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Sustainable machining of the magnesium alloy materials in the CNC lathe machine and optimization of the cutting conditions

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1. Introduction

As is now universally acknowledged, our planet is suffering and the natural resources on this Earth are limited. Sustainable manufacturing necessitates conservation of both materials and energy. Sustainability is associated with environmental impact, energy consumption, operational safety, workers' health, waste management, and production costs. Sustainability is very important in the field of machining processes. In the paper are presented and evaluated two sustainable machining alternatives: dry machining and machining with minimum quantity lubrication.

Minimizing or eliminating the use of cutting fluids because of their adverse effects on health and the environment has received increasing attention since the mid-1990s. When cutting fluids inappropriately discharged, they may damage water and soil resources. On the shop floor, the workers may have respiratory and skin problems. This in turn means more economic problems for manufacturing companies. Furthermore, it has been estimated that metalworking fluids constitute about 7 to 17% of the total machining costs according to [1]. The elimination of use of cutting fluid also provides economic benefits. From sustainability point of view, avoiding the cutting fluids usage by applying dry machining applications is very beneficial. These applications improve air quality in manufacturing plants and reduce health hazards. Workers, operators are safer against to the toxicity, bacteria and fungi risks that come with wet machining. Machining is cheaper, surface quality is better and the chips are easier to recycle. The fact that near dry machining has better performance in terms of cutting forces and tool life in turning has been reported by many researchers [2].

In this study, sustainable machining processes such as Minimum Quantity Lubrication (MQL) and dry turning are chosen.

Using CNC lathe improves the sustainability of the present work [3, 4]. In order to maximize sustainability performance of this study, magnesium is selected as a workpiece material. Magnesium is a sustainable metal due to the following benefits. It's perfectly recyclable. The energy needed for the process of magnesium recycling is much lower than every other material. Magnesium is the lightest of all design metals and its high specific toughness and rigidity, good machinability make it attractive for automotive. Automotive manufacturers use magnesium automobile parts in order to lighten vehicles because weight reduction of vehicles provides fuel savings and reduction of carbondioxide released to the atmosphere. Most machining of magnesium alloys can be done dry and it is also a suitable material for minimum quantity lubrication.

This research focuses on sustainable machining of magnesium alloy at different cutting conditions by investigating dry and mql machining processes and comparing these processes through their optimum cutting parameters. In the study, External Minimal Quantity Lubrication System was used as minimum quantity lubrication system. Figure 1 show & Microdroplets sprayed by a triple concentric flow nozzle. There are one or mixture regulation units and lubricant lines with spray nozzles and a lubricant reservoir in the minimal quantity lubrication systems. The lubricant reservoir is presurized by the compressed air and lubricant is transported through a system of ducts and lines to the spray nozzle. That produces extremely fine lubricant particles with carrier air (Fig. 1) [5]. During each test, cutting temperature, cutting forces and surface roughness are measured and compared. Literature research, the experimental condition, experimental results and discussion and conclusion are presented in the following sections.

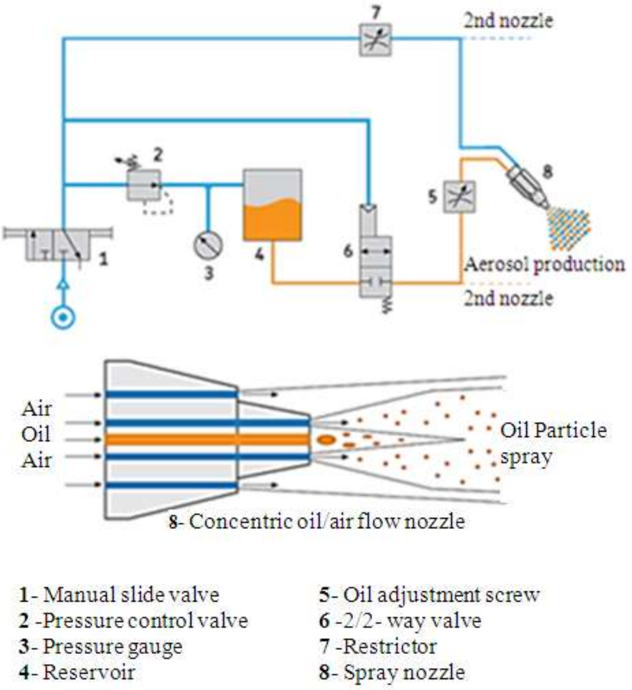

Fig. 2 External Minimal Quantity Lubrication System & Microdroplets sprayed by a triple concentric flow nozzle

Papers relating to minimum quantity lubrication (MQL) and dry turning of the magnesium material are limited and have appeared in technical literature only recently. MQL Turning quality characteristics such as cutting force, surface roughness, cutting temperature, tool wear progress, chip formation have been investigated through experimental observations in most studies [6].

M. Villeta, E. M. Rubio, J. M. Sáenz De Pipaón, and M. A. Sebastián [7-12] reported that feed rate has the greatest effect on the surface finish. Effect of feed rate on surface roughness was around 84%. Better surface finishes were obtained for lower feed rates on the magnesium workpieces. Tool coating, cutting speed, and the interaction of cutting speed with tool coating were also effective but less significant. Tools for steels (TP200 and TK2000) were better than tools for non-ferrous alloys (HX). Moreover, the variation of the surface roughness depending on the length mechanized (L) and the generatrices (G), it does not present significant variations. Interaction between the tool and the length of mechanized is not meaningful as suggesting other preliminary work.

Magnesium is generally easy to machine. But there are some critical problems in machining magnesium and magnesium alloys because magnesium has a tendency to be flammable due to the heat generated during machining process. Igniting and starting burning of the chips and dust when the high temperatures are reached is one of the most important problems. If such a fire occurs, water or waterbased coolants mustn't be used because magnesium decomposes water to form hydrogen gas.

The surface roughness using tools with round nose can be calculated as follows:

$$R_{a_{ideal}} = 0.032 f^2 / r, \tag{1}$$

where $R_{a_{ideal}}$ is surface roughness ideal, f is feed and r is nose radius of the used tool in the mechanized.

Xuhong Guo and the others presented the cutting properties of magnesium alloy AZ91D for turning using kentanium cutting tools under dry conditions. They reported that the cutting depth was the main influence factor on cutting force, followed by feed rate and cutting speed. The main form of tool wear showed to be diffusive wear and adhesive wear. The feed rate was the main influence factor on chip form and the workpiece surface roughness, cutting speed was less effective, the cutting depth was the least [13].

Friemuth and Winkler reported that DP cutting tools are better in dry machining of magnesium alloys than uncoated and TiN-coated cemented carbide tools. If diamond coatings are used, adhesion between tool and workpiece material can be avoided. Because machining forces are low by DP tools, the chip temperature and hence the danger of chip ignition can be reduced. DP-tipped tools are recommended for machining magnesium due to the resistance of DP tools against abrasion [14-18].

According to researchers [19, 20] MQL machining shows better performance than dry machining of steels. The fact that cutting temperature is lower with MQL has been revealed by the analysis of chip morphology. MQL reduces cutting force significantly by reducing cutting as a result of this, MQL increases tool life. In dry machining, more friction and adhesion between the tool and the workpiece occur because they are subjected to higher temperature because of this tool wear increases and tool life decreases. MQL provides better surface finish of the turned part.

2. Experimental equipment and procedures

In the actual work, in order to analyze machinability of magnesium in terms of cutting parameters and the cooling lubrication environments, dry machining and machining with minimum quantity lubrication were used. The chemical composition of Magnesium alloy is given in Table 1.

Table 1

Chemical composition of workpiece

Chemical composition *w* %	Mg	Ca	Mn	Cu	Fe	Si
	99.91	0.0036	0.027	0.0018	0.028	0.018
	Al	Ni	Cl	Pb	Na	Zn
	0.016	0.0007	0.0033	0.0028	0.0031	0.0028

Experiments have been carried out by turning cylindrical bars with a diameter of 45 mm and length of 290 mm of magnesium alloy in a Johnford TC 35 CNC lathe at different cutting speeds, feeds and cutting depths under dry and MQL conditions. Used cutting tools which are made exclusively by Ingersoll External Tool Holders THSNR/L. The machinability characteristics of that work piece material mainly in respect of cutting temperature, cutting forces, surface roughness have been investigated.

During each test, cutting forces, surface roughness and cutting temperature are measured and compared. The surface roughness value on the workpiece obtained after the machining process was measured by MAHR Perthometer surface roughness measuring instrument. Three measurements were performed on the machined surfaces to determine the R_a values. For the force measurements, Kistler 9121 force sensor, Kistler 5019b charge amplifier and DynoWare analysis program were used. Kistler 9121 three component dynamometer was used for turning operations. The integrated cable connected the dynamometer to the three channel charge amplifier and the output of the amplifier was connected to the data acquisition system.

Temperature measurements were taken with infrared camera in order to measure the temperature of the machined surface. The emissivity of the material affects the accuracy of the measurement results greatly. An emissivity of 0.1 and humidity of 45% were used for this study. The experiments were conducted with air pressure of 6 bars and a flow rate of 40 ml/hour through the external nozzle. Experimental set-up for turning under minimum quantity lubricant conditions was showed in Fig. 2.

Taguchi experimental design method was used for determining the settings of turning parameters. Taguchi developed several methods such as orthogonal arrays and signal-to-noise (*S/N*) ratio to evaluate and optimize products and processes.

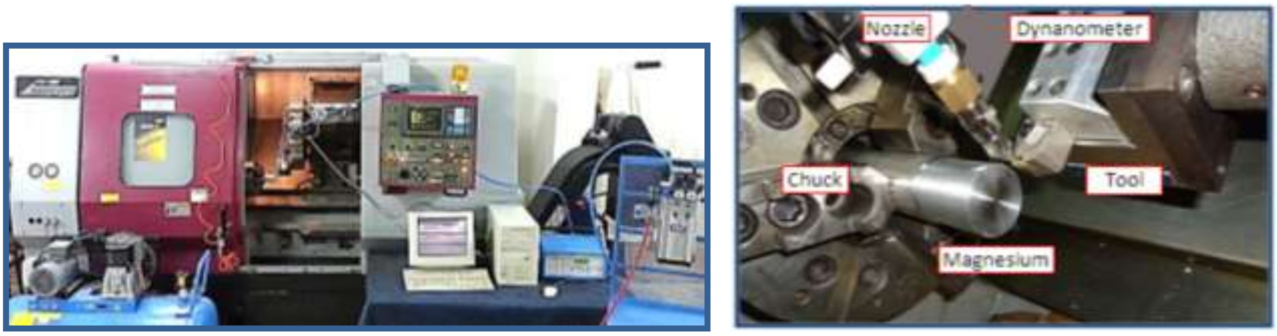

Fig. 2 Photographic view of the experimental set-up for turning under minimum quantity lubricant conditions

Taguchi Method is an experimental design technique that reduces the number of experiments significantly by using a simplified method of putting together an experiment.

After Sir R. A. Fischer had developed the concept originally in England, Taguchi added three OAs to the list. Then National Institute of Science and Technology (NIST) of the United States added three [21]. Taguchi method includes the following steps:

The first step is to select factors and their levels. In this study, the interaction between the factors is neglected. The cutting conditions in Table 2 were determined by taking into account the constraints of the measurement instruments, the recommendations of the cutting tool manufacturer and the related literature.

Table 2

Determined factors and their levels

	Factors		
	A Cutting Speed, m/min	*B* Feed Rate, mm/rev	*C* Depth of cut, mm
Level 1	230	0.20	1
Level 2	330	0.35	2
Level 3	430	0.50	3

The next step is to identify performance characteristics. The third step is to plan the experiment by appropriate orthogonal array using Minitab 16 Software.

The smallest three level OA, *L9*, has four 3 level columns. With three 3 level factors in this study, the *L9* is appropriate for the design. The factors are placed in the first three columns, leaving the fourth column unused. This design reduces 27 (3^3) configurations to 9 experimental evaluations. Experimental design is shown in Table 3.

Table 3

Experimental design according to the *L9* orthogonal array

Exp. No.	*A*	*B*	*C*
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The fourth step is to conduct the experiments. For the next step, the *S/N* ratio, the analysis of variance (ANOVA) were carried out to determine the optimum levels and to analyze the effect of turning parameters such as cutting speed, feed rate, cutting depth on surface roughness, temperature and cutting forces during dry and MQL turning. The experimental results are converted into *S/N* ratio.

The signal-to-noise (*S/N*) ratio is used to measure the quality characteristics deviating from the desired values. Usually, *S/N* ratio characteristics can be divided into three types, i.e. the-lower-the-better, the-higher-the-better, and the-nominal- the-better. The *S/N* ratio for each level of process factors is computed based on the *S/N* analysis. Whatever the category of the performance measure (quality characteristic) is the larger, *S/N* ratio is the better. Therefore, the optimum level of the process factors is the level with the largest *S/N* ratio [22-23].

The smaller the better characteristic from the Taguchi method was applied to the average roughness R_a, cutting forces, and cutting temperature.

$$S/N = -10\,log_{10}\left(MSD\right), \tag{2}$$

where *MSD* = mean squared deviation from the target value of the quality characteristic.

The value *S/N* is intended to be large, therefore the value of MSD should be small. The greater *S/N* value, the smaller the product variance around the target value is:

$$S/N_s = -10\,log_{10}\left[\left(\sum y^2\right)/n\right], \tag{3}$$

where *n* is number of tests in a trial, *y* is results of experiments.

The optimum process parameters can be predicted based on the *S/N* and ANOVA analyses. The purpose of ANOVA is to examine which cutting parameters significantly impact the quality characteristic. A statistical package (Minitab) is used to conduct analysis of variance (ANOVA). Data collected from experiments are analysed by ANOVA.

3. Experimental results and discussion

In this study, optimum settings of the cutting parameters for cutting forces, surface roughness and cutting temperature were obtained with the results of the *S/N* and ANOVA analyses.

3.1. Cutting forces

It is clear from Fig. 4 that the optimum cutting parameters for cutting forces are cutting speed at level 2, feed rate at level 1, and depth of cut at level 1 under dry conditions $A = 330$ m/min, $B = 0.2$ mm/rev, $C = 1$ mm. The predicted result for cutting force is 34.7 N for optimum cutting parameters *A2-B1-C1* under dry conditions. The main effects plot of cutting speed, feed rate, and depth of cut to cutting forces in dry turning are shown in Fig. 3.

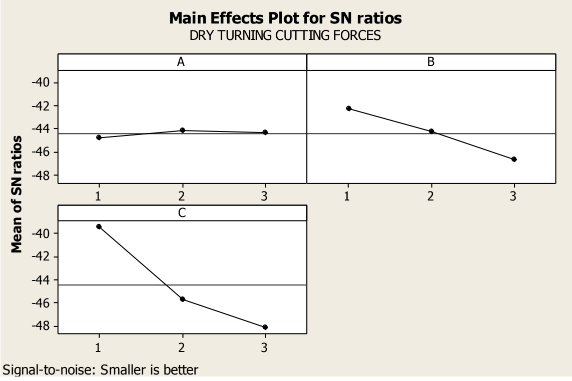

Fig. 3 Main affects plot for S/N ratios dry turning cutting forces

The optimum cutting parameters for cutting forces are cutting speed at level 3, feed rate at level 1, and depth of cut at level1 under MQL conditions $A = 430$ m/min, $B = 0.2$ mm/rev, $C = 1$ mm. The predicted result for cutting force is 46.14N for optimum cutting parameters A3-B1-C1 under minimum quantity lubricant conditions shown in Fig. 4.

The optimum cutting parameters for cutting forces are cutting speed at level 3, feed rate at level 1, and depth of cut at level1 under MQL conditions $A = 430$ m/min, $B = 0.2$ mm/rev, $C = 1$ mm. The predicted result for cutting force is 46.14N for optimum cutting parameters *A*3-*B*1-*C*1 under minimum quantity lubricant conditions shown in Fig. 4.

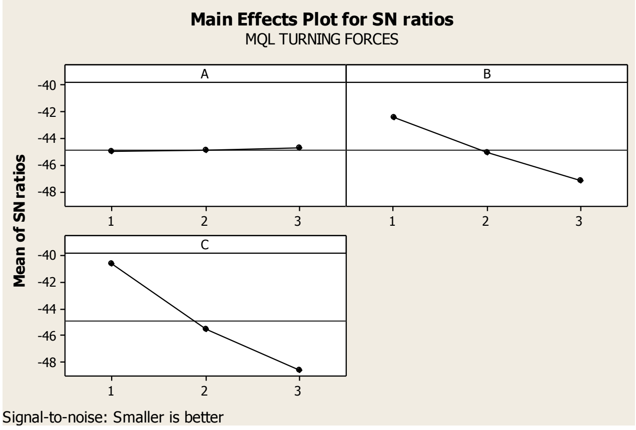

Fig. 4 Main affects plot for S/N ratios MQL turning cutting forces

The effect of minimum quantity lubrication on cutting forces under different cutting speed, feed rate and depth of cut by comparing the effects of dry conditions are shown in Fig. 5.

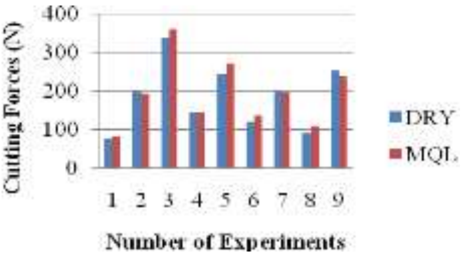

Fig. 5 Cutting forces comparison

In this study, dry conditions reduced the average cutting force by about 3.6%. But, according to the review of the literature in which steel is the workpiece material, MQL reduces the cutting forces up to 10%. Results of ANOVA indicate that depth of cut is the most significant cutting factor for affecting the cutting forces.

From the analysis for dry turning, we can observe that the depth of cut (73%), the feed rate (24%), and the cutting speed (2.4%) have significances on cutting forces, especially cutting depth. The depth of cut is the cutting condition that has highest influence on the cutting forces (72%), right after the feed rate (27%), and the cutting speed (0.5%) for turning with minimum quantity lubrication.

3.2. Surface roughness

The optimum cutting parameters are cutting speed at level 1, feed rate at level 1, and depth of cut at level 2 under dry conditions $A = 230$ m/min, $B = 0.2$ mm/rev, $C = 2$ mm. The predicted result for surface roughness is 1.31 μm for optimum cutting parameters *A*1-*B*1-*C*2 under dry conditions. (Fig. 6)

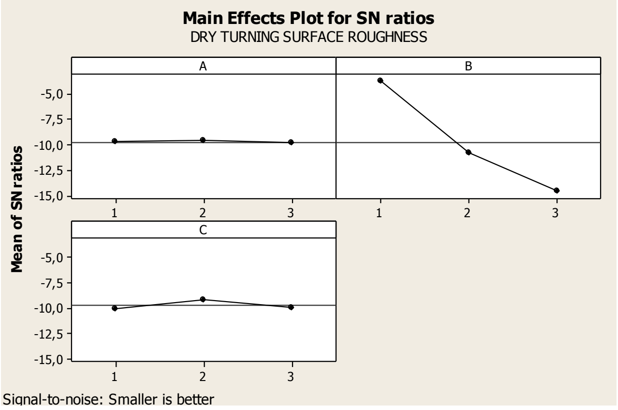

Fig. 6 Main affects plot for S/N ratios dry turning surface roughness

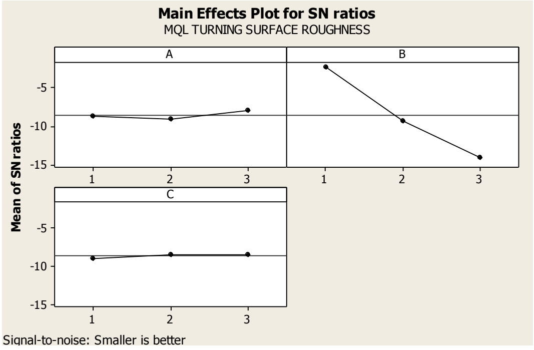

Fig. 7 Main affects plot for S/N ratios MQL turning

The optimum cutting parameters are cutting speed at level 3, feed rate at level 1, and depth of cut at level 2 under minimum quantity lubricant conditions $A = 430$ m/min, $B = 0.2$ mm/rev, $C = 2$ mm are shown in Fig. 7.

The predicted result for surface roughness is 1.16 μm for optimum cutting parameters *A*3-*B*1-*C*2 under MQL conditions.

The variation in surface roughness observed with progress of machining of the magnesium alloy under dry and MQL conditions have been shown in Fig. 8.

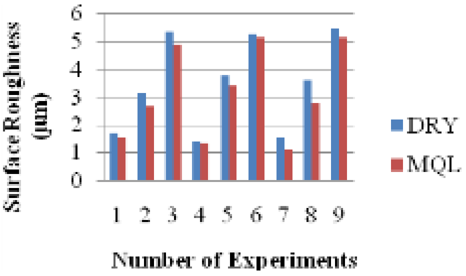

Fig. 8 Surface roughness comparison

Surface roughness was reduced by 10% with the application of MQL. The principal result is that the best surface finishes are obtained for low feeds. The best surface finish has been obtained for a feed of 0.2 mm/rev. As a result, it was observed that effect of cutting feed on roughness was great, cutting speed was less and cutting depth was the least. Compared with dry machining, surface finish substantially improved by the application of minimum quantity lubricant.

3.3. Temperature

The optimum cutting parameters for temperature are cutting speed at level 1, feed rate at level 1, and depth of cut at level 3 under dry conditions $A = 230$ m/min , $B = 0.2$ mm/rev, $C = 3$ mm. The predicted result for temperature is 107°C for optimum cutting parameters *A*1-*B*1-*C*3 under dry conditions (Fig. 9).

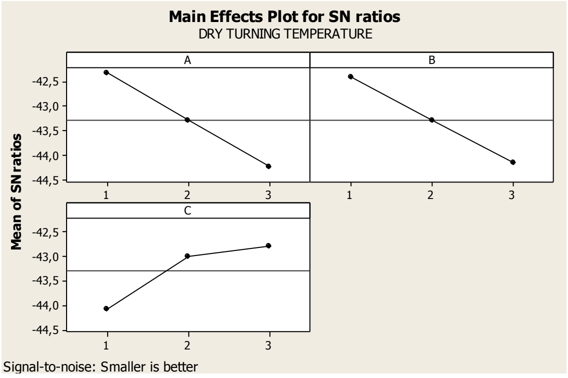

Fig. 9 Main affects plot for *S*/*N* ratios dry turning cutting temperature

Fig. 10 shows that the optimum cutting parameters for temperature are cutting speed at level 1, feed rate at level 1, and depth of cut at level 3 by using minimum quantity lubricant in turning process.

The predicted result for temperature is 63°C for optimum cutting parameters *A*1-*B*1-*C*3 under MQL conditions $A = 230$ m/min, $B = 0.2$ mm/rev, $C = 3$ mm.

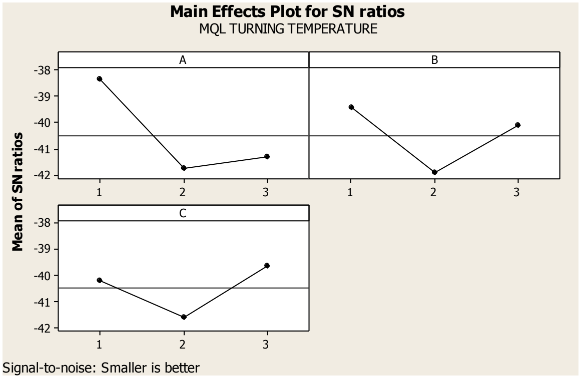

Fig. 10 Main affects plot for *S*/*N* ratios dry turning cutting temperature

The effect of MQL on temperature at various cutting speed, feed rate and depth of cut under dry and MQL condition has been shown in Fig. 11.

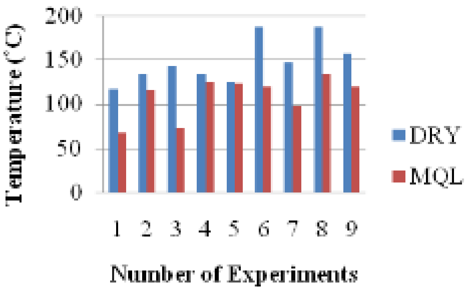

Fig. 11 Temperature comparison

The results indicate that cutting temperature is reduced by the application of minimum quantity lubrication. The cutting speed is the most significant cutting factor that influences the cutting temperature according to the results of ANOVA. Cutting speed is the cutting condition that has highest effect on the cutting temperature (55%), right after the feed rate (31%), and the cutting depth (13%) under dry conditions. According to the ANOVA for turning with MQL, cutting speed (57%), the feed rate (28%), and the cutting depth (15%) have significance on cutting temperatures. The lowest material removal rate results show lowest cutting temperature and the highest cutting temperature was obtained with the highest material removal rate.

4. Conclusions

This study focuses on sustainable machining of magnesium alloy at various cutting conditions by investigating dry and mql machining processes and comparing the effectiveness of these methods through their optimum cutting parameters. Taguchi design of experiments technique was used and repeated for each of cooling/ lubrication conditions: dry, mql machining, which were compared under the range of different cutting parameters (cutting speed, feed rate, depth of cut). Cutting forces, surface roughness and cutting temperature were measured. The following conclusions may be drawn from present study:

Based on the results mql machining process shows the better performance. Results show that even improving sustainability issues with application of mql machining, the productivity and quality of machined surface can be improved. Turning with MQL supply is more effective because MQL provides the benefits mainly by reducing the cutting temperature, which increases tool life.

All of the cutting conditions, cooling lubrication environments have effect on cutting temperature. In dry conditions, heat generation causes temperature rise at higher speeds. Friction increases, chip stick on the face of the tool and a new shearing geometry created. Build up edge (BUE) acts as a part of tool, effective rake angle increases, energy consumption drops. MQL provides flushing away chips from the cutting zone. Because one of the functions of a cutting fluid is to flush chips from the cutting zone. This function seems to be problematic with dry machining. However, tool designs have been developed that allow the application of pressurized air, often through the tool shank. The compressed air provides only limited cooling, but is very effective at clearing chips from the cutting interface.

The numbers of experiments were reduced by using the Taguchi experimental design in order to determine optimum cutting conditions in machining. Results were satisfying and they may be used for academic studies in future. From this point of view, this study is a useful application of Taguchi Methods.

The cost of manufacturing and environmental hazards can be reduced by MQL. Optimum quantity of the MQL lubrication can be investigated with further experiments.

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EFEKTYVUS MAGNIO LYDINIU APDIRBIMAS CNC STAKLĖMIS IR PJOVIMO SALYGŲ OPTIMIZAVIMAS

Reziumė

Šiame straipsnyje palygintas tekinimas minimaliai aušinant su sausu tekinimu. Magnio lydinys buvo tekinamas esant šliejimosi kampui 90º. CNC staklės panaudotos abiem tekinimo procesams. Buvo panaudota MINITAB 16 programinė įranga eksperimento planavimui. Atliekant tyrimus ruošinys buvo tekinamas 230, 330 ir 430 m/min greičiu, su pastūmomis 0.20, 0.35 ir 0.50 mm/aps ir pjovimo gyliais 1, 2 ir 3 mm. Tekinimo parametrų nustatymui panaudotas Taguchi eksperimento planavimo metodas. Taguchi vektoriai sudaryti iš santykio (*S/N*), o variantų analyzė (ANOVA) buvo panaudota optimumo radimui ir pjovimo greičio, pastūmos, pjovimo gylio įtakos paviršiaus glotnumui, pjovimo temperatūrai ir jėgoms nustatyti minimalaus aušinimo ir sauso tekinimo atvejais.

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SUSTAINABLE MACHINING OF THE MAGNESIUM ALLOY MATERIALS IN THE CNC LATHE MACHINE AND OPTIMIZATION OF THE CUTTING CONDITIONS

Summary

In this study, MQL turning performance was compared to dry conditions. The magnesium based material will be formed by applying the orthogonal cutting. The CNC Lathe shall be used for both cutting processes. The experiment used MINITAB 16 software to establish the experiment plan. In this study, workpiece was turned at cutting speeds of 230, 330 and 430 m/min, feed rates of 0.20, 0.35 and 0.50 mm/rev and cutting depth of 1, 2 and 3 mm. Taguchi experimental design method was used for determining the settings of turning parameters. Orthogonal arrays of Taguchi, the signal-to-noise (*S/N*) ratio, the analysis of variance (ANOVA) were carried out to determine the optimum levels and to analyze the influence of cutting speed, feed rate, cutting depth on surface roughness, temperature and cutting forces during dry and MQL turning.

Keywords: Dry turning, MQL (Minimum Quantity Lubrication), Magnesium, Signal to Noise Ratio, ANOVA (Analysis of Variance).

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