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STUDY OF THE DRILLING PROCESS IN BIMETALLIC MATERIALS WITH DIFFERENT HARDNESS USING A FULL FACTORIAL DESIGN

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Abstract. *Drilling process is amongst the cutting processes more used in modern industry. Nowadays, all industrial components have a hole to allow the assembly of two or more parts. However, drilling is a process difficult to be monitored due to the enclosure of the tool into the hole. Based on this, drills with a small-diameter increase the difficulty and control of the process during the cut in drilling process. It occurs because the difficulty of extraction of chip increases as the hole diameter decreases. This work shows a study of the drilling process in bimetallic materials with drills of 3.5 mm in hardened materials. Three cutting speeds, two feed rate and two cooling systems were used as input parameters. The responses were torque, thrust force, diameter variation, and burr formation. The results showed that feed rate and cutting speed are the input parameter more significant on thrust force and torque. The cutting speed and feed rate were also the most important values to minimize the burr formation.*

Keywords: *Burr, Drilling, Torque, Thrust force, Roughness surface.*

1. INTRODUCTION

Drilling is widely used as a machining process because the industrial parts have a hole to allow the assembly of components. Moreover, drilling has great economic importance, mainly because it is usually among finishing steps in the production lines. However, according to Li et al. (2007) the tool geometry and material deformation in drilling are complicated of the complete understand. It occurs due to in the center of the drill the cutting speed is zero, and the material is plowed under a high negative rake angle.

The monitoring of drilling parameters is very difficult due to the complex geometry of drills. Cutting speed and feed rate are two important process parameters to achieve the desired material removal rate (MRR) and productivity in drilling. Torque and thrust force are responses main in the research to define and optimize the material and drill geometry. Generally, drilling process is carried out applying cooling systems, but due to environmental requirements, the use of coolants in drilling is being questioned in order to be decreased.

Authors as Li et al. (2007), Strenkowski et al. (2004), Laporte et al. (2009), and Lei and Liu (2002) have been studied torque and thrust force in drilling of materials hard-to-cut in the conditions dry flooded. The authors used experimental tests and simulating to study the influence of input parameters on torque and thrust force. The study shows a feasibility and importance of feed rate and internal cutting fluid supply to improve the drill life. It demonstrates that the feed rate and cooling system are important input parameters that must be controlled to optimize the drilling.

Wang and Zang (2008) studied the influence of drill geometry on thrust force and torque. The authors support that cutting speed has only a marginal effect on the thrust force and torque for the both types of drills used in experimental tests. Thus, it can be found that both thrust force and torque increase almost linearly with an increase in feed per revolution. The sharpness and geometry of drills are the most important parameter to optimize the torque and thrust force in the process. According to Paul et al. (2005) the rake angle distributions indicate that the optimized drills have increased rake angles and show reduced forces using HSS drills with TiN coating.

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It can be supported that the control of the input parameters affects directly not only the torque and thrust force but also the burr formation. The burr is the most undesirable structure formed in machining processes. The burr formation requires steps after the finishing that increase the costs of the machining process. In some cases, special tools need to be developed to eliminate burrs and this process is called deburring. Kim and Dornefeld (2001) support that the cost of drilling operation consists of hole makind and deburring. The authors used Bayesian statistics applied to predict the probability of formation of certain types of burrs, and the method can be used to minimize the total cost of a drilling operation with productivity and hole quality.

According to Lauderbaugh (2009) drilling is the machining process that has a large burr formation mainly in the drill exit of parts. It occurs due to the tearing model of the material whom generates high speed cutting nearest the hole wall and zero speed in the center of the tool provoking the bending of material from the center to the extremity. Liang and Bi (2011) studied the efforts in drilling in stacked materials. According to the authors during the drilling, the exit and enter surface burrs, a burr will form in the gap between the inter layers because of the drill thrust force and the different bending properties of the material for each layer.

Designs of industrial components not take into account the existence of burrs. In drawings, it is considered a geometric ideal shape disregards the burr formation. Based on this, Aurich et al. (2009) carried out a study aiming the descriptions and classification of burrs. The study demonstrates that in drilling, according to the author's classification, appears three kinds of burrs such as major cutting edge, corner cutting edge, and learned burr.

However, Kim et al. (2001) categorizes drilling burrs as uniform burr with or without a drill cap, crown burr or petal burr based on their shapes and formation mechanism. The classification used by the authors was focused for each metallic material such as steel, stainless steel and non-ferrous materials. Independent of the machining process or material, the use of incorrect cutting parameters will provide the appearance of burrs, and deburring is required. Thus, the study of cutting values based on the catalogue values is not efficient and enough. A complete study for each pair tool/material using the correct cutting conditions not only minimizes the burr height, but also it can eliminate the deburring.

Besides on the formation of burrs, the diameter variation is another important parameter to be evaluated in the drilling process. The diameter error can occur at the entrance or exit of drill. According to Brandão et al. (2011-a) evaluated holes in hardened materials in drilling using different cooling systems. Considering the circularity and roundness errors, the results showed that the circularity error is affected mainly by the cooling/lubrication system and by the cutting speed, but it is not affected by the drill condition.

It can affirm that the cutting speed has great influences on hole quality and the best results can be obtained using high speeds. The influence on form errors in drilling such as circularity and roundness is inversely proportional the diameter of the hole due to the smaller diameter of the hole more difficult to control the errors of form. The run out in great diameters has a small influence on hole's quality.

According to Watanabe et al. (2008) that used drills of 0.1 mm to drill glass fiber cloth base copper clad to laminate used in electronic circuits the radial run-out which is below 0.1 mm hardly affects the hole quality and the orbital revolving drills primarily move toward the centripetal direction just after contact with a work surface. The purpose of this paper is to study the thrust force, torque, burr, and diameter error, which are controversial problems regard as small drills. Thus, drills of 3.5 mm diameter drills were applied in experiments of drilling in hardened stacked materials.

2. METHODOLOGY

In this study, the drill was chosen to carry out simple drilling tests in bimetallic materials. The work piece was three circular plates of 72 mm of diameter composed of SAE 1045 steel up with 4 millimeters of thickness, SAE 4340 steel in the middle with thickness of 12 millimeters, and SAE steel 1045 bottom with thickness of 4 millimeters. The three plates were fixed together according to Fig. 1. The work piece was previous machined using a flat grinding machine before mounting onto a piezoelectric dynamometer for force measurement (model Kistler 9272).

Each plate that formed the work piece had a different hardness such as 32 HRC for SAE 1045 and 39 HRC for SAE 4340. The whole setup was then clamped to the machine bed as shown in Fig.1. The acquisition rate was 750 Hz that corresponding to 4.5 times the frequency of the maximum spindle speed of the machine center. This data acquisition is recommended to avoid noise in the signal, according to Shaw (2004).

Drilling trials were carried out on a CNC machining center varying cutting speeds of 15, 25, and 110 m/min. The feed rate varying was about 0.06 and 0.1 mm/rev. Drilling trials were confined to through holes under the action of a 6% concentration of oil emulsion coolant at a flow rate of 20 l/min and with the dry condition.

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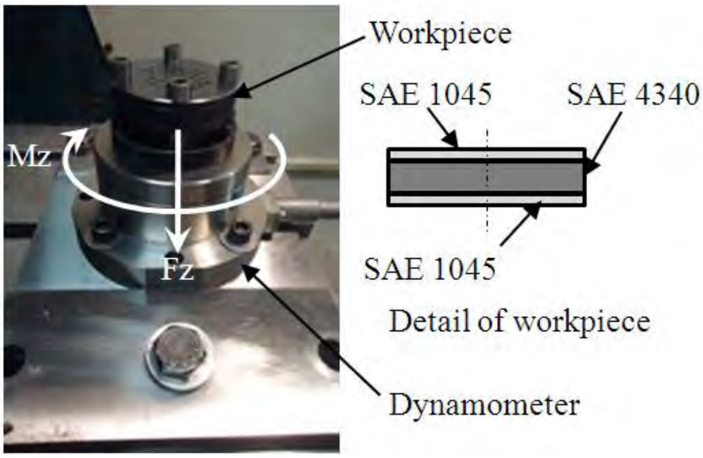


Figure 1. Set-up of experiments to measure Thrust Force and Torque and scheme of bimetallic work piece used in experimental tests

Burr's height was measured using a dial gage Mitutoyo with 0.001 micrometers of accuracy. Surface roughness (Ra parameter) was measured using a surface tester Mitutoyo model SJ-401. The drills used in the experiments were coated carbide TiAlN code R458 (DIN 6357K). Drills were from the K30/40 grade with a similar substrate of WC/Co. The code and mechanical properties of the drills are given in Table 1 according to the tool's supplier (DORMER, 2006).

Table 1. Mechanical properties of drills

Tool specification	Coated-carbide (TiAlN)
Drill type	2 flute twist drill
Drill diameter [mm]	3.5
Flute length [mm]	20
Overall length [mm]	62
Point angle [º]	140
Helix angle [º]	25
Grain size [μm]	0.5 [ultrafine]
Coating thickness [μm]	3
Hardness [kg/mm^2]	3700
Tool run-out [μm]	2

Table 2 lists, controllable factors (input drilling parameters) and their levels considered in this study. Input drilling parameters were cutting speed, feed rate, and cooling system. Cooling system and feed rate had two levels and cutting speed had three levels. The other factors such as hardness of work piece, flow of coolant, and tooling were kept constant. The responses in this study were thrust force, torque, surface roughness, diameter variation of the holes, and burr height.

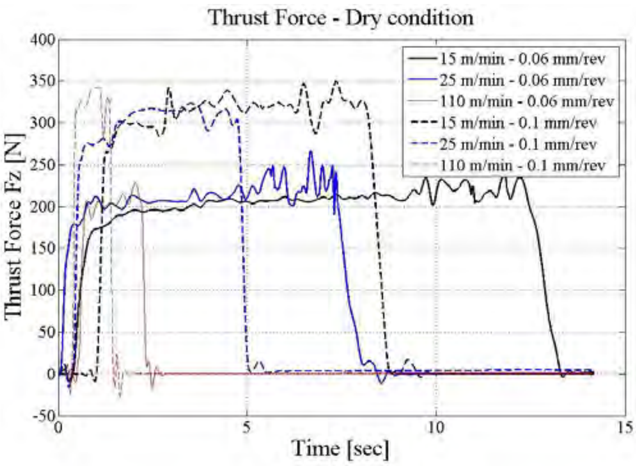
Table 2. Factors and levels for input parameters

Factor	Levels	Values
Cutting Speed [m/min]	3	15; 25; 110
Feed rate [mm/rev]	2	0.06; 0.10
Cooling system [Adm]	2	Dry; Oil emulsion

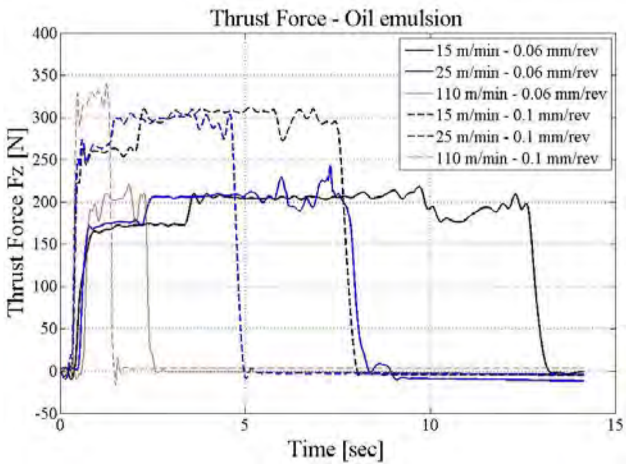
3. ANALYSIS OF RESULTS

The development of thrust force obtained for TiAlN-coated carbide drills operated at various cutting speeds in dry condition and oil emulsion are given in Figs. 2(a) and 2(b), respectively. It may be seen that during the drilling using TiAlN-coated-drill a quick increase of the thrust force was observed for both conditions of cooling. The small difference of hardness of the steels (SAE 1045 and SAE 4340) not affected the behavior of thrust force not generated a graphic with different levels for dry cutting condition.

It can observe that the difference of hardness is noticeable to the two first cutting speeds but only in oil emulsion. Considering the difference of hardness, it increased the thrust force by about 50 N. Thus, it can consider negligibly the difference of hardness of the steels in the thrust force for dry and oil emulsion tests. The variations observed in all graphics at the end of hole represent the sliding of drill on the last bulk of material.



(a) Dry condition



(b) Oil emulsion

Figure 2. Thrust Force Fz all trials in dry condition and oil emulsion

According to the results obtained, the maximum value of thrust force was 345 N occurred for the cutting speed of 110 m/min and feed rate of 0.1 mm/rev in dry condition. On the other hand, the minimum value of thrust force was of 200 N for cutting speed of 15 m/min with feed rate of 0.06mm/rev. It can observe that, according to the Figs. 2(a) and 2(b) by increasing the cutting speed from 15 m/min to 110 m/min the thrust force doesn't rise. Nevertheless, by increasing the feed rate to 0.06 mm/rev to 0.10 mm/rev the thrust force rise, in mean values, by about 100 N or 67%. Considering both speeds, the thrust force is constant independent of the cooling system used. Based on this, an analysis of variance was carried out to support this statement.

According to Table 1, the cutting speed (factor A) and feed rate (Factor B) are distinguished on the average response (thrust force). Moreover, the interaction AB and AC are significant too. The P-values defined in Table 3, with 95 % of reliability, show that the feed rate is the most important factor singly because it shows the lowest value as well as the interaction AB and AC. The cooling systems are insignificant on the average for the thrust force. Therefore, based on the analysis of variance and the thrust force values in Figs. 2(a) and 2(b) it can affirm with reliability that the feed rate (controllable factor) is the main input parameter on the drilling of bimetallic materials with different hardness. Thus, the change of the feed rate will generate the decrease or increase of thrust force.

Table 3. Analysis of Variance for Thrust Force [N] (Using adjusted Sum of Square for tests)

Source	*F*	P-value
Cutting Speed (A)	7.51	***0.011***
Feed rate (B)	6.84	***0.004***
Coolant (C)	2.22	0.149
AB	7.34	***0.003***
AC	3.76	***0.038***
BC	1.62	0.215
ABC	6.26	***0.006***

Figures 3(a) shows the mean of thrust force according to the input parameters given in Table 3. Therefore, interpretations may be made according to the p-values in Table 3. In spite of the cutting speed has the lowest value in Table 3, feed rate is the controllable factor that has the highest slope and oil emulsion the lowest according to Fig. 3(a). The cutting speed shows an increase in the range of 15 to 25 m/min and it decrease after. Thus, it can support that the feed rate is the input parameter more significant on thrust force.

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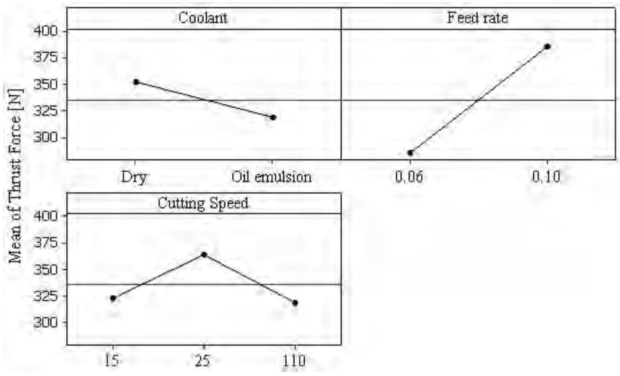
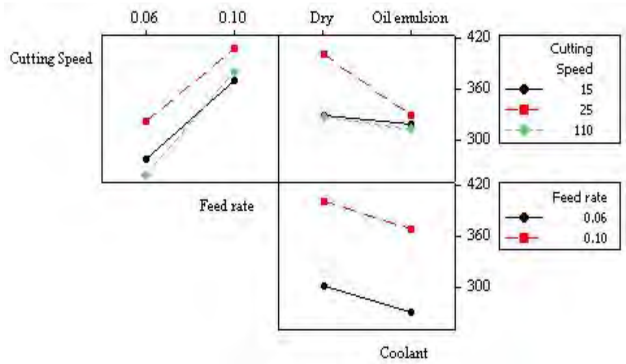


(a) Main effects for Thrust Force [N] (data means)



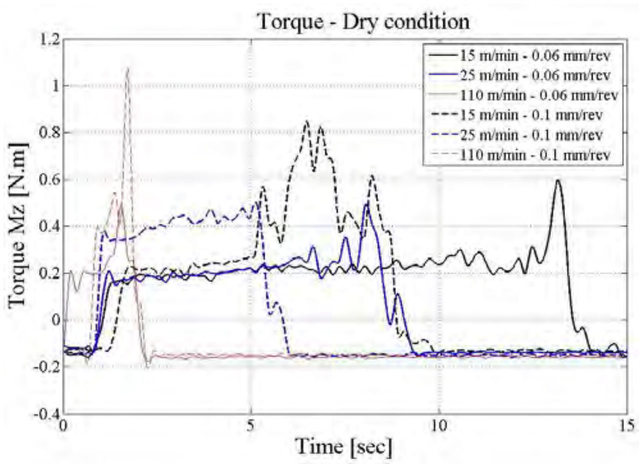
(b) Interaction for Thrust Force [N] (data means)

Figure 3. Graph of main effects of Thrust Force

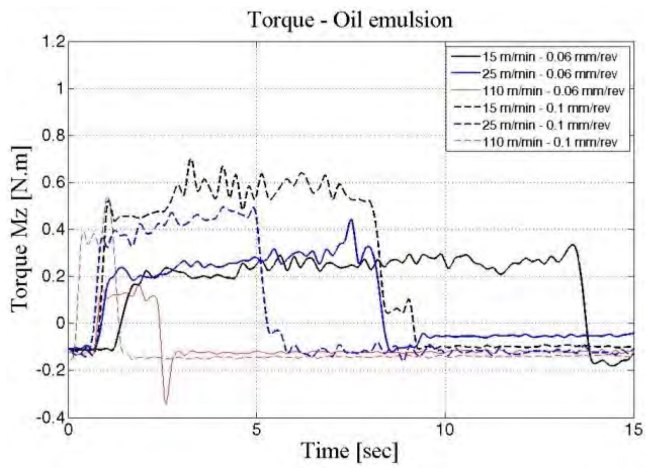
The interaction effects of thrust force are shown in Fig. 3 (b). It can see that, considering the lowest value for thrust force, and take account the productivity the best choice is cutting speed of 110 m/min, feed rate of 0.06 mm/rev, and oil emulsion. Considering different feed rates, the straight lines that represent the coolant are parallel confirming this assertion. Despite this, the use of oil emulsion must be considered due to the tool wear is smaller than dry condition (Anshu and Balaj, 2009). Figures 4(a) and 4(b) show the graphs for torque in dry and oil emulsion condition.

The maximum torque (1.02 Nm) occurred for 110 m/min and feed rate of 0.1 mm/rev in dry tests. Dry test had been a random behavior with several peaks of torque. The minimum value of torque in dry tests was 0.48 Nm for the cutting speed of 15 m/min and feed rate of 0.06 mm/rev. The behavior for torque in the test using oil emulsion was less random. The torque maximum was 0.54 for cutting speed of 15 m/min, feed rate of 0.1 mm/rev. The torque increased, at the end of the hole, because the resistance of the chip ejection had the more significant effect on torque.

The difficulty for chip ejection resulting from chip welding to the drill flute near the cutting edge was the likely cause. It can observe that this effect was higher to cutting speed of 110 mm/min in dry condition, because high cutting speed generates great heating of the chip into cutting zone. According to Brandão et al. (2011-b) when the torque and temperature are monitored simultaneously, it can be seen that both reach peak values when the cutting speed increase due to dry condition.



(a) Dry condition



(b) Oil emulsion

Figure 4. Torque Mz for all trials in dry condition and oil emulsion

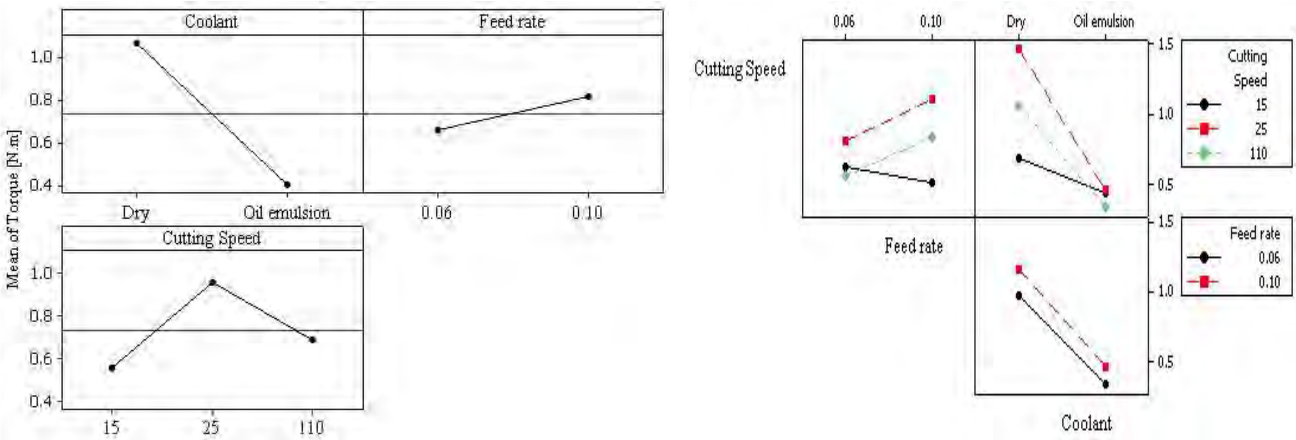
In the same way, as was done with the thrust force, analysis of variance was carried out to define the controllable factors more influence on torque. According to Table 4, it can observe that cutting speed and coolant are the input parameters that have more significance because the P-value is less than or equal to 0.05. A α-level of 0.05 is the level of significance, which implies that there is 95% of probability of the effect being significant. The feed rate has significance, but not as the cutting force and coolant. It can observe that there is an interaction for AB, AC, and ABC. The interaction of the feed rate (factor B) and coolant (factor C) has no significance on torque.

Based on this, it can support that the cutting speed and cooling system are the main factors that must be controllable to minimize the torque. The use of oil emulsion has a great advantage in the process because can minimize the tool wear. It can be confirmed in Figs. 5 (a) due to the decrease showed for coolant and cutting force. Cutting force shows an increase until 25 m/min and decrease after. The straight line for feed rate doesn't show great values of increase or decrease demonstrating the low significance for torque.

Table 4. Analysis of Variance for Torque [Nm] (Using adjusted Sum of Square for tests)

Source	F	P-value
Cutting Speed (A)	14.38	***0.000***
Feed rate (B)	6.19	***0.020***
Coolant (C)	113.03	***0.000***
AB	4.67	***0.019***
AC	12.99	***0.000***
BC	0.31	0.584
ABC	4.07	***0.030***

Thus, according to Figures 5(b) that shows the interaction effects for the torque, it can consider that the best setup for input parameters, considering the productivity, is cutting speed of 110 m/min, feed rate of 0.06 mm/rev, and oil emulsion. This set up, according to the results will generate the lowest value for torque. Moreover, the oil emulsion will help the minimizing of tool wear improving the tool life.



(a) Main effects for Torque [Nm] (data means) (b) Interaction for Torque [Nm] (data means)

Figure 5. Graph of main effects and interaction for Torque

3.1 Burr formation

Figure 6 shows several formats and burr heights generated at the end of holes drilled. Considering the end of the hole, burrs in a cap format were generated in all experiments. This kind of burr occurred not only due to the thickness of material, but also due to the point angle of drills. The cap thickness is lesser than three times the feed rate, and it doesn't generate a perfect shear mechanism due to the low strength of the material. The cap thickness depends on directly on its radial location such as thick with the tip, thin elsewhere on the cutting edge.

Moreover, the point angle is higher than 118 degrees, thus the drill works as a punch tool and not can tear perfectly the material. Fig. 6(a) shows the highest burr height and Fig. 6(b) the lowest. Figs. 6(c) and 6(d) show the burr height for the setup with the lowest cutting conditions. Figs. 6(e) and 6(f) show the burr height for the highest cutting conditions, for both cooling systems. According to Fig. 6, it is observed that, the requirement of drilling is low cutting speed and high feed rate. Intermediate cutting speed of 25 m/min caused the biggest burr height.

According to Aurich et al. (2009), the burr format can be classified as uniform burr type with drill cap. According to the authors the burr is formed when a sharp drill exits out work piece, and a Poisson burr is formed from rubbing at the margins of the drill. In all experimental tests were used new drills being negligible the tool wear. According to Fig. 6(a) the highest burr height was formed with a dry condition that confirms the assertion of the authors. Generally, the dry conditions provoke heat flux high at the end of hole not only due to the friction but also at the inefficiency of the cooling system in decreasing the temperature at cutting zone.

It can be seen in Table 5, the controllable factor that had more significance was cutting speed (factor A) and feed rate (factor B). The main effects of the torque, according to the Table 5 and Fig. 7(a) show that intermediate cutting speed can form high burr height. According to Fig. 7(b) shows the best set up to minimize burrs is cutting speed of 15 m/min, feed rate of 0.10 mm/rev, and oil emulsion.

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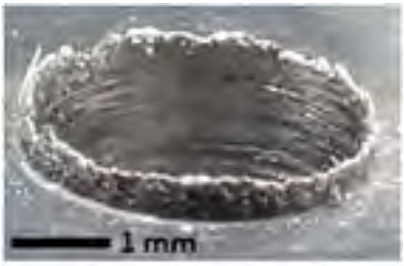
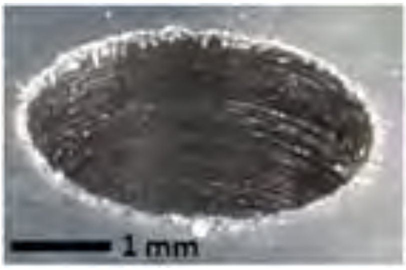
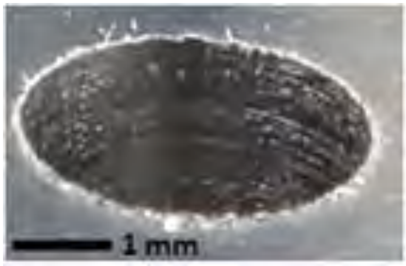


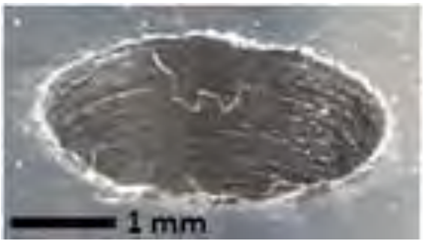
(a) Burr height = 492 µm
Vc = 25 m/min, f=0.06, Dry



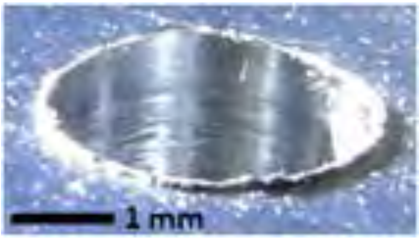
(b) Burr height = 13 µm
Vc =15 m/min, f=0.1, Oil emulsion



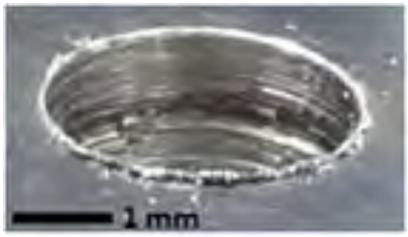
(c) Burr height = 51µm
Vc =15 m/min, f=0.06, Oil emulsion



(d) Burr height = 50 µm
Vc = 15 m/min, f=0.06,Dry



(e) Burr height = 103 µm
Vc = 110 m/min, f=0.1, Oil emulsion

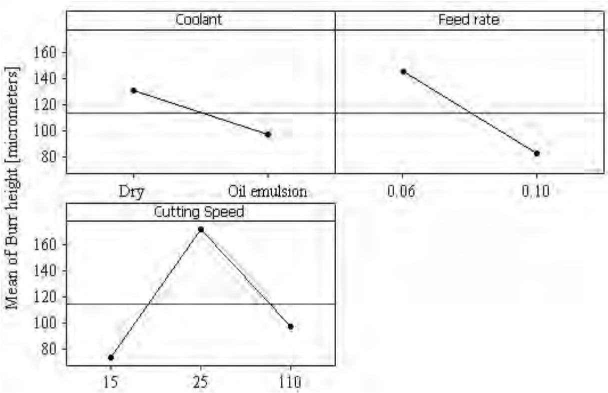


(f) Burr height = 70 µm
Vc = 110 m/min, f=0.1,Dry

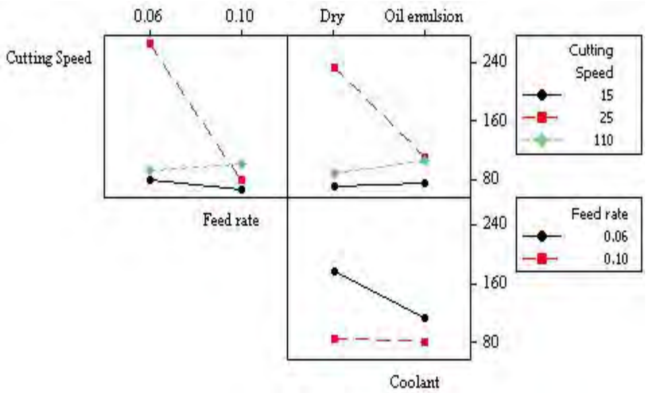
Figure 6. Burrs used in the set-up of drilling

Table 5. Analysis of Variance for Burr height [mm] (Using adjusted Sum of Square for tests)

Source	*F*	P-value
Cutting Speed (A)	6.84	***0.004***
Feed rate (B)	7.51	***0.011***
Coolant (C)	2.22	0.149
AB	7.34	***0.003***
AC	3.76	***0.038***
BC	1.62	0.215
ABC	6.26	***0.006***



(a) Main effects for Burr height [mm] (data means)



(b) Interaction for Burr height [mm] (data means)

Figure 7. Graph of main effects and interaction for Burr height

3.2 Diameter Variation

Table 6 shows the interaction for the input parameters; cutting speed, feed rate, coolant, and interaction of both. According to P-value (significant) we can support that the cutting speed, cutting speed x feed rate (AB), and cutting speed x coolant (AC) are effective on the variation of input diameter because the results are lower than 0.05. Fig. 8(a) shows the plot for main effects of variation of input diameter. It can observe that, according to Fig 8(a), cutting speed is the parameter that has more influence on the variation of input diameter because it increases from 15 to 25 m/min and

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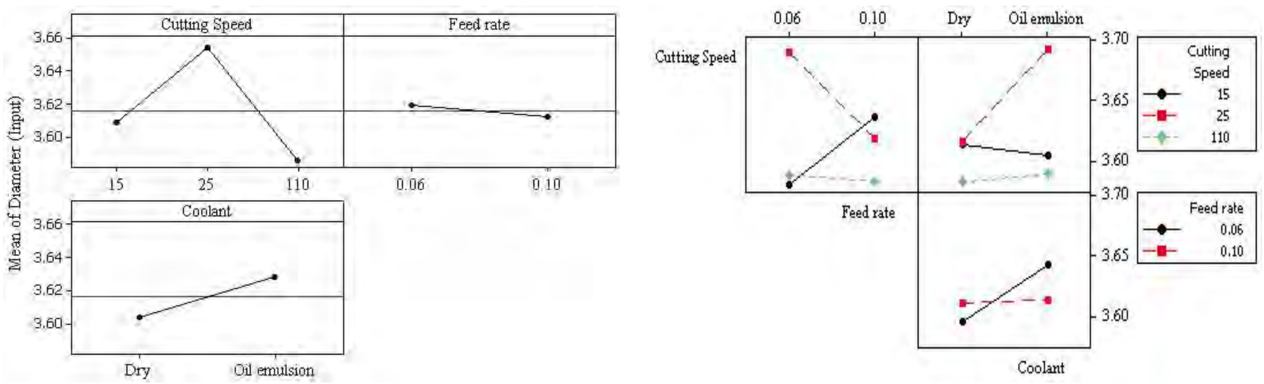
decrease after. Thus, considering feed rate and coolant, it can note that low increase for coolant and feed rate represent a low influence of variation of input diameter. Figure 8(b) shows a graph of interaction for variation of input diameter. Accordingly, Fig. 8(a) and Table 6 show that cutting speed is the most important parameter of variation of diameter due to the high increase/decrease in the graph. Thus, the optimum condition to minimize the variation of input diameter is 25/min for cutting speed, 0.10 for feed rate, and dry condition of coolant. Based on this, it can support that the influence of cutting speed on the variation of input diameter occurs due to the point angle of drill that tends to a misalignment for cutting speeds higher than 25 m/min.

Table 6. Analysis of Variance for variation of diameter [mm] – INPUT and OUTPUT (Using adjusted Sum of Square for tests)

Source	F	P-value	F	P-value
	INPUT		OUTPUT	
Cutting Speed (A)	8.58	***0.002***	1.58	0.226
Feed rate (B)	0.26	0.616	1.96	0.175
Coolant (C)	3.27	0.083	0.42	0.521
A.B	7.23	***0.003***	1.56	0.231
A.C	3.60	***0.043***	1.06	0.360
B.C	2.57	0.122	1.07	0.312
A.B.C	2.01	0.156	1.40	0.265



(a) Main effects for diameter variation [mm] (Input)

(b) Interaction for diameter variation [mm] (Input)

Figure 8. Graph of main effects and interaction for input diameter

The corresponding ANOVA for output variation of diameter in Table 6 gives the sum of squares for the 7 effects. According to p-values (significant), it does not show a significant level within the reliability interval of 95%. In other words, cutting speed, feed rate, coolant, and the interaction between them have no effect on the output diameter. Thus, it can be supported that there is not misaligns in drilling at the end of the process. The drills are well aligned in the hole during the drilling process for all trials. Drill is held into the hole due to the entire contact with the secondary cut edge of the hole wall, and that condition, guarantees a perfect aligned, and it doesn't generate variations in output diameter.

4. CONCLUSIONS

- ✓The feed rate is the input parameter more significant on thrust force variation. Cooling systems singly are insignificant on the average for the thrust force.
- ✓Cutting speed and cooling system are the main factors that must be controllable to minimize the torque. Thus, considering the productivity, cutting speed of 110 m/min, feed rate of 0.06 mm/rev, and oil emulsions are the best set up to minimize the torque.
- ✓Cutting speed is the most important parameter of variation of diameter. Based on this, the optimum condition to minimize the variation of input diameter is 25/min for cutting speed, 0.10 for feed rate, and dry condition of coolant. Cutting speed, feed rate, coolant, and the interaction between them have no effect on the output diameter.
- ✓Burrs in a cap format were generated in all experiments. This kind of burr occurred not only due to the thickness of material, but also due to the point angle of drills.
- ✓The cap thickness depends on directly on its radial location such as thick with the tip, thin elsewhere on the cutting edge. The best set up to minimize burrs is cutting speed of 15 m/min, feed rate of 0.10 mm/rev, and oil emulsion.

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