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EXPERIMENTAL AND STATISTICAL PARAMETRIC OPTIMISATION OF SURFACE ROUGHNESS AND MACHINING PRODUCTIVITY BY LAPPING

Summary

The quality of surfaces machined by lapping depends on numerous variables, some of them controllable and others not. Their existence renders the task of selecting adequate working parameters and their values (set points) such as to obtain the desired response difficult. For this reason, this paper discusses the robust parameter design as an optimisation method for plane lapping. The paper presents the working equipment, the utilized methodology as well as the obtained experimental results. The output quantities selected for describing the lapped surface quality and the machining productivity, respectively, were roughness *Ra* and the height of the cut layer *h*.

Key words: *Lapping, robust design, roughness, height of the cut layer.*

1. Introduction

Lapping is a surface smoothing process based on abrasive erosion, where material is removed by means of grains located at the interface of the so-called transfer object and the machined workpiece. It falls into the category of cutting processes with geometrically undetermined tool edges [10]. The abrasive grains are dispersed in a holding fluid, and cutting is typically caused by a form-transmitting counter-part known as the transfer object [16].

The main purposes of lapping are: increasing the dimensional and the geometric accuracy, flattening of surface micro-asperities, correcting the relative position of the processed objects, and increasing the contact area of coupled parts. Lapping processes are used to produce dimensionally accurate specimens to high tolerances. The lap plate will rotate at a low speed (< 80 rpm) and a mid-range sized abrasive particle (5 - 20 μm) is typically used [3], [14].

There are two regimes of lapping: free abrasive lapping and fixed abrasive lapping [14]. This paper deals with the free abrasive lapping. Machining involves introducing an abrasive paste between the lap plate and the workpiece. It is the most accurate machining variant as it least affects the cut surface (heating and/or hardening of the surface layer). Figure 1 shows the principle of free abrasive lapping.

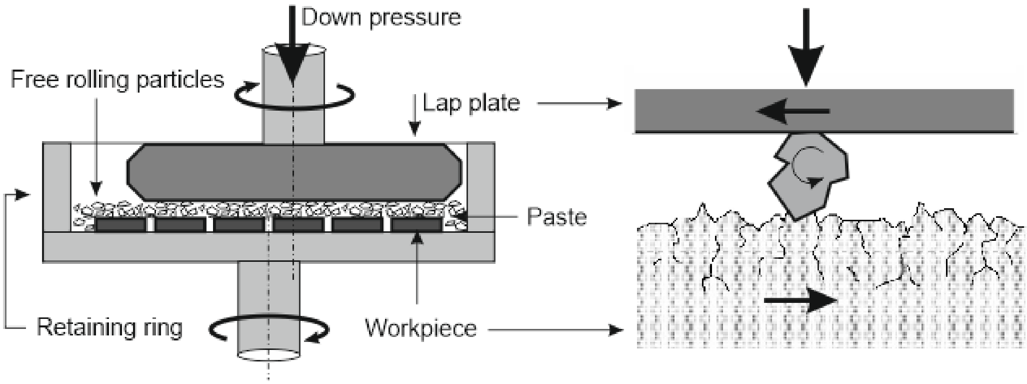

Fig. 1 Principle of free abrasive lapping

Slurry consisting of abrasive particles and a holding fluid is introduced in the gap between the lap plate and the workpiece. The abrasive suspension is fed into the gap continuously or intermittently; the purpose of such circulation of the fluid is to continuously allow fresh, unused particles to come into contact with the workpiece and to remove the resulting chips. Thus, this machining process does not deploy a classic cutting tool. The tool is generated during the machining process by the abrasive grains in suspensions [6], [7].

One of the analyses of the mechanics of lapping processes shows that material removal is caused by the rolling effect of grains [10]. The relative motion generated between the workpiece and the lap plate will cause the abrasive grains at the interface between these two components of the system to roll and thus to pit the surfaces and dislodge miniature chips from the material.

In the case of ductile materials, by repeated penetration of grain tips into the workpiece surface, the surface layer is deformed beyond its fatigue limit and removed [9]. In such materials, the sizes of surface cavities created on the surface by pitting are significantly smaller than the size of any abrasive particle, i.e. they are in the range between 2 - 5% of the volume of an abrasive grain.

In the case of brittle and hard materials, micro-cracks develop on the surface and their growth causes removal of material [15]. Cracks are deeper in this case, of magnitude comparable to that of an abrasive grain. The existence of such cracks allows, in certain conditions, a temporary immobilization of the abrasive grains in the workpiece and the lap plate.

Recent studies, based on images acquired by scanning with electron microscopes, have shown that the surface obtained by lapping is the result of all elementary pits caused by the penetration of abrasive grains into the material [4], [10].

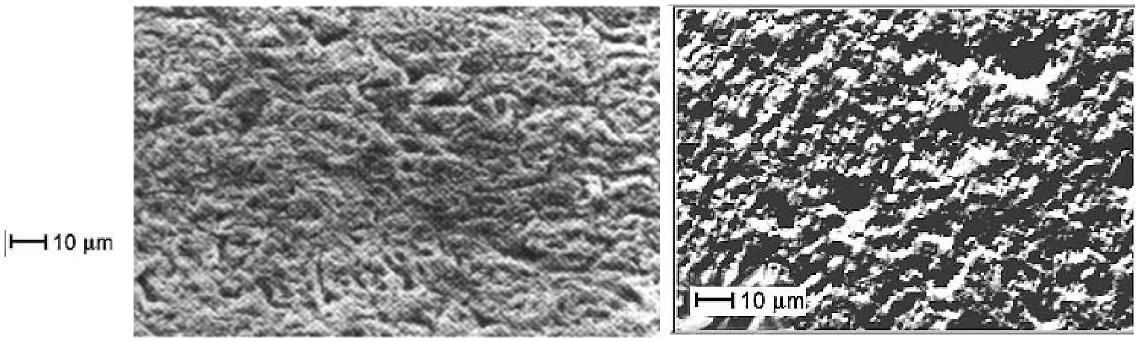

Fig. 2 Views of the surfaces machined by lapping

2. The workpiece – lap plate tribosystem

Due to the small volume of removed material, surface cutting by lapping can be considered as a special case of abrasive wear. In practice, this type of wear does not occur by itself; it is also accompanied by adhesive wear, corrosion wear, or fatigue, all of which depend on the specific factors of the environment in which the friction couple is functioning [2], [8]. For this reason, the mechanics of surface cutting by lapping calls for an analysis from a wider perspective, considering the interdependence of the numerous factors that contribute to the removal of the material.

In surface lapping, the elements of the friction couple form a tribosystem. The tribosystem and its components are presented in Figure 3.

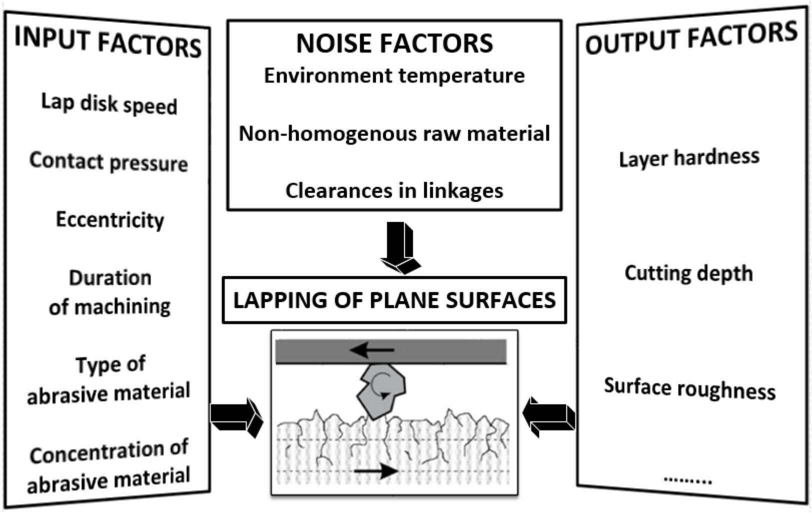

Fig. 3 Tribosystem of plane lapping

The tribosystem consists of four elements: the lap disk, the workpiece, the medium separating completely or partially the two semi-couples, and the immediate environment.

The first two elements are the main components of the tribosystem as they form the friction couple. The two semi-couples are characterized by parameters like hardness, surface roughness, type of material, state of the surface layer, etc. The third element of the tribosystem is the separating medium, which in the case of lapping is the abrasive paste. The fourth element is the environment hosting the relative motion of the elements.

The input quantities of the tribosystem are of two categories: controllable and uncontrollable (noise) factors. The first category includes working pressures and speeds, abrasive type and graining, characteristics of the work equipment, duration of machining, etc. The category of uncontrollable quantities includes, inter alia, vibrations occurring in the system, internal stress, environmental temperature, clearances in the work equipment, etc. The quantities of this latter category while undesired, cannot, however, be eliminated.

The input quantities are transformed by the system into output quantities, which appear as either useful or harmful effects. It is evidently desirable for the useful effects to be predominant at the output of the system. In the case of lapping, the aim is efficient material removal in the form of chips while obtaining the best possible surface quality.

The harmful effects are mainly represented by the heat generated through friction. A consequence of friction is energy dissipation by a heat flow, the magnitude of which depends on the type of the friction couple, the thermo-physical properties of the materials, the dimensions and geometry of the semi-couples, and the cutting parameters.

Most non-conformities occurring upon the completion of a manufacturing process are a consequence of inefficient noise management. Noises appear individually, as surprises during a manufacturing process, have costly effects, and lead to improvised solutions. Such problems can be avoided by the robust parameter design, that is, by a by-passing technique of the noise-generating causes during a manufacturing process.

The existence of numerous variables at the input of a tribosystem makes the task of selecting adequate working parameters and their values (set points) such as to obtain the desired response difficult. The use of theoretical optimisation models is not possible as lapping is a very complicated and random process, affected by numerous variables and factors of the process and the environment. Thus, experimental approaches are needed to analyse the lapping process. It is the merit of G. Taguchi to have provided a strategy aimed at minimizing the impact of noise factors instead of identifying and eliminating them [1]. Concretely, the strategy consists of identifying those set points of the system input parameters that reduce the effects of parasite causes, without, however, addressing these causes directly [13].

In Taguchi's vision, after having experimentally identified the optimum set points to be assigned to the controlled variables at the system input, the response obtained at the output will satisfy the desired functional performance; thus, the system is made robust, that is, insensitive to noise factors (Figure 4).

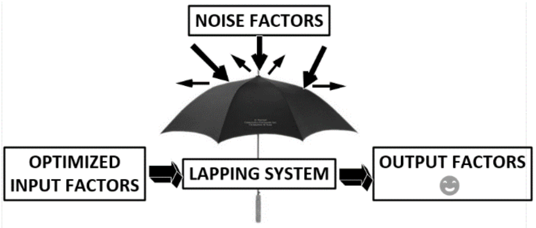

Fig. 4 Representation of a robust lapping system

The method selected for the discussed study is robust parameter design, which has proved successful in the case of many types of machining. The aim of the study is to investigate systematically the effects of different lapping parameters on the roughness of machined surfaces and on the height of the removed material layer by means of novel eccentric lapping equipment.

3. Experimental set-up

3.1 Machine

The experimental study on the robust optimisation of the plane lapping process was conducted by means of specially designed equipment, adaptable to a milling machine. Figure 5 shows the principle and a view of this equipment [5].

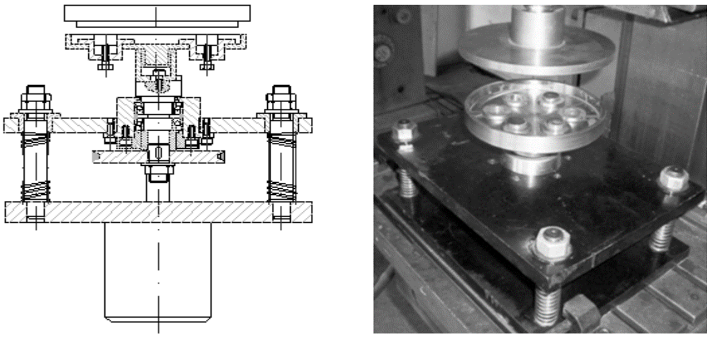

Fig. 5 Schematic and a photograph of the eccentric lapping equipment

The schematic of the machining system shows the displacement of the lap disk axis in relation to the axis of the part-bearing plate; the thus obtained eccentricity can be adjusted in a range of 0-6 mm. Eccentricity is adjusted by displacing the part-bearing plate in relation to its rotational axis. Up to six workpieces can be placed in the seats of the rotating part-bearing plate and machined simultaneously.

By lifting the milling machine table, the lap disk and the workpieces come into contact, the springs of the device are compressed and thus the pressure needed for machining is generated. The magnitude of this pressure is continuously adjusted, depending on the deformation of the springs.

The lap disk is turned via the main shaft of the milling machine, while the part-bearing plate is rotated in the same or the opposite direction by a DC motor.

The main parameters that contribute to achieving the purposes of lapping are: the rotational speed of the lap disk, the rotational speed of the eccentric plate, the contact pressure, the eccentricity. In addition, the concentration of the abrasive in the lapping paste, the type of the utilized abrasive, and the duration of machining are as important parameters as those listed previously. All the parameters listed above are input quantities of the system, each having different set points.

The roughness of the machined surfaces, the height of the removed material layer and the hardness of the surface layer represent the output quantities of the system, their values depending on the input parameters and the influence of various disturbing factors.

Considering the numerous input and output parameters characterizing a surface lapping process, its optimisation will be addressed by *robust parameter design*.

3.2 Procedure

The experimental research on plane surface lapping was conducted on workpieces made from various materials. The tested workpieces were made from OLC45, 18MoCr10 and 40Cr10.

The abrasive paste used in experiments is a mixture of green silicon carbide micropowder and mineral oil. The abrasive micrograins are symbolized F800, which corresponds to a mean dimension of 6.5 μm. The utilized mineral oil is symbolised H38.

The roughness of the machined surfaces (Ra) was measured by means of a Dektak 6M Profiler, and the height of the removed material layer (h) was determined by means of a Carl Zeiss orthotest device. The height of each part was measured before and after machining, and the height of the removed material layer was determined as the difference between the two measurement results.

Preparation of the experiments included the following steps:

- cutting of the test pieces, followed by their simultaneous grinding on both plane surfaces;
- cleaning, degreasing, and drying of the test pieces;
- roughness (Ra) and height measurement of each piece, prior to machining by lapping;
- placing of six test pieces, all made from the same material, in the seats of the part-bearing plate;
- adjustment of the vertical position of each test piece in its seat so that the frontal surfaces are in the same plane;
- conducting the experiments.

The steps are repeated for the three types of tested materials.

The data sets obtained by experimenting were processed by LappMaster, a software application developed by the authors, which yielded the optimum set points of the tested controlled factors. The mathematical modelling of the experimental results allowed determining the coefficients of the equations that describe the evolution of the roughness and of the height of the removed material layer versus the variation of the system input quantities.

4. Experimental design

Optimisation of the lapping process was conducted by the method of orthogonal fractional factorial arrays of experiments, developed by G. Taguchi. For this, five factors with major contributions were selected from the multitude of input quantities affecting the lapping process. The larger the number of tested input parameters is, the greater are the chances of correctly identifying the factors that decisively influence the analysed manufacturing process. On the other hand, however, including more factors into the analysis delays the decision making process because of the increased number of tests to be run.

Table 1 shows the five considered factors, each of which can assume two or three set points during experimenting.

Table 1 Selected factors and set points

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

The factors were selected such as to satisfy the principle that each of them needs to allow the association of their tested values with those considered for the other factors.

The experiments were conducted according to an array of experiments with 8 runs (Table 2). In brackets, next to the set point number of each factor, the actual value of this set point is indicated.

Table 2 L_8 modified orthogonal array

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)

This orthogonal array is derived from the standard one, L_8 (2^4+4^1) used in Taguchi's method; the modification refers to factor E, for which the set point ***1*** is the most important.

The array of experiments provides 8 different runs, each entailing a different combination of input factor set points. A line of the response table corresponds to each run.

For a certain material, in each run provided by the orthogonal array (Table 2, above), six identical test pieces were machined simultaneously. After lapping, roughness and height of the removed material layer were determined for each of the six test pieces. The arithmetic mean of the six measured values of the roughness *Ra* is recorded in the column Test1 of Table 3, and the arithmetic mean of the six determined values of the height of the removed material layer is recorded in the column Test1 of Table 4.

In order to ensure a higher degree of confidence of the experimental results, each run was repeated by the above methodology four more times; the corresponding results were recorded in the columns Test2 to Test5 of Tables 3 and 4.

The last three columns of Tables 3 and 4 contain, for each run, the computed arithmetic mean ($\bar{y}$) of the values recorded in the columns Test 1 to Test 5, then the standard deviation (s) and the signal-to-noise ratio (S/N).

Table 3 Experimental data obtained by measurement of roughness

	Material: OLC45							
Run	Test 1	Test 2	Test 3	Test 4	Test 5	$\bar{y}$	s	S/N
1	0.129	0.124	0.132	0.131	0.133	0.1299	0.0036	17.72448
2	0.271	0.267	0.261	0.263	0.265	0.2654	0.0038	11.52109
3	0.110	0.116	0.114	0.118	0.112	0.1140	0.0032	18.85848
4	0.097	0.086	0.090	0.093	0.089	0.0910	0.0042	20.80993
5	0.153	0.136	0.132	0.148	0.156	0.1450	0.0105	16.74993
6	0.119	0.119	0.120	0.121	0.120	0.1198	0.0008	18.43067
7	0.081	0.098	0.101	0.113	0.103	0.0992	0.0116	20.01078
8	0.185	0.179	0.191	0.179	0.180	0.1828	0.0052	14.75696
	Material: 18MoCr10							
1	0.254	0.253	0.254	0.252	0.250	0.2526	0.0017	11.95114
2	0.327	0.323	0.330	0.326	0.324	0.3260	0.0027	9.73535
3	0.130	0.134	0.131	0.129	0.124	0.1296	0.0036	17.74455
4	0.118	0.110	0.109	0.115	0.119	0.1142	0.0045	18.83994
5	0.141	0.140	0.140	0.135	0.135	0.1382	0.0029	17.18793
6	0.134	0.130	0.140	0.124	0.134	0.1324	0.0059	17.55362
7	0.173	0.183	0.169	0.179	0.182	0.1772	0.0060	15.02575
8	0.215	0.221	0.223	0.216	0.217	0.2184	0.0034	13.21389
	Material: 40Cr10							
1	0.188	0.186	0.186	0.183	0.187	0.1860	0.0019	14.60929
2	0.337	0.345	0.335	0.332	0.333	0.3364	0.0052	9.461843
3	0.212	0.208	0.210	0.207	0.213	0.210	0.0025	13.55500
4	0.106	0.115	0.103	0.109	0.107	0.1080	0.0045	19.32399
5	0.192	0.200	0.198	0.198	0.197	0.1970	0.0030	14.10967
6	0.098	0.105	0.103	0.101	0.102	0.1018	0.0026	19.84221
7	0.116	0.144	0.123	0.136	0.141	0.1320	0.0120	17.55278
8	0.233	0.241	0.240	0.235	0.240	0.2378	0.0036	12.47477

Table 4 Experimental data obtained by measuring the height of the removed material layer

	Material: OLC45							
Run	Test 1	Test 2	Test 3	Test 4	Test 5	$\bar{y}$	s	S/N
1	9.2	9.1	9.3	8.9	9	9.1	0.1581	19.17690
2	5.3	5.2	5.2	5.5	5.3	5.3	0.1224	14.47857
3	9.5	9.4	9.4	9.1	9.1	9.3	0.1870	19.36439
4	8.1	7.9	7.9	8.1	8	8	0.1000	18.05976
5	7.6	7.4	7.4	7.4	7.7	7.5	0.1414	17.49660
6	6.4	6.2	6.2	6.3	6.4	6.3	0.1000	15.98353
7	8.8	8.9	8.6	8.6	8.6	8.7	0.1414	18.78694
8	6	5.9	5.9	6.1	6.1	6	0.1000	15.55941
	Material: 18MoCr10							
1	11.8	11.5	11.6	11.8	11.8	11.7	0.1414	21.36181
2	6.9	6.8	6.7	7	7.1	6.9	0.1581	16.77015
3	11.8	11.6	11.9	11.9	11.8	11.8	0.1224	21.43624
4	10.1	9.9	9.9	9.9	10.2	10	0.1414	19.99740
5	9.9	9.9	9.8	9.8	10.1	9.9	0.1224	19.91071
6	8.2	8.5	8.2	8	8.1	8.2	0.1870	18.26950
7	11.6	11.3	11.4	11.6	11.6	11.5	0.1414	21.21199
8	7	6.8	6.8	6.9	7	6.9	0.1000	16.77425
	Material: 40Cr10							
1	11.2	10.9	11.4	11.4	11.1	11.2	0.2121	20.97969
2	5.8	6	6.6	6.3	6.3	6.2	0.3082	15.81575
3	11.8	11.1	11.3	11.2	11.6	11.4	0.2915	21.12958
4	10.6	10.7	11.1	10.2	10.4	10.6	0.3391	20.49280
5	10.2	10.1	9.7	9.9	10.1	10	0.2000	19.99479
6	8.9	9.2	9.3	8.9	9.2	9.1	0.1870	19.17532
7	11.1	11.7	11.1	11.3	11.3	11.3	0.2449	21.05545
8	7.8	7.6	7.5	8.1	8	7.8	0.2549	17.82799

The *signal-to-noise ratio S/N* is the performance indicator of a production process, considering both the target value of the analysed quality criterion and its variability around the target. The desired value is defined as the signal ($\bar{y}$ = the arithmetic mean of the measured values), while its undesired variability (s = standard deviation) is defined as the noise.

Equations (1) and (2) provide the computational relationships of the signal-to-noise ratio for those quality characteristics that, in order to be optimum, need to tend towards a minimum or a maximum, as is the case of the roughness and the height of the removed material layer, respectively.

$$S/N_m = -10 \cdot \log(s^2 + \bar{y}^2) \qquad [\mathrm{dB}] \tag{1}$$

$$S/N_M = -10 \cdot \log\left[\frac{1}{\bar{y}^2} \cdot \left(1 + 3 \cdot \frac{s^2}{\bar{y}^2}\right)\right] \qquad [\mathrm{dB}] \tag{2}$$

5. Evaluation and analysis of the data

S/N responses were computed based on the experimental results, as well as the mean effects generated by each set point of the studied factors. The mean S/N response for each factor set point corresponds to the arithmetic mean of the signal-to-noise ratios of all runs including the same set point of that factor. The mean S/N effect of each factor set point is computed as the difference between the mean S/N response of that set point and the general arithmetic mean of the signal-to-noise ratios for all conducted runs.

Based on the principle that a higher algebraic value of the signal-to-noise factor yields a better performance of the production process, the optimum set point for each analysed factor can be determined. Thus, those set points of the considered factors that have the highest algebraic value of the signal-to-noise factor will be selected. Table 5 presents the optimum set points for the analysed factors, based on the results computed above.

Table 5 The optimum combination of factor levels

Factor	Factor description	Optimum level	Set point of optimum level
	Roughness of machined material		
	Material: OLC45 and 18MoCr10		
A	Eccentricity of disk	2	3 mm
B	Abrasive concentration	2	10 %
C	Speed of lapping disk	1	100 rpm
D	Contact pressure	1	2.1 bar
E	Duration of machining	3	5 min
	Material: 40Cr10		
A	Eccentricity of disk	2	3 mm
B	Abrasive concentration	2	10 %
C	Speed of lapping disk	2	63 rpm
D	Contact pressure	1	2.1 bar
E	Duration of machining	3	5 min
Height of machined material layer			
	All materials		
A	Eccentricity of disk	1	6 mm
B	Abrasive concentration	2	10 %
C	Speed of lapping disk	1	100 rpm
D	Contact pressure	1	2.1 bar
E	Duration of machining	3	5 min

In the case of roughness, Table 5 shows that for two of the materials the resulting combination of factor levels is the same, while for the material 40Cr10, only the level of factor C is different (the speed of the lapping disk). The different value of the speed of the lapping disk for the material 40Cr10 is caused by the fact that this material undergoes a heat treatment (hardening + annealing at high temperature) which allows the generation of sorbite, a softer and more malleable structural constituent. Under these circumstances, the speed of the lapping disk has to be smaller.

In the case of the height of the material layer removed by lapping, Table 5 shows that the obtained combination of optimum levels is the same for all machined materials.

The results shown in Table 6 were obtained by setting the factors at these optimum levels and associated set points. These values ensure a robust lapping process, insensitive to the noise factors.

Table 6 The values obtained by running an optimized robust process

Material	Roughness		Height of lapped layer	
	Ra / µm	S/N / dB	*H* / µm	S/N / dB
OLC45	0.019	23.78	11.28	21.82
18MoCr10	0.048	20.66	14.85	24.44
40Cr10	0.051	20.90	14.20	23.87

6. Mathematical modelling of the obtained results

The next stage in analysing the lapping process of flat surfaces consists in establishing the dependency of the surface roughness and of the height of the removed material layer on the input quantities of the system.

Based on all the measured results (given in Tables 3 and 4), the aim of modelling is to identify relationships describing the dependency of the roughness *Ra* and of the height of the removed material layer *h* on the following input parameters: the eccentricity of the part-bearing plate (*ec*), the concentration of the abrasive (*C*), the relative speed (*vr)*, the pressure (*p*) and the duration of machining (*t*), that is, the relationships of the type *Ra = f(ec, C, vr, p, t)* and *h = f(ec, C, vr, p, t)*, respectively:

$$Ra = K_R \cdot ec^{xR} \cdot C^{yR} \cdot v_r^{zR} \cdot p^{uR} \cdot t^{vR} \tag{3}$$

$$h = K_h \cdot ec^{xh} \cdot C^{yh} \cdot v_r^{zh} \cdot p^{uh} \cdot t^{vh} \tag{4}$$

In logarithmic form these equations become:

$$\mathrm{lgRa} = \mathrm{lgK_R} + \mathrm{xR \cdot lgec} + \mathrm{yR \cdot lgC} + \mathrm{zR \cdot lg(vr)} + \mathrm{uR \cdot lgp} + \mathrm{vR \cdot lgt} \tag{5}$$

$$\mathrm{lgh} = \mathrm{lgKh} + \mathrm{xh \cdot lgec} + \mathrm{yh \cdot lgC} + \mathrm{zh \cdot lg(vr)} + \mathrm{uh \cdot lgp} + \mathrm{vh \cdot lgt} \tag{6}$$

In the above equations the relative speed (*vr*) [m/min] between the lapping plate and the part-bearing plate has replaced the speed of the lap disk. This substitution was required out of the necessity of considering the rotational speed of the lap disk as well as the rotational speed of the eccentric plate. As the positioning radius of the test pieces on the part-bearing plate is known, the relative speeds were determined for the two considered pressures combined with the two directions of rotation. The thus obtained four values are: 37.3 m/min, 30.23 m/min, 40.69 m/min, and 26.81 m/min.

The coefficients KR, xR, yR, zR, uR, vR, and Kh, xh, yh, zh, uh, vh, were determined in the *MathCad* software by means of the function *lsolve(A, b)*, used for finding numerical solutions of systems of linear equations. In each column, matrix *A* contains the values of the coefficients of the six terms of the right hand side of the above equations, and *b* is the column vector that represents the free term. The computational relationships for the two quantities of interest (*Ra* and *h*), obtained for the three materials are:

- for OLC45:

$$Ra = 0.222 \cdot ec^{0.023} \cdot C^{-0.465} \cdot v_r^{0.218} p^{-1.581} \cdot t^{-1.144} \tag{7}$$

$$h = 0.181 \cdot ec^{0.188} \cdot C^{0.195} \cdot v_r^{0.804} \cdot p^{0.988} \cdot t^{0.376} \tag{8}$$

- for18MoCr10:

$$Ra = 0.009 \cdot ec^{0.208} \cdot C^{-0.865} \cdot v_r^{0.533} p^{-0.343} \cdot t^{-0.943} \tag{9}$$

$$h = 0.234 \cdot ec^{0.141} \cdot C^{0.166} \cdot v_r^{0.818} \cdot p^{0.945} \cdot t^{0.356} \tag{10}$$

- for 40Cr10:

$$Ra = 0.029 \cdot ec^{0.294} \cdot C^{-0.49} \cdot v_r^{0.619} p^{-2.012} \cdot t^{-0.624} \tag{11}$$

$$h = 0.332 \cdot ec^{0.088} \cdot C^{0.305} \cdot v_r^{0.809} \cdot p^{1.228} \cdot t^{0.314} \tag{12}$$

The variation diagrams of the roughness *Ra* and of the height of the removed material layer *h* were plotted using the fixed input values that ensure the robustness of the machining system (Table 5).

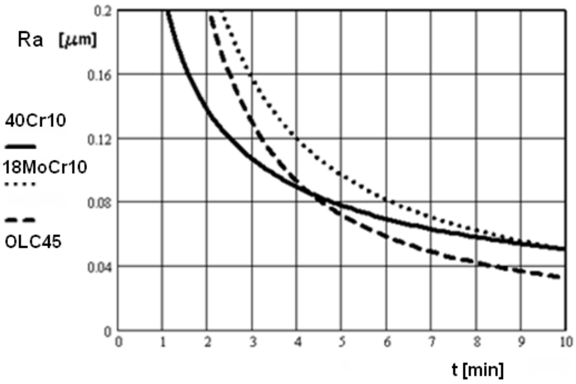

Fig. 6 *Ra* vs. the duration of machining

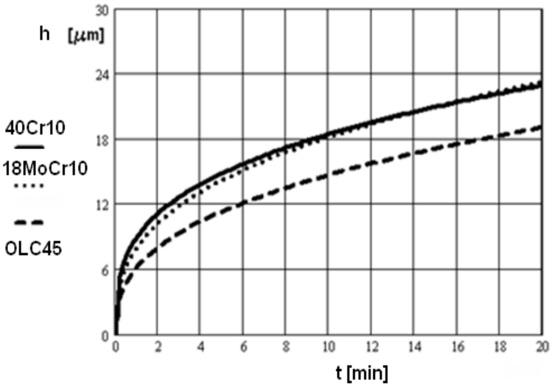

Fig. 7 *h* vs. the duration of machining

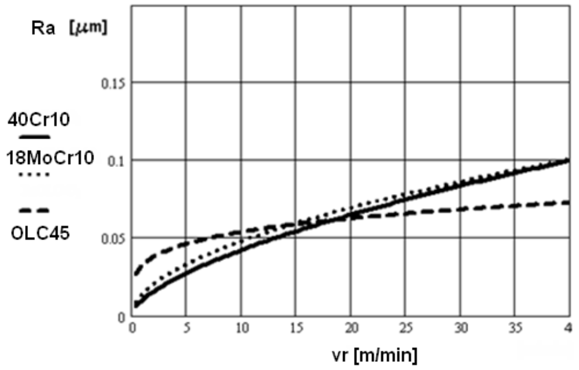

Fig. 8 *Ra* vs. the relative velocity

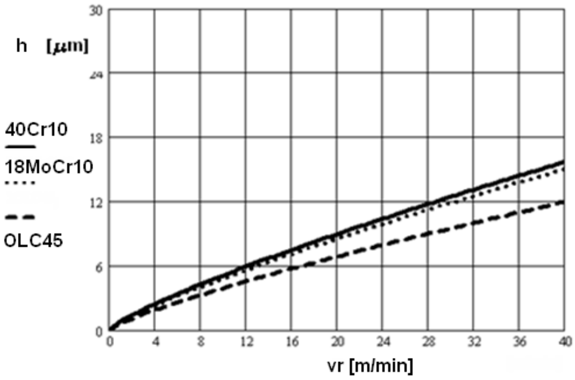

Fig. 9 *h* vs. the relative velocity

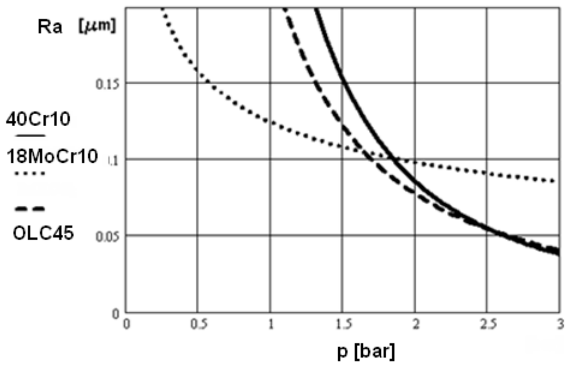

Fig. 10 *Ra* vs. the contact pressure

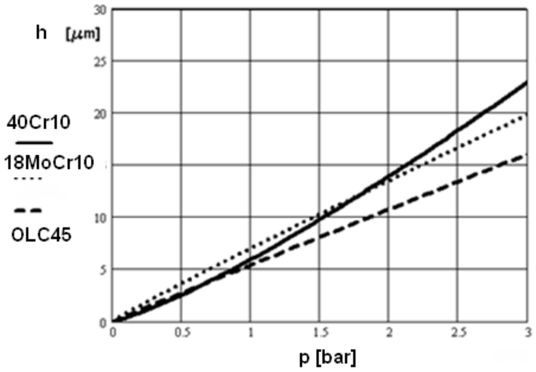

Fig. 11 *h* vs. the contact pressure

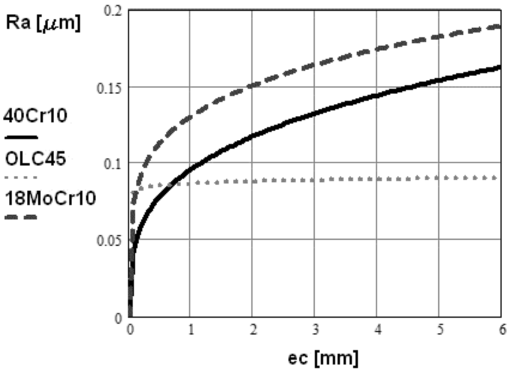

Fig. 12 *Ra* vs. the eccentricity of disk

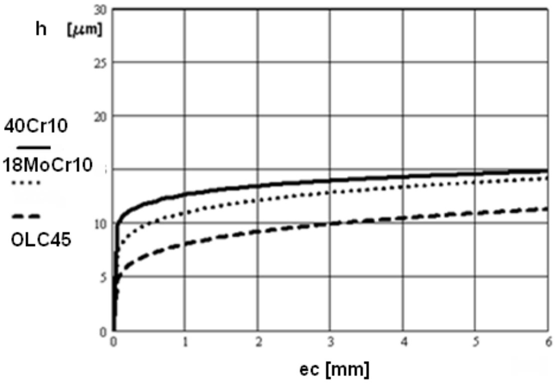

Fig. 13 *h* vs. the eccentricity of disk

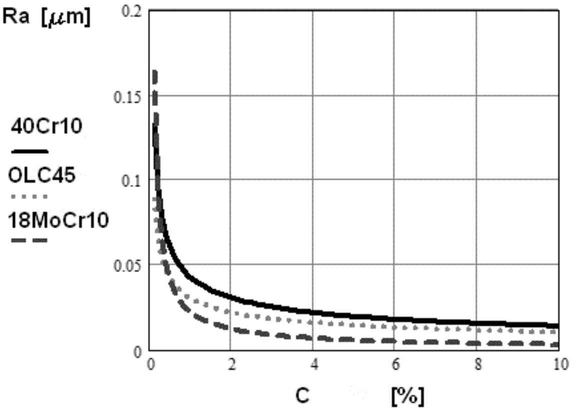

Fig. 14 *Ra* vs. the concentration of the abrasive

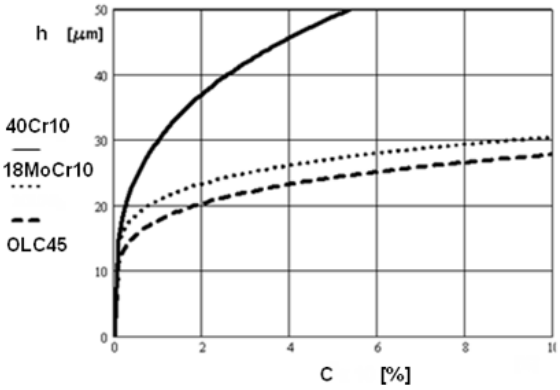

Fig. 15 *h* vs. the concentration of the abrasive

7. Discussion of the results

The influence of the duration of machining on the roughness of the lapped surface (Figure 6) can be explained by the fact that, in time, an increasing number of asperity tips are smoothed. The graphs show that the value of the surface roughness decreases at a higher rate during the first part of machining, while towards the end, the curve is less steep.

During the first moments of lapping, the volume of the removed material (Figure 7) is smaller as only the tips of the asperities that have remained from the previous operation are cut. Although the volume of the removed material is small, the height of the cut layer is great, which causes the roughness value to decrease rapidly. As the cutting advances deeper into the material, while the quantity of the removed material increases progressively, no significant modifications to the roughness occur.

Figure 8 shows that the surface roughness increases with the relative speed. The higher the algebraic sum of the lap disk and the part-bearing plate speeds is, the greater the resulting roughness will be. An explanation is that at high relative speeds, the actual contact time of a grain with an asperity of the lapped surface (to be flattened in order to improve *Ra*) is too short to allow the generation of contact stress capable of causing flattening by the material flow. Because of the high relative speed, the grain is transported to another point of the lapped surface, and thus its contact with any one asperity ceases before flattening occurs, rendering the contact inefficient. For this reason, relative speeds in surface lapping are recommended to be small in order to obtain small values of the surface roughness.

As to the height of the removed material layer, this varies approximately linearly with the relative speed (Figure 9). The obtained results are in agreement with the Preston equation of wear that states that the volumetric removal rate ($\dot{h}$) on a workpiece, due to the relative motion between surfaces, is proportional to the contact pressure (p) and the relative velocity (v) [11], [12].

$$\dot{h} = C \cdot p \cdot v \tag{13}$$

The influence of the contact pressure is similar to that of the duration of machining. Thus, the higher the pressure is, the deeper the abrasive grains will penetrate into the workpiece and will flatten the surface more intensively, yielding a smaller roughness (Figure 10). It is known that the surface quality is improved also by the rolling effect of abrasive grains. The tips of the abrasive grains penetrate the material to a depth depending on the working pressure and cause rounding of the surface.

Figure 11 shows an almost linear increase in the height of the removed material layer with increasing pressure for all tested materials. The explanation for this behaviour is the same as in the case of relative speed, provided by the Preston equation of wear.

Regarding the influence of the part-bearing plate eccentricity on the roughness, Figure 12 shows that for the studied range (0-6 mm), this parameter does not affect the machining quality in any significant way. Only a slight increase in the values of roughness is recorded with increasing eccentricity.

In relation to the height of the removed material layer, the eccentricity of the part-bearing plate has a major influence only when ranging between 0 and 0.3 mm, within which span the value of parameter h makes an abrupt leap (Figure 13). Beyond this range, the height of the cut layer is influenced by the eccentricity only to an insignificant degree. In conclusion, it can be said that the eccentricity of the part-bearing plate does not influence the two studied output quantities significantly. The eccentricity, however, cannot be eliminated, as it is the factor that generates the cycloid trajectories of the abrasive grains, which ensure a uniform surface roughness in any direction.

According to the graphs in Figures 14 and 15, increased concentrations of the abrasive material in the lapping paste ensure a better surface roughness and a higher productivity of machining. A significant reduction in the roughness values can be noted for concentrations ranging between 0 and 10%, after which the roughness does not further evolve in a significant manner. Theoretically, a smaller roughness should be obtained by increasing the concentration of the abrasive material in the paste. Practically, however, the concentration must be limited to 10-15% because higher values would cause accelerated wear of the lap disk.

8. Conclusion

The paper presents a study into a tribosystem for plane surface lapping; the method utilized for optimising the lapping process is robust parameter design. The aim of this approach is to render the analysed system insensitive to the action of the noise factors by identifying an adequate combination of the input factor set points.

By using the method of orthogonal fractional factorial arrays of experiments developed by G. Taguchi, five factors were selected, each having two or three possible set points. Upon assigning each factor the set point provided by Taguchi's orthogonal array and subsequent conducting of experiments, a combination of optimum set points of the analysed factors was obtained as a result.

The input quantities were assigned the optimum set points that were determined such as to render the process robust. Upon subsequent experimenting, the variation diagrams of the roughness *Ra* and of the removed material layer height *h* were plotted. Their analysis allowed the determination of the tendencies of the machined surface roughness as follows:

- the roughness has a decreasing tendency as the duration of machining, the working pressure, and the concentration of the abrasive paste increase;
- the roughness has an increasing tendency with increasing the relative velocity, while the eccentricity has only a negligible impact on the roughness of the lapped surface.

In relation to the height of the lapped material layer, it could be stated that it tends to increase with higher values of all input parameters.

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