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Improve Processed Surface's Precision of Optical Elements by Grinding under Kinematic Program Control

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Based on the definitions of the local coating coefficient, the average local coating coefficient and the speed coefficient in grinding of optical elements and on theory of multibody kinematics, the software for kinematic program control during grinding process of optic elements was worked out in the Hanoi University of Technology. Using this software some research results for increasing processed surface's precision of optic elements by grinding under kinematic program control were presented in this paper.

1 Introduction

With the development of high precision mechanical and optical sectors, optical tools and devices play an important role in many industrial sectors. Key components in optical tools and devices are elements made by optical glasses, hereafter called "optical elements". Grinding is one of the most effective methods to achieve high precision though technology facilities are not so high precision level.
The problem of improving processed surface's precision of optical elements by grinding is very interesting. It's related to many of technological factors. Studying the influence of kinematics on precision of the processed element's surface is an effective method to improving processed surface's precision of optical elements. It should be paid proper attention.
Study on kinematic program of processed optical elements is still limited (M.N. Semibratov, 1978). By applying results of kinematics of multibody systems, the present paper's authors established a kinematic program for processing optical elements on grinding equipment to improve processed surface's precision of optical elements.
Experiments were carried on optical element grinding equipment with four - bar mechanism. Considered the above mechanism on a type grinding equipment (see Figure 1), in which:

- ω_1 is the angle speed of level 1,
- ω_3 is the shaking speed of bar 3,
- ω_4 is the angle speed of disk 4,
- ω_5 is the angle speed of grinding instrument 5,
- disk 4 is supported for fixing the processing element.

Due to friction between the grinding instrument's surface and processing element's surface, the support disk shakes with bar 3, and rotates relatively around center 0_4 with the angle speed ω_4.
In the case of grinding, the ratio between ω_4 and ω_5 or ω_1 and ω_5 is selected corresponding to technology conditions: $\omega_4/\omega_5 = k_2$, $\omega_1/\omega_5 = k_1$.

2 Coating Coefficient of Processing Part Surface

Concept of the coating coefficient of processing element's surface is established on an assumption that polishing instrument 5 is divided into m hoops with the same width ΔR as shown in Figure 2, where:

$$\Delta R = R / m .$$

The j-th hoop is defined by external radius R_2^j and internal radius R_1^j (Figure 2). The support disk 4 plano-parallelly moves relative to polishing instrument 5. Suppose that the support disk 4 is divided into n hoops with a width Δr.

$$\Delta r = r / n$$

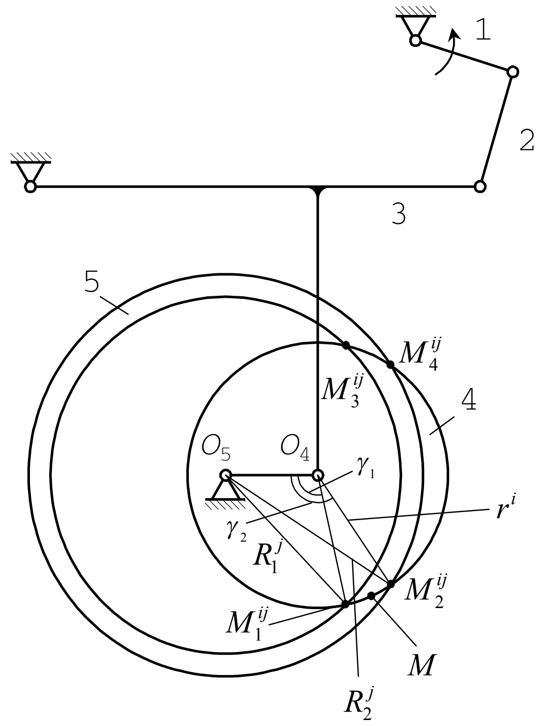

Figure 1. The four - bar mechanism of optical element grinding equipment

The i-th hoop of the support disk 4 is defined by the external radius r_2^i, and internal radius r_1^i, average radius r^i (Figure 3).

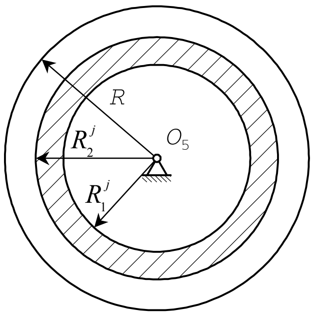

Figure 2

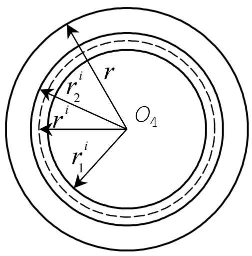

Figure 3

Intersectional points of the circle with radius r^i on disk 4 and hoop ΔR on disk 5 are $M_1^{ij}, M_2^{ij}, M_3^{ij}, M_4^{ij}$ (Figure 1).

*Definition 1***.** Local coating coefficient $C_{ij}(t)$ is the ratio between the length of arc defined by two circles with radius R_1^j and R_2^j of grinding instrument 5 on i-th hoop average circle periphery of the support disk 4. This coefficient is defined by the following formula (Figure 1)

$$C_{ij}(t) = \frac{\overset{\frown}{M_1^{ij} M_2^{ij}}}{\pi r^i} \tag{1}$$

So, $C_{ij}(t)$ is a function of variables *t* (time), r^i , R_1^j , R_2^j and kinematic parameters of the mechanism and can be written as:

$$C_{ij}(t) = f(t, r^i, R_1^j, R_2^j)$$

The following symbols are used:

$\angle O_5O_4M_2^{ij} = \gamma_2^{ij}$, $\angle O_5O_4M_1^{ij} = \gamma_1^{ij}$,

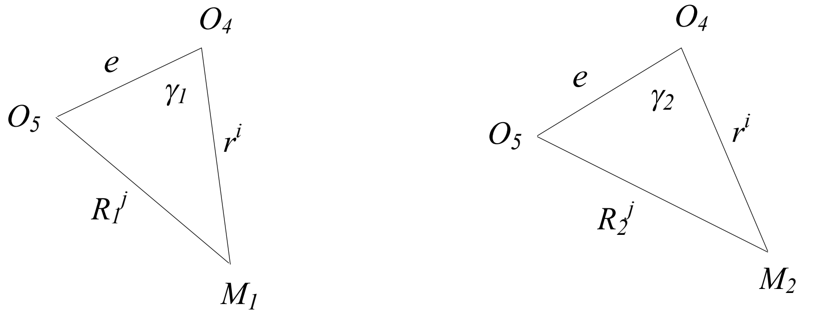

Figure 4

From Figure 1 we have the following relation

$$\Delta\gamma^{ij} = \gamma_2^{ij} - \gamma_1^{ij}$$

Using trigonometrically relationships in triangles $\Delta\, O_5O_4M_1$ and $\Delta\, O_5O_4M_2$ (Figure 4) we receive

$$\cos\gamma_1 = \frac{e^2 + (r^i)^2 - (R_1^j)^2}{2er^i} = A_{ij}\,,\ \cos\gamma_2 = \frac{e^2 + (r^i)^2 - (R_2^j)^2}{2er^i} = B_{ij} \quad (2)$$

Therefore

$$\gamma_1 = \arccos A_{ij} = f_1(\alpha), \gamma_2 = \arccos B_{ij} = f_2(\alpha) \quad (3)$$

$$\Delta\gamma = \gamma_2 - \gamma_1 = \arccos B_{ij} - \arccos A_{ij}$$

$$\overset{\frown}{M_1^{ij} M_2^{ij}} = r^i \left(\arccos B_{ij} - \arccos A_{ij}\right) \quad (4)$$

By replacing formula (3) in formula (1) we have

$$C_{ij}(t) = \frac{1}{\pi}(\arccos B_{ij} - \arccos A_{ij}) \quad (5)$$

From (5) it's clear that the local coating coefficient $C_{ij}(t)$ is a non dimension factor $0 \le C_{ij}(t) \le 1$. If r^i, R_1^j, R_2^j fixed, the local coating coefficient $C_{ij}(t)$ depends on the eccentric e between center O_4 of the support disk 4 and the center of the grinding instrument 5.

Definition 2. The average local coating coefficient is the local coating coefficient calculated within cycle of the level and expressed by $\overline{C}_{ij}$ (M.N. Semibratov, 1978)

$$\overline{C}_{ij} = \frac{1}{T}\int_0^T C_{ij}(t, r^i, R_1^j, R_2^j)dt \quad (6)$$

In which T is cycle of the level, from formula (5) and formula (6) it can be found out:

$$\overline{C}_{ij} = \frac{1}{T\pi}\int_0^T (\arccos B_{ij} - \arccos A_{ij})\,dt \quad (7)$$

When quantity of hoops j varies from 1 to m on grinding instrument 5, the average local coating coefficient of the instrument in every hoop r^i on processing part is defined by formula

$$\overline{C}_i = \sum_{j=1}^{m} \overline{C}_{ij} \quad \text{(i=1,…,n)} \quad (8)$$

Here factor $\bar{C}_i$ is average local coating coefficient characterized for the ability of the hoop with radius r^i of the support disk on the grinding instrument.

The distance from rotation center O_4 of the support disk 4 to rotation center O_5 of the grinding instrument 5 is a function of the angle α. From Figure 1 it can be received

$$e(\alpha) = O_4O_5 = \sqrt{\left({}^5\xi_{O4}\right)^2 + \left({}^5\eta_{O4}\right)^2} \tag{9}$$

In which (P.E. Nikravesh, 1988; A.A. Shabana 2001; W. Schiehlen, 1986)

$$\begin{aligned} {}^5\xi_{O4} &= \left[x_{O4}(\alpha) - a\right]\cos\theta + \left[y_{O4}(\alpha) - b\right]\sin\theta \\ {}^5\eta_{O4} &= -\left[x_{O4}(\alpha) - a\right]\sin\theta + \left[y_{O4}(\alpha) - b\right]\cos\theta \end{aligned} \tag{10}$$

In the equations (10) α is rotation angle of level 1, and θ is rotation angle of grinding instrument 5

$$\theta = \frac{1}{k_2}(\alpha - \alpha_o) + \theta_o, k_1 = \frac{\dot{\alpha}}{\dot{\theta}} = \frac{\omega_1}{\omega_5} \tag{11}$$

3 Control of Processing Kinematic Program while Grinding

The relative speed influences abrasion intensity of optical elements. In order to express relationships of abrasion intensity and the relative speed, a non dimension factor is introduced, called as the speed coefficient.

Definition 3. Factor

$$\chi_{ij}(t) = \frac{{}^5v_{ij}^r(t)}{V_{R\max}} \tag{12}$$

is called as the speed coefficient.

In which $V_{R\max} = \omega_5 D_5 / 2$ is the speed of a point on an external hoop of the grinding instrument 5, and ${}^5v_{ij}^r(t)$ is the average relative speed of points M on support disk 4 in arc $M_1^{ij}M_2^{ij}$ against grinding instrument 5, D_5 is the diameter of the grinding instrument.

From Figure 1, the relationship of relative velocity can be found by following formula

$${}^5v_{ij}^r(t) = \frac{1}{\gamma_1 - \gamma_2}\int_{\gamma_1}^{\gamma_2} {}^5v_M^r d\gamma \tag{13}$$

In which: $\gamma_1(t) \leq \gamma(t) \leq \gamma_2(t)$, ${}^5v_M^r(t)$ is the speed of any point M in the arc $\widehat{M_1^{ij}M_2^{ij}}$ on support disk 4 that is defined by formula (P.E. Nikravesh, 1988; A.A. Shabana 2001; W. Schiehlen, 1986)

$$\begin{bmatrix} \dot{\xi}_M^{(5)} \\ \dot{\eta}_M^{(5)} \end{bmatrix} = \mathbf{A}_5^T \left\{ \begin{bmatrix} \dot{x}_{O4} \\ \dot{y}_{O4} \end{bmatrix} + \dot{\varphi}_4 \mathbf{I}^* \mathbf{A}_4 \begin{bmatrix} \xi_M^{(4)} \\ \eta_M^{(4)} \end{bmatrix} \right\} + \dot{\varphi}_5 \mathbf{I}^{*T} \mathbf{A}_5^T \left\{ \begin{bmatrix} x_{04} \\ y_{04} \end{bmatrix} - \begin{bmatrix} x_{O5} \\ y_{O5} \end{bmatrix} + \mathbf{A}_4 \begin{bmatrix} \xi_M^{(4)} \\ \eta_M^{(4)} \end{bmatrix} \right\}$$

In this equation the cosine directive matrices $\mathbf{A}_i$ and the matrix $\mathbf{I}^*$ have the following forms

$$\mathbf{A}_4 = \begin{bmatrix} \cos\varphi_4 & -\sin\varphi_4 \\ \sin\varphi_4 & \cos\varphi_4 \end{bmatrix}, \quad \mathbf{A}_5 = \begin{bmatrix} \cos\varphi_5 & -\sin\varphi_5 \\ \sin\varphi_5 & \cos\varphi_5 \end{bmatrix}, \quad \mathbf{I}^* = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

If the higher speed coefficient is known, the more abrasion intensity and the lower speed coefficient, the less abrasion intensity (M.N. Semibratov, 1978).

Now assuming the concept of average is the speed coefficient in a cycle of the level of drive element (M.N. Semibratov, 1978) is introduced

$$\overline{\chi}_{ij} = \frac{1}{T}\int_0^T \chi_{ij}(t)\,dt = \frac{1}{TV_{R\max}}\int_0^T {}^5v_{ij}^r(t)\,dt \tag{14}$$

Assuming relative average speed coefficient of the i-th hoop of the support disk 4 against grinding instrument 5

$$\overline{\chi}_i = \frac{1}{m^*}\sum_{j=1}^{m^*} \overline{\chi}_{ij} \tag{15}$$

In which m* is the quantity of hoops on grinding instrument 5, where $\overline{\chi}_{ij} \neq 0$, and j = 1,...,m. Two factors (speed coefficient $\overline{\chi}_i$ and coating coefficient $\overline{C}_i$) express kinematic influence of grinding process of the instrument 5 on abrasion intensity of the element's surface on hoops with any radius r^i of the support disk 4. Their influences are simultaneous, co-operating and may compensate each other.

In that case the condition in which grinding instrument 5 smoothly processes element's surface on the support disk 4 is (M.N. Semibratov, 1978)

$$\overline{C}_i\overline{\chi}_i = \text{const}, \qquad (i = 1,...,n), \tag{16}$$

Improvement of processed optical element's surface quality by grinding is an important requirement of technology. To meet condition (16), after setting kinematic program to achieve reasonable relative speed function, coating coefficient $\overline{C}_i$ should be adjusted.

Footnote: in practice, coating coefficient $\overline{C}_i$ may be adjusted by variation of one parameter so called filling in instrument surface coefficient η_{Rj} (M.N. Semibratov, 1978).

4 Some Results of Study on Kinematic Program Control of Grinding Optical Elements

Based on concept of above mentioned coating coefficient and speed coefficient, a kinematic control program for processing elements on grinding machine type (Figure 1) was worked out. With every set of kinematic parameters of this grinding machine, kinematic control program is formulated for respective processing elements (Nguyen Van Khang et al. 2003; Nguyen Trong Hung, 2003).

Hereafter are some received results of kinematic control program for processed optical elements on grinding machine (Figures 5, 6).

Based on above established kinematic control program for processing optical elements, some following imitated cases were investigated:

- Variation of level of the length the link 1,
- Variation of length of connecting link 2 and length of the ground,
- Variation of gear ratio k_1 between level axle and grinding instrument axle,
- Variation of gear ratio k_2 between support disk and polishing instrument.

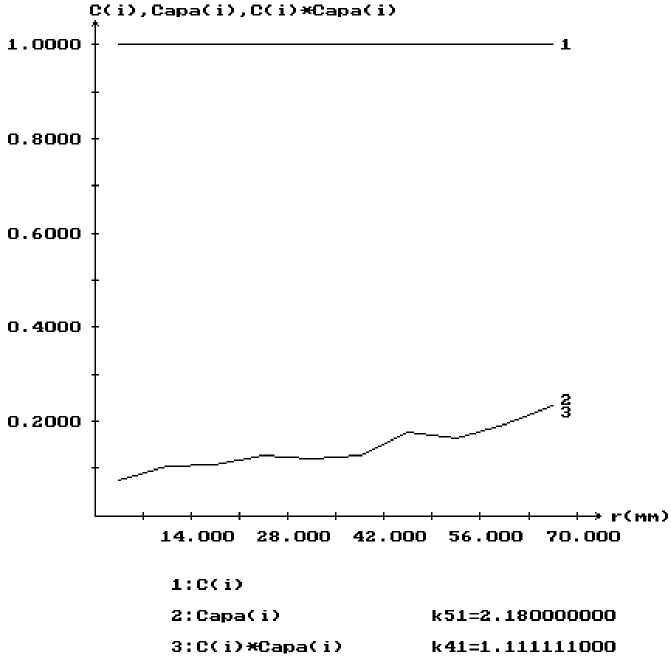

Figure 5a. Kinematic program with $l_1 = 10mm$,
low processing intensity on central area makes more convexes

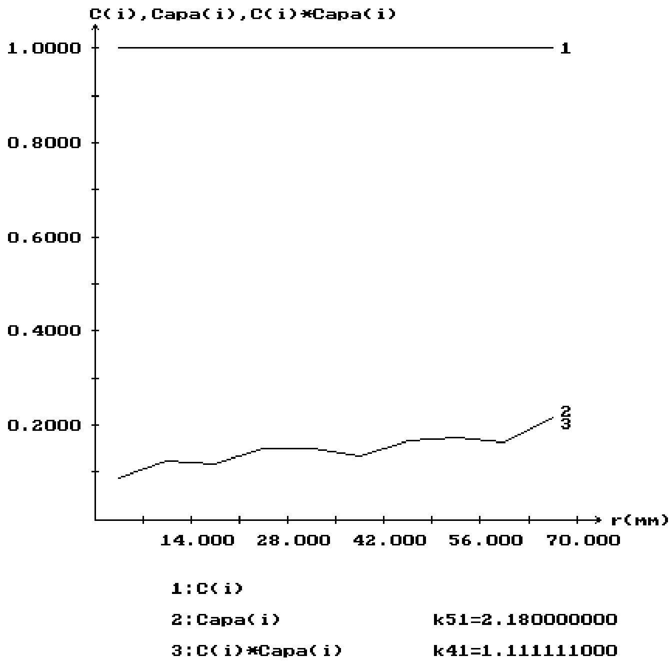

Figure 5b. Kinematic program with $l_1 = 20mm$,
low processing intensity on central area makes more convex spots

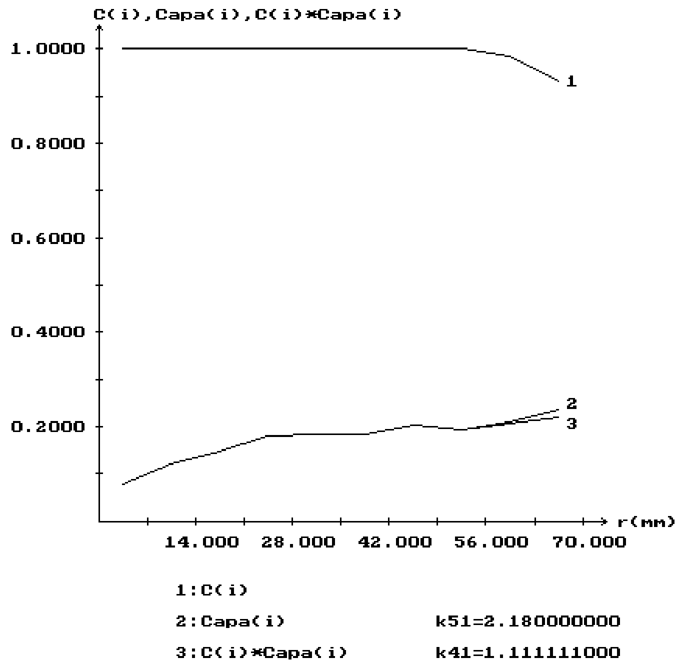

Figure 5c. Kinematic program with $l_1 = 30mm$,
relatively regular processing intensity from central to external end

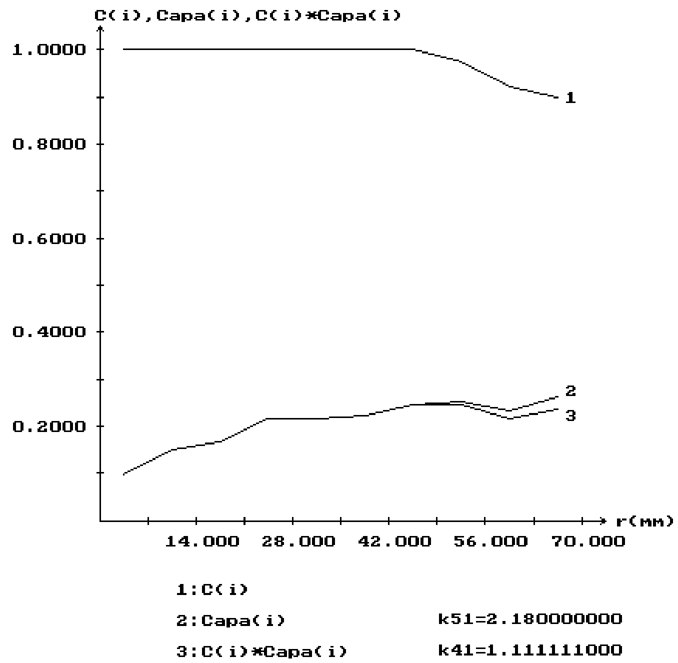

Figure 5d. Kinematic program with $l_1 = 40mm$,
relatively regular processing intensity from central to edge

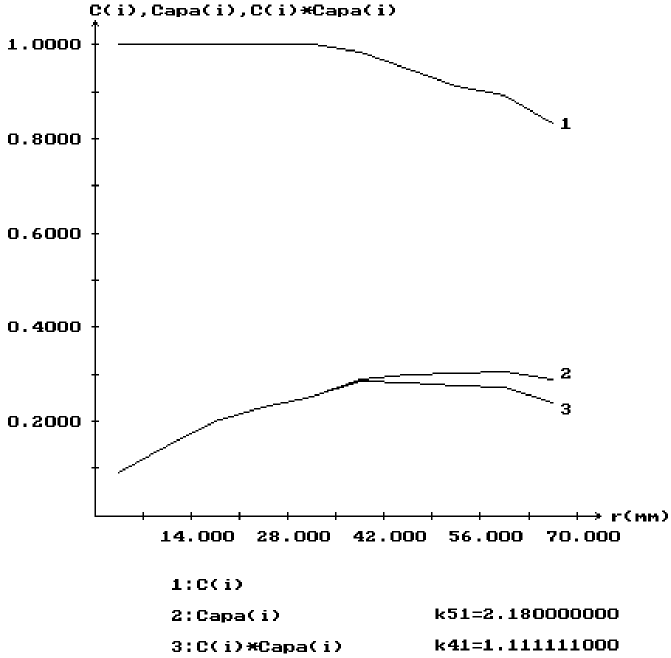

Figure 5e. Kinematic program with $l_1 = 50mm$,
strong processing intensity makes more sunken spots

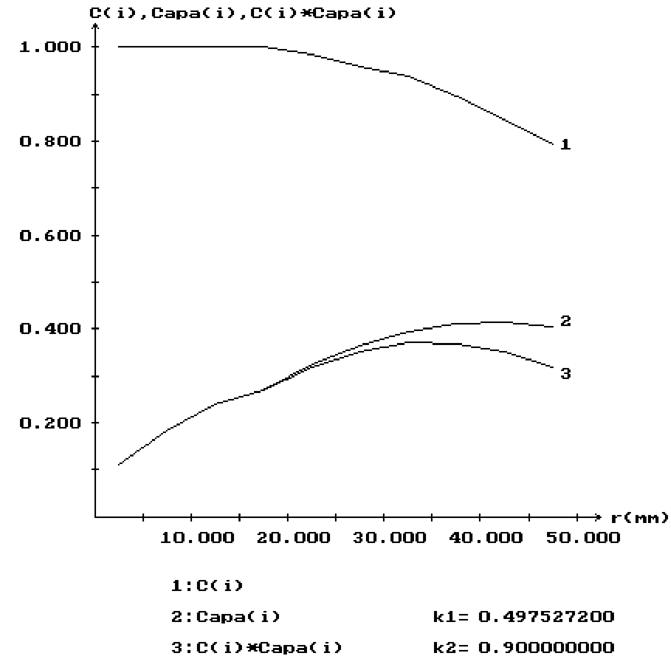

Figure 6a. Kinematic program with
$l_1 = 40mm, k_1 = 0,4975272, \xi_3 = 150, \eta_3 = 310$
The curb expresses smooth kinematic program,
reducing local vein errors

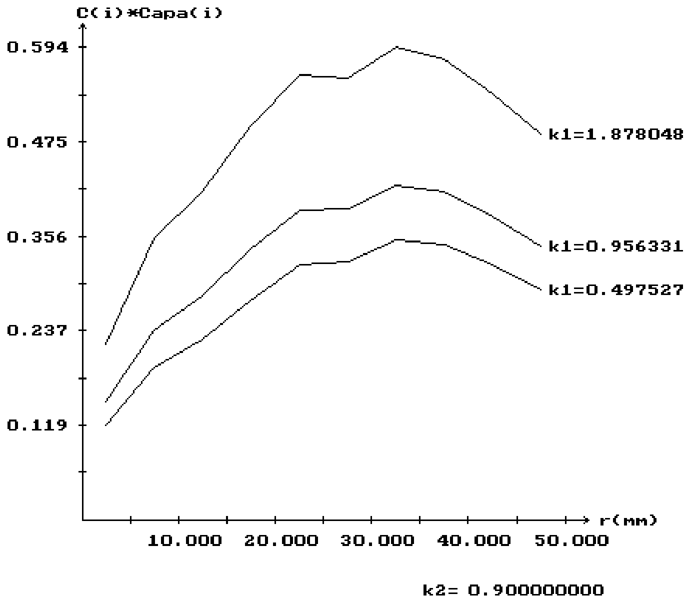

Figure 6b. Kinematic program with
$l_1 = 40mm$, and variation of parameter k_1:
Rough grinding $k_1 = 1{,}87804878$ (upper curb),
Pre-final grinding $k_1 = 0{,}95633187$ (central curb),
Final grinding $k_1 = 0{,}4975272$ (lower curb)

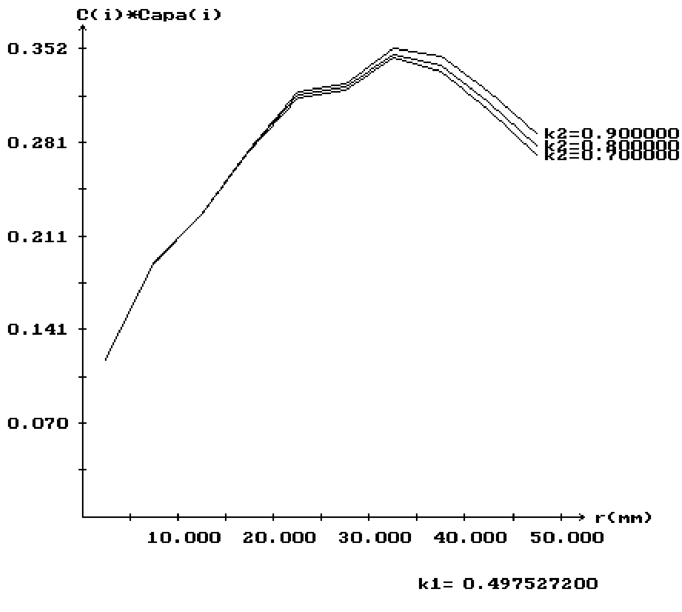

Figure 6c. Kinematic program with $l_1 = 40mm$,
variation of parameter k_2, coefficient k_2 was chosen by an empirical formula,
when grinding $k_2 = 0{,}9$ (upper curb), and polishing $k_2 = 0{,}7$ (lower curb)

From the investigated kinematic program of grinding optical elements surfaces, the following facts were recorded:

- With the short length of level, processing intensity at central area makes few convexity of grinding elements,
- With a medium length of level, processing intensity is relatively regular at both the central areas and edge areas of grinding elements,
- With a long length of level, processing intensity is strong at central area, so it makes concavity of grinding elements,
- When rough grinding, high speed of the level and high gear ratio are chosen to achieve high production capacity,
- When pre-final grinding, medium speed of the level and medium gear ratio, are chosen to achieve production capacity and precision,
- When final grinding, low speed of the level and small gear ratio to achieve high precision.

5 Conclusion

Through results of study on adjustment of kinematic program of optical grinding elements, can be made a conclusion:
Change of accumulative value of coating coefficient and speed coefficient depends on:

- Shaking amplitude of support disk against polishing instrument,
- Variation of transformation ratio between level and main axle.

Control of kinematic program together with variation of filling in instrument surface coefficient and directive processing under distribution of local superfluous quantity of needed processing surface can improve precision of grinded surface of optical elements (M.N. Semibratov, 1978 and Nguyen Trong Hung, 2003).

Acknowledgement

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