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ASPECTS REGARDING THE ROUGHNESS OF SURFACES OBTAINED BY LAPPING

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***Abstract**:*
The paper presents experimental research results obtained by plane surface lapping. The experiments were aimed at measuring the roughness of the lapped surfaces for several types of materials, in view of setting up a data base as complete as possible.
The paper presents in addition to the research results also the equipment employed for experimenting. The influence on surface roughness of various working factors (concentration of the abrasive paste, eccentricity, relative speed, duration of machining, working pressure) is discussed. Further the paper presents the mathematical models obtained by experimental data processing, and which describe lapped surface roughness for several types of materials.

***Keywords**: lapping, surface roughness*

Lapping is a procedure for surface smoothing by abrasive erosion, its main purposes being improving dimensional and geometric accuracy, chamfering of surface micro-asperities, correction of the reciprocal position of the geometric elements of the machined objects, as well as increasing the contact area of parts working as couples.

Due to the small volume of removed material, the cutting of part surfaces by lapping can be considered a particular case of abrasive wear. In practice this type of wear does not appear isolated, but is accompanied by wear due to adhesion, corrosion or fatigue, all depending on the specific factors of the working environment of the friction couple. For this reason the surface cutting mechanics by lapping needs to be analysed from a broader angle, including the numerous factors contributing to material removal.

The principle of surface lapping is shown in figure 1:

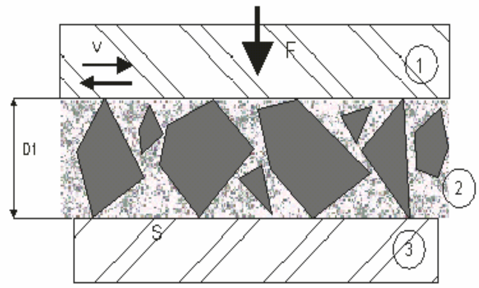

Fig. 1: *Principle of plane surface lapping*

The tooling allowance is removed by the relative motion between transfer object 1 and part 3 in the presence of the abrasive powder in suspension in a fluid 2. For erosion to take place a certain pressure generated by force F needs to intervene between part and tool.

While an older view of this process assumed that the grains are stuck into the transfer object (OT) and then move together with this cutting the part, more recent analyses of lapping mechanics show that material removal takes place by the rolling effect of the grain [3]. Thus the tips of the abrasive grains penetrate the part material and generate micro-cracks. Penetration depth depends on the applied working pressure.

By repeated penetration of grain tips into the surface of the part, in the case of ductile materials the superficial layer is deformed and removed upon reaching the fatigue limit.

In the case of breakable and hard materials cracks are generated at the part surface, which in time form a mesh and cause the tearing out of material particles.

The classical approaches to machining by lapping assume that the machined surface is a result of the tracks (scratches) left on the part by the abrasive grains. Thus figure 2 shows the cycloid trajectories of abrasive grain tips [4]:

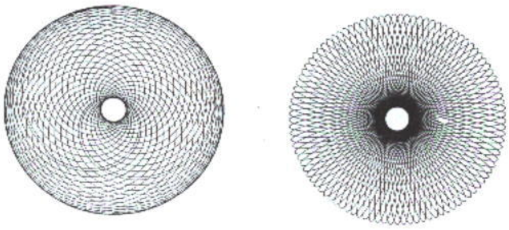

Fig. 2: *Trajectories of abrasive grains*

In accordance with this approach the state of the machined surfaces depends on the density of the characteristics scratches, which should be the great as possible in order to decrease surface roughness.

More recent studies based on electron microscope images state that the surface obtained by lapping is a result of all elementary craters determined by the penetration (indenting) of the abrasive grains into the material.

Figure 2 shows the electron microscope image of a lapped surface [3]:

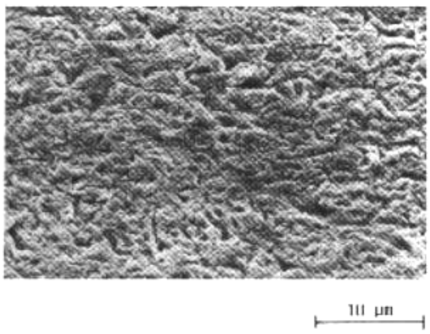

Fig. 3: *Characteristic aspect of a lapped surface*

The image of the surface structure does not reveal scratch type machining tracks, but rather a material removal mechanism based on the tearing out of small particles from the part. This process of material particle removal is facilitated by the prior cold hardening of the superficial layer, due to the permanent plastic deformation to which the part is subjected.

The elements of the friction couple in the case of surface lapping form a tribological system. This receives from the exterior input variables which are *controllable* or *non-controllable* (the so-called “noise factors”). The controlled input quantities are forces, velocities, speeds, pressures, energy, etc., as required by the cutting process. The uncontrolled input variables are undesired, parasite elements of the system, which however cannot be or are difficult or costly to eliminate. Such quantities can be vibrations, internal strain, structure defects, physical-chemical defects, etc.

The input variables are subjected within the tribological system to the transfer functions which turn them into output variables. These appear as effects, which can be useful or damaging. The main output quantities resulted from applying surface lapping are the quality of the superficial layer, roughness and machining productivity.

The paper presents experimental research results obtained by plane surface lapping. The experiments were aimed at determining the roughness of the lapped surface for most usual types of materials, in view of setting up a data base as complete as possible.

The evolution of part surface roughness depending on the controlled input variables can be studied by means of the equipment shown in figure 4 [1]:

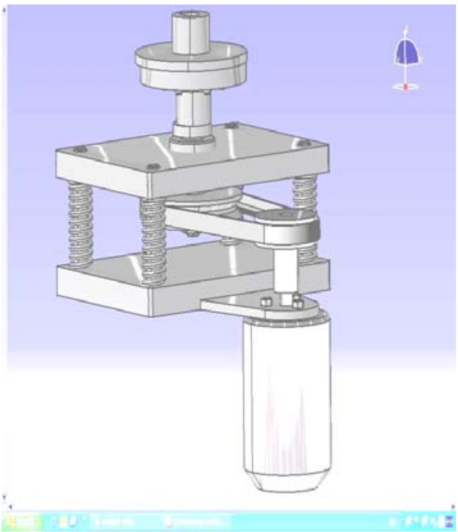

Fig. 4: *Lapping equipment*

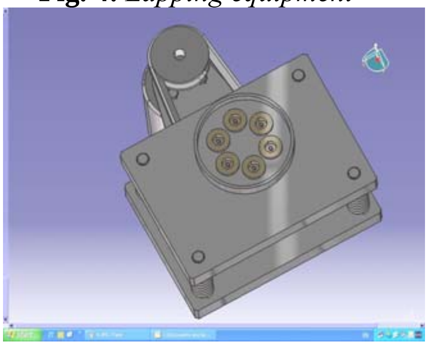

Fig. 4: *bis Lapping equipment*

The inferior plate of the lapping device is placed on the table of a milling machine and is fixed by means of a clip. The superior plate can slide along four cylindrical columns (pillars) and is maintained in its upper limit position by four springs. A rotating part-bearing plate is placed on this superior plate. Its seats accommodate up to six parts which can be machined simultaneously. The part-bearing plate can be positioned eccentrically in relation to the rotation axis of the device, the eccentricity being adjustable between 0 and 6 mm.

The working pressure is achieved by lifting the milling machine table together with the entire lapping device. Thus, after achieving contact of the lapping disk and the machined parts, the helical springs are compressed yielding a continuously adjustable working pressure, depending on the deformation of the springs.

The lapping disk is rotated by the vertical main shaft of the milling machine. The rotation speeds achievable by the lapping disk are those given by the milling machine gearbox; experimental research has used the three smallest values: 63 rot/min, 100 rot/min and 125 rot/min.

The part-bearing plate also rotates, in the same or opposite sense to the lapping disk. This rotation is generated by a dc motor, by means of a V-belt transmission. The rotation speed of the part-bearing plate can be adjusted continuously in the range of 0 … 1400 rpm, by means of adjusting the feed voltage in the range 0 … 30 V.

Research included the lapping of several material categories, the input parameters (eccentricity of the part-bearing plate, concentration of the abrasive paste, lapping disk speed, working pressure, duration of machining) being adjusted to various values.

In order to obtain relevant results while simultaneously taking into consideration all combinations of adjusted parameter levels and minimising time and cost of research, experiments were designed by method of Dr. G. Taguchi; having established the number of adjusted levels for each controlled parameter/factor, Taguchi indicates a fractional factorial array for the experiments to be carried out.

According to the used method, five working parameters were tested simultaneously, four of which being adjustable to two levels and one to three levels. A full factorial array of experiments would require an unacceptably high number of $2^4 \cdot 3^1 = 48$ runs, in order to combine each adjusted level of each factor with every other adjusted level of all other factors. For this reason fractional factorial arrays are used, reducing the number of runs to 8, hence saving considerable time and cost dedicated to experimenting.

The experimental results were processed in order to establish equations describing the dependence between output and input quantities of the system, thus formulating the links between causes and effects. The coefficients of the equations of the mathematical models were determined by applying the method of regression. Such calculations are typically complex and require homogeneity of data as well as a large as possible number of measurements.

The objective of modelling is identifying a relationship of dependence between the roughness R_a of the machined surface and the following input parameters: eccentricity of the part-bearing plate (e), concentration of the abrasive paste (C), relative velocity (*vr*), working pressure (*p*) and duration of machining (*t*), that is a relationship of type: $R_a = f(e, C, vr, p, t)$ or :

$$R_a = K_R \cdot e^{xR} \cdot C^{yR} \cdot v_r^{zR} \cdot p^{uR} \cdot t^{vR}$$

Following logarithmation the equation becomes:

$$lgR_a = lgK_R + xR \cdot lge + yR \cdot lgC + zR \cdot lg(v_r) + uR \cdot lgp + vR \cdot lgt$$

The coefficients K_R, *xR, yR, zR, uR* and *vR* were determined by using MathCAD programme, that is by applying the *lsolve(A, b)* function for the numerical solving of linear system of equations.

The equations for computing machined surface roughness for the six tested materials are [2]:

- for **40Cr10** :
$R_a = 0.029 \cdot e^{0.294} \cdot C^{-0.49} \cdot vr^{0.619} \cdot p^{-2.012} \cdot t^{-0.624}$
- for **OL37** :
$R_a = 0.0051 \cdot e^{0.267} \cdot C^{-0.64} \cdot vr^{0.528} \cdot p^{-0.686} \cdot t^{-0.067}$
- for **38MoCr09** :
$R_a = 0.158 \cdot e^{0.051} \cdot C^{-0.817} \cdot vr^{0.387} \cdot p^{-2.439} \cdot t^{-1.799}$
- for **OLC45**:
$R_a = 0.222 \cdot e^{0.023} \cdot C^{-0.465} \cdot vr^{0.218} \cdot p^{-1.581} \cdot t^{-1.144}$
- for **50WCr11**:
$R_a = 0.05 \cdot e^{0.075} \cdot C^{-0.905} \cdot vr^{0.805} \cdot p^{-2.291} \cdot t^{-2.201}$
- for **18MoCr10**:
$R_a = 0.009 \cdot e^{0.208} \cdot C^{-0.865} \cdot vr^{0.533} \cdot p^{-0.343} \cdot t^{-0.943}$

The variation curves of R_a were plotted based on the above equations [2]:

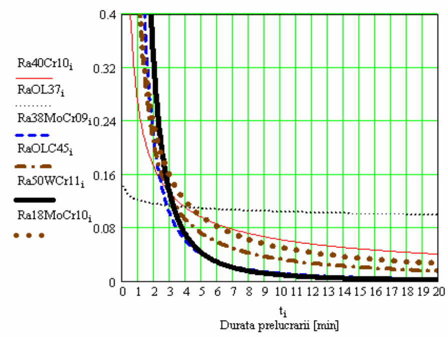

Fig. 5: R_a *= f(duration of machining)*

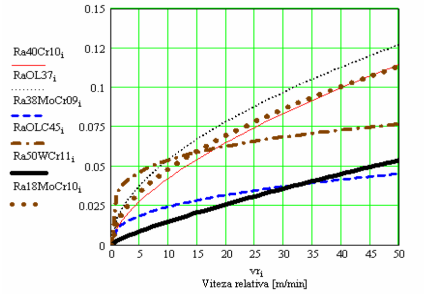

Fig. 6: R_a *= f(relative velocity)*

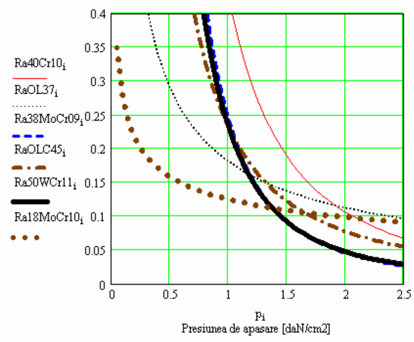

Fig. 7: R_a *= f(working pressure)*

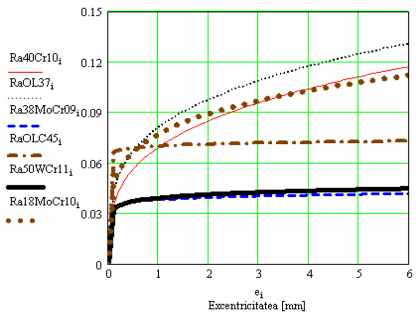

Fig. 8: R_a *= f(eccentricity)*

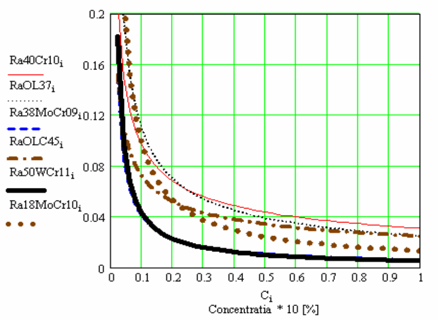

Fig. 9: R_a *= f(concentration of the abrasive paste)*

The above graphs show that the roughness of the machined surfaces has the following tendencies:

- a descending tendency as duration of machining, working pressure and concentration, respectively, have higher values;

- an increasing tendency as the relative velocity and eccentricity are greater.

Explanations of this behaviour of the roughness are:

The influence of the *duration of machining* of the lapped surface can be explained by the fact that with time, more and more tips of asperities are smoothed. The graphs show that while the decrease of roughness is accelerated in the interval of the total machining time, towards the end of machining time the slope of the curve is lesser.

In the first moments of lapping the volume of removed materials is smaller, as only the tips of the asperities remaining from the previous machining operation are cut. Although the quantity of removed material is small, the height of the cut layer is large, this causing a rapid decrease of roughness. As the abrasive grains penetrate deeper into the material, the quantity of removed material decreases, while the roughness does not record significant modifications of its value. The time related variation of lapped surface quality can be studied in figure 10 below:

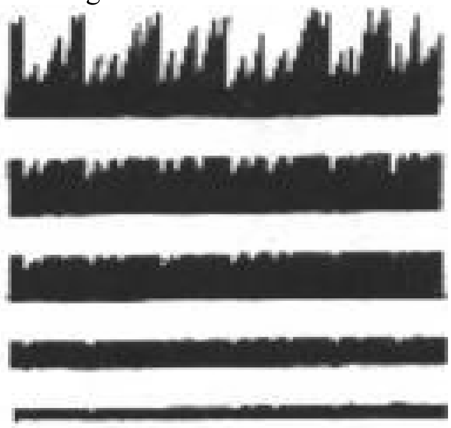

Fig. 10: Asperity height vs. time

The relative velocity has an inverse influence on roughness. As the algebraic sum of the lapping disk and part-bearing plate speeds increases, the resulting roughness will be greater. A possible explanation is that, at high relative speeds, the actual contact time of a grain with an asperity of the lapped surface (which has to bee chamfered in order to improve R_a) is too short to allow the generation of a contact tension capable of achieving chamfering by material flow. Due to high relative speed the grain is rapidly transported to another point of the lapped surface, hence the contact of the grain with the respective asperity ceases before chamfering is achieved, thus being inefficient. For this reason small relative speeds are recommended in surface lapping, particularly for obtaining very small values of surface roughness.

Working pressure has an influence similar to the one of the duration of machining. The greater the pressure, the deeper the grains penetrate into the machined part, chamfer the surface more intensely and yield a smaller surface roughness. It is known that machined surface quality is improved also by the rolling effect of the abrasive grains. Depending on working pressure the tips of the abrasive grains penetrate part material on a certain depth and generate roundings of the part surface. An analysis of surface profile diagrams plotted before and after lapping shows that the tips of the asperities remaining from previous machining are rounded, thus ensuring a better R_a.

For the considered interval (0 … 6 mm) the influence of the *eccentricity* of the part-bearing plate on roughness is nearly linear. The higher the eccentricity, the worse the obtained surface quality is. An initial leap of roughness can be noticed, after which its variation becomes insignificant. However, eccentricity is an important parameter required in lapping, in order to generate hypocycloid and not concentric trajectories of the abrasive grains. Thus a better intersection of the trajectories is achieved and a preferential direction on the machined surface is avoided, a direction by which R_a would have a minimum value. The presence of an eccentricity assures a homogenous roughness by any direction on the lapped surface. Further more, the presence of an eccentricity enhances machining productivity.

According to the graphs, the greater the *concentration* of the abrasive in the lapping paste, the better the obtained surface roughness will be. A sudden decrease of roughness can be noticed for 0 … 5% concentration, after which roughness has only a slightly decreasing tendency. Although better roughness values could be obtained for higher concentrations, this should be limited to 10 … 15%, as for higher values the wear of the lapping disk becomes significant.

The obtained values were used for setting up a data base, appealed by a technological processor. This is a useful tool for technology designers, providing information related to optimised plane surface lapping.

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