

Improving the Quality of Surfaces Finished by Lapping by Robust Parameter Design

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Abstract—Obtaining special quality surfaces as well as higher dimensional and geometrical precision entails deployment of surface smoothing processes, one of which is lapping. A lapping process is strongly influenced by a number of input parameters, the most important ones being machining speed, pressure, duration of lap plate – abrasive paste – workpiece contact, kinematics of the machine-tool etc. The paper presents a study on the influence of machining speed in lapping on the roughness of metal surfaces.

Index Terms—Lapping, machining speed, robust design, roughness.

I. INTRODUCTION

One of the elements defining product quality is the degree of finishing of workpiece surfaces. For this reason special emphasis needs to be placed on the study of surface smoothing processes, given their decisive role in determining high dimensional and geometric precisions.

One of the most widespread surface smoothing processes is lapping. Lapping operates by abrasive erosion, the tooling allowance being removed by means of grains located at the transfer object (lap plate) and workpiece interface. Lapping falls into the category of cutting processes deploying tools with undefined cutting edges. It is a final processing method where the abrasive grains are freely dispersed in a holding fluid, while cutting is conducted typically by a form transmitting counter-part known as transfer object. Fig. 1 presents the principle of surface lapping.

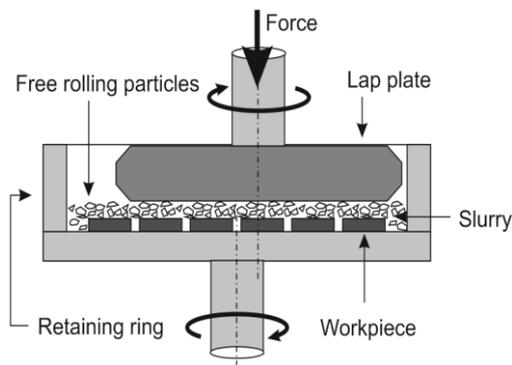


Fig. 1. Principle of lapping.

The tooling allowance is removed by inducing a relative motion between the lap plate and the workpiece in the presence of slurry, consisting of abrasive powder in

suspension in a fluid. For erosion to take place, a certain pressure generated by a downward oriented force is required between the lap plate and the workpieces.

Compared to other surface machining processes, lapping stands out by a number of characteristics:

- 1) Highest requirements related to planeness and roughness can be satisfied;
- 2) The reduced heat quantity developed during machining influences the structure of the superficial layer only to a small;
- 3) Lapped surfaces retain minimal stress and are burr-free;
- 4) Most workpieces can be machined without special clamping devices;
- 5) Several parts can be machined simultaneously.

Lapping processes are strongly influenced by numerous input parameters, the most important ones being machining speed, pressure, duration of lap plate – abrasive paste – workpiece contact, kinematics of the machine-tool etc.

Lapping speed is one of the working parameters with particular impact on obtaining small roughness surfaces with a superficial layer as little as possible affected thermally. Compared to other machining processes, lapping involves smaller speeds, between 20 and 150 m/min. The smaller speed values of this range (20 ... 40 m/min) are used for finishing, while the greater ones are applicable for preliminary lapping. Excessive increase of the machining speed causes an overheating of the processed surface and a diminishing of its quality [1].

Experiments confirmed that machining productivity increases with speed. This increase in productivity is however not unlimited, as with growing lap plate speed the centrifugal forces reach values that cause the abrasive slurry to be evacuated from the working area. Too high cutting speeds further affect the planeness of the machined surface, as a consequence of uneven distribution of the lapping paste in the working gap [2].

The paper presents further an analysis of lapped surface roughness variation versus machining speed.

II. WORKING EQUIPMENT

Experimental research was conducted on a specially developed device adapted to FUS 22 milling machine. Testing concerned plane lapping of workpieces made from various categories of materials (heat treated by cementing and annealing, respectively). The surface roughness (R_a) was measured, of workpieces made from: 18MoCr10, 38MoCr09 and 50WCr11.

Fig. 2 presents the schematic and a view of the lapping device [3].

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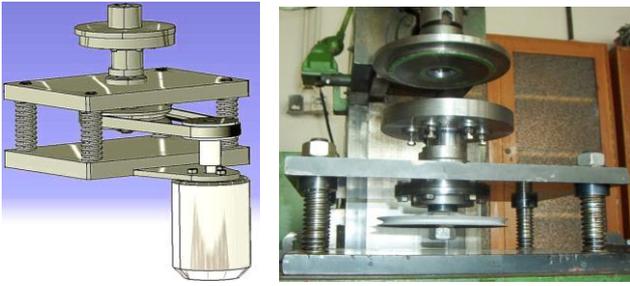


Fig. 2. Schematic and view of the device.

The inferior plate of the lapping device is clamped to the machine table by means of brackets. The upper plate can glide along four cylindrical pillars and is maintained in its superior limit position by four springs. On this upper plate a rotating retaining ring is mounted, with seats that can ensure the simultaneous machining of up to six workpieces. The retaining ring can be positioned with an eccentricity adjustable between 0 and 6 mm in relation to the rotation axis of the device shaft.

The working pressure is achieved by lifting of the machine table together with the entire lapping device. Thus, upon achieving contact between the lap plate and the workpieces the helical springs are compressed and a continuously adjustable pressure is obtained, depending on the deformation of the springs.

The lap disk is set into rotation from the vertical main shaft of the milling machine. The possible speeds of the lap disks are determined by the gearbox of the milling machine. The speeds used in the discussed research were of 63 rpm and 100 rpm.

The retaining ring bearing the workpieces also carries out a rotation, in the same or opposite direction to the lap disk, being driven by a d.c. motor via a V- belt. The speed of the retaining ring can be continuously adjusted in the range of 0 ... 1400 rpm, by adjusting the feed voltage between 0 and 30 V.

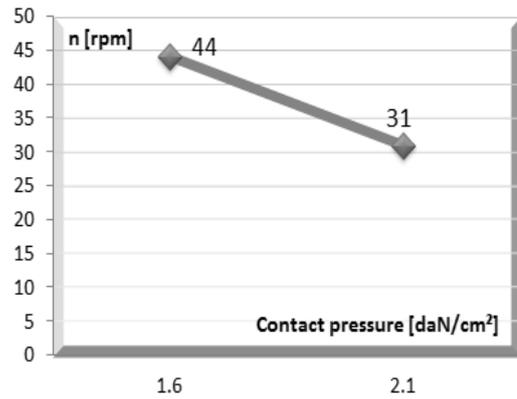


Fig. 3. Mechanical characteristic of the d.c. motor

TABLE I: RELATIVE SPEEDS USED FOR PLANE LAPPING

Working pressure [daN/cm ²]	Lap disk speed \curvearrowright [rpm]	Retaining ring speed \curvearrowright [rpm]	Relative speed \rightleftarrows [m/min]
1.6	63	44	30.23
	100		40.69
2.1	63	31	26.56
	100		37.3

Fig. 3 presents the mechanical characteristic of the motor driving the retaining ring ($U = 5.5$ V). Based on this characteristic the relative machining speed can be calculated, that is the relative speed of lap disk and workpieces. Table I features the relative speeds calculated with a known display radius of the workpieces in the retaining ring ($r = 45$ mm) for opposite rotation directions of lap disk and retaining ring.

III. ROBUST PARAMETER DESIGN OF THE MACHINING SYSTEM

The method of robust parameter design proved useful in many types of machining, and has been applied, as discussed further on, for the study of plane surface lapping. The aim of this study is to investigate systematically the effects of different lapping parameters on the roughness of the machined surface.

TABLE II: SELECTED FACTORS AND SET POINTS

Set point	Factors				
	A Eccentricity [mm]	B Abrasive concentration [%]	C Speed of lap disk [rpm]	D Contact pressure [bar]	E Duration of machining [min]
1	6	5	100	2.1	4
2	3	10	63	1.6	3
3	-	-	-	-	5

Optimisation of the lapping process was achieved by the method of fractioned orthogonal factorial arrays of experiments devised by G. Taguchi. It is Taguchi's merit to have provided a strategy that, instead of identifying and eliminating noise factors affecting the operation of the machining system, aims at minimizing their impact. Concretely, the strategy consists in identifying those combinations of input parameter set points that will reduce the effects of noises, without however, addressing these directly.

For this, five factors were selected from the numerous

input quantities that affect the lapping process, namely those factors whose contribution to the machining process is considered as major [4], [5]. Table II presents these factors, with the 2 or 3 set points considered for each of these. Factor selection was made also according to the principle that each of these needs to allow all associations of its tested set points with those retained for the other factors.

Experiments were conducted according to an array providing 8 runs, each representing a different combination of input factor set points. Table III presents the array underlying the conducted research. Next to the set point

number of each factor the corresponding value is indicated between brackets.

TABLE III: UTILIZED ARRAY OF EXPERIMENTS

Run	Factors				
	A	B	C	D	E
1	1 (6)	1 (5)	1 (100)	1 (2.1)	1 (4)
2	1 (6)	1 (5)	2 (63)	2 (1.6)	2 (3)
3	1 (6)	2 (10)	1 (100)	2 (1.6)	3 (5)
4	1 (6)	2 (10)	2 (63)	1 (2.1)	1 (4)
5	2 (3)	2 (10)	1 (100)	2 (1.6)	1 (4)
6	2 (3)	2 (10)	2 (63)	1 (2.1)	2 (3)
7	2 (3)	1 (5)	1 (100)	1 (2.1)	3 (5)
8	2 (3)	1 (5)	2 (63)	2 (1.6)	1 (4)

TABLE IV: OPTIMUM COMBINATION OF FACTOR SET POINTS

Factor	Description	Optimum set point	Value of optimum set point
Material: 18MoCr10, 38MoCr09 and 50WCr11			
A	Eccentricity	2	3 mm
B	Abrasive concentration	2	10 %
C	Speed of lap disk	1	100 rpm
D	Contact pressure	1	2.1 bar
E	Duration of machining	3	5 min

This orthogonal is derived from the standard L8 (2^4+4^1) one proposed by Taguchi, which has been modified such as to consider for factor E set point 1 as being the most important.

A line of the response table corresponds to each of the 8 runs of the array (each with a different combination of input factor set points).

The data sets obtained upon experimenting were processed by LappMaster software developed by the authors, yielding the optimum set points of the tested controlled factors (Table IV).

By setting the five factors to the thus determined optimum values, roughness R_a is expected to be of $0.081 \mu\text{m}$ for 18MoCr10 steel, of $0.041 \mu\text{m}$ for 38MoCr09 steel, and of $0.042 \mu\text{m}$ for 50WCr11 steel, respectively. These values render the lapping process robust, i.e. insensitive to noise factors.

IV. MATHEMATICAL MODELLING OF THE OBTAINED RESULTS

Further research was aimed at establishing a mathematical relationship describing the dependency of lapped surface roughness on the five input quantities of the machining system. An equation of form (1) is proposed:

$$R_a = K_R \cdot ec^{xR} \cdot C^{yR} \cdot v_r^{zR} \cdot p^{uR} \cdot t^{vR} \quad (1)$$

where ec = eccentricity of the retaining ring, C = abrasive concentration, v_r = relative speed, p = pressure and t = machining time. As can be noticed, in the above equation the *relative speed* (v_r) [m/min] factor has replaced the *lap disk speed*. This substitution was required in order to simultaneously consider both lap disk speed and the speed of the retaining ring bearing the workpieces. In experiments the *relative speed* factor was set at 37.3 m/min.

The coefficients and exponents in equation (1) were determined by regression. Formulae (2) – (4) were eventually

determined for computing the roughness of the three tested materials:

- for 18MoCr10:

$$R_a = 0.009 \cdot ec^{0.208} \cdot C^{-0.865} \cdot v_r^{0.533} \cdot p^{-0.343} \cdot t^{-0.943} \quad (2)$$

- for 38MoCr09:

$$R_a = 0.158 \cdot ec^{0.051} \cdot C^{-0.817} \cdot v_r^{0.387} \cdot p^{-2.439} \cdot t^{-1.799} \quad (3)$$

- for 50WCr11:

$$R_a = 0.05 \cdot ec^{0.075} \cdot C^{-0.905} \cdot v_r^{0.805} \cdot p^{-2.291} \cdot t^{-2.201} \quad (4)$$

Fig. 4 shows the diagrams describing machined surface roughness versus relative speed, plotted for a configuration of the input quantities as provided by Table IV.

This Fig. reveals that surface roughness increases with relative speed. The higher the algebraic sum of lap disk and retaining ring speeds is, the higher the obtained roughness will be. An explanation is, that at high relative speeds the effective contact time of an abrasive grain with an asperity of the lapped surface (that needs to be flattened in order to improve R_a) is too short in order to allow generation of a contact tension capable of flattening by causing material flow. Because of the high relative speed the grain is transported to another point of the lapped surface and the contact of the grain with any asperity ceases before flattening occurs, being thus rendered inefficient. For this reason in surface lapping relative speeds are recommended to be small for targeted small roughness values.

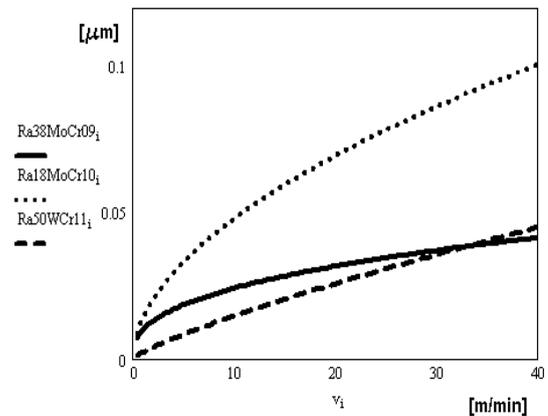


Fig. 4. Roughness vs. relative speed

TABLE V: INFLUENCE OF ROTATION DIRECTIONS ON ROUGHNESS

Working parameters	Set point values	
Eccentricity	3 mm	
Abrasive concentration	10%	
Relative speed	26.56 m/min	
Contact pressure	2.1 bar	
Duration of machining	5 min	
	Direction of rotation	
	↺ ↺	↻ ↻
Obtained roughness (R_a)	0.082	0.079

Another stage of experimental research concerned the study of a potential influence of lap disk and retaining ring rotation directions. For this the rotation direction of the lap

disk was maintained unchanged, while the retaining ring bearing the workpieces was rotated in the same and in opposite direction, in alternating experiments. Thus two sets of roughness values were measured, first for the two disks rotating in the same direction, and then for opposite directions. In both cases the relative speed was set at 26.56 m/min.

Tests concerning the influence of rotation direction on roughness were conducted on workpieces made from 18MoCr10 steel, the input parameters being set at the values given in Table V.

Upon experimenting the two measured values of roughness parameter R_a were very close, thus yielding the conclusion that the rotation directions of the two disks have no significant influence on the quality of lapping.

V. CONCLUSIONS

The paper discussed a study on the influence of machining speed on the quality of lapped surfaces. The method utilized for the optimisation of machining was robust parameter design, with the purpose of rendering the analysed system insensitive to the action of noise factors, by identifying an adequate combination of input factor set points.

Utilization of fractioned orthogonal factorial arrays of experiments lead to obtaining optimum values for the main system input quantities. The values measured by experimenting with these optimum settings of the input quantities, which ensure the robustness of machining system, allowed the plotting of roughness R_a versus machining speed variation diagrams.

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