Vol. 35, No. 4 (2013) 276-285

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Experimental Research Using of MQL in Metal Cutting

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Keywords:

Lubrication
Cutting
MQL
Effects

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A B S T R A C T

In this paper an effect of using of minimal quantity lubrication (MQL) technique in turning operations is presented. Experimental research was performed on carbon steel C45E. Technological parameters: depth of cut, feed rate and cutting speed were adjusted to semi-machining and roughing. Higher values of feed and cutting speed were used, than recommended from literature and different types of cooling and lubrication conditions in turning were applied. As a conventional procedure and technology, lubrication with flooding was applied. As special lubrication technique the MQL was used. During research, monitoring of the cutting force, chip shape, tool wear and surface roughness was performed. Relations between parameters, material machinability and economy of process were analyzed.

1. INTRODUCTION

The future of metal machining by 2020 is in the development of flexible machining systems, economical and productive processes, energy-efficient processes, production without waste, ecological production with a reduced quantity of the cooling and lubrication fluids and etc. This conclusion is based on the study National Research Council of the USA and other teams of researchers [1-4].

Increasing of productivity (Fig 1.) is impossible without utilization of modern tools and machines, modern types of cooling and lubrication fluids (CLF), CLF dosing techniques, and modern equipment. Progress is not possible without knowledge of the materials machinability and expert systems for the selection of suitable machining regimes based on machinability and process modelling [3,11,16,17].

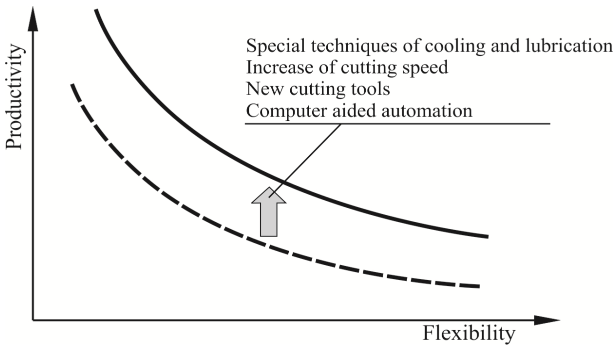


Fig. 1. Possibilities to increase the productivity of manufacturing.

Phases of research, obtaining and application of knowledge in the field of cutting process are (12,14,15):

- study of materials machinability based on experimental research,
- modelling of the cutting process and
- integration of knowledge in expert systems and specialized databases.

The main progress in developing of high productive machining processes is realized in the area of special CLF dosing techniques. One of these techniques is minimum quantity lubrication (MQL). The analysis of previous researches have shown that this CLF dosing technique was applied for lower cutting speed (v_c = 100 -150 m/min) [5-7,13] with turning and cutting speed v_c = 15 - 26 m/min with drilling [10].

From the structure of the cost of machined part, it can be concluded that the cost of CLF participate 15 %, costs of tools 10 % and costs of energy consumption 4 % of total costs (Fig 2).

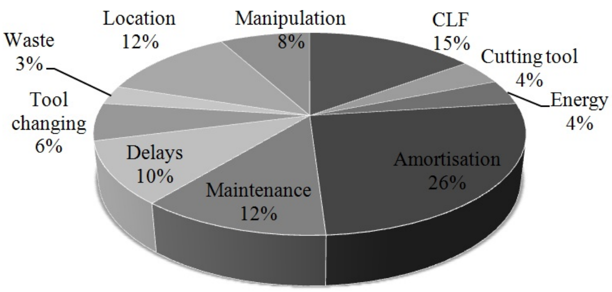


Fig. 2. Structure of the machining costs.

The focus of researches presented in this paper was on effects of different CFL dosing techniques in the field of higher cutting speed (v_c = 200 - 400 m/min), which contributed to the expansion of technological fields. In order to analyse the machinability when applying standard and MQL CFL dosing techniques, analysis of machining energy balance, effect of chip formation, tool life and quality of machined surface were also included [8,9].

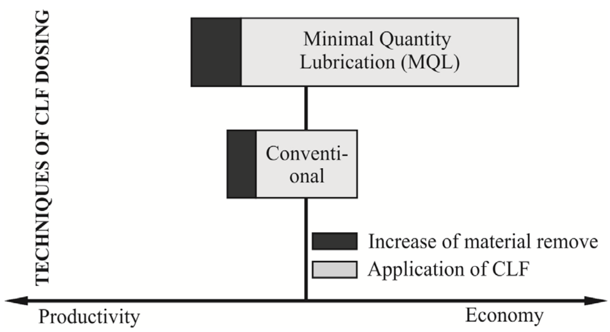


Fig. 3. Influence technique of lubrication on productivity and efficiency.

The studies that are presented in this paper are related to the analysis of use of modern techniques CFL dosing, with the aim of defining the directions of increasing productivity and efficiency of machining process (see Fig. 3).

2. EXPERIMENTAL SETUP

The material that was used for the experimental researches is the carbon steel C45E. This steel belongs to the group of construction steels which are used for essential parts in the machines and constructions. Workpiece is cold-rolled steel bar with a diameter of 120 mm and length of 300 mm. Research was performed on universal lathe BOEHRINGER with the following properties: 8 kW of power, maximum spindle speed of 2240 rev/min, and feed of 1.6 mm/rev. Carbide cutting tool for semi machining SNMG 1204 08 NMX was used. Tool clearance angle was 10°, rake angle 0°, and a tool tip radius was 0.8 mm without chip breakers. Tool holder was PSDN 2525 M12 with inclination angle 45° (Fig. 4).

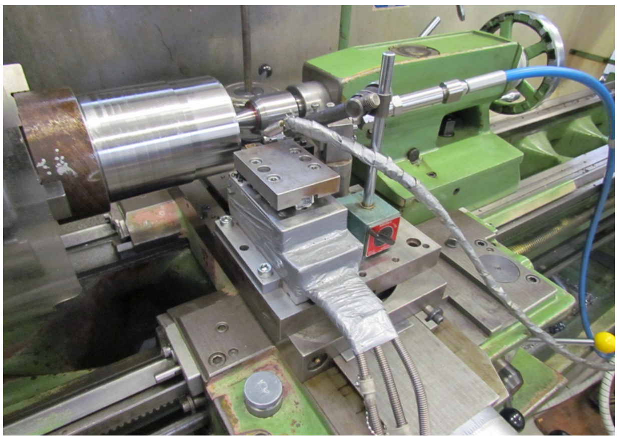


Fig. 4. Experimental setup on machine.

In this research two different CLF dosing techniques were analysed:

- conventional flooding and
- special dosing technique - MQL.

In conventional flooding, CLF is dosed at the top of machining zone, from a distance of approximately 150 mm. CLF was directed on non-machined workpiece surface and rake surface of insert.

In the MQL technique, CLF was dosed using a special device which utilizes a compressed air to form an oil mist in the mixing chamber (Fig 5).

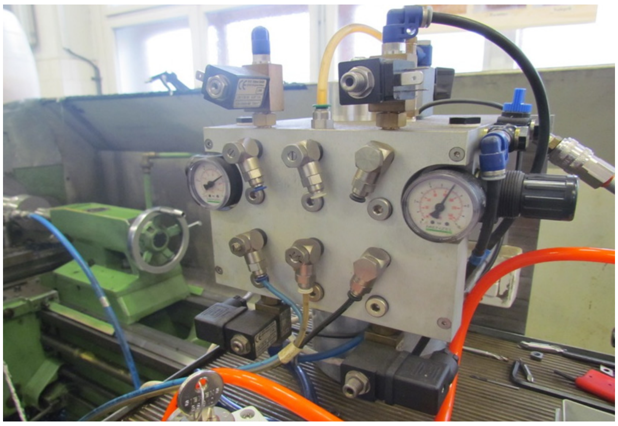


Fig. 5. MQL device.

During machining with MQL technique, the tool was protected from sudden changes of heat loads. The effects of rapid expansion and contraction of the tool material and the cracks appearance and coatings cracking were avoided. During the machining, due to the effect of the spray, the tool was enveloped with a thin layer of emulsion. In MQL technique spray nozzle was installed at a distance of 30 mm (L_{MQL} = 30 mm), normal to the cutting edge, with an angle of 30° (ψ_{MQL} = 30°) regarding to the rake face of tool (Fig 6.).

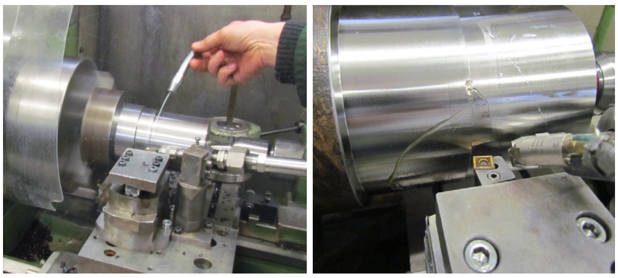


Fig. 6. Position of conventional flooding (left) and MQL nozzle (right) during the experiments**.**

With such recommended position of the nozzle quality lubrication of machining zone were ensured. Table 1 shows the values of the hydraulic conditions for both CLF dosing techniques.

Table 1. The values of pressures and flow.

Technique of CLF dosing	Pressure *p* [MPa]	Flow *Q* [l/min]
Standard flooding	0.3	2
MQL	0.3	0.0005

Technological parameters varied in the experiments were as follows: depth of cut (*a*), feed (*f*) and cutting speed (v_c). Technological parameters were adjusted to the semi- turning, with the use of higher values (Table 2). The total numbers of experiments for both dosing techniques were 72.

Table 2. The levels of technological parameters.

Parameter	The levels of variation			
	1	*2*	*3*	*4*
Cutting depth a [mm]	1.5	2.0	2.5	-
Feed s [mm/rev]	0.224	0.280	0.355	0.400
Cuuting speed v_c [m/min]	210	310	400	-

KISTLER dynamometer was used to measure three cutting force components in turning: main cutting forces (F_c), feed cutting forces (F_f) and penetration cutting force (F_p). For processing of the measured signals LabVIEW software package with specially designed program framework was used. The developed program framework enables data transmission to software package MATLAB. Monitoring and measurement of tool wear was performed using a tool microscope TM MITOTOYO 510 equipped with high-resolution camera (Fig 7). Surface roughness was measured using a mobile measuring device MITOTOYO SURFTEST SJ 301. During the experiments a chip formation process was monitored as well.

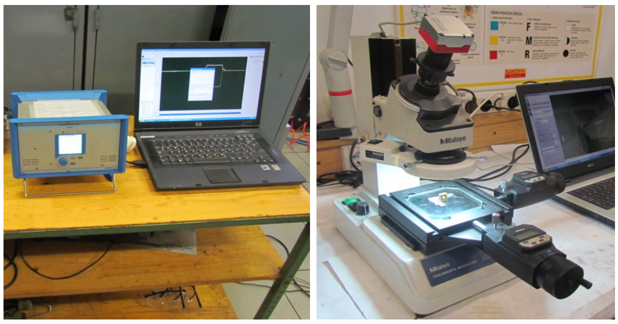


Fig. 7. Measuring devices: force data acquisition (left) and tool microscope (right)

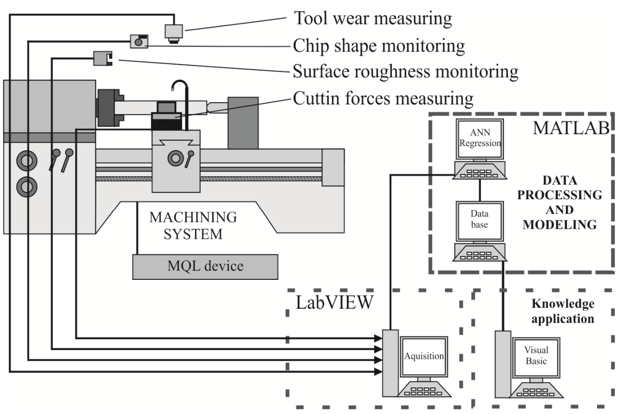


Fig. 8. Data flow in measuring and monitoring.

In the first phase of research cutting forces (F_c, F_f and F_p) for different combinations of input parameters were measured. At the same time the formed chips were collected, and the shape was evaluated with the purpose of technological frames definition (Fig 8).

In the second phase of the experimental tests tool wear was measured, as follows: the values of concentrated wear (VB), tool wear on tool clearance face (VB') and the size of the crater on the rake face (b_w). Due to wear of tools values of surface roughness were measured, as follows: mean values of roughness (R_a) and maximum height of roughness (R_y).

3. ANALYSIS OF RESULTS

The results of experimental investigations which concerning the values of machinability parameters: cutting resistances, shape of chip, tool wear and surface roughness is shown. Modelling was performed using regression analysis and artificial neural networks (ANN).

From the analysis of the cutting forces components (Figs. 9-11) in case of conventional CLF dosing application, it can be concluded that the value of the cutting forces components increase with increasing feed and depth of cut. When MQL technology is applied, the values of cutting forces increase with feed and depth of cut as well. The values of force components F_f and F_p were smaller than the values of F_c component for both dosing techniques, which is consistent with the theoretical assumptions. Penetration cutting forces F_p and feed cutting forces in MQL technique are greater than conventional technique of CLF dosing.

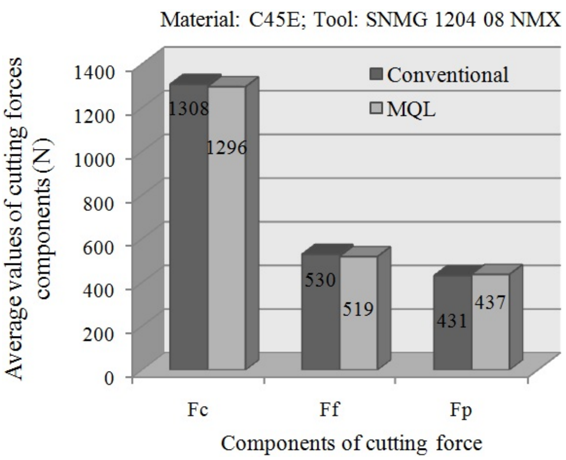


Fig. 9. Comparison of the mean value of components of cutting force for both dosing techniques.

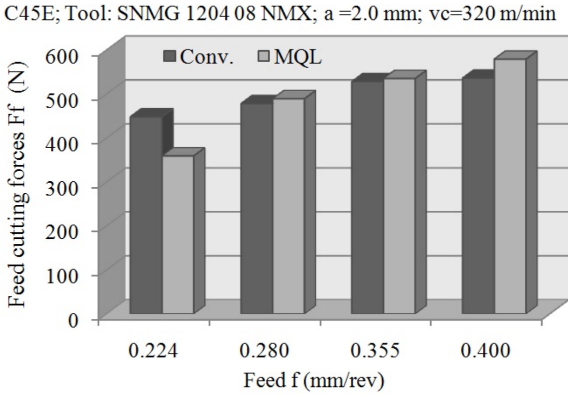


Fig. 10. Values of feed cutting forces.

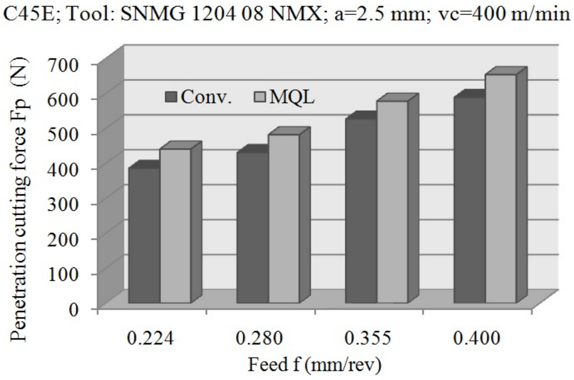
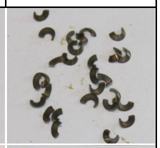


Fig. 11. Values of penetration cutting force.

One of the main indirect indicators of the machining process condition is chips shape. Based on chip shapes the following features can be determined: tool wear, surface roughness, the amount of generated heat and related phenomena. Conclusions based on chip shape were adopted on the basis of recommendations from the literature [1-3].

Table 3. Chip shape during machining with conventional flooding.

Depth a [mm]	Cutting speed v_c [m/min]	Feed f [mm/rev]		
		0.224	0.280	0.400
1.5	210			
2.0				
2.5				

In Table 3 forms of chips obtained when machining steel C45E while using conventional technique of CLF dosing are shown. Based on analysis of chip shapes it can be concluded that machining with lower feed rates (f = 0.224 mm/rev) and greater depths (a = 2.5 mm), creates an unfavourable chip shape. However, for the same parameters, in conditions with higher speeds, it forms more favourable chips shape.

Table 4. Chip shape during processing with MQL technique.

Depth a [mm]	Cutting speed v_c [m/min]	Feed f [mm/rev]		
		0.224	0.280	0.400
1.5	210			
2.0				
2.5				

Some chip shapes during machining of the same steel C45E, with the same tool, using MQL technique are shown in Table 4. Chips are dark, which indicates that in the machining area a larger amount of heat is generated and dissipated through the chips. It can be concluded that MQL technique provides good effects of lubrication, but the bad effects of cooling the machining zone. Based on a chip shape, it can be concluded that the use of MQL technique provide favourable shapes of chip for all analyzed machining conditions.

The technological areas for both techniques of lubrication and different depths of cut are shown in Figs. 12 and 13.

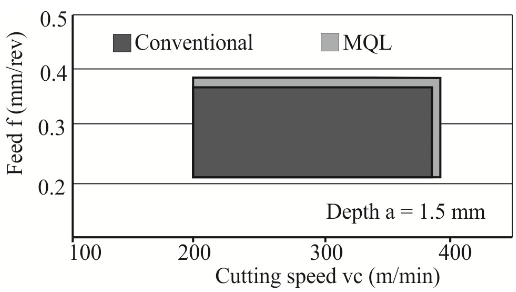


Fig. 12. Technological areas for depth a = 1.5 mm.

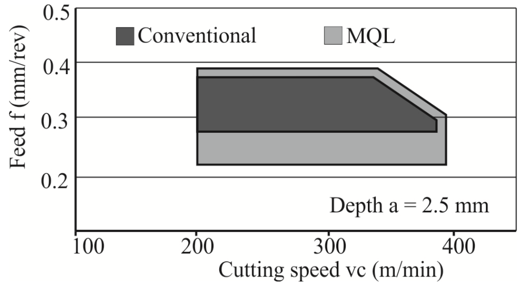


Fig. 13. Technological areas for depth a = 2.5 mm.

They are based on the assessed chip suitability. From the analysis of the technological areas, it can be concluded that MQL technique offers a wider field of machining.

Previous studies have shown that different techniques of lubrication have a great impact on the wear of tools as well. In our study the measured parameters of tool wear were as follows: concentric wear (VB) and wear on the secondary surface of tool (VB'), and crater wear - see Table 5 and 6.

Table 5. Tool wear during machining with conventional CLF dosing.

Time T [min]	Machining lenght L_c [m]	Tool wear on tool face		
		Secondary rake	Primary rake	Clerance
0.93	272			
3.75	1286			
7.23	2080			

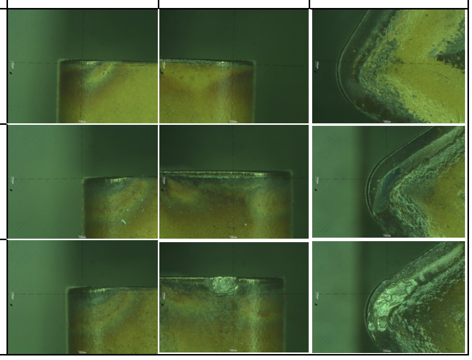
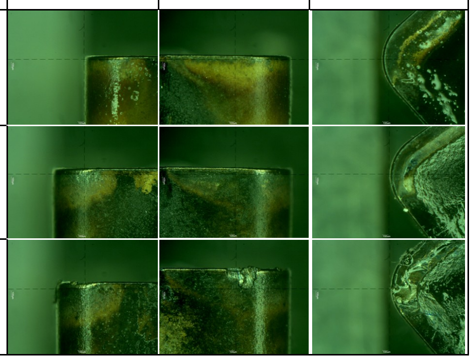


Table 6. Tool wear during machining using MQL technique.

Time T [min]	Machining lenght L_c [m]	Tool wear on tool face		
		Secondary rake	Primary rake	Clerance
1.10	339			
5.92	1952			
9.65	3163			



This parameters has direct impact on the machining process, and thus on the machinability. Criterion of tool wear was VB = 0.3 mm. Tool life in the case of MQL technique was for about 33 % longer (see Fig. 14). The parameters of the surface roughness - mean height of roughness (R_a) and maximum roughness (R_y) were measured depending on the machining time. As regimes for machining the mean values of the obtained technological areas have been adopted: a = 2.0 mm and f = 0.280 mm/rev, cutting speed v_c = 320 m/min (Figs. 14 and 15).

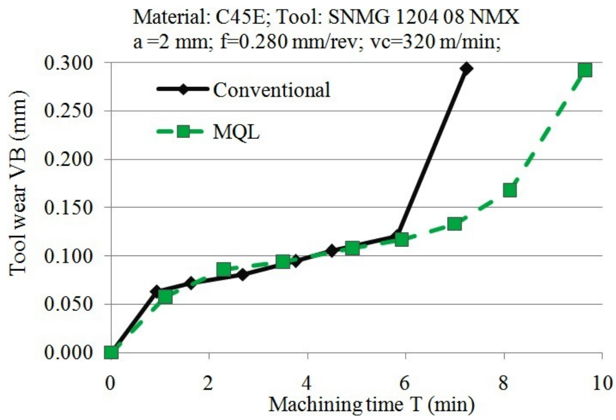


Fig. 14. Comparative diagram of tool wear for different techniques of CLF dosing.

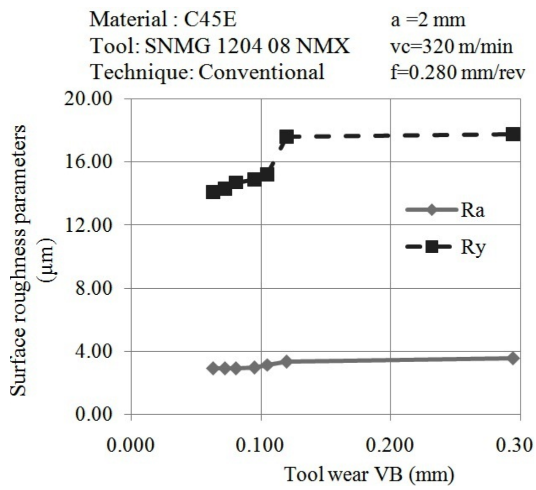


Fig. 15. Surface roughness regarding the tool wear in machining with conventional CLF dosing.

Figure 15 shows that tool wear take affects on the surface roughness parameters R_a and R_y. Roughness is influential parameter in assessing the machinability, and in the flooding conditions of machining, and this parameter was increased from the initial 14 µm to 18 µm at the time when tool wear achieved criterion 0.3 mm. Tool life for the given machining conditions was T = 7.23 min.

In Table 6 the values of the tool wear parameters during machining with MQL technique of lubrication is shown. The regime a = 2.0 mm, f = 0280 mm/rev, v_c = 320 m/min was applied. In this case, it can be concluded that the tool insert enveloped with a thin layer of emulsion, which is not the case with conventional CLF dosing. Tool achieved full damage at T = 9.65 min. The higher value of tool life with MQL technique compared to conventional flooding is the result of a thin film that completely covered the tool insert surface (Fig. 17).

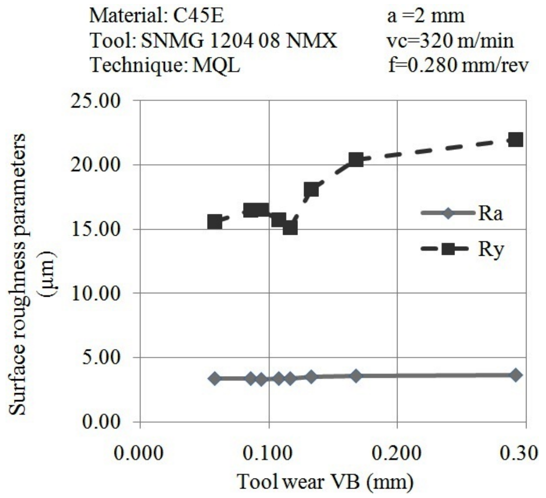


Fig. 16. Changes of parameters Ra and Ry, depending on the tool wear in machining with MQL technique.

The increase of R_a the parameter value during machining with MQL technique is shown in Fig. 16. It can be seen, that due to a higher percentage of heat generated during processing the value of parameter R_y is higher when machining with MQL technique than in conventional lubrication.

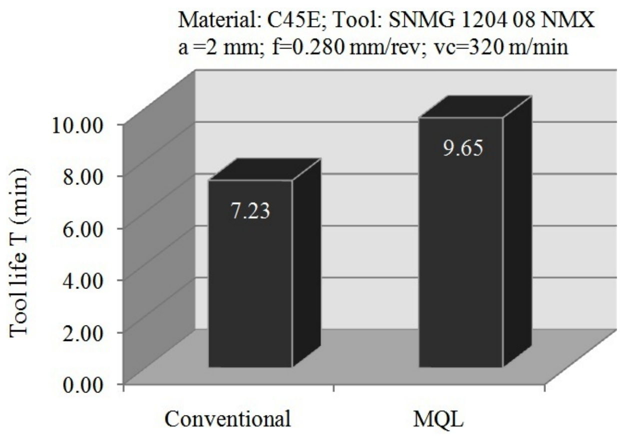


Fig. 17. Values of tool life for different lubrication techniques.

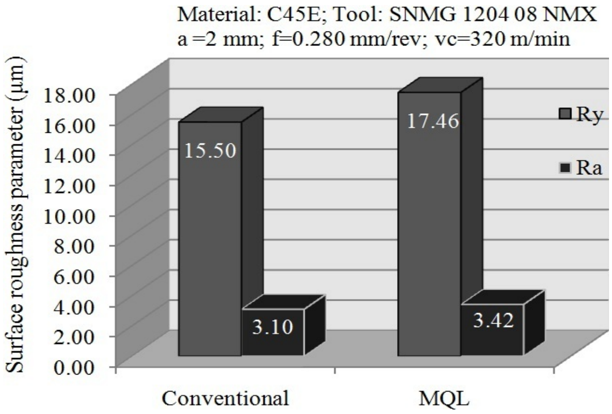


Fig. 18. Values of surface roughness parameters for different lubrication techniques.

Comparative analysis of results 1n the Figs. 17 and 18 indicates that the MQL technique provides better results in aspect of tool wear and tool life, but slightly worse results in aspect of the surface quality as consequence of thermodynamic processes in the cutting zone.

4. MODELING OF RESULTS

Examination of the experimental results was performed by multiple regression analysis. (see Fig. 19). The output values from the regression model showed a significant correlation with the experimentally measured values. The average relative error of the regression models does not exceed 5 %. The models presented in the form of regression equations can be used with high accuracy of prediction. The models of main cutting force (F_c) have errors less than 2 %, while the main square errors for models of forces (F_f) and (F_p) are higher. This corresponds to the theoretical assumptions of cutting parameters behaviour in the case of machining of steel C45E.

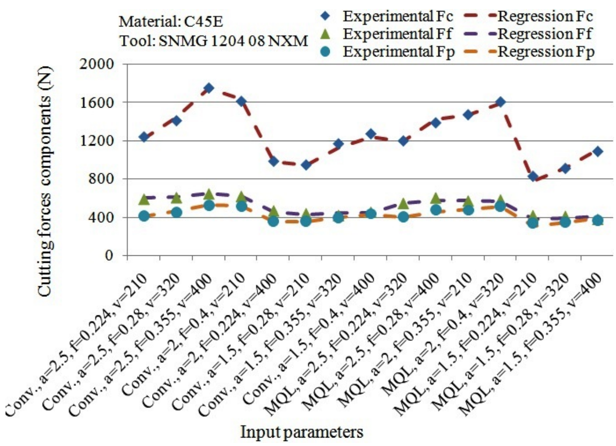


Fig. 19. Comparison of outputs regression model with experimental results.

The biggest errors is expected in the predictive models of forces (F_f) and (F_p) in machining with MQL technique; 4.93 % and 4.44 % respectively. In addition to modelling the of cutting force components, also a resultant force $F_{f,p}$, which is a resultant of (F_p) and (F_f) was modelled. These resultant forces have a higher value than the main cutting force. The resultant force ($F_{f,p}$) is a main indicator of tool wear, and with its growth usually intensive tool wear occurs.

Analyzing the models, and their corresponding exponents (Fig. 19 and Table 7), it can be concluded that the depth of cut has the highest, while the cutting speed has the least influence on the main cutting force and resultant cutting force. Cutting speed and feed have a great influence on the force (F_f) and (F_p), and the resultant forces ($F_{f,p}$), especially during machining with MQL technique. It can be concluded that the increase of feed and depth of cut increases the value of the components of the cutting force. Increasing cutting speed reduces the values of cutting force because there is no negative phenomenon, such as the burrs on the tool edge.

Table 7. Models of cutting forces with coefficients of machining.

Material: C45E Tool: SNMG 1204 08 NXM		Colleration coefficient	Relative error (%)
$F_c = 2485 \cdot a^{0.878} \cdot f^{0.844} \cdot v^{-0.047} \cdot K_1$		0.99	1.9
$F_f = 1154 \cdot a^{0.838} \cdot f^{0.391} \cdot v^{-0.157} \cdot K_2$		0.93	3.9
$F_p = 822 \cdot a^{0.589} \cdot f^{0.644} \cdot v^{-0.052} \cdot K_3$		0.93	3.7
Techniques	*K_1*	*K_2*	*K_3*
Conventional	1	1	1
MQL	0.99	0.96	1.02

Modelling of cutting force for different techniques of CLF dosing using regression analysis was done. The developed models are presented in Table 7, where the influential factors represented by the corresponding coefficient *Ki*. Developed regression models have error less than 4 %, which indicates the high accuracy of the model. The applying MQL technique reduces the energy consumption compared to the conventional lubrication technique. MQL technique should be favoured in highly productive processes.

Often, multiple regression analysis is not suitable for the modelling of complex processes, which depends on a many number of factors. For modelling of such processes a large number of experimental data are needed. In our study ANN technique was applied. For this technique a special module Neural Toolbox in the software package MATLAB, is used. Modelling with ANN was conducted using a model of two-layer neural network with forward propagation.

Figures 20, 21 and 22 give the measured and predicted values for all cutting forces respectively. The results of predicting with the model based on ANN show that the developed models can be used for modelling the cutting force, although the set of learning, validation and testing include a relatively small number of combinations of input and output values. In order to analyse the accuracy of the multiple regression model the output values of the model are also shown on the same chart (Table 7).

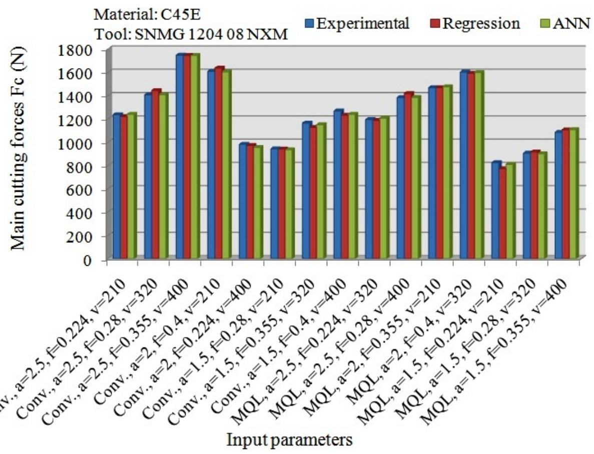


Fig. 20. Output values of the main cutting force from regression model and ANN model.

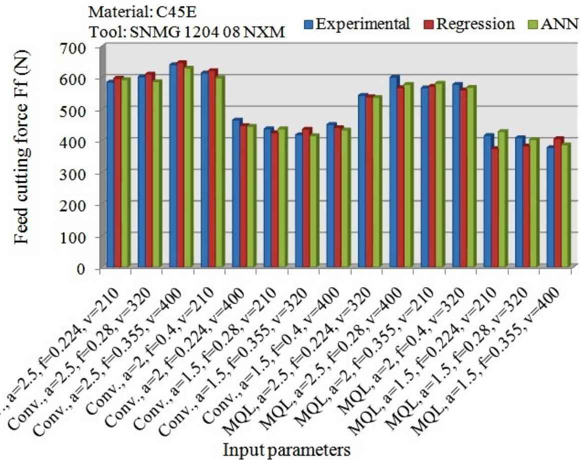


Fig. 21. Output values of the feed cutting force from regression model and ANN model.

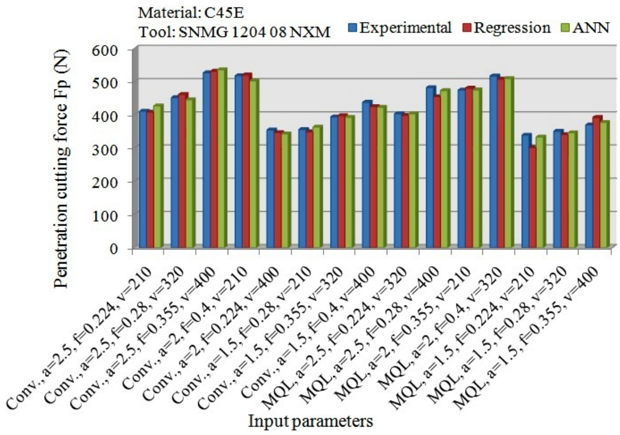


Fig. 22. Output values of the penetration cutting force from regression model and ANN model.

From the analysis of the diagram it can be concluded that the output values of both types of model correspond to experimental values. Mean relative error of predicted values for forces F_c, F_f and F_p in the model based on ANN is 1.01 %, 2.24 % and 1.71 % respectively, while for regression model error is 1.85 %, 3.55 % and 2.92 % respectively.

Modelling of tool wear was performed with a third order polynomial function. It can be concluded from Fig. 23 that matching of output values of model with the experimental values is excellent.

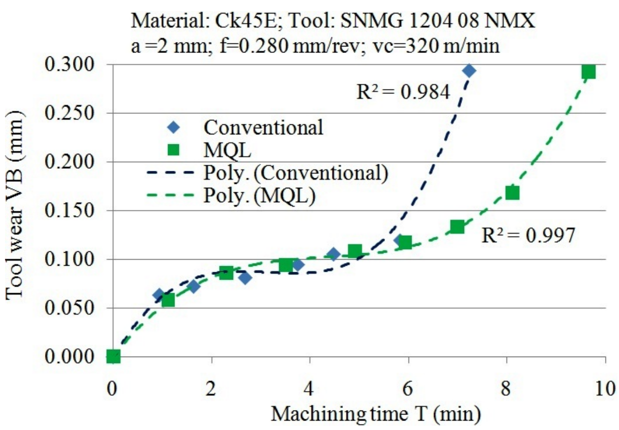


Fig. 23. Modelled curves of tool wear for different lubrication technique in machining steel C45E.

The parameters of the surface roughness R_a and R_y were modelled with linear function depending on the machining times and depending on the tool wear using regression analysis.

Table 8. Models of surface roughness in dependence of tool wear for different lubrication techniques.

Material: C45E; a = 2.0 mm; vc = 320 m/min Tool: SNMG 1204 08 NXM	
Conv.	$R_y = 15.15 \cdot VB + 1.45 + (f^2 \cdot 10^3 / (8 \cdot r))$
MQL	$R_y = 30.50 \cdot VB + 1.18 + (f^2 \cdot 10^3 / (8 \cdot r))$

If the analysis is carried out from the aspect of materials machinability, R_y is a more relevant factor than R_a, because parameter R_y indirect indicator of process condition and a direct indicator of quality as well (Fig. 24 and 25). R_y models based on regression analysis are presented in the form of the function of tool wear VB, feed *f* and the radius of the tool tip *r* for both CLF dosing techniques. The second part of this function is taken from the known empirical expression for the theoretical level of roughness.

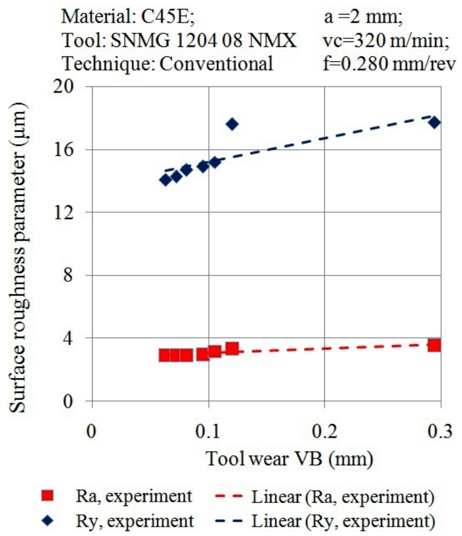


Fig. 24. Models of parameters roughness for the conventional technique of CLF dosing.

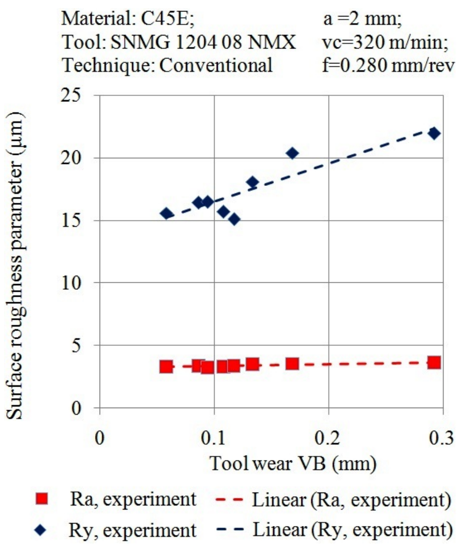


Fig. 25. Models of parameters roughness for the MQL technique.

Comparison of material machinability was made for both lubrication techniques under consideration. Machinability index of i-th material in regard to referent material is defined as:

$$I_i = \left(p_i / p_r\right)^{\pm 1} \cdot 100\% \qquad (1)$$

where is I_i machinability index of i-th material, p_i parameter value accepted for machinability evaluation of i-th material, p_r parameter value accepted for machinability evaluation of referent material.

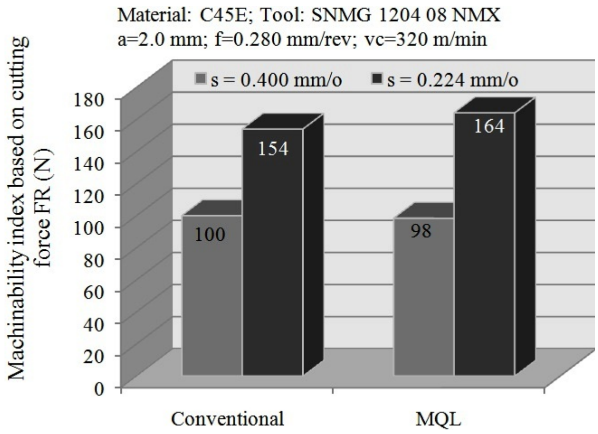


Fig. 26. Values of machinability index based on energy aspect.

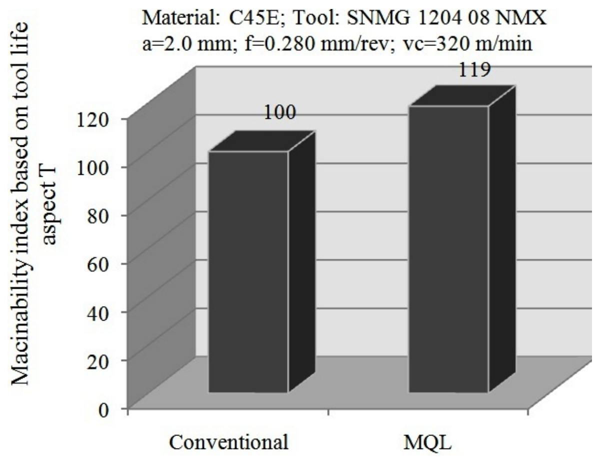


Fig. 27. Values of machinability index based on the tool life aspect.

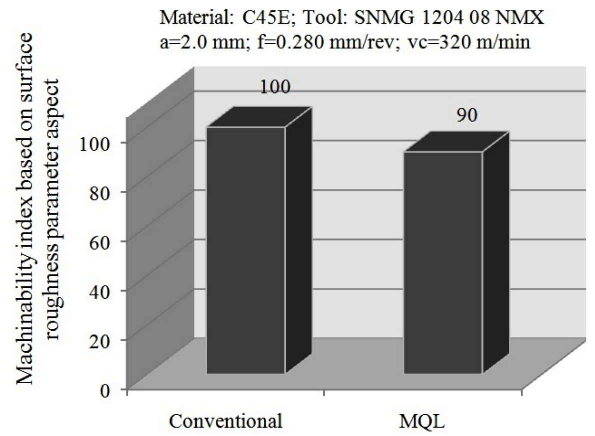


Fig. 28. Values of machinability index based on surface roughness aspect.

Exponent of ratio p_i/p_r has value of +1 in case that increase of chosen parameter has positive effect on machining process development; otherwise it is a -1 if effect is negative. Results of comparison from economic, energy consumption aspect and the aspect of quality of machining are presented in Figs. 26, 27 and 28.

5. CONCLUSION

Machinability is very important category in the industry. Based on experimental research and using the novel model, machinability of different cooling lubrication techniques can be concluded. Cutting forces, intensity of tool wear and surface roughness were used as the machinability criteria. Analysis shows that turning with MQL is a good alternative for conventional lubrication. It is important for cost of machining and for ecology as well.

Future research will be performed in area of low cost technologies, high productive and hybrid machining processes.

ACKNOWLEDGEMENT

This paper is part of project TR35034 - The research of modern non-conventional technologies application in manufacturing companies with the aim of increase efficiency of use, product quality, reduce of costs and save energy and materials, funded by the Ministry of Education and Science of Republic Serbia.

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