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Tool Selection in Drilling of Magnesium UNSM11917 Pieces under Dry and MQL Conditions based on Surface Roughness

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Abstract

Nowadays, the use of lighter materials for transportation purposes is still a challenge; especially in the aeronautical and aerospace sectors. The use of certain materials, such as magnesium alloys which have exceptional mechanical properties relative to density as structural materials, allows a remarkable reduction of weight. These alloys have significant challenges in machining. On the one hand, their use with water-based lubricants can produce flammable hydrogen atmospheres and, on the other hand, the operational parameters can produce tiny chips which, at high temperature, could burn. Regarding the tools, drills are the most used ones in drilling operations; manufacturers do not always take in consideration magnesium alloys. This is why, sometimes, the data from other types of similar alloys need to be extrapolated. This work shows an experimental study about the drilling of magnesium pieces based on surface roughness. The main goal is to determine the tools that best suit the requirement of surface roughness for this type of operations, which, for the aeronautical sector, is from 0.8 to 1.6 µm. The tests have been conducted under different cutting conditions, using several types of tools and two sustainable lubrication systems. In particular, dry machining and minimum quantity of lubrication (MQL) system have been used. A design of experiments (DOE) has been used to optimize the resources. The average roughness, *Ra*, has been selected as a response variable. The roughness values obtained are lower than 0.9 µm (namely, from 0.13 µm to 0.87 µm); so, it is possible to increase some of the parameter values, in order to improve the productivity, without they go outside the established limits. The results have been analyzed using the analysis of variance (ANOVA) method. A model for estimating the expected surface roughness in terms of the *Rae*, has been developed.

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Keywords: magnesium alloys, dry drilling, Minimum Quantity Lubrication, surface roughness, tool selection

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1. Introduction

In recent years, there has been a growing interest in the application of structural materials which allow weight reduction in the aeronautical and automotive sectors. Such materials, on the one hand, provide lower fuel consumption and, on the other hand, allow the reduction of pollutant emissions. In this sense, the interest in the use of magnesium, as a substitute for traditional structural materials, has grown considerably, mainly due to its low density [1].

The main primary use of magnesium is that of an alloying element in aluminum alloys and in the desulfurization of steel and ductile iron. In terms of its use as a structural material, it is mainly formed by casting, having about 70% processed by casting permanent mold, from which the automotive industry requires around 85% of this production [2]. After this primary processing, subsequent machining operations are necessary being, in most cases, drilling one of the most common [3].

Magnesium alloys are considered one of the easiest metals to machine. This is due to the combination of several factors such as low forces during the machining, low temperature increments in the cutting area, improved surface finish, short chips, high tool life and the possibility of machining under dry conditions. This good machinability allows the execution of all common machining operations and, at the same time, the use of high values of feed rate and cutting speed, which allows high values of material removal rate, maintaining strict tolerances [4].

Nevertheless, there are two potential risks in the machining of magnesium alloys; the danger of ignition when chips reach temperatures of 450ºC and the danger of explosion when the size of magnesium particles is lower than 500 μm. Furthermore, water can react to magnesium, forming atmospheres of hydrogen, which are flammable and potentially explosive [5]. Due to these potential dangers, the selection of the proper system of lubrication is very important. Taking into account the improved machinability of magnesium alloys and considering the risks aforementioned, the machining of these materials with no cutting fluids or with Minimum Quantity Lubrication (MQL), can be considered as an alternative to the cooling/lubrication systems with an aqueous base.

In the main studies on drilling operations of magnesium alloys, cutting speed and feed rate ranges are set between 35 and 188 m/min, and feed rates between 0.05 and 0.7 mm/r, respectively [1]. This implies that the focus is placed on cutting parameters of low performance, which are framed within the context of this work and it possible to avoid the risks inherent to the machining of these alloys.

The production of magnesium covers the manufacturing from large series to single parts, as, for example, in repair or maintenance operations. In the aeronautical sector, commonly unique pieces without spare parts are machined. As a result, the selection of the most adequate cutting conditions is key to reach the dimensional characteristics and surface roughness quality within certain limits in order to maintain their functionality [5].

Gariboldi [6] has studied the dry drilling operations of magnesium with twist drills with PVD coating. This study reveals that tool failure occurs due to the adhesive action of magnesium. The adhesive layer appears and progresses depending on feed rate and has, therefore, an influence, in the same way, on the surface quality of the drills. The application of feed rate of 0.37 mm/r and cutting speed of 63 m/min with the use of coated drills, the tool life reached the high value and the surface roughness was maintained within adequate margins. In addition, the adhesions varied depending on the type of coating used and the cutting parameters.

Regarding the forces and moments during the drilling of magnesium, the study carried out by Weinert [3] shows that, the values are almost constants in the range of cutting speeds from 100 to 700 m/min and depend on the value of the feed rate. In addition, the influence of different types of geometries of the drills was analyzed and it was pointed out that the minimum force value was obtained with the type N or normal twist drill, being approximately 1.5 times lower than the others. Meanwhile, the obtained torque values, at feed rates lower than 0.4 mm/r, were approximately equal in all three types of drills. Regarding the surface quality, at cutting speeds of 500 m/min the increase of the feed rate reduced the surface roughness quality. It is also important to remark that, in the study, two types of lubrication, emulsion and cutting oil, were used, not having important differences on the surface roughness.

Bhowmick and his partners [7] studied different lubrication systems: dry, MQL with cutting fluid, MQL with water and by flood with oil. Important advantages were found using MQL lubrication with cutting fluid, in terms of: improving the surface roughness, diminishing torque, obtaining lower temperatures, increasing superficial hardness, obtaining uniform forces and torques, and achieving a lower amount of adhered magnesium to the drill. In addition, similar values of surface roughness were obtained with all the cooling/lubrication systems employed, except when dry machining was used. Under these conditions, higher *Ra* values were obtained.

Due to the fact that the use of magnesium alloys is not as widespread as other light alloys such as aluminum alloys, the manufacturers of drills do not always include them in their catalogs as a specific type of material. They are normally included together with the aluminum alloys, having different behaviors in terms of machinability. Thus, taking into account the recommendations from manufacturers, the drills recommended for machining magnesium alloys are made for a wide field of applications, with different geometries.

Previous studies have analyzed the influence of tools, drills with different geometries, sizes and coatings [3], the most prominent varying the point angle and helix angle. Based on this work, it can be stated that the best results were obtained when drills with normal helix were used. Besides, the increment of the point angle deteriorates the surface quality, and consequently, different force and torque values are registered.

In the present study, the influence of point angle of drills on the surface quality was analyzed, considering the main factors, namely: feed rate, cutting speed and using environmentally sustainable lubrication systems. For this purpose, an experimental design was developed with 4 factors and 2 levels, making a replica of it. The objective was to determinate the tool which allowed obtaining the requirements of surface roughness owned by the aeronautical applications under the different cutting conditions used in this study.

2. Materials and experimental procedures

2.1. Workpiece and cutting tool

In this study, twist drills were used, manufactured by Van Ommen (Nederlands), in HSS steel, according to DIN 1897. The geometric characteristics are; diameter of 6 mm, straight shank, total length of 66 mm and, flute length of 28 mm. Point angles of 118º and 135º were employed (Fig. 1).

Fig. 1. Drills with point angles of 118º (on the top) and 135º (on the bottom).

The workpiece is a die casting magnesium alloy UNS M11917 that was mechanized in a rectangular block of 110 x 62 x 50 mm. Its composition in percentage of mass is 8.5-9.5% Al, <0.03 Cu, <0.005% Fe, >0.13% Mn <0.002 Ni, <0.1 Si, 0.35-1% Zn and the mechanical properties are listed in Table 1.

Table 1. Mechanical properties of die casting magnesium alloy UNS M11917.

Brinell hardness	63 HB
Tensile strength	230 MPa
Yield strength	173 MPa
Elongation	3.0 %
Modulus of elasticity	44.8 GPa
Charpy impact	2.7 J

2.2. Drilling test

All drilling tests were carried out using a vertical machining center EMCO VMC100, with a maximum power of 800 W and a maximum rotational speed of 4000 r/min, equipped with a computer numerically controlled (CNC) EMCO TM02 (Fig. 2).

Fig. 2. EMCO VMC100 vertical machining center

Drilling tests were performed with two different types of lubrication. One of them, without using any cooling/lubrication system and, the other one, using an external Minimum Quantity of Lubrication system Noga Minicool (Fig. 3), at a rate of 50 ml/h (3.6×10^{9} ml/h = $1m^3/s$). The MQL fluid was r.rhenus Nor SSL with a kinematic viscosity at 40ºC of 4.7×10^{-5} m^2/s and a density at 20ºC of 920 kg/m^3.

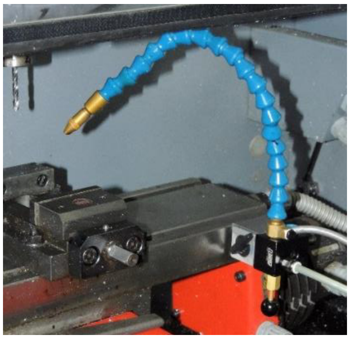

Fig. 3. Noga Minicool MQL system.

Cutting parameters were established according to previous studies towards magnesium drilling [6-8], as shown in Table 2. The point angles were set according to the manufacturer's recommendations and the type of material considered. The systems of lubrication were established taking into account the framework of this study, and keeping close in mind safety and environmental conditions. Therefore, MQL system and dry machining were used as cooling/lubrication methods.

Table 2. Process factors and levels

Factor	Parameter	Levels	
γ	Point angle (º)	118	135
S	Cutting speed (m/min)	40	60
f	Feed rate (mm/r)	0.05	0.2
L	MQL flow (ml/h)	0	50

Design of experiments (DOE) is an analysis tool for analyzing and modeling the influence of process parameters over the response variable. It allows optimizing the response as a function of these parameters. In this study, our aim is to find the influences of point angle, feed rate, cutting speed and lubrication over the surface quality.

Drilling experiments were conducted using a factorial design of experiments, 2 levels and 4 parameters (2^4), with 1 replication. The factor considered for evaluating the surface quality was the surface roughness. It is one of the main features that being tracked in drilling process [3]. It was quantified by the arithmetical average roughness, *Ra*, which is defined as the arithmetical average of the absolute values of the deviations of the profile of roughness *R* [9]. It is calculated by equation 1.

$$Ra = \frac{1}{l_m}\int_0^{l_m} |Z(x)| dx \tag{1}$$

Complete experiment consisted of 32 holes, that were machined on both sides, top and bottom, of the magnesium block by drilling to a depth of 20 mm (approximately 3 times its diameter), with a minimum center to center spacing of 17 mm between each two holes, it is shown in Fig. 4. After that, machined holes were cleaned of all traces of chips and loose particles, by compressed air and ethanol.

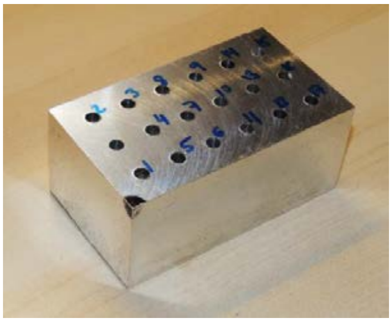

Fig. 4. Top surface of magnesium alloy block.

Surface roughness was measured using a contact surface tester Mitutoyo Surftes SJ 401, this shows directly the calculated values of *Ra* in a display. Measurements were made at a depth of about 10 mm, placing the magnesium block and tester on a surface plate.

The analysis of the results obtained of the experimental design was made by the statistical method of analysis of variance (ANOVA), also a multiple regression model was built to make predictions about surface roughness at the intervals considered.

3. Results and analyses

After completing the machining operations, the next step of the experimental methodology consisted of measuring the surface roughness of all drilled holes. The results of each measurement are shown in Table 3. From the results, it can be checked that the minimum obtained surface roughness is 0.13 μm and the maximum is 0.87 μm. These results show that all selected cutting conditions provide an excellent roughness quality, taking into account that the range of values established for the aeronautical sector is from 0.8 to 1.6 μm [10]. So that, in many cases, the application of higher feed rates and cutting speeds could be possible. This is desirable from the point of view of time machining

The most improved combination of factors, in terms of the surface quality, obtained were: feed rate of 0.05 mm/r, cutting speed of 60 m/min, MQL lubrication system and, a point angle of 118°, obtaining *Ra* values of 0.13 μm and 0.24 μm.

Table 3. Process factors and levels

Test No	Feed rate, *f* [mm/r]	Cutting speed, *S* [m/min]	Cooling system, *L* [ml/h]	Point angle, *γ* [°]	*Ra* [μm]
1	0.05	60	50	118	0.13
2	0.05	60	50	135	0.22
3	0.05	40	50	135	0.34
4	0.2	60	50	118	0.25
5	0.05	40	0	135	0.54
6	0.2	40	50	118	0.22
7	0.2	60	0	135	0.56
8	0.05	60	0	135	0.25
9	0.2	40	50	135	0.32
10	0.05	40	0	118	0.76
11	0.2	40	0	135	0.52
12	0.2	60	50	135	0.33
13	0.2	60	0	118	0.52
14	0.05	40	50	118	0.87
15	0.2	40	0	118	0.45
16	0.05	60	0	118	0.21
17	0.05	60	50	118	0.24
18	0.05	60	50	135	0.23
19	0.05	40	50	135	0.24
20	0.2	60	50	118	0.28
21	0.05	40	0	135	0.40
22	0.2	40	50	118	0.65
23	0.2	60	0	135	0.55
24	0.05	60	0	135	0.30
25	0.2	40	50	135	0.39
26	0.05	40	0	118	0.66
27	0.2	40	0	135	0.27
28	0.2	60	50	135	0.39
29	0.2	60	0	118	0.34
30	0.05	40	50	118	0.47
31	0.2	40	0	118	0.43
32	0.05	60	0	118	0.48

The *Ra* measurements were evaluated by the analysis of ANOVA in the Minitab 17 package program, and are presented in Table 4. First column collects influential main factors and interactions, followed by sum of squares, degree of freedom, mean squared, F value and p-value. The last one shows the percent contribution *P* of the factors that was statistically influential on the surface roughness.

This experimental study shows that cutting speed, *S*, and type of lubrication, *L*, were influent on the surface roughness as main parameters, but nevertheless feed rate *f* and tool geometry *γ* did not; so, they were removed and a new ANOVA was made. Regarding the interactions, feed rate and cutting speed, *f*S*, feed rate and tool geometry, *f*γ* and, cutting speed and tool geometry, *S*γ*, were also statistically influent.

Firstly, it is noteworthy that, unlike previous works, feed rate does not have direct influence on the surface roughness [3,6]. These results can be explained by the relatively low values of cutting speeds and feeds employed.

Table 4. Analysis ANOVA of *Ra*.

Source	Sum of square	D.F.	Mean square	F value	p-value	*P* (%)
Cutting speed, *S*	0.158	1	0.158	10.52	0.003	26.82
Cooling system, *L*	0.087	1	0.087	5.80	0.023	14.77
*f*S*	0.149	1	0.149	9.97	0.004	25.41
f γ*	0.069	1	0.069	4.61	0.041	11.76
S γ*	0.109	1	0.109	7.27	0.0124	18.52
Error	0.375	26	0.015	0.06	0.808	
Total	0.950	31				

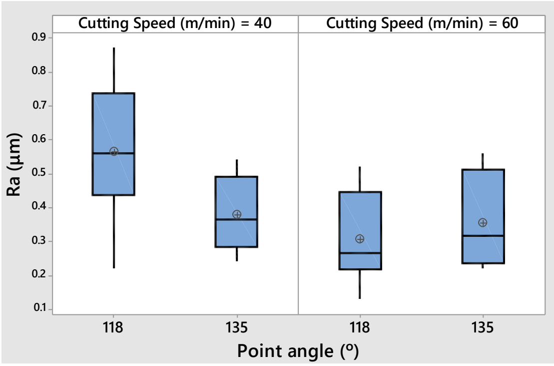

Fig. 5. Box and whiskers graph for point angles and cutting speed.

At the values of feed rate applied, the cutting speed has a great influence on *Ra*, with a contribution of about 27%. In general, the use of higher cutting speed of 60 m/min, improved the surface roughness. Nevertheless, it is important to remark the different behaviors of tools with respect the cutting speed as it is shown in Fig. 5. At a cutting speed of 40 m/min, the lower values of *Ra* were obtained with the use of point angles of 135º. Meanwhile, at high cutting speed of 60 m/min with the tools of point angle of 118º values slightly lower were achieved (Fig. 4). Furthermore, the use of MQL improves roughness compared with dry machining, in both cutting speeds. The interaction between feed rate and cutting speed, *f**S*, is the second influent factor in importance. At lower cutting speed, with the application of higher feed rates of 0.2 mm/r, surface roughness obtained was lower and, at 60 m/min, this tendency changes, this is the surface roughness increases with feed rate. This behavior could be explained by the formation of long chips generated in machining holes with a feed of 0.05 mm/r, which are more difficult to evacuate, that could damage the machined surface and thereby, increase the surface roughness.

The effect of the interaction between feed rate and point angle, *f**γ*, has the same influence tendency (in a lesser extent) on *Ra* than the interaction, *S**γ*, and it is shown in Fig. 6. This is, at a feed rate of 0.05 mm/r, the use of drills with a point angle of 135° improves the surface quality, while at a feed rate of 0.2 mm/r an improvement is not achieved. Using drills with point angles of 118°, surface roughness was reduced by increasing the feed rate from 0.05 to 0.2 mm/r.

In this sense, the selection of drills with a point angle of 118° using higher cutting speeds and feed rates, are more advantageous in applications in which a better surface quality is needed. Thus, to achieve lower values of *Ra* with drills with a point angle of 135° it is necessary to use a feed rate of 0.05 mm/r.

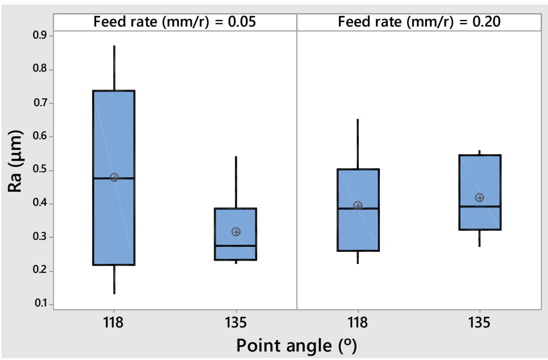

Fig. 6. Box and whiskers graph for point angles and feed rate.

In each mechanized hole, the type of chips was analyzed; being, in most cases, short chips with a shape of cylindrical or cone of about a diameter of 2 mm and a length of 3-4 mm and other powdered (Fig. 7a). However, in some drilling tests, at feed rates of 0.05 mm/r, long chips were generated (Fig. 7b).

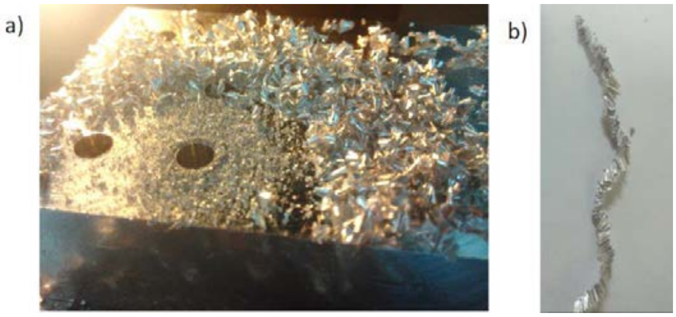

Fig. 7. Chips obtained in drills number a) 5, b) 32.

Although the length machined by each twist drill is very short (20 mm), focusing the attention on the margins, it clearly appears the meaning effects of the adhesive wear (Fig. 8). Nevertheless, it cannot be observed neither on the cutting edge nor flank or rake face. These adhesions have been referenced in previous works in which it is remarked an earlier formation of build-up layer of magnesium on the margin and the layer extension from the margin to the rake face [6,7]. Thus, heating the AZ91 alloy during drilling resulted in the reduction of the alloy´s hardness and promoted adhesion of softened material on the drill [11].

Adhesions were found using a visual inspection in the margin of drills, in tests numbers 1, 8, 16, 17, 24 and 32. All of them were taken place at a cutting speed of 60 m/min and a feed rate of 0.05 mm/r. All using dry machining, except in the test number 1, in which drilling test was performed under MQL lubrication. Contrary to what can be initially assumed, the measured *Ra* in those tests was lower than in the others, and therefore adhesion had an effect of improving the surface roughness. This result has been encountered in alloys with similar properties in their machining, such as aluminum alloys [12,13].

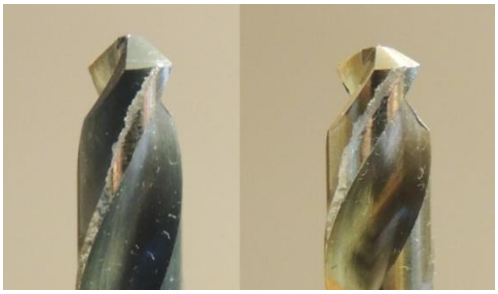

Fig. 8**.** Adhesions in drills number 16 (on the left) and 8 (on the right)

A linear multivariable predictive model of surface roughness was developed. It is presented in equation 2. This equation is based on the cutting conditions using in this work, i.e. cutting speed, feed rate, cooling/lubrication system and point angle, in which feed rate and point angle have been kept to maintain the hierarchy model, cooling/lubrication system is expressed in coded units. Correlation coefficient of this equation was calculated as R^2 = 0.64, which implies the existence of parameters not taken into account that affect the response variable.

$$R_{ae} = 7.34 - 13.75 f - 0.1054 S - 0.0522 L - 0.0476\gamma + 0.0912 f \cdot S + 0.0730 f \cdot \gamma + 0.000688 S \cdot \gamma + \varepsilon \qquad (2)$$

Table 5 shows the experimentally measured value of surface roughness, *Ra*, the estimated values obtained using equation 2, *Rae*, and the residual. Furthermore, in Fig. 9, the values of *Ra* and *Rae* are plotted for each tool.

Table 5. Measured and estimated *Ra* values and residual.

Test No	*Ra* [μm]	*Rae* [μm]	Residual	Test No	*Ra* [μm]	*Rae* [μm]	Residual
1	0.13	0.228	-0.098	17	0.24	0.228	0.011
2	0.22	0.182	0.0375	18	0.23	0.182	0.047
3	0.34	0.343	-0.003	19	0.24	0.343	-0.10
4	0.25	0.280	-0.030	20	0.28	0.280	-0.00
5	0.54	0.447	0.0925	21	0.40	0.447	-0.04
6	0.22	0.400	-0.180	22	0.65	0.400	0.249
7	0.56	0.525	0.0350	23	0.55	0.525	0.025
8	0.25	0.286	-0.036	24	0.30	0.286	0.013
9	0.32	0.307	0.0125	25	0.39	0.307	0.082
10	0.76	0.726	0.0331	26	0.66	0.726	-0.06
11	0.52	0.411	0.1081	27	0.27	0.411	-0.14
12	0.33	0.420	-0.090	28	0.39	0.420	-0.03
13	0.52	0.384	0.1356	29	0.34	0.384	-0.04
14	0.87	0.622	0.2475	30	0.47	0.622	-0.15
15	0.45	0.505	-0.055	31	0.43	0.505	-0.07
16	0.21	0.332	-0.122	32	0.48	0.332	0.147

The use of both type of drills obtained an excellent surface quality reaching minimum values of approximately of 0.2 μm. Nevertheless, it can be observed that due to the lower difference of range of values of obtained *Ra* (from of 0,4 μm), that in general the behavior of the tools with the angle point of 135º, at this excellent level of surface roughness, was slightly more improved. As similar values of *Ra* were obtained independently of the cutting conditions selected.

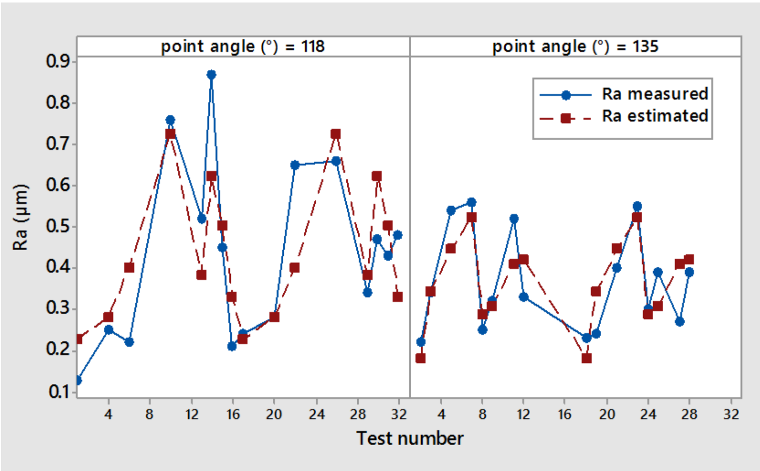

Fig. 9. Measured and estimated *Ra* for different point angle.

Finally, based on the predictive model of *Ra*, considering two ranges of *Ra* (as close as possible to the aeronautical surface requirements), this is values from 0.5 to 0.6 μm and values higher than 0.6 μm, a selection of the tool is proposed for each cutting conditions and collected in the Table 6.

Table 6. Selection of the best tools for each combination of the cutting conditions.

Range of *Ra* [μm]	Feed rate [mm/r]	Spindle speed [r]	Cooling system [ml/h]	Tool angle point [º]
0.5<*Ra*<0.6	0.2	60	0	118
	0.2	40	0	135
	0.05	40	0	135
	0.2	60	0	135
	0.2	60	0	135
Ra>0.6	0.2	40	50	118
	0.05	40	50	118
	0.05	40	0	118
	0.05	40	0	118

3. Conclusion

The main conclusions extracted from the work are:

- The minimum and maximum *Ra* values obtained in this study are 0.13 μm and 0.87 μm respectively.
- The combination of cutting parameters that provides the optimal *Ra* value (the lowest one) is: 60 m/min, 0.05 mm/r, MQL and 118º.
- The statistically influent factors on the surface roughness, from highest to lowest, are: cutting speed, interaction of cutting speed*feed rate, interaction of cutting speed*point angle, cooling/lubrication system, and interaction of point angle*feed rate.
- In order to achieve the lowest surface roughness using MQL system, tools with point angle of 118º are the best options at higher cutting speeds while, at lower cutting speeds, tools with point angle of 135º are better.
- Low surface roughness values (<0.9 μm) can also be achieved by dry drilling; being, this, the most sustainable solution.
- All the tests have been carried out under safety conditions since the low parameters values used that serve to prevent the chips ignition.
- A linear multivariable predictive model of surface roughness has been established that can be used for selecting the best tool, for a certain range of *Ra*, in the drilling process once the rest of parameters have been fixed.

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