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Experimental study of magnesium drilling based on the surface quality

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Abstract

Nowadays, the use of magnesium and its alloys for transport applications is based on the combination of high mechanical properties and low density. In general, the machinability of these materials is considered to be good. Nevertheless, it has been reported that the machining of these alloys involves some critical problems regarding their tendency to be flammable at high temperatures and consequently, there is a risk of chip ignition in the working area during the process. This fact is especially critical when the size of chips is reduced. In this study, the influence of cutting conditions on surface roughness, in terms of *Ra*, obtained by drilling of magnesium alloy (AZ91D-F) was carried out. A factorial design 2^4 was employed for the planning of the drilling tests. The factors considered were the feed rate (0.05 and 0.2 mm/r), cutting speed, 40 and 60 m/min, the type of tool, in particular, the point angle of 118º and 135º, and the cooling system, Dry conditions and *MQL* (Minimum Quantity Lubrication) system. As main conclusions it can be affirmed that improved surface roughness is obtained with the cutting conditions selected in this study. Furthermore, at 0.05 mm/r and 40 m/min the use of tools with a point angle of 135º provides lower values of *Ra* than the tool of 118º point angle. Slightly lower values of *Ra* are obtained with tools of 118º point angle at 0.2 mm/r and 60 m/min.

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Keywords: Magnesium alloys; Dry drilling; Minimum quantity lubrication; surface roughness; Factorial design

1. Introduction

The interest towards the employment of magnesium and its alloys for transport applications has been growing in the last years, due to their low density and high specific strength, being the lightest of all the engineering metals. For such applications, weight reduction is the most cost effective option to reduce fuel consumption and CO_2 emissions [1].

In general terms, magnesium and its alloys are considered to have a good machinability; the machining process performs with the formation of short chips, long tool life, low power consumption and the achievement of improved dimensional accuracy and surface quality [2].

Nevertheless, it has been reported that the machining of these alloys involves some critical problems regarding their tendency to be flammable at high temperatures and consequently, there is a risk of chip ignition in the working area during the process. This fact is especially critical when the size of chips is reduced [3]. Also the use of water-based lubricants during the process increases the risk of the reaction with water to form hydrogen atmospheres which are highly explosive.

The addition of certain elements in these alloys can improve its machinability by the modification of its ignition temperature (430ºC). In the case of the magnesium alloy, AZ91, the ignition temperature decreases due to the presence of aluminium, meanwhile other elements such as calcium,

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berilium o itrium, allow the increment of the ignition temperature by the formation of a surface oxide layer, as it is point out in previous research [4].

In this sense, the study carried out by Rao and Li [5] shows how it is possible to increment the ignition temperature of a magnesium-aluminium alloy by the incorporation of 0.1% of rare earth elements in its composition.

Due to growing social preoccupation towards environmental conservation, recent studies [6-8] on machining of magnesium are focused on the development of cleaner production technologies as dry machining or using Minimum Quantity Lubrication, *MQL*.

The machining of magnesium alloys under dry conditions can lead to obtain poor surface quality by the adhesion of material on the tool, with a consequent reduction of tool life, and a difficult evacuation of the chips [9].The latter aspect is especially important in drilling processes in which working area is not accessible and high temperatures can be approached.

Nevertheless, it is possible to obtain favorable chips by the selection of optimum combination of cutting parameters under dry conditions as the study developed by Arai [10] shows. In addition, it is important to limit the cutting speed to avoid adhesion wear on the flank tool [11].

Furthermore, in previous research Wang and partners [12] made an evaluation of the tool wear during the dry drilling of magnesium alloy AZ91 to design a map on which, 5 wear zones were distinguished. The main wear mechanisms identified were abrasion, adhesion and diffusion. Based on that map plotted, the optimum selection of cutting parameters can be determined to reduce as much as possible the tool wear during the drilling process.

In other experimental studies in which *MQL* techniques were used, improvements over dry machining of magnesium alloys are reported. Bhowmick and Alpas [13] analysed the behavior of the NH-DLC (Non Hydrogenated Diamond Like Carbon) coated tools during the drilling of a magnesium alloy AZ91under dry conditions and with the application of water-based *MQL*. Such study reveals that the use of *MQL* reduces the adhesion of magnesium to this type of tool as well as increments tool life, being the drilling process as efficient as it was with the use of HSS (High Speed Steel) uncoated tools under conventional lubrication conditions. Also, the feasibility of using *MQL* drilling of a cast magnesium alloy AM60 was investigated by Bhowmick and partners [14] using distilled water (H_2O-*MQL*) and a fatty acid-based *MQL* fluid (FA-*MQL*) with uncoated HSS drills. In this study, other benefits under *MQL* conditions were pointed out; reduction of the cutting temperature, uniform torques and thrust forces with no abrupt increase in torque during each drilling test and the attainment of a smooth surface.

Finally, it is important to remark that the amount of research studies towards the machining of magnesium alloys are still scarce compared to those on the machining of other lights alloys such as aluminium and titanium alloys. Therefore, further research work should be developed within this area.

In this study, the influence of cutting conditions on surface roughness, in terms of *Ra*, obtained by drilling of magnesium alloy (AZ91D-F) was carried out. A multifactorial design 24 with one replication was employed for the planning of the drilling tests. The factors considered were the feed rate, the cutting speed, the geometry of the drill (different angle points) and the lubrication (under dry conditions and with MQL system).

2. Experimental methodology

The different steps carried out and the main characteristics of cutting conditions, workpiece, tools and equipment employed in this experimental study, are included in the following points:

2.1. Drilling tests

Drilling tests were planned using a factorial design of experiments 2^4 with 1 replication, these are, 32 tests. The response variable considered is the surface roughness in terms of *Ra*. The factors selected were feed rate, *f*, 0.05 and 0.2 mm/r and cutting speed, *V*, 40 and 60 m/min, and point angle of the tool, *T*, (118º and 135º) and the cooling system, *Q* (*Dry* and *MQL*).

2.2. Workpiece and tools employed

All the drilling tests were performed on a 110 mm × 62 mm × 48 mm rectangular block of magnesium alloy (AZ91D-F) (Fig. 1). Regarding the tools, two types of uncoated *HSS* (High speed Steels) drills from Phantom were employed for the tests, both with a diameter of 6 mm and different point angle, 118 and 135º, designated as PSD-HSS and PCD-HSS-E, respectively (Fig. 2).

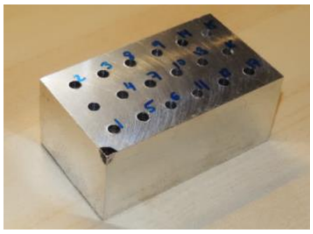

Fig. 1. Top surface of magnesium alloy block.

The performing of the tests consisted of 32 holes with a diameter of 6 mm and a length of 20 mm, drilled on both surfaces of the workpiece; 16 holes on each one. The distribution of the holes on one surface is shown in the Fig.3.

Fig. 2. Drills with point angles of 118º (on the left) and 135º (on the right).

The drilling tests were carried out on EMCO VMC100 Vertical machining center with a control EMCO TM02 equipped with a Minimum Quantity Lubrication system (Minicool Model system). A spray lubricant (r.rhenus Nor SSL) was employed with a flow rateof 50 ml/h.

For each drilling test, surface roughness measurements were taken on, approximately, the middle of the length hole.

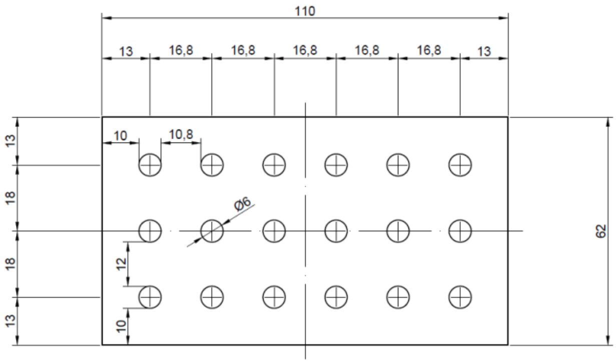

Fig. 3. Distribution of the drilling holes on one surface of the workpiece

2.3. Surface roughness measurements

The equipment used was a surface roughness tester Mitutoyo Surftest SJ 401 (Fig. 4).

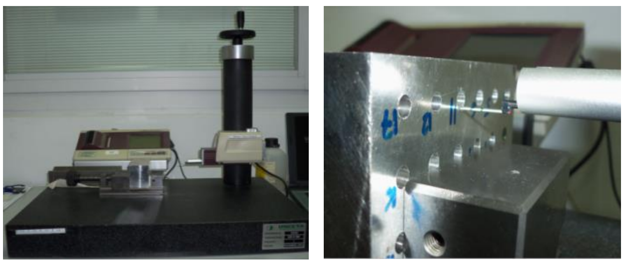

Fig. 4.a) Mitutoyo SJ-401 tester and its software Surftest SJ-401 and b) Detail of the surface roughness measurement process

2.4. Statistical analysis of the data

For analysing the results of the experimental designs by statistical tests, an analysis of variance (ANOVA) was developed by the use of the Statgraphics software.

3. Discussion of results

First of all, it can be seen that for all the drilling tests (Fig. 5), an improved surface roughness was obtained; concretely, *Ra* values from 0.13 to 0.87 µm were obtained.

The influence of the factors considered on *Ra* was evaluated by the analysis of ANOVA and is presented in Table 1, in which uniquely the influential factors are collected.

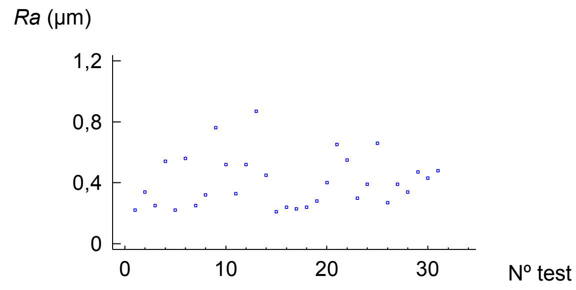

Fig. 5. Dispersion of values of *Ra* obtained in drilling tests

Table 1. Analysis ANOVA of *Ra*

Source	Sum of square	DF	Mean square	F value	p-value	P(%)
Cutting speed, *V*	0.158203	1	0.158203	10.52	0.0033	26.82
Cooling system, *Q*	0.0871531	1	0.0871531	5.80	0.0238	14.77
*f*V*	0.149878	1	0.149878	9.97	0.0041	25.41
*f*T*	0.0693781	1	0.0693781	4.61	0.0416	11.76
*V*T*	0.109278	1	0.109278	7.27	0.0124	18.52
Blocks	0.000903125		0.000903125	0.06	0.8084	
Error Total	0.375903	25	0.0150361	--	--	
Error Corr	0.950697	31	--	--	--	

The results of the ANOVA analysis show that the influent factors on *Ra* were: cutting speed, *V*, interaction between feed rate and cutting speed, *f*V*, the interaction between spindle speed and the type of tool, *V*T*, the cooling system, *Q*, and the interaction between feed rate and type of tool, *f*T*; mentioned in order of importance.

The most improved the surface roughness was approached with the use of high cutting speeds of 60m/min and *MQL* (Fig 6).

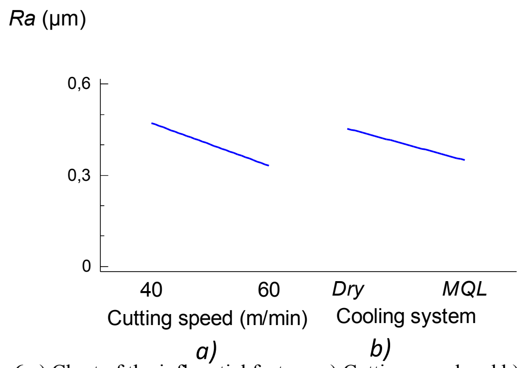

Fig. 6.a) Chart of the influential factors: a) Cutting speed and b) Cooling system

It is important to remark that feed rate had an influence on the *Ra* in relation with the spindle speed and type of tool, *f*V* and *f*T,* as it is shown in Fig. 7.

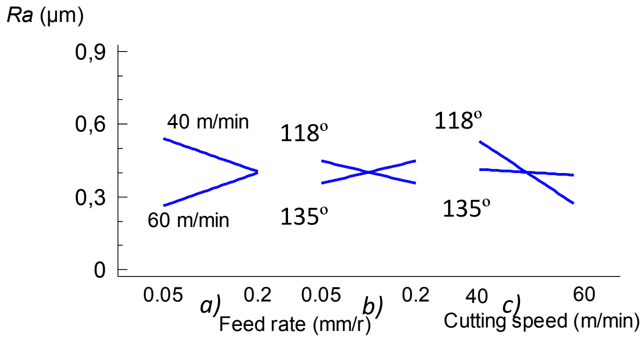

Fig. 7.a) Chart of the interactions of a) feed rate and cutting speed, b) feed rate and tool and c) cutting speed and tool

With respect to the interaction with the cutting speed at the higher feed rates, 0.2 mm/rev, similar values of *Ra* were obtained, around 0.4 µm. Thus, at low feed rates 0.05, lower *Ra* was achieved (less than 0.3 µm) with higher cutting speeds of 60 m/min (Fig. 7, a). At such cutting conditions, it is important to indicate that the chips obtained were less favorable; this is the formation of long chips that are difficult to evacuate and could deteriorate the surface roughness in some part of the drilled hole (Fig 8).

Fig. 8. Chip obtained at 0.05 mm/r and 60 m/min under dry conditions with the tool with a point angle of 118º

Regarding the interaction feed rate and the tool, it can be observed opposite behaviors of tools, in a way that lower *Ra* was obtained at lower feed rates with the tools of point angle of 135º, meantime, at higher feed rates, the most improvement of surface roughness was obtained with the other tool (Fig. 7, b). The same tendency can be seen from the interaction of the tool and the cutting speed (Fig 7, c). In this sense, the selection of a drill with lower point angle, 118º, results more advantageous from the point of view of the productivity in those applications in which high level of surface quality are required, as both higher feed rates and cutting speeds contribute to reach lower surface roughness. Though this tendency is slightly notable as it can be observed in the following box and whisker graphics, in which the dispersion of *Ra* values is plotted regarding the feed rates and cutting speeds employed. This is, in Fig. 9 and Fig. 11. Meanwhile, at low values of feed rates and cutting speeds with tool of 135º the dispersion of *Ra* was highly different (Fig. 8 and Fig. 10). Under such as cutting parameters the use of these tools (135º point angle) presents a more stable behavior independently of the other cutting conditions selected.

Ra (µm)

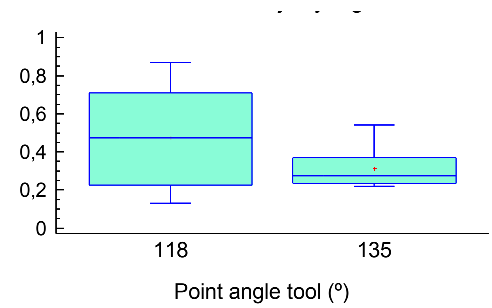

Fig. 8. Box and whiskers graphic of *Ra* obtained at feed rates of 0.05 mm/r for each tool

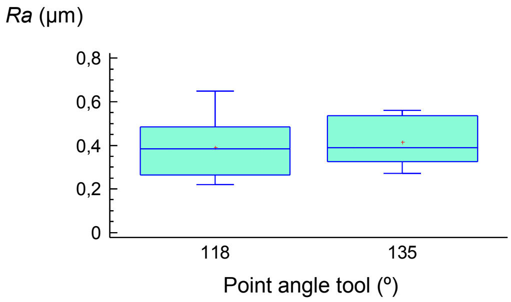

Fig. 9. Box and whiskers graphic of *Ra* obtained at feed rates of 0.2 mm/r for each tool

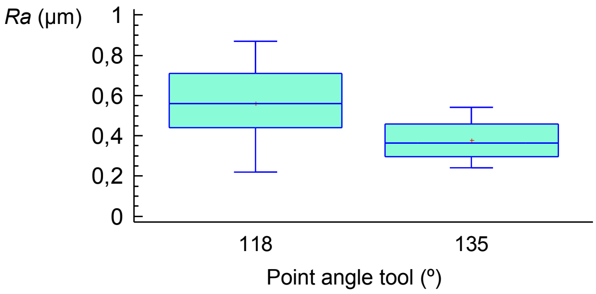

Fig. 10. Box and whiskers graphic of *Ra* obtained at cutting speeds of 40 m/min for each tool

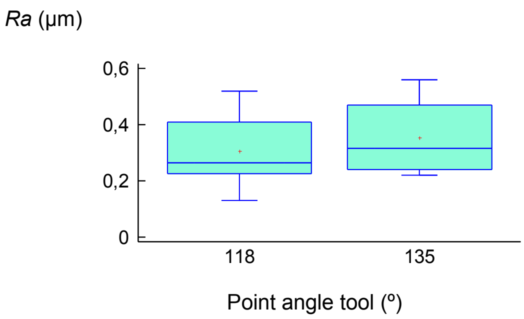

Fig. 11. Box and whiskers graphic of *Ra* obtained at cutting speeds of 60 m/min for each tool

4. Conclusions

An experimental study was carried out for the analysis of the machinability of a magnesium alloy under Dry and *MQL* conditions. A design of experiments was applied to evaluate the influence of feed rate, cutting speed, geometry of the drill (point angle) and the cooling system (Dry and *MQL* conditions) on the surface roughness, in terms of *Ra*, obtained by drilling processes of a magnesium alloy (AZ91D-F).

The main conclusions extracted from this study are:

For all the cutting conditions selected this study, improved surface roughness is obtained.

The factors and interactions that are statically influent on *Ra* are in order of importance: cutting speed, interaction between feed rate and cutting speed, the interaction between spindle speed and the type of tool, the cooling system, and the interaction between feed rate and type of tool.

The use of the higher cutting speeds and *MQL* system improve surface roughness as long as the value of cutting speed does not exceed certain magnitude.

The most improved surface roughness is achieved at the higher cutting speed and lower feed rate employed in this study. Nevertheless, under such conditions, unfavorable chips are obtained that can deteriorate in part the surface drilled.

The selection of a drill with lower point angle of 118º results more advantageous from the point of view of the productivity in those applications in which high level of surface quality are required, as higher feed rates and cutting speeds contribute to reach lower surface roughness.

5. Acknowledgements

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