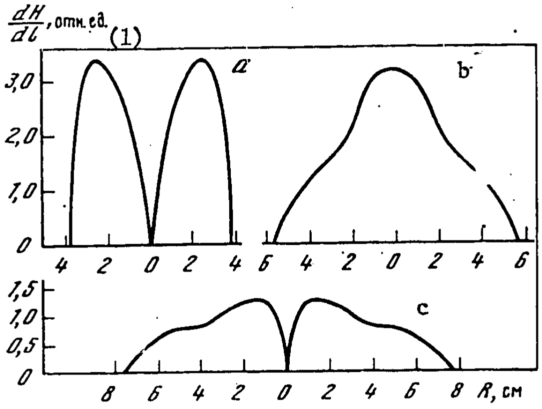


Figure 1.12. Removal profiles of a material for various oscillation amplitudes of the tool.
a -- tool does not oscillate; b -- oscillation amplitude is equal to the tool radius; c -- oscillation amplitude is equal to twice the radius of the tool element.
The distance from the center of the tool in cm is plotted on the x-axis.

Key:
1. relative units

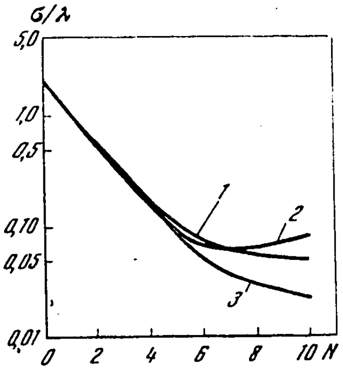


Figure 1.13. Results of model calculations of the convergence of a technological process for various amplitudes of the epicyclic movement of the tool.
1 -- tool does not oscillate, 2 -- oscillation amplitude is equal to the radius of the tool element, 3 -- oscillation amplitude is equal to twice the radius of the tool element.

In the given model experiment it was considered that the initial surface is an ideal plane, and the required surface is a sphere with a pointer of 1/10 of the wave length. The coverage factor was taken proportional to the required material removal, and the removal profile was selected so that half the material subject to removal would be removed in one pass of the tool. Analogous results were obtained also for other types of machined surfaces.

Thus, the described model tool leads to the conclusion that it is necessary to use a material removal profile in the form of a triangle. This profile can be obtained if the multielement rotating tool is given oscillating motion. In this case the tool rotates at high speed around its axis, and the tool axis rotates with lower speed around a center.

Figure 1.12 shows the results of calculations of the removal profile of the material by a two-element tool for three amplitudes of the oscillating motion. On the figure it is obvious that the best profile is the one with oscillation amplitude equal to the radius of the tool element inasmuch as in this case the profile is closest to a triangle.

In Figure 1.13 results are presented from model calculations of the convergence of the technological process for three cases of oscillating movements. The tool is two-element, the spacing between the centers of the elements is equal to twice the radius of the tool. Just as should be expected, the best quality of surface is achieved for oscillation amplitude equal to the element radius: in 10 surfacing cycles the mean square error decreases to 1/50 of the wave length, and further improvement of the surface is possible in this case. The conditions of the model experiment are the same as those corresponding to Figure 1.10.

Finally, the adopted configuration and dynamics of the tool are illustrated in Figure 1.14. The tool elements are demonstrated in the figure by solid circles. Both tools 3.5 cm in diameter rotate at high speed around the midpoint. The spacing between the centers of the tool is 3.8 cm, which insures a clearance between edges of the tools of 0.3 cm, keeping them from contact. A separate drive provides for movement of the midpoint of the tool around a circle 3.8 cm in diameter.

In Figure 1.15 a comparison is made between the material removal profiles for three different structural designs of the tool. Curve 3 corresponds to the final version of rotating and oscillating tools.

In the initial CCP system the coverage factor was selected equal to the required material removal. However, later the correction was introduced considering the difference between the required removal of material and that calculated for a real tool. Let us denote this difference for the i-th surfacing section in terms of E_i; the required material removal is D, and the actual removal will be expressed as the convolution of the coverage factor T_i with tool removal profile R:

$$E_i = D - T_i \ast R, \tag{1.5}$$

where the asterisk denotes the convolution operation. In equation (1.5) the coverage factor T_i is determined by the method of successive approximations according to the following algorithm. The value of the required material removal is taken as the initial value:

$$T_1 = D. \tag{1.6}$$

The residual chart of normal deviations will in the first approximation have the form

$$E_1 = D - D \ast R. \tag{1.7}$$

In the second approximation

$$T_2 = D + E_1, \; E_2 = D - D \ast (2\delta - R) \ast R, \tag{1.8}$$

where δ is the delta function. The entire iterative process can be written in the form of the expression

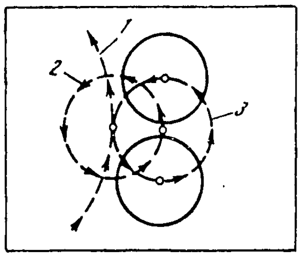
$$T_i = T_{i-1} + E_{i+1} = D \ast G_i(R), \; E_i = D - D \ast G_i(R) \ast R. \tag{1.9}$$

The auxiliary function $G_i(R)$ is defined by the recurrent formula

$$G_1 = \delta, \; G_i = G_{i-1} + \delta - G_{i-1} \ast R. \tag{1.10}$$

The sign of convergence of the process is smallness of the value δ defined by the expression

$$|G_i \ast R - \delta| < \epsilon. \tag{1.11}$$



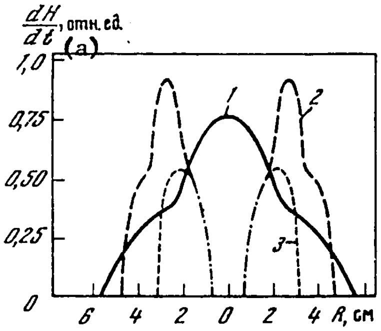


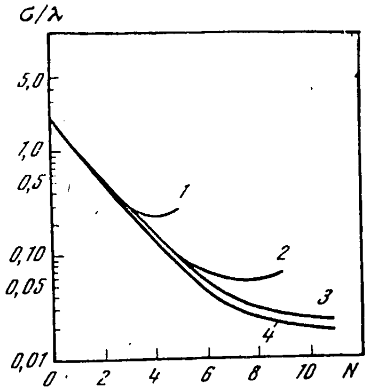
Figure 1.14. Diagram of the oscillating movement of a rotating tool.
1 -- trajectory of the center of the polishing head on the optical surface; 2 -- trajectory of rotation of the tool elements relative to the midpoint; 3 -- trajectory of motion of the midpoint.
Solid lines --tool elements

Figure 1.15. Rate of removal of material for tools of different structural designs.
1 -- two rotating elements 2.5 cm in diameter; 2 -- four rotating elements 1.5 cm in diameter; 3 -- rotating and oscillating tools with elements 3.5 cm in diameter

Key:
a. relative units

The results of model calculation of the convergence of the technological process indicating the effect of the correction of the coverage factor are presented in Figure 1.16. The model conditions are the same as when obtaining the results shown in Figure 1.10. Curve 1 corresponds to the case where a correction to the coverage factor is introduced for a rotating two-element tool. Surface quality with mean square error 0.11 of the wave length is achieved. Further improvement of the surface turns out to be impossible. Curve 2 indicates the convergence process for a rotating tool, but without correction of the coverage factor. However strange, the best shape of the surface is obtained here, which can indicate that for a rotating tool (without oscillation) the correction procedure can be degenerate. Finally, the best results permitting achievement of the surface with a mean square error of 1/50 of the wave length are illustrated by curve 4 which corresponds to the rotating and oscillating tools with correction of the coverage factor.

In the CCP systems special attention is given to the selection of the optimal trajectory of the tool over the optical surface. Two requirements are imposed on the trajectory: the constancy of the step size and absence of turning points. These requirements are satisfied by an Archimedes spiral. The tool begins movement from the center of the part, the movement takes place from the center to the edge and from the edge to the center without changing the direction of rotation. For calculation of the trajectory of the tool center along a circular or elliptic spiral, the following iterative procedure is used:



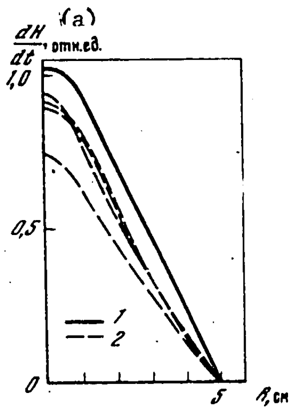


Figure 1.16. Results of model calculations of the convergence of the technological process for different operating conditions of the tool.
1, 2 -- rotating tool with correction and without correction, respectively; 3, 4 -- rotating and oscillating tools without correction and with correction of the removal profile, respectively

Figure 1.17. Material removal function by the rotating and oscillating tools.
1 -- theoretical removal of the material; 2 -- experimental removal profiles of the material

Key:
a. relative units

$$\begin{aligned} & C_i = \left(C_{i-1} + \frac{LS}{2\pi}\right)^{1/2}, \; \theta_i = \theta_{i-1} + \frac{2L}{C_i + C_{i-1}}; \\ \text{if} \quad & k = 1,\; R_i = C_i, \\ \text{for} \quad & k \neq 1,\; R_i = C_i/(k^2 \sin\theta_i + \cos\theta_i)^{1/2}, \\ & X_i = R_i \cos\theta_i,\; Y_i = R_i \sin\theta_i. \end{aligned} \qquad (1.12)$$

Here S is the spiral pitch which is considered to be positive for untwisting spirals and negative for twisting spirals; L is the length of the trajectory element, C_i is the distance from the part center to the i-th point on a steep spiral, θ_i is the position angle of the i-th point of the spiral, k is the ratio of the major and minor axes of the ellipse if the spiral is elliptic, R_i is the distance from the center of the part to the i-th point of the elliptic spiral, X_i and Y_i are the rectangular coordinates of the i-th point of the elliptic spiral with location of the X-axis along the major axis of the ellipse.

Table 1.1

Characteristic	Number of part No 1	 No 2	 No 3	 No 4
Surface type	Plane	Plane	Complex	Hyperbola
Size, mm	380 in diameter	813x883	305x330	1500 in diameter
Material	Servite	Beryllium	Servite	ULE
Mean square error, microns				
initial	0.14	0.25	1.0	0.83
final	0.008	0.03	0.1	0.05
Machine tool time, hours	4	65	99	-

In order to check the reproducibility of the removal of the material, trial experiments were run in which the tool completed rectilinear movement. In Figure 1.17 the line 1 indicates the theoretical removal profile; 2 indicates experimental profiles. From a comparison of them it is obvious that the reproducibility of the technological process is on the order of 10%. Knowledge of this factor is very important for determining the requirements on hardware entering into the automated system designed for manufacture of the optical system. In particular, the same order of accuracy or somewhat better (3-5%) must be required of the means of monitoring the surface shape and the devices removing the material.

Laboratory experiments in the manufacture of optical surfaces which are complicated for classical technology are of special value in the Jones papers [1975, 1977, 1978]. Information is presented in Table 1.1 on experiments performed using the CCP. The provisional numbers of the optical surfaces are presented in the first row.

The part 1 was a plane mirror made of servite. Practicing opticians well know how complicated it is to make a high-quality plane surface. The diameter of the part was 380 mm, the initial surface at a mean square error of 0.22 of the wave length; after surfacing on the CCP system, 0.012. The wave length was taken equal to 0.6328 microns. The total polishing time was 4 hours of machine tool time. Figure 1.18 schematically shows the course of improvement of the optical surface. If the relation between the mean square normal deviation σ expressed in wave length units and the surfacing time t(hours) are represented by a function of the type

$$\sigma = \sigma_0 z^{-t}, \tag{1.13}$$

the value of z characterizes the convergence rate of the technological process. According to Figure 1.18, the value of z=1.34. This convergence is rarely achieved in classical technology. In addition, and this is even more important, such precision for a plane surface is achieved by rare masters.

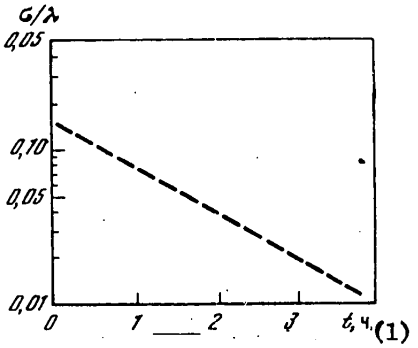


Figure 1.18. Experiment in finishing a servite mirror.
t -- surfacing time in hours, σ -- mean square deviation of the surface in fractions of a wave length (wave length is 0.6328 micron)

Key:

1. t, hours

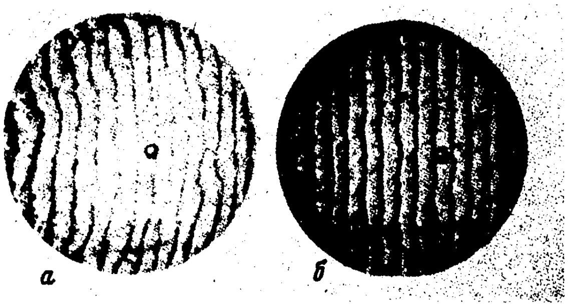


Figure 1.19. Experiment in finishing a servite mirror.
a -- interferograms of the optical surface before beginning the finishing operation; b -- interferogram of the surface after finishing in less than 4 hours of machine time.
The mean square error of the surface λ/80.[sic].

Figure 1.19 gives interferograms of the initial and final optical surfaces. From a comparison of the interferograms significant improvement of the surface, in the given case by almost 20-fold, is obvious. If we assume that the area distribution with respect to amplitude is subject to a gaussian law with dispersion of 0.012 wave lengths, the error amplitude for 95% of the mirror area does not exceed 0.048 of the wave length. The obtained plane satisfies the Rayleigh number which is formulated as λ/8.

The mirror 2 (see Table 1) is also plane. It is designed for use in a Newton type telescope, and therefore the shape of the billets is in the form of an ellipse with 813 and 883 mm axes. The mirror material is beryllium, the billet is lightened to a weight of 15 kg. Polishing by diamond abrasive continued for 65 hours of machine time. In order to avoid the effect of removal of the edge, the billet was placed in an aluminum ring which by using special attachments was installed flat against the part. The shape of the optical surface was measured by a Fizeau interferometer. In one procedure the interferometer permitted measurement of only part of the optical surface 760 mm in diameter. Therefore information about the entire surface was obtained by comparing three interferograms, and three resuperimposed sections of the optical surface were matched so as to achieve the least mean square difference in the common sections. After grinding and coating of the mirror the mean square error of the surface was 0.4 of the wave length. After completion of the surfacing of the CCP system the mean square error of the entire surface turned out to be 0.06 of a wave length, and on a diameter of 760 mm, 0.048 of a wave length. The interferograms of the central part of the mirror before and after treatment are shown in Figure 1.20. The value of z characterizing the convergence rate of the technological process, according to formula (1.13) is 1.033.

The manufacture of the mirror 3, which is a corrector, the optical surface of which does not have axial symmetry is of exceptional interest. The manufacture of this part by classical procedures is connected with enormous difficulties. The form of the optical surface is a segment of a Schmidt reflecting plate, and the material is servite. The billet has the shape of an ellipse with axes of 305 and 330 mm. After the billeting operation and coating, the optical surface turned out to be so complicated that the application of automated scanning of the interferograms turned out to be impossible (see Figure 1.21, a). From the mirror a plane was made which gives a mean square deviation from the required surface of 1.56 of a wave length. During machining on the CCP, the quality of the interferograms became so good that it became possible to use the scanning procedure. In 17 sessions with a total duration of 99 hours, the deviation became equal to 0.17 of a wave length with a requirement of 0.2. Figure 1.21, b shows the interferogram of the completed surface. In the optical control system the wave front is reflected from the corrector twice; therefore the distance between the bands on the interferograms is equal to $\lambda/4$.

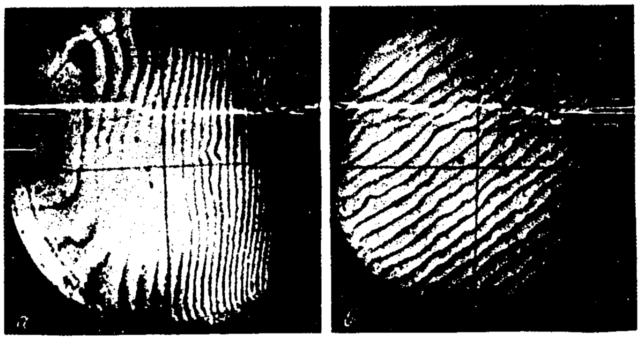


Figure 1.20. Interferograms of a plane beryllium mirror before surfacing (a) on the CCP system and after completion of surfacing (b)

The procedure for manufacturing a large flexible aspherical mirror 4 is of interest (see Table 1). The shape of the optical surface is hyperbolic, the part diameter is 1500 mm with a billet thickness of 90 mm. The material is ULE which has a small coefficient of linear expansion. During the process of surfacing and control the mirror was set up for unloading, simulating behavior of the part under conditions of weightlessness.

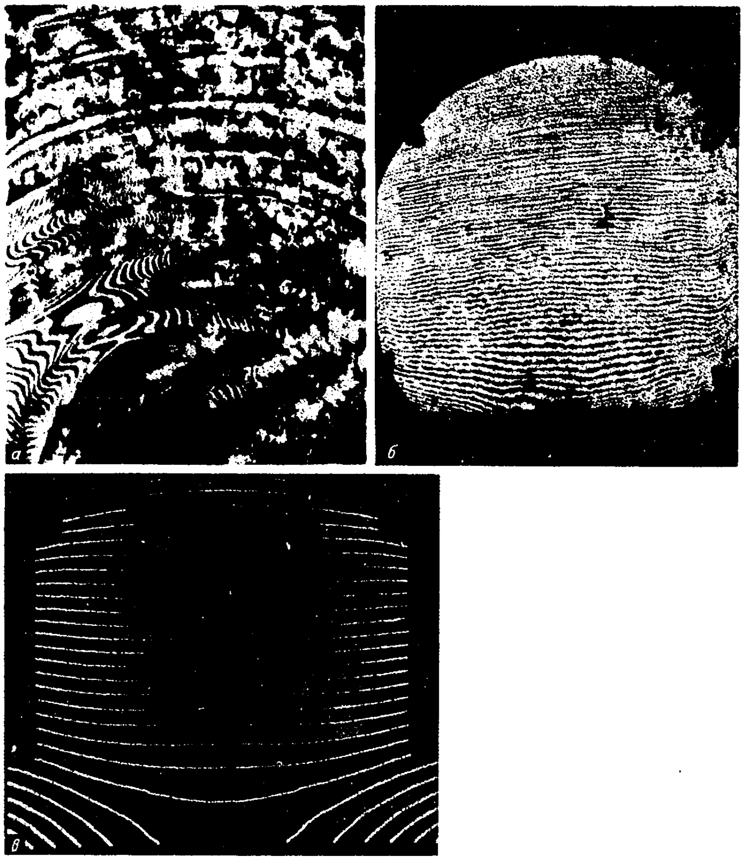


Figure 1.21. Interferograms of an aspherical nonaxisymmetric correction plate which is a segment of a Schmidt plate.
a -- before beginning of surfacing on the CCP; b -- after completion of surfacing; c -- model of an interferogram calculated on a computer for an ideal plate with some inclination of the optical axis.
On all of the interferograms the spacing between the bands is $\lambda/4$, where $\lambda=0.6328$ micron.

The studies were performed in a vacuum corridor; a corrector was included in the optical system. The initial mean square error of the optical surface was 1.35 of the wave length, and the final mean square error was 0.074. Here the greatest error amplitude is achieved for the edge of the part (see Figure 1.22). If we exclude the edge zone from the investigation, the error turns out to be 0.059 of the wave length. The radius of curvature of the mirror in the papers by Jones is not indicated, it is only mentioned that the surface deviates significantly from a plane. The total duration of the surfacing is also not presented.

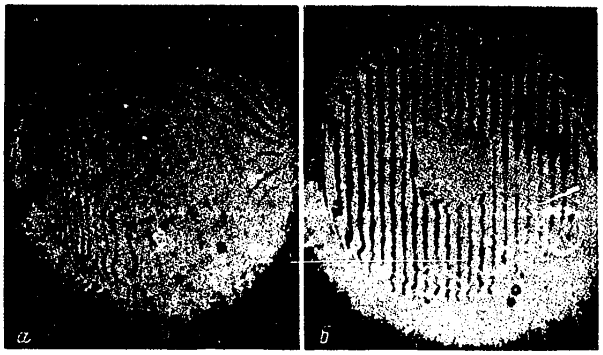


Figure 1.22. Interferograms of a hyperbolic mirror 1500 mm in diameter before the beginning of surfacing on the CCP (a) and after completion of surfacing (b)

2. Tool Speed Control

The tool speed vector with respect to the part has three components: the rotation rate of the part on the machine tool spindle, rotation part of the tool and speed connected with harmonic movement of the upper element.

The control of the rotation rate of the part is difficult in view of the fact that astronomical measures have great mass. For this reason significant variations of the velocity are impossible, and small variations of the velocity create a small dynamic range of regulation which leads to long surfacing time. Nevertheless this type of control is exercised on the START type machine tools produced in small series by industry. As a result of absence of software for designing the process conditions and absence of methods of controlling the shape of the optical surface these machine tools in practice are not used. In a number of foreign patents (see, for example, [patent No 3566544, 1971]) original methods of controlling the speed of the part are described, but these methods are hardly applicable to large products.

In the classical optical machine tool the upper element bearing the tool undergoes harmonic oscillations. The extreme positions of the tools are in a special position: here the linear velocity is close to zero. Even if the law of motion of the upper element is varied, the edge positions of it become singularities. In order to create the possibility of controlling the movement of the carrier it is necessary decisively to change the kinematics of the optical machine tool; the part must not turn on the spindle; otherwise it becomes impossible to eliminate local errors; speed control software must be created.

Forced rotation of the tool is most frequently used not to control the material removal, but to stabilize the shaping process. If we use a variable rpm to control the removal of the material, the effect of directional wear of the tool appears, which in turn, creates "craters" on the part at the points of increased removal. This effect has the same physical meaning as "corrugation" of parts during zonal control of the machining time. So far as we know, no work is being done in this area.

3. Tool Trajectory Control

This procedure was implemented by the American "Aytek" company [Aspden, et al., 1972]. On a specially built machine tool permitting displacement of the small tool in two mutually perpendicular directions, a trajectory is realized which provides for the required removal of material. This trajectory is calculated in advance by the results of the monitoring, and it is output to punch tape, by means of which the tool is controlled by the calculated trajectory. The method is successfully tested for manufacturing errors up to 1 meter in diameter. In several hours of finishing it was possible to obtain surface quality with a mean square normal deviation of $\lambda/40$, which satisfies the Marechal criterion [Marechal, 1947]. The classical procedures are unable to obtain surfaces of this quality and the surfacing time is reduced by tens of times by comparison with the surfacing time by classical technology.

In contrast to classical technology, in the CAOS/XY system the part does not rotate, but remains stationary. The tool has a possibility of completing any movements over the optical surface with constant pressure. The size of the tool, also in contrast to classical technology, is much less than the part diameter. As a rule, the tool diameter is 1/3 or less of the part diameter. The complete process cycle (session) consists of the following steps.

1. Obtaining interferograms of the optical surface subject to surfacing. Inasmuch as only the finishing step is considered, the optical surface is polished.

2. The interferogram is scanned either manually or using an automatic device, and then the chart of normal deviations in the entire optical surface is constructed. The chart is digitalized so that the entire surface will consist of hexagonals adjacent to each other. The normal deviation pertains to the center of the hexagon.

3. Using a computer, the size of the tool is calculated so that the possibility of eliminating the majority of errors in minimum time will be created. The tool also is represented in the form of adjacent hexagons.

4. Using a computer the time is calculated during which the tool must surface each of the hexagons of the optical surface until the error is eliminated. The calculations are made under the assumption of constant speed of the tool with respect to the part and constant force of the tool on the part.

5. Using the computer, a continuous trajectory is calculated for which the center of the tool is in the process of its movement within the limits of each hexagon during the time calculated in the preceding section. The coordinates of this trajectory are recorded successively on magnetic tape.

6. The control of the tool trajectory is realized by a special device by the coordinates recorded on the magnetic tape. Then the optical surface is investigated again by the interferometer, and the entire cycle is repeated until the given quality of optical service is achieved.

In Figure 1.23,a, a chart of normal deviations is provisionally illustrated which was constructed using lines of equal levels. In Figure 1.23,b, a chart of the same surface is presented, but separated into elementary areas having the shape of right hexagons. In the center of each area, the height of the material subjec to removal is indicated in provisional units.

After the size of the tool is selected, its elemental areas are assigned some removal function which is nonuniform with respect to the tool area. In Figure 1.24 a schematic model of the tool and normal deviation chart are presented; the removal of the material for each pass of the tool over the element of optical surface is shown in each elemental area by the numbers. In the given example it is proposed that the central part of the tool remove twice as much material as the peripheral element. The chart of normal deviations is constructed with simulation of the tool trajectory. The boldfaced line outlines the position of the tool, and the negative numbers indicate the amount of material removed at the given time.

As was mentioned, in one process session it is impossible to completely eliminate all of the errors inasmuch as the inverse problem does not have an accurate solution. This inaccuracy of the solution is first of all connected with the finite size of the tool. The solution turns out to be a fact only for infinitely small size of the tool and infinitely long surfacing time. Figure 1.25 illustrates what has been stated. The normal deviation chart is shown here which, according to the calculations, remains after the production session. This chart must have two characteristic features: the error amplitude must be several times less than in the additional chart; the characteristic size of the errors must be less than for the initial optical surface. The satisfaction of these conditions is an indirect indication of the correctness of the calculated session.

The final result of simulating the movement of the tool is a chart indicating how many times the center of the tool must hit the given elemental area. Such a chart is shown in Figure 1.25, a.

The trajectory of motion of the tool satisfying the conditions of the required removal of the material is presented in Figure 1.25, b.

Figure 1.26 shows a photograph of the CAOS/XY machine tool. The white broken line was obtained as follows. A light (the experiment was performed in a dark facility) was fastened to the carrier, and a prolonged exposure was made during which the carrier completed the movement calculated by the computer and recorded on magnetic tape twice. This machine tool permits the parts to be machined to 1100 mm in diameter. A part 800 mm in diameter was installed on the machine tool (see Figure 1.26). In the front plane of the figure, the guide along the Y axis is visible, and in the rear plane, the control unit.

The results of the experiments on the CAOS/XY system demonstrated high effectiveness of the system both with respect to the achieved quality of the optical surface and with respect to their manufacturing times. Thus, the spherical mirrors 600 mm in diameter with a radius of curvature of 3000 mm could be finished to the shape the mean square error of which from the nearest comparison sphere is $\lambda/40$. The interferogram of this surface is shown in Figure 1.27. An obstruction on the edge amounting to 5-8% of the part diameter is visible on the interferogram. This obstruction is obtained also when using a large tool, so that the small tool does not introduce additional errors when surfacing the edge zone.

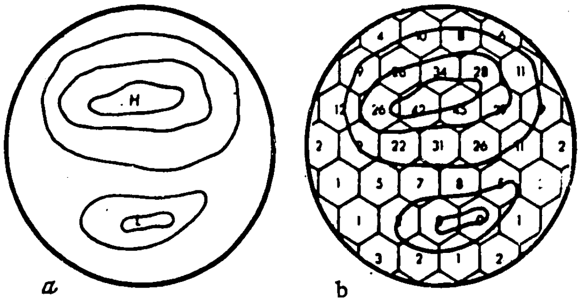


Figure 1.23. Schematic representation of an optical surface.
a -- mockup of the optical surface (H is the local mound on the optical surface, L is a hole); b -- digital representation of an optical surface in the form of hexagonal elemental areas.

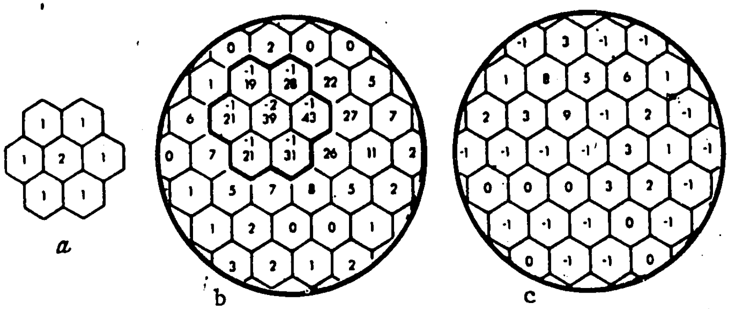


Figure 1.24. Diagram of the machining of an optical surface using the CAOS/XY system.
a -- schematic representation of the tool (the numbers indicate the removal material in provisional units); b -- schematic representation of the part and operation of the tool; c -- optical surface after the production session

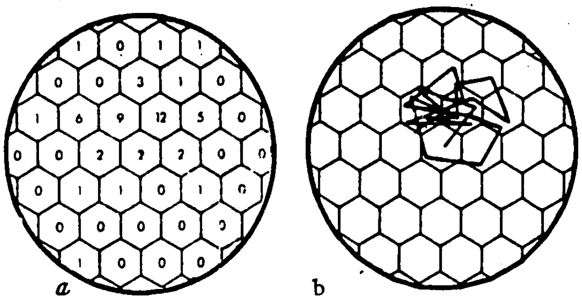
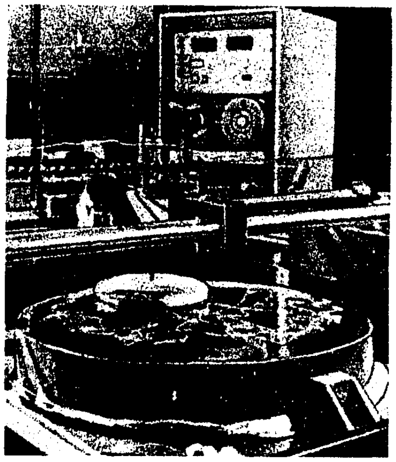


Figure 1.25. Relation between the shape of the optical surface and the method of moving the tool in the system.
a -- mockup of the optical surface; b -- path of the center of the tool calculated by computer



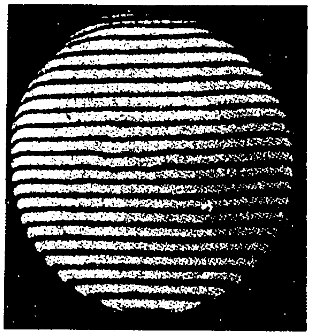


Figure 1.26. Trajectory of motion of the tool on the CAOS/XY-machine tool permitting parts to be surfaced to 1100 mm in diameter.

Figure 1.27. Interferogram of a spherical surface 600 mm in diameter with a radius of curvature of 3000 mm (the part is made on the CAOS/XY machine tool).

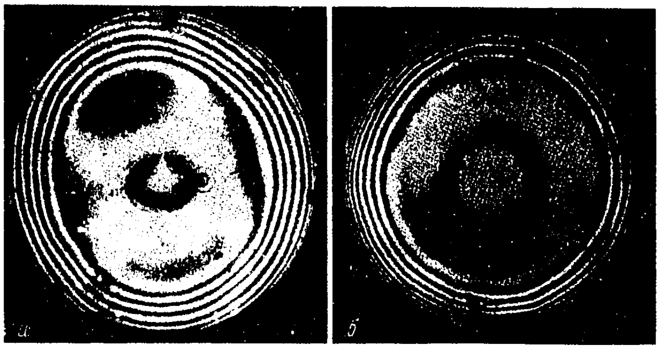


Figure 1.28. Interferograms of surfaces indicating correction of astigmatism using the CAOS/XY machine.
a -- significant astigmatism; b -- the same surface after surfacing for 13 hours.

In the opinion of the authors, the CAOS/XY system cannot demonstrate high effectiveness on simple spherical surfaces. The main area of application of the system is the creation of nonspherical and even nonaxisymmetric surfaces and also elimination of local errors. Astigmatism of the optical surface of an astronomical mirror presents special danger for classical technology.

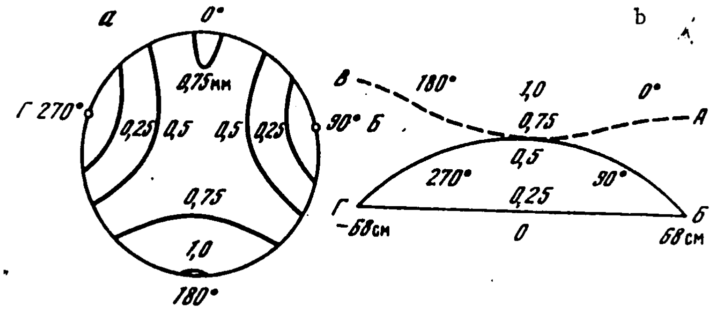


Figure 1.29. Diagram of the structure of an optical surface on an extra-axial parabolic segment
a -- chart of normal deviations from the comparison sphere;
b -- surface cross sections.
All the values are given in mm

Figure 1.28 shows how the astigmatism was reduced significantly using the system. The left interferogram belongs to the surface having astigmatism which opticians could not eliminate by the methods of classical technology. In the righthand figure there is an oscillogram of the same surface after 13 hours of surfacing. From a comparison of the interferograms it is obvious that the astigmatism is reduced significantly, although it is not completely eliminated. Neither the part diameter nor the radius of curvature nor the nature of the shape of the optical surface are indicated in the article.

For certain types of telescopes and for fast cameras of spectrographs, segments of aspherical surfaces are needed. The existing practice of obtaining them consists in manufacturing a symmetric aspherical surface, from which segments of the required shape are then cut. The inefficiency of this method is obvious. The CAOS/XY system permits segments of aspherical surfaces to be made.

Figure 1.29 shows the shape of an aspherical segment. The deviation from the nearest sphere is about 300 wave lengths. The part diameter is 1360 mm. The experiments were also performed on an aspherical segment 800 meters in diameter with a radius of the maximum sphere of 5000 mm, asphericalness of 100 wave lengths, the axis of symmetry was 75 mm from the end of the part. In both cases after grinding, before finishing the local errors were 5-10% of the asphericalness.

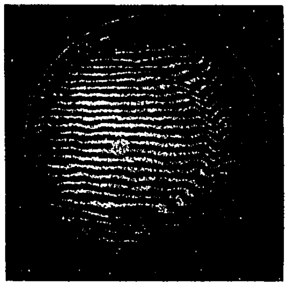


Figure 1.30. Interferogram of an extra-axial aspherical surface during the machining of it (the asphericalness is 300 wave lengths)

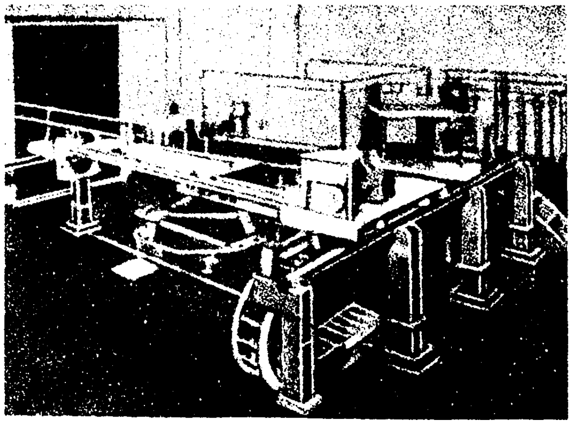


Figure 1.31. CAOS/XY type machine tool surfacing parts up to 2.5 meters in diameter

Figure 1.30 shows an interferogram of a surface with asphericalness of 300 wave lengths obtained during the process of finishing.

Figure 1.31 shows the CAOS/XY machine tool permitting parts up to 2500 mm in diameter to be surfaced. A symmetric aspherical part 1000 mm in diameter was made on it; the mean square error of the final surface was 1/10 wave length.

A still more important system for finishing astronomical mirrors was proposed by another American company "Perkin Elmer" [Jones, 1977]. Here, a computer was included in the control circuit, that is, the realization of the trajectory originated with the computer.

The decisve advantage of the described systems is the possibility of eliminating local errors and also the manufacture of parts of complex asymmetric shape, for example, extra-axial paraboloids. The only, but very serious deficiency of this system is the necessity for manufacturing a special optical machine tool.

The manufacture of the special optical machine tool or special tool is a necessary condition of realizing all of the control methods described above. This fact greatly complicates the application of these methods in industry inasmuch as two difficulties arise here.

The first of them is of an economic nature and is connected with the necessity for replacing the machine tool fleet of industry which leads to large expenditures of time and resources. These expenditures are paid for, but the return time is large in connection with the enormous organizational difficulties. A second difficulty is of a psychological nature, and overcoming it can turn out to be even more complicated. The fact is that in the last decades optical machine tools have changed little with respect to structure; the master opticians have become accustomed to them and have accumulated a great deal of experience in handling them. If the machine tool fleet is replaced by unfamiliar machine tools the accumulated experience is lost, and the necessity arises for retraining the practicing opticians. This again requires great time and organizational expenditures and can greatly reduce the production output in the optical industry for several years.

4. Control of the Tool Force

At the Leningrad Institute of Precision Mechanics and Optics an attachment has been built which permits smooth variation of the force (pressure) of the tool on the part. The attachment is shown in Figure 1.32 and is set up as follows [Rusinov, 1973]. The optical part 7 is rotated on the spindle of the optical machine tool. The grinder 8 is connected by a ball hinge 6 to the carrier 1 which undergoes oscillatory movement. The shaft of the carrier 1 is suspended on the carrier frame 4, which permits the grinder to rub freely against the optical surface. New elements in the optical machine tool are the weight 2, which permits the creation of a constant force of the tool on the part which does not depend on the tool position; the second arm 3 with weight 5 attached to it. During rocking of the carrier, the arm of the weight 5 changes, which leads to variation of the pressure P of the tool on the part by the law

$$P = \frac{A}{B + e} + C, \qquad (1.14)$$

where the constants A, B and C are related to the masses of the weights 2 and 5 and also to the arms of the levers in the system, e is the eccentricity, that is, the shift of the center of the tool with respect to the center of the part.

The control of the removal of the material using this device is possible only for a special case. An analysis of formula (1.14) and conclusions of a general nature contained in the book by Rusinov [1973, p 286] remain valid only in the case where the machine tool function is equal to one for any value of the eccentricity. For real optical machine tools this is not done at all. In addition, nonmonotonic errors characterisic of astronomical optical systems cannot be eliminated even if the machine tool function is equal to one. We are primarily talking about local errors without symmetry with respect to the center of the part.

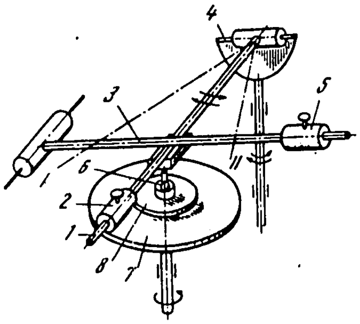


Figure 1.32. Device for monotonic variation of the force of the tool along the optical surface zones.
1 -- lever; 2 -- weight; 3 -- second lever; 4 -- carrier frame;
5 -- weight of the second lever; 6 -- ball hinge; 7 -- rotating part;
I, II -- extreme positions of the lever; 1, 8 -- grinder.

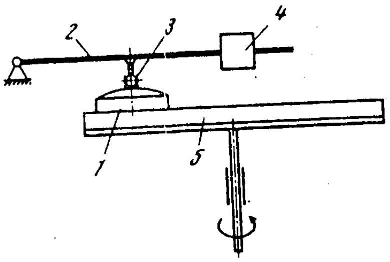


Figure 1.33. Lever device for programmed pressure on the optical surface zones
1 -- grinder; 2 -- lever; 3 -- ball hinge; 4 -- weight; 5 -- rotating part

In formula (1.14) the value of e changes sign when the tool passes through the center of the part. An elementary analysis of formula (1.14) indicates that the radius of curvature of the part must increase in the surfacing process if it is concave and decrease if it is convex.

In the book by Rusinov [1973] another method of controlling the force, digitally, is described. The diagram of this device is shown in Figure 1.33. The grinder 1 which is connected by a ball hinge to the lever 2 is installed on the rotating part 5. One end of the lever 2 is fastened to the bearing so that the lever can turn around the horizontal axis, and the weight 4 is fastened to the other end of the lever. The magnitude and position of the weight 4 determine the force of the tool on the part. It is possible to install several grinders of similar type in various zones on the part, thus insuring programmed removal of the material.

By this tool it is possible to eliminate any axisymmetric errors and apply different asphericalness. However, each of the tools will be directionally worn, which leads to "corrugation" of the optical surface. In addition, the procedure will not permit elimination of local errors.

In Soviet industry a tool has been being developed for many years which will permit programmed variation of the force of the tool on the part using hydraulic devices. The structural principle of the multielement tool is used [author's certificate No 218687, 1968; author's certificate No 370014, 1973; author's certificate No 360199, 1972].

A diagram of the tool appears in Figure 1.34. The surfaced optical part 2 is rotated on the spindle of the machine tool. The working elements 1 are connected by ball hinges to the pushers 3. The pushers can be displaced inside the cylinders installed in a flexible diaphragm 4. In the upper part of the tool 5 cylinders are installed with a liquid which regulates the magnitude of the pressure of the tool 1 on the part 2. The tool does not rotate, but undergoes oscillatory motion. For connection to the hydraulic device, flexible hose 6 are used. There can be several operating elements. The device operates only if the upper part of the tool 5 is attached so that it has no freedom of movement along the normal to the optical surface.

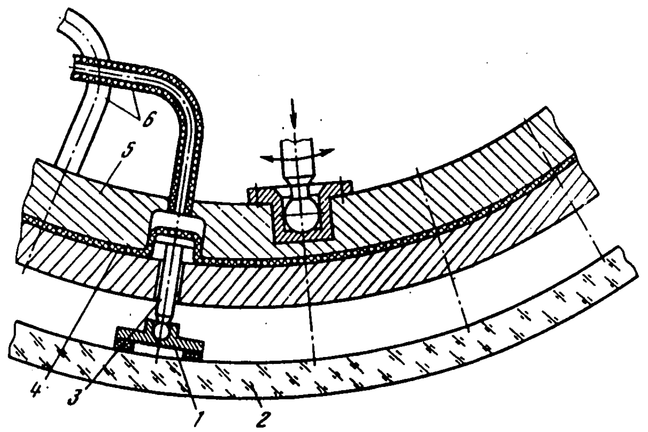


Figure 1.34. Diagram of the tool permitting variation of force in the surfacing process.
1 -- operating tool, 2 -- surfaced part, 3 -- pusher, 4 -- diaphragm, 5 -- upper part of the tool, 6 -- flexible hoses

It is possible to use the tool (see Figure 1.34) for axisymmetric removal of material. A deficiency is the impossibility of eliminating local errors. In addition, the system has one specific deficiency characteristic of multielement tools, the working elements of which have different load. The fact is that variation in load on one of the working elements leads to redistribution of the load on the remaining elements which leads to instability of the development of the forces. Theoretically the described element can also be used to eliminate local errors. For this purpose it is necessary to install a sensor of the rotation of the angle of the optical part and use a computer to execute variable forces on each of the tools in time. However, the hydraulic drives have low speed. This leads to the fact that the force will not be executed where needed. Therefore the hydraulic drives must be replaced by electrodynamic drives, the speed of which is one or two orders higher.

In one of the first attempts to control the removal of the material by varying the pressure [Dvornikov, et al., 1960] the control effect was not achieved. The cause was that a full sized tool was used. It is obvious that in the pressure control mode, just as in any other local retouching mode, it is necessary to use a small tool, the theory of the application of which was developed in the papers by Lysyannyy [1972, 1974] and Semibratov [1958]. The proportionality of the removal of the material to the applied force has been checked more than once [Kachalov, 1958].

We have stated the following problem. By using local pressure control of the small tool on the part in real time and using an ordinary optical machine tool, let us obtain the possibility of making high-precision optical surfaces, including extra-axial, aspherical surfaces. Strictly speaking, the degree of complexity of the optical surface in our statement of the problem has no bearing on the technology inasmuch as for realization of the production we must know only the tolerance of the part h(x,y), that is, the difference between thetrue and the required shapes of the optical surfaces. The information about h(x,y) is obtained in the control subsystem.

In order to solve the stated problem in accordance with (1.1) it is necessary to create a force P(x,y) in real time according to the law

$$P(x,y) = h(x,y)/KT\psi(\rho), \qquad (1.15)$$

where ρ is the current radius of the zone on the optical surface, the function $\psi(\rho)$ determines the removal of material with constant pressure (hereafter, the machine tool function), K is the process constant (see (1.1)), T is the surfacing time.

Formula (1.15) is accurate, but under the assumption that the size of the tool is much less than the diameter of the part. In practice the tool has finite dimensions. However, the performed experiments in the case of this restriction turns out to be insignificant, and the given approximation can be successfully used. The size of the tool can be considered, but in this case the calculations of the process conditions become so awkward that the necessity arises for using expensive large computers for many hours of computation.

The most important advantages of the force control method are the following: the possibility of automating any series optical machine tool without significant modification of it; the use of an ordinary tool in the form of a free lapping tool; simplicity of automation with the application of a computer both in the adviser mode and in the control mode; possibility of servicing parts of as complex a shape as one might like and elimination of the types of errors, including local errors; as a result of classical kinematics the "corrugation" effects connected with the application of a small tool are absent.

When using the given control procedure, as a result of convergence of the shaping process, acceleration of the finishing operation by tens of times is achieved, and the possibility is created for improving the shape of the optical surface by several times by comparison with classical technology [Prokhorov, et al., 1978, 1979].

5. Requirements on Automation Hardware

The most astonishing feature of optical technology is the possibility of creating exceptional surfaces with respect to precision, using comparatively rough machine tools. The same comment applies to the hardware which is used in the ZEBRA automated system.

Let us know the normal deviations h(x,y) of the existing optical surface from the required surface where x,y are the coordinates on the optical surface. Let the normal deviations be stored in a computer memory. Let us consider the requirements on the hardware permitting elimination of the indicated errors by progammed alteration of the force.

In addition to the ordinary optical machine tool the hardware must include the following devices:

Tool center position sensors with respect to the coordinate system on the optical surface; one of the sensors determines the current angle of rotation of the spindle, and the othe-, the carrier;

A pressure (force) gauge for the tool on the part;

A servomechanism which permits the force of the tool on the part to be varied in real time;

A control unit in which information is stored about the relation between the coordinates on the optical surface and the code of the servosignal. The control unit, the role of which can be played by the control computer, combines the position sensor and pressure gauge and the servoelement of the system.

A common requirement on all of the elements of the automated system is sufficient speed. Let us determine this value as follows. Let ν_m be the maximum admissible speed of the tool with respect to the part. This speed exists inasmuch as it is known [Krupenkova, et al., 1973] that with an increase in speed the removal of material begins to increase, and then it decreases sharply. Then let us assume that the optical surface is characterized by a mean size of the irregularities ℓ. Then the speed of the automated system (the time constant) is defined by the inequality

$$\tau<\ell/\nu_m. \qquad (1.16)$$

Let us consider an example. Let it be necessary to improve the quality of the astronomical mirror 1 meter in diameter. As was demonstrated in the paper by Vitrichenko [1976], the characteristic size of the irregularities for astronomical errors is on the order of 0.1 of the part diameter, that is, in our case it is 0.1 meter. The recommended polishing speed is a value on the order of 1 m/sec [Krupenkova, et al., 1973]. By formula (1.16) we obtain the required speed of the system $\tau < 0.1/1=0.1$ second. This speed is comparatively easily realized by modern electronic devices. However, let us note that hydraulic and pneumatic devices of appropriate power have an order less speed and are not suitable for our purposes.

The next requirement on the hardware is position accuracy of the sensors. The error in determining the coordinates of the tool center σ must satisfy the obvious inequality

$$\sigma<\ell. \qquad (1.17)$$

If the part diameter is D, then the spindle rotation angle gauge must provide precision of Δ_1 defined by the inequality

$$\Delta_1<\ell/\pi D. \qquad (1.18)$$

Let L be the arm of the carrier, and let Δ_2 be the required precision of the rotation angle gauge. The value of Δ_2 is defined by the inequality

$$\Delta_2<\ell/L. \qquad (1.19)$$

Let us estimate the order of magnitude in the example of surfacing a 1-m mirror. According to (1.17) for position precision $\sigma<0.1$ m. For the spindle and carrier angle gauges we obtain $\Delta_1<0.1/\pi \simeq 0.3$ meters and $\Delta_2<0.1/1 \simeq 5^\circ$, respectively. When using the gauges with double system for regulating the angle four or five bits are sufficient.

In order to determine the precision which must be provided by the force gauge and servo, we use the fact that the applied methods of monitoring the shape of the optical surface have precision on the order of 10% of the error amplitude [Beskin, et al., 1975]. The technological polishing process is reproduced with the same precision or somewhat worse. For these reasons it is necessary to require a precision on the order of 10% of the force amplitude of the force gauge and servo. In the investigated example with maximum admissible specific pressure of 100 g/cm^2 and a tool diameter of 300 mm, the limiting force is 80 kg, and the required precision with respect to the force is 8 kg.

Conclusions

It is possible to automate the process of shaping optical surfaces by many methods. However, in our opinion, it is preferable to use the method of controlling the local pressure of a small tool in real time with the application of a minicomputer. For implementation of this procedure there is no necessity for manufacturing new models of optical machine tools or complicated tools.

As a result of the application of ordinary movement of the tool over the surface, that is, rotation of the spindle with the part and harmonic oscillation of the upper elements, effects connected with the application of a small tool do not arise in this procedure. It turns out to be possible to manufacture parts of complicated shape and eliminate any types of errors of the optical surface.

The hardware existing at the present time permits complete solution of the problem. Laboratory and plant tests of models of the system realizing the indicated principle have demonstrated the prospectiveness of this procedure.

CHAPTER 2. AUTOMATED SYSTEM SOFTWARE

The division of the control of the removal of part material investigated here is based on breakdown of the part into annular zones and assignment of a pressure (force) within the limits of each zone which will provide the required removal of material. For the given procedure it is indifferent whether we eliminate the zonal errors or give the part an aspherical shape. It is also indifferent what the process of removal of the material is: grinding or polishing. For determinacy, hereafter we shall consider the process of improving the surface quality of a part having its zonal error by the polishing method inasmuch as the process of controlling polished parts has been well developed [Vitrichenko, 1980]. The problem of whether the given machined surface is a sphere, paraboloid or other figure of rotation has no significance for the given procedure inasmuch as it pertains to the surface shape control subsystem. The quality control subsystem defines the tolerance subject to removal as the difference of the real and ideal surfaces whatever the ideal surface may be.

Introduction

The production cycle of manufacturing an optical surface of an astronomical mirror can be schematically represented as consisting of three basic steps as illustrated in Figure 2.1. The state of the optical surface where the polishing is done after all the rough and fine grinding operations have been completed, eliminating the surface mat after the last grinding, is taken as the finishing process. The optical surface can have the shape of a sphere, in spite of the fact that a parabolic mirror, for example, is required. The operations of asphericalization and elimination of zonal errors are combined in the automated system.

During the work on the optical surface the question of its real shape or, more precisely, the deviation of the real shape on the surface from the required ideal shape comes up as the most important question. These deviations which are measured along the normal to the optical surface will be called normal deviations. The shaping process reduces to the elimination of normal deviations (tolerance). There are a number of methods of determining the shape of the surface. A detailed analysis of them can be found in the books by Puryayev [1976] and Vitrichenko [1980]. In the ZEBRA-1 system investigated here, an express version of a classical Hartmann method is used which permits operative determination of the mean normal deviations along the radius of the part based on an analysis of the transverse aberrations along two mutually perpendicular diameters. The HART2 program, which implements the given approach, is described in the paper by Vitrichenko and Karagarov [1978], and the text of the program is presented in the book by Vitrichenko [1980].

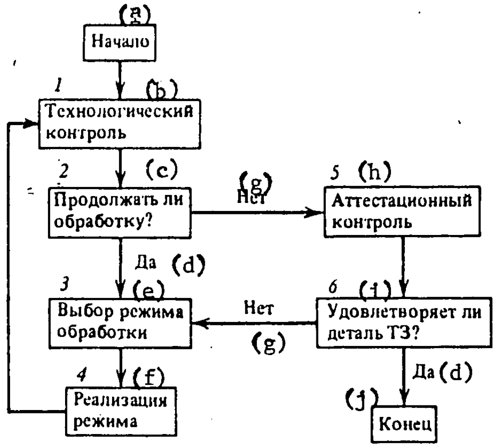


Figure 2.1. Process flow diagram of the finishing of the optical surface of an astronomical mirror

Key:

a. Begin
b. Process control
c. Continue surface?
d. Yes
e. Choice of surfacing conditions
f. Realization of the mode
g. No
h. Certification control
i. Does the part satisfy the technical assignment?
j. End

The next problem arising for the manufacturing optician consists in making the decision (see Figure 2.1, block 2) whether to continue or end the machining of the optical surface. When making this decision it is necessary to generate the criterion by which the decision is made. The criterion, whatever it may be, is of the nature of a voluntary decision. In this case it is not the formulation of the criterion itself that is important, but its determinacy. In the most general case the formulation of the criterion depends on the purpose of the part. For astronomical mirrors the starting point when shaping the criterion can be a comparison of errors of the optical surface with the mirror resolution having the given type of error. The lower quality limit of the mirror can be obtained, analyzing the astroclimatic conditions at the point of installation of the telescope. The problems of the quality criterion of astronomical mirrors are investigated in the papers by Gascoigne [1973] and Hale [1973].

As an example and, considering the process that we have adopted, it is possible to propose the following formulation of the criterion for completion of the work on the part: it is necessary to stop work on improvement of the surface shape if one of two conditions is satisfied: 1) the amplitude of the mean normal profile on the part radius does not exceed $\lambda/8$; 2) the amplitude of the local errors is comparable to the amplitude of the mean normal profile along the radius of the part.

Both of the presented criteria are checked using the HART2 program. The first criterion corresponds to the Rayleigh number which has been criticized many times, but it still remains the most widespread number. In astronomy we take $\lambda=0.55$ micron. Let us denote the amplitude of the normal profile by A; then the first criterion is written in the form

$$A<0.07 \text{ micron}. \tag{2.1}$$

When satisfying the first criterion further surfacing can lead to insignificant improvement of the mirror both with respect to resolution and with respect to energy concentration inside the Airy circle. This improvement does not exceed 20%, and the expenditures on achieving it can turn out to be unjustifiably high.

The second criterion is connected with the characteristic feature of the technology that we have adopted. Pressure control of the small tool on the part by zones leads to success only in the case where the errors of the optical surface also have a zonal structure. However, as a result of nonuniformity of the billet with respect to grindability, local errors obtained when grinding or as a result of the effects of adjusting the machine tool, nonzonal errors can occur with which our procedure is in no position to deal. This is an emergency situation, and in this case it is necessary to stop work on the optical surface and, depending on which of the indicated effects has occurred, either begin work with another billet or eliminate the systematic errors connected with the machine tool adjustment or regrind the part. A more radical solution to the situation is also possible: create a process which permits elimination of nonzonal errors [Aspden, et al., 1972; Jones, 1977]. The second criterion can be written as follows:

$$A<3\sigma, \tag{2.2}$$

where A is the amplitude of the normal profiles along the part radius, σ is the mean square error in determining the mean normal profile.

If it has turned out that none of the criteria is satisfied, it is necessary to continue to machine the optical surface for which it is necessary to develop the parameters of a new production session (block 3, see Figure 2.1). In the "surfacing mode" concept there are three variables: the matrix of forces in each of the zones of the part, the total surfacing time and the size of the tool. The first two values are calculated by the PRES3 program, the tool size is calculated by the SIZE1 program. The initial data for operation of the programs are the file of normal deviations along two diameters of the part which is formed by HART2 program. In addition, using the PRES3 program it is necessary to know the removal of material per unit force per unit time $\psi(\rho)$ and the process constant K defining the absolute removal of the material at the center of the part with a unit force per unit time. In the next section the methods of determining these values will be considered. Here we shall only give a definition of the process function which we shall hereafter call the "machine tool function."

$$\psi(\rho)=h(\rho)/h(0), \tag{2.3}$$

where $h(\rho)$ is the thickness of the removed material with constant force of the tool at a distance ρ from the center of the part, $h(0)$ is the thickness of the removed material at the center of the part. By whatever method the machine tool function and the process constant are determined, they must be more precisely determined in experiments. In particular, when calculating the machine tool function it is very complicated to consider the well-known edge effects: the effects of "holding up" or "breaking off" of the edge. This problems will be considered in the next section.

The tool size is calculated as the average distance between the extrema on normal profiles of the optical surface. This means that in 50% of the cases the tool size turns out to be larger than or on the order of the irregularity dimensions, and in 50% of the cases, less. However, the small irregularities with respect to dimensions, as a rule, have lower error amplitude so that the assumption made turns out to be satisfactory.

After choosing the process conditions comes the implementation of the process by the hardware (see Figure 2.1, box 1). In the ZEBRA-1 system, the part is installed on a rotating spindle, the carrier which bears the free lapping tool undergoes harmonic oscillations. During the movement of the carrier, the angle gauge measures the position of the tool center relative to the part center; this angle is input to the control unit which generates the signal for the servoelement. The servoelement realizes the required force.

After realization of the process conditions (see Figure 2.1, block 4) it is necessary to return to the production control (block 1), thus completing the basic production cycle.

Let us consider the situation where the condition (2.1) is satisfied, and the condition (2.2) is not satisfied. This case corresponds to normal completion of the work on the optical surface. The decision is made to curtail the surfacing and proceed to certification of the finished part (see Figure 2.1, block 5). The certification control and the production quality control pursue different goals. Whereas the shape of the optical surface is basically of interest during the production studies, which offers the possibility of eliminating errors, during certification primary attention is given to investigation of the dispersion circle inasmuch as this characteristic is the most important for use of an astronomical mirror for its designed purpose.

The production control and certification control are also distinguished by degree of detail with which the optical surface is studied. For example, in the ZEBRA-1 system during production control only two diameters have been studied on the optical surface. For certification of the finished mirror, information is obtained about the entire optical surface. This, in turn, makes it possible to obtain detailed information about the dispersion circle by calculation methods. It is exceptionally important to investigate the dispersion circle also experimentally inasmuch as no mathematical simulation is in a position to consider all of the details of the formation of the dispersion circle.

The possibility is not excluded that the shape of the optical surface will satisfy the selected requirements, and the dispersion circle will turn out to be unsatisfactory with respect to certain characteristics. Therefore, the step of comparing the given and the satisfied requirements with respect to size and shape of the dispersion circle is necessary (see Figure 2.1, block 6). If the requirements of the technical assignment are not satisfied, it is necessary to return to the basic production cycle. If these requirements are satisfied, the work on the astronomical mirror is considered to be successfully completed.

1. Architecture of the Applied Programs

The applied programs forming the software of the ZEBRA system are the ideological bases of the system. According to the calculations of American specialists the software of automated systems constitutes on the average 80% of all of the expenditures on its development.

Let us consider the architecture of the package of applied programs supporting the ZEBRA-1 system. Figure 2.2 shows the chart explaining the interrelation of the programs of the applied package. On investigation of the figure it is necessary to compare it with the technological process flow diagram of Figure 2.1.

During the process of production quality control we obtain a Hartmann pattern using a diaphragm, the openings in which are made in such a way that it is impossible to examine the entire optical surface. On the Hartmann pattern we measure the coordinates of only the spots which are located on two mutually perpendicular diameters [Vitrichenko, Katagarov, 1978; Vitrichenko, 1980]. The file with the coordinates is the basic initial file for the HART2 program. In addition to this file it is necessary to know the date of the measurements of the picture, the number of the mirror and the number of the photographic plate with the Hartmann photograph. These data are needed for documentation of the work, and during the process of the operation of the program they are printed out without changes. The initial parameters are also the number of spots on the photograph along the diameter, the distance between the centers of adjacent openings on the diaphragm, the radius of curvature of the paraxial zone of the lining of the mirror and the approximate distance from the photographic plate to the paraxial image. The last value is more precisely determined during operation of the program.

The HART2 program operates on the M-6000 computer for 1-2 minutes, and it generates the following values: the coordinates of the center of the Hartmann photograph, the exact distance from the photographic plate to the paraxial image, the mean square transverse operation, the technical Hartmann constant, the mean square normal deviation, the amplitude of the normal deviations, the profiles of the normal deviations and profiles of the transverse operations along two parameters and the recommendation with respect to the continuation of surfacing. In addition, the program outputs the values of the normal deviations along two parameters to a punch tape.

This punch tape is used by four other programs entering into the package. First of all it uses the PRES3 program which calculates the process conditions. For operation of the PRES3 program the following information is needed: the date, the mirror number, the distance between openings in the Hartmann diaphragm, the number of spots along the diameter of the part, the value of the process constant, the minimum and maximum forces, the radii of the centers of the control zones, the machine tool function for these radii, and the number of control zones.

The PRES3 program operates on the M-6000 computer for 2-3 minutes and prints out the following messages: the date of operation, the mirror number, the value of the process constant, the given maximum and minimum forces, the mean normal deviations for the centers of the control zones, the radii of the control zones, the machine tool function for the middle of the control zones, the recommendation

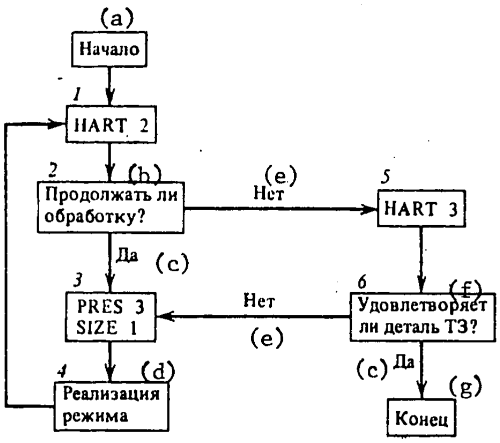


Figure 2.2. Architecture of the package of applied programs supporting the ZEBRA-1 automated system

Key:

a. Begin.
b. Continue surfacing?
c. Yes
d. Realization of conditions
e. No
f. Does the part satisfy the technical assignment?
g. End

with respect to continuation of surfacing, the amount of ballast removal of material, the values of the required forces on the control zones, the total duration of the production session. During operation the PRES3 program selects the new Gauss reference sphere, beginning with the principle of minimizing the surfacing time.

The forces calculated by the PRES3 program are established using the control unit and the force gauge, the optical machine tool is switched on, and for the time indicated by the program this regime is realized.

The punch tape with the values of the normal deviations generated by the HART2 program is used by the SIZE1 program for determining the size of the tool. In addition to the indicated punch tape, the initial data for the program are as follows: date, mirror number, number of the photographic plate with Hartmann photograph, distance between centers of adjacent openings in the diaphragm, number of spots on the Hartmann photograph along the diameter, mean square error in constructing the normal profile.

The SIZE1 program prints out the following information: the date of the calculations, the mirror number, the number of the photogaaphic plate with the Hartmann photograph, the number of spots on the photograph along the diameter, the distance between centers of adjacent holes in the diaphragm, the mean square error of constructing the normal profile, the normal deviations along two parameters, the error distribution function with respect to their sizes, the average size of the irregularities as the recommended size of the tool, the smoothness coefficient of the optical surface and the conclusion as to whether the given surface is smooth or unsmooth.

In practice the recommended size of the tool is rounded to 1/3 or 1/6 of the diameter of the machined part. In accordance with these two dimensions the machine tool function is calculated in advance. As a rule, in the initial stage of finishing a tool with a diameter that is 1/3 of the part diameter is used, and in the final stage, 1/6. Thus, the basic role of the SIZE1 program consists in determining the time when it is necessary to convert from the large to the small tool. Frequently this necessity does not arise in general, and the entire finishing operation can be performed with one tool. The punch tape with normal deviations generated by the HART2 program is also used by the DIFR1 program for calculation of the dispersion circle according to the wave representations. If the quality of the optical surface is close to the Rayleigh number, then the geometric approach for determining the dispersion circle used in the Hartmann method can lead to incorrect results. In particular, the energy concentration of the central part of the Airy circle can differ by several times if it is calculated by one method or another.

In addition to the punch tape with normal deviations, the initial data for operation of the DIFR1 program are the date, the mirror number, the plate number with the Hartmannogram, the distance between centers of adjacent holes on the diaphragm, the number of spots on the Hartmann recording along the diameter of the part, the number of elementary zones and the number of elementary sectors into which the part is divided.

The program prints out the following: the specific illumination, the photometric cross section for the dispersion spot and the energy distribution in the dispersion spot, that is, the amount of light energy for circles of different diameter. The program also prints out these values for an ideal mirror. The program prints out the following reference data: the date, the mirror number, the plate number and the base of the diaphragm.

The fourth program, which uses the punch tape with normal deviations, is the DIFINE program. This program calculates the process constant and determines the systematic corrections to the machine tool function. The initial data are as following: date, mirror number, number of two used plates with Hartmann recordings (pertaining to two successive surfacing sessions), the machine tool function, the initial process constant and the executed surfacing conditions, that is, the used forces and the duration of the session.

The output of the program is as follows: the new value of the process constant, corrections to the machine tool function and reference information.

In the software a special role is played by the DVCE1 program. Its purpose is to determine the machine tool function. For operation of the program it is necessary to install a carrier angle gauge on the machine tool connected to the M-6000 computer. The data from the gauge is input in real time (when the machine tool is operating) to the computer memory, and the computer calculates the probability that the tool will be in the control zones. It is sufficient to multiply this probability times the speed of the tool with respect to the part which can be calculated analytically, normalize the product obtained, and we obtain the machine tool function. The initial data which are printed out for reference are as follows: the part diameter, the tool diameter, the angular velocities of the spindle and the crankshaft and also the radii of the centers of the control zones. The primary output of the DVCE1 program is a punch tape with a machine tool function.

In the following sections a study will be made of the mathematical formulation of each of the indicated programs. Their algorithm will be presented, and a control example will be given. In the appendix the texts of all of the programs except the HART2 program are presented. The text of this program was presented in the book by Vitrichenko [1980].

2. Methods of Determining the Machine Tool Function and the Process Constant

In the ZEBRA-1 automated system, an ordinary optical machine tool is used in which the lower element is the uniformly rotating spindle with the part fastened to its shaft, and the upper element is the carrier with free lapping tool undergoing harmonic oscillations. The small tool is used, the diameter of which is calculated by the SIZE1 program and is usually taken equal to 1/3 or 1/6 of the diameter of the optical surface. If the pressure of the tool on the part is constant, the removal of the material can be represented by an approximate expression based on Preston's law [Preston, 1927, 1928]:

$$h(\rho) = KTP\nu(\rho)\,t(\rho). \tag{2.4}$$

Here h is the thickness of the removed material; ρ is the radius on the optical surface reckoned from the center of the part; ν(ρ) is the speed of the tool with respect to the part; t(ρ) is the time during which the tool is in the zone with a radius ρ which in Semibratov's terminology [1962] is equivalent to the coverage factor; P is the pressure (force) of the tool on the part; T is the total duration of the production session; K is the process constant.

Let us define the concept of the "machine tool function" as follows:

$$\psi(\rho) = \frac{h(\rho)}{h(0)} = \frac{\nu(\rho)\,t(\rho)}{\nu(0)\,t(0)}, \tag{2.5}$$

where the values of h(0), ν(0) and t(0) pertain to the center of the part. In order to understand the physical meaning of the machine tool function let us carry out the following mental experiment. Let us install a part having an ideal plane surface on an optical machine tool. Let us switch the optical machine tool on for some time so that the material will be removed, and then let us use the absolute method to measure the thickness of the removed material along the radius of the part h(ρ). The ratio of h(ρ) to h(0) gives the value in units of removal of material at the center of the part. This is also the machine tool function.

The machine tool function has a number of important properties. The main one of them is the fact that it depends only on the geometric parameters -- the ratio of the angular velocities of the spindle and the crankshaft, shift and eccentricity -- and on the ratio of the tool diameter to the part diameter. The function does not depend on the process parameters: the materials of the part, the tool and abrasive, it does not depend on the thermal conditons of processing, and finally, it does not depend on the nature of the removal of the material, whether it is grinding or polishing. For the center of the part by definition $\psi(0)=1$.

Let the optical surface have mirrors $h=h(x,y)$ which must be eliminated. In the case of controlling the force of a small tool for successful manufacture of the optical surface it is necessary to satisfy the condition following from formula (2.3):

$$P(x,y) = \frac{h(x,y)}{KT\,\psi(\rho)}, \qquad (2.6)$$

where $P(x,y)$ are the forces at the points of the part with the coordinates x,y.

Then let us consider the methods of determining the machine tool function $\psi(\rho)$ and the process constant K. As soon as they become known the process conditions can be determined using expression (2.6).

The table method of determining the machine tool function $\psi(\rho)$ is based on the application of tables compiled by Semibratov. They are published in three editions [Semibratov, 1962; Semibratov, Yefremov, 1976; Semibratov, et al., 1978]. By these tables it is possible to determine the coverage factor $t(\rho)$ and the rate coefficient $\nu(\rho)$. The application of formula (2.5) gives the desired function. The rate coefficient can also be defined by the approximate formula

$$\nu(\rho) = (\nu_1^2(\rho) + \nu_2^2(\rho))^{1/2}. \qquad (2.7)$$

Here $\nu_1(\rho)=\omega_1\rho$ is the linear velocity of the optical surface connected with rotation of the spindle; $\nu_2(\rho)=2\pi\omega_2\cos(\pi\rho/e)$ is the linear velocity of the tool connected with the movement of the carrier; ω_1, ω_2 are the angular velocities of the crankshaft spindle, e is the eccentricity. When deriving equation (2.7) it is proposed that the angular velocity of the tool is equal to zero.

An example of the machine tool function defined using the Semibratov tables with the following parameters is presented in Figure 2.3: the part diameter D=300 mm, the tool diameter d=100 mm, the eccentricity d=120 mm, the angular velocity of the spindle $\omega_1=2.35\ \text{sec}^{-1}$, the angular velocity of the crankshaft $\omega_2=1.5\ \text{sec}^{-1}$. The angular velocity of the tool is taken as zero.

Investigation of curve 1 (Figure 2.3) permits two conclusions to be drawn. First, the existence of the local minima indicates that under the given surfacing conditions local zonal errors will be created. In order to avoid this effect, it is necessary, in addition to the forces of the tool aimed at eliminating the errors of the optical surface, to create forces that compensate for creation of the zones. This fact is considered in formula (2.6). Secondly, the systematic behavior of the curve with negative slope indicates that in the surfacing process the radius of curvature of the part will be systematically decreased. Both of the indicated effects emphasize the necessity for determination and consideration of the machine tool function in the automated system.

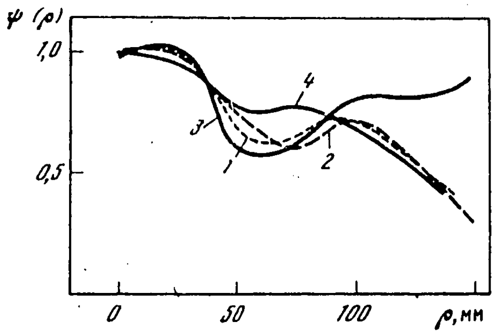


Figure 2.3. Examples of some machine tool functions determined by different methods.
1 -- by the Semibratov tables; 2 -- graphically; 3 -- experimental correction; 4 -- numerical integration

The graphical method of determining the machine tool function consists in the following. From the power engineering point of view the volume of removed material V in the zone ρ is proportional to the amount of expended work W

$$V(\rho) \cong W(\rho). \tag{2.8}$$

Let us select the width of all of the annular zones identical and equal to Δ. Then the volume of the removed material can be written as follows:

$$V(\rho) = 2\pi\rho\, h(\rho)\Delta, \tag{2.9}$$

where $h(\rho)$ is the height of the removed material in a zone of radius ρ.

Let us break down the tool area into elemental areas; let us determine the length of the trajectory of the center of each area inside each elemental ring zone into which the optical surface $\ell(\rho)$ is broken down. Then the work performed inside the annular zone of the part with width Δ and average radius ρ can be expressed as follows:

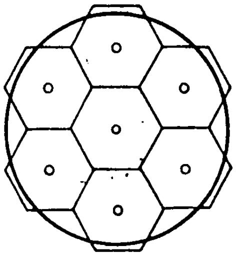
$$W(\rho) \sim PT\,l(\rho)\,\Delta. \tag{2.10}$$

Here P is the constant force of a tool, T is the total work time. Using formulas (2.8)-(2.10), after simple transformations we obtain

$$\psi(\rho) = l(\rho)\rho_0 / l(\rho_0)\rho\,. \tag{2.11}$$

where ρ_0 is the average radius of the internal zone itself.

In order to determine the machine tool function by the graphical method it is possible to recommend the following practical procedure. Let us fasten a sheet of paper to the optical surface which we propose to machine. Instead of the tool let us fasten a mockup of it on the carrier. The mockup is divided into seven regular hexagons as shown in Figure 2.4. Let us fasten a writing pen at the center of each hexagon. Switch on the machine tool and bring the writing pens into contact with the sheet of paper for one rotation of the crankshaft. Then the paper is removed from the part, a family of concentric circles is drawn on it with equal radius step size. A curvimeter is used to determine the total length of the circles of the trajectories inside each of the zones $\ell(\rho)$. The use of formula (2.11) gives the machine tool function.



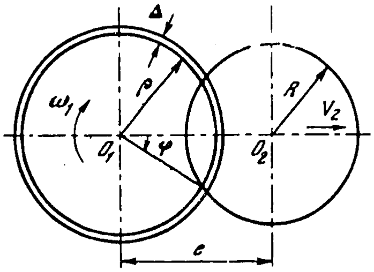


Figure 2.4. Example of breakdown of the area of the tool into elemental areas using hexagons. The circle bounds the area of the tool; the little circles are the centers of the elemental areas in which the writing pens are installed.

Figure 2.5. Determination of the area of the elemental annular zone. O_1 -- center of rotation of the optical surface which is an infinite rotating plane, O_2 -- center of the tool of radius R

Curve 2 (see Figure 2.3) is the machine tool function defined graphically. The adjustment parameters of the machine tool were selected the same as when using the table method. A comparison of the two curves indicates good agreement.

The computer method of determining the machine tool function is based on direct indication of the Preston formula. The integration is carried out over the area of the tool, the area of the part and with respect to time.

Curve 4 (see Figure 2.3) was obtained by the calculation method. A comparison of this curve with the results obtained by other methods turns out to be good. Inasmuch as the computational method requires the application of awkward calculations, its use turns out to be possible only if a large computer is available.

When determining the machine tool function by the calculation method we make a number of assumptions. The basic one of them is proportionality of the volume of the removed material to the amount of energy expended by the optical machine tool on the shaping process. The same principle is used also when deriving the Preston relation. It is possible to write the indicated assumption in the following form with accuracy to a constant factor:

$$dV(\rho) = dW(\rho), \tag{2.12}$$

dV is the volume of the removed material in the optical surface zone with an average radius ρ and width Δ; dW is the amount of energy generated by the optical machine tool in the same zone.

The volume of removed material is obtained from simple geometric expressions

$$dV(\rho) = 2\pi\rho\, h(\rho)\, \Delta. \tag{2.13}$$

In formula (2.13) the value of $h(\rho)$ is the height of the removed material as a function of the radius of the part. This value is of primary interest to us inasmuch as by the definition of the machine tool function there is a height of removed material normalized to the height of the removed material at the center of the part:

$$\psi(\rho) = h(\rho)/h(\rho_0), \tag{2.14}$$

ρ_0 is the average radius of the internal zone of the part itself.

Comparing (2.12)-(2.14), for the machine tool function we obtain the following expression:

$$\psi(\rho) = \frac{dW(\rho)\Delta}{2\rho\, dW(\Delta/2)}, \tag{2 15}$$

where the average radius of the internal zone itself is taken equal to $\Delta/2$.

For the calculation of the amount of work in the zone, let us consider the following simplified diagram of the optical machine tool as illustrated in Figure 2.5. The machined part is an infinite plane rotating around the center O_1 with constant angular velocity ω_1. Let us isolate a concentric annular zone on the part of width Δ at a distance ρ from the center of rotation of the part. The tool is a flat disc of radius R with center at the point O_2. The tool, without rotating, undergoes harmonic symmetric oscillations with respect to the center of the part O_1. The distance between the centers O_1 and O_2 varies according to the law

$$e = e_m \sin \omega_2 t, \tag{2.16}$$

e_m is the maximum distance between the centers O_1 and O_2, ω_2 is the angular velocity of the crankshaft of the optical machine tool causing the tool to undergo the harmonic oscillations with respect to the point O_1. The work done in the process of friction of the two surfaces against each other, and this is how we interpret the shaping process, is proportional to the frictional force F, the contact area of the working surfaces S(e) and the rates of their relative displacement $\nu(e)$. If we consider the frictional force F constant, then with accuracy to a constant factor

$$dW(\rho, t) = S(e)\nu(e). \tag{2.17}$$

The contact area of the working surfaces (see Figure 2.5) is

$$S(e) = 2\varphi\rho\,\Delta. \tag{2.18}$$

The angle ϕ entering into formula (2.18) is defined from the known formula (see, for example, [Zakaznov, Gorelik, 1978, p 150]

$$\varphi = \arccos \frac{\rho^2 + e^2 - R^2}{2\rho e}. \tag{2.19}$$

Finally, for the contact site we obtain

$$S(e) = 2\rho\Delta \arccos \frac{\rho^2 + e^2 - R^2}{2\rho e}. \qquad (2.20)$$

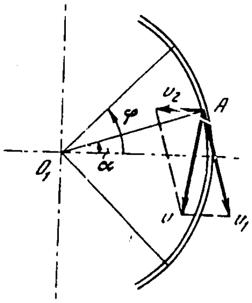


Figure 2.6. Velocity components of the relative motion of the tool and the optical part.
v_1 is the linear component of the rotational velocity of the part, v_2 is the velocity of the tool related to the movement of the carrier, O_1 is the center of rotation of the part.

Let us define the average velocity of the relative motion of the tool and the part. Figure 2.6 shows what components the velocity vector is made up of.

The velocity v_1 is defined as the rotation of the part around the point O_1:

$$v_1 = \omega_1 \rho. \qquad (2.21)$$

The velocity v_2 can be obtained by differentiating equation (2.16) with respect to time

$$v_2 = de/dt = e_m \omega_2 \cos \omega_2 t. \qquad (2.22)$$

By the cosine theorem we find the modulus of the resultant velocity

$$v(\rho, \alpha) = (v_1^2 + v_2^2 - 2 v_1 v_2 \sin \alpha)^{1/2} \qquad (2.23)$$

For substitution in formula (2.17) it is necessary to calculate the weighted mean relative velocity with respect to the entire annular segment. Inasmuch as the symmetry with respect to the center of the segment is absent, we obtain

$$v(\rho) = \int_{-\varphi}^{+\varphi} v(\rho, \alpha)\, d\alpha/2\varphi, \qquad (2.24)$$

where the integration limit is defined by equation (2.19).

Finally, for determination of the value of dW(ρ), it is necessary to integrate the value of dW(ρ,t) with respect to time. Here

$$dW(\rho) = \int_{t_1}^{t_2} W(\rho, t)\, dt. \qquad (2.25)$$

The integration limits are determined from the condition of the first and last contact of the tool plane with the annular segment

$$t_{1,2} = \frac{1}{\omega_2} \arcsin \frac{\rho \pm R}{e_m}. \qquad (2.26)$$

Let us define the amount of work $dW(\Delta/2)$ generated on the innermost elemental area. This value enters into formula (2.15). Let us use expression (2.17). The contact area of the working surfaces in the given case is equal to the area of the internal zone itself, that is,

$$S(\Delta/2) = \pi \Delta^2. \qquad (2.27)$$

Here it is possible to neglect the velocity related to the rotation of the part; then the velocity factor ν according to (2.22) and (2.24) turns out to be equal to ν_2. Using formula (2.25) we finally obtain

$$dW(\Delta/2) = \pi \Delta^2 R. \qquad (2.28)$$

Considering (2.28) the expression for the machine tool function assumes the form

$$\psi(\rho) = \frac{dW(\rho)}{2\pi\rho\Delta R}. \qquad (2.29)$$

When using the above-presented expressions it is necessary to consider that the time interval is analyzed beginning with the time when the centers of the tool and the part coincide and ending with the time when the center of the tool is removed from the center of the part a distance e_m. This time interval corresponds to a quarter of a turn of the crankshaft. With further movement of the tool the picture of the removal of the material is repeated every quarter of the turn of the crankshaft. Inasmuch as in the process of machining an optical surface as a rule the crankshaft undergoes thousands of rotations, it is possible with sufficient accuracy to consider that our arguments are valid also for the entire production session as a whole. The set of formulas (2.29), (2.17), (2.20), (2.21)-(2.26) defines the desired expression for the machine tool function.

The algorithm described above is executed by the LAP1 program (see Appendix 1).

It is important to note that the presented relations are valid with sufficient accuracy only for astronomical mirrors for which low speed and small asphericalness are characteristic.

The symmetric movement of the tool with respect to the center of the part is not a significant assumption. It is sufficient to write

$$e = e_0 + e_m \sin \omega_2 t, \qquad (2.30)$$

instead of (2.16), where e_0 is the shift of the center of vibration of the tool with respect to the center of the part, and all the remaining arguments remain valid.

The automated method for determining the function $\psi(\rho)$ is based on connection of sensors that pick up the displacement of the tool to the optical machine tool, input of the readings of these sensors to a computer and calculation of the machine tool function using the DVCE1 program (see Appendix 1). The above-presented four methods of determining the machine tool function have common deficiencies. In particular, the methods do not permit consideration of the following effects: the influence of free rotation of the tool, the pressure distribution under the area of the tool, the effect of the wear of the tool and part and also the effect of the tool going beyond the edge of the part, which leads to increased removal of material on the edge of the part. Accordingly, the necessity arises for checking by experimental procedures to determine whether the machine tool function has any peculiarities which have not been considered in the calculations. For this check the following two experimentally-based methods are used.

The fitting method is based on analyzing the shape of the optical surface before and after the production session.

Let the normal deviation along the radius be $h_1(\rho)$ before beginning of the session. Let us perform a surfacing session, applying the forces $P(\rho)$ in the zones of the part. After surfacing the normal deviaions become $h_2(\rho)$. Then the function $\psi(\rho)$ can be written in the form

$$\psi(\rho) = (h_2(\rho) - h_1(\rho) + a + b\rho^2)/P(\rho)\,KT, \qquad (2.31)$$

where a is the difference of the zero points of the normal profiles, the term $b\rho^2$ is related to the difference in radii of the gaussian reference spheres using when determining $h_1(\rho)$ and $h_2(\rho)$. Let us differentiate formula (2.12), let us take the machine tool function defined by one of the previously described methods as the zero approximation, and then varying the constants a and b, by the least squares method, let us match the zero approximation function with the one obtained from equation (2.12). In Figure 2.3, curve 3 is the machine tool function obtained in this way. This curve agrees well with the curves obtained by other methods with the exception of the edge zone. The increase in removal of material at the edge of the part is noticeable, which is connected with the effect of the tool going beyond the edge of the part. This effect is well known to practician opticians.

Repeating the above-described experiments several times, it is possible to correct the machine tool function with the help of systematic differences so that all the experimental characteristics will be taken into account. The method is implemented by the DIFINE program (see Appendix 1).

The superposition method is entirely based on experimentation. For realization of it, it is necessary to carry out as many production sessions as zones have been selected on the optical surface.

Let the force P be realized in each session in only one of the zones with the number i. For simplification let us take the surfacing time T identical for all sessions. Let us propose that in each of the i sessions an amount of material is removed $h_i(\rho)$. The determination of the amount of removal is facilitated by the fact that part of the optical surface is not subjected to surfacing. This makes it possible to avoid the effect of free parameters of the null point type and variation of the radius of the gaussian reference sphere.

The machine tool function is obtained in the form of a monomial [Wagner, Shannon, 1974]

$$\psi(\rho) = \sum_{i=1}^{N} h_i(\rho) / \sum_{i=1}^{N} h_i(0). \tag{2.32}$$

Here it is possible to calculate the absolute removal of material in the center of the part which offers the possibility of determining the value of the process constant

$$K = \sum_{i=1}^{N} h_i(0)/PT. \tag{2.33}$$

The only deficiency of this method is the great labor consumption of performing the experiments and when determining the absolute removal of material. At the same time this method gives the most reliable value of the process constant.

Let us consider the methods of determining the process constant further.

The above-discussed method of determining the process constant will be called the superposition method.

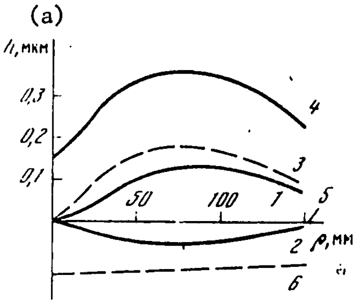


Figure 2.7. Diagram of determination of the null point of the function of experimental removal of material.
1 -- normal profile before surfacing, 2 -- profile after surfacing, 3 -- difference in profiles 1 and 2, 4 -- theoretical removal of material, 5 -- null points for theoretical profile and initial null point for experimental profile, 6 -- new null point for experimental profile

Key:
a. microns

The following two methods of determining the process constant are based on the procedures for more precise definition of it.

The corrected method of determining the process constant is based on analyzing the normal deviations determined before and after the processing session. Here it is assumed that the machine tool function will be properly defined. The calculations are made by the DIFINE program (see Appendix 1).

Let the normal profile along the radius of the part be $h_1(\rho)$ before the beginning of the processing session, and $h_2(\rho)$ after it. Then the removal of the material in the session will be $\Delta(\rho)=h_1(\rho)-h_2(\rho)$. The value of Δ is determined with precision to two free parameters connected with the indeterminacy of the null point and the comparison sphere. Let us make the following assumption: consideration of the variation of the reference comparison sphere is felt insignificantly in the analysis results. We shall consider how justified this assumption is later. This assumption permits unique determination of the null point of the difference Δ.

For clarity we shall plot the value of Δ and the theoretical removal of material on a graph (see Figure 2.7). Let us select points on the theoretical removal graph corresponding to the maximum and minimum of the curve. Let the removal of material at these points be equal to H_1 and H_2. Let us determine the values of Δ reckoned from the still arbitrary null point for the same radii. Let these values be Δ_1 and Δ_2. Then from arguments of proportionality of the values of H and Δ we obtain the desired correction Δ_0 to the null point of the values of Δ

$$\Delta_0=\frac{H_2\Delta_1-H_1\Delta_2}{H_1-H_2}. \tag{2.34}$$

If the experimental removal is calculated with the process constant K_0, the new value of K will turn out to be equal to

$$K=\frac{K_0}{N}\sum_{i=1}^{N} H_i/(\Delta_i+\Delta_0). \tag{2.35}$$

It is interesting to note that for the given procedure it is indifferent what initial value is taken for K_0.

By the corrected method described above we determine the value of the process constant for KV type quartz and K8 type glass. These values are presented below. The adjustment of the machine tool was the same as indicated earlier; resin No 10 was used, the part temperature and the ambient temperature were maintained at +25°C with precision to 1°C. The contact spot was fed a suspension of Polirit and water with a ratio by weight of 1:5. The values of K are presented with mean square error.

Material	K, microns/(hr-kg)
KV quartz	0.025±0.005
K8 glass	0.050±0.005

The estimate method of determining the process constant K can be applied when the tool and abrasive materials remain as before, but the adjustment of the machine tool is changed, and the part made of a different material is surfaced. For the previous adjustment of the machine tool and the previous material the value of K is known. In this case it is possible to use the following approximate expression:

$$K_2=K_1\frac{l_2(\rho_0)\,\kappa_2}{l_1(\rho_0)\,\kappa_1}, \tag{2.36}$$

where $\ell_1(\rho_0)$ and $\ell_2(\rho_0)$ are the sums of the wave lengths of the trajectories of the centers of the tool element in the central zone of the part for old and new adjustments of the machine tool, respectively; K_2 and K_1 are the new and old values of the process constant; k_1 and k_2 are the grindability factors for the old and new materials. If the grindability factors are unknown, then it is possible with sufficient accuracy to use the inverse hardness of the material which can be measured directly [Yeremina, et al., 1980].

Expression (2.36) is approximate, but for the majority of important cases in practice it turns out to be sufficient. This is all the more the case in that after the first session it is possible to determine it more precisely by the correction method.

Let us return to the assumption that the radius of the comparison sphere does not vary. This assumption is used only for the corrected method of determining K. In the general case this is not so. However, inasmuch as the DIFINE program calculates not only the process constant but also the systematic corrections to the machine tool function, the difference in the comparison spheres enters into these systematic corrections. Inasmuch as we are engaged in an analysis of the finishing operation where the absolute amount of material removed is small, a change in the radius of the part has no significance. In addition, averaging the systematic errors to the machine tool function for several surfacing sessions, we average the errors of a different sign in the systematic corrections and thus decrease the error introduced by this assumption.

3. Determination of the Process Conditions

When using the principle of controlling the pressure of a small tool on the part, the problem of determining the operation by zones is solved. The problem is formulated as follows: by the given normal deviations along the radius of the part find the forces on each zone and the duration of the process session such as to reduce the normal deviations to zero. Here the duration of the process session must be minimized.

The presented formulation of the problem is simplified. In particular, as a result of the finite size of the tool, reduction of the normal deviations to zero cannot be achieved. Errors remain, the dimensions of which are less than the tool dimensions. In addition, new errors arise at the points on the optical surface where the normal profile has large derivatives. There are a number of other causes not permitting solution of the problem by one approximation. These include the following: the finite dynamic range of the servoelement, insufficient reproducibility of a number of the process conditions, idealization in determining the machine tool function.

The algorithm described below is part of the entire software of the automated process of shaping an astronomical optical system, the general structure of which is presented in §1 of this chapter. The algorithm, the description of which we shall go over to is executed by the PRES3 program (see Appendix 1).

The initial data for operation of PRES3 program are the following functions and variables:

1. The normal deviations $h_{i,k}$ at the points of the optical surface located on two mutually perpendicular diameters and coinciding with the location of the centers of the holes in the Hartmann diaphragm. Here i=1 to n is the number of the point along the radius of the part, k=1 to 4 is the number of the radius. For the center of the part it is assumed that $h_{1,k}=0$. The normal deviations are calculated by the Hartmann method using the HART2 program described in the paper by Vitrichenko and Katagarov [1978] and in the book by Vitrichenko [1980].

2. The machine tool function $\psi(\rho)$ characterizing the removal of material at constant pressure and defined by one of the methods described in the previous section.

3. The minimum and maximum forces P_{min} and P_{max} which are given by the operator and are calculated in advance, beginning with the concepts of the upper bound of the specific pressures of the tool and the dynamic range of the servoelement.

4. The process constant K, the methods of determination of which are presented in the preceding section.

Inasmuch as the system permits only axisymmetric removal of the material, it is necessary to average the normal deviations for all four radii.

Let us determine the mean value of normal deviations h_i and the mean square error in determining the normal deviation σ_i which will be needed later

$$h_i = 1/4 \sum_{k=1}^{4} h_{i,k}, \sigma_i = (1/3 \sum_{k=1}^{4} (h_{i,k} - h_i)^2)^{1/2} \qquad (2.37)$$

Further surfacing with zonal control of the removal of material is considered expedient if the zonal errors with respect to amplitude exceed the local errors. The relation between the amplitude of the zonal and local errors is checked using the formalized criterion

$$\max\{h_i\} - \min\{h_i\} > 6\sigma, \qquad (2.38)$$

$$\sigma = \frac{1}{n} \sum_{i=1}^{n} \sigma_i. \qquad (2.39)$$

The value of σ is the mean square error in determining the mean normal deviation averaged over all of these zones. The condition (2.38) is also checked in the HART2 program, but it has a different value: using the same criterion a check is made to see whether it is possible to make further use of the HART3 program used for analysis of axisymmetric errors or it is necessary to go over to the use of the HART3 program permitting investigation of the entire optical surface, the basic errors of which in this case are local.

If condition (2.38) is satisfied, the computer prints out the message RECOMMEND CONTINUATION OF SURFACING. Otherwise the message RECOMMEND STOPPING SURFACING is put out. The second type of message marks an emergency situation, and the methods of resolving it were discussed at the beginning of the chapter.

In the ZEBRA-1 system the part is broken down into zones of equal width. During the time when the center of the tool is within the limits of the given zone, the servoelement insures the creation of the given force of the tool on the part. On transfer of the center of the tool to the adjacent zone the force varies continuously and resumes a new value. Practice has demonstrated that the transient processes arising in this case have no influence on the execution of the given process conditions. Smooth variation of the forces will not create any advantages inasmuch as the size of the tool is much greater than the width of the annular zones, which leads to the same smoothing of the effects of the force gradients as on smooth variation of them.

Let $\rho_0, \ldots, \rho_m$ be the distances from the center of the part to the middle of the zone, within the limits of which the force remains constant. In the general case these distances are distinguished from the distances of the centers of the openings in the Hartmann diaphragm from the center of the diaphragm itself. At the same time these distances do not coincide with the position of the points on the optical surface, at which the normal deviations are measured. Therefore it is necessary to calculate the normal deviations $h_j=h(\rho_j)$, where j=0 to m for the average radii of the control zones.

The control zone is an annular zone on the optical surface, within the limits of which the force remains constant. The values of $h(\rho_j)$ are determined by linear interpolation of the values of h_i.

In order to minimize the duration of the process session it is necessary to use the directrix method proposed by Ivon to select the comparison sphere again. In modern terminology reselection of the comparison sphere is based on the displacement theorem. On variation of the comparison sphere it is necessary to require that the following condition be satisfied:

$$\max \{h(\rho_j)/\psi(\rho_j)\} = \min. \tag{2.40}$$

The new comparison sphere in the general case does not coincide with the comparison sphere selected using the HART2 program when calculating the normal deviations. In the indicated program the comparison sphere is selected from the principle of minimizing the mean square transverse aberration as is always done in the Hartmann method [Vitrichenko, 1980]. It is entirely clear that for technological purposes this principle is unsuitable. Analysis shows that if the comparison sphere is not altered, the duration of the process session increases by 20-30% on the average, and in individual cases it can double.

If h'_j are the normal deviations for a new comparison sphere and h_j are the normal deviations calculated by the HART2 program, the difference between them can be written as follows:

$$h'_j - h_j = a + b\rho_j^2, \tag{2.41}$$

where the term a is related to the shift of the new comparison sphere with respect to the old one along the optical axis, $b\rho^2$ is related to the variation in radius of curvature of the comparison sphere. In order to minimize the surfacing time it is necessary to find the minimum of the functional $\mu(a,b)$ which is defined as follows:

$$\mu(a,b) = \max\left\{h_j' - (a + b\rho_j^2)\right\}. \tag{2.42}$$

The problem reduces to determining the values of a and b. Let us denote the variable values of a and b in terms of x and y. The values of x and y are determined by the condition

$$h_j > x + y\rho_j^2, \ \min\left\{\mu(a,b)\right\} = \mu(x,y). \tag{2.43}$$

Let us set

$$z(\rho, x, y) = x + y\rho^2 \tag{2.44}$$

and let us define x and y as follows. According to the Bernstein theorem the numbers i_1 and i_2 exist such that

$$\begin{aligned} &0 \leqslant i_1 \leqslant i_2 \leqslant m, \\ &\mu(x,y) = h_{i_1}' - (x + y\rho_{i_1}^2) = h_{i_2}' - (x + y\rho_{i_2}^2). \end{aligned} \tag{2.45}$$

The equality (2.43) makes it possible to find y. The value of x is

$$x = \min\left\{h_j' - y\rho_j^2\right\}, \tag{2.46}$$

which provides for satisfaction of the condition (2.43). It must be considered that equation (2.45) has no solution if for the refocused comparison sphere $i_3 > i_4$ exists such that

$$h_{i_3}' - (x + y\rho_{i_3}^2) = h_{i_4}' - (x + y\rho_{i_4}^2) = 0. \tag{2.47}$$

This leads to complication of the determination of the values of x and y. The situation where (2.47) is satisfied is a special case, but inasmuch as it is unknown in advance, it must be considered. In general form the algorithmic part of the definition of the values of x and y considering the possibility of satisfaction of (2.47) is given by the following sequence of calculations. First we find

$$\begin{aligned} y_h(i_1, i_2) &= (h_{i_2} - h_{i_1})/(\rho_{i_2}^2 - \rho_{i_1}^2), \\ x_h(i_1, i_2) &= \min\left\{h_i - \rho_i^2 y_h(i_1, i_2)\right\}, \\ y_p(i_1, i_2) &= (h_{i_2}' - h_{i_1}')/(\rho_{i_2}^2 - \rho_{i_1}^2), \\ x_p(i_1, i_2) &= \min\left\{h_i - \rho_i^2 y_p(i_1, i_2)\right\}. \end{aligned} \tag{2.48}$$

Then by direct sorting of the versions we determine x_1, y_1; x_2, y_2 from the conditions

$$\begin{aligned} \min\left\{\max(h_j' - z(\rho_j, x_h, y_h))\right\} &= \max\left\{h_i' - z(\rho_i, x_1, y_1)\right\} = \Delta_1, \\ \min\left\{\max(h_j' - z(\rho_j, x_p, y_p))\right\} &= \max\left\{h_i' - z(\rho_i, x_2, y_2)\right\} = \Delta_2. \end{aligned} \tag{2.49}$$

The final values of x and y will be found as follows:

$$\begin{aligned} &x = x_1, \ y = y_1, \ \text{if} \ \Delta_1 < \Delta_2, \\ &x = x_2, \ y = y_2, \ \text{if} \ \Delta_1 > \Delta_2. \end{aligned} \tag{2.50}$$

At the same time the problem of selecting the comparison sphere insuring minimum surfacing time is solved.

Let us determine the process conditions. We shall find the regime vector $(P_0, \ldots, P_m)$ which is the forces which must be created on the zones from 0 to m for successful removal of the machining allowance. Each component of the vector P_j must satisfy the condition

$$P_{\min} \leqslant P_j \leqslant P_{\max}. \tag{2.51}$$

The values of $P_{\min}$ and $P_{\max}$ are estimated from the following arguments. From operating experience it is known that for a given specific pressure it is possible to achieve a defined polishing output capacity, but at some critical pressure P_{cr} the polishing rate begins to diminish sharply, and with a further increase in pressure it can stop altogether. This phenomenon is connected with the properties of resin and the peculiarities of the interaction of resin and Polirit. If the tool area is S, then the greatest force which can be used is defined as

$$P_{\max} = P_{cr}S. \tag{2.52}$$

On the other hand, an infinitely small force is impossible to create for two reasons: as a result of the finite weight of the polisher which in the given case is not unloaded and as a result of the finite dynamic range of the servoelement.

Let the dynamic range of the servoelement be Q. Then the minimum force $P_{\min}$ is determined from the expression

$$P_{\min} = P_{tool} + P_{\max}/Q, \tag{2.53}$$

where P_{tool} is the tool weight.

The impossibility of creating a zero force leads to the fact that it is necessary to calculate the process conditions so as to remove some additional tolerance which will hereafter be called the "ballast removal."

The duration of the process session for T is defined by the formula

$$T = \frac{1}{P_{\max} K} \max\left\{ \frac{1}{\psi_i} (h_i - z(\rho_l, x, y) + B) \right\}, \tag{2.54}$$

where B is the ballast removal of the material insuring the possibility of satisfying the condition (2.51). According to this condition the value of B will be determined from the expression

$$\frac{P_{\min}}{P_{\max}} \leqslant \frac{\min\{(h_i - z(\rho_l, x, y) + B)/\psi_i\}}{\max\{(h_l - z(\rho_i, x, y) + B)/\psi_i\}}. \tag{2.55}$$

The process of calculating the process conditions proceeds in the following sequence: first we determine the value of B by (2.55), then the surfacing time T by (2.54) and, finally, the forces on the control zones by the formula

$$P_j = (h_j - z(\rho_l, x, y) + B)/(\psi_j KT). \tag{2.56}$$

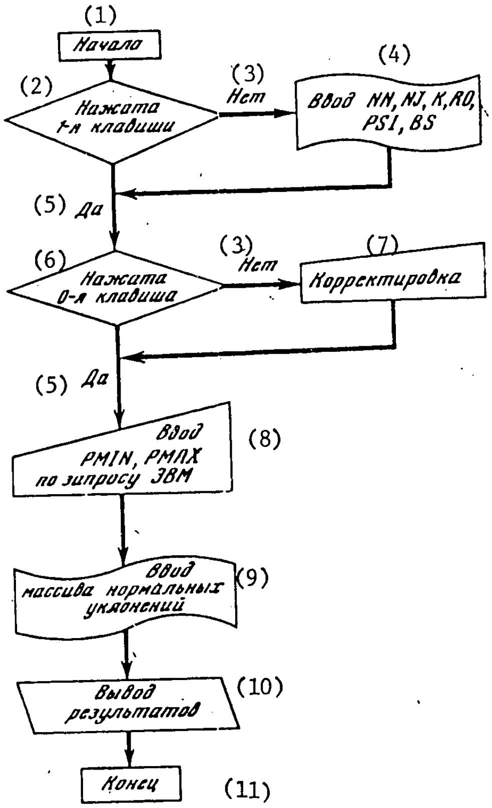


Figure 2.8. Consolidated block diagram of the PRES3 program

Key:

1.	Begin	8.	Input P_{min}, P_{max} by computer request
2.	First key depressed	9.	Input of the normal deviations file
3.	No	10.	Output of results
4.	Input NN, NJ, K, RD, PSI, BS	11.	End
5.	Yes		
6.	0-th key depressed		
7.	Correction		

The problem is thus solved.

In Figure 2.8 a consolidated block diagram of the PRES3 program is presented. The operation of the program begins in input of the punch tape with normal deviation $h_{i,k}$ which is generated by the HART2 program [Vitrichenko, Katagarov, 1978]. Then the punch tape is input with the machine tool function in values of P_{min}, P_{max} and K. In the program the possibility is created for correction of these values from teletype. Then the program successively calculates the parameters of the new comparison sphere x and y, the amount of ballast removal B, the surfacing time T and the regime vector P.

An example of the printout of the PRES3 program is as follows:

```
NN, NJ, K, Z
...
RO(0),...,RO(NJ)
...
PSIO(0),...,PSI(NJ)
...
PMIN,PMAX
3,15
INSTALL ON THE PUNCH TAPE READER WITH THE DEVIATIONS TABLE AND PRESS START
PAUSE

                                         Initial Data
         J       0      1      2      3      4      5      6
      RO(J)     74     98    124    148    172    197    209
     PSI(J)    1.48   1.71   1.91   1.75   1.53   1.32   1.16
                             PMIN=3.0    PMAX=15.0
                               K=0.608
                             BASE 30.0 MM
 RECOMMEND STOPPING SURFACING
      Mean deviations at the control point
   J      0     1     2     3     4     5     6
  H(J)   .39   .40   .36   .27   .17   .12   .11

 BALLAST REMOVAL .07 microns

                                     Regime
        J      0      1      2      3      4      5      6
       P(J)   15.0   13.3   10.6   8.2    5.5    4.0    3.9
```

The printout is provided with comments. The radii of the control zone are expressed in mm, the machine tool function $\psi(\rho)$ is dimensionless, the forces are expressed in kg, the process constant K has dimensionality of microns/(hr-kg), and the normal deviations are expressed in microns.

4. Determination of the Size of the Tool

In classical technology the tool diameter is selected equal to the part diameter. However, when using the principle of controlling the shaping process by varying the source, this approach is inapplicable; otherwise the principle becomes unrealizable. In the paper by Aspden, et al. [1972] the use of a small tool with the control of the trajectory of its displacement over the optical surface is described. The authors recommend a tool diameter equal to 1/2-1/3 of the part diameter. It is stated that for selection of the tool size it is necessary to use information about the shape of the optical surface. A small tool of such shape is considered in the paper by Jones [1977]. However, there is no formalization of the approach to the problem of selecting the tool diameter in either paper.

Here we shall propose an algorithm for determining the tool diameter. The algorithm is implemented by the SIZE1 program entering into the software set of the ZEBRA-1 automated system (see Appendix 1).

The tool diameter must not be too small inasmuch as under other equal conditions the removal of the material is proportional to the contact areas of the tool and the optical surface. When using a small tool this area is determined only by the tool area. If the size of the tool is too small, the surfacing time will become unjustifiably long. This effect is the most important. Another consequence of selecting a tool that is too small is its ability to create local defects on the optical surface of the types which were discussed earlier: "corrugation," emphasis of the edge effects, and so on.

A tool of too large diameter leads to the fact that the principle of local retouching itself becomes limited with respect to its capabilities. This phenomenon is connected with the fact that the linear dimensions of the sections of the surface on which it is necessary to remove material can be less than the tool size, which leads to "diffusion" of the local retouching effect.

In order to find the defined algorithm for determining the tool diameter, let us make the following basic assumption: the tool diameter must be equal to the average size of the irregularities on the optical surface. By average size of irregularities here we mean the average distance on the optical surface between adjacent local extrema along the normal profiles of this surface.

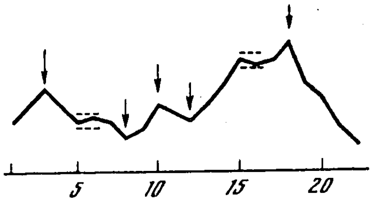
Let us denote by ℓ the mean size of the irregularities. Let D be the part diameter, and n be the number of maxima and minima along this diameter. Then

$$\ell = D/n. \tag{2.57}$$

When using formulas (2.57), the following difficulty arises. Let us investigate the ideal optical surface by the Hartmann method. As a result of errors in measuring the Hartmann photograph we obtain the normal profile with nonzero deviations having local extrema. We assign this structure to the optimal surface and at the same time improperly determine the size of the tool. Figure 2.9 illustrates what has been said. An example is presented here of the normal profile along some diameter of a real optical surface having errors. The x-axis of the figure is the order numbers of the points (spots) on the Hartmann recording. For determinacy we shall consider that the profile is obtained by the Hartmann method, for example, by the HART2 program; here the method is characterized by a mean square error of σ, and this error occurs at a distance between centers of adjacent holes in the diaphragm. In this case no change in sign of the derivatives is realistic. For example, near the points 5 and 6 (see Fig 2.9) two extrema are reached, but the change in normal deviations does not exceed σ. In the figure the dotted lines bound the confidence region. Accordingly, we shall consider that near points 5 and 6 the sign of the derivative does not change, and a normal profile keeps the negative sign of the derivative from point 3 to point 8. An analogous situation also occurs near points 14 and 15. In all on the given profile there are 7 extrema inasmuch as in the given procedure the ends of the normal profiles are provisionally taken as the extrema. In the figure the real extrema lying outside the boundaries of the profile are denoted by arrows. Thus, in our example the recommended tool size will be D/7.

For technological problems and for the problems of quality control of the shape of the optical surface not only the average size of its irregularities has significance, but also the nature of the distribution of the irregularities by size. Small irregularities are difficult to eliminate by a tool having large size by comparison with the irregularities. Small irregularities create difficulties in using the Hartmann method inasmuch as the basic postulates of this method discussed in the paper by Vitrichenko [1976] are violated.

Figure 2.10 shows two extreme cases of the irregularity size distribution. In case a (see Figure 2.10) the probability of encountering small sizes is negligibly small, that is, P(0)=0. This type of optical surface is called ideally smooth. In case b, on the contrary, the probability of small sizes is the largest, that is, P(0)=max. Let us call this surface ideally unsmooth.



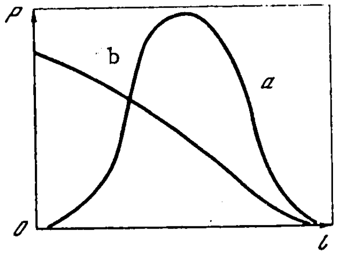


Figure 2.9. Example of the normal profile of an optical surface

Figure 2.10. Two extreme cases of size distribution of irregularities of an optical surface.
1 -- size of irregularities, P -- probability density of the given size of irregularities.
a -- ideally smooth mirror, b -- ideally nonsmooth mirror

For numerical analysis of the degree of smoothness of the surface let us introduce the concept of the smoothness coefficient k_{smooth} [Vitrichenko, 1976], but in somewhat different form than was done in the mentioned paper:

$$k_{\underset{(1)}{\text{гл}}} = 1 - 2P(0)/P_{\max}. \qquad (2.58)$$

Key: 1. smooth

With this definition k_{smooth} varies within the limits from -1 (an ideally nonsmooth surface) to +1 (an ideally smooth surface).

The SIZE1 program uses the punch tape with normal deviations along two parameters of the part which is produced by the HART2 program, and the initial data. The program calculates and prints out the following: the size distribution function of the irregularities, the average size of the irregularities which is recommended as the polisher diameter, and the smoothness coefficient. If $k_{\text{smooth}}>0$, the following message is put out: MIRROR SMOOTH. If $k_{\text{smooth}}<0$, the message meaning the opposite is put out.

An example printout by the SIZE1 program:

```
DATE 1 7 1977
MIRROR 0
PLATE 0
KT=21
BS=15.000
EPS= .010
PAUSE

NORMAL DEVIATIONS (IN MICRONS)
HX     HY
.100   .100
.000   .000
.100  -.100 0
..............

                 ERROR DISTRIBUTION FUNCTION BY SIZES
SIZE OF ERROR             PROBABILITY IN PERCENTAGES
  15.0                                 50.0
  30.0                                 31.8
  45.0                                  9.1
  60.0                                  4.5
  75.0                                  4.5

                  AVERAGE SIZE OF IRREGULARITIES
                 (RECOMMENDED TOOL SIZE)
                              27.3 MM
                  SMOOTHNESS COEFFICIENT OF THE INVESTIGATED SURFACE
                             -.500
                   CONCLUSION:  INVESTIGATED SURFACE NONSMOOTH
```

Initially the program prints out reference data which is input by the operator from teletype and is used for documentation of the experiment. This type of information includes the following:

Day, month and year when the experiment is performed. In the example this is 1 July 1977;

The provisional number of the mirror, on the printout it is mirror No 0;

The number of the photographic plate which contains the Hartmann photograph, here it is No 0;

The number of spots on the Hartmann photograph along the diameter, in the given case there are 21 spots;

The distance between centers of adjacent holes in the Hartmann diaphragm; this number is designated by BS on the printout and is 15 mm;

The mean square error in constructing the normal profile on the base between centers of two adjacent holes in the Hartmann diaphragm. This value is noted by EPS and is 0.01 micron;

The normal profile along two mutually perpendicular diameters of the optical surface; in the lefthand column, for the horizontal diameter, in the righthand column, for the vertical diameter. On the printout only the first three values of the normal deviations are presented, but there should be KT of them.

The program then prints out the values which it calculates. The table called the ERROR DISTRIBUTION FUNCTION BY SIZE contains the size of the error expressed in mm in the lefthand column, and the probability of an error of this size in the righthand column. In the given case the errors of 15 mm are encountered in 50% of the cases, 30 mm errors in 31.8% of the cases, and so on.

The recommended size of the tool is 27.3 mm. The printout is printed for a model example. When surfacing 300 mm spherical and parabolic mirrors recommendations were made for a tool size in the range from 50 to 100 mm. Before beginning work on the part, we manufactured two tools: one 100 mm in diameter and the other 50 mm in diameter. The recommended tool size was rounded to the nearest of these two numbers, and the corresponding tool is used. For the majority of cases the 100 mm tool was used.

The program calculates k_{smooth}; in the given model example it is 0.5. If it turns out to be negative, a message is printed out which is given in the printout: CONCLUSION: INVESTIGATED SURFACE NONSMOOTH. This message forces the optician to think about many things. We have already discussed the importance of such a message, but we shall repeat the basic principles again. On the technological level the nonsmooth surface cannot be significantly improved by a tool, the diameter of which is greater than the sizes of the irregularities. Nevertheless, in classical technology there is a procedure for smoothing small irregularities. This procedure consists in using a full-size polisher in creating small specific forces on the order of 1 g/cm^2. This procedure is not excluded even when using an automated system. This is all the more the case in that a small tool sometimes emphasizes small errors or even creates them.

On the level of quality control of the optical surface when there is nonsmoothness of it the situation can be created where the Hartmann method used here will inadequately describe this surface. In this case the results obtained by the Hartmann method must be duplicated by another method having better resolution with respect to the surface of the part. For example, it is possible to recommend the Foucault-Philbert method which gives resolution an order better than the Hartmann method.

The nonsmoothness of the optical surface has significant influence on the approach to the analysis of the dispersion circle. If the error is small in size, but the derivatives on the optical surface are large, the geometric approach to calculating the dispersion surface can give nonreproducible and inadequate results. When calculating the dispersion circle by the wave methods it is important to know the correlation radius of the surface errors. With a small correlation radius it is necessary to break down the optical surface into small elemental areas which leads to large volumes of calculations.

Conclusions

The software of the automated system designed to finish astronomical mirrors solves three basic problems. First, the calculation of the process conditions based on the data on the shape of the optical surface. Secondly, determination of the process constants and the process functions, without the knowledge of which it is impossible to control the shaping process numerically. The process conditions in the proposed control procedure are the force vector on the zones of the tool and the duration of the processing session.

By the process constants we mean K defining the absolute removal of material at the center of the part per unit time by a unit force, and the machine tool function $\psi(\rho)$ giving the dependence of the relative removal of material on the part radius.

The process constants can be more precisely determined during operation by considering the systematic corrections.

Thirdly, in the system the size of the tool is defined as the average size of the irregularities of the optical surface, and the degree of smoothness of the optical surface is investigated. The last characteristic has important significance both in technological aspect and when solving the quality control problems.

The software presented here cannot in any way be considered the only possible or the complete software. It is possible to propose a set of versions of the systematic approach and also an entire series of areas of further development of the system.

CHAPTER 3. EXPERIENCE IN WORKING WITH THE ZEBRA-1 AUTOMATED SYSTEM

Improvement of the quality of astronomical mirrors and shortening the time required to manufacture them are basic goals of astronomical instrument making [Prokhorov, et al., 1978]. There can be only one way to solve this problem -- the development and assimilation by industry of automated methods of optical technology and the application of objective quantitative methods of controlling the shape of the optical surface and the dispersion circle created by the astronomical mirror.

At the Space Research Institute of the USSR Academy of Sciences a problem laboratory for the development and introduction into industry of digital methods of the control and manufacture of astronomical mirrors was created. The ZEBRA-1 automated complex was created. The complex includes a procedure for quantitative control of the shape of the optical surface of an astronomical mirror based on the Hartmann method and a technological subsystem which permits the use of digital procedures to improve the shape of the optical surface. The system also includes software described in the preceding chapter.

The experimental laboratory versions of the ZEBRA-1 system were developed, put together and passed laboratory tests in 1975. In December 1976 this system went into trial operation at several enterprises of the country.

In all of the organizations special groups of coworkers were created who participated actively in the development of the automated system. The introduction of the development is taking place simultaneously with the development process. This path reduces the time interval between completion of the development and its assimilation by industry to a minimum. In addition, the joint work is generating an atmosphere of mutual understanding and permits the developers to consider the level of modern production. The accumulated positive experience of the joint work can certainly be recommended for application also in subsequent steps of the development of automated systems.

Introduction

In industry there are many years of experience in the automation of the process of shaping an astronomical optical system. It is especially necessary to note the works of the schools of Semibratov [1958, 1962, 1970, 1972, 1973, 1976] and Tsesnek [1970]. The most significant deficiency of the available development is absence of quantitative methods of controlling the shape of the surface. This problem began to be given attention only in recent years. It is quite clear that without information about the real surface it is impossible to develop an automated technological process. In the ZEBRA system a closed "control-manufacture" cycle is realized by using digital and analog equipment.

Another deficiency is the "mechanical" approach to the automation problem. With this approach optimal machine tools are developed which have a great variety of kinematic possibilities, but how to realize these possibilities for the control of the removal of material remains unclear. Another version of the mechanical approach is the creation of mechanical templates or tools of complex shape.

The weak software of the production cycle is a large brake on the development of the automation of optical technology. In essence, the computers are used only to calculate the shape of the mask.

The most significant step along the path of automating the shaping process was creation of the START and PLANETA type machine tool. In the START machine tool, provision was made for the possibility of varying the spindle speed as a function of the position of the tool center with respect to the part center. As a result of the fact that the control of the START machine tool is not provided with software and the machine tool is produced in small series, it has not become widespread.

In the PLANETA type machine tool [Kuks, 1980], a special tool is used which is made in the form of radial springs, the tension on which can be adjusted, thus creating the possibility of variation of the shape of the lapping surfaces. For evaluation of the "corrugation" effect the tool is given oscillating movements of small amplitude. This machine tool also has failed to become widespread for the same reasons as the START type machine tool.

The fact of the production of machine tools on an industrial level itself, the hardware for the controlled process of manufacturing aspherical parts indicate the urgent necessity for solving the automation problem.

Above, the creation of automated technological systems for the manufacture of large optical parts has been given a great deal of attention. The American company "Aytek" has developed an original system which permits the manufacture of complex optical surfaces with great precision in a short time [Aspden, et al., 1972]. Another American company "Perkin Elmer" has built a still more improved system [Jones, 1977]. In both cases the technological process is computer-controlled in real time, a quantitative interferometric control of the shape of the optical surface is provided, and the systems software has been developed.

The ZEBRA-1 system was developed by the Space Research Institute of the USSR Academy of Sciences in close cooperation and with the participation of industrial enterprises. The general direction of this work was by the Division of General Physics and Astronomy of the USSR Academy of Sciences. The electronic part of the ZEBRA-1 system was developed and implemented jointly with the Izhevsk Mechanics Institute. The programming of the software was basically done by the University of Friendship of Peoples imeni Patrice Lumumba.

1. Technical Description of the ZEBRA-1 System

In this section a description is presented of the hardware used for implementation of the ZEBRA-1 automated system [author's certificate No 701773, 1979]. The system is designed for axisymmetric controlled removal of material.

The basic principles when selecting the hardware are as follows: use of finished products series produced by industry. In particular, the ZEBRA-1 system can be implemented on the basis of any series produced optical machine tool;

The hardware must satisfy the requirements of precision and speed formulated in Chapter 2;

The operating reliability of the hardware must be the highest.

As has already been mentioned, the basis for the automated system can be any optical machine tool that is industrially produced. The machine tool is modified as follows:

The carrier is lengthened in the direction opposite to the location of the part and the tool by an amount somewhat greater than the length of the working part of the carrier;

Under this elongated part of the carrier a device is installed which executes and transfers the force through the carrier to the tool. The servoelement is electrically connected to the control unit which gives the force conditions depending on the position of the tool center with respect to part center;

The carrier angle gauge, the readings of which are input to the control unit through a decoder is installed on the shaft of the carrier;

A force gauge [author's certificate No 717571, 1980] is installed on the carrier under the pin leading the tool.

The block diagram of the technical part of the ZEBRA-1 system is shown in Fig 3.1. Feedback with respect to execution of the force is not provided in the system inasmuch as it turned out under laboratory conditions that there is no necessity for stabilization of this sort. Under plant conditions if the stress in the network turns out to be insufficiently stable, the necessity may arise for doing this.

For a model test of the principle of local control of the tool force, a device was built based on the ShPZ-350M machine tool which was at our disposal. The mockup of this unit is presented in Figure 3.2. The experience in working with this system demonstrated the possibility of implementing the indicated principle, but a number of deficiencies were discovered. The ShPZ-350M machine tool can be adjusted only for ratios of the angular velocities of the spindle and the carrier close to multiple spin. This adjustment can lead to polishing of astigmatism. The angular velocity of the spindle, even the smallest, turned out to be too high for the finishing operations with 300-mm mirrors. Finally, discrete switching of speeds turned out to be inconvenient for laboratory operations. Therefore, further experiments were continued on the PD-500M machine tool which has continuous adjustments of the spindle and crankshaft speed.

Figure 3.3 shows the general view of the hardware for the ZEBRA-1 system implemented on the basis of the PD-500M machine tool. The experience in working with the ZEBRA-0 system implemented on the basis of the ShPZ-350M machine tool demonstrated that the polishing process is so unstable that it is necessary to take special measures to stabilize it. These measures consisted in the following:

An organic glass hood is installed under the part. This is necessary primarily for thermal stabilization of the part and the tool. The hood also prevents dust from getting on the surface of the part and creates the potential capability of machining toxic materials;

An automatic heating element is installed under the hood which makes it possible to maintain the temperature within the given limits and accuracy to 0.5°C;

A Polirit suspension in water is mixed in a thermostat, the temperature in which is maintained with an accuracy to 0.02°C, and it is fed through a special dropper in excess on the part. At the same time the classical procedure of "daubing" the part with the suspension by a brush is eliminated, and the danger of "dry adherence" of the tool to the part is eliminated;

The resin on the contact surface of the tool is shaped in a strictly defined way (see Figure 3.4).

The above-indicated measures are not directly in the field of automation, but the operating experience with the system has demonstrated that without taking these measures the shaping process will become nonreproducible and, consequently, uncontrollable. Moreover, in spite of the adopted measures, complete

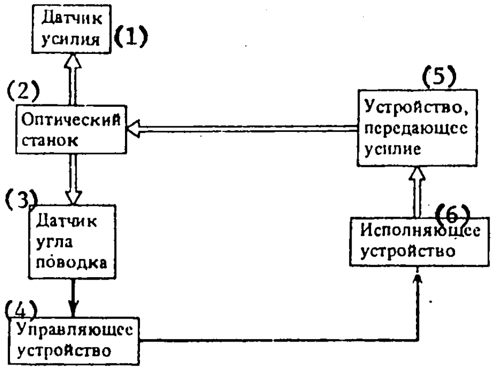


Figure 3.1. Block diagram of the hardware for the ZEBRA-1 automated system.
The double line indicates mechanical couplings between the subassemblies and the system, and single lines, electrical couplins.

Key:

1. Force gauge
2. Optical machine
3. Carrier angle gauge
4. Control unit
5. Device that transfers the force
6. Servoelement

stabilization of the technological process cannot be achieved. In certain cases which amount to up to 10% of all of the surfacing sessions, the polishing process is not carried out, and sometimes the shape of the part even becomes worse. An analysis of such situations requires special investigation. Here the effects connected with reselection of the comparison sphere can play a role, that is, the problem can be related to the peculiarities of quality control, and not the technological process. It is possible to propose experiments which reveal the importance of stabilizing the execution of the force; it is also necessary to study the influence of the hardness of the resin, to try to stabilize the process by forced rotation of the tool. In general, there can be many causes destabilizing the process; the degree of their importance differs, and the problem itself is still not fully understood.

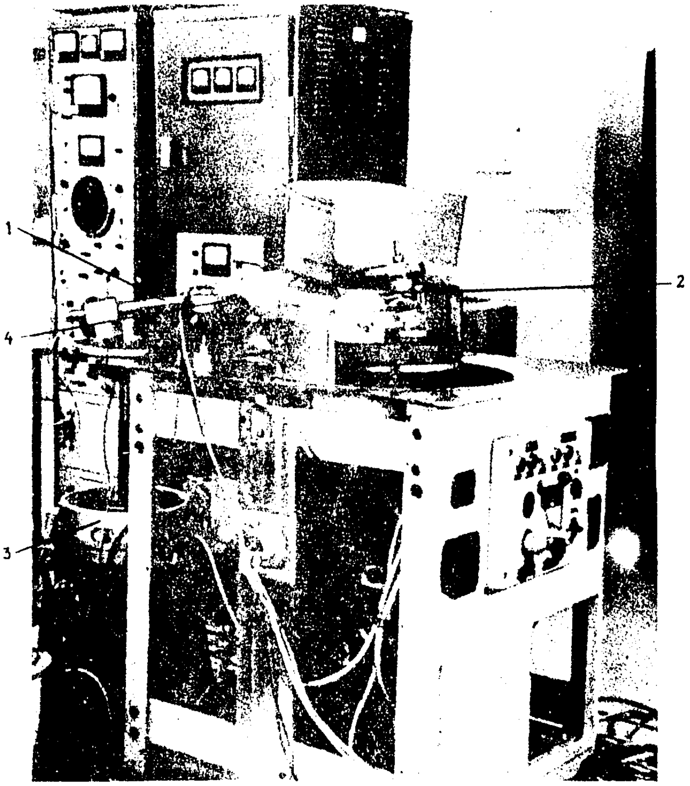


Figure 3.2. ZEBRA-0 automated system in the mockup execution developed on the basis of the ShPZ-350M machine tool.
1 -- carrier extender, 2 — force gauge, 3 — servoelement, 4 -- carrier angle gauge.
The control unit is installed on the rear part of the machine tool housing and is not visible in the figure. In the rear plane are the VEDS control bays.

For conversion of an ordinary optical machine tool to the ZEBRA-1 system it is necessary to introduce four basic elements: the force gauge, the force servo, the carrier angle gauge and the control unit. Let us consider the peculiarities of each of these elements.

The control of the force of the tool on the part requires knowledge of this force. For determination of it a force gauge is installed on the carrier (Figure 3.5) directly above the tool in the ZEBRA-1 system. This installation of the gauge makes it possible to consider all the factors influencing the force except the weight of the tool. In our experiments the weight of the tool was 70-100 grams, which is negligibly small by comparison with the range of the force reaching 8-10 kg.

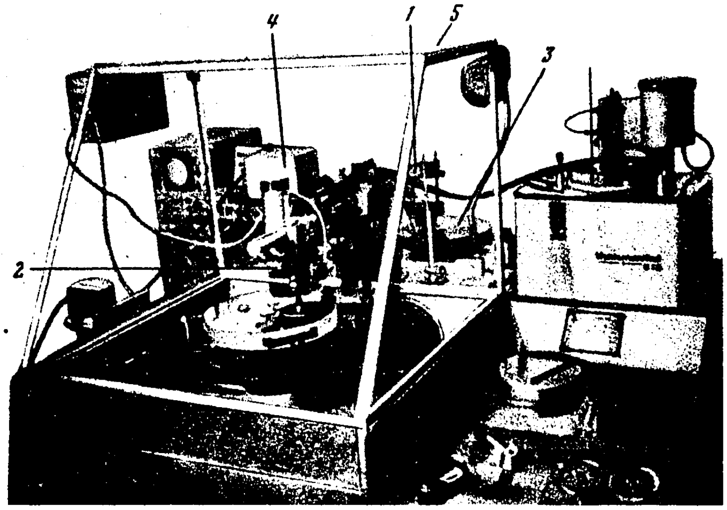


Figure 3.3. Mockup of the ZEBRA-1 automated system developed on the basis of the PD-500M optical machine tool.
1 -- extended part of the carrier, 2 -- force gauge, 3 -- supporting table for the servoelement, 4 -- carrier angle gauge, 5 -- hood

The basis for the force gauge is a dynamometric clamp of the DOSM type produced industrially. In the development process three types of sensors were tested: mechanical, analog and digital.

The mechanical sensor is the DOSM device. The force is indicated by a pointing device, the readings of which are calibrated in advance using weights of known mass. The gauge measures the displacement of the upper part of the clamp with respect to the lower part. The upper part is fastened to the carrier, and the lower part is connected to the pin which carries the tool. If we use a clamp designed for forces to 1000 kg, the scale division on the pointing device turns out to be equal to 400 grams. The measurement error, as practice has demonstrated, is 0.5 of the division. The maximum forces which were used when

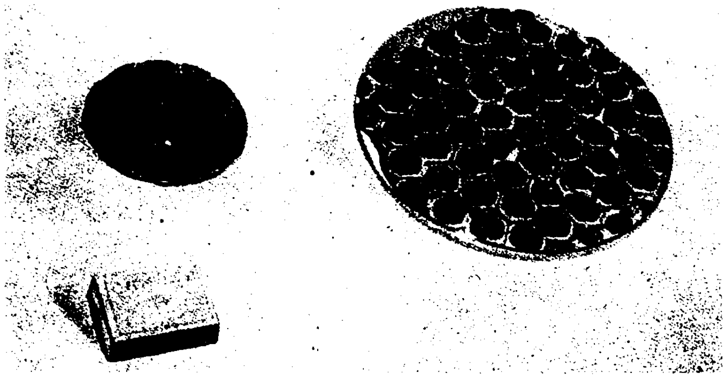


Figure 3.4. Polishers with shaped working surfaces

working with mirrors 300-400 mm in diameter are 8-10 kg. Thus, the dynametric range provided by the mechanical sensor is 40-50. The most important deficiency of the sensor is its nonprospectiveness in the sense that it is impossible to realize force feedback with its help, and it is also impossible to use it when developing a system for communication with a computer. The sensors that measure displacement on electronic or electrical principles are free of these deficiencies.

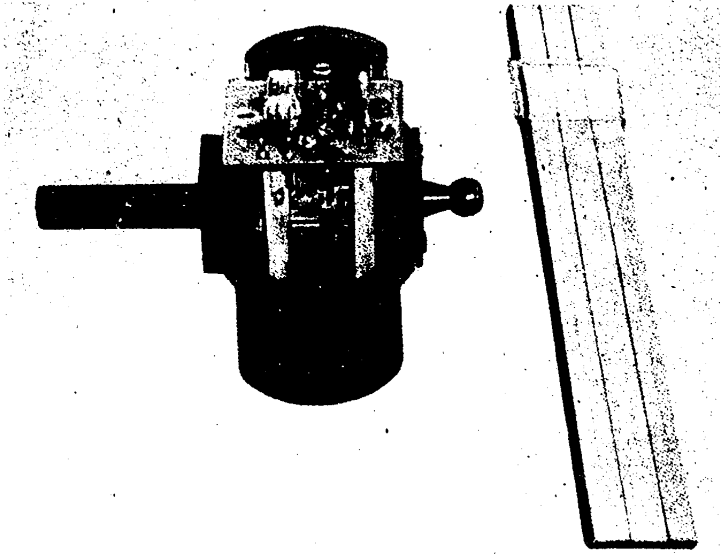


Figure 3.5 Force Gauge

In the analog sensor the principle of a bar which bends is used to measure the forces, and the amount of bending is measured by a strain gauge. Display is possible both on a digital voltmeter and by a pen recorder. By using an analog sensor, the characteristics of the ZEBRA-0 system were investigated. It turned out that if rectangular pulses are fed to the servoelement, the amplitude of which is in the operating range, then the time resolution of the entire force system as a whole consisting of the servo producing the forces, the system transmitting the force, the force gauge and pen recorder is 0.02 sec for the leading edge of the pulse and 0.06 for the trailing edge. Here it turned out that for the leading edge the speed is noted by the interaction of the pen recorder and by the trailing edge, the dynamometric clamp. Here, by time resolution we mean the time interval between the beginning of the pulse and the time when the force gauge indicates half the force amplitude. For the trailing edge the determination is analogous. These studies have demonstrated that the speed of the entire force system is entirely sufficient for our purposes.

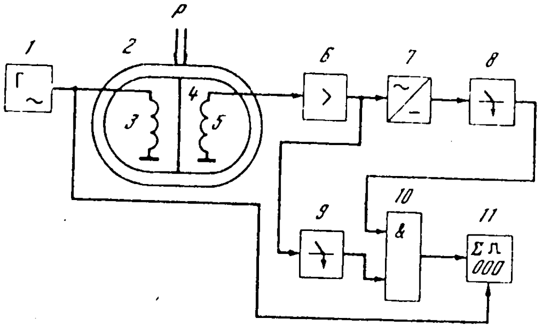


Figure 3.6. Circuit diagram of the force gauge (P -- measured force). 1 -- AC generator, 2 -- elastic element, 3 -- measuring coil, 4 -- ferromagnetic core, 5 -- remagnetizing coil, 6 -- amplifier, 7 -- quadratic detector, 8 -- time interval shaper, 9 -- discharge shaper, 10 -- comparison circuit, 11 -- binary-decimal counter

In the ZEBRA-0 system when studying the time characteristic, a clamp is used designed for maximal forces of 3000 kg. In the ZEBRA-1 system the clamp was designed for 1000 kg; therefore the time characteristic of the ZEBRA-1 system can be better.

During prolonged testing of an analogous gauge it was discovered that it is impossible to use it as a result of its time and temperature instabilities. The electronic part of the gauge is constructed on the principle of measuring a direct current, and the deficiencies of this principle are generally known. This forced conversion to the induction type displacement sensor which is free of time instabilities.

In the digital gauge the force is measured by measuring the deformation of the clamp. This deformation leads to variation of the distance between the induction coil, and the electronic circuit of the sensor fixes the inductance variation in the form of code and analog signals. The analog output makes it possible to use a digital voltmeter for indication of the force, and the code output permits the gauge to be connected to the computer through the interface card. The possibility of creating feedback with respect to the force arises.

In Figure 3.6 we have a schematic diagram of the electronic force gauge [author's certificate No 717571, 1980]. The system operates as follows. The output current of the generator 1 passes through the magnetic wall 3 and creates a periodically varying magnetic field, as a result of which the ferromagnetic core 4 is remagnetized. Let us consider the case of the absence of a load P on the elastic element 2. In this case a preliminary load on the core 4 is created as a result of the tension of the element 2. The emf pulses induced in the remagnetizing winding 5 are amplified by the amplifier 6 and go to the quadratic detector 7 and the time interval shaper 8. The spike shaper 9 brings the signal to some selection level. The formed pulses go to the input of the comparison circuit 10. The signal from the amplifier 6 also goes to the detector 7, which includes a smoothing filter. From the output of the detector 7 the signal goes to the time interval shaper 8 which compares the voltage of the envelope with some standard voltage and shapes the time interval during which the envelope voltage exceeds the standard voltage.

The standard voltage and the initial tension of the core 4 are selected so that when P=0 the length of the time interval will also be zero. Then P=0 the readings of the counter 11 are also equal to zero, for the comparison circuit 10 is closed by the corresponding attention of the shaper 8.

For P≠0 the voltage in the core 4 decreases as a result of bending of the elastic element 2, the signal power from the remagnetizing winding 5 increases, the envelope voltage increases and the pulse duration from the output of the shaper 8 increases. Correspondingly, the number of pulses reaching the counter 11 increases. Before the beginning of the measurement the counter 11 is automatically set to 0 from the generator 1. The two low-order decades of the counter 11 are not indexed, and they are used as frequency devices. The dispersion of the number of spikes does not exceed the uniformity of the two low-order decades and does not influence the counter readings.

The basic advantage of the investigated device is absence of an analog to digital converter which introduces its own errors. Another advantage is the functional flexibility. By varying the selection level and magnitude of the standard voltages it is possible to obtain different characteristics of the gauge and select those which are most acceptable for the given operating conditions. The gauge is easily connected to a computer which makes it irreplaceable in the ZEBRA-2 system.

The technical specifications of the implemented force gauge are as follows:

Operating range of measured forces	0-50 kg
Elastic element displacement	30 microns
Output code	binary, parallel, six-bit
Information update time	30 microns
Power	+5 volts ±12 volts
Reduced relative error	no more than 2%

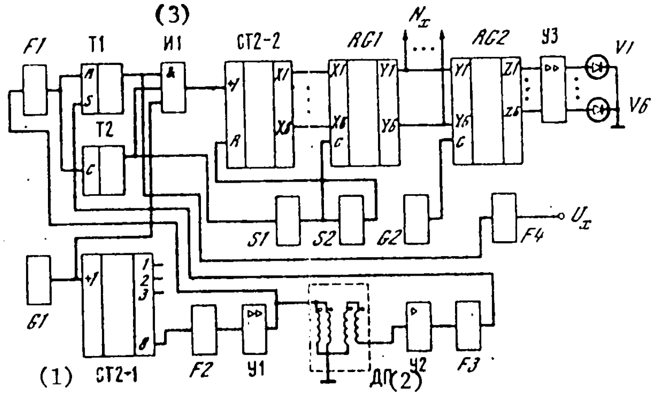


Figure 3.7. Functional circuit diagram of the force gauge. G1 -- master oscillator; STR-1 -- binary counter; F1, F2 -- shapers; Y1-Y3 -- amplifiers; T1, T2 -- triggers; RG1, RG2 -- registers; S1, S2 -- pulse shapers

Key:

1. ST2-1	3. AND1
2. DP	

The functional circuit diagram of the force gage is illustrated in Figure 3.7. The quartz-stabilized master oscillator G1 generates s square pulse train with a frequency of 8192 kilohertz. The signal from the oscillator G1 goes to the ST 2-1 light-bit binary counter used here as a frequency divider. The counter output is connected to the pulse shaper input F-2, the circuit of which contains a low-frequency filter with cut-off frequency of 35 kilohertz. The shaper F-2 creates a sinusoidal voltage with a frequency of 32 kilohertz which goes from its output to the shaper F1 and the amplifier Y1.

The output of the amplifier Y1 is connected to the primary windings of the deformation gages. The shaped output voltage goes to the input of the trigger T1. A reference voltage is fed to the input R of this trigger from the output of the shaper F1. The pulse duration at the output of the trigger T1 turns out to be proportional to the output voltage phase of the sensor shown in the figure by a dotted rectangle.

A reference voltage goes to the input C of the trigger T2 from the output of the shaper F1. The output signal of the trigger T2, the frequence of which is 16 kilohertz, is used to control the ST2-2 counter. Signals go to the comparison circuit AND1 from the outputs S1, T1 and T2. The signal from T2 realizes a forbid for one period of the reference voltage, which is necessary to increase the reliability of the circuit. From the output of the AND1 circuit, bunches of pulses are picked up where the number of pulses in the bunch is proportional to the phase of the voltage picked up from the sensor.

The bunch of pulses goes to the input of the six-bit binary counter ST2-2, and then the binary number is entered in parallel code in the register RG1 (the signals X1-X6). The write pulse is shaped by the circuit S1, and the pulse to clear the contents of the counter ST2-2, by the circuit S2. The contents of the register RG1 go through the number buses to the M-6000 control computer (the signals Y1-Y6). The outputs of the register RG1 are also connected to the display register RG2. Then the logical levels Z1-Z6 go through the amplifier Y3 to the light diodes V1-V6. The entry is made in the register RG2 by a pulse from the generator G2, the frequency of which is 1-2 hertz. This frequency is selected for convenience of visual monitoring of the readings of the light diodes indexing the force in binary code. The signal from the output of the trigger T1, the off-duty factor of which is proportional to the phase shift, goes to the shaper F4 which includes the mean value detector. The output voltage is proportional to the duration of the volts from the output T1 and the phase shift.

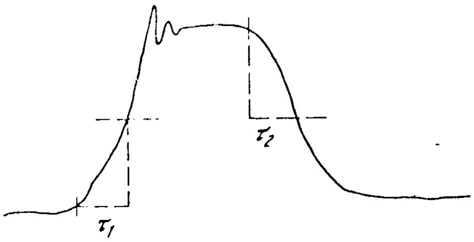


Figure 3.8. Example of recording of forces by a pen recorder. Force amplitude is 5 kg; τ_1, τ_2 -- time resolutions of the leading and trailing edges in a square pulse (the wiggles are connected with the pen recorder)

In the present execution of the sensor there are two deficiencies. The first of them is insufficient dynamic range. The actually built sensors have a range of about 5 which leads to great difficulties when calculating the process conditions. It appears to us that this deficiency can be eliminated. Another deficiency of the sensor is unsuccessful mechanical reinforcement of it. As was discovered during the operating process, the readings of the sensor depend strongly on the lateral loads on the tool. This is no accident; the DOSM type gauge is not designed to work under dynamic conditions. The way out of the situation is obvious: transmit the force to the gauge through the guides which take the lateral loads. It is possible to propose another way out: replace the bracket of the DOSM by devices which do not have deformations in the vertical direction under lateral loads. Such devices have been developed.

An example of a recording of forces obtained under operating conditions is presented in Figure 3.8. A force of 5 kg was assigned for one of the zones of the part. The force builds to half its rated value in a time on the order of 0.02 sec. Then come the wiggles which, as special experiments have demonstrated, are connected with the pen recorder. When removing the force, the decay time to half amplitude takes 0.06 seconds. It turns out that this delay is explained by the mechanical inertia of the DOSM bracket. All of the remaining elements of the force part of the ZEBRA system have characteristic times of less than 0.01 second.

During continued work with the force gauge it was discovered that its readings differ depending on the direction of motion of the carrier by 10-30%. This effect is connected with the influence of lateral loads on the bracket of the DOSM, which complicates the adjustment of the machine tool, but the development of the forces takes place correctly.

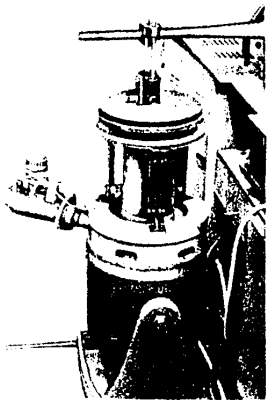
The next important element of the ZEBRA type system is the force servo. The variable force of the tool on the part is programmed in th. system. As the device executing the force, a vibration electrodynamic stand (VEDS) which is series manufactured industrially is used. The stand is designed for vibration testing of instruments; it is used as the force control element in the ZEBRA system. For conversion of the device to a force element, a rectifying bridge and smoothing filter are installed in the output signal circuit.

The use of the VEDS type device in an automated system as a force element opens up broad possibilities for automating many types of optical machine tools produced industrially. These devices are made inversions with maximum forces from 10 to 1400 kg, which is sufficient for making astonomical mirrors of in practice any dimension. For the VEDS type device the two basic advantages over the force system of the ordinary optical machine tool are speed and simplicity of control. The speed is provided by the electrodynamic principle of the force element. The pneumatic drives used in optical machine tools have a time constant in the range of 0.1 to 1 second. The industrially produced hydraulic drives with appropriate power at the output have a still faster speed.

The simplicity of controlling the VEDS is connected with the fact that the VEDS is an electrical instrument; it is easily connected to other elements of the system, and in the future, to a computer. For connection of the pneumatic or hydraulic drives to the system, it is necessary to develop special matching circuits, and in the final analysis, electronic sensors.

The VEDS instrument is installed behind the optical machine tool so that the distance from its axis to the rocking axis of the carrier and the distance from the rocking axis of the carrier to the center of the part will be equal in the projection of the carrier axis. This is necessary for it to be possible to use a full size grinder as the support table (which will be discussed later), by means of which the given part was ground earlier. In the case of unequal arms of the carrier it is necessary to manufacture the support table especially.

A device which transmits the force from the dynamic system to the extended part of the carrier is installed on the sliding coil of the dynamic system. This device, which is presented in Figure 3.9, consists of a cylinder, a support table installed on a cylinder and a roller fastened to the carrier. The cylinder is installed on guides which limit the movement of the cylinder up and down. The upper part of the cylinder has a standard thread which permits the support table to be screwed on it. The table has the same radius of curvature as the machined part, but of opposite sign. As has already been mentioned, the role of the support table can be played by the grinder by which the same part was machined. The roller fastened to the carrier moves over the support table. It insures strong closure of the entire force transmission system. If all the elements of the force unit have the deformation, then there would be no displacements of the support table during the machining process. However, in connection with the deformations of the carrier, the dealignment of the shafts and so on the movements occur within the limits of several tenths of an mm. With these displacements no changes take place in the force as a result of the properties of the dynamic system (the force does not depend on small displacements). In addition, for small displacements the force turns out to be linearly dependent on the current in the sliding coil.



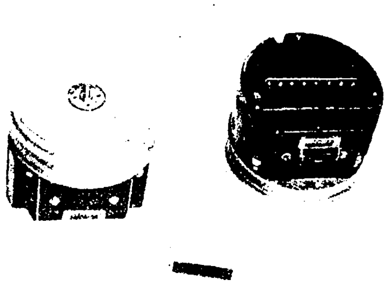


Figure 3.9. Device for transmitting the force from the dynamic system to the carrier

Figure 3.10. Carrier angle gauge

As a result of the smoothing properties of the dynamic system, the shape errors of the former surface of tenths of an mm do not lead to variations of the force. The requirements on the obliqueness of the plane of the support table with respect to the plane of the part are of the same order. These requirements are easily satisfied. The support table has adjustment with respect to slope permitting the slopes of the planes to be matched. Only pits and dents on the surface of the support table are dangerous inasmuch as when the roller turns, impact loads occur.

Let us consider the role of the carrier angle gauge in the system. The variations in force of clamping the tool against the optical surface take place with variation of the carrier angle. The carrier angle α is linearly related to the radius of the zone ρ of the optical surface

$$\rho = a\alpha, \qquad (3.1)$$

where a is the length of the carrier arm. The angle α is determined by the angle gauge installed on the horizontal rolling shaft of the carrier. In practice the gauge shaft is connected to the carrier shaft by a belt drive. The signal from the gauge is input to the control unit.

The carrier angle gauge is illustrated in Figure 3.10. It is set up by the principle of a contactless induction sensor. In addition, the sensor is positional. These properties are important for operation and maintenance of it under plant conditions. In contrast to contact sensors, the contactless ones have immeasureably greater service life. Inasmuch as the angle gauge is positional, it "forgets" the preceding reading which is important for use under plant conditions where the interference with respect to feed and induction interference on the cables create difficulties for using gauges based on counting pulses.

The primary purpose of the gauge is to isolate the annular zone on the surface of the optical part. Within the limits of this annular zone the force remains constant, and at the time the center of the tool makes a transition from one zone to another the force assumes the new value discontinuously. If the gauge switches by a low-order bit on rotation of the axis by the angle $\Delta\alpha$, the width of the zone δ which will be called the control zone will be

$$\delta = ka\ \Delta\alpha. \qquad (3.2)$$

Here k is the transmission ratio of the belt drive connecting the shaft of the gauge and the carrier. If the number of binary bits of the gauge in a complete rotation is N, then the angle $\Delta\alpha$ is represented as follows:

$$\Delta\alpha = 2\pi/2^N. \qquad (3.3)$$

The ZEBRA-1 system uses a six-bit gauge, the carrier length a=400 mm, the transmission ratio k=1, so that the width of the control zone turns out to be 25 mm. The experience in working with the system has demonstrated that this width is sufficient to eliminate the majority of types of errors of the optical surface and to obtain aspherical parts with small asphericalness encountered in astronomical mirrors. When necessary to change the width of the zone it is possible either to use a gauge with a different number of bits or to change the transmission ratio k.

The functional electric circuit of the carrier angle gauge is shown in Fig 3.11. The output signal of the master oscillator ZG goes to the shift register for interrogation of RO and simultaneously to the interrogation shaper FO. With each negative output voltage gradient of the ZG the FO shapes the gauge interrogation signal which goes to the first inputs of the bit comparison circuits of the RS. The corresponding outputs of the RO are connected to the second inputs of the comparison circuits. The gauges are interrogated successively, beginning with the low-order bit, on comparison of the FO signals and the corresponding RO bit (the signals T1-T6). The sixth bit gauges are interrogated simultaneously in the first cycle T1 where a one is entered in the low-order bit of the RO. A shift by one in the RO is realized for positive output voltage gradients of the ZG. Thus. the unit shift times in the RO and the gauge interrogation times are separated in time by half a period of the output voltage of the ZG. The use of only one FO for all bits of the gauge permits the dispersion of the interrogation pulse parameters to be diminished and the carrier angle gauge circuit to be simplified.

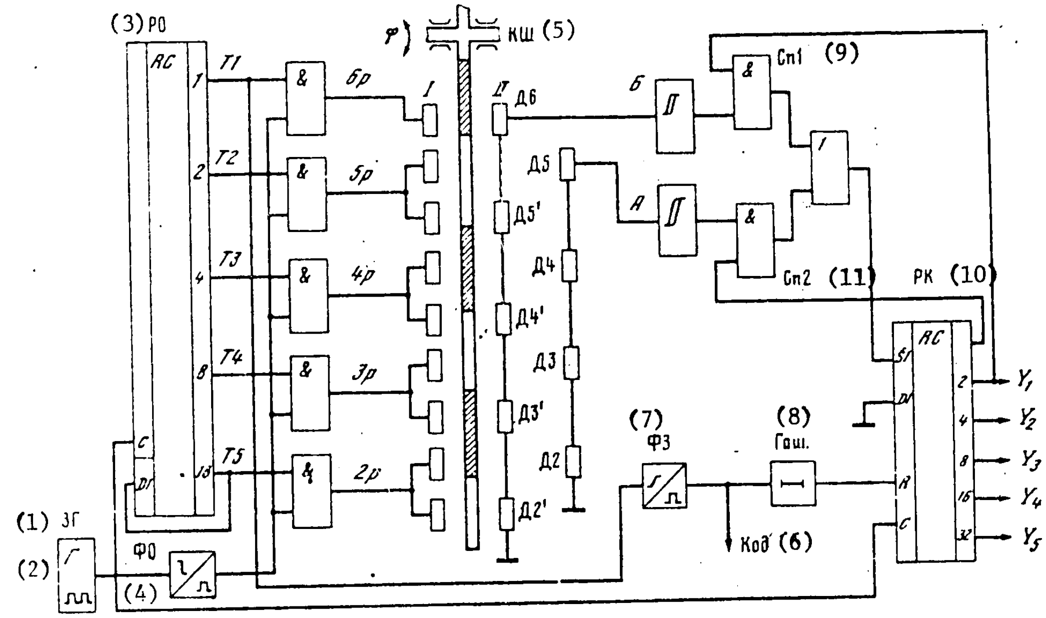


Figure 3.11. Functional diagram of the carrier angle gauge. ZG -- master oscillator, KSh -- code scale, FO -- interrogation shaper, RO -- interrogation register, Sp1 and Sp 2 -- comparison circuits

Key:

1. ZG	5. KSh
2. G	6. code
3. RO	7. FZ
4. FO	8. extinguish
	9. Sp1
	10. RK
	11. Sp2

The output signals of the six-bit gauges A_1 and A_4 go to the threshold elements which realize amplitude selection of the signals. The output signals of the subbits A and B go through the threshold elements to the comparison circuits Sp1 and Sp2, after which they go to the low-order bit of the code register RK. The information shift in the RK is realized simultaneously with the unit shift in the RO with a positive voltage gradient of the ZG. The choice of the subbits A or B is made by the comparison circuit Sp1 and Sp2 depending on the code of the preceding low-order bit which is stored in the second bit of the RK.

The FZ write shaper shapes the write signal which goes to the input R of the register RK. The clearing of all units is realized by the same "write" signal delayed by the delay line for the time of recording the information in the RK.

The entire operating cycle of the electronic circuit consists of six ZG cycles which amount of 120 microseconds.

The technical specifications of the carrier angle gauge are as follows:

Output code	binary, parallel
Number of bits of the output code	6
Frictional moment of the shaft	No more than 10 g-cm
No of binary bits of the code scale	6
Conversion cycle time	120 microseconds
Feed	+5 volts and ±12 volts
Element base	microcircuits of the 155 and 140 series
Operating temperature range	from -10 to +70°C
Overall dimensions	height with shaft 115 mm, diameter 110 mm
Weight	1.3 kg

When using the code sensor for isolating the control zones, the following problem arises: on movement of the carrier gauge in the forward or return directions the control unit will output various forces in the same zone. Figure 3.12 shows the circuit explaining this effect. In order to eliminate this effect, the indicator of the direction of motion is built into the electronic part of the cage. It subtracts or adds one low-order bit depending on the direction of motion. In this case in each zone independently of the direction of motion the given force will be sustained.

The carrier angle gauge has another purpose. If it is necessary to determine the machine tool function, the readings of the gauge in real time for the machine tool under no load are input to the computer which by the DVCE1 program determines the machine tool function. This method permits frequent determinations of the spindle and crankshaft speeds and complex calculations to be avoided.

The last device, with which we shall conclude the survey of ZEBRA-1 system hardware is called the control unit. Its purpose is to store the program for executing forces in the optical surface zones and in accordance with this program, outputting a signal to the servoelement to develop a force as a function of the signal coming from the carrier angle gauge (see Figure 3.13).

The structural diagram of the control unit appears in Figure 3.14. The digital angle converter TsPU (carrier angle gauge) converts the angle of rotation of the input shaft ϕ to the digital code Y_2-Y_6, which is entered in the buffer register BR of the control unit by the WRITE signal generated by the TsPU. Inasmuch as the angle of rotation of the angle gauge shaft does not exceed 180°, the first bit of the angle gauge Y_1 is not used. From the BR the angle code is transmitted to the zone number decoder DNZ which generates the annular zone number in which the tool center is located. This number N is transmitted to the commutation unit BK which switches on the corresponding relay which, in turn, connects the potentiometer in the setting module BU to the output circuit. An AC voltage with frequency on the order of 1000 hertz is fed to the BU module; the signal U_{0i} is picked up from the output of the included potentiometer, and the voltage $U(N)$ which is fed to the input of the servoelement is picked up from the output of the commutation unit.

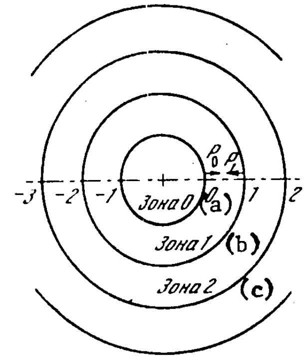


Figure 3.12. Diagram explaining the effect of the direction of motion of the tool.
In the zone of part 1 when the tool moves to the left the force P_1 is generated, and in the same zone when the tool moves to the right, P_0

Key:

a. Zone 0
b. Zone 1
c. Zone 2

The relay commutation unit simultaneously with connection of the required potentiometer switches on the display light indicating the current number of the zone. This display is used to assign the process conditions and to investigate the automated system.

With a position of the tool center left and right with respect to the center of the part at identical distances the tool center turns out to be in the same zone of the part. It would be possible to commute the readings of the carrier angle gauge so that the force control will be realized through one potentiometer. At the same time, in the control unit the situation is such that the force setting is realized by two different potentiometers. This leads to the fact that the operation with respect to setting the forces in the zones is redundant. However, there are two advantages. First, in this case there is no danger of misalignment of the plane of the part with respect to plane of the support table. Secondly, some error compensation occurs in the execution of the forces. If one of the potentiometers changes resistance during operation and generates a force with an error ΔP, then as a result of the fact that the other will generate the force correctly, the total error in executing the force will be $\Delta P/2$.

The control unit has indicator lights which indicate the position of the tool with respect to the center of the part. This display facilitates tracking of the course of the machining process by the operator, but its most important purpose is to facilitate the setting of the forces in the zones before the beginning of operations. The machine tool has a manual drive for shifting the carrier.

The operator, turning this drive, moves the tool center from zone to zone and in each of them, turning the potentiometer, sets the required force. With some skill the adjustment of the machine tool to the new conditions takes 10 to 15 minutes.

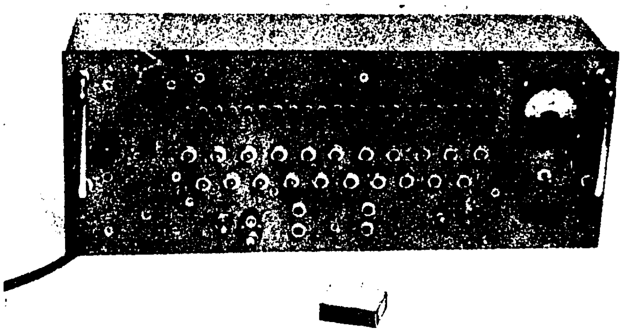


Figure 3.13. Control Unit

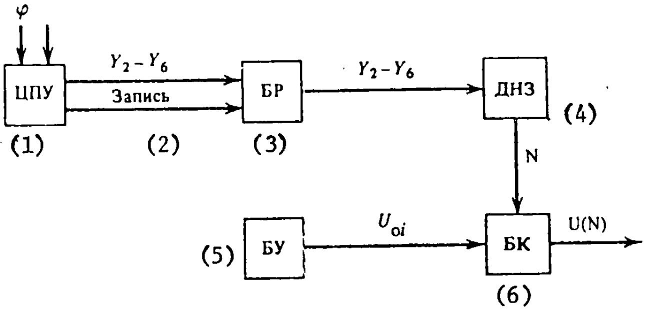


Figure 3.14. Block diagram of the control unit.
TsPU -- digital angle converter, BR -- buffer register, DNZ -- zone number decoder, BK -- commutation unit, BU -- setting module

Key:

1. TsPU
2. Write
3. BR
4. DNZ
5. BU
6. BK

2. Manufacture of Series Mirrors

In April 1975 the Space Research Institute of the USSR Academy of Sciences turned over the ZEBRA-0 automated system created on the basis of the ShPZ-350M machine tool for laboratory test operation in a mockup execution. The system permitted a mirror 300 mm in diameter to be made. During the process of making the mirror the forces were created only in the zone having a maximum error. During operation many machining sessions were carried out with a total duration of several tens of hours, but the primary goal of these sessions was not so much to improve the quality of the mirror as to master the system itself and study its characteristics. The experiments concluded successfully; the basic result of the experiment was proof of the possibility of implementing the principle of local control of the force of the tool on a machine tool with ordinary kinematic system. During operation deficiencies were also discovered, an analysis of which permitted the creation of a new, improved system based on the PD-500M machine tool which we have called ZEBRA-1. This system began laboratory testing in August 1976, and three more mirrors were made on it (two parabolic and one spherical).

The basic goal of all of the laboratory experiments was to check the fitness of the principle of shaping control itself by local operation of the force. The other goal was to check the limiting possibilities of the system with respect to the attainable machining precision of the optical surfaces. An experimental check of the possibility of manufacturing the aspherical optical system also plays an important role.

Let us consider two problems having significance for the statement of the problem of manufacturing the optical surfaces. The first of them is what should the initial error in the shape of the optical surface be before beginning machining of it on the ZEBRA system and also what value characterizes this error. The second problem is to what magnitude of error the optical surface must be machined, that is, what to consider to be the end of the finish operation.

As the initial error we have selected a value on the order of 0.5 micron, that is, approximately equal to the wave length (the effective wave length in astronomy). Experience shows that the optical system of the fifth to sixth category after elimination of mat of the surfaces of the measured dimension (300-500 mm in diameter) obtains an error of the same order of magnitude. If the error is appreciably greater, then it is necessary to eliminate it by grinding which insures significantly higher speed of removal of the material than polishing. If the error is appreciably less than 0.5 microns, the part can not require finishing in general. It is important what we mean by error.

In practice a large set of definitions of the values characterizing the errors of the optical surface are used. The most widespread concepts are "local error" denoted by ΔN*and "general error" denoted by ΔN. These concepts are used by the optician when applying standard glass. The value of N characterizes the difference between the radius of curvature of the investigated part and the sample glass. Inasmuch as during the finishing operations the removal of material is insignificant, the radius of curvature in the majority of cases does not change. Therefore for us the value of N plays no role. The value of ΔN is defined as the maximum deviation of individual interference bands from the ideal case. From the definition itself it is clear that the amplitude of the real errors on the optical surface can be several times greater than ΔN. In addition, when estimating the value of ΔN the smoothly varying surface errors cannot be taken into account. Very frequently when determining ΔN the edge of the part is not considered. All of these details lead to such large indeterminacy in estimating the value of ΔN that it is in practice impossible to use it.

The ZEBRA-1 system is designed for axisymmetric removal of material. Therefore it is meaningful to consider only the radial component of the error. Thus, by the error in the optical surface we mean the amplitude of the normal profile

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*[sic] [probably should be N.]

averaged along the radius of the part, and in this case the choice of the comparison sphere is determined by the minimum amplitude of this error.

The error amplitude of the entire optical surface is always greater than its radial component. It is desirable to indicate two types of errors, that is, in essence to construct the normal deviation chart of the entire optical surface each time. However, inasmuch as the construction of this chart always remains a labor-consuming process and it is frequently important for us to discover not the absolute value of the error, but the course of its variation, during the experiments we operated with a mean radial error output by the HART2 program [Vitrichenko, 1980]. Here the normal profile is refocused to the minimum normal deviations inasmuch as in the HART2 program the comparison sphere is selected by a different principle -- by the minimum mean square transverse aberration.

Thus, we have determined what the initial error must be before the beginning of the finishing operation and also the concept of "error" itself. Here there is a defined measure of arbitrariness, but any other determination of the use of values can also be met with objections inasmuch as the description of a complex three-dimensional surface such as the optical surface of an astronomical mirror by one number is a question of agreement.

The finite error of the optical system, on achievement of which the operation can be considered successfully completed is also a question of agreement.

Let us consider two versions of completion of the work on a part -- normal and emergency. We shall consider normal completion when the average normal profile on the radius is within the limits of $\lambda/8$, which corresponds to the Rayleigh number. As is known, the energy concentration in the Airy circle will in this case turn out to be 20-30% below the theoretical limit.

In the case of emergency completion of the work, the normal profile along the radius of a part will be outside the limits of $\lambda/8$, but the local errors in the surface with respect to amplitude exceed the zonal component. The HART2 and PRES3 programs communicate about this situation. Inasmuch as the ZEBRA-1 system is designed only for zonal removal of material, further machining does not lead to improvement of the optical surface. In this case it is necessary to analyze the sources of occurrence of local errors and take measures to eliminate them outside the framework of the system. There can be several such sources. First, the part could have local errors after grinding. After elimination of the zonal errors local errors are discovered. In this case it is necessary again to regrind the part. Secondly, as a result of nonuniformity of the material with respect to the grindability factor, the local errors could be formed in the grinding phase, and new grinding will not eliminate them. In this case it is necessary to reject the billet. Thirdly, the peculiarities of adjustment of the machine tool, fastening of the tool and the part can lead to the occurrence of local errors. It is necessary carefully to check the effect of these factors on the shape of the optical surface and to take measures to eliminate the indicated factors.

The experience in working with the system has demonstrated that if the billet is uniform, the part is installed without misalignments, the machine tool does not have beading, and so on, the ZEBRA system will not create local errors.

As a result of surfacing the mirror 300 mm in diameter on the ZEBRA-0 system the characteristics presented in Figure 3.15 were obtained. The average radial profile is within the limits of $\lambda/8$ where λ=0.5 micron. The study of the entire optical surface demonstrated that the total error amplitude is 0.3 micron, and the basic types of errors are local mounds and holes. A number of experiments of a technological nature were performed with three mirrors; therefore it is complicated to evaluate the machining time. The initial and final normal profiles of the mirror are shown in Figure 3.15.

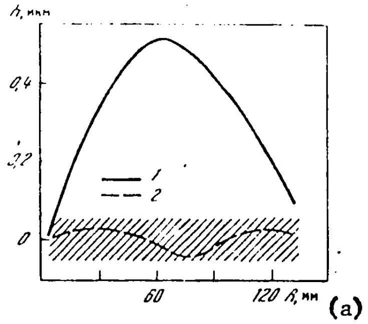
The mirror surfacing system can be represented as follows. The average normal profile of the part radius was calculated by the HART2 program. The position of the maximum error was determined on this profile. The force was executed only in the control zone which turns out to be close to this maximum. The magnitude of the force was calculated manually, the process constant was determined during the experiment.

The mirror was spherical, 300 mm in diameter with a radius of curvature of 2400 mm. The mirror material was K8 glass. The feed of the contact spot was realized by a suspension of water and Polirit by smearing with a brush as the opticians do. After completion of the process session the mirror was held (let stand) for 3 to 4 hours. This time was determined experimentally.

All further work in the laboratory testing of the ZEBRA-1 system was done on mirrors of the diameters and radii of curvature of ~2400 mm. Type KV quartz produced by the Government Scientific Research Institute of Quartz Glass was used as the material. The choice of the material is connected only with the fact that as the experiments demonstrated, quartz requires no more than 20 minutes of standing. This permits 2 or 3 machining sessions in one working day. Other materials with a diameter of 300 mm require standing of several hours which does not permit more than one session in a working day. Under plant conditions when a large number of parts are made simultaneously and the machining and investigation of the surface shape are done by the flow system, this reason turns out to be insignificant.

An important property of quartz as a material is that during the machining of it in practice no polishing errors arise around the small discovered bubbles. Other material, for example, LK5 glass, give significant polishing errors.

The second spherical mirror was surfaced by the sterilized procedure on the ZEBRA-1 system. The surfacing system appeared as follows. The average normal profile along the radius of the part was calculated by the HART2 program. This profile was recalculated by manual calculations so that the normal deviations would be zero in the center of the part and at a distance of 135 mm from its center. A value of 135 mm was selected so that the center of the last measured spot on the Hartmann recording is a trace of a beam formed by an opening in the Hartmann diaphragm at the same distance from the center of the part. This normalization is arbitrary, but corresponds to determination of the nearest comparison sphere adopted during asphericalization of the optical surfaces. The corrected normal profile was used by the PRES2 program which calculated the regime in each of the control zones. This regime was realized, and then the entire cycle was repeated.



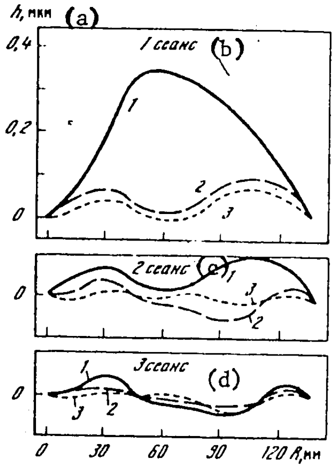


Figure 3.15. Average normal profile h along the radius of the part for mirror No 5 before beginning of surfacing (1) and after completion (2).
The width of the crosshatched section is λ/8, and the surfacing time, 3 hours 40 minutes

Key:
a. h, microns

Figure 3.16. Average normal profiles for three sessions of surfacing the mirror No 9.
1 -- initial profile, 2 -- profile obtained after the surfacing ession, 3 -- theoretical profile which must be obtained after the surfacing session

Key:
a. h, microns
b. Session 1
c. Session 2
d. Session 3

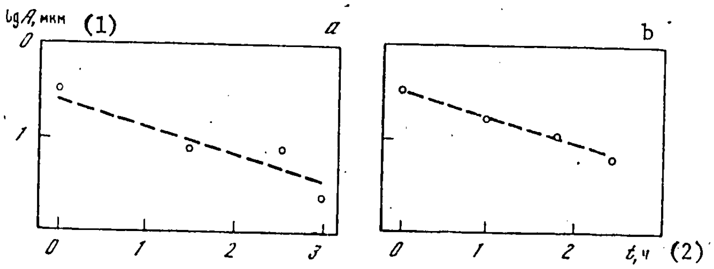


Figure 3.17. Relation between the amplitude of the average normal profile and the total surfacing time.
a, b -- for mirrors No 9 (spherical) (a) and No 11 (parabolic) (b)

Key:
1. microns
2. hours

A total of 3 polishing sessions were held with the mirror with a total duration of 3 hours. The experimental conditions were as follows -- tool diameter 100 mm, resin No 10. The suspension was made up of solid and liquid parts (Polirit and water) in a 1:5 ratio and it was fed through the dropper in excess. The suspension temperatures in the space around the part were stabilized and amounted to 25°C.

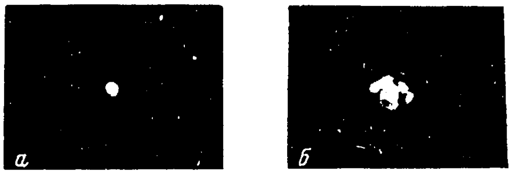


Figure 3.18. Photograph of the light source (a) and its image (b) created by mirror No 9.
The light source is a laser with a wave length of 0.44 micron, and the diameter of the central spot on the image in the original is 4 microns.

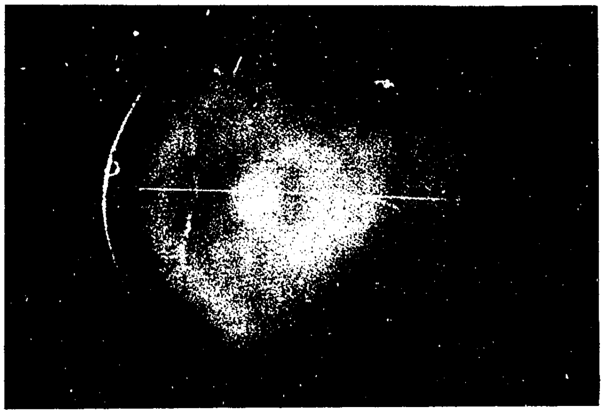


Figure 3.19. Schlieren pattern for mirror No 9

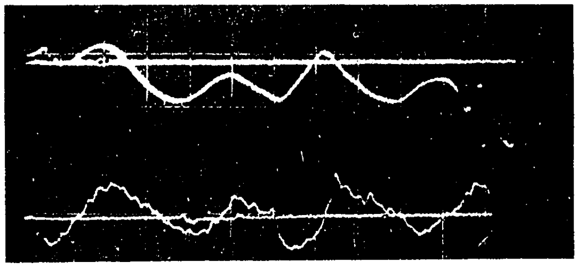


Figure 3.20. Normal profile along the diameter of mirror No 9

The initial amplitude of the normal profile was 0.35 micron, the amplitude of the final normal profile was 0.05 micron. The experimental results are shown in Figure 3.16. The relation between the surfacing time and the amplitude of the normal profile is illustrated in Figure 3.17.

From investigation of Figures 3.16 and 3.17 it is possible to draw the following conclusions:

The shaping process is converging; in three surfacing sessions the optical surface was improved by sevenfold. Let us consider that the process of improving the surface shape is described by the law

$$A = A_0 z^{-t}, \qquad (3.4),$$

where A is the amplitude of the normal profile, A_0 is the amplitude of the initial normal profile, z is the value characterizing the convergence rate of the process, t is the total surfacing time in hours. The value of z indicates how many times the optical surface is improved in 1 hour of work (in the experiment with mirror No 9, the value of z=1.2);

The amplitude of the normal profile and the mean square error of the optical surface vary by this law;

The mean square divergence between the predicted profile and the profile obtained as a result of the experiment will be on the average 0.02 micron. This value coincides with the mean square error of the Hartmann method, which indicates that even when surfacing this mirror complete reproducibility of the experiment is achieved;

The normal profile obtained as a result of the experiment satisfies the Rayleigh number. Further improvement of the optical surface is impossible inasmuch as the zonal errors are smaller with respect to amplitude and local errors.

An analysis of the entire optical surface of mirror No 9 demonstrated that the total error amplitude will be 0.2 micron. In the edge zone of the part 15 mm wide there is edge damage with an amplitude of about 0.3 micron. The quality of the image created by the error is shown in Figure 3.18. An analysis of this image shows that with respect to resolution and energy concentration in the Airy circle this image is inferior to the theoretical limit by 10-15%. When photographing a point, the outer zone was screened. Thus, the central part of the part 270 mm in diameter turns out to be in practice ideal (see Figures 3.19 and 3.20). Successful completion of the experiments in manufacturing spherical mirrors revealed the possibility of beginning operations of the manufacture of a spherical surface which play an important role in astronomical instrument making.

3. Parabolic Mirror Production

Two parabolic mirrors were made under laboratory conditions. The peculiarity of their manufacture consisted only in the application of a more flexible tool when making spherical mirrors. Whereas the base of the tool for spherical mirrors was a disc made of duralumin 5 mm thick, when going over to parabolic mirrors this disc was made thicker (its thickness was 2 mm). In both cases the disc diameter was 100 mm.

The control subsystem provides for obtaining normal deviations for any conicoid so that in this sense the surfacing of the aspherical surface does not differ from surfacing of a spherical surface. In order to calculate the tolerance, the HART2 program is used; for calculation of the process conditions, PRES1. The PRES1 program differs from the PRES3 program presented in the appendix only by the fact that the comparison sphere is not reselected by the principle of the minimizing the surfacing time. This leads to the fact that the duration of the session calculated by the PRES1 program is on the average 20 to 30% longer than the session calculated by the PRES3 program.

Table 3.1

Characteristics	Provisional number	
	No 1	No 2
Initial error, microns	0.34	0.34
Final error, microns	0.09	0.08
Total surfacing time, hours	11.2	2.4
No of sessions	5	3

Information is presented in Table 3.1 of the surfacing of parabolic mirrors. The initial and final normal profiles are shown in Figure 3.21. If we select the comparison circuits so that the amplitude of the normal profile be minimal, the profiles change form somewhat. The profiles which are generated by the HART2 program are presented in the figure (see Figure 3.21).

The experimental result can be summed up as follows. The ZEBRA system permits an aspherical optical system to be built. The surfacing time in practice does not differ from the time spent on making spherical surfaces. Another important conclusion is that for aspherical surfaces, just as for spherical surfaces, the Rayleigh number is reached. Here a comment must be made. The book is on the problems of manufacturing astronomical optical systems. Astronomical mirrors have comparatively low speed and little asphericalness. During the effort to use the ZEBRA system to manufacture either very high-speed mirrors or mirrors having great asphericalness new technical difficulties can arise. It is very probable that modification of the force drive will be required, reexamination of the approach to selecting the size of the tool and its design is possible, additional difficulties will arise in the sphere of quality control of the surface shape. The investigation of these problems is beyond the scope of this book; useful information can be found in the book by Zakaznov and Gorelik [1978].

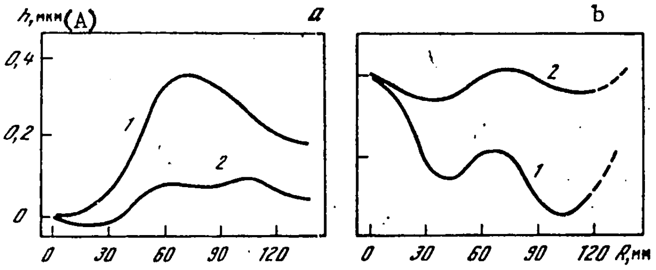


Figure 3.21. Initial (1) and final (2) average normal profiles for parabolic mirrors No 6 (a) and No 11 (b) made using the ZEBRA-1 system

Key: A. microns

By formula (3.4) the value of z for mirrors No 1 and No 2 turned out to be 1.12 and 1.5, respectively. The surfaces obtained by the average profile are close to the Rayleigh number, and further surfacing is impossible as a result of local errors. Mirror No 2 had a physical diameter of 300 mm, but inasmuch as there was a mat zone on the edge of the part remaining after grinding, only its central part having a diameter of 240 mm was subjected to surfacing and analysis.

4. Manufacture of Lenses Under Plant Conditions

In December 1976 the ZEBRA-1 system was turned over for trial operation. The plant system differs from the system installed in the laboratory of the Space Research Institute only in that the DOSM instrument in its plant execution designed for forces to 100 kg was used as the force gauge. A mechanical pointing instrument is used in it to indicate the forces. Later, by the plant's initiative, the pointing instrument was replaced by an induction displacement indicator, and the dynamometric clamp was left the same.

The problems stated during the course of trial operation of the system under plant conditions can be formulated as follows:

Determine the limiting possibilities of the system both with respect to precision and with respect to speed of manufacture of the optical parts up to 500 mm in diameter, basically machining spherical surfaces.

Performance of experiments on parts entering into the plant nomenclature for comparison of the result obtained using the system with results obtained by master opticians;

Instruct the plant personnel locally in the procedures for working with the system.

According to the preliminary data, 15 surfacing sessions have been carried out in 4 months of operation of the ZEBRA-1 system. The concave surface of a concave-convex lens made of TF-4 material was machined. The thickness of the lens with respect to the center is 20 mm. The lens was placed on an unloading device having nine self-adjusting unloading supports. The total duration of all sessions was 11 hours. Simultaneously with the experiments work was done to compare various procedures for calculating the process conditions. The result of this work is the conclusion that the regime can be calculated with sufficient accuracy by the PRES type programs.

Table 3.2

Characteristics	Provisional number		
	No 1	No 2	No 3
Initial error amplitude, microns	1.5	0.15	0.08
Final error amplitude, microns	0.1	0.1	0.04
Initial mean square error, microns	0.42	0.08	0.04
Final mean square error, microns	0.07	0.03	0.02
Astigmatism, microns	to 0.5	to 0.5	0.1
Machine tool time, hours	8.5	2.0	0.8
Value of z	1.3	1.5	2.0
No of sessions	9	4	2

The results of the experiments with the ZEBRA-1 system are presented in Table 3.2.

An analysis of Table 3.2 permits the following conclusions to be drawn.

1. In all of the plant experiments the quality of the optical surface is improved, which confirms the conclusion obtained as a result of laboratory experiments: the principle of controlling the removal of material by changing the force on the small tool is workable.

2. The convergence of the process is characterized by the value of z within the limits of 1.3-2.0, that is, it turned out to be better than in the laboratory experiments. It must be noted that in laboratory and plant experiments the problem of analyzing the forced surfacing conditions was not stated, but only the fact of convergence of the technological process itself was studied. When convergence is reached, the surfacing time decreases sharply automatically.

3. In all of the experiments further improvement of the quality of the surface is limited by local errors, the amplitude of which is within the limits of 0.1 to 0.5 micron. Neither under laboratory or plant conditions has a case been discovered indicating that astigmatism or other local errors arise in the process of surfacing a part on the ZEBRA-1 system. On the contrary, special experiments have demonstrated that if there are local errors on the initial surface, then during surfacing using the ZEBRA-1 system they either decrease or remain as before.

4. Of the three machined parts, only part No 3[1] fits in the plant tolerances.

The results obtained at the plant in some respects are based on the results of the laboratory experiments. The convergence of the process turned out to be better, and the maximum precisions, worse. Here it can be stated that experience in handling the system has still not been accumulated. In particular, the requirements on the initial optical surface have not been sufficiently clearly formulated. On the other hand, in the general opinion of the master opticians TF-4 material is one of the most "capricious" materials in the sense of formation of local errors. It is possible to propose more successful results on other materials.

5. Analysis of the Advantages and Disadvantages of the System

The ZEBRA-1 system is based on local control of the force of the small tool. It has two purposes. First, to demonstrate the fitness of the control principle itself. The fact is that neither in Soviet nor in foreign practice has such a principle been implemented. The system has completely satisfied this purpose. Secondly, the system permits elimination of zonal errors and performance of

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[1] It is important to note that when determining the quality of the optical surface, the Hartmann method is used, but the values of N and ΔN figure in the tolerances, the peculiarities of the determination of which we have already mentioned. The transition from certain parameters to others was not studied.

asphericalization of optical surfaces. This possibility opens up new paths of improving the quality of astronomical mirrors.

There are other advantages of the system such as organization of the logically closed cycle between the process of controlling the shape of the optical surface and the technological process of improving its quality. The control subsystem and the technological subsystem are basied on numerical analysis.

The system is realized using elements, the majority of which are produced industrially and can be created on the basis of any optical machine tool. The system is prospective in the sense that there are broad possibilities for its development and improvement. In particular, for elimination of local errors it is sufficient to install an angle gauge connected with the spindle of the machine tool, to break down the optical surface into zonal-sectoral elements as shown in Figure 3.22, and to modify the control unit and software.

A basic disadvantage of the system is the impossibility of eliminating the local errors in the given execution. This deficiency is not insurmountable. We just indicated how it is possible to avoid this deficiency. However, this path is irrational inasmuch as during the procedure of adjusting the machine tool to the selected surfacing conditions it is necessary to handle a large number of tunable potentiometers. The process of adjusting the machine tool is comparable to the process session with respect to duration. The radical way out is to include a computer in the control circuit of the optical machine tool in real time. This system, called ZEBRA-2, has been developed [Prokhorov, et al., 1979] and tested under mathematical simulation conditions at the Special Research Institute; a model version has been developed jointly with one of the plants. Next come the laboratory and plant testing of the system on real optical parts.

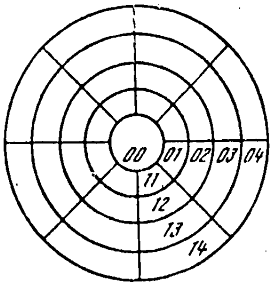

Figure 3.22. Possible breakdown of the optical surface into zonal-sectoral elements. The numbers indicate the possible numbering of the elemental areas.

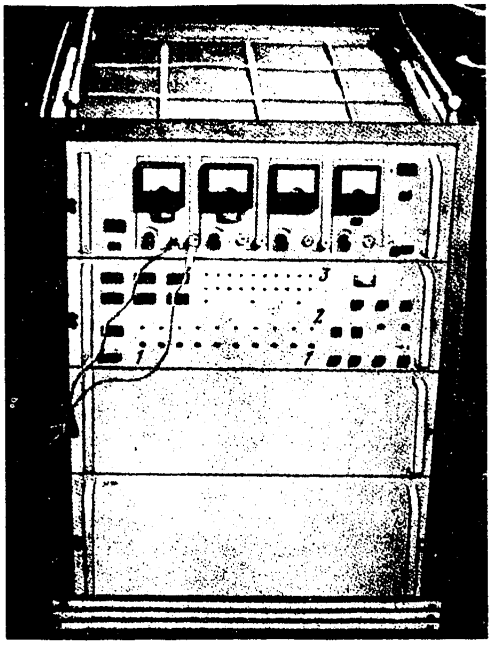

Figure 3.23. Control unit for the second generation ZEBRA-1 system.
1 -- potentiometers for setting up the process conditions,
2 -- indication of the current number of the control zone,
3 -- indication of the current force of the clamping of the tool.

Conclusions

The work experience accumulated in the operation of the ZEBRA-1 automated system under laboratory and plant conditions demonstrated that by the method of local control the force of the small tool is possible to obtain high-quality spherical and aspherical surfaces in a short time.

At the present time the ZEBRA type system is in operation at several enterprises. The experience of introducing the systems has demonstrated that the primary difficulty in assimilation of them is not in the field of engineering but in the field of psychology. The experimental developers of the plants are accustomed to measuring optical surfaces in terms of N and ΔN. These values do not carry any information about how to correct the optical surface. On the other hand, the Hartmann method on which the ZEBRA system is based is almost unknown in industry. This method, just as any other, has many details which confuse the production people, cause them to not have faith in the method and great efforts must be expended to overcome this.

Furthermore, in modern production the pressure of the tool against the part is not varied. The basic method of dealing with errors in the optical system consist in changing the adjustment of the machine tool (the span, spindle speed or crankshaft speed, eccentricity).

An analysis of the structure of the electronic part of the ZEBRA-1 system demonstrated that the control bays of the VEDS instrument do not correspond to modern requirements with respect to many parameters. First, they are made with tubes, that is, they belong to the first generation of electronic engineering. Secondly, the power consumption of them is unjustifiably large. A deficiency of the system was the fact that the electronic subassemblies are "scattered" throughout the system: the force indicator is installed on the machine tool, the control zone display, in another place, and so on. In order to eliminate these deficiencies a new control unit has been developed which is illustrated in Fig 3.2. This instrument was developed by the Special Design Office of Physical Instrument Making of the USSR Academy of Sciences. It is equipped with technical manuals and is constructed on a modern base. The size and weight of the device are a fourth that of the VEDS control bays; the power consumption has been decreased by several times, and the output characteristics have been improved. The given instrument plays the role of a pilot model; a small series of such devices will be built in the near future which will facilitate setting up their series production.

CHAPTER 4.[1] AUTOMATED ZEBRA-2 AND ZEBRA-3 SYSTEMS

As was pointed out in the preceding chapter, the primary deficiency of the ZEBRA-1 system is impossibility of eliminating local errors on the optical surface. The ZEBRA-2 and ZEBRA-3 systems do not have this deficiency. The operating principle of the ZEBRA-2 system is the same as in the ZEBRA-1: the control of the clamping force of the tool against the optical surface. The operating principle of the ZEBRA-3 system is different; the removal of the material is controlled as a result of different surfacing time of the elementary segments of the optical surface. Each of the systems has its own peculiarities which make them noncompetitive and complementary.

Introduction

The ZEBRA-1 system permits two types of operations to be performed: elimination of the zonal errors of the optical surface of spherical and aspherical parts and also asphericalization of optical surfaces. After completion of work on the optical surface on the ZEBRA-1 system the conditions of the technical assignment for the given part can be met (in this case the work has been successfully completed) or it can turn out that after elimination of the zonal errors and asphericalization, local errors remain uncorrected, the elimination of which within the framework of the ZEBRA-1 system is impossible (here the technical assignment for the quality of the optical surface turns out to be unsatisfied).

Further improvement of the quality of large optical surfaces (more than 300 mm in diameter) can be achieved only by local control of the shaping process with the application of a small tool.

From the practice of producing optical parts of large dimensions it follows that the basic shape errors of the optical surface when using traditional methods of surfacing arise for two basic reasons: imperfection of adjustment of the machine tool and the structure of the billet material. In the digital method of surfacing the adjustment of the tool is precisely taken into account (see the Appendix). Then the basic restriction remains the influence of the structure of the material. As a rule, the structure of the material, for example, with respect to grindability has a clearly expressed local nature. We shall not consider the problems of obtaining billet material that is uniform with respect to physical structure for

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[1] This chapter was written by the authors jointly with O. A. Yevseyev.

astronomical mirrors. However, let us note that digital shaping opens up the possibilities for considering the nonuniformity of the material. To make this consideration, it is necessary to introduce self-training elements into the system (see Appendix 1). Investigating the convergence of the shaping process for several successive surfacing sessions, it is possible to introduce a correction into the process that takes into account the nonuniformity of the material.

The basic advantage of the ZEBRA-2 and ZEBRA-3 production systems is complete closure. By closure we mean a unique relation between the results of investigating the shape of the optical surface and the given conditions of surfacing the optical part, that is, the hardware and software of the systems permit improvement of the optical surface entirely on digital principles, excluding experience and intuition of the master optician.

1. Automated ZEBRA-2 System

The operating principle of the technological part of the system is explained in Figure 4.1. An optical part 2 (mirror or lens) is installed on the uniformly rotating table 1. The table has unloading devices (not shown in the figure) which provide for alignment of the part on the table and uniform distribution of the weight of the part with respect to area. The optical surface can be concave or convex, spherical or aspherical, symmetric with respect to the mechanical axis of the billet or asymmetric. Thus, the ZEBRA-2 system permits surfacing of in practice any optical parts so long as the control methods provide for determining the machining allowance of the material, that is, the difference between the true and the required shape of the surface.

The table is rotated around the shaft 3 using the electric motor 4 through the reduction gear 5. Elements 1-5 form the lower element of the ordinary optical machine tool. Modification of the machine tool consists in the fact that the position sensor that sends the position 6 of the rotating table 1 is installed on the shaft 3. The sensor 6 generates a digital code for the angle of rotation of the table with respect to some initial angle ϕ_0. The sensor 6 transmits the code for the angle ϕ through the communications module 7 to the computer 8 which continuously reads the readings of the sensor 6 in its intermediate register and inputs these readings on program request (see Appendix 2) to the ready-access memory of the computer 8.

The movement of the upper element of the optical machine tool is provided for by the electric drive 12 which turns the shaft 10 through the reduction gear 11. A sensor of the linear displacements 9 is installed on the shaft 10. The sensor 9 transmits the code for the linear displacement through the communications module 14 to the computer. The servoelement 13 provides for variation of the pressure of the tool against the optical surface.

The sensor of the current force of the clamp 15 is structurally connected with the servoelement 13 and the tool 16 so that it measures the magnitude of the clamping of the tool 16 against the optical surface of the part 2 and transmits the force code through the communications module 17 to the computer. The computer controls the operation of the electric drive 12 through the communications module 18, and the operation of the electric motor 4 through the communications module 19.

The servoelement 13 can be displaced by using the lead screw 20 along the traverse 21. If the servoelement passes through the center of the optical surface and the reading of the sensor 9 for the center is equal to ρ_0, and the current value is ρ, the coordinates of the center X and Y of the servoelement in the coordinate system connected with the part are

$$X = (\rho - \rho_0)\cos(\varphi - \varphi_0), \quad Y = (\rho - \rho_0)\sin(\varphi - \varphi_0). \tag{4.1}$$

Here it is proposed that the X-axis on the optical surface is selected so that its position angle in the system of the sensor 6 will be ϕ_0.

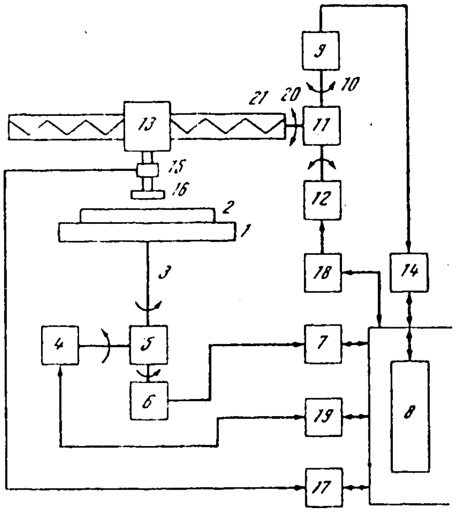

Figure 4.1. Diagram of the structure of the technological part of the ZEBRA-2 system. 1 -- table, 2 -- part, 3 -- shaft, 4 -- electric motor, 5 -- reduction gear, 6 -- sensor of the angle of rotation of the table, 7 -- communications module, 8 -- computer, 9 -- sensor of the linear displacements, 10 -- shaft, 11 -- reduction gear, 12 -- electric motor, 13 -- force executor, 14 -- communications module with the computer, 15 -- force sensor, 16 -- tool, 17 -- communications module with the computer, 18 -- communications module, 19 -- communications module, 20 -- lead screw, 21 -- traverse.

The program which contains the chart of the clamping of the tool to the part for each elemental area of the optical surface is stored in the computer memory. This chart is obtained on the basis of analyzing the normal deviation chart generated by the HART 3 program.

ZEBRA-2 operates as follows. By formula (4.1) the current coordinates of the center of the tool with respect to the part are determined. The sensor of the current value of the force is interrogated simultaneously. Using the coordinates X and Y, the required force is determined, and the difference in the required and current forces is generated for execution. At the same time feedback with respect to the force turns out to be organized through the computer.

The ZEBRA-2 system is assembled on the basis of the PD-750 machine tool. It has been tested in the mockup mode, which has confirmed the fitness of its electronic part and software (see Appendix 2.2). Figure 4.2 shows the general view of the ZEBRA-2 system assembled in the shop.

In the realized ZEBRA-2 system there are many possibilities. For example, an addition to the control of the clamping of the tool to the optical surface, it is possible to control the speeds of the electric motors, which permits control of the machine tool function $\psi(\rho)$. Programmed adjustment of the machine tool for equidistant removal is possible, that is, $\psi(\rho) = 1$. In this case after precision grinding of the part, polishing without distortion of the shape of the optical surface is possible. The adjustment of the tool for equidistant removal advantageously complements the control of the clamping of the tool inasmuch as in this case the dynamic range of the system increases. The ZEBRA-2 system opens up broad possibilities for various technological experiments. Let us propose, for example, a prospective experiment. The simulation calculations (see Appendix 1) are used to select the machine tool function $\psi(\rho)$, so that by adjustment of the machine tool alone it will be possible to eliminate the largest errors of the optical surface. The remaining errors will be eliminated by controlling the clamping of the tool. With this approach the convergence of the technological process increases, the duration of the machine tool time is decreased, and the possibility arises for achieving the best quality of optical surface.

Such experiments have now been completed both in the mathematical simulation mode and in real optical parts. However, we shall not discuss this in detail.

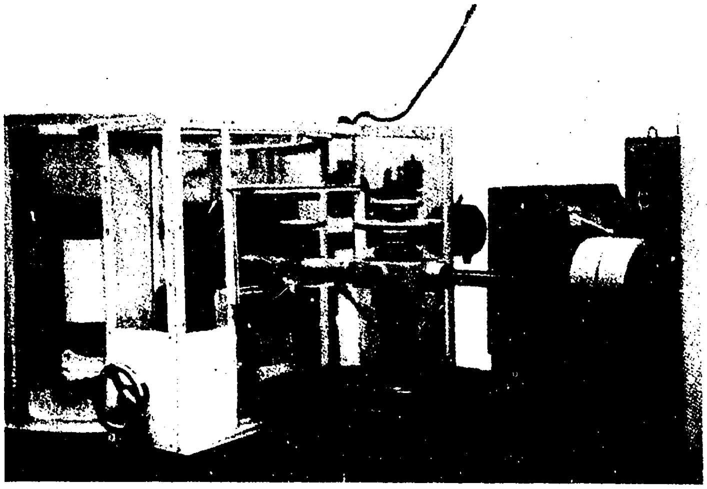

Figure 4.2. General view of the ZEBRA-2 system.

2. Automated ZEBRA-3 System

The ZEBRA-3 system differs significantly from the other two previously investigated systems. First, the principle of controlling the surfacing time of the elemental areas of the optical surface is used, and the pressure of the tool remains constant. Second, the "cutting" element in the system is the tool turning around its own axis. Thirdly, the billet does not turn, and it is installed stationary. Fourthly, the tool is shifted by the program in a rectangular coordinate system. The ZEBRA-3 system resembles the CAOS/XY system kinematically, but it has a different logic of tool displacement. In the CAOS/XY system, the control of the trajectory of motion of the tool is used, and here it is the surfacing time.

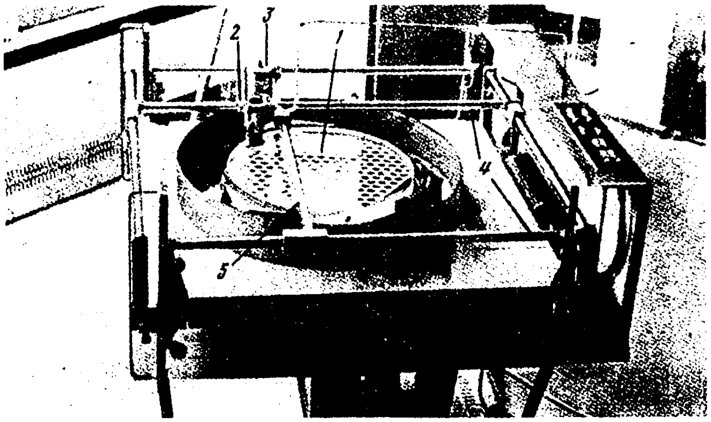

Figure 4.3. General view of the technological part of the ZEBRA-3 system. 1 -- part, 2 -- tool with electric motor, 3 -- dropper, 4 -- guides along the X-axis, 5 -- guide along the Y-axis.

A general view of the ZEBRA-3 system appears in Figure 4.3. The part 1 is installed stationary. Just as in the ZEBRA-2 system, the part can be any part (a lens or a mirror), the surface can be convex or concave, spherical or aspherical, symmetric or asymmetric. In particular, the part 1 can be an extra-axial segment of a parabola.

The tool 2 of small diameter is connected by a hinge suspension to the electric motor which turns the tool at constant angular velocity. The linear velocity on the edge of the tool is several tens of times greater than the displacement rate of the tool over the optical surface. This makes it possible to neglect the removal of material occurring as a result of shifting of the tool from one elemental area to another. Let us remember that in the CAOS/XY and the CCP systems this displacement system is the "cutting" displacement.

Along with the tool 2, a dropper 3 is installed which feeds a suspension of polirit of strictly defined composition to the optical surface in excess. The X-axis coincides with the tool displacement along the guides 4, and the Y-axis, along the guide 5. This displacement is realized by the electric drives which are controlled from the device (seen in the rear plane of the figure). In turn, the control unit has a punch input in which the punchtape with the control commands is installed. The commands and the punchtape itself are formed by the system software based on analyzing the shape of the optical surface (see Appendix 3).

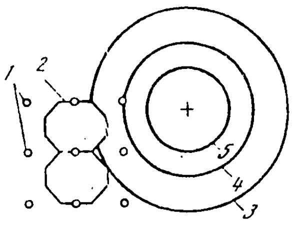

Figure 4.4. Diagram explaining the concept of an "elementary cycle". 1 -- projections of the centers of the elemental areas on the optical surface; 2 -- "Figure 8," which describes the center of the tool on the elemental area; 3-5 -- dimensions of the tools 50, 80 and 120 mm in diameter, respectively.

The systems software calculates the number of elementary surfacing cycles for each segment of the optical surface. Here, a segment of the optical surface is considered to be a square on the optical surface, the center of which coincides with the projection of the center of a hole in the Hartmann diaphragm, and the side of this square is equal to the base of the Hartmann diaphragm, that is, the distance between the centers of adjacent holes.

Figure 4.4 shows a diagram explaining the elementary surfacing cycle. The duration of one cycle is constant and is 3.5 seconds. As a result of this complex movement of the tool and the finite dimensions of the tool it is possible to avoid polishing in annular errors which unavoidably arise if the tool turns and halts on an elemental area.

3. Experience in Working with the ZEBRA-3 Automated System

The developed algorithms for controlling the polishing process presented in Appendix 3 were tested in the laboratory when making real mirrors.

The series of technological experiments with a spherical mirror made of K-13-500 quartz and two parabolic mirrors made of S-17-500 and S-18-500 pyroceram demonstrated the fitness of the system. The mirror diameters were 500 mm, and the speed, 1:5. The surfacing conditions were calculated by the ASTRO and ASTR programs; both programs provided for improvement of the surface with respect to all parameters on the average by 10-20% per session. The duration of one session on the average was 1 hour, and the total duration of all sessions was about 10 hours for each of the mirrors.

The surface quality of a parabolic S-17-500 pyroceram mirror was improved by twofold, in spite of the very unfavorable error distribution over the optical surface. Before the beginning of surfacing, the mean square normal deviation signal was 0.17 microns. After three surfacing sections which were calculated by the ASTRO program, a value of $\sigma = 0.10$ micron was obtained. Analogous results were also obtained for two other mirrors.

A normal deviations chart is presented in Figure 4.5 for the S-17-500 mirror built by the MAP2 program after the second surfacing session. Here is obvious that the

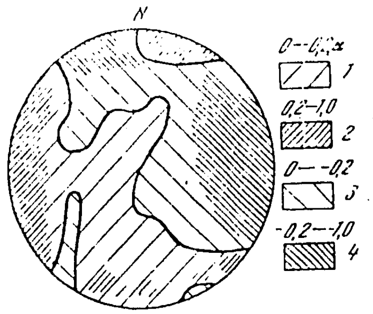

Figure 4.5. Normal deviation chart for the S-17-500 mirror before beginning of the third surfacing session. 1-4 -- gradations of the chart.

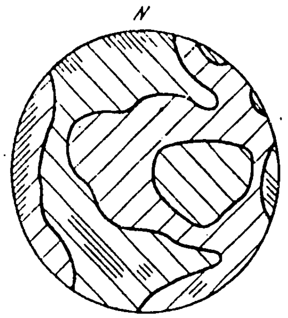

Figure 4.6. Normal deviation chart for the S-17-500 mirror after the third surfacing session. The designations of the gradations are the same as in Figure 4.5.

local errors predominate over the zonal errors. The report of this content is also generated by the HART2 program.

The surfacing conditions chart constructed by the ASTRO program is as follows:

```
                    0   0   5  14  12
              0   0   0   0   3  11  16  25  24
          0   0   0   0   0   0   6  11  20  27  30
      12  6   0   0   0   0   0   0   0   0   0   0   0
  13  10  2   0   0   0   0   0   1   0   0   0   0   0   0
  16   8  1   0   0   2   2   2   2   0   0   0   0   0   0
13  10   4  0   0   0   2   1   1   1   0   0   0   0   0   0   0
16  12   5  2   1   2   2   1   2   0   0   0   0   0   0   0   0
18  13   7  4   3   4   4   3   2   0   0   0   0   0   0   0   0
17  13   7  3   2   3   4   2   0   0   0   0   0   0   0   0   0
15  13   6  2   0   2   4   2   0   0   0   0   0   0   0   0   0
     5   8  2   0   1   3   3   2   2   0   0   0   0   0   0
    14  12  3   0   1   2   3   2   2   1   0   0   0   0   0
        10  5   0   1   2   2   1   2   1   1   1   1   0
            1   1   3   3   3   2   3   2   5   6   2
                0   9   8   6   5   6   4   5   0
                        5   3   4   4   4
```

The number 0 denotes the sections of the optical surface where the surfacing is not done. These sections are located below the "cut off level" given by the operator. The numbers 1, 2, and so on indicate the number of elementary cycles in the surfaced sections. Figure 4.6 shows the normal deviations chart of the same mirror constructed by the MAP2 program according to the results of the control by the HART3/MAP1 programs after the third surfacing session. Before the beginning of the third session σ = 0.15 micron, after surfacing σ = 0.13 micron, which indicates improvement of the surface by 10%. From investigation of Figures 4.5 and 4.6 it is obvious that the area of the optical surface occupied by the largest errors was reduced by several times.

The calculation of the surfacing mode in the ZEBRA-3 system was made by the following formula:

$$N(i,\ k) = \frac{h(i,\ k) - h_0}{k}, \qquad (4.2)$$

where h is the normal deviation on the elementary area with row number i and column number k; h_0 is the cutoff level; n is the number of surfacing cycles; k is the process constant indicating the absolute removal of material in one surfacing cycle. The value of k was determined in the experimental process.

The values of the process constant for the S-17-500 mirror (the material is pyroceram, specific pressure 70 g/cm^2) for two tool diameters:

Tool diameter, mm	Process constant k, micron/cycle
50	0.0015
80	0.008

From elementary arguments it follows that the process constant must be proportional to the square of the tool diameter. From the presented data it follows that this relation is not satisfied.

The proposed and executed ASTRO and ASTR algorithms for controlling the polishing process in the stage of final finishing insures stable convergence of the technological process; worsening of the shape of the optical surface was not obtained in any of the experiments.

The general layout of the experiments consisted in the following. The quality of the optical surface was controlled by the Hartmann method; the diaphragm was used with holes at the corners of the square grid. According to the Vitrichenko classification [1980] this is a type 2 diaphragm. The Hartmann pictures obtained were measured on the "Askorekord-ZDR" instrument, as a result of which a punchtape was obtained with measurements in the internal"Askorekorda" code. Recoding of the punchtape was done by the ASHAR program (see the Appendices), the new recoded punchtape was used by the HART3/MAP1 program (see [Vitrichenko, 1980]). The normal deviations chart was recalculated by the MAP2 program (see the Appendices); the new normal deviation chart was used either by the ASTR program or the ASTRO program. The programs generated punchtape with control effects (the number of surfacing cycles) in accordance with formula (4.2), and this punchtape is installed in the control unit of the ZEBRA-3 system.

The S-17-500 mirror was installed on the TM-500 telescope mount which is designed for astroclimatic research. A photograph of this mount is presented in Figure 4.7. The quality of the main mirror has exceptional importance for this type of work. According to research the mirror insures resolution close to the theoretical limit, that is, on the order of 0.3".

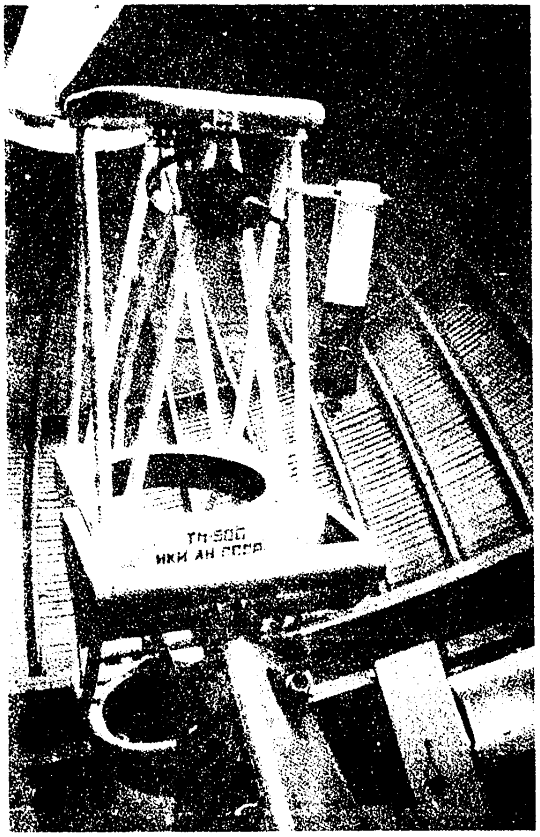

Figure 4.7. TM-500 telescopic mount designed for astroclimatic research. Newton system. The S-17-500 mirror made for the ZEBRA-3 system is used as the principal mirror.

Conclusions

The ZEBRA-1, ZEBRA-2 and ZEBRA-3 automated systems can solve a broad class of problems of optical technology. They were basically tested in the laboratory and at the plant for manufacturing astronomical mirrors, but using them to finish lenses and lens systems presents no difficulties, and it is possible to manufacture asymmetric surfaces, and so on.

However, the systems also have important deficiencies. In particular, the most complex problem remains the study of the limiting possibilities of the system. None of the mirrors made in this system has the qualities of better diffraction limit. This is ununderstandable inasmuch as from an analysis of the systems infinite improvement of the surface quality is theoretically possible. Possibly we are dealing with properties of the material here which influence the quality of the optical surfaces.

During the development of the systems and investigation of them the problem of forcing the surfacing conditions, that is, accelerating the output of the parts, was not stated. We were interested in the problem only of convergence of the technological process. In industry frequently special materials are used to accelerate the polishing process. For these reasons, a comparison of the output capacity of classical technology with automated technology is difficult. Specially stated experiments are needed.

In the conclusion of this chapter, it is possible to state that the developed automated systems have not only solved a number of problems of optical technology, but they have also posed new problems.

CHAPTER 5.[1] PROSPECTIVE AUTOMATED METHODS OF BUILDING ASTRONOMICAL ASPHERICAL OPTICAL SYSTEMS

In the preceding chapter a study is made of the methods of automating the widespread and most labor-consuming operation of manufacturing an astronomical optical system, such as finishing or asphericalization of the optical surface while polishing it. The methods and means developed under the direction of the authors and with their direct participation are creating good prerequisites for broad industrial manufacture of high-quality astronomical optical systems.

At the same time a large amount of other information has appeared which is contained primarily in patent literature and the scientific and engineering periodicals about the ways to solve the investigated problem. This information, in our opinion, is of significant interest for specialists. The fact is that the application of a number of new modern ways to work materials, technical means and principles of shaping which are nontraditional for optical technology are opening up the prospects for further improvement of it.

New methods and means of manufacturing astronomical optical systems, the majority of which have been studied experimentally, are already beginning to be introduced into industry, and in a number of cases they are permitting significant improvement of the precision of the machined surfaces and insurance of greater variety of geometric shapes of the latter. In addition, the prospects for improving the efficiency of technological process itself as a result of the intensification of certain operations are obvious.

Therefore the effort to combine different (both already implemented and prospective) means of manufacturing astronomical optical systems within the framework of a single set of methods which would be the most efficient and effective is natural. An effort to solve this problem is presented in this chapter.

Introduction

A necessary step in the construction of an efficient, prospective complex for the manufacture of an astronomical aspherical optical system is the analysis of possible areas of use of various directions of the solution of the investigated problem on the basis of substantiated classification of them.

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[1] This chapter was written by V. V. Gorelik.

Let us briefly discuss this process. In the known classification [Kachkin, et al., 1962], the nature of the tool contact with the machined surface (point, linear and surface) is proposed as the basic attribute. This was natural and correct for the level of development of optical technology at the beginning of the 1960's. Actually, at that time it appeared indisputable that the classical process of mutual shaping of the surfaces of the part and the tool by an interstitial layer of free abrasive between them -- lapping (the term was introduced by Kumanin in 1962) -- is not only distinguished by the shaping precision attainable by it, but is the only possible process for optical parts [Kuznetsov, Shevel'kova, Sergeyev, 1962]. Unfortunately, insurance of a significant contact area (surface) required for the "classical" process was difficult to achieve when manufacturing an aspherical optical system. Therefore the methods of shaping aspherical surfaces which had less contact area with the operating surface of the tool -- linear and point contacts -- appeared as a worse, but unavoidable way out of the developed situation.

In recent years a number of prospective studies have appeared which have decisively changed some of the ideas about "classical" optical technology which recently appeared to be unshakable.

Let us mention three basic principles explaining this fact.

1. The achievements of modern engineering and technology in the field of optical machine tool building and its automation which greatly increased the precision possibilities of the shaping methods based on point contact.

2. The creation of new ways to surface optical materials opening up prospects for obtaining optical surfaces of geometric shape and precision which were theoretically unattainable earlier.

3. The creation of new and the improvement of the existing principles of shaping optical parts and systems which significantly expanded the possibilities of obtaining an astronomical aspherical optical system.

Let us consider these new trends in the development of optical technology which are reflected in the classicification illustrated in Figure 5.1 in more detail.

Methods with Point Contact. It is widely known that these methods are the most universal, for they permit the manufacture of surfaces of any shape. It is also known that they are the most efficient and can be realized with the use of intense surfacing conditions which were theoretically unattainable when surfacing by a free abrasive. Unfortunately these indisputable advantages of the investigated methods are continuously related to the basic deficiency by comparison with the "classical" process -- the absence of mutual correction of the machined surfaces of the tool and the billet as a result of their small contact area. Therefore the errors of the formers, the errors in adjustment of machine tool , the clearances and other factors cause deviation of the given trajectory of motion of the tool, which influences the precision of the machined surface. These reasons have caused the use of spot contact methods in optical technology until recently only in billeting operations.

However, the experience of the foreign companies "Rank Taylor Hobson" and "Bell and Howell" [Horn, 1972] with respect to series manufacture of aspherical elements to 280 mm in diameter by such methods for various objectives has changed the developed concepts. These elements had frosted surfaces made with precision to tenths of a micron, the subsequent intense polishing of which by means of elastic polishers did not change their geometric shape. The shaping of the frosted surface was achieved in this case using a diamond cutting tool or thin-wall diamond tube, the control of the movement of which is realized by a computer into which data has been input on the required profile of the machined surface in the form of polar or rectangular coordinates written on a paper punchtape. The high precision of the surfacing has been achieved by corresponding technical execution of machine tools, constant thermal conditions of the facilities and correction of the initial program by the results of measuring a sample polished surface.

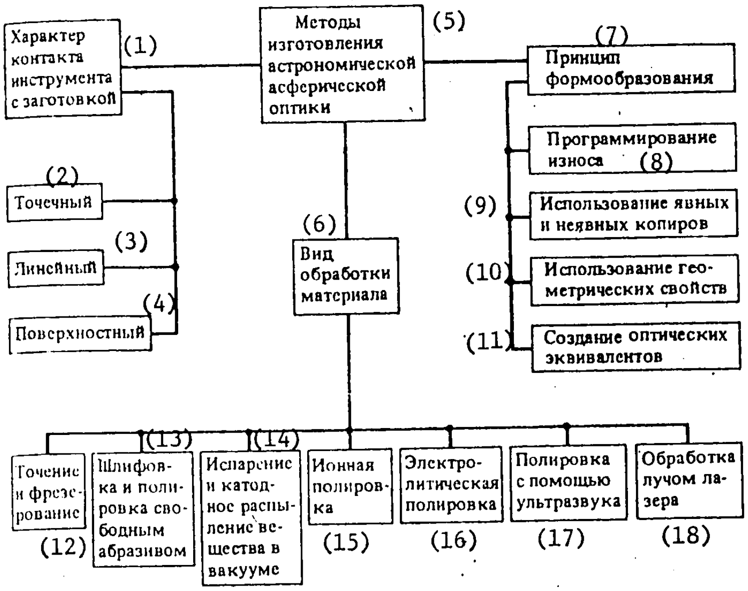

Figure 5.1. Classification of the methods of manufacturing an astronomical aspherical optical system.

Key:
1. nature of the contact between the tool and the billet
2. spot
3. linear
4. surface
5. methods of manufacturing an astronomical aspherical optical system
6. form of machining the material
7. shaping principle
8. wear programming
9. use of explicit and implicit formers
10. use of geometric properties
11. creation of optical equivalents
12. turning and milling
13. grinding and polishing by free abrasive
14. evaporation and cathode sputtering of a material in a vacuum
15. ion polishing
16. electrolytic polishing
17. ultrasonic polishing
18. laser beam surfacing

The structural peculiarities of these machine tools (Figure 5.2) were high-precision spindles, bearings and radial bearings, the guides and the rotating parts of which were polished with optical precision. In addition, the spindle control was realized without direct mechanical contact through a magnetic control unit, and the position of the carriages moving the tool was determined by a special capacitive sensor in the form of a so-called "electrostatic nut" (Figure 5.3).

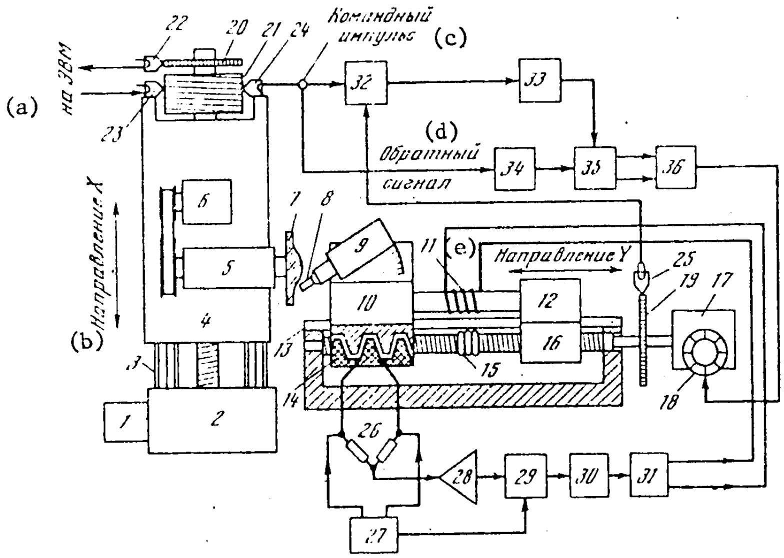

Figure 5.2. Diagram of the machine tool built by the "Rank Taylor Hobson" Company. 1 -- drive motor for the X-axis; 2 -- reducer; 3 -- V-type guides, 4 -- feed carriage for the X-axis, 5 -- operating spindle, 6 -- operating spindle motor, 7 -- billet, 8 -- tool (drill), 9 -- drive for turning the tool; 10 -- tool feed carriage; 11 -- magnetostrictive converter, 12 -- power part of the feed carriage with respect to the Y-axis; 13 -- roller bearings; 14 -- measuring coupling ("electrostatic nut"); 15 -- bellows coupling; 16 -- drive coupling; 17 -- reducer; 18 -- stepping motor for drive of the Y-axis; 19-21 -- magnetic drums; 22, 24, 25 -- magnetic reading heads, 23 -- magnetic recording head ; 26 -- measuring bridge; 27 -- generator; 28 -- amplifier; 29 -- phase discriminator; 30 -- signal processing unit; 31 -- power amplifier; 32 -- bidirectional counter; 33 -- pulse generator; 34 -- counter with preliminary manual setting; 35 -- switch; 36 -- power amplifier.

Key: a. to the computer
b. X direction
c. command pulse
d. feedback
e. Y direction

Reports have also appeared on the experimental work [Bryan, Donaldson, 1973] toward the manufacture of metallic aspherical mirrors to 380 mm in diameter by analogous means using a diamond cutting tool without subsequent polishing.

Thus, the experience of the foreign companies who have traveled the path of implementation of the point contact method indicates that in order to solve the stated problem, the most complicated computer-control precision machine tools are needed. Naturally this solution is complicated and requires great expenditures, but it has opened up the paths of industrial manufacture of large-scale aspherical surfaces of in practice any shape with precision to tenths of a micron.

Finding and developing analogous methods of shaping optical surfaces which, retaining all the advantages mentioned above, are distinguished by great simplicity of structural design, do not require such high precision of manufacturing the guides and other elements transmitting the motion and also have a simplest device for giving the surfacing program are the most economical and, at the same time, prospective.

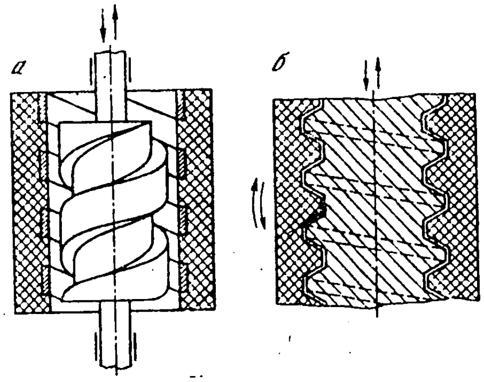

Figure 5.3. Capacitive measuring sensors of the screw type with variable area of the plates (a) and variable clearance between plates (b).

Soviet machine tools that implement this approach have been developed. The characteristic features of these machine tools which will be investigated in detail in the next section are as follows: 1) the use of hydroaerostatic guides which insure the above-mentioned precisions of relative displacements, are in practice not subject to wear during operation and can be made with precisions usually used in machine building; 2) the application of the simplest (flat) templet, the position of which with respect to the servoelements of the machine tool insures the possibility of shaping a broad class of aspherical surfaces.

New Shaping Principles. The methods of obtaining an astronomical aspherical optical system can be classified as follows by the shaping principle (see Figure 5.1): 1) with respect to the programming of the wire over the zones of the machined surface; 2) with respect to the use of explicit and implicit formers; 3) with respect to the use of geometric properties of the machined surfaces; 4) with respect to the creation of optical equivalents to the astronomical aspherical parts and systems.

The first principle, as has already been noted above, consists in the fact that the effect of the basic process factors determining the wear of the material during surfacing is calculated in advance and distributed with respect to defined sections of the machined surface. A significant part of the given book is devoted to the study of this shaping principle and also new automated systems for implementing it.

The principle of shaping optical surfaces using explicit and implicit formers consists in the fact that a defined trajectory of the displacement of the tool is given with their help. New possibilities for realizing implicit formers for the control of the tool displacement when machining aspherical surfaces by a computer have already been investigated in this chapter. Below, just as detailed a study will be made of the ways of implementing explicit formers which have the simplest (flat) shape for the same purposes.

The third and fourth principles of shaping were proposed significantly later, and therefore they are not so obvious.

The methods based on using the geometric characteristics of aspherical surfaces create shaping conditions analogous to those which are characteristic of the "classical" process of manufacturing spherical optical systems [Zakaznov, Gorelik, 1978].

The essence of this shaping principle consists in the fact that on the basis of the defined geometric properties of the machined surface mutual displacement of the tool and billet are created which provide in advance for obtaining a defined aspherical surface as a result of their mutual correction. Indisputable advantages of the asphericalization methods belonging to this group are the possibilities of machining a broad class of surfaces in the presences of the simplest trajectories of the operating movements of the tool and the billet and significant contact area of them and also the possibility of isolating a parameter that is invariant for any segment of the machined surface, which most simply and reliably insures the shaping monitoring and control conditions.

In the next section there will be a detailed study of some of the new means of machining various aspherical surfaces having two planes or an axis of symmetry, by the methods of geometric shaping. These methods, along with automated methods, have already been investigated in detail in this book; they can be successfully used for finishing with precision to hundredths of a micron of optical surfaces previously surfaced by a diamond tool with point contact with the billet.

In recent years many reports have appeared on the creation of optical equivalents for various aspherical parts and systems. Thus, a report has been made [Frederieks, 1969] about the development of optical systems for shaping holograms simulating cylindrical, conical and hyperbolic lenses and also an anamorphotic optical system.

The new possibilities for shaping the wave front also consist in varying the index of refraction of the lens material [Patent No 3486808, 1969]. This can be achieved by creating a defined layer saturated with metal ions, for example, cesium, rubidium, thallium or silver in the lens by diffusion of the latter into the basic material.

The diagram of the device for saturation is presented in Figure 5.4. Here the billet 1 is touched by a solution of metal salts filling the vessel 2 which is placed in a thermostatic chamber 3.

In Figure 5.5 it is shown how as a result of successive surfacing of a lens which is saturated with a uniform metal layer, it is possible to obtain lenses with different thickness of the saturated layer with respect to the annular zones.

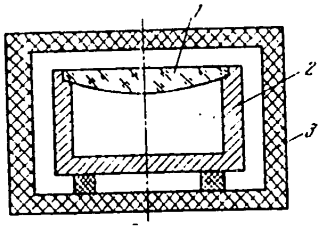

Figure 5.4. Diagram of a device for saturating the layer of a lens by metal ions. 1 -- billet; 2 -- container; 3 -- heating chamber.

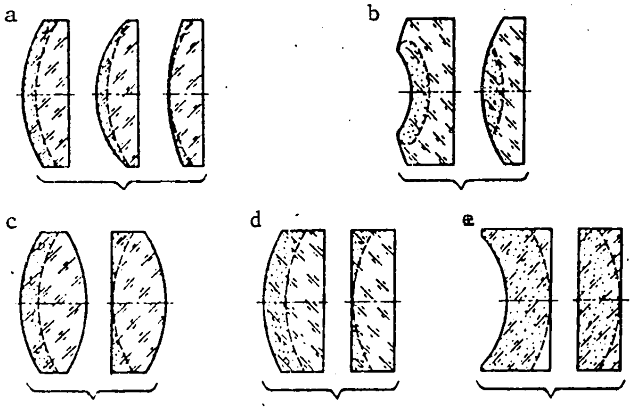

Figure 5.5. Obtaining various lenses (a-e), the effect of which is equivalent to an aspherical system by surfacing one side of the lens by a uniform layer of metal ions.

The path of creating an optical equivalent of an astronomical optical system which is unique with respect to precision and complexity consisting in the following appears to be highly prospective. Previously the manufactured and assembled optical system was carefully investigated by one of the known methods (for example, [Vitrichenko, 1980]) with the construction of the wave front topography. Then a special optical corrector is manufactured, one of the surfaces of which has a specially calculated complex asymmetric shape differing from the nearest spherical one by a fraction of a micron and made with precision to hundredths of a micron.

After manufacture, this corrector, which can be appreciably smaller than the optical system itself, is installed at the corresponding point of the system to compensate for the errors of the components entering into it.

The most complex and problematic in this approach is the problem of obtaining an aspherical corrector surface. However, the new ways to surface optical materials appearing in recent years make this problem resolvable at the present time. Let us investigate these surfacing procedures.

New Ways to Surface Optical Materials. One such means of surfacing consisting in fine turning or milling of the optical surface by a diamond tool which has a "point" contact with the billet has already been mentioned above.

A great deal of attention on the part of the specialists has been deservedly attracted in recent years by another new type of optical surfacing -- ion polishing. The studies [Schreder, et al., 1971; Tanigushi, et al., 1973] confirmed the effectiveness and prospectiveness of such surfacing for the shaping of especially high-precision optical surfaces. Thus, Horn [1972] presents data on the finishing of the optical surface using ion polishing to 0.01 λ.

Various known structural elements of ion guns, the basic ones of which are the "duoplasmatron" the Penning source, the Kaufman source, are used as ion sources for ion surfacing. Theoretically the presence of a gas plasma (most frequently, an argon plasma), from within which positive ions are extracted under the effect of an electric field, is theoretically common to all sources. Ions accelerated by the electric field are directed at a target in the form of a broad particle flux (such as, for example, in the Kaufman source where the diameter of the ion beam reaches 20 cm or more), or the ion flux is focused by an electric or a magnetic field in a narrow beam, the diameter of which in the target region can reach 5-2 mm or less.

Depending on the production requirements, ion sources of various types are used, but in the general case it is possible to present two basic versions of the surfacing of the target; 1) irradiation of the largest target surface possible by a wide ion beam through slits in a functional mask, the shape and the displacement of which are determined by the law of surfacing the target; 2) displacement of a narrow ion beam over the surface of the target in accordance with the surfacing law.

Surfacing by a broad beam is more acceptable for the case of relatively simple optical surfaces, for example, with axial symmetry or requiring equidistant removal. The second version -- machining the optical surface by a thin ion beam in accordance with the given surfacing law -- theoretically permits the realization of any optical surfaces with high precision of manufacturing them, in particular, it permits retouching of the high-precision optical surfaces in accordance with the surfacing program calculated on the basis of the shape control data (preliminary or periodic during the surfacing process) of the machined surface. A computer can be used for ion beam scanning providing for removal of the machining allowance to obtain a surface of the given shape.

Let us also briefly discuss other new types of surfacing. Electrolytic polishing [Aspden, 1972] is used for surfacing large metallic mirrors to eliminate defects in the form of local errors on aspherical surfaces and asphericalization of a spherical or plane surface with small magnitude of the removed layer.

The surfacing is done using an electrolyte which is fed through the electrodes and washes over the machined surface. The size of the electrodes, the arrangement, their speeds are determined by the surface topography which is obtained from a computer analysis of the interferogram. A computer or a special tracking system also controls the movement of the electrodes [Patent No. 3589996, 1971].

Polishing by ultrasound [Patent No. 3589071, 1971] is done with placement of the part with an aspherical surface in a watertight case which is filled with polishing fluid under pressure. There are a number of ultrasonic sensors in the case, under the effect of which the liquid receives high-frequency ultrasonic vibrations. The surface is polished under the effect of these vibrations.

There is a report [Herziger, 1973] on the dimensional machining of complex profiles by a laser beam. This beam is controlled by a device equipped with a holographic system.

The investigated new forms of surfacing are used at the present time to remove small layers of material.

Here, ion beam polishing is distinguished by a higher degree of realization and unique results. It is a type of logical continuation of the above-investigated methods of shaping using a point diamond tool and automated finishing of the surface in the polishing process. With respect to the essence of the matter, ion beam surfacing permits superthin layers of material to be removed (to monoatomic), and it opens up the possibilities for obtaining optical surfaces with any precision which can actually be controlled.

For this reason the following areas of improvement of ion beam polishing are of significant interest.

1. The creation of automated systems for controlling the shape of the machined surfaces built into the process equipment [Patent No. 3543717, 1970].

2. The creation of devices combining the possibilities of superfine removal of material by the means of ion beam technology with the possibilities of the application of an additional layer of material [Shapochkin, 1961; Kuzichev, 1965] by thermal evaporation and cathode sputtering of it in a vacuum [Patent No 3543717, 1970].

A detailed study will be made below of some new ways to implement these prospective areas.

1. Preliminary Machining of Optical Surfaces by the Point Contact Method

All of the methods of asphericalization belonging to this group in the final analysis reduce to insurance of forced displacement of the tool by a given trajectory corresponding to the profile of one of the cross sections of the machined surface.

Here the application of various templets, the profile of which is transferred by the tool to the machined surface opens up great possibilities.

A general view of the machine tool [Author's Certificate No 448119, 1974] providing for the machining of various aspherical surfaces using flat templets is shown in Figure 5.6. The operation of the machine tool is based on the properties of the flat cross sections of aspherical surfaces. The trajectory of motion of the tool provided by the spindle assembly which is schematically depicted in Figure 5.7 is made up of the two simplest movements (rectilinear and rotational). The application of hydrostatic guides, on which the spindle assembly is executed insures operating displacement errors not exceeding one micron.

The tool 10 (see Figure 5.7) which can be made, for example, in the form of a diamond cutting tool, milling cutter, grinder or polisher, is connected stationary

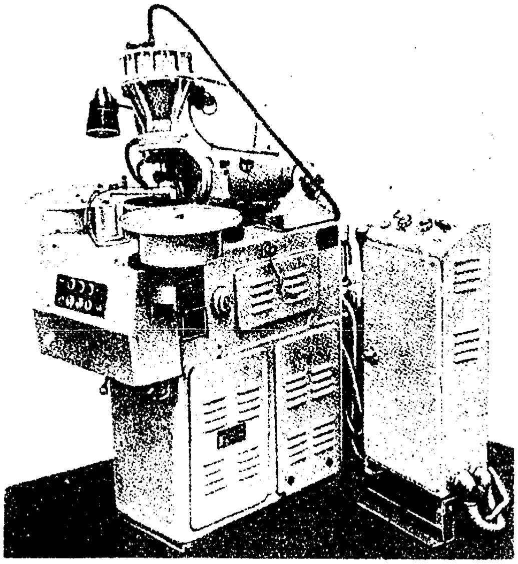

Figure 5.6. General view of a machine tool for machining aspherical surfaces with the application of a flat templet.

through the spindle 9 to the plate 6 having a standard plane surface 5 which interacts with the hydrostatic ball hinge 3, the case 1 of which is attached to the stationary base.

The spindle 9 is installed in hydrostatic bearings 13 and 15 between which a cavity 14 is formed inside the housing. A shoulder 8 protruding into the cavity 14 is made on the spindle 9. The spindle 9 is rotated, for example, by the pulley 7 and belt drive.

In order to insure constancy of the characteristics of the hydrostatic ball hinge in the case 1 of the hinge 3 hydrostatic supporting pockets 17 which take the radial load and an annular pocket 2 which takes the axial load are made.

Supporting hydrostatic pockets 4 exist on the surface of the hinge 3 conjugate to the standard surface 5. They are connected by holes made in the body of the hinge 3 to the pressure source.

Special chokes 16 can be built into the holes.

The billet 12 which can have convex or concave machined surface is installed on the spindle 11 which is turned from a separate drive (not shown in the figure).

During the surfacing, the billet 12 is turned from the spindle 11.

The tool rigidly connected to the spindle 9 receives two motions together with it: rotational by the belt drive and pulley 7 and reciprocal in the hydrostatic bearings 13 and 15 with sliding of the standard surface 5 of the plate 6 over the eccentrically installed hinge 3.

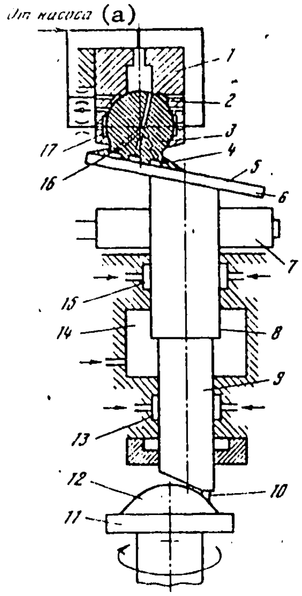

Figure 5.7. Diagram of the spindle assembly of a machine tool.

Key: a. from the pump

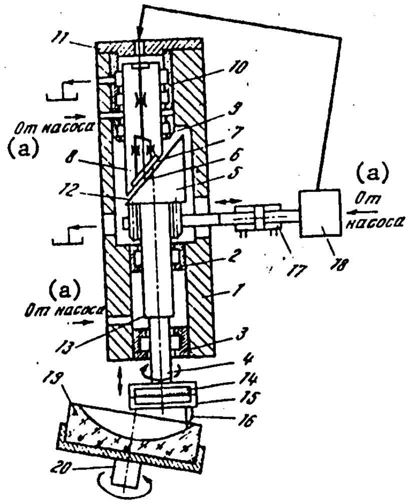

Figure 5.8. Diagram of a machine tool with cylindrical hinge.

Key: a. from the pump

As a result of the addition of the rotational and the reciprocal motions the tool 10 describes a curvilinear trajectory in space . The parameters of the latter, which are determined by the amount of misalignment of the spindle shaft 9 with respect to the center of the hinge 3, the radius of rotation of the tool 10 and the angle of inclination of the standard surface 5 to the spindle axis 9, is selected so that this trajectory will coincide with the flat cross section of the machined surface passing through its apex. On communicating the indicated movement to the billet and the tool and selecting the parameters of the trajectory of motion of the tool, we obtain all of the conditions of shaping aspherical surfaces with given parameters. The constant condition of clamping the spindle 9 with the tool 10 to the hinge 3 is insured by pressure of the liquid on the shoulder 8 of the spindle. Compressed air or gas can be used instead of the liquid to feed the pockets 2, 17 of the ball hinge, the bearings 13 and 15 of the spindle and also to clamp the spindle 9 to the hinge 3.

In a number of cases, predominately for machining large parts, a tool spindle bearing a tool, for example, a grinding disc and a drive for it, can be installed on the spindle. Figure 5.8 shows the schematic diagram of the machine tool which, retaining the advantages of the preceding system, permits expansion of the range of machined surfaces and elimination of the systematic errors in the surfacing. This is achieved by replacement of the ball hinge by a cylindrical hinge, the axis of rotation of which is parallel to the axis of rotation of the tool spindle and by creation of additional translational motion of the tool spindle to correct the profile erors.

Additional movement is created by varying the gap in the hydrostatic thrust bearing of the cylindrical hinge. This variation of the gap causes axial displacement of the hinge, and the tool spindle together with it. The control of the additional displacement can be connected with rotation of it and the systematic error.

In addition, a mechanism has been introduced into the machine tool which can shift the tool to any position within the limits from 0 to 180° with respect to the tool spindle axis, which permits variation of the direction of the axial motion of the tool during the machining of the part and obtaining a nonmonotonic surface on it as a result.

Let us consider the schematic diagram of the machine tool. In the housing 1 (see Figure 5.8) of the spindle head, the spindle 4 is installed in the hydrostatic bearings 2 and 3. A templet 5 with standard plane 6 is attached to this spindle. The plane 7 conjugate to the plane 6 belongs to the cylindrical hinge 8 which is installed in radial hydrostatic bearings 9 and 10 and is supported on the hydrostatic thrust bearing 11.

The planes 6 and 7 are separated by a hydrostatic layer of lubricant 12. The constant clamping of the spindle 4 against the cylindrical hinge 8 is realized by the oil pressure on the shoulder 13 of the spindle 4.

A faceplate 14 is fastened to the free end of the spindle 4, on which the device 15 with the tool 16 is installed. The latter is located at a given distance from the spindle axis 4. Rotation of the spindle 4 is realized from a rack type mechanism driven by the cylinder 17. Simultaneously with rotation of the spindle 4 the cylinder 17 can act on the correcting device 18 which regulates the flow of liquid from the pump to the thrust bearing 11. In accordance with the flow rate of the liquid in a thrust bearing 11, a defined gap is established.

The billet 19 is fastened to the spindle 20 and is turned from a drive.

The machine tool operates as follows. In accordance with the given equation of an aspherical surface and the diameter of the surfaced part, the parameters of the surfacing system are established:

1) the angle of inclination of the spindle 4 to the axis of rotation of the machined part, 2) shifting of the templet axis, 3) the radius of rotation of the tool, 4) angle of turn of the tool attachment 15 with respect to the face plate 14.

Trial surfacing of the part is carried out, and then its profile is checked. By the magnitude of the deviations from the theoretical profile a program is compiled, for example, in the form of a former, for the correcting 18, and it is introduced into this device. The program is used to compensate for the surfacing errors. The cylinder 17 of rotation of the spindle 4 matches the signal speed from the correcting device by the amount of the axial displacement of the cylindrical hinge 8 with the angle of rotation of the spindle 4.

In this case the spindle 4 will simultaneously take two axial displacements: 1) as a result of slipping of the standard plane 6 with respect to the eccentrically arranged surface plane 7 of the cylindrical hinge, 2) as a result of axial shift of the cylinders 8 with variation of the clearance in the thrust bearing 11, in accordance with the signal from the correcting device 18.

These two displacements are summed on the tool 16 providing it with complex trajectory of motion which will be transferred to part 19 during its rotation.

The precision of the shape of the machined aspherical surface depends on the precision of all of the servomotions and especially, the clearances in their mechanisms.

In order to exclude the play and insure high precision of rotation, the bearings 2, 3, 9 and 10 are made hydrostatic or aerostatic, which permits their use, in addition, as guides for axial displacement of the spindle 4 and the hinge 8.

On turning the spindle 4, the hinge 8 must also turn for self-adjustment of the plane 7 with respect to the plane 6 of the templet 5. In order to facilitate this turning, the angle of inclination of the plane fixed to the spindle axis is made equal to 45°.

The constancy of the clearance 15 is determined by the constant force of clamping the spindle 4 against the hinge 8 realized through the shoulder 13 of the spindle. The machine tool permits complex and concave aspherical surfaces to be machined with a diameter to 300 mm with controlled parameters of these surfaces within the ranges of p from 20 to 2000 mm, and e from 0.1 to 5.

2. Finishing and Asphericalization of the Optical Surfaces in the Grinding and Polishing Process

It is unquestioned that exceptional results with respect to accuracy of the "classical" method used in industry for the manufacture of a spherical optical system are primarily determined by the set of characteristics of its geometric prerequisites and mutual lapping of the tool and the surfaced product.

The method of surfacing close to the process which is widely used in industry for the series manufacture of a spherical optical system is based on the studies of the properties of planar cross sections of aspherical surfaces.

Figure 5.9 shows the diagram of the machine tool [Author's Certificate No. 325163, 1972] realizing this procedure.

The lower unit of the machine tool is analogous to the usual optical grinding and polishing machines. The billet 11 is fastened to the spindle 12 which has the possibility of turning.

The upper unit of the machine tool has a number of distinguishing features. The carrier 2 is installed on the shaft 1 located on the bed with the possibility of oscillatory motion around this shaft from the drive and simultaneous axial displacement in the guides. The plate 3 with standard plane to which the working elements 7 are clamping using the spring 4 is hinged to the carrier 2. One end of the spring 4 is supported on the flange of the working element 7, and the other in the plate 6 installed in the cardan suspension 5 in the housing 9. The latter is installed in the bearings using rotation around the carrier shaft 2. The working elements 7 are located in the plates 8, for example, along an Archimedes spiral (for more uniform distribution of them) with the possibility of axial displacement. Using the intermediate bushing 10 the plates 8 are connected to the housing 9. The machine tool operates as follows.

The billet 11 turns together with the spindle 12 from the drive. The working elements 7 are lapped to the machined surface of the billet using a free abrasive. The working elements, constantly clamped by the springs 4 against a standard plate 3 undergo rotational motion around the axis 2 of the drive together with the housing 9. During surfacing the plate 3 is freely oriented with respect to the machined surface. The ends of the working element 7 are displaced at any arbitrary point in time along ellipses of constantly variable parameter which permits any second-order surface to be machined.

In order to obtain defined surfaces of an ellipsoid and hyperboloid of rotation on the machine tool it is necessary to select the corresponding position of the shaft 1.

The surfaces of a paraboloid of rotation can be obtained if the carrier 2 is fastened in the guides with the possibility of displacment of it relative to the spindle axis 12.

The shaping process on the proposed machine tool is controlled analogously to the process used for the surfacing of a spherical optical system on the usual series-produced machine tools.

The application of the plane standard surface offers the possibility of making it with high optical precision. The preliminary shape of the working surfaces of the tool and the billet can be sperical. Figure 5.10 shows the general view of a machine tool for machining parabolic surfaces.

Figure 5.11 shows the diagram of a device [Author's Certificate No 343830, 1972] for machining cylindrical and gently sloping toric surfaces on optical grinding and polishing machines. The plate 2 is hinged to the carrier 1 of the machine tool. The attachment 5 with the billets is installed on the plate on the shafts 15. In addition, a parallelogram mechanism consisting of the cleats 12 and 14 which are connected to each other by the bearings 3 and 13 is installed on the plate 2 in the bearings 4. The parallelogram mechanism is connected to the face plate 7 using two cleats 8 which are fastened to the mechanism and to the face plate in the bearings 11 and 9. The tool 6 is fastened to the face plate 7 which is connected to the spindle by means of the adaptor chuck 10.

During operation two motions are transmitted from the machine tool simultaneously to the device: 1) rotational from the spindle of the machine tool through the adaptor chuck 10, 2) reciprocal, from the carrier 1. The movement from the carrier is divided into two movements of the tool 6 with respect to the billets required for shaping: 1) rectilinear from the parallelogram mechanism as a result of turning of the cleats 12 in the bearings 3 and 13; 2) oscillatory as a result of turning of the cleats 8 with respect to the axes 9 and 11.

The required radius of the oscillatory motion is automatically insured by turning the tool 6 together with the plate 2 with respect to the parallelogram mechanism on the bearings 4. The machining of the gently sloping toric surfaces is insured by turning the attachment 5 with the billets around the shafts 14.

Since the device is continuously turned on the machine tool spindle with respect to the direction of displacement of the carrier 1, the rectilinear and oscillatory

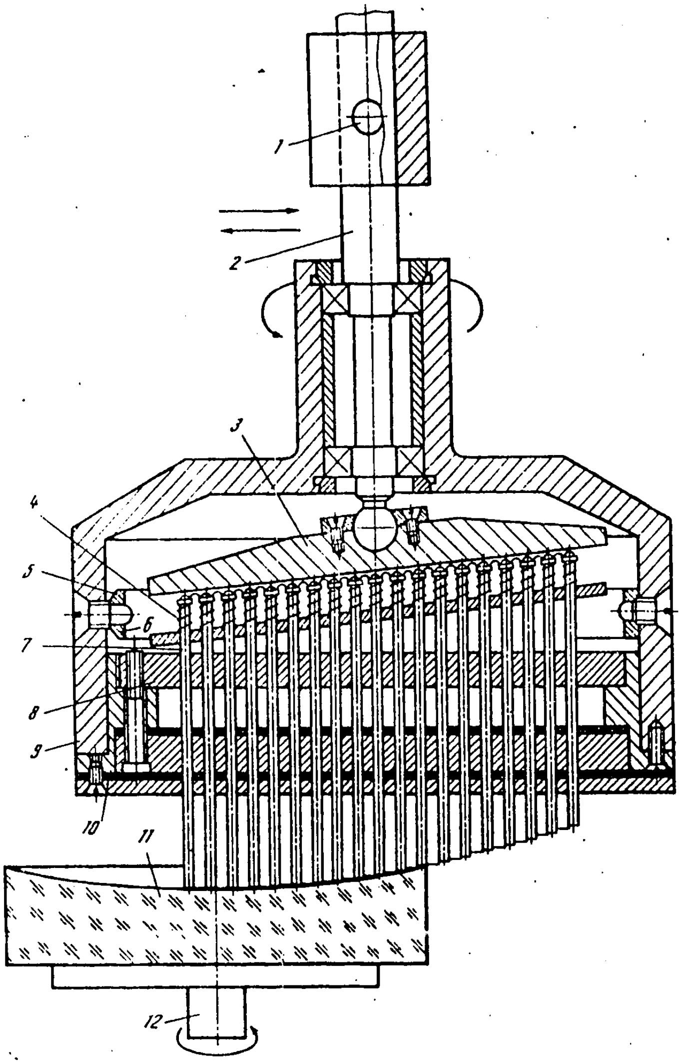

Figure 5.9. Diagram of a machine tool for machining aspherical surfaces.

components of the movements of the tool vary continuously from the minimum value to some maximum value so that the decrease in one component corresponds to the increase in the other.

The device is distinguished by simplicity and convenience of servicing. The smooth- and the precision of the operating displacements of the device will permit the machining of cylindrical and gently sloping toric surfaces of increased precision with its help.

Let us also briefly discuss the new possibilities of active monitoring and automated control of shaping which are opened up by using the geometric properties of the machined surfaces for this process.

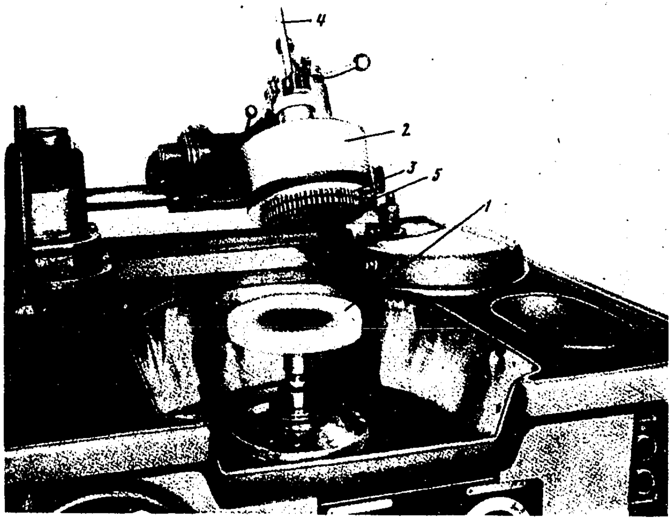

Figure 5.10. General view of a machine tool for machining parabolic surfaces. 1 -- billet, 2 -- tool housing, 3 -- working elements, 4 -- carrier, 5 -- working thrust bearings.

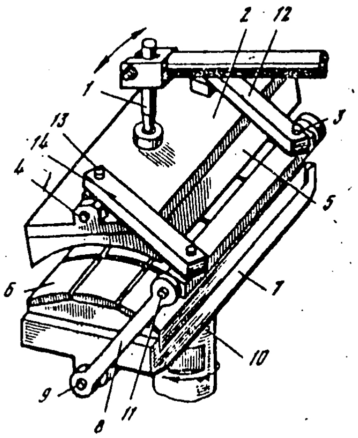

Figure 5.11. Diagram of the device for machining cylindrical and gently sloping toric surfaces.

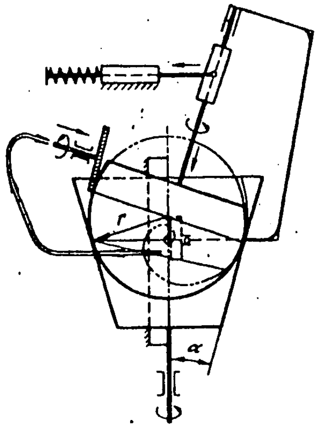

Figure 5.12. Diagram of the machining of an aspherical surface by a conical tool.

A study has already been made above of machine tools in which the shaping of the aspherical surfaces was carried out as a result of mutual lapping of numerous operating elements on the rotating billet. These working elements underwent rotational and rectilinear movements so that their edges, making contact with the billet, moved along elliptic trajectories. The distance of all of these working elements from the standard plane, according to the theoretical surfacing system (see Figure 5.9) must be invariant during the shaping process. Using the known contact, pneumatic and other sensors of linear displacements, these distances can be measured with high precision (fractions of a micron), and the results of the measurements using the feedback system are automatically transmitted to the controlling elements of the machine tool directly in the surfacing process. Analogously, it is possible to control the position of the standard plane in the case of hinged attachment of the tool to the axis of rotation during reciprocal motion of the latter.

Another example indicating the possibilities of active monitoring and automatic control of the asphericalization of optical surfaces is presented in Figure 5.12. According to the "classical" process in the investigated case the tool and the billet have working surfaces of rotation which are during surfacing in the process of mutual lapping using an interlayer of free abrasive. Let us provisionally call the lapped part with convex surface a billet and the part with concave conical surface, the tool. In reality any of them can be both tool and billet. As the billet goes deeper into the cavity of the conical tool during surfacing, continuous angular rotation of it takes place, the magnitude of which is controlled using the simplest copying device with plane templet (in the case of mutual lapping of the surface of a right cone and the surface formed by rotation of the arc of a logarithmic spiral).

In the investigated case invariant properties of the logarithmic spiral moving without slipping along a straight line are used for shaping.

These properties consist in coincidence of the roulette formed by the pole of the logarithmic spiral during rolling of it without sliding along a straight line, with another straight line. The latter is inclined to the straight line along which the spiral rolls at a defined angle α defined by the spiral parameter and located in the same plane with it.

According to the theoretical diagram of the surfacing process, the straight line which is the roulette of the spiral when moving along another straight line (the generatrix of the conical tool) coincides with the axis of rotation of the conical tool.

Therefore the sensor of linear displacements rigidly connected to the shaft for turning the lapped billet must be shifted along the standard plane coinciding with this axis. The distances from the standard plane fixed by this sensor can be measured with precision indicated above, and they are automatically transferred to the controlling elements of the machine tool in order to correct the shaping process.

Thus, the direction of obtaining an aspherical optical system investigated here and based on using the geometric properties of the machined surfaces will make it possible to use the experience available in industry from finishing spherical surfaces during grinding and polishing, to make the process of mutual lapping similar to the ordinary processes of machining as a result of the possibility of active monitoring and control of the shaping.

3. Super-precision Finishing of Optical Surfaces

Device for Machining an Optical Surface under the Effect of Ion Beams with the Hartmann Ion Method of Control. The ion beam device, the diagram of which is presented in Figure 5.13 consists of a vacuum chamber equipped with an ion beam source, a process unit, a Hartmann control system and computer-control program system with computer. In this diagram provision is made for a system to monitor the temperature of the machined surface.

A vacuum chamber, the dimensions of which must provide for the location and the technological displacement of an optical part 0.5 meters in diameter, is evacuated to a vacuum no worse than $1 \cdot 10^{-5}$ torr by oil-free pumps (turbomolecular, cryogenic or mercury vapor).

The detailed drawings for the process equipment for ion beam surfacing of a part 0.5 meters in diameter which insures translational displacement of the part along the vertical axis of the device and horizontal displacement along the axis of the ion beam and rotation of the optical part around its axis with the required precision, have been developed. The part for surfacing is located at a fixed angle 45° to the horizontal. This angle is selected from arguments of optimal use of the vacuum space of the process chamber while maintaining sufficient efficiency of the ion beam.

The flow chart for the surfacing with displacement of the part relative to an ion beam is structurally simple and economically advantageous if the local machining of the optical surface does not require observation of the boundaries of the machined regions with precision of more than 0.1-0.05 mm. (In practice such requirements are rarely encountered. As a rule, another condition is set up: to smooth the transition from the surfaced section to the unsurfaced one to the maximum).

The high-voltage ion source is located opposite the machined surface of the part where the axis of provocation of the ion beam is horizontal. In the investigated system the ion source is arranged stationary, but provision is made for the possibility of moving the ion beam over the surface of the part under the effect of a controlled electromagnetic field.

Considering the thermal effect of the ion beam on the machined part, the density of the ion current on the machined surface must not exceed 1-3 milliamps/cm^2 for an ion energy to 30 kev. In this case effective removal of the surface layer takes place with insignificant heating of the part. The amount of removal of the surface for the majority of glass is 1-5 microns/hr for the given parameters of the ion beam.

These parameters can insure an ion source of the "duoplasmatron" type or a source based on a cold plasma cathode equipped with electrostatic and electromagnetic focusing system. There is the possibility of smoothly varying the dimensions of the spot of the ion effect on the targets (the surfaced part) from several millimeters to several centimeters in diameter which can be convenient for production purposes.

The technical assignment has been compiled, and a controllable, high voltage ion source has been developed for optical technology.

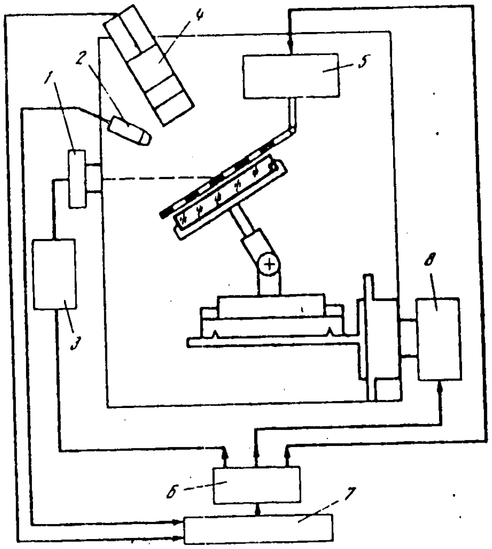

Figure 5.13. Automated "Hartmann-ion" ion-beam device. 1 -- ion source, 2 -- heat gage; 3 -- gun control; 4 -- shape monitor; 5 -- mask control, 6 -- programmed module, 7 -- computer, 8 -- control of the displacement of the part.

The device for monitoring the shape by the Hartmann method is combined with the surfacing device. Its application in the device is expedient for reasons primarily of high precision of the control, considering the modern requirements and resistance to vibrations, which is especially valuable for a process unit where vibrations are very difficult to absolutely exclude.

The machined part is connected to the optical measuring system directly at the surfacing location if necessary or remote monitoring can be realized both in intermediate stages of surfacing and at the certification stage. For monitoring at the surfacing location provision is made for the placement of a Hartmann diaphragm in a vacuum chamber. This diaphragm can be installed in the working position by a remote-controled device and adjusted. The same device is used for putting a functional mask in the working position if the surfacing goals require it.

The system for monitoring the temperature of the machined surface based on, for example, a scanning pyrometer has sufficient resolution with respect to temperature (on the order of 0.5° C) and coordinates (to 1-1000), and during ion-beam surfacing it permits a degree of heating of the various sections of the surface, the temperature equalization rate over the surface, the standing time of the part after surfacing. This permits monitoring of the technological process with respect to an additional parameter (temperature) and correction of the course of the process of ion surfacing from the point of view of minimizing the thermal deformations, lowering the degree of overall heating of the part. This permits the power of the surfacing also to be batched, and the data from the thermal monitoring of the part when monitoring the shape of its surface to be considered.

The control of the entire technological process of surfacing is from a standard programming unit which controls the operating conditions of the ion source with respect to a given program, controls the functional mask, displaces the surfaced part with respect to the ion beam by a given wall with required precision, the performance of the complete given program, bringing the unit into the control mode. The results of controlling the shape are input to a computer where the chart of normal deviations of the machined surface is calculated by the builtin program, and a conclusion is drawn regarding of halting of surfacing if the given requirements are satisfied; otherwise the corrected surfacing program is calculated which is input to the programming unit, and the surfacing cycle is repeated.

"Shadow-Ion" Ion-Beam Device for Polishing and Finishing Optical Surfaces. The ion-beam device, the block diagram of which is presented in Figure 5.14 is equipped with a builtin system for monitoring the shape of a machined surface by the modified shadow method with an automatic system for analyzing the Schlieren pattern. The converted videosignal from the control system is used to control the ion surfacing of the optical part.

The device contains a controlled ion source, a system for checking the shape by the Foucault-Philbert method an analog control computer system including modules (synchronization, scanning, coordinate, memory, amplitude analysis, reference signal, comparison, multiplication by the process constant, delay and control of the ion beam gun). There is also a sensor for the position of the ion beam gun.

It is most expedient to use an ion beam device with analogous operative control system for the solution of the problems of ion machining of simple surfaces, where the actual number of controlled points (10-20) corresponding to relatively large fields of identical deviation from the ideal surface can be selected. It is possible to machine surfaces with local shape defects of the "mound" type that are small in area. Beginning with the general arguments of the nature of the optical surfaces, let us assume that the majority of real surfaces can be reduced to these two cases with one degree of assumption or another.

The surfacing technology of an optical part is as follows in this case. The part, the shape of the machined surface of which has been checked in advance, is installed at the surfacing location which is simultaneously the location of the controlled part in the optical system of the Schlieren device. The surface of the part is checked by the Schlieren device, the control data at the surfacing location are compared with the preliminary control data, after which the control points for the analog control computer system, the coordinates of which are input to the synchronization unit in analog form, are finally selected on the surface of the part.

The Schlieren pattern is reproduced, for example, by a vidicon transmitting television tube, and it is wholly lit up on the television screen. The video image carrys complete information about the checked surface (the brightness signal of the image points corresponds to the surface relief and is easily converted to a signal that is proportional to the normal deviation of the surface, and the coordinates of each image point are uniquely determined by the magnitude of the scanning signals of the image with respect to X and Y). One selected line of the image or another with the selected reference points is "cut out" in parallel from the overall

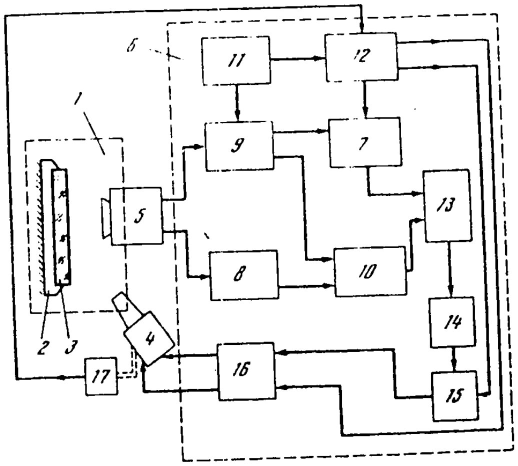

Figure 5.14. Automated "shadow-ion" ion beam unit. 1 -- vacuum chamber, 2 -- assembly for attaching the part; 3 -- part, 4 -- ion beam gun, 5 -- Schlieren device, 6 -- analog control computer system, 7 -- memory module, 8 -- amplitude analyzer, 9 -- coordinate unit, 10 -- reference signal module, 11 -- synchronization module, 12 -- scanning module, 13 -- comparison module, 14 -- module for multiplication by the process constant, 15 -- delay unit; 16 -- ion beam gun control unit, 17 -- gun position sensor.

pattern, and the corresponding videosignal is simultaneously analyzed in the coordinate module and the amplitude analyzer. Here, by the synchronization module commands which correspond to the selected reference points, amplitude signals proportional to the normal deviations of the monitored points are sent to the corresponding cells of the memory module. A signal corresponding to a point on the surface of the "lowest" level, to which the entire machined surface will be reduced, is automatically sent to the reference signal module.

The ion gun is aimed at the point of beginning of the surfacing, for example, the edge of the part. The gun position sensor signals the coordinates of the surfacing point, as a result of which the scanning module outputs signals to the memory module corresponding to these coordinates. A signal is extracted from the corresponding cell of the memory module proportional to the normal deviation of the established surfacing region, which is compared with the reference signal in the comparison unit. The difference signal is proportional to the amount of removal of material, which must be done at the given point or the region near the reference point. In the module for multiplication by the process constant, the difference signal is converted in accordance with the established operating conditions of the ion gun, and it goes through delay unit to the ion beam gun control unit. In the simplest case the control of the surfacing conditions is realized by the irradiation time of the selected region of the surface of the part by the ion beam.

In the automatic mode the surfacing is done with continuous or periodic control of the shape of the machined surface; in this case the machining continues until the difference signal from the comparison module is equal to zero or less than the given value which must be selected from the condition of admissible local error of the machined surface.

On completion of surfacing of one section of the surface, the ion gun is moved to the next section, and the surfacing cycle is repeated for this section.

Operation in the automatic mode permits another version of surfacing: the entire machined surface is scanned by the ion beam, where the scanning rate is variable, that is, the section with a smaller amount of given material to be removed passes under the ion beam faster than the section where more has to be removed. If a section with zero removal (the difference signal from the control system is zero) hits the scanning trajectory, the ion beam is blocked, and this section is not machined.

This version of the surfacing process is somewhat more complex technically than the discrete surfacing, but it insures high output capacity, better temperature conditions by the surfaced part and automatic veraging of the ion effect on transition from one surfacing region to another. In this case the ion gun is controlled simultaneously on two channels (the surfacing mode and the gun aiming coordinates).

Device for Shaping the Surface of an Optical Part in a Vacuum. The known vacuum asphericalization technology consists in depositing an optical material evaporated using a resistive, electron beam or other evaporator in a vacuum chamber on the surface of the optical part. The shape of the surface is created by the law of displacement of the functional mask with respect to the part. Thus, asphericalizing layers to 20-25 microns thick are obtained. Thicker coatings have unsatisfactory optical properties and insufficient adhesion, as a result of which the asphericalizing layer is peeled off and destroyed.

The application of ion beam surfacing opens up new possibilities for the vacuum asphericalization method. First of all, preliminary cleaning of the initial surface by the ion beam directly before the application of the asphericalizing layer greatly increases the degree of adhesion of the applied layer to the initial surface, which permits an increase in thickness of the asphericalizing layer and it makes it possible to obtain a layer with better optical properties.

The combination of two processes (application and removal of optical material) in one device permits organization of a theoretically new process along with obtaining asphericalizing coatings with high properties. The new process is high asphericalization of optical surfaces with simultaneous evaporation of local surface errors. For this purpose, a schematic design of a device has been developed which is shown in Figure 5.15. The surfaced optical part which can be turned relative to its own access is arranged horizontally in the upper part of the vacuum chamber. Opposite the machined surface are the electron beam evaporator of optical material and the ion beam gun. The ion beam gun is separated from the evaporator by a protective shield. In practice this shield must be made in the form of a tube encompassing the ion gun and the space of propagation of the ion beam to the surface of the part.

A functional mask or systems of masks with holes for the deposition and spraying of the machined surface by a given law is used in the device. For this purpose the masks can be shifted independently or synchronously; the optical layer can be

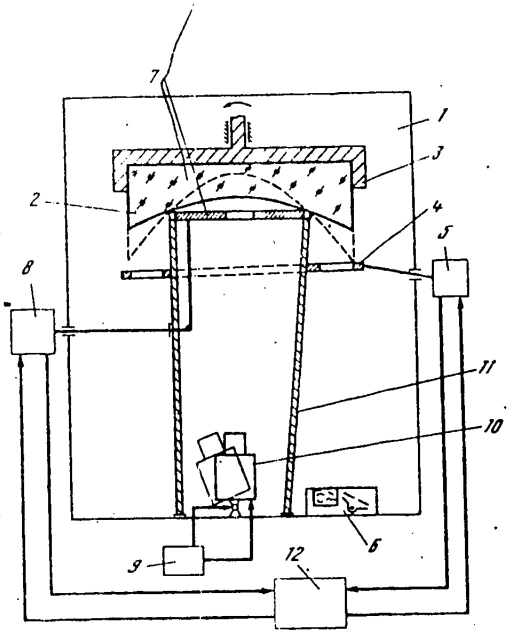

Figure 5.15. Device for shaping the surface of an optical part in a vacuum. 1 -- vacuum chamber, 2 -- part, 3 -- collet, 4 -- deposition mask, 5 -- mask control, 6 -- electron evaporator, 7 -- spraying mask, 8 -- mask control, 9 -- ion source control, 10 -- ion source, 11 -- shield, 12 -- programming device.

applied simultaneously for asphericalization and also correction of the negative local or zonal errors and spraying of the surface layer of the initial surface for deep polishing, asphericalization and removal of positive local or zonal errors.

The ion source is made to move together with the shield and the functional spraying mask, and it must shifted automatically by the given program.

Beginning with the requirements of structural simplicity, technological advantages and also convenience of servicing and safety engineering, it appears expedient to use a low-voltage ion plasma source with orthogonal electric and magnetic fields in this device. The ion plasma source has comparatively small dimensions (80-100 mm with respect to the largest dimension), and it does not require application of a neutralizer when machining the dielectricsinasmuch as it gives a beam that is neutral with respect to the total charge. The working characteristics of the ion-plasma source are quite stable, which permits control of the amount of material removed from the machined surface with respect to surfacing time or with respect to radiation dosage (beam current per unit time). According to the accumulated experimental data on surfacing samples of different materials it is possible to do the surfacing with the required precision (to hundredths of a micron) on high-precision optical parts.

It must be noted that the output capacity with respect to the removal of the low-voltage ion-plasma source is appreciably higher than for the above-mentioned ion sources, which can be explained by the large value of the ion current (to several amperes).

The proposed diagrams of the ion-beam surfacing devices encompass the majority of problems with respect to the manufacture of large-scale, high-precision optical parts.

Theoretically it is possible to use ion surfacing to remove a layer of optical material with a thickness to tens of microns or more, but the primary advantage of ion surfacing consists in the possibility of removing superthin (monoatomic) thicknesses of optical material and thus controlling the amount of material removed with sufficient accuracy. Therefore it is expedient to consider ion surfacing as the final step in superfine finishing of the optical surfaces with precision limit to $\lambda/20$-$\lambda/40$.

The creation of a set of ion beam surfacing devices combined with means of high-frequency control of the shape and equipped with automatic surfacing control systems are the results of continuous or cyclic monitoring is an urgent requirement of the development of optical technology. At the same time prospects are being opened up not only for reliable satisfaction of the ever-growing requirements on the precision of manufacturing optical surfaces, but also radical modification of the approach to optical system surfacing technology.

Conclusions

An analysis of the material discussed in the book will permit the construction of the overall picture of the manufacturing technology of astronomical mirrors. First of all, the billeting operation is automated in such a way that an aspherical surface will be obtained with precision on the order of 1 micron. Then comes the finishing operation permitting elimination of the zonal and local surface errors, finishing them to a value on the order of 1 micron. Finally, superfinishing using the principles of ion surfacing permits an optical surface to be obtained with a precision to 0.01 micron or better.

These systems which form a complex, do not compete, but complement each other. They are arranged so that the surfacing precision will be improved, and the output capacity drops off. Each of the steps in this "cascade" technology has been developed at this time and has been experimentally tested. The next step is broad introduction of all the methods into production practice.

CONCLUSION

Automated production systems are used to build optical parts. In turn, the optical parts are component parts of optical devices. Finally, the optical devices are used to obtain observations.

Two basic requirements are imposed on astronomical optical devices: the highest possible angular resolution and the largest possible amount of light energy collected on the light receiver. Both conditions are satisfied simultaneously when observing the following conditions: the largest possible area of the entrance pupil and simultaneously the best possible quality of the optical channel. These two conditions turn out to be poorly compatible. First, the manufacture of a precision optical surface with large area is an exceptionally complicated technological problem. Secondly, even if such a surface were made, as a result of the deformations under its own weight and thermal deformations, the preservation of the precision optical surface would become still a more complicated problem.

For the indicated reasons, the future of large-scale terrestrial telescopes lies with multielement (composite) mirrors. The advantage of this approach is obvious, there is no necessity for creating large precision surfaces, but it is sufficient to make a number of small ones. This is significantly simpler. Then, the optical system of the multielement telescopes weighs appreciably less than a solid mirror. Finally, the small mirrors are less sensitive to thermal deformations than when solid mirror.

However, the creation of composite mirrors requires the solution of new problems. The mechanical system holding the elements of the composite mirror has large deformations under the weight of the structural elements and the thermal deformations. For matching all of the mirrors it is necessary to create a telescope adaptation system, that is, a device which continuously measures the amount of mismatch of the mirrors and introduces the necessary correction to their position. A new possibility arises here. If the indicated device is sufficiently fast, then it can be used to consider the deformation of the wave front introduced by the effect of the earth's atmosphere. It is possible to obtain diffraction images of stars in this way (see ADAPTIVNAYA OPTIKA [Adaptive Optical System], 1980).

When creating multielement mirrors there is another difficulty. In the telescopes of the Cassegrainian system the main mirror is parabolic, and in the Ricci-Cretien system, hyperbolic. Thus, the individual elements of the composite mirror will be surfaces that do not have axial symmetry. The creation of precision optical surfaces of this type is now an exceptionally difficult problem which is irresolvable for classical technology. Here automated technological systems described in this book come to our assistance. Without them the creation of segments of aspherical surfaces is impossible. In this sense, the CAOS, CCP and ZEBRA type systems are a necessary condition for the creation of the telescopes of the future.

The extra-axial segments of aspherical surfaces are used in astronomy as the collimators of spectrographs. If a collimator is fast, but the receiving equipment is awkward (image converters, digicon, television set), then the problem of the dimensional structure of the device arises. The problem is solved by the application of an extra-axial aspherical segment, the creation of which is difficult without a ZEBRA type system.

Finally, nonspherical lens elements are used in astronomy. As an example we can use the Schmidt plate. Complex technological procedures are now used to manufacture it. On the automated ZEBRA type system its creation presents no difficulties. The manufacture of fast large lens cameras present significant difficulty at the present time. When using lens elements with spherical surfaces the optical system of such cameras consists of ten lenses, the size and weight of the cameras are large, the cameras are deformed under their own weight, and adjustment of the cameras turns out to be a complicated problem. When using nonspherical surfaces the number of lenses is decreased by two or three times, the size and weight decrease the resolution improves, and so on [Rusinov, 1973]. For an automated system, in contrast to classical technology, it is indifferent whether the tolerance is removed from the spherical or the aspherical surface. It is only necessary that the control methods insure definition of the magnitude and the location of this tolerance. Thus, the automation of the shaping process opens up possibilities also for creating objectives with aspherical lens elements.

It would be erroneous to think that the automated systems permit the solution of all the problems and exclude classical optical technology. The two methods complement each other, and automated technology creates new possibilities more than it replaces the classical methods of manufacturing optical systems.

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