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EFFECT OF THE ACCESS OF AMBIENT AIR IN DRILLING OF STEEL

Eder Silva Costa
Matheus Carrara Martins
Wisley Falco Sales
Álisson Rocha Machado
Faculty of Mechanical Engineering - Federal University of Uberlândia - UFU, Av João Naves de Ávila, 2160, Campus Santa Monica - Block 1M, CEP 38400-902, MG, Uberlândia, MG, Brazil.
eder@mecanica.ufu.br; matheuscarrara@hotmail.com; wisley@ufu.br; alissonm@mecanica.ufu.br

James Wallbank (*in memorian*)
School of Engineering - University of Warwick, Coventry, Reino Unido, UK.

Abstract*. The aim of this work is to analyse how the ambient air restriction, which surrounds the workpiece-tool-chip system, influences the surface roughness Ra, the thrust force and torque, in drilling of AISI 1010 steel with HSS twist drills. This research was developed in the laboratories of Warwick Manufacturing Group - WMG - School of Engineering - University of Warwick, Coventry, England, UK. The workpiece was a plate with dimensions of 200x100 mm and 50 mm thick. Tests consisted of machining holes of 10 mm diameter and 40 mm deep, pre-drilled with 3 mm diameter in two conditions: 1) pre-drilled with 45 mm depth, but non through holes; 2) pre-drilled through holes – in this case it was intended to facilitate the entry of ambient air during the drilling of the holes. Sixteen (16) tests were performed and for each trial was used a fresh drill for each set of 5 holes. The tests were carried out under the following atmospheres: ambient (dry machining) and application of nitrogen gas at pressures of 300 bars, in order to create a protective atmosphere in the inlet region of drilling, and thereby inhibit the presence of oxygen. The results obtained, using a Design of Experiments - 2^4, indicated that the situation that facilitates the access of air during machining worsened the surface roughness and increased the thrust force and torque.*

Keywords: *Drilling, HSS drills, Quality of holes, Oxygen restriction, N2 Protective atmosphere*

1. INTRODUCTION

It is well known that the drilling process is facing difficulties in terms of accuracy. Small form errors and good surface finish is essential in many cases, such as: bearing surfaces, surfaces that require painting, surfaces that receives flow of fluids and gases, where visual brilliance is required, surfaces that should reflect rays and lights, among others (Machado et al., 2011). The surface finish is influenced by various machining parameters, including: the geometry of the cutting tool, part geometry, machine tool rigidity, workpiece material, cutting conditions and tool material (Nakayama 1966; Shouckry, 1982).

Machining forces, acting in the main cutting edges during drilling with twist drills can be divided into three components: cutting force, thrust force and passive force (Teixeira, 1995; Stemmer, 1995 and Weingaertner et al., 1995). Assuming that the drill point geometry has been correctly constructed, the resulting passive force acting on the edges is zero, also the value of the passive force is negligible when compared with the cutting forces and thrust forces (Diniz et al., 2008; De Castro, 2001).

The cutting force is due to the shear strength of the work material. It is predominantly responsible for the torque acting on the drill. The thrust (or feed) force is due to the performance of the chisel edge and shear strength of the work material (penetration into the workpiece). The friction of the drill margins and the chips onto the hole wall also contributes to the increased thrust force and torque. This contribution depends on the quality of drill surfaces (obtained by grinding) and of the cutting fluid used (De Castro, 2001; Sandvik Coromant, 1994; Teixeira, 1995).

The conditions of the chip-tool interface have great influence in the machining process. In the sliding region/zone, that are observed in the periphery of the chip-tool contact area, the local atmosphere has access to the interface and can influence the machining forces and tool wear (Machado et al., 2011). When machining steel, Trent (1988) found that the tool wear was accelerated in the presence of oxygen, and delayed in the presence of nitrogen or argon, however, it was not influenced by the local atmosphere.

This paper aims to examine how the restriction of the oxygen in the atmospheric air influences the surface roughness parameter Ra, the thrust force - Fz and torque - Mz when drilling AISI 1010 steel. Two types of pre-hole were machined with a twist drill of 3 mm. In the through-hole atmospheric air had access to the cutting area by the bottom of the hole that was being machined by a twist drill of 10 mm of diameter. In the blind pre-hole, to inhibit the entry of the atmospheric air through the top of the hole during drilling, a protective atmosphere of nitrogen gas applied at a pressure of 3 bar was used. The results were analysed via factorial Design of Experiments with 4 variables and 2 levels (2^4). The input variables are: the atmosphere, the cutting speed, feed rate and type of pre-hole.

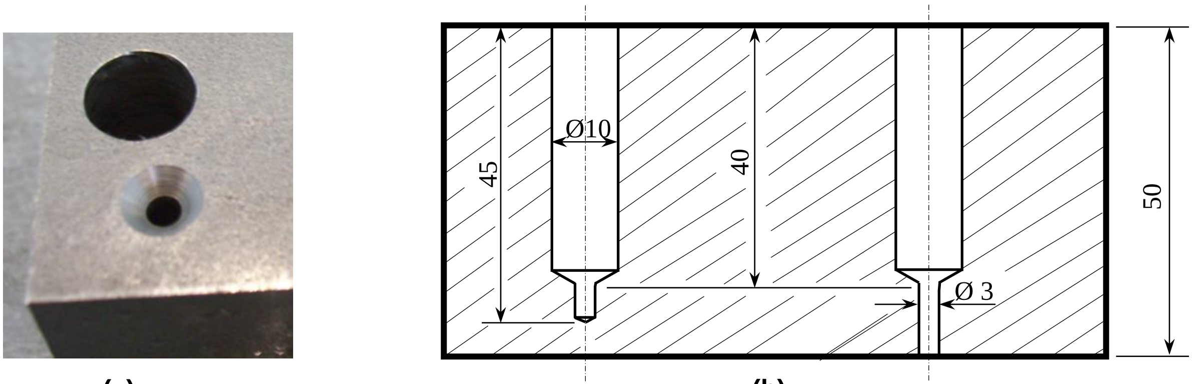
2. METHODOLOGY

2.1. Experimental apparatus

This research was fully developed in the laboratories of the Warwick Manufacturing Group -WMG - School of Engineering - University of Warwick, Coventry, England - United Kingdom. The experiments consisted of machining non through holes 40 mm deep, performed with 10 mm in diameter HSS twist drills. These tools, which are commonly used in industry, were steam tempered, have two cutting edges, type N, cutting lip (point) angle of 118° and other dimensions according to DIN 338.

In order to ensure the stability of the 10 mm twist drill during the early stages of the cutting and also facilitate the passage of atmospheric air to the cutting area, pre-holes were machined firstly with a center drill of high speed steel (HSS) with point angle of 90° and in sequence using a high speed steel (HSS) twist drill (M35 class) coated by TiAlN, diameter of 3 mm, 2 cutting edges, W type, cutting lip (point) angle of 130º and other dimensions according to DIN 340.

Two types of pre-holes with diameter of 3 mm were machined. The first one with depth of 45 mm resulting in a blind pre-drilled hole and the second one with depth of 55 mm (through hole) allowing inlet of the atmospheric air from the bottom of the hole that was being machined. For the machining of 3 mm diameter pre-holes intermittently feed (woodpecker process) was adopted with the application from the top of mineral-based cutting fluid (flooding) in a concentration of 6%. Fig. 1a shows the workpiece with a hole machined by the 10 mm diameter twist drill and the initial pre-drilled holes with the center and 3 mm diameter drills. It also shows schematically a cross section view of the two types of holes machined (blind and through holes), Fig. 1b.



(a) (b)

Figure 1. (a) Holes machined in the workpiece (with the 10 mm diameter drill and with the center and 3 mm diameter drills); (b) Cross section of the workpiece showing the two types of holes machined (blind and through holes)

The work material was the BS970 EN3 B (AISI 1010) carbon steel, with the dimensions of 50x100x200 mm. The workpiece material was fixed on the top of a stationary dynamometer platform (Kistler 9257B) and this set on the table of the CNC machine-tool with clamps and screws. Four steel bars were used (two at the bottom e two at the top) to help fixing the workpiece material, according to Fig. 2. With this set-up through holes are possible to be machined.

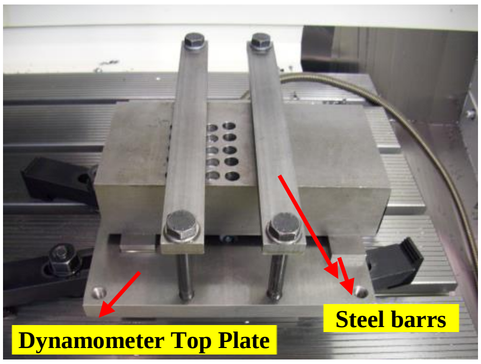
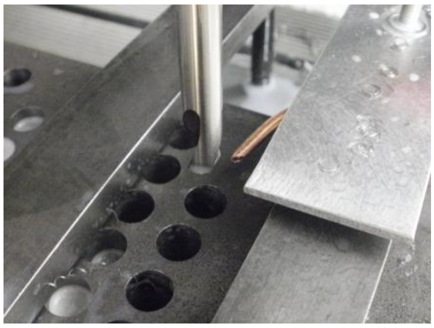


Figure 2. Workpiece set-up on the table of the CNC machine center

Drilling tests were performed in a 3-axis vertical machining center, with 13 kW of power, torque of 83 Nm and maximum speed of 8,000 rpm, model DMC 635V, manufactured by DMG (Fig. 3a). A total of 16 tests with 5 replicas each were carried out in sequence, using a new 10 mm diameter twist drill for each one. The input variables investigated were the surrounding atmosphere, the cutting speed, the feed rate and the type of pre-hole (blind and through holes). Tab. 1 shows the cutting conditions used in each test.

(a)



(b)

Figure 3. (a) CNC machine center and the cylinder containing nitrogen gas; (b) position of the copper tube in the vicinity of the hole entrance area for the application of nitrogen gas

Table 1. Worksheet of drilling tests

Test Nº	Atmosphere	v_c (m/min)	f (mm/rev)	Pre-hole	Test Nº	Atmosphere	v_c (m/min)	f (mm/rev)	Pre-hole
01	Atmospheric air (dry cutting)	18	0.11	Blind	**09**	Nitrogen at 3 bar	18	0.11	Blind
02		18	0.11	Through	**10**		18	0.11	Through
03		18	0.22	Blind	**11**		18	0.22	Blind
04		18	0.22	Through	**12**		18	0.22	Through
05		36	0.11	Blind	**13**		36	0.11	Blind
06		36	0.11	Through	**14**		36	0.11	Through
07		36	0.22	Blind	**15**		36	0.22	Blind
08		36	0.22	Through	**16**		36	0.22	Through

2.2. Atmospheres used in the experiments

Tests were carried out under two different atmospheres: dry cutting and nitrogen. For dry machining, tests 01 to 08, only the atmospheric air is present. For tests 09 to 16 nitrogen gas free of oxygen, with an approximate 99.998% of purity (in accordance with BS4366 Standard), was used. This gas was stored in a cylinder and used with the purpose of creating a protective atmosphere in the hole inlet region and thereby inhibiting the presence of oxygen in that region, because of their chemical inertia. Nitrogen, adjusted to a pressure of 3 bars, was jetted directly from its storage cylinder through a hose and copper pipe with inner diameter of 3.2 mm to the cutting area (Fig. 3).

2.3. Evaluated parameters - Output variables

The responses obtained from drilling tests were the Ra roughness parameter of the holes, thrust force, Fz, and torque, Mz, which were monitored during the drilling operation.

2.3.1. Evaluation of the roughness of the holes

To evaluate the Ra roughness parameter of the holes a Surtronic3 profilometer manufactured by Taylor Robson, Model 112/1500 was used. This equipment was set with a cut-off of 2.5 mm, resulting in a measurement length of 12.5 mm.

The roughness was measured in two positions along the hole, at 9,75 and 29,75 mm from the workpiece top surface for the 5 holes corresponding in each test condition. On both positions 4 measurements were performed, along of hole perimeter, 90º away from each other (regions B1, B2, B3 and B4, in the top of the hole and A1, A2, A3 and A4), Fig. 4. The mean values of the eight regions analysed was the Ra value assigned to the hole.

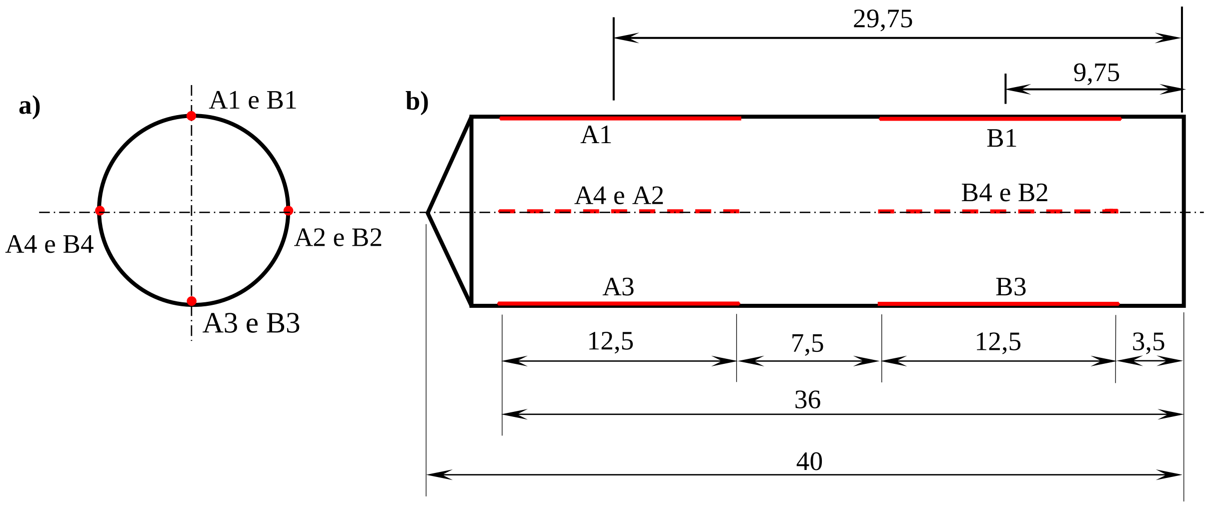


Figure 4. Positions where Ra parameters were measured

2.3.2. Thrust force (Fz) and torque (Mz) monitoring

For monitoring the thrust forces (Fz) and torque (Mz) a stationary dynamometer 9257-B model connected to a multi-channel charge amplifier, model 5070A11100, both manufactured by Kistler was used. After amplification the signal was sent to a computer and treated by the Dinoware software, also from Kistler. This dynamometer has a top plate with dimensions of 100x170 mm (Fig. 2), high rigidity and high natural frequency (2.3 kHz to Fx / Fy and 3.5 kHz for Fz).

An acquisition time of 60 seconds at a rate of 50 Hz was adopted for measurement during the machining of a hole. After signal processing, the average values of Fz and Mz were calculated for each test.

2.4. Strategy for analysis of results

The influences of the input variables in the responses were analyzed via results of a Design of Experiments (DOE) factorial with 4 variables in 2 levels (2^4) with a reliability of 95%. For this, the STATISTICA software 7® was used. The mean values of the responses assigned to each test were fed in the software. In the analysis, emphasis was given to the pre-drilled hole and atmosphere, focus of this work.

3. RESULTS E DISCUSIONS

The results of experimental tests are shown in Tab. 2. With the analysis, the effects of the input variables on the responses Ra, Fz and Mz were obtained.

Table 2. Mean results of the experimental tests with their respective standard deviations

Test Nº	Ra (μm)		Fz (N)		Mz (N.m)		Test Nº	Ra (μm)		Fz (N)		Mz (Nm)	
	Average	S.D.*	Average	S.D.	Average	S.D.		Average	S.D.	Average	S.D.	Average	S.D.
01	6.05	0.58	378	16	2.88	0.08	**09**	5.97	1.24	351	26	2.84	0.09
02	3.99	0.48	349	48	2.89	0.12	**10**	5.15	0.73	436	13	3.28	0.14
03	6.00	0.79	611	20	5.69	0.18	**11**	4.81	1.35	617	23	5.47	0.12
04	5.93	2.04	658	35	5.90	0.45	**12**	10.34	1.53	691	14	6.79	0.58
05	7.17	1.92	357	14	2.70	0.04	**13**	3.53	0.45	360	22	2.79	0.17
06	5.99	0.93	362	25	2.86	0.13	**14**	6.26	1.04	383	43	3.30	0.22
07	5.37	0.95	547	27	4.99	0.15	**15**	7.00	2.09	603	24	5.34	0.14
08	9.32	1.33	618	30	5.48	0.32	**16**	8.05	1.11	650	19	6.37	0.65

***S.D. Standard Deviation**

3.1. Results of the surface roughness parameter Ra

The average effects of the input variables on the parameter Ra and their interactions are shown in the Pareto chart (Fig. 5). The three main effects on Ra were, in decreasing order, the feed rate, the interaction 1-4 (pre-hole and feed rate) and pre-drilled hole. However, as shown in the figure, none of these effects could reach a "$p \leq 0.05$" (maximum error probability) and for this reason the software did not identify them as statistically significant.

The effect of the feed rate on the surface finishing is well known machining. The height of the peaks and the depth of the valleys in a machined surface tend to increase with the square of the feed rate. In the tests the variation of feed rate from 0.11 mm/rev to 0.22 mm/rev increased Ra values, on average, of 1.59 µm in relation to the overall mean value (6.31 µm) corresponding to an increase of 25%.

When changing the cutting condition from through holes to blind holes, the third most important variable in Ra, in general caused a reduction of 1.14 µm (18%), which means that when the passage of the air was restricted Ra values decreased. Fig. 6 shows that the reduction in Ra is higher when using nitrogen gas applied at a pressure of three bars than when machining dry. This result suggests that when machining with atmospheric air (dry) the oxygen present has access to the cutting area from the top, and thus the fact of machining through hole or blind hole is not important. On the other hand, the protective atmosphere created by the pressurized nitrogen at the top of the hole prevents access of ambient oxygen from that part, and thus the only way to enter into the cutting area would be from the bottom in through pre-drilled hole, as illustrated in Fig. 1b.

Note also in the results of Ra the interaction effect between the type of pre-hole and feed rate variables (interaction 1-4), which was the second largest effect (Fig. 5). According to this result, when machining with blind pre-drilled hole and highest feed rate (0.22 mm/rev) against through pre-drilled hole and a lowest feed rate (0.11 mm/rev), Ra values decreased an average of 1.47 µm (23%).

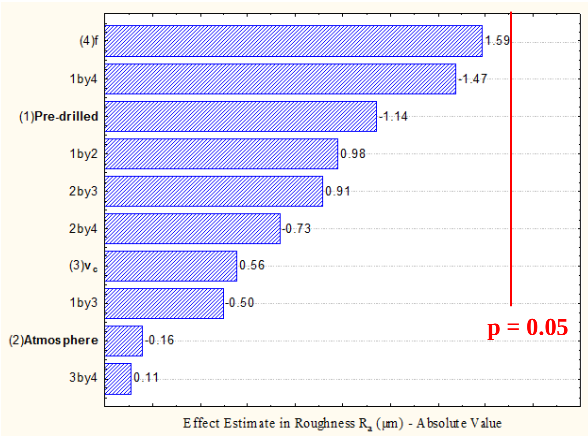


Figure 5. Pareto chart of effects. Analyses of the Experimental Design 2^4 - Variable: Ra

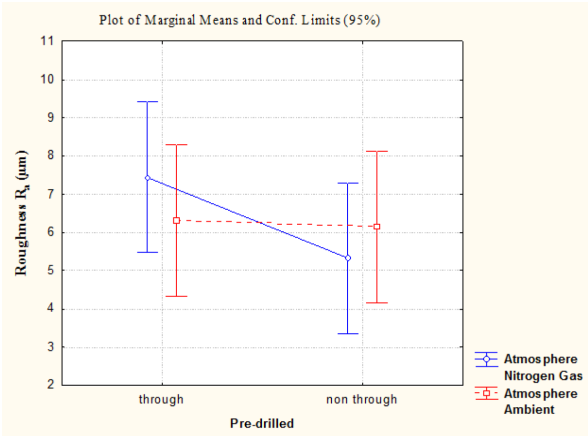
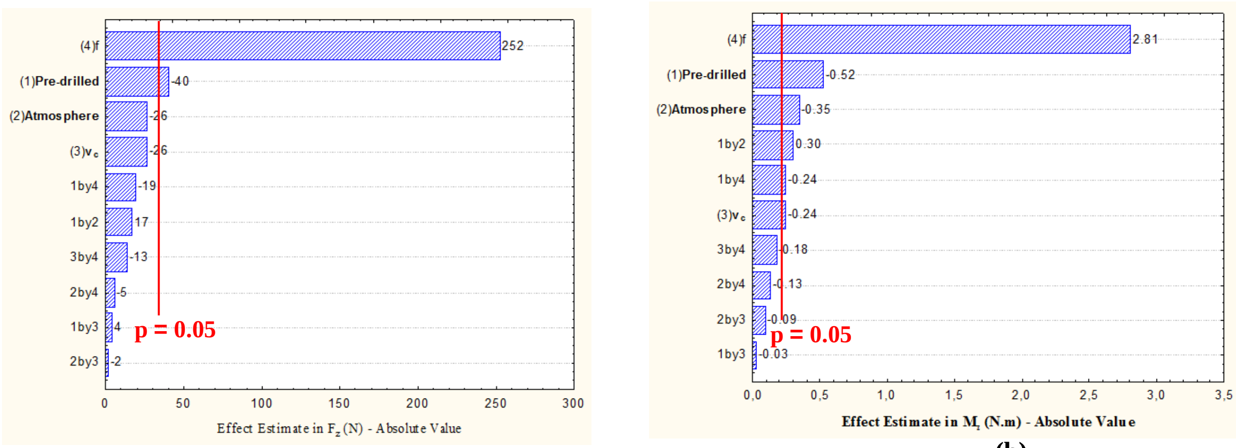


Figure 6. Analyses of an Experimental Design 2^4 - Ra versus Atmosphere and type of pre-drilled hole

3.2. Results of thrust force -Fz and torque-Mz

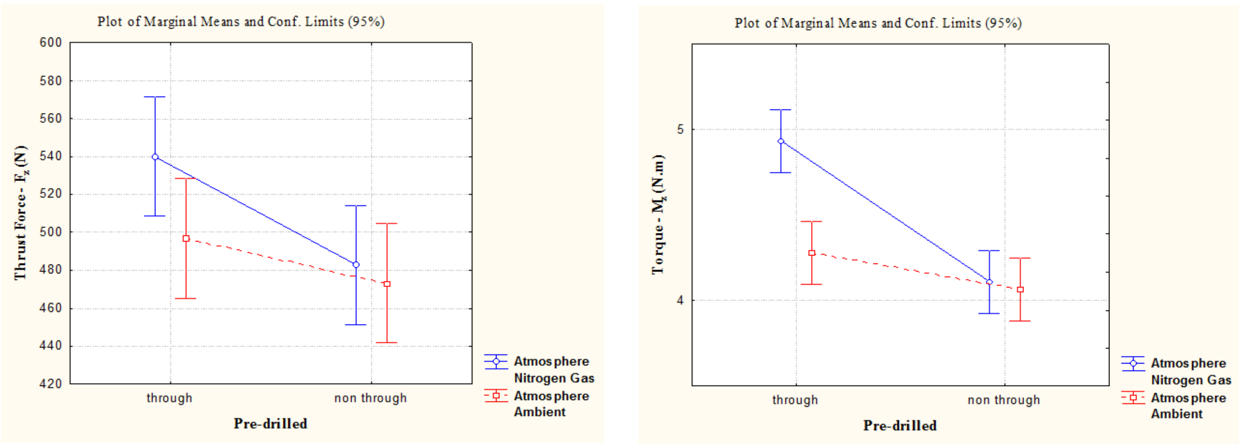
The average effects of the input variables in Fz and Mz are highlighted in descending order, in the Pareto's charts of Fig.7. This figure shows that the three most influential variables in both the force and torque were, in decreasing order, feed rate, the type of the pre-drilled hole and the machining atmosphere. As seen in Fig. 7a, the statistically significant variables on the thrust force Fz are the feed rate and the type of pre-drilled hole. While for Mz (Fig. 7b) apart from these, the atmosphere, interactions 1-2 (type of pre-drilled hole and atmosphere) and 1-4 (type of pre-hole and feed rate), and the cutting speed were also statistically significant.

The second most important variable for Fz and Mz was the type of pre-drilled hole. When machining with pre-drilled blind holes, instead of through holes, oxygen supply is restricted and both thrust force and torque reduced 40 N and 0.52 Nm, that in relation to the average values of the tests (498 N and 4.35 Nm) corresponds to 8% and 12%, respectively (Figs. 7a and 7b). The reduction in Fz and Mz, when machining with blind pre-drilled holes, is more pronounced when the cut is made with the "Nitrogen" atmosphere, as shown in Fig. 8. Once again, the results suggest that the application of nitrogen at 3 bar of pressure created an effective protective atmosphere on the top of the work material surface and thus preventing environmental oxygen entry through that region, while when machining in dry condition (atmosphere "ambient air") some percentage of oxygen can penetrate, which may have attenuated the efficiency of the through-holes in conducting ambient air to the cutting area. Fig. 8 also confirms that the thrust force and torque are higher when machining under the nitrogen atmosphere as compare to dry machining.



(a) **(b)**

Figure 7. Pareto Chart of Effects. Analyses of the Experimental Design 2^4. (a) Variable: Fz; (b) Variable: Mz



(a) **(b)**

Figure 8. Analyses of the Experimental Design 2^4. (a) Fz versus atmosphere and type of pre-drilled hole; (b) Mz versus atmosphere and type of pre-drilled hole

The presence of oxygen quickly promotes the formation of a thin film of iron oxide on the steel surface with low friction coefficient when sliding against TiAlN. This will facilitate cutting, reducing forces and heat generation.

The variable “atmosphere” was the third most influential variable in the cutting forces, Fz and Mz, raising 26 N (5%) and 0.35 Nm (8%) when machining with nitrogen. These increases may be associated with a greater cooling of the work material during the application of pressurized nitrogen, which increases the shear strength of the material in the shear zones (Machado et al., 2011; Santos and Sales, 1997).

The overall average effect of varying the feed rate (0.11 mm/rev → 0.22 mm/rev) was to raise Fz and Mz of 252 N and 2.81 Nm, which in relation to the average values of the tests (498 N and 4.35 Nm) corresponds to 51% and 65%, respectively, making this the most important variable also in the thrust force and torque.

The thrust and cutting forces in drilling are basically originated from the resistance of penetration and cutting of the drill. Thus, there is a direct relationship between the increase in feed rate with the increasing cutting energy needed to seizure and shear the work material in drilling (Sandvik Coromant, 1994; Teixeira, 1995; Costa 2004).

4. CONCLUSIONS

The results obtained in this work allow the following conclusions to be drawn:

- Among the four variables studied and their six interactions, the variable type of pre-drilled hole produces the second largest effect on thrust force and torque with statistic significance, and the third largest effect on the surface roughness Ra.

- The blind pre-drilled holes, restricting the ambient oxygen entry to the cutting area, resulted in holes with lower roughness Ra (generally 18% lower) and promoted lower thrust force (8%) and torque (12%) as compared with through holes.
- When drilling with the atmosphere of "nitrogen gas at 3 bar" there are reductions in Fz and Mz, when machining with blind and through pre-drilled holes. They are more than double when machining dry (with ambient air).
- Among the interactions that involving type of pre-drilled hole and feed rate was, in general, the most important. In Ra parameter only the feed rate was more important than the interaction. Feed rate was always the variable that produced the greatest effects in Ra, Fz and Mz.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Costa, E. S. 2004,“Furação de Aços Microligados com Aplicação de Mínima Quantidade de Fluido de Corte-MQF”. Tese Doutorado, Universidade Federal de Uberlândia-MG,2004, 311p.

De Castro, P.R.A., 2001, “Aspectos Tecnológicos da Usinagem a Seco e com Mínima Quantidade de Fluido de Corte na Furação com Broca Helicoidal”, Dissertação de Mestrado do Programa de Pós-Graduação em Eng. Mecânica da UFSC, Florianópolis-SC ,178 p.

Diniz, A. E., Marcondes, F. C. e Cuppini, N. L., 2008, “Tecnologia da Usinagem dos Materiais”, 6 ed., Editora Artliber, São Paulo, 262 p.

Machado, A. R.; Abrão, A. M.; Coelho, R. T.; DA Silva, M. B. Teoria da Usinagem dos Metais, 2 ed. Editora Blucher, 2011.

Nakayama, K., Shaw, M. C. and Brewer, R. C., 1966, “Relationship Between Cutting Forces, Temperature, Built-up Edge and Surface Finish”, Annals of CIRP, Vol. 14, pp 211-223.

Sandvik Coromant, 1994, “Modern metal cutting – a practical handbook”, Sweden: 1. ed. 840 p. ISBN 91972299-0-3.

Shouckry, A. S., 1982, “The Effect of Cutting Conditions on Dimensional Accuracy”, Wear, Vol. 80, pp 197-205.

Santos, S.C. and Sales, W.F. Aspectos Tribológicos da Usinagem dos Materiais, Ed. Artliber, São Paulo, 2007.

Stemmer, C. E., 1995, “Ferramentas de Corte I e Ferramentas de Corte II”, Ed. da UFSC, 249 p e 314 p, respectivamente.

Teixeira, C. R., 1995, “Influência dos Erros Geométricos de Afiação nas Brocas Helicoidais de Aço-rápido na Qualidade dos Furos Produzidos”, Dissertação de Mestrado do Programa de Pós-Graduação em Eng. Mecânica da UFSC, Florianópolis-SC, outubro, 110 p.

Trent, E.M., 1988, “Metal Cutting and the Tribology of Seizure: II-Movement of Work Material Over the Tool in Metal Cutting”, Wear, vol. 128, pp. 47-64.

Weingaertner, W. L. et al., 1995, “Monitoramento da Furação através da Emissão Acústica e da Força de Avanço, COBEM-CIDIM.

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