Some considerations regarding the performances of machining by superfinishing process

Badea Lepadatescu, Adela-Eliza Dumitrascu

***Abstract*—** In the paper is presented some considerations regarding the use of superfinishing process in machining rotationally symmetrical workpieces to improve their surface structure as fine as 0,012 μm Ra. Also are related some results of our research connected to this manufacturing process using different process parameters. The data that were obtained by these researches allow us to design and to realize a machine tool of superfinishing method by using two types of reciprocating motions of the abrasives tool which led us to achieve a better surface texture parameters of the workpieces.

***Keywords*—**productivity, accuracy, surface finish, reliability, wear, cost-performance.

I. INTRODUCTION

In this process, the main aim is to remove the burnt out layer of the surface to improve the surface finish and to correct the inequalities in geometry. The correction of shape and dimensional accuracy is not aimed at. This leads to even distribution of the load. It is a slow speed abrasive machining process. The abrasive stick is made of very fine grains. The work is rotated between centers and abrasive stick holder is reciprocated back and forth with short strokes but rapidly. The rotational speed of work is very low: 2 to 20 m/min. The sticks stroke may be 2 to 5 mm long which a frequency of up to 1800 stroke/min. A lubricant made of kerosene oil is used to give fine finish. Superfinishing can be accomplished on a lathe or on a special purpose machines are also available for finishing crank shafts, cam shafts, etc.

Superfinishing enables the user to achieve virtually any-surface texture parameter, because only the roughness peaks are removed. The Superfinishing process is a very clean process, because coolant or grinding emulsion is used instead of honing oils like stone grinding. Recycling and waste disposal are simplified. The geometry of the workpiece remains unchanged. The superfinishing process is shown in Fig.1.

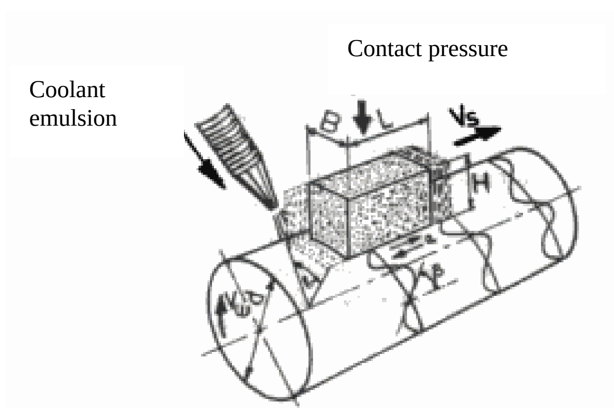

Fig.1 Process parameters in superfinishing.

where:

P = contact pressure between stone and workpiece = 0, 5-4, 0 kg/cm^2;

$$tg\beta = \frac{\pi \cdot d \cdot n}{a \cdot f} \quad (1)$$

a = amplitude of stone vibration [mm];

f = number of strokes per min (about 500 cycles/min);

d = diameter of workpiece [mm];

n = rpm of workpiece;
V_s = traverse speed [m/min];
If the work is longer than the stone, then a traverse motion is also required parallel to the axis of work. It should be noted that the stone gradually "wears in" to the average radius of the part. The early stages of the operation consist of the abrasion of the peaks and ridges of the workpiece. The stone will have contact with the workpiece at isolated points. However, as the work approaches nearer to a true cylinder the area of contact increases thus reducing the pressure on unit area.
In the straight oscillatory superfinishing (when the feed is parallel to the workpiece axis), shown in Fig.2, the path of the grain is projected on a developed cylindrical workpiece surface.

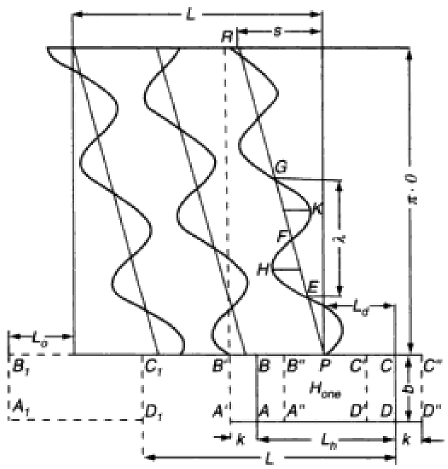

Fig.2 Path of grain motion on work surface and cutting speed components in straight superfinishing.

The composition of the rotary motion and feed motion yields the path of grain motion PR. As a result of the periodic (mostly sinusoidal) tool oscillation of an amplitude a and wave length λ the resulting grain path motion P passes through the points E-H-F-G-R. The amplitude a may be controlled; the wavelength λ results from the condition that the number of waves along the periphery should not be full amplitude.

$$f\lambda = \pi d N \tag{2}$$

where, f is the frequency of oscillation, N is the rotational speed in rpm, d is the workpiece diameter.
The cutting speed of straight superfinishing constitutes the vertical sum of the peripheral speed of the workpiece V_w oscillating motion V_0 and longitudinal feed rate S determined by:

$$V = \sqrt{V_p^2 + (V_0 + S)^2} \tag{3}$$

For a sinusoidal oscillation,

$$V_0 = 2\pi \cdot f \cdot a \cdot \cos(2\pi f t) \tag{4}$$

The maximum oscillation occurs for stick displacement equaling zero, e.g., for points E and F. the maximum cutting speed occurs at point E where V_{max} agrees with that of the longitudinal feed rate vector and thus:

$$V_{\max} = \sqrt{V_p^2 + (2\pi f a + S)^2} \tag{5}$$

The minimum speed occurs when V_0 is zero.

$$V_{\min} = \sqrt{V_p^2 + S^2} \tag{6}$$

Practically, the actual motion is characterized by the average speed, which is determined when:

$$V_0 = 2af\,. \tag{7}$$

II. DETERMINATION OF THE VOLUME OF MATERIAL REMOVED BY AN ABRASIVE GRAIN FROM THE WORKPIECE SURFACE

The efficiency of the superfinishing process is influenced by the material quantity removed from an abrasive grain from the workpiece surface. To calculate the relation of volume of material removed by an abrasive grain during machining is calculated the volume of material Q [mm^3/min] removed in time unit – minute.

$$Q = \pi . d_p . l_p . t . n_p \tag{8}$$

where d_p is the diameter of workpiece [mm], l_p is the wotkpiece length [mm], t is the stock material, n_p is the number of revolution of workpiece being machind [rev/min].
We can use to calculate the volume of material removed from the workpiece surface in a minute taking into consideration all the abrasive grain that work simultaneously.

$$Q' = q_m . N_g . K \ \ [mm^3/min] \tag{9}$$

where: q_m = is the elementary volume of material removed by one abrasive grain in a unit time, N_g is the number of abrasive grains of the abrasive tool in contact with the workpiece, k is a coefficient that take into consideration that not all the abrasive grains from the surface tool work in the same time.

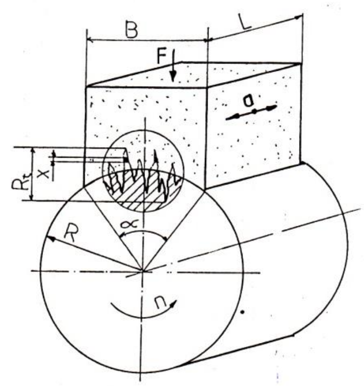

Fig.3 Calculation of the volume of material removed from the workpiece surface.

Looking to Fig.1, x is the thickness of the material removed at one reciprocating motion of the abrasive tool, To remove all the material t in this phase of machining are necessary a number of f' reciprocating motions.

$$f' = t/x \quad (10)$$

The time t_1 to do all these f' reciprocating motions is:

$$t_1 = f'/f \quad (11)$$

where f is the frequency of reciprocating motion of the tool.
During the time t_1 the workpiece will make n_1 revolutions:

$$n_1 = f'\cdot n_p/f \quad (12)$$

Using (10) and (11) will have:

$$n_1 = t\cdot n_p/x\cdot f \quad (13)$$

The total number of abrasive grains N_g that remove the stock material will be:

$$N_g = \xi_g\cdot R\cdot \alpha\cdot n_1 \quad (14)$$

Where ξ_g is number of abrasive grains from unit surface of the tool, R is the workpiece radius [mm], α is the angle that tool covers the workpiece surface [rad].
Using relation (13) equation (8) becomes:

$$Q' = q_m\cdot \xi_g\cdot R\cdot \alpha\cdot n_1\cdot k \quad (15)$$

Because Q = Q', will have:

$$\pi\cdot d_p\cdot l_p\cdot t\cdot n_p = q_m\cdot \xi_g\cdot R\cdot \alpha\cdot n_1\cdot k \quad (16)$$

and $q_m = \pi\cdot d_p\cdot l_p\cdot x\cdot f / \xi_g\cdot R\cdot \alpha\cdot k.$ (17)

From equation (16) result the factors that influence the efficiency of the machining process, where the abrasive tool frequency f is one of the most important.

III. SUPERFINISHING WITH A COMBINATION OF TWO VIBRATION MOTION WITH DIFFERENT FREQUENCIES

During the processing of the superfinishing, the abrasive particle has a complex path on the workpiece surface due to the combination movements of the tool and the workpiece.
The kinematics of a current point of abrasive grain on the workpiece surface will be studied during one rotation of the part being machined. This is necessary to optimize working parameters in order to obtain a good surface finish that has an important influence on the load bearing surfaces in contact.
Technical and economic performance of the superfinishing machining process is dependent on the type of reciprocal movement generation for the abrasive tool which can be done mechanic, pneumatic, hydraulic or electric. Due to the constructive and operational safety reasons are preferred mechanic or pneumatic methods to generate oscillatory motions of the abrasive tool.
The technical systems for generating vibratory movement should allow strict control of their amplitude and frequency of the tool movement to control its function.
Sometimes it is used the combination of the methods to generate reciprocal movement of the abrasive tool, each providing a specific frequency and amplitude.
If we consider that the two harmonic vibrations have the motion equations given by the next relations:

$$X_1 = a_1\sin(p_1 t + \varphi_1) \quad (19)$$
$$X_2 = a_2\sin(p_2 t + \varphi_2) \quad (20)$$

The amplitude a of the resulting motion after combining these two types of vibrations is:

$$a = \sqrt{a_1^2 + a_2^2 + 2\cdot a_1 a_2 \cos[(p_2 - p_1)t + (\varphi_2 - \varphi_1)]} \quad (21)$$

Because this amplitude of the movement varies with time, the motion that result isn't harmonic. The graph which represents the resulting motion takes different shapes according with amplitude, frequencies and dephased angles of motion components.

In Fig.3 is shown the combination of two vibrations with frequencies in the ratio 3: 1, upper harmonics having amplitude smaller that lower harmonics. In Fig.3a, vibrations are in phase at origin of time, in Fig.3b vibrations are dephased with the angle of $\pi/2$, and in Fig.3c, vibration are dephased with angle π. When the ratio of these two frequencies is a whole number, the resulting motion will have the period of smaller motion.

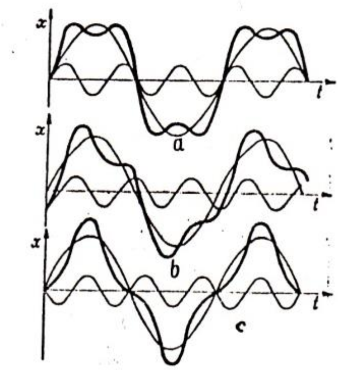

Fig.4 Combination of two vibration motions with different frequencies.

A. Determining the equation of motion for a point of abrasive tool on the workpiece surface when the tool has two vibratory motions

To increase the efficiency of the machining process we will study the solution of using a combination of two vibratory motions for abrasive tool. One of movement will have greater amplitude (10-15 mm) and a lower frequency (60 ds / min) being mechanically generated, and the other will have smaller amplitude (3-5 mm) and a higher-frequency (100-1500 ds / min), pneumatically generated. In this way the coefficient of overlapping the workpiece surface with traces left by abrasive grains will increase and is possible to obtain a better surface finish in a smaller time for machining (ds- means double stroke).

To determine the equations of movement for a point of the abrasive tool during the superfinishing process in the case of two vibratory motions of the tool is used Fig.5.

The workpiece has a rotation angular speed ω and the abrasive tool accomplishes two vibratory movements, one with the magnitude of the amplitude of a_1 and other with a_2. These two movements are generated mechanically by the mechanism 1 and respectively by a pneumatic generator 2. To increase the cutting capacity of the tool, the workpiece can have a traverse feed motion v_0. To obtain the trajectory equation of an abrasive grain of the tool 3, on the workpiece surface 4 is considered Cartesian coordinate system Oxyz attached to the working technological system.

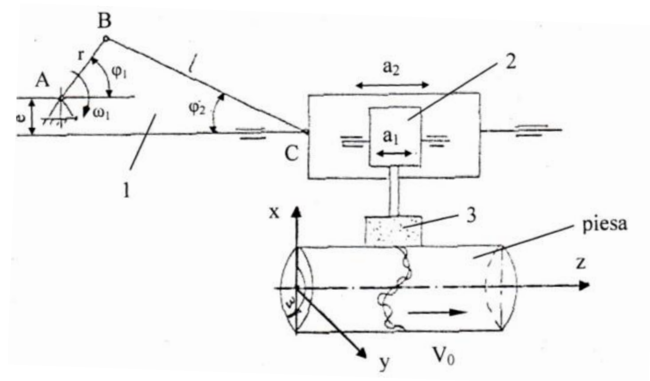

Fig.5 Scheme of the machining by superfinishing with two vibratory movements of the tool.

The radius vector OM of an arbitrary point of the tool can be resolved in three components of the system Oxyz (1).

$$\begin{cases} x = R\sin\theta \\ y = R\cos\theta \\ z = v_0\tau + s \end{cases} \quad (17)$$

where s is the deplacment of a point of the mechanism 1 given by equation (18):

$$s = r\cos\varphi_1 + l\sqrt{1-\left(\lambda\sin\varphi_1 + k\right)^2} \quad (18)$$

where $\varphi = \omega\cdot\tau$ (19)

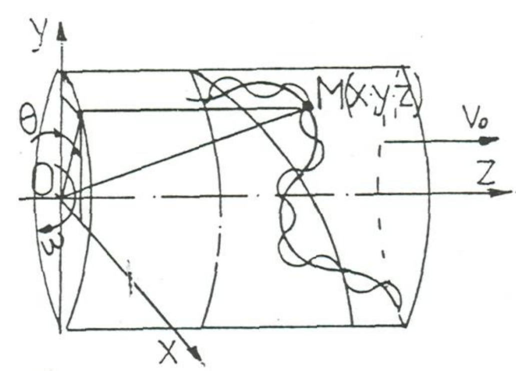

Fig.6 Workpiece coordinate system attached at machining by superfinish with two vibratory movements of the tool.

Given the relationship (18) and (19), the system (17) becomes:

$$\begin{cases} x = R\sin(\omega\tau) \\ y = R\cos(\omega\tau) \\ z = v_0\tau + r\cos(\omega_1\tau) + l\sqrt{1-\left[\lambda\sin(\omega_1\tau)+k\right]^2} \end{cases} \quad (20)$$

Cartesian components of speed of a point M are determined by the relationship:

$$\begin{cases} V_x = \dfrac{dx}{d\tau} = \omega R\cos(\omega\tau) \\ V_y = \dfrac{dy}{d\tau} = -\omega R\sin(\omega\tau) \\ V_z = \dfrac{dz}{d\tau} = v_0 - r\omega_1\sin(\omega_1\tau) - \dfrac{\lambda\omega_1\cos(\omega_1\tau)[\lambda\sin(\omega_1\tau)+k]}{\sqrt{1-[\lambda\sin(\omega_1\tau)+k]^2}} \end{cases} \quad (21)$$

Using relations:

$$k_1 = \frac{\omega_1}{\omega}; k_2 = \frac{v_0}{\omega} \quad (22)$$

$$\begin{cases} x = R\sin(\theta) \\ y = R\cos(\theta) \\ z = k_2\theta + r\cos(k_1\theta) + l\sqrt{1-[\lambda\sin(k_1\theta)+k]^2} \end{cases} \quad (23)$$

The components of velocity of a point M on the three coordinate axis become:

$$\begin{cases} V_x = \omega R\cos(\theta) \\ V_y = -\omega R\sin(\theta) \\ V_z = v_0 - r\omega_1\sin(k_1\theta) - \dfrac{\lambda\omega_1\cos(k_1\theta)[\lambda\sin(k_1\theta)+k]}{\sqrt{1-[\lambda\sin(k_1\theta)+k]^2}} \end{cases} \quad (24)$$

In Fig.6 is shown the coordinate system attached to the workpiece when is used two vibratory motions for the abrasive tool.

K' = 1/R, u = Rθ, $k_3=k_2/R$, $k_4=k_1/R$ (25)

Using Fig.6 and the relationship (25) the system (23) becomes:

$$\begin{cases} x = R\sin(k_1' u) \\ y = R\cos(k_1' u) \\ z = k_3 u + r\cos(k_4 u) + l\sqrt{1-[\lambda\sin(k_4 u)+k]^2} \end{cases} \quad (25)$$

$$ds = du\sqrt{1+\left(\frac{dz}{du}\right)^2} \quad (26)$$

The of elementary arc is given by

$$\left\{ \frac{dz}{du} = k_3 - k_4 r\sin(k_4 u) - l\frac{[\lambda\sin(k_4 u)+k]k_4\lambda\cos(k_4 u)}{\sqrt{1-[\lambda\sin(k_4 u)+k]^2}} \right.$$

$$\left\{ S = \int_{u_1}^{u_2} du\sqrt{1+\left\{k_3 - k_4 r\sin(k_4 u) - l\frac{[\lambda\sin(k_4 u)+k]k_4\lambda\cos(k_4 u)}{\sqrt{1-[\lambda\sin(k_4 u)+k]^2}}\right\}} \right.$$

From equation (28) the following conclusions can be drawn regarding the most important factors influencing the trajectory of an abrasive grain on the workpiece surface. Thus, it appears that to increase the length *S* of abrasive grains trajectory angular it is necessary to increase the velocity ω_1 of the radius and the crank arm length *l* in the mechanism 1 (Fig.5), from the construction point of view. In terms of technology, to increase the path length of the abrasive grain we must increase the amplitudes a_1 and a_2 of the two vibratory movements.

Determination of the equations for a point of abrasive tool on the workpiece surface during the superfinishing process is important because in that way is possible to modify the technological parameters to optimize the machining process.

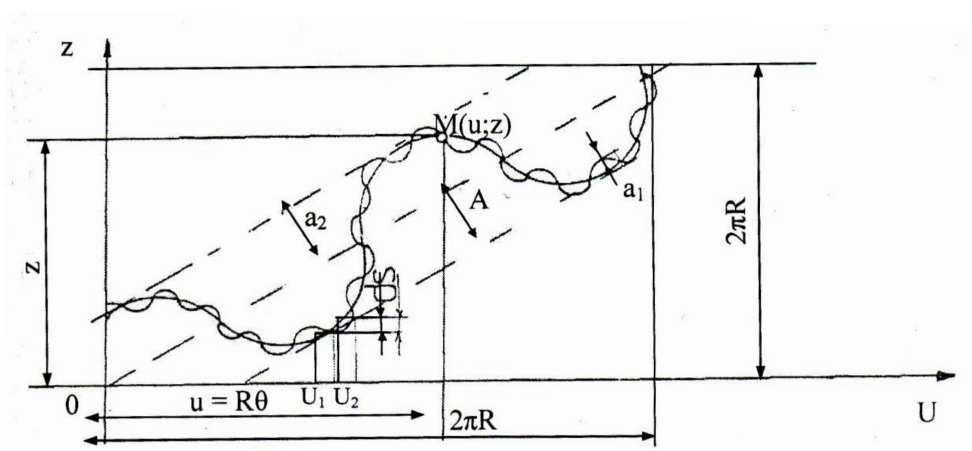

Fig.6 The path of the grain is projected on a developed cylindrical workpiece surface when is used two vibratory motions for the abrasive tool.

In this case it becomes easier to obtain the surface finish according with the technical documentation in shorter time and to know exactly where we must increase or decrease some values of mechanical movements of the mechanism that generate the vibratory movement necessary to the machining by superfinishing method.

IV.TEST RESULT REGARDING THE INFLUENCE OF PROCESS PARAMETERS ON THE SURFACE FINISH

The main process parameters that have influence on the surface finish of the workpiece obtained are: grain size of abrasive stone, time of superfinishing process, pressure of abrasive stone on the part surface, the rotational speed of the part, initial roughness of the part being machined, amplitude of the tool oscillations motion, percentage of the bearing ration.

In the next graphs are shown the result of influence of process parameters to the efficiency of machining process that allow to establish the optimum parameters for different type of parts.

A. Influence of the initial roughness of the workpiece to the surface finish obtained

In Fig.7 is shown the test results regarding the influence of the initial roughness of the part being processed to the final surface finish. It can be seen that to reduce the time of machining is necessary that the workpiece must have after previously machining processes a surface quality smaller than R_a = o,8 μm.

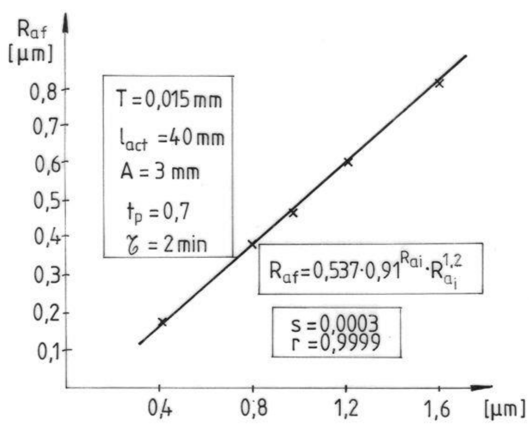

Fig. 7 Dependence of the initial surface finish on the final quality of the workpiece.

B. The influence of the reciprocating motion of the abrasive tool to the surface finish

The amplitude of the oscillation motions of the abrasive tool has an important role to the quality of the part that is obtained. It is recommended that the amplitude of these oscillations to be smaller in the first stage of machining and bigger on the final stage when is obtained the final roughness.

It can be seen that the amplitude of reciprocating motion of the tool to have a value of maximum 6 mm in the first stage of machining and of 1-2 mm in the final stage (Fig.8).

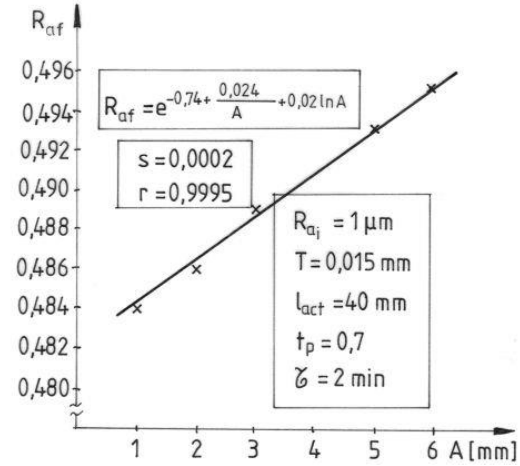

Fig.8 Dependence between the amplitude of oscillation motions on the surface finish of the workpiece.

C. The influence of the contact length of the tool with the workpiece surface on the roughness of the part

In Fig.9 is shown the connection of the quality of workpiece surface obtained and the bearing ratio that result after machining through superfinishing process. Bearing ratio, symbol t_p is the ratios (expressed as a percentage) of the profile bearing length at any specified depth in the profile to the evaluating length.

Thus t_p is useful whenever bearing surfaces must be analyzed for wear or lubrication properties. Bearing area ratio depth is critical for machining processes that have characteristic peaks, such as grinding, hard turning, or milling. It can be seen that to increase bearing ratio is necessary to obtain a high surface quality smaller than R_a = 0.6 μm. Superfinish improves the bearing ratio (t_p) resulting in greatly improved wear resistance

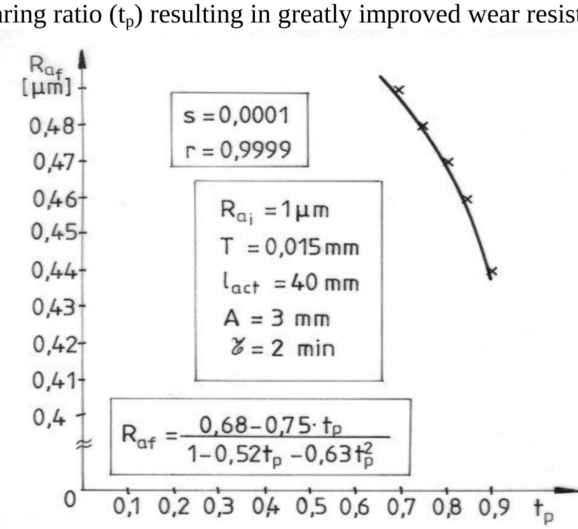

Fig.9 Connection of the quality surface and the bearing ratio t_p.

D. Influence of the processing time and surface finish obtained

Superfinishing is a machining process where the tool cutting action is interrupted automatically after a specific time. This time have different values according with the factors as: the initial roughness of the part, the abrasive stone grade, the part material and the surface finish value that has to be obtained.

In Fig.10 is presented the test results of the surface roughness R_a according with the processing time where the initial roughness of the part was R_a = 0.6μm. It is recommended that the processing time to be shorter than 2 minutes because after this value the roughness obtained is not improved.

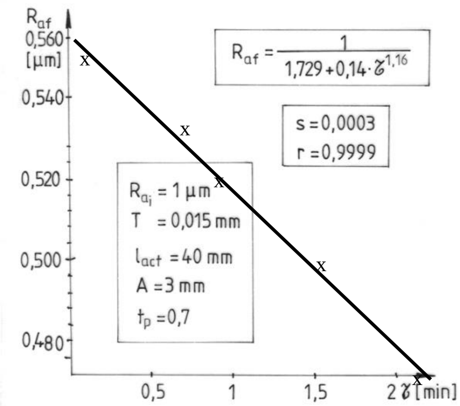

Fig.10 Dependence of the roughness and the processing time.

Based on the test results it was designed and realized a special machine to superfinish cylindrical part as are shown in Fig.11.

Fig.11 Shapes of parts that are machined with machine through superfinishing process.

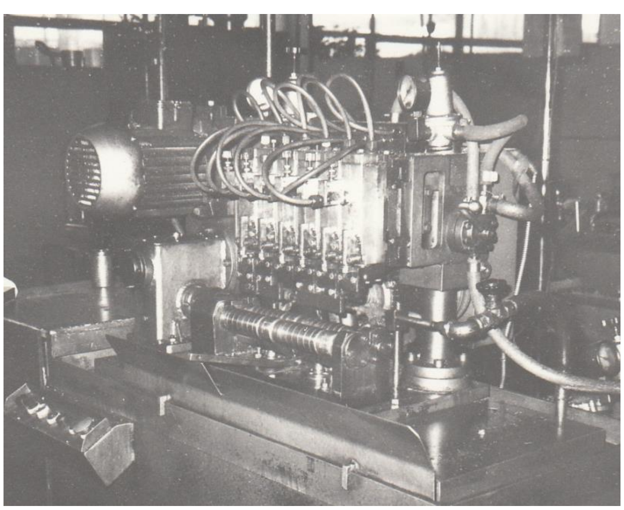

Fig.12 Machine tool for machining by superfinishing process.

The machine that are presented in figure 12 use for machining method Through Feed Process. This process is used to finish cylindrical parts, such as tapered rolls, piston pins, shock absorber rods, shafts, or needles.

The parts are transported and rotated between two rotating drive rolls. The rotating workpiece passes underneath a series of six stone stations with stones of decreasing grit size that are mounted to an oscillator mechanism. The oscillating stones contact the workpiece at a 90 degree angle, with appropriate pressure to achieve optimum results. The time of machining process was between 25-30 seconds and the roughness surface obtained was between R_a = 0.4-0.2 μm, that was in concordance with the technical documentation of the part being machined.

V. CONCLUSIONS

By using superfinishing process the roughness average (R_a) is improved to a value of 0.02 microns and the bearing area curve characteristics are significantly improved, while surface geometry remains unchanged.

The superfinishing process meets new market demands both in superior results and in competitive cost-performance, compared with other finishing processes. In addition, the superfinishing process reduces friction, wear, and energy consumption, and leads to savings in service and maintenance costs.

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Badea Lepadatescu is Assoc. Professor at Transylvania University of Brasov, Romania, Department of Manufacturing Engineering, Eroilor Street, no. 29, e-mail: lepadatescu@unitbv.ro.

Adela-Eleza Dumitrascu is Assoc. Professor at Transylvania University of Brasov, Department of Manufacturing Engineering, Eroilor Street, no. 29, Romania.