MATHEMATICAL MODELS FOR SMOOTHING PROCESS BY MECHANICAL SHOCKS OF CYLINDRICAL SURFACES

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Abstract: Smoothing by mechanical shocks is a processing method based on the impact effect of the balls with the work piece material. Specific phenomena such processing methods result in changes of mechanical properties of the surface layer of the piece; also change the appearance of the original surface layer. The surface obtained after processing the outer cylindrical surface by mechanical shock is considered a chain of small cavities generated by the impact of the balls with the workpiece material. The outer cylindrical surfaces roughness obtained after the smoothing using centrifuged balls, is an important parameters of this process. The aim of this paper is to present ways to develop mathematical models of surfaces roughness. Also are presented experimental results that confirm the validity of mathematical models and their level of approximation of the real situation.

Keywords: *Smoothing, Roughness, Plastic deformation, Hardening*

1. Introduction

Industrial practice highlights a number of technological possibilities for surface finishing of pieces belonging to metal parts. The specialists consider that the cold plastic deformation of the metallic workpieces could be included into the group of cold manufacturing processes, when the temperature during the process does not exceed 30 % of the melting temperature of the respective material. There are various cold manufacturing processes; even the machining processes (cutting, drilling, turning, milling, grinding etc.) have as initial basic phenomenon the plastic deformation of the workpiece material. Along with cutting or nonconventional processes, cold plastic deformation is used extensively in surface finishing.

Extensive research conducted over the last categories of interest to show their development processes [6]. The advantages of these processes, compared to the other are obvious: can be applied to a variety surfaces, high mechanical characteristics of the surface layer, surface roughness comparable to that obtained from cutting, much lower costs related to processing. A manufacturing techniques based on the cold plastic deformation is caused by the impact effect of the hard metallic balls with the workpiece material.

From finishing processes of surfaces by plastic cold deformation, cold centrifuged ball striking process, so-called *ball peening* [4] appears more economically due to its simplicity and because it can be applied to pieces with lower stiffness.

The method involves the hitting of the workpiece material by balls found in motion, so that each impact contributes to the generation of small cavity in the workpiece surface layer.

The actions of hard balls sent with specific force and frequency over metallic surface of the workpiece have significant effects on the structure of the superficial surface layer but also on the size of micro-irregularities surface.

The balls can be directed to the workpiece surface in different ways; they could be transported by a gas jet [4], but there are also equipments which direct the balls just to the workpiece surface to be processed.

During the process there is a clash of distorting element (hard ball) to piece surface. The ball hardness is much higher than the one of the piece to be processed. The shape of piece after crash will result in form of a spherical cap with size dependent of working conditions.

Observing the condition of generating cylindrical surface, strikes (collisions) will be carried throughout the circumference of the piece by turning it with speed n_p. It can be concluded that collisions constantly producing at part rotation angle at the center φ_p (Fig. 1) there will always be an oscillation of level with a certain height R_{max} surface, which is micro-irregularities of the process with the same size [3].

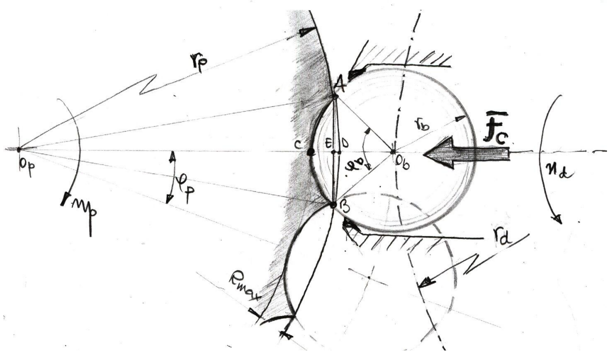

Figure 1: *Schematic diagram of the smoothing process with centrifuged balls.*

Methodology presented in this paper is to determine theoretical mathematical expressions (models) of the roughness R_{max}. Also are presented some experimental results obtained after applying the smoothing process by mechanical shocks to determine the reliability of the models obtained, compared with experimental results.

2. Developing mathematical models

From Fig. 1 can be observed that the surface deformation is in the shape of a spherical cap, with a radius equal with balls radius, r_b. This highlights the possibility that a complete rotation of the part obtain a number of spherical caps N_c, that can be computed with Eq.(1).

$$N_c = \frac{2\pi r_p}{l'_c}. \qquad (1)$$

The spherical cap length l'_c ($\overset{\frown}{ADB}$ arc) can be approximated with length rope (AEB), the value of segment ED is insignificant in relation to the size of rope. Using geometrical relations existing in the triangle $O_b AE$ can be expressed the Eq. (2).

$$l_c = 2\sqrt{2r_b \cdot R_{\max} - R_{\max}^2}. \qquad (2)$$

By entering into Eq. (1) the obtained value of l_c, the resulted relationship it will have the form of Eq. (3).

$$N_c = \frac{\pi R_p}{\sqrt{2r_b R_{\max} - R_{\max}^2}}. \qquad (3)$$

On the disk tool are mounted a number of balls, N_b. After processing will be performed a number of spherical shape on the parts surface, expressed by the Eq. (4):

$$N_c = \frac{n_d}{n_p} \cdot N_b. \qquad (4)$$

In Eq. (4), with the n_d is expressed the disk tool rotation, and n_p represent part rotation. Combining Eqs. (3, 4) results equation (5):

$$R_{\max}^2 - 2r_b \cdot R_{\max} + \left(\frac{\pi \cdot r_p \cdot n_p}{n_d \cdot N_b}\right)^2 = 0. \qquad (5)$$

The solutions of Eq. (5) are:

$$R_{\max} = r_b - \sqrt{r_b^{\,2} - \left(\frac{\pi \cdot r_p \cdot n_p}{n_d \cdot N_b}\right)^2}. \qquad (6)$$

It will be considered for the value of R_{max} only

$$R_{\max} - \sqrt{r_b^{\,2} - \left(\frac{\pi \cdot r_p \cdot n_p}{n_d \cdot N_b}\right)^2}.$$

Because for the higher values of R_{max} than the ball radius r_b, the circle of maximum section has the radius $r_b = l_c / 2$, and the approximation is inconclusive.

The analysis of Fig. 1 shows the fact that to each spherical cap from the surfaces part corresponding a center angle:

$$\varphi_p = \frac{2\pi}{N_c}. \qquad (7)$$

The N_c parameter from Eq. (7) represent the number of spherical cap resulted on the part surfaces in one pass of disk tool over the piece.

Accepting the idea that the geometrical figure ADBE represent a spherical cap, can be written the following mathematical relations:

$$\begin{aligned} \left|\overline{ED}\right| &= 2r_p \sin^2 \frac{\varphi_p}{4}; \\ l_c = \overline{AEB} &= 2r_p \sin \frac{\varphi_p}{2} \end{aligned}. \qquad (8)$$

Replacing the N_c parameter from Eq. (4) in Eq. (7) we get next relation:

$$l_p = \frac{2\pi n_p}{n_d \cdot N_b}. \tag{9}$$

The $\overline{AEB}$ rope is common to both circles with radius r_p (piece) and r_b (deformation ball). Relations based Eqs. (8, 9) can be written:

$$2r_b \cdot \sin\frac{\varphi_b}{2} = 2r_p \cdot \sin\frac{2\pi \cdot n_p}{n_d \cdot N_b}. \tag{10}$$

Applying mathematical rules can be obtained the expression for calculating the angle corresponding to a center ball of a spherical cap:

$$\varphi_b = 2\arcsin\left(\frac{r_p}{r_b} \cdot \sin\frac{2\pi \cdot n_p}{n_d \cdot N_b}\right). \tag{11}$$

φ_b angle allows finding the height of spherical cap ($\overline{CE}$) in the relationship

$$\begin{aligned}\overline{CE} &= r_b\left(1-\cos\frac{\varphi_b}{2}\right) = 2r_b \sin^2\frac{\varphi_b}{4} = \\ &= 2r_b \sin^2\left[\frac{1}{2} \cdot \arcsin\left(\frac{r_p}{r_b} \cdot \sin\frac{2\pi \cdot n_p}{n_d \cdot N_b}\right)\right]\end{aligned} \tag{12}$$

To determine the expression for calculating the roughness surface R_{max} we will consider the Eqs. (8, 9, 12).

$$\begin{aligned}R_{\max} &= \overline{CE} + \overline{ED} = \\ &= 2r_p \sin^2\left[\frac{1}{2} \cdot \arcsin\left(\frac{r_p}{r_b} \cdot \sin\frac{2\pi \cdot n_p}{n_d \cdot N_b}\right)\right] + . \\ &+ 2r_p \sin^2\frac{2\pi \cdot n_p}{n_d \cdot N_b}\end{aligned} \tag{13}$$

From the analysis we see that for the theoretical calculation of height, R_{max}, of micro irregularities can use different expressions (see Eqs. (6, 13).

3. Experimental research

To see the approximation of the theoretical results by applying the expressions referred to those achieved in practice, were performed experimental tests. To convert the surface roughness R_{max} in R_a was used the approximate relations [2]:

$$\begin{aligned} R_a &= \frac{R_{\max}}{5} - for\ R_a > 10\mu m \\ R_a &= \frac{R_{\max}}{10} - for\ R_a < 1\mu m \end{aligned} . \tag{14}$$

2.1 Equipment and work piece material

Research, [8] has been conducted with a special device mounted on a universal lathe (Fig. 2). The device features a disk tool with balls. It used a special tool to direct balls to the surface of the workpiece. It consists of a cylindrical disk with holes in witch are placed in predetermined diameter balls.

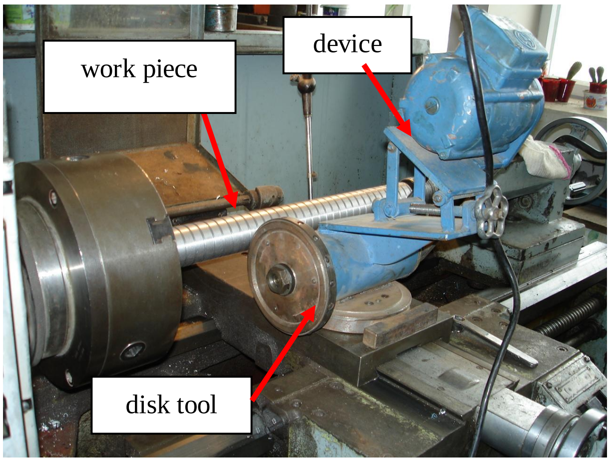

Figure 2: *Device for smoothening by plastic deformation with centrifuged balls.*

At the periphery of this disc, there is a ring which is made a number of holes equal to the number of holes; diameter of these holes is smaller than the diameter of balls inserted. In this way, the balls move short distances in cylindrical holes; when the disc is rotated, (Fig. 3) the balls are rolled on the ring under the action of centrifugal force and parts thereof beyond the outer cylindrical surfaces of the ring.

To be affected by the ball peening process, the hardness of the ball material has to exceed the hardness workpiece material with at least several HRC unities. The process of the ball peening presented in this paper is applied in the case of the workpiece materials able to be affected by a certain plastic deformation and hardening; this means that usually, the workpiece material must have a phase structure corresponding to that obtained by an annealing heat treatment.

In the considered case, the axis of the workpiece and the axis of the disk tool are parallel and placed in the same horizontal plan.

When the disk tool does not perform the rotation motion, the balls existing in the holes from the disk tool body has a position essentially determined by the presence of their weight force.

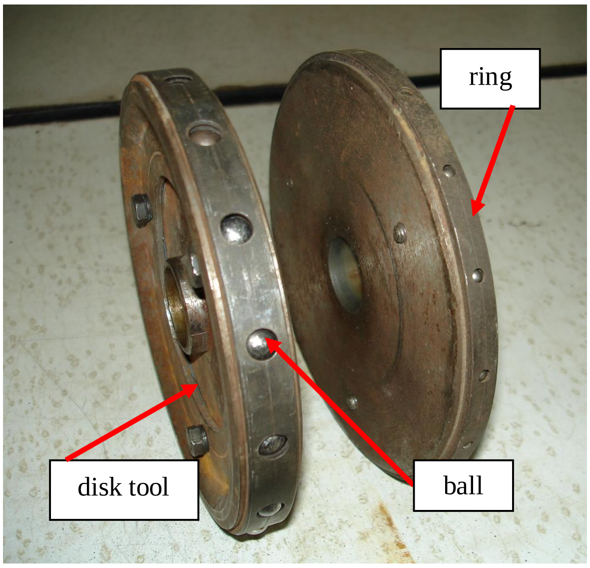

Figure 3: *Disks with deforming balls (different diameters of balls).*

Striking force was achieved by centrifugal force resulted at disk tool turning with n_d speed.

The workpiece and the disk tool perform rotation motions in the same direction; due to this fact, the ball takes contact with the external cylindrical surface of the workpiece in a position situated over the horizontal plan determined by the workpiece and the disk tool axes.

As consequence of the impact, if the pressure exerted by the ball under the action of the centrifugal force on the workpiece surface layer is higher than the compression resistance of the workpiece material, a small cavity is generated on the workpiece surface. At the same time, the ball is pushed on a low distance in the conical hole existing in the disc tool body, but it is obliged by the ring to continue the motion along a trajectory which is partially circular. Because in the contact zone the workpiece surface and the ball perform motions in opposite directions, the shape of the cavity generated in the workpiece surface layer is modified; of course, really the initial theoretical spherical shape of this cavity is also affected by the elastic recovery of the workpiece material.

Experimental researches were complying with the scheme from Fig. 1.

The experimental test samples for smoothing by mechanical shocks were selected from commonly used materials in tree construction. Was considered that smoothing process by plastic deformation is applied mainly journal shaft couplings that are used in friction [1]. The test pieces were made of rolled steel containing 0.37% carbon, quality steel containing 0.45 % carbon and an alloyed steel containing 0.17 % carbon, 0.22 % molybdenum, 0.95 % chromium, 1.3 % nickel.

Experiments were performed on cylindrical samples of diameter Φ = 45 mm and length L = 300 mm. To ensure good crosses were made during experiments centering holes. Cylindrical surface was divided into portions with a length of 30 mm, Fig. 4; with "S" is noted the safety section left to avoid possible influence of the chuck over the finishing operation results.

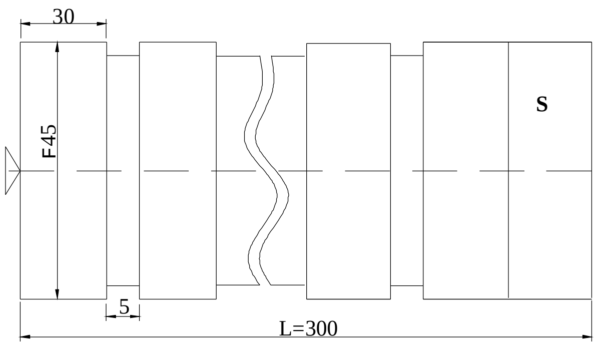

Figure 4: *Dimensions and geometry of workpiece*

Before being subjected to experimental research, all samples were processed by finishing turning.

2.2 Smoothing conditions

Smoothing by mechanical shock occurs at an ambient temperature, the temperature well below the recrystallization, which draws after itself that all changes in the metal structure can be easily recognized, as a result of plastic deformation occurred [5]. The considered parameters in order to express the theoretical point of view (Eqs. 6, 13), of a cylindrical outer surface roughness results applying the finishing process by mechanical shocks, were: parts radius (r_p), part speed (n_p), disk tool speed (n_d), number of balls on disk tool (N_b) and ball radius (r_b).

The experimental research carried out will take into account the initial roughness (R_{ai}) of the workpiece undergoing processing by mechanical shock [7]. The parameter constant during the experiment was piece diameter; the used diameter was Φ = 45 mm. Smoothing process conditions are given in Table 1.

Table 1: *Synthesis of smoothing conditions*

Theoretical parameters	*Experimental parameters*	Part radius (mm)	5 – 30 *17,5*
		Part speed (rot/min)	16
		Disk tool speed (rot/min)	2890
		Number of balls on disk tool (mm)	16
		Ball radius (mm)	4
		Initial roughness (µm)	*2 – 4*

3. Results and discussion

The experimental study of the ball meaning process was made by using the device schematically presented in Fig. 2; the device was mounted on a universal lathe, instead of the tool holder. The disk tool had a diameter D_d of 200 mm; it presented a single balls row, the ball radius being r_b=8 mm.

In order to study and discuss the effect of the input parameters and to determine the theoretical models that express surface roughness near reality, were realized the construction from Figs. 5 – 8. These graphs show the effect of smoothing conditions in four different conditions in the cases of expression (6) and expression (13) considered over the workpiece surface. In this condition, four of the input parameters were constant, and varied only one.

The effect of *deforming ball diameter* on the variation of surface roughness, using theoretical models, can be appreciated from figure 5. In the case of first mathematical model (Eq. 6), as the deforming ball diameter increases, the surface roughness decreases.

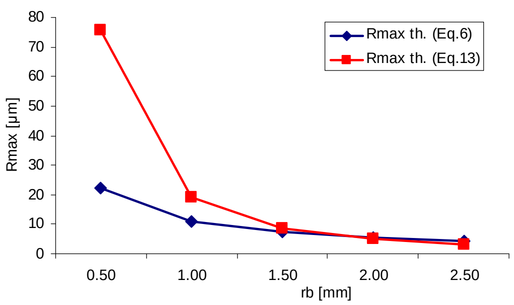

Figure 5: *Theoretical results of roughness surface expressed with theoretical models at different deforming ball diameter*

Figure 6 constitute the effect of the *part speed* on the theoretical surface roughness, in case of the mathematical models. With increases of part speed a good value for roughness surface is indicated by the Eq. 6. From the graph it is preferable to avoid smoothing at high part speed, because surface roughness increases.

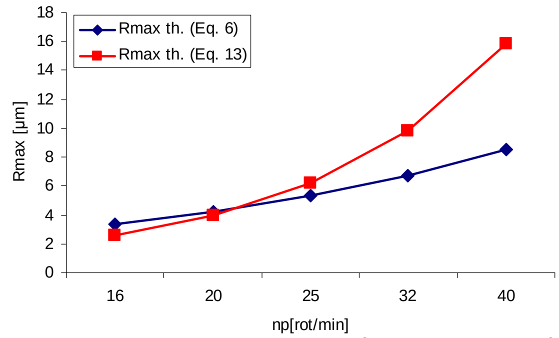

Figure 6: *Theoretical results of roughness surface expressed with theoretical models at different part speed*

Number of balls on disk tool represents an important smoothing parameter that affects the results of process. The increase of number of balls on disk tool will improve (decreases) the roughness surface. The shape of graph recommends using Eq. 13 from the theoretical models.

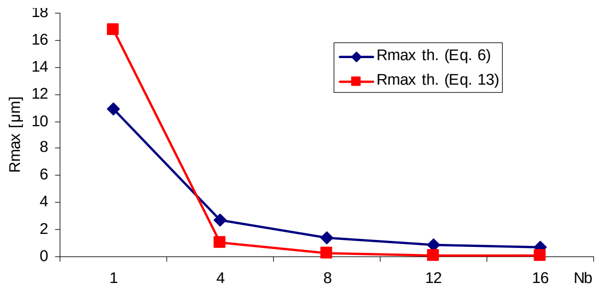

Figure 7: *Theoretical results of roughness surface expressed with theoretical models at different number of balls on disk tool*

Effect of workpiece diameter on the theoretical roughness is shown in Fig. 8. The graphics rendering is seen as a small roughness is obtained when is used the mathematical model 2 (Eq. 13). Also it is observed that lower values of surface roughness parameter, are obtained at different diameters of the part but maintaining a constant optimal value of the other input parameters in the process.

Mathematical models and experimental results (Fig. 8) were verified. Values obtained for a given situation confirms the practical approximation model 2 (Eq. 13).

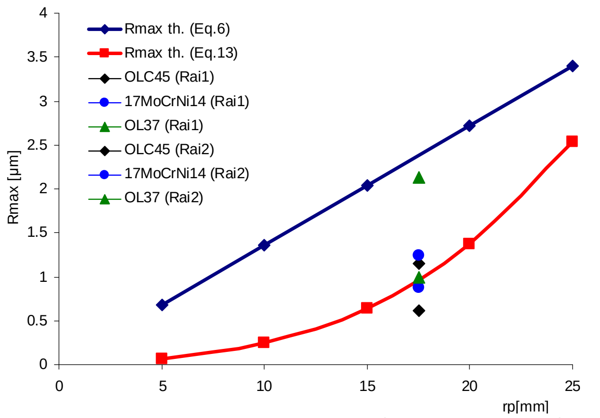

Figure 8: *Theoretical results of roughness surface expressed with theoretical models at different part radius; experimental points, resulted in same working conditions, on different materials.*

Deviations from theoretical values of the experimental results may have several causes:

- processed material behaves elastic plastic due to the phenomenon of hardening;
- as a result of the initial hypothesis, according to which was considered the circular contour footprint, occur deviations;
- due to superficial hardening phenomena, every shot is applied near the previous. That why the processed material by mechanical shocks it is partial hardened, fact that gives elastic plastic properties, which change in practice the initial assumptions made.
- practice values deviation in comparison with the theoretical values can be explained due to the fact that during the collision, the hard ball is deforming because it elasticity resulting a print that deviate from a spherical cap (as considered)

Taking into account the elements of the local strains theory for massive bodies collision is justified the reduced roughness values increasing parts diameter.

Some deviations from theoretical values are due to other factors of influence (initial surface roughness, longitudinal advance of the disk tool reporting to piece).

Also different values were obtained and variation due to plasticity of tested materials. Note that the processing of material with high plasticity (OL37), we obtain a higher roughness. More tenacious material (elastic plastic) with a higher content of perlite (OLC45, 17MoCrNi14) allows obtaining lower roughness.

4. Conclusions

The smoothing method presented in this paper is a processing way of the workpiece cylindrical surface which is based on the impact effects of the balls found under the action of the centrifugal force with the workpiece surface. Also as result of the smoothing by mechanical shocks, the workpiece surface layer is affected by a hardening process. Theoretical considerations were used to obtain different mathematical relations to characterize the superficial surface roughness of the work piece resulted after the impact phenomena. Some experimental researches were finalized to offer an image concerning the influence exerted by certain work conditions on the surface roughness parameter R_a. Because each encounter is repeated in the immediate vicinity of micro crater above is possible that by increasing the superficial surface layer micro hardness the plastic deformation approach to partially elastic deformation.

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