ISTRAŽIVANJE HRAPAVOSTI OBRAĐENE POVRŠINE PRI MQL OBRADI ČELIKA Č.1530

SURFACE ROUGHNESS INVESTIGATION ON C.1530 STEEL DURING MQL MACHINING

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REZIME
Konvencionalna sredstva za hlađenje i podmazivanje (SHP) pri obradi metala na bazi mineralnih ulja štetna su za životnu sredinu i zdravlje ljudi i uzrokuju dodatne troškove proizvodnje. Kao rezultat toga, SHP sredstva su prepoznata kao glavni problem pri postizanju samoodrživog procesa obrade, zbog čega se alternativne tehnike hlađenja i/ili podmazivanja sve više razvijaju. S tim u vezi, jedan od pravaca razvoja je strategija kombinovanja različitih alternativnih tehnika koje se međusobno mogu nadopunjavati. U ovom radu istražena je primjena MQL (minimum quantity lubrication) tehnike podmazivanja kao mogućeg ekološki prihvatljivog rješenja za struganje čelika Č.1530. Cilj ovog istraživanja bio je utvrditi utjecaj režima obrade na hrapavost obrađene površine, tačnije na faktor Rz, koji predstavlja srednju visinu neravnina za pet najviših i pet najnižih tačaka profila na referentnoj dužini. Stoga je provedeno eksperimentalno istraživanje u kojem su varirani posmaci, brzina rezanja i dubina rezanja, te mjerena vrijednost faktora hrapavosti površine. Na osnovu dobijenih rezultata, koji su simulirani u MS Excel-u uz pomoć regresione analize, dobijeni su modeli koji najbolje opisuju zavisnost faktora Rz od načina obrade (brzina, posmak, dubina). Uočeno je da brzina ima najveći utjecaj na hrapavost obrađene površine, odnosno faktor Rz.

Ključne riječi: MQL, kvalitet obrađene površine, Rz, regresiona analiza

ABSTRACT
Conventional mineral oil-based metalworking fluids are detrimental to the environment and human health, and they bring significant additional costs to production. As a result, they are also recognized as a major unsustainable element of the machining process, and alternative cooling and/or lubrication techniques are increasingly being developed. In this regard, one of the development directions is the strategy of combining different alternative techniques that can complement each other. The application of the MQL (minimum quantity lubrication) lubrication technique as a possible environmentally friendly solution for turning Č.1530 steel was investigated in this paper. The goal of this research was to determine the influence of the treatment regime on the roughness of the machined surface, more precisely on the factor R_z, which represents the mean height of the prominences. Therefore, an experimental study was carried out in which the displacement, speed and depth were varied, and surface roughness factors were measured. Based on the obtained results, which were simulated in MS Excel using regression analysis, models were obtained that best describe the dependence of the factor R_z on processing modes (speed, feed, depth). It was observed that the speed has the greatest influence on the roughness of the machined surface, i.e. factor R_z.

Key words: MQL, quality of machined surface, R_z, regression analysis

1. INTRODUCTION

Conventional metalworking fluids based on mineral oils are harmful to the environment and human health, and they introduce large additional costs into production. Because of this, awareness is being raised about sustainable machining. In general, sustainability represents the ability to maintain the balance of certain processes or conditions in a system. The United Nations has defined sustainability as: "Development that meets the needs of the present without compromising the possibility of future generations to meet their own needs" [5,6]. According to the Department of Commerce, USA, sustainable manufacturing is defined as: "Manufacturing using processes that minimize negative impacts on the environment, conserve energy and natural resources, and are safe for employees, the community, and consumers, while also being economical" [7] . The basic dimensions of sustainability are: ecological, social and economic. Characteristics of sustainable production are: environmental friendliness, lower processing costs, minimal energy consumption, personnel health, waste reduction and operational safety. In order to achieve sustainable metal machining, the conditions for its current development should be improved. In a sustainable machining process, cutting tool durability, productivity, and efficient use of resources will increase, while production cost, energy (power) required for cutting, and adverse effects of cooling and/or lubricating fluids will decrease. Pictures 1.1., 1.2. and 1.3. respectively present the basic dimensions of sustainability, the characteristics of sustainable production and the model of sustainable processing.

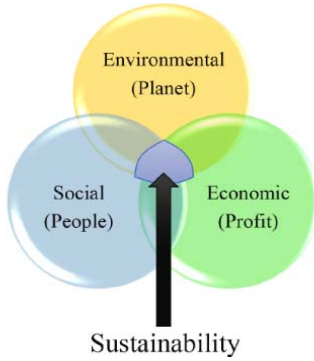

Figure 1.1. Basic dimensions of sustainability

Figure 1.2. Characteristics of sustainable production

MQL (Minimum Quantity Lubrication) is a cooling and lubrication technique that delivers very small quantities of metalworking liquid in the form of an aerosol (a liquid droplet with a diameter of less than 1 micrometer in a gas) to the cutting zone. It attracts a lot of attention from researchers because it adheres to the unique philosophy of "more is not always better."

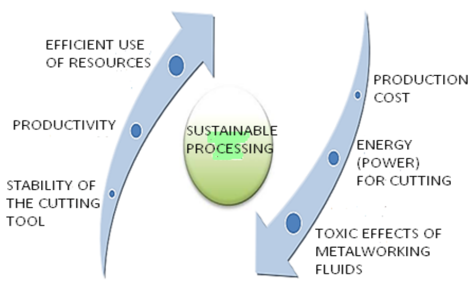

Figure 1.3. Model of sustainable processing

According to Boswell et al. [1] the term "minimum quantity lubrication" was first used by Weck and Koch [2] in 1993 in their research on bearing lubrication. Since then, more attention has been paid to research related to the implementation of MQL in machining operations. The first research on MQL in machining appeared in 1997 for grinding [3], and shortly thereafter in 1998 for cutting [4].

Biodegradability is the main reason for choosing vegetable oil as the base fluid when applying the MQL technique. However, if the awareness of environmental protection and ecological issues were not taken into account, the production industry would not abandon conventional liquids precisely because of the high input cost of vegetable oil. The cooling effect of MQL is negligible since it is achieved by evaporation of oil microdroplets. That is why advanced variants of MQL for use in machining metal cutting include electrostatic MQL, or EMQL for short (Electrostatical MQL), MQL system "Oil on Water" and the use of nano and ionic liquids. Also, to increase the cooling effect, Minimum Quantity Cooling Lubrication (MQCL) systems are applied, which use cold air below 0 °C to form aerosols or to mix with aerosols.

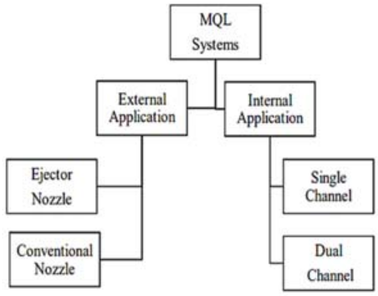

Figure 1.4. MQL delivery system

The MQL/MQCL technique significantly reduces the negative impact on the environment by reducing the consumption of metalworking fluids and eliminating the need for treatment and disposal. Reduced consumption also reduces the health hazard to workers at their workplaces caused by liquid emissions in inhaled air and on workers' skin. The liquid for metalworking does not overflow or splash around the machine tool, which contributes to less contamination of the workplace and the immediate environment. The shavings produced during metal processing are clean, so they can be easily recycled.

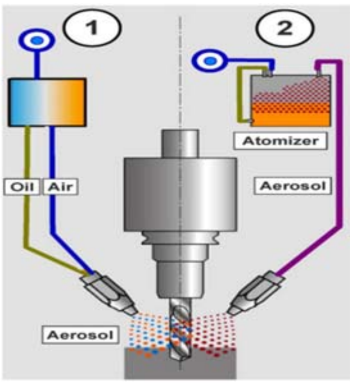

Figure 1.5. Ejector and conventional nozzle principles in MQL outdoor applications

Oil droplets for MQL/MQCL should be small enough to enter the cutting zone, but larger than 5 to 10 µm so that they do not linger in the air and pose a health risk to the worker.

In summary, according to the literature [8,9] there are 2 basic methods of fluid delivery in the MQL technique. One is external and the other internal, picture 1.4. In the case of external application, the mixture of air and oil is fed from the chamber through the external nozzle into the cutting zone. There are 2 possible methods for external application. The first is an ejector nozzle, where air and oil are fed separately, and mixing takes place after exiting the nozzle. The other is a conventional nozzle where the aerosol is prepared in an extreme atomizer and then transported to a conventional nozzle. Figure 1.5. illustrates the external application method. In the case of internal application, the aerosol is delivered through the tool. Two different internal application configurations are available. The first is single-channel where oil and air are mixed before being fed through the cutting tool. The second is two-channel, where oil and air are delivered in different channels, and are mixed before the tool holder. Figure 1.6. illustrates the internal application method. Workpiece materials and type of machining play an important role in determining efficiency when using MQL. Today, there are numerous studies comparing the effectiveness of MQL in relation

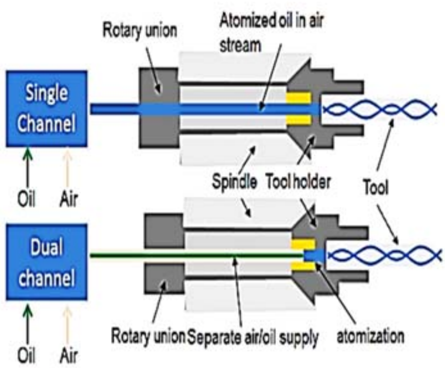

Figure 1.6. The principle of one-channel and two channel application in MQL internal applications

to conventional cooling and lubrication processes when machining different workpiece materials.
Ali et al. [10] in their experimental research on turning carbon steel came to the conclusion that: tool wear, dimensional irregularity and roughness of the machined surface were reduced when using the MQL technique for cooling and lubrication compared to dry machining. That the MQL technique for cooling and lubrication has significant advantages compared to dry machining during turning machining was also concluded by: Kapil Gupta et al. [11] in their experimental research on titanium turning, E.A. Rahim et al. [12] in their experimental research on orthogonal cutting, where they noticed that the MQL technique compared to dry machining gives better results related to the reduction of temperature, cutting forces, tool-chip contact length and that a better chip thickness is obtained, then Nusret T. and others [13] in research on hard turning and Marco Aurello et al [14] in their research on turning hardened steel SAE1045 where MQL gave better results in terms of machining forces and reduced the appearance of white layer.
When it comes to drilling, Vasim Shaikh [15] in his master's thesis observed the drilling of AISI 1018 steel using HSS (high speed steel) tools and observed that the tool life is longer and the surface roughness is lower at lower speeds and feeds. Sukhraj Singh et al [16] investigated the milling of AISI 304 stainless steel and concluded that the MQL technique gives better results in terms of tool wear compared to conventional cooling and lubrication methods.
In their experimental research, Wahida Nawrin and others [17] tried to obtain optimal cutting parameters when turning mild steel. They concluded that the speed and feed have the greatest influence on the temperature and the roughness of the machined surface, but in their work they did not present models that talk about the dependence of the cutting mode and the roughness of the machined surface.

2. EXPERIMENTAL RESEARCH

2.1 Experimental setup

The experiment was carried out in such a way that 10 channels were cut on a sample of Č.1530 steel with a diameter of 51 mm, and 11 separate ribs were obtained. For each rib, the processing modes were changed according to the plan matrix that will be shown below. During processing, the forces for each rib were measured using the Kistler 5070 device. The processing was performed on a Potisje lathe (type: ADA PA 501M) in the LORAM laboratory (laboratory of the Faculty of Mechanical Engineering in Zenica). For the purposes of the experiment, an MQL lubrication system of medium level was used (water 17.5 ml, oil 12 sec.). The chosen device for generating MQL is JOOM (Jet Oil on Water Mist) manufactured by DAIDO METAL CO Japan. The processing was performed with an interchangeable cutting plate type SNMG120408-MAUS735, manufactured by MITSUBISHI. Figure 2.1.1. shows a pictorial representation of the experiment setup.

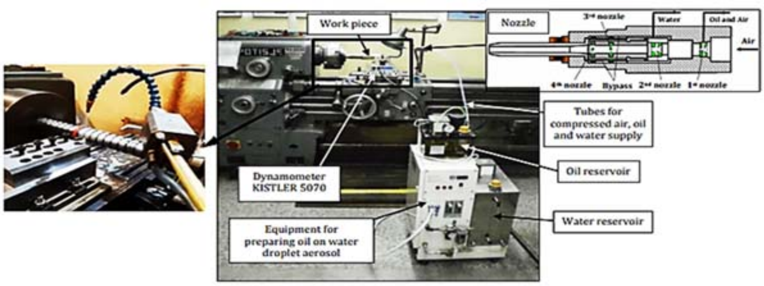

Figure 2.1.1. Pictorial representation of the experiment setup

The roughness of the processed surface was measured by a non-contact method using the MahrSurf device. The roughness was measured in 3 points, and for the purposes of the experiment, the mean value was used. Table 2.1.1. gives the limits of the experiment, i.e. factor values that change at given levels. In table 2.1.2. the plan of the matrices and input data for manipulation are given.

Table 2.1.1. Limits of the experiment

Factor levels	Level mark	Number of revolutions n [rpm]; X1	Displacement s [mm/r]; X2	Depth d [mm]; X3
Basic	0	600	0,124	1
Upper	+1	910	0,196	1,5
Lower	-1	265	0,049	0,5

Table 2.1.2. Matrix plan + input data (measurement results)

Exp. Point	Matrix plan								Measurement results				
	X_0	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	X_1X_2X3	Rz_1	Rz_2	Rz_3	Rzavg	Ln (Rzavg)
1	1	1	1	1	1	1	1	1	16,4	18,1	18	17,5	2,86
2	1	-1	1	1	-1	-1	1	-1	18,4	18,3	20,2	18,97	2,94
3	1	1	-1	1	-1	1	-1	-1	11,1	13,4	13,7	12,73	2,54
4	1	-1	-1	1	1	-1	-1	1	20,9	17,7	17,2	18,6	2,92
5	1	1	1	-1	1	-1	-1	-1	15,7	19,4	18,9	18	2,89
6	1	-1	1	-1	-1	1	-1	1	19,9	22,4	23,7	22	3,09
7	1	1	-1	-1	-1	-1	1	1	16,8	18,8	16,9	17,5	2,86
8	1	-1	-1	-1	1	1	1	-1	23,7	17,6	18,6	19,97	2,99
9	1	0	0	0	0	0	0	0	15,3	14,9	14,6	14,93	2,7
10	1	0	0	0	0	0	0	0	17,2	17,8	19,7	18,23	2,9
11	1	0	0	0	0	0	0	0	19,3	18,6	15,4	17,77	2,88

2.2 Results and discussion

After the regression analysis, 4 different equations/models were obtained that describe the dependence between the roughness factor R_z and the cutting mode (speed/number of revolutions, feed, depth).

The first equation is: $R_z=22,512-0,005\ n+1,209\ d$

This equation was obtained based on the first eight experimental points and the mean value of the factor R_z. The values used in the analysis are marked in blue and yellow in table 2.1.2. Figure 2.2.1. shows the microstructure of the machined surfaces for each rib individually in one of the three points for which measurements were made.

Regression Statistics	
Multiple R	0,835283183
R Square	0,697697996
Standard Error	0,095140873
Observations	11

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	2,87	0,028686	100,0486	2,63E-12
B(v)	-0,09875	0,033637	-2,93572	0,021846
C(s)	0,05875	0,033637	1,746569	0,124213
D(d)	-0,07125	0,033637	-2,11818	0,071915

Figure 2.2.2. Results obtained by regression analysis for equation 2

Very important parameters in this analysis are: coefficient of determination, correlation coefficient and standard error. The coefficient of determination, R^2, is a descriptive measure of the strength of the regression relationship that measures how well the regression equation fits the data. It has values [0,1]. The closer the value is to 1, the better the regression equation fits the given data. The correlation coefficient, R, is a measure of the degree of linear relationship between two similar variables. It has the values [-1,1]. A value of 0 means that there is no correlation between the variables, a value of 1 represents a complete correlation of the positive direction, and a value of -1 a complete correlation of the negative direction. The closer the absolute value of the coefficient is to 1, the closer the connection. The standard error, S_{ey}, is an absolute measure of the variation of the empirical data from the regression model.

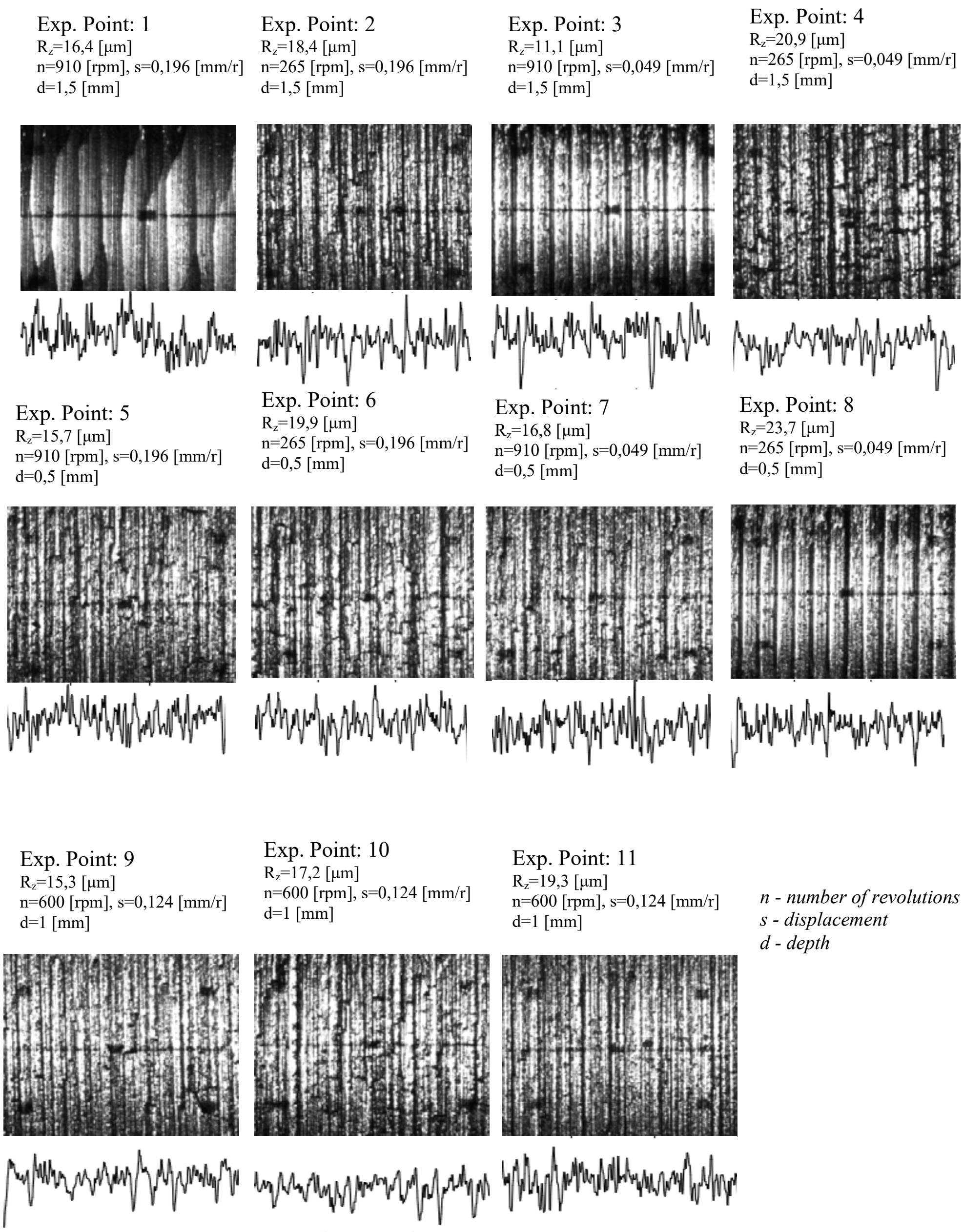

Figure 2.2.1. Surface roughness measurements results and machined surface profiles

The obtained values of the coefficient of determination, correlation coefficient and standard error for the first equation are: $R^2=0,870641$; $R=0,933081$; $S_{ey}=1,262077$.
The second equation is: $R_z=4,087\ n^{-0,16}\ s^{0,082}\ d^{-0,127}$
This equation was obtained on the basis of 11 experimental points and the logarithmic value of the R_z factor (in table 2.1.2. these values are marked with blue, orange and green colors). Figure 2.2.2. shows the results obtained from the analysis. All the most important parameters can be seen from the picture.
The third equation is: $R_z=17,84 - 1,73\ [(n\text{-}600)/310]$
This equation was obtained on the basis of 11 experimental points with included interactions and the mean value of the factor R_z (in table 2.1.2. these values are marked with blue, orange, gray, yellow and violet colors). Figure 2.2.3. shows the values of the coefficient of determination, correlation coefficient and standard error for equation 3.
The fourth equation reads: $R_z=13,81\ n^{-0,16}$
This equation was obtained on the basis of 11 experimental points with included interactions and logarithmic values of the factor R_z (in the table 2.1.2 these values are marked with blue, orange, gray and green colors). The correlation coefficient has a value $R=0,9207635$, the coefficient of determination has a value $R^2=0,8478054$ and the standard error has a value $S_{ey}=0,1027553$.

Regression Statistics	
Multiple R	0,916076
R Square	0,8391953
Adjusted R Square	0,4639842
Standard Error	1,7736748
Observations	11

Figure 2.2.3. Correlation coefficient, determination coefficient, standard error

3. CONCLUSION

Based on the obtained models that describe the dependence between the cutting mode and the roughness of the processed surface, i.e. factor R_z, we can conclude that speed has the greatest influence. By increasing the number of revolutions (speed), the R_z factor decreases.
The coefficient of determination for the first equation has a value of $R^2=0,870641$, which means that *87,06 %* of the connections are explained by this model. The coefficient of determination for the second equation has the value $R^2=0.697697$, which means that *69,77 %* of the connections are explained by the second equation. The coefficient of determination for the third equation has the value $R^2=0,8391953$, which means that *83,92 %* of connections are explained by this equation. The coefficient of determination for the fourth equation has a value of $R^2=0,8478054$, which means that *84,78 %* of connections are explained by this equation. Therefore, we can conclude that the first equation, $R_z=22,512 - 0,005\ n + 1,209\ d$ represents the equation that best describes the dependence of the cutting mode and the R_z factor because it explains the largest number of connections. The highest correlation coefficient was obtained for the first equation and has a value of $R=0.933081$.

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