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OPTIMIZATION OF THE LAPPING PROCESS OF PARTS MADE FROM X2 CrNiMo 17-12-2 STAINLESS STEEL

Summary

Austenitic stainless steel with nickel and molybdenum content (X2 CrNiMo 17-12-2) is frequently used in the food, chemical, or nuclear industries, as well as in medical applications like endourology. Due to the high content of nickel and molybdenum in these steels, their machinability is difficult; however, the surface finishing by lapping of parts made from X2 CrNiMo 17-12-2 steel remains an issue to be addressed. The paper investigates the possibility of obtaining the smallest possible surface roughness based on the selection of an optimum combination of the main parameters that influence machining. The optimization of the machining system could be achieved by changing the setpoints of the four selected input factors (lap disk eccentricity, concentration of the abrasive paste, contact pressure, and duration of machining). Response surface methodology was applied to determine the combination of factor values that ensures the minimum roughness of the machined surface.

Key words: *lapping equipment, austenitic stainless steel, surface roughness, response surface methodology*

1. Introduction

Stainless steels are high-alloyed materials with a chromium content of over 10.5% and are in demand mainly for their special property of high corrosion resistance. This property is due to the thin layer of chromium oxide (Cr_2O_3) that forms on the surface of parts in the presence of water or atmospheric oxygen. In addition, chromium stainless steels are also alloyed with nickel, molybdenum, silicon, or titanium, the elements that improve the mechanical properties and corrosion resistance of the steels [1]. According to their chemical composition, the main three types of stainless steels are austenitic, ferritic, and martensitic steels. Austenitic steels contain chromium (about 18%) and also nickel, which increases their corrosion resistance. Their carbon content is below 0.15%. Ferritic steels have a low carbon content (< 0.05%) and a high content of chromium (13-17%). Martensitic steels contain 12% chromium and a medium level of carbon (1%).

Austenitic steels represent about 70% of the production of stainless steels and are the materials most widely used in industry [2]. The main fields of application are the chemical, petrochemical, aircraft, textile, food, photographic, and papermaking industries. Other fields of application are the automotive and energy industries, fixings and bolts, pharmaceuticals, and hydraulics and couplings [3, 4].

Due to the bio-tolerance of these steels, they are used in medical applications specific to endourology, like guide wires, that are thus not affected by the chemicals contained in the urinary system fluids [5].

The surface quality of stainless-steel components is of paramount importance in the nuclear industry for the manufacturing, for example, of high-pressure stop and check valves [6] or in hydraulics for stainless steel cryogenic globe valves [7]. The seat rings of these valves are made from stainless steel and require finishing by lapping so as to reach a roughness level that ensures optimum sealing.

The machinability of austenitic stainless steels has been studied by researchers in the field, and a number of machining technologies that ensure an optimum in terms of either material removal productivity or surface quality have been identified. The main technologies include milling, turning, drilling, grinding, and abrasive jet cutting. Further on, the authors present some of the most significant published results in relation to surface generation and the quality of austenitic stainless steels.

Equbal et al. [8] investigated the CNC milling performance of AISI 316 stainless steel using a carbide cutting tool insert. The study concerns the effect of cutting speed, feed speed, and depth of cut on the removal rate and surface quality and puts forward recommendations for the optimum selection of input quantity values. Li et al. [9] studied tool wear and surface topology and optimized the cutting parameters for machining parts made from AISI 304 steel. The response surface method (RSM) was utilized to optimize cutting parameters in view of optimizing the surface roughness. Messinese et al. [10] studied the influence of cold-finished surface roughness on the corrosion resistance of various types of stainless steels. It was demonstrated that the grinding of cold-drawn bars improves corrosion resistance.

Del Risco-Alfonso et al. [11] presented the optimization of cutting parameters in turning AISI 316L steel for biomedical purposes. Dependencies were identified of the main cutting force and the surface roughness on the cutting parameters in turning AI-SI 316L steels. Deaconescu et al. [12] studied the cutting of X2 CrNiMo 17-12-2 stainless steel bars by abrasive waterjet machining (AWJM). The research was aimed at obtaining the smallest possible surface roughness values using an optimum combination of the machining system input factor values (traverse speed, waterjet pressure, stand-off distance, and grit size). Response surface methodology (RSM) was used as an optimization tool. Akkurt et al. [13] studied the machining of 304 stainless steels by AWJM. They found that a low traverse rate resulted in decreased roughness only in the case of thin workpiece material (5 mm), whereas for workpiece thickness of 20 mm and above, the surface roughness increased.

Surface finishing of parts made from austenitic stainless steels can be conducted by various technologies, such as grinding, burnishing, lapping, honing, and shot peening [14]. Following such procedures, improvements in surface quality, roughness, and residual stress are obtained. *The Fabricator* journal [15] includes information on the requirements to be met for the grinding of stainless steels. Thus, wheels with zirconia grains grind faster than those with aluminium oxide, but in most cases, a ceramic grinding wheel works best. Another requirement relates to the power of the grinding machine. This has to be sufficiently large so as not to allow a decrease in the ping disk speed once it cuts into the machined material. In relation to the possibility of grinding the stainless steels, Mellowpine [16] states that the high chromium content of stainless steels leads to the formation of chromium oxide, which is harder than the aluminium oxide on the abrasive wheel, causing excessive wheel wear. The grinding ratio (the amount of material removed per unit of wheel wear) is, in the case of stainless steels, significantly smaller than that of steels in general. This ratio ranges from 6 to 12 for stainless steels, while for ordinary steels it varies between 40 and 80.

Torres et al. [17] highlight the influence of stainless-steel microstructure on tribological behaviour and surface integrity after ball burnishing. Research results have shown that the improvement in the integrity of burnished component surfaces is determined by the interaction between the ball and the part, which is quantifiable by means of the friction coefficient. The same finishing process, i.e., the ball burnishing carried out on stainless steels, was also studied in [18]. The authors report the results of research conducted in relation to the fatigue durability of AISI 304 and AISI 316L austenitic stainless steels and put forward some analysis models.

Lapping is yet another machining method for stainless steels that entails rubbing two surfaces together by means of an interface that is an abrasive film. This technology differs from grinding by the absence of a rigid tool, i.e., the abrasive disk used in grinding. In lapping, the cumulative action of a very large number of abrasive grains suspended in a carrier fluid performs the cutting. The abrasive fluid ensures the cooling and evacuation of the material chips that result from machining. Kemet International [19] presents a case study on stainless steel lapping. The roughness *Ra* obtained by deploying a copper disk and a diamond slurry was 0.025 μm. Pratheesh Kumar et al. [20] present the effects of different process parameters on the material removal rate and the roughness of the machined surfaces. The experiments revealed that a diminished concentration of the abrasive yields a decrease in surface roughness and a slight increase in the material removal rate. In the lapping of 304 stainless steel, Jianxiu Su et al. [21] studied the effects of several input factors, such as pressure, rotation speed, lapping time, and abrasive grain size, on the roughness of the machined surfaces and the material removal rate (MRR). For certain combinations of the input parameter values, *Ra* roughness values as small as 41 nm were obtained.

The reviewed literature points to the fact that austenitic stainless steels are generally more difficult to machine than ferritic or carbon steels due to their nickel content. Some of the challenges identified in relation to the machining of austenitic stainless steels are high cutting forces, heat generation, edge buildup, and notch wear. The high cutting forces, together with the low heat conductivity of steel, cause the hardening of the machined surfaces [22]. Such challenges can be met by using large flows of cooling fluid combined with low depths of cut and low feed speeds.

Lapping of austenitic stainless steels with a high nickel content was less often studied, most likely due to the difficulties encountered in the cutting of such steels. Within this context, this paper presents an experimental study on the cutting performance of the lapping of austenitic stainless steel X2 CrNiMo 17-12-2. The focus of our research is the influence of four parameters, i.e., lap disk eccentricity, concentration of abrasive, contact pressure, and duration of machining, on the surface finish of austenitic steel. The significance of these four factors resulted from our previous research published in [23]. Response surface methodology (RSM) was used to analyse the collected experimental data. RSM proved to be a faster technique for identifying an optimization solution for the studied machining process. Section 2.1 of the paper presents the properties of the studied steel and the specifics of the deployed lapping equipment. Section 2.2 discusses the working parameters with the greatest impact on the machining process. Section 3 describes the applied method and discusses the obtained results. The paper closes with a section of conclusions.

2. Materials and methods

2.1 Materials and lapping equipment

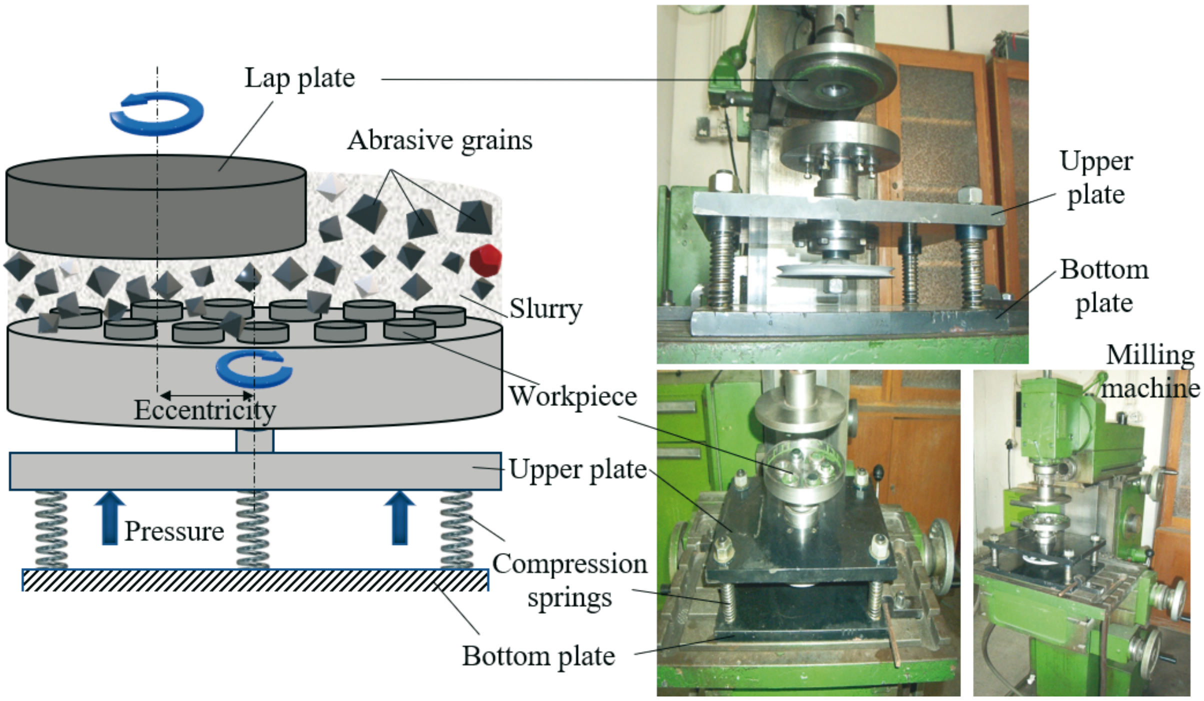
The research discussed in this paper was aimed at studying the influence of various input factors of the lapping process on the roughness of the finished surfaces. The investigated material was austenitic stainless steel X2 CrNiMo 17-12-2 (equivalent to 316L -AISI Standard). Due to its reduced content of molybdenum, X2 CrNiMo 17-12-2 steel exhibits very good resistance to high temperatures and corrosion. Hence, its frequent use in the food and nuclear industries. Its main disadvantage, however, is that it is the most difficult to machine amongst all other typically utilized stainless steels.

According to the EN 10088-1:2014 standard, the chemical composition of X2 CrNiMo 17-12-2 austenitic steel is as shown in Table 1 [24]:

Table 1 Chemical composition of X2 CrNiMo 17-12-2 austenitic steel

C	Si	Mn	P	S	Cr	Mo	Ni	N
% by mass								
0.03	1	2	0.045	0.015	16.5…18.5	2…2.5	10…13	0.1

Solid cylindrical tablet-shaped workpieces of 20 mm in diameter were finished by lapping on an original piece of equipment conceived by the authors. Figure 1 shows the structure of the lapping equipment that can be attached to a universal milling machine [23].



(a) **(b)**

Fig. 1 Lapping equipment: (a) Principle; (b) Equipment and mounting on the milling machine

The bottom plate of the lapping equipment is mounted on the table of the milling machine; the upper plate slides vertically, guided by columns. Compression springs maintain the distance between the two plates. The workpieces are placed on a supporting plate that is pivot-mounted on the upper plate. A DC motor sets the supporting plate into rotation by means of a V-belt transmission. The supporting plate can accommodate up to six workpieces and can be positioned eccentrically in relation to the main shaft of the milling machine (the axis of the lap disk). The eccentricity is adjustable between 0 and 6 mm.

The lap disk is set into rotation by the main shaft of the milling machine; the required rotational speeds are achieved by adjusting the machine's gearbox correspondingly.

Cutting is done by the lap disk, which applies pressure to the workpieces by means of abrasive grains suspended in a slurry. Work pressure is generated by the compression of the springs caused by lifting the milling machine's table together with the entire lapping equipment. After the lap disk comes into contact with the workpieces, the helical springs are compressed additionally, and a continuously adjustable pressure that depends on the compression height of the springs is generated.

Lapping requires the use of a fluid working medium that is applied between the surface of the machined workpiece and a disk. As the chromium oxide on the surface of the workpieces requires the use of hard abrasives, the lapping paste used in this case is an emulsion diamond slurry [25]. A copper lap disk was used for machining.

2.2 Parameters of the lapping process

Lapping of workpiece surfaces is a finishing technology with a very small machining allowance. Hence, the lapping process can be viewed as a process of abrasive wear accompanied by adhesive and corrosion wear. The mechanics of lapping is extremely complex because material removal depends on a multitude of factors, the influences of which are cumulative.

A machining system for lapping is an open system characterized by the existence of inputs and outputs. The input factors depend on the given technical possibilities; thus, certain input factors can be controlled and others cannot. As the input factors are interdependent, a different value of one input factor causes different outcomes, resulting in the non-linear evolution of the results. The system outputs are materialized as finished parts with clear specifications as to dimensions and technological requirements.

The surface finishing process by lapping can be defined by the following elements: input factors (controlled parameters), output factors, and disturbing factors (noise). Figure 2 shows the parametric diagram of the process:

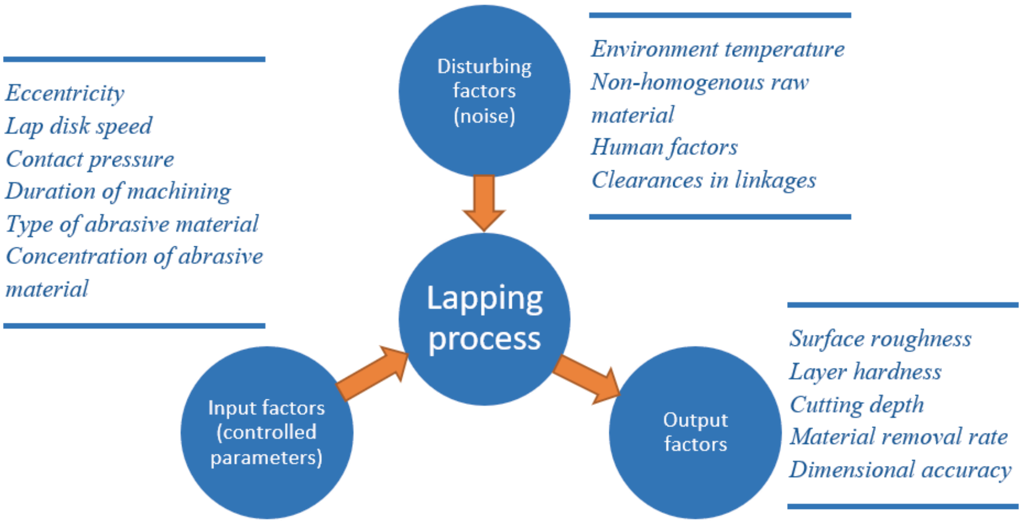


Fig. 2 Lapping process parametric diagram

The figure highlights the fact that the lapping process is subject to the influence of numerous parameters (input factors); a number of them are fixed (the workpiece material properties, the characteristics of the working equipment, etc.), while others are variable and can be adjusted and controlled (contact pressure, lap disk speed, eccentricity, etc.). Each of the latter factors can have values within a certain range, so they can operate at several levels.

In addition to the input factors, the lapping system is also subject to disturbing factors (noises) that cannot be controlled and that have a somewhat reduced effect.

The outputs of the machining system are the expected results obtained consequently to adequately configuring the levels of the controlled factors.

The optimization of the machining process is obtained by varying the values of the input factors in view of identifying the most favourable combination that generates an acceptable response. Studying each possible combination of input quantity levels is non-economical because of the large amount of work entailed. For this reason, swift optimization solutions for the machining results need to be identified while complying with both the technical and economic requirements.

One of several known rapid optimization techniques is the design of experiments (DoE) that can be applied to any process with measurable inputs and outputs. In the case of the finishing process by lapping discussed in this paper, response surface methodology (RSM) was deployed together with DoE. The goal of RSM is to generate a map of responses, either in the form of contours or as a 3D rendering [26]. Response surface methodology is a statistical instrument that includes optimization procedures for the settings of factorial factors such that the response reaches a desired value. The main idea of RSM is to use a sequence of designed experiments to obtain an optimal response [27, 28].

Starting from the lapping equipment shown in Figure 1, the input factors used for this study were disk eccentricity e [mm], abrasive concentration C [%], contact pressure p [MPa], and duration of machining t [min]. The considered output quantity of the machining system was the roughness Ra [µm]. Each run was carried out one time, and for each run, the surface roughness was measured five times. The surface roughness was measured at half of the workpiece diameter (20 mm). Thus, five measured results were obtained for each run. Subsequently, the arithmetic mean of these five measured results was computed.

Subsequently to machining, the roughness Ra of the resulting surfaces was determined; the roughness gauge used for measurements was the TESA Rugosurf 10G, manufactured by Tesa, in Switzerland. The travel of the roughness sensor was 4 mm.

Table 2 shows the values, also referred to as levels, of the input factors that were considered for this study:

Table 2 Selected factors and values

Set point number	Factors			
	Eccentricity of disk	Concentration of abrasive	Contact pressure	Duration of machining
	/mm	/ %	/MPa	/min
1	3	5	0.16	3
2	4.5	7.5	0.185	4
3	6	10	0.21	5

Following the experiments, it is expected to arrive at relationships of the following form:

$$Ra = f(x_1, x_2) + \varepsilon \tag{1}$$

where ε is the response error, and $f(x_1, x_2)$ is the expected response; x_1 and x_2 represent the two input factors, whose values are varied in one set of measurements.

3. Results and discussion

The method involves varying the values of only two input factors while maintaining the values of the other two input factors constant, set at their middle levels. This working scheme entails six possible test variants.

The first set of experiments included lapping at a contact pressure set to 0.185 MPa and a duration of machining of 4 minutes. The other two working parameters were set sequentially to each of the three possible levels. This yields an array with nine experiments. Table 3 shows the obtained results.

Table 3 Roughness values obtained by varying the values of disk eccentricity and abrasive concentration

Eccentricity of disk *e* /mm	Concentration of abrasive *C* / %	Contact Pressure *p* /MPa	Duration of machining *t* /min	Roughness *Ra* /µm
3	5	0.185	4	0.177
4.5	5			0.224
6	5			0.224
3	7.5			0.138
4.5	7.5			0.181
6	7.5			0.195
3	10			0.134
4.5	10			0.172
6	10			0.174

Figure 3 shows the effects of varying the values of disk eccentricity and abrasive concentration.

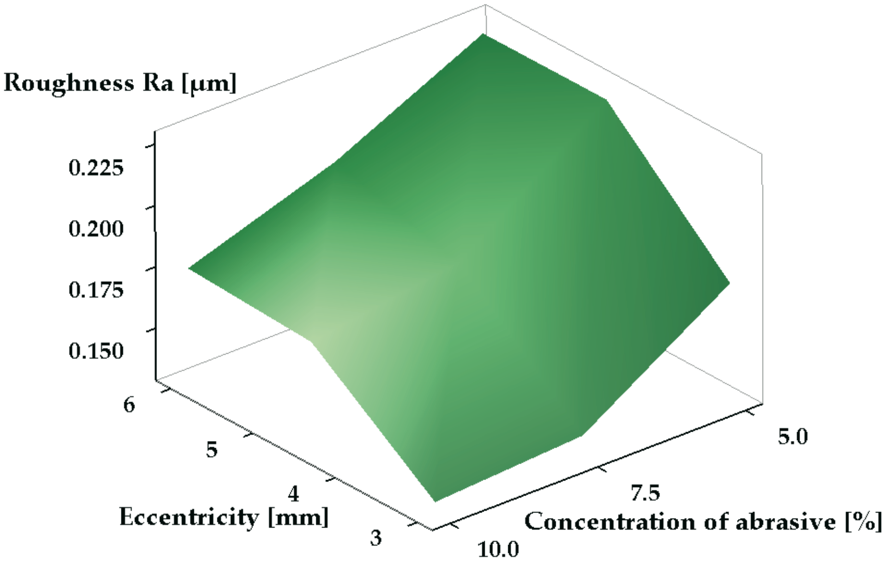


Fig. 3 Roughness versus varied values of eccentricity and abrasive concentration: 3D response surface

As can be observed in Figure 3, small values of the lap disk eccentricities and high values of the abrasive concentrations have beneficial effects on the quality of the machined surface (small roughness values). Concerning the eccentricity, in the first part of the variation interval, a more rapid increase in roughness can be noticed; after that, its variation becomes insignificant. Despite its low relevance to the roughness of the machined surfaces, eccentricity is nevertheless a necessary parameter of the machining process used to generate the cycloid trajectories of the abrasive grains. Thus, the intersection of grain trajectories is enhanced, and preferential directions of grain movement on the machined surface are avoided. High abrasive concentrations have positive effects on the quality of lapped surfaces. Even though better roughness could be achieved at a high abrasive concentration, it has to be limited to about 10-15 % because, at higher concentration values, the wear of the lap disk would be significant.

The data in Table 3 yield a regression equation of the following form:

$$Ra = 0.1804 + 0.01614 \cdot e - 0.00969 \cdot C \tag{2}$$

Table 4 shows the roughness values of the surfaces finished by lapping after having varied the values of the pair of input factors: eccentricity and contact pressure. Figure 4 shows the dependencies of the surface roughness on these input factors in this case. For these experiments, the abrasive concentration and the duration of machining were maintained at 7.5% and 4 minutes, respectively.

Table 4 Roughness values obtained by varying the values of disk eccentricity and contact pressure

Eccentricity of disk *e* /mm	Concentration of abrasive *C* / %	Contact pressure *p* /MPa	Duration of machining *t* /min	Roughness *Ra* /µm
3	7.5	0.16	4	0.177
4.5		0.16		0.224
6		0.16		0.224
3		0.185		0.138
4.5		0.185		0.181
6		0.185		0.195
3		0.21		0.134
4.5		0.21		0.172
6		0.21		0.174

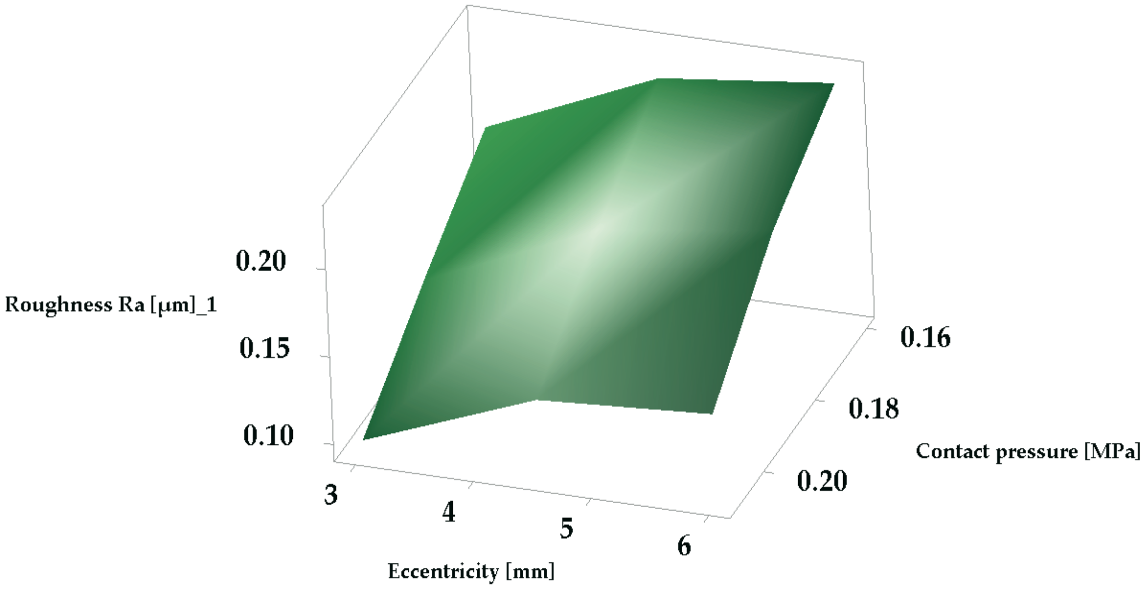


Fig. 4 Roughness versus varied values of eccentricity and contact pressure: 3D response surface

The graph reveals the possibility of obtaining a reduced roughness when the eccentricity of the disk is set at small values and the contact pressure at higher values. The higher the contact pressure, the deeper the abrasive grains penetrate the material, tamping the surface more intensively, thus yielding a lower roughness of the machined surface.

Equation 3 follows from the analysis of the data in Table 4.

$$Ra = 0.3923 + 0.01724 \cdot e - 0.1633 \cdot p \tag{3}$$

Table 5 shows the experimentation scheme and corresponding results when the values of the pair of input factors, eccentricity and machining duration, are varied. In this case, the values of the abrasive concentration and the contact pressure are set to 7.5% and 0.185 MPa, respectively.

Table 5 Roughness values obtained by varying the values of disk eccentricity and duration of machining

Eccentricity of disk *e* /mm	Concentration of abrasive *C* / %	Contact pressure *p* /MPa	Duration of machining *t* /min	Roughness *Ra* /µm
3	7.5	0.185	3	0.180
4.5			3	0.219
6			3	0.234
3			4	0.138
4.5			4	0.181
6			4	0.195
3			5	0.091
4.5			5	0.121
6			5	0.129

Figure 5 shows the effects of varying the values of disk eccentricity and duration of machining.

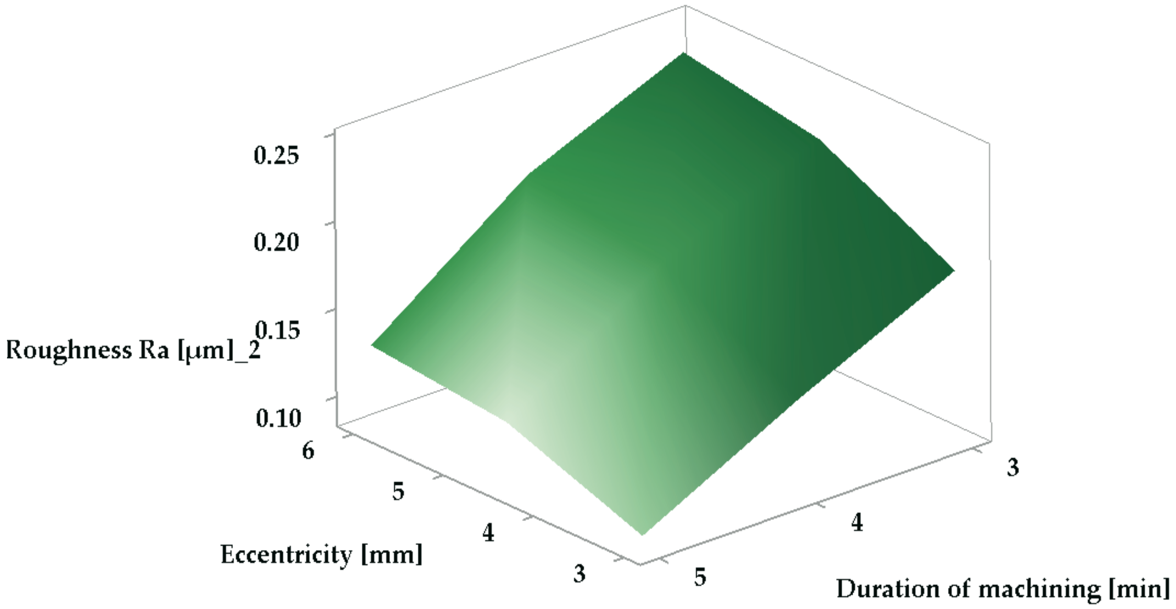


Fig. 5 Roughness versus varied values of eccentricity and duration of machining: 3D response surface

A longer duration of machining improves the roughness of the lapped surface; this can be explained by the fact that, over time, a growing number of asperity tips are smoothed out.

The regression equation corresponding to this case is:

$$Ra = 0.2855 + 0.0166 \cdot e - 0.04862 \cdot t \tag{4}$$

The fourth set of measurements entailed varying the values of the concentration of the abrasive and the contact pressure. Disk eccentricity and the duration of machining were kept in each case at 4.5 mm and 4 minutes, respectively. Table 6 shows the experimental results, and Figure 6 shows the corresponding graph.

Table 6 Roughness values obtained by varying the values of abrasive concentration and contact pressure

Eccentricity of disk *e* /mm	Concentration of abrasive *C* / %	Contact pressure *p* /MPa	Duration of machining *t* /min	Roughness *Ra* /μm
4.5	5	0.16	4	0.241
	7.5	0.16		0.217
	10	0.16		0.205
	5	0.185		0.224
	7.5	0.185		0.181
	10	0.185		0.172
	5	0.21		0.156
	7.5	0.21		0.135
	10	0.21		0.130

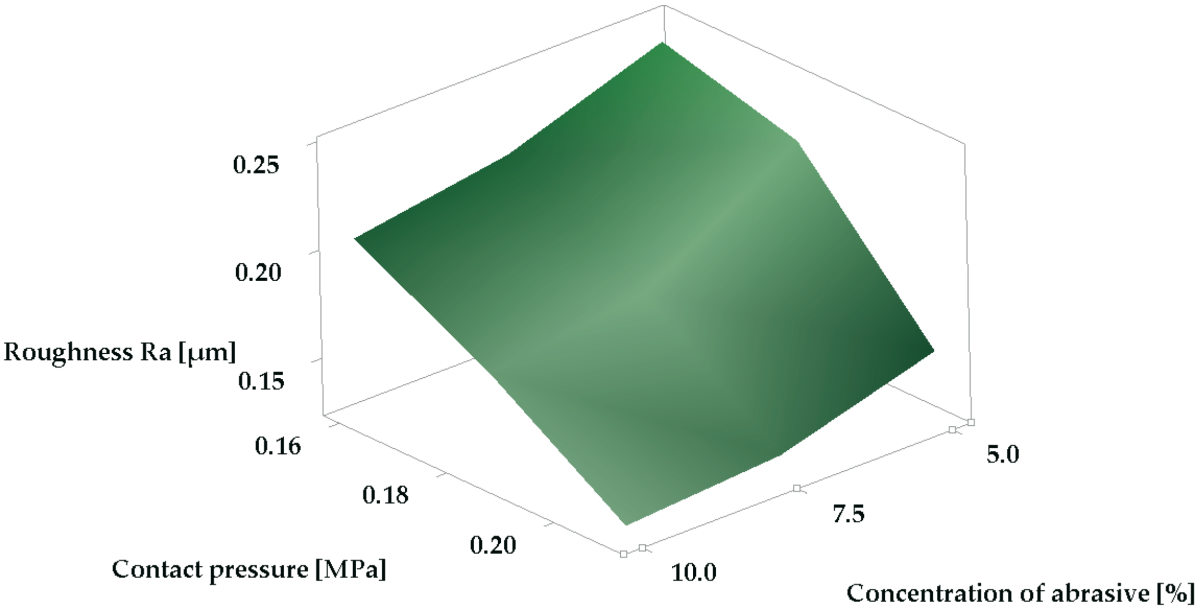


Fig. 6 Roughness versus varied values of concentration of abrasives and contact pressure: 3D response surface

The graph shown above leads to the following conclusions: the simultaneous increase in contact pressure and abrasive concentration yields a lower roughness of the finished surface. This is due to the fact that a greater pressure is applied to a larger number of abrasive grains, which results in additional tamping of the surface and a more pronounced rounding of the asperity tips.

The following equation describes the variation in roughness depending on the values of the pair of parameters (C and p):

$$Ra = 0.5414 - 0.00769 \cdot C - 0.1615 \cdot p \tag{5}$$

Further, the fifth possible combination of varied values of the considered input factors was studied, namely, the variation in the values of abrasive concentration and machining duration. The disk eccentricity was set at 4.5 mm and the contact pressure at 0.185 MPa. Table 7 and Figure 7 show the obtained values.

Table 7 Roughness values obtained by varying the values of abrasive concentration and machining duration

Eccentricity of disk e /mm	Concentration of abrasive C / %	Contact pressure p /MPa	Duration of machining t /min	Roughness Ra /µm
4.5	5	0.185	3	0.219
	7.5		3	0.196
	10		3	0.177
	5		4	0.224
	7.5		4	0.181
	10		4	0.172
	5		5	0.145
	7.5		5	0.136
	10		5	0.121

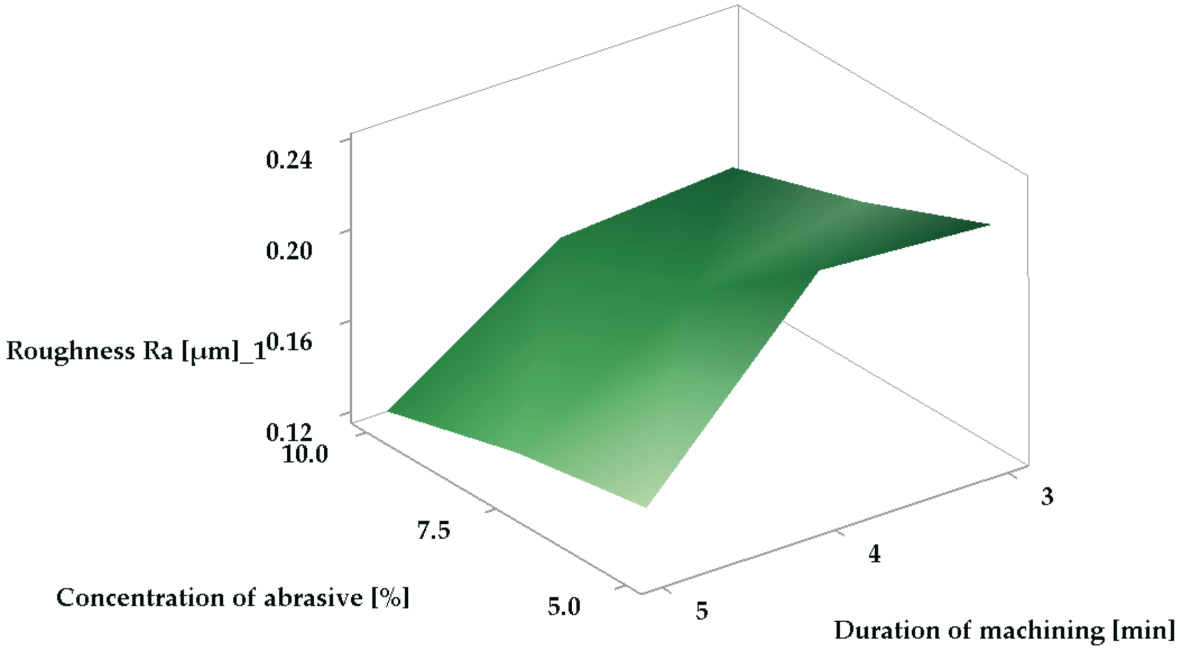


Fig. 7 Roughness versus varied values of concentration of abrasive and duration of machining: 3D response surface

The conclusion drawn from Figure 7 is that increasing both the abrasive concentration and the duration of machining contributes to decreasing the roughness of the lapped surface. The corresponding regression equation is:

$$Ra = 0.3618 - 0.00795 \cdot C - 0.03178 \cdot t \tag{6}$$

The last possible combination of a pair of input parameters entails varying the values of the contact pressure and the duration of machining, while the eccentricity and the concentration of the abrasive are maintained constant (e = 4.5 mm and C = 7.5%). Table 8 and Figure 8 show the results obtained subsequent to machining.

Table 8 Roughness values obtained by varying the values of contact pressure and duration of machining

Eccentricity of disk *e* /mm	Concentration of abrasive *C* / %	Contact pressure *p* /MPa	Duration of machining *t* /min	Roughness *Ra* /µm
4.5	7.5	0.16	3	0.217
		0.185	3	0.200
		0.21	3	0.186
		0.16	4	0.198
		0.185	4	0.181
		0.21	4	0.169
		0.16	5	0.160
		0.185	5	0.148
		0.21	5	0.135

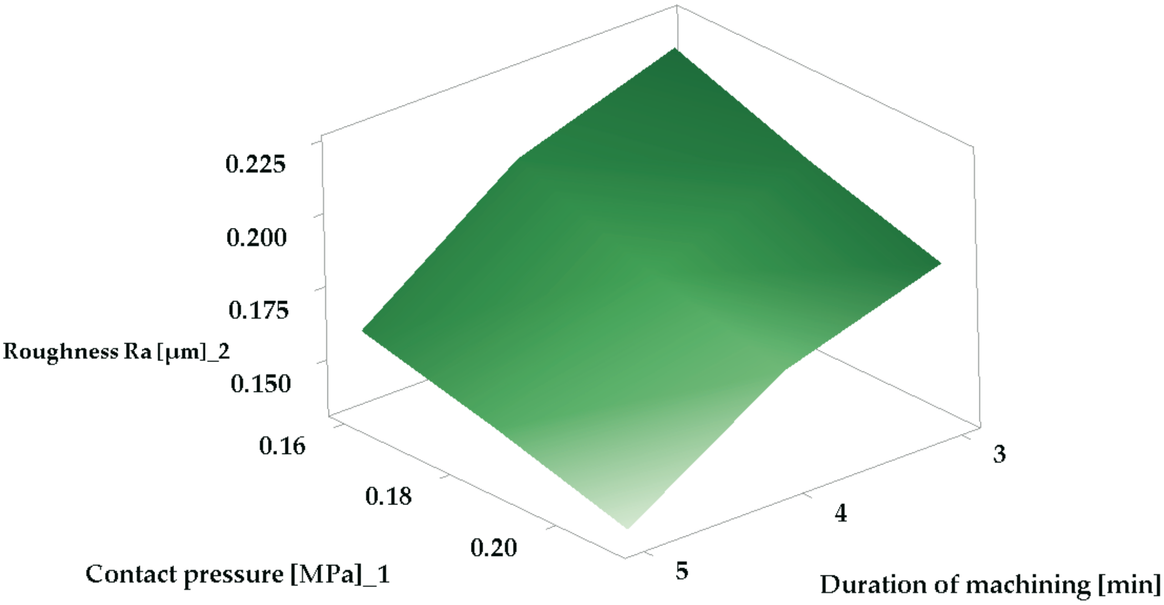


Fig. 8 Roughness versus varied values of contact pressure and duration of machining: 3D response surface

The obtained results confirm once more that setting the contact pressure and the duration of machining at the highest possible values contributes to achieving a reduced surface roughness. Equation 7 describes the dependency of roughness on the two input factors:

$$Ra = 0.3877 - 0.02667 \cdot t - 0.05587 \cdot p \tag{7}$$

The purpose of the conducted research was to identify solutions to minimize the roughness of lapped surfaces by selecting an optimum combination of the values of input factors. A parallel analysis of all the graphs shown in the paper indicates the best solution. The following recommendations can be made:

- The eccentricity of the lap disk does not impact the quality of machining significantly, but it is nevertheless necessary to avoid the formation of preferential directions on the surface of the machined part.
- The concentration of the abrasive has to be as high as possible, without exceeding 10-15%; higher concentration values would cause premature wear of the lap disk.
- The contact pressure, too, has to be set at the highest possible value, thus ensuring a more intensive tamping effect on the machined surface.
- The longer the duration of machining, the better the surface quality because, over time, more asperity tips get smoothed out.

From a quantitative viewpoint, the tables and graphs presented above indicate the following optimum combination of the input factor values: $e = 3$ mm, $C = 10\%$, $p = 0.21$ MPa, and $t = 5$ min. Machining was resumed with the lapping equipment adjusted to these values. The obtained surface roughness was $Ra = 0.084$ μm.

4. Conclusions

The paper presents a performance study of the surface lapping of parts made from X2 CrNiMo 17-12-2 austenitic stainless steel. The objective of the research was to obtain as low a roughness as possible through specially designed experiments conducted by means of original lapping equipment. The experimental data were processed using response surface methodology.

Regarded as a system, the lapping process is a complex process characterized by a series of input and output factors. The research objective could be achieved by identifying and selecting an optimum combination of the input factor values. Four controllable input factors were selected, and three values were considered for each. The four relevant input factors considered in the analysis were disk eccentricity, abrasive concentration, contact pressure, and duration of machining.

The experiments conducted with input factors grouped in pairs demonstrated the direct impact of these operational parameters on the surface roughness. With the exception of the eccentricity of the lap disk, whose influence is marginal, the other three parameters have to be set at the highest possible values in order to ensure a minimum surface roughness. For the considered values of the input factors, the surface roughness varied between 0.091 μm and 0.241 μm.

The desired minimal surface roughness was obtained by adjusting the input factors to the recommended values that resulted from the analysis of the experimental data. Thus, the objective of the research was attained. An optimum recommended combination of the input factor values resulting from the conducted research is: $e = 3$ mm, $C = 10\%$, $p = 0.21$ MPa, and $t = 5$ min. Although the sets of tests did not include this combination of values, the final machining carried out with the equipment adjusted according to this recommendation yielded a very good roughness of $Ra = 0.084$ μm, thus confirming the adequacy of the proposed optimization method.

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