Burr Produced on the Drilling Process as a Function of Tool Wear and Lubricant-Coolant Conditions

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This work shows the resulting height and shape of the burrs produced by drilling holes with ratio L/D = 3. The tool used in the tests was the solid twist HSS drill coated with TiAlN, with diameter of 10 mm, to drill the microalloyed steel DIN 38MnS6. The height of the burr was studied under different lubricant/coolant systems, namely: dry machining, use of Minimum Quantity Lubrication (MQL) at the flow rate of 30 ml/h, and fluid applied in the conventional way (flooding). The following cutting fluids were used: vegetable oil (MQL), mineral oil (MQL and flooding) and semi-synthetic oil (flooding). The trials were carried out at two cutting speeds (45 and 60 m/min) and the criterion adopted for the end of the test was the catastrophic failure of the drill. The results showed that the height of the burr increases primarily with the wear of the tool and that this increase is almost exponential after 64% and 84% of drills life, for the speeds of 45 and 60 m/min, respectively. Furthermore, the results generally showed that the smallest burr height was obtained for the dry machining and the largest for the MQL systems.

Keywords*: drilling, burr, through-holes, twist drills, cutting fluids, MQL*

Introduction

Burrs are undesirable projections of material in most machining processes. In precision parts, the deburring operations and edge finishing can account for more than 30% of the total cost of the piece produced. In case they are not removed, the contact between the pieces can be imperfect and generate, for instance, improper fitting between the surfaces and imprecise assembly, besides offering risk of accident for operators that can be hurt when handling the parts (Bordinassi, et al., 2004; Kaminise, 2004).

The first studies on this topic were only concerned with the height of the burr but after the observation of the properties that influence their removal they evolved to consider the root hardness and thickness as most important (Kaminise, 2004).

The drilling process forms burrs at the entrance and at the end of the hole. The burr at the entrance is formed by the plastic flow of the material, and at the end by the conformation of the material due to the high compression rates in the centre of the hole. The main parameters that affect the burr formation in the process of drilling are (Soares Filho, 1995 and Bordinasse, et al., 2004):

Drill: geometry (point angle, helix angle, chisel edge relief, wedge geometry), sharpness state (wear), symmetry, diameter and material;

Machined part: properties of the material (hardness, ductility and mechanical resistance), thickness and geometry;

Conditions of the process: rigidity of the machine-tool-workpiece system (vibration), cutting speed, feed rate, use of cutting fluid.

Min et al. (2001) and Bordinassi et al. (2004) explain the mechanisms of burr formation in drilling. As the drilling depth increases, the deformation accumulated at the bottom of the hole also increases. When this value is enough to reach the tension of rupture (failure stress) of the material, the fracture begins at the point of greater deformation. The fracture also depends on the geometry of the drill, because drills with large chisel edge tend to increase the axial force in the centre of the hole.

The burr at the end of the hole can be divided into three types:

Uniform: small dimensions and uniform height around all the perimeter of the hole. Usually a cap is formed, which can come off the part during the process, or it can be easily removed afterwards. The formation process usually happens by means of a first fracture in the centre of the hole, where high rates of compression stress are exerted on the material by the chisel edge.

A secondary cap adheres to the main one. With the drill feed the area of plastic deformation expands from the centre of the hole to the lips of the drill, and a second fracture occurs at the perimeter of the hole creating the cap. Shikata (1980) defined the secondary part of this burr, cap (conical lid), as being a chip/burr. Figure 1a shows the mechanism of formation of this type of burr.

Crown: large height and irregular on the perimeter of the hole. With the increase of the feed rate the axial force of drilling increases as well as the plastic deformation at the centre of the hole, mainly with drills of conical sharpening with large chisel edge. The fracture happens at the centre of the hole and the burr is produced with the deformation of the material remaining on the perimeter of the hole, Fig. 1-c.

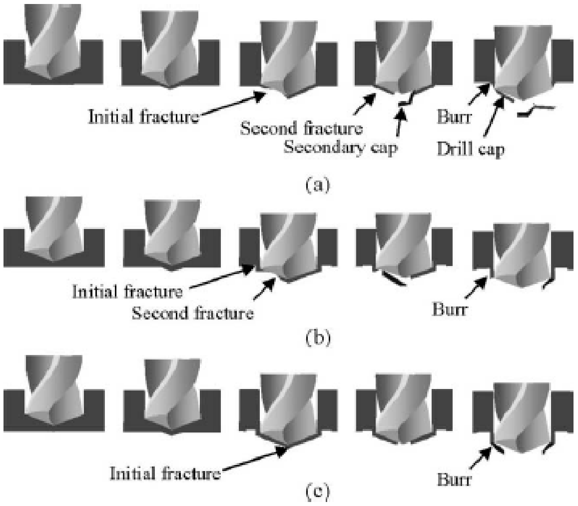

Figure 1. Mechanism of burr formation in drilling. a) Uniform Burr; b) Transient Burr; c) Crown Burr (Min et al., 2001 and Bordinassi et al., 2004).

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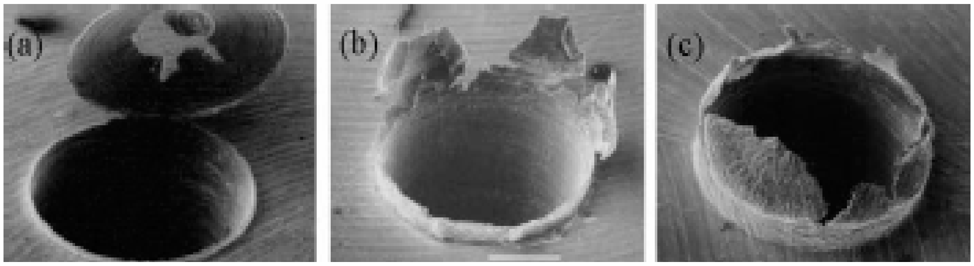


Figure 2. Burr types. a) Burr type II (uniform); b) Burr type III (transient); c) Burr type I (crown) (Min et al., 2001).

Transient: this mechanism of burr formation is intermediate to the uniform and crown ones. The fractures happen almost simultaneously at the centre of the hole and on the periphery. Therefore, the burrs that are formed first are of the crown type and, then, of the uniform type, Fig. 1-b.

Shikata (1980) classified the types of burr into type I (crown), type II (uniform) and type III (transient), besides burr type IV, which has very small volume of material, with small projections in some parts of the edge of the hole. Examples of burr types I, II and III can be seen in Fig. 2.

The degree of wear of the drill is a variable quite influential on the size of the burr at the end of the hole. Sharp drills produce relatively small burr, while worn drills produce large burrs. In drilling, the chisel edge has only indirect influence on the burr formation. The action of the lips (cutting point) of the tool is predominant, whose geometry and state of wear should be watched carefully. Drills with round lips (radial-lip drill) produce less burring, due to the existence of a larger amount of material left as support for the drill, before it breaks the workpiece at the end. Therefore, instead of the material being pushed out forming the burr, as in the case of conventional drills, it is cut before this happens. The wear of the cutting point has marked influence on the drilling process, favouring the earlier appearance and the formation of larger burrs. There is also a tendency to burr reduction with the increase of the helix angle, the lip relief angle and the peripheral rake angle (Soares Filho, 1995).

The cutting conditions can be adjusted to minimize burr size. Usually, any factor that reduces the cutting force will also reduce the burr size. Increasing cutting speeds decreases the cutting force and, therefore, reduces burr size.

Due to the formation of irregular burrs, it is considered that the profiles of drilling burrs are complex for evaluating geometrical features. Usually, measurements of the thickness and height of burrs are accomplished using universal profile projectors. However, Nakao and Watanable (2006) used a new technique that enables the effective measurement of burrs profiles. This measuring method uses image-processing techniques that automatically measure the burr dimensions. The software of this measuring system allows the number of measured points to be arbitrarily selected. The standard function of this newly developed system is to generate profiles of the thickness and height of the burr, and hence to calculate the averages of the profiles. Also, two additional sub-functions are integrated into the system, one evaluates the uniformity of the burr profiles and the other removes the influence of large irregular burrs from the measured original data.

Several works (Heisel et al., 1998; Kalhöfer, 1997; Klocke and Eisenblätte, 1997; Machado and Diniz, 2000) have been calling attention to the need to reduce to a minimum the use of coolants and/or lubricants in production lines. The important factors that justify this recommendation include the high operational costs, the ecological aspects, the legal demands related to environmental conservation and to the human health.

The method of Minimum Quantity Lubrication (MQL) can be a promising alternative when dry machining, baptized by many authors as the ecological machining, is economically unviable or meet operational limitations for some applications. It is the case of the drilling process, where the inexistence of the fluid, and the consequent lack of a medium to transport the chips, can lead to an earlier catastrophic failure of the tool (Dörr and Sahm, 2000; Machado and Diniz, 2000).

The MQL system can be defined as the spray of a minimum amount of lubricant in a flow of compressed air (Machado and Diniz, 2000). According to Sahm and Schneider (1996), the flow in the system MQL varies, usually, from 10 to 100 ml/h, at pressures from 4 to 6 kgf/cm^2. These minimum amounts of fluid are enough to substantially reduce the friction at the tool and to avoid the material adherence, since the area of chip-tool contact is very small, suggesting that the flow necessary to promote lubrication is small. Machado and Wallbank (1997) studies and theoretical calculations concluded for a flow of 0.1 ml/h as the minimum adequate for lubrication, ensured by the oil, and for cooling, ensured mainly by the compressed air (Heisel et al., 1998).

Dry and MQL machining are becoming ever more feasible as new technologies appear, such as: the increasing use of materials with improved machinability and, mainly, the great developments in tool materials, coatings and geometries, with high wear resistance. This allows machining at high temperatures, compensating for the absence of adequate amount and even the inexistence of lubricants/coolants in the process (Miranda et al., 2001; Kubel, 1998 and Teeter, 1999).

This work studies the parameters height and shape of the burr at the end of holes with L/D ratio equal to 3.0, full-drilled into microalloyed steel DIN 38MnS6, at several stages of tool wear (twist HSS drill coated with TiAlN and diameter of 10 mm). The experimental tests were carried out at cutting speeds of 45 and 60 m/min and under the following different lubricant/coolant systems: extremely low amounts of cutting fluid (MQL) using vegetable and mineral oils (both neat oils), conventional lubrication/cooling (flooding) using mineral and semi-synthetic oils and machining without any cutting fluid (dry).

Nomenclature

HSS = *high speed steel*
HV = *vickers hardness*
KW = *specific heat*
L/D = *length to diameter ratio*

MQL = *minimum quantity lubrication*
TiAlN = *titanium aluminum nitride*

Experimental Procedure

The drilling trials were carried out in the vertical position, up-down, without guiding and pre-hole (full drilling). The through-holes had a depth of 30 mm and a depth/diameter ratio of 3.0 (L/D=3.0). The feed rate was set to 0.25 mm/revolution and maintained constant throughout the tests. The parameters that were varied during the tests and their respective values are shown in Tab. 1.

Table 1. Variables used in the drilling tests with L/D=3.0 and f=0.25 mm/revolution.

VARIABLE		VALUE
Lubricant/Coolant System	DRY	–
	MQL – vegetable oil	30 ml/h
	MQL – mineral oil	
	FLOODING – mineral oil	750 l/h
	FLOODING – semi-synthetic oil	1230 l/h
Cutting Speed (v_c)		45 e 60 [m/min]

The criterion adopted for the end of the test was the catastrophic failure of the drill (NT MECH 038, 1997), and the tool life was established as the number of holes machined. Tab. 2 presents all the drilling tests.

Table 2. Numbers of the tests and their respective cut conditions.

Test #	Lubricant/Coolant System	Cutting Speed (m/min)
01	FLOODING MINERAL	45
02	FLOODING MINERAL	60
03	FLOODING SEMI-SYNTHETIC	45
04	FLOODING SEMI-SYNTHETIC	60
05	DRY	45
06	DRY	60
07	MQL VEGETAL	45
08	MQL VEGETAL	60
09	MQL MINERAL	45
10	MQL MINERAL	60

Each test was run (run A) and repeated (run B). When the deviation as to the number of holes between the test and its repetition was greater than 20%, a new repetition was carried out (run C). The average for the number of holes in the runs was the value attributed to the drill life in the respective test.

A dial indicator gauge (resolution of 0.01 mm) and a surface plate were used to measure the height of the burr at the end of the holes. The stylus was first referenced to the surface next to the holes. Then, the stylus was swept slowly towards the periphery of the hole by moving the base of the dial indicator gauge on the surface plate. The largest value registered on the dial was taken as the burr height at that point. Four points were taken on the border of the hole at 90° angles. Figure 3 illustrates the positioning of the dial indicator gauge on a machined workpiece. Differently from the described systems used by others, the stylus of the dial gauge can deform the burr and lead to small errors that are neglected here.

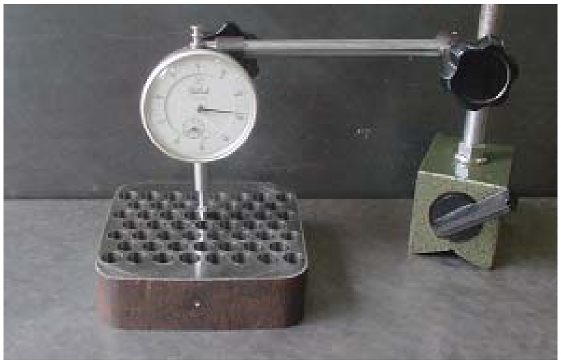


Figure 3. Illustration of measurement of the burr height at the end of the holes of a sample.

The drill used in the tests was the M42 HSS/(8% Co) with TiAlN (10HSS-Co.FUTURA®) coating, diameter of 10 mm, helix and point angles of 30° and 130°, respectively. The coating had hardness of 3300 HV and friction coefficient against steel of 0.4. This drill has the lip relief surface divided into stages. Figure 4 shows a view of the drills used in the experimental tests.

Figure 4. View of the twist drill used in the experimental tests.

The Machine Tool used for the tests was a Vertical Machining Centre CNC, Discovery series, model 760 with main motor power of 9 KW, maximum rotating speed of 10.000 rpm, manufactured by Indústrias Romi S.A.

Due to the impossibility of evaluating the burr in all the machined holes, a procedure was adopted to divide the tool life into 7 stages: 1%, 18%, 36%, 50%, 64%, 82% and 98% of the total machined holes up to the end of the drill life. For each representative hole of these 7 levels of a drill life, the previous and the subsequent holes were also evaluated. Therefore, for each run (test repetition) 21 holes were analysed. The value adopted for the height of the burr for each level of drill life was given by the average of all of the measurements taken at that level for all the test runs.

The cutting fluids used in the drilling tests were oils of vegetable and mineral origin, both neat oils, and semi-synthetic oil used at the concentration of 5%. The lubrication methods, characteristics and flow rates of the cutting fluids can be seen in Tab. 3.

Table 3. Characteristics, lubrication method and flow rate of the cutting fluids.

Cutting Fluid	Composition/Density	Lubrication Methods	Flow
Vegetal (Accu-Lube- LB-2000®) ITW	Biodegradable, atoxic and insoluble in water. Composition of vegetable oils (soy, corn and canola) and anticorrosive additive. Density (20/-3°C): 0.900-0.940	MQL	30 ml/h
Mineral (DMI 410®) Shell	Composed of refined mineral oils, paraffinics derived from petroleum, sulphur, animal fat and additives for extreme pressure, anticorrosive and antifoam. Density (20/4°C): 0.9032	MQL	30 ml/h
		FLOODING	750 l/h
Semi-synthetic (DMS 250 EP ®) Shell	Contains mineral lubricating oil, anticorrosive agent, antifoam, biostable emulsifying base and additive for extreme pressure. It forms semi-translucent micro-emulsion and was used at the concentration of 5%. Density (20/4°C): 0.9850	FLOODING	1230 l/h

The apparatus used to spray the fluid, model O2AO-STD, manufactured by ITW Fluid Products Group, worked with a continuous flow of compressed air, set around 4.3 bar, and intermittent fluid spray at the rate of 1 pulse per second. The cutting fluid was carried by a hose of smaller diameter inside another one carrying the compressed air. The mixture fluid/compressed air was externally injected at the tool-workpiece area via 2 symmetrically opposite nozzles.

The system used to apply the fluids in the flooding method was the pumping system of the CNC machine itself, which distributed the total flow of the cutting fluid through three nozzles, as shown in Fig. 5.

Figure 5. Application of the cutting fluid by flooding over the tool-workpiece.

The material of the workpieces for the tool life tests of the drills was the microalloyed pearlitic steel DIN 38MnS6, with average hardness of 252 HV. The chemical composition of this steel, supplied by the manufacturer Aços Villares S. A, is shown in Tab. 4. This material with square section of 100 mm was received in bars of 3.5 m of length, which were transversely sawed into blocks of 30 mm and later face milled to produce the workpieces. Therefore, the dimensions of the workpieces were 100x100x30 mm and the transverse section allowed the machining of 53 holes, in alternate rows of 8 and 7 holes, and with lateral distance between two holes of approximately of 2.1 mm. The workpieces were fastened to the CNC machine table through a vise and two shims were used at the extremities to allow through-holes to be machined.

Table 4. Chemical composition of the DIN 38MnS6 steel.

C	Mn	P	S	Si
0.3960	1.4400	0.0180	0.0650	0.5900
Cu	**Pb**	**Ti**	**Nb**	**B**
0.1000	0.0030	0.0021	0.0050	0.0008
Ni	**Cr**	**Mo**	**V**	**Al**
0.0500	0.1300	0.0200	0.0040	0.0040
Sn	**Ca**	**H2**	**N2**	**Te**
0.0050	0.0006	0.0002	0.0171	0.0001

Results and Discussions

The tool life results can be seen in Tab. 5, and the burr height (average and standard deviation) as a function of the drill life levels in Tab. 6. It can be seen that for the tests at higher cutting speed (60 m/min), even-number tests in Tab. 5, the average drill’s lives are reasonably similar. This means that the cutting fluids had little effect on the results. The same does not happen for the tests at the smaller cutting speed (45 m/min), the odd-number tests. This confirms that the efficiency of the fluid at reducing the temperature decreases with the increase of the cutting speed (Machado and Da Silva, 2004).

Table 5. Tool life results (number of holes machined) for the drilling tests shown in tab. 2.

Test #	Run		Deviation (%)	Run C (Deviation > 20%)	Average Life (Number of holes)
	A	B			
01	253	238	5.9	-	246
02	147	81	44.9	108	112
03	256	290	11.7	-	273
04	120	148	18.9	-	134
05	164	196	16.3	-	180
06	120	90	25.0	78	96
07	234	226	3.4	-	230
08	99	165	40.0	138	134
09	244	209	14.3	-	227
10	83	154	46.1	134	124

Table 6. Average burr height and standard deviation as a function of the level of drill life.

Test #	Level of the drill life						
	1%	18%	36%	50%	64%	82%	98%
	Average Burr Height/Standard Deviation [mm]						
01	0.14/0.05	0.19/0.09	0.33/0.06	0.52/0.17	0.53/0.19	1.01/0.61	2.85/0.93
02	0.13/0.05	0.17/0.05	0.22/0.06	0.27/0.09	0.31/0.09	0.64/0.24	1.76/0.66
03	0.15/0.05	0.19/0.03	0.22/0.08	0.36/0.12	0.63/0.29	1.68/0.62	2.36/0.76
04	0.11/0.03	0.14/0.05	0.23/0.18	0.25/0.07	0.57/0.75	0.77/0.18	1.52/0.53
05	0.11/0.03	0.14/0.05	0.19/0.06	0.33/0.08	0.45/0.15	0.70/0.17	1.95/0.82
06	0.14/0.05	0.26/0.20	0.53/0.32	0.59/0.26	0.58/0.25	0.68/0.14	1.01/0.45
07	0.12/0.05	0.22/0.08	0.24/0.08	0.39/0.12	0.81/0.18	2.22/1.38	3.96/2.23
08	0.11/0.02	0.15/0.05	0.34/0.14	0.73/1.35	0.48/0.14	0.82/0.26	0.93/0.33
09	0.10/0.02	0.18/0.06	0.26/0.10	0.48/0.09	0.61/0.13	1.52/0.75	3.68/0.81
10	0.10/0.03	0.15/0.05	0.26/0.05	0.37/0.08	0.83/0.99	0.85/0.26	2.56/2.01

Figures 6 and 7, which illustrate graphically the results of Tab. 6, show the resulting average burr height as a function of the drills life (in percentage), and of the lubricant/coolant systems for the cutting speeds of 45 and 60 m/min, respectively. These figures indicate in a clear way that the burr height grows with the wear of the drills, and this growth is practically exponential after 64% of the drill life for the tests with v_c= 45 m/min and after 82% of the drill life for the tests with v_c = 60 m/min. The degree of wear of the drill is a variable quite influential on the size of the burr at the end of the hole. Sharp drills produce relatively small burrs, while worn drills produce large burrs, since the wear increases the cutting force and consequently the material deformation. This anticipates the fracture, forming larger burrs (Soares Filho, 1995 and Sofronas, 1975).

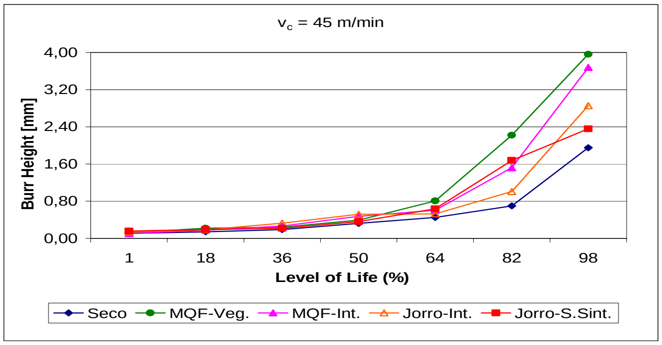


Figure 6. Average burr height at the end of the through-holes with L/D = 3.0 and v_c = 45 m/min, as a function of the lubricant/coolant systems and of the life of the drills.

It can also be seen in Figs. 6 and 7 that the cutting speeds of 45 m/min and 60 m/min produced relatively similar average burr heights for all lubricant/coolant systems up to about 64% of life of the drills. After this value, the average burr heights for 45 m/min were practically twice the ones for 60 m/min. Because it reduces the cutting force, the increase of the cutting speed reduces burr size. Bordinassi et al. (2004) observed in their drilling tests of the ABNT 1040 steel, for fixed feed rates of 0.094 and 0.229 mm/rev., that the burr height decreased when the cutting speed increased from 15 to 25 mm/min.

For the lower cutting speed, Fig. 6, the dry machining always produced the smallest average burr height and the MQL systems with vegetable and mineral oils, in general, the largest height after 64% of drill life. For the cutting speed of 60 m/min, Fig. 7, the dry system generally produced average burr heights slightly larger than the ones for other systems, up to near 50% of drill life. However, after 82% of drill life, this system began to produce the smallest burr heights.

The flooding systems (mineral oil and semi-synthetic oil) resulted in similar values for the average burr height for the two speeds. Up to 82% of drill life, for v_c=60 m/min, these systems generally produced the smallest burr heights, and after this wear level, values intermediate to the other systems.

The MQL systems produced different burr height values for v_c = 60 m/min, after approximately 57% of drill life. The MQL system with mineral oil produced the largest average burr heights, while the MQL system with vegetable oil, along with the dry system, generally produced the smallest burr heights.

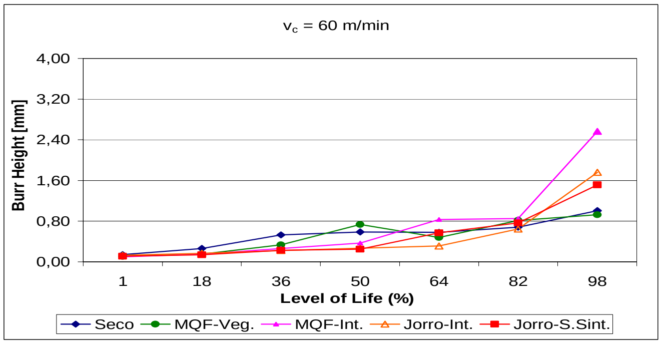


Figure 7. Average burr height at the exit of the through-holes with L/D = 3.0 and v_c = 60 m/min, as a function of the lubricant/coolant systems and of the life of the drills.

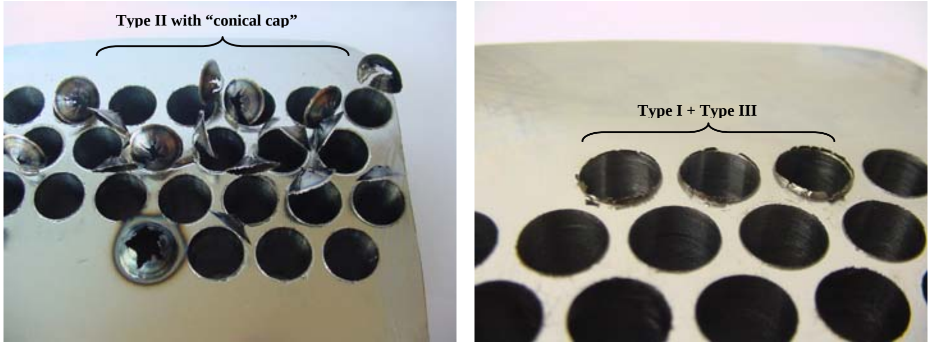
A cutting fluid has two main functions. It acts as coolant and as lubricant. Usually the lubricant action prevails at low cutting speeds and the coolant action at high cutting speeds. Both actions will have influence on the burr formation process because they modify the plastic deformation involved. As coolant it reduces ductility of the work material (and its deformation ability) and may reduce the burr size. As lubricant it reduces forces and therefore the compressive stress and deformation involved necessary to form the burr. Based on these facts the final influence of a cutting fluid depends on its lubricant and coolant efficiency (Wright and Trent, 2000 and Machado and Da Silva, 2004). Therefore, the results shown in Tab. 6 and Figs. 6 and 7 reflect the simultaneous lubricant and coolant actions of the cutting fluids used in each case.

The observation of the burrs at the end of the holes revealed that when the cutting conditions caused the drill to wear gradually, as in the cases of the MQL and flooding systems, the burrs were very evident, mainly at the final phase of the drill life. In other words, when the drill continued machining even at high wear levels, the burrs were inevitable.

On the other hand, the dry machining tests caused a severe and sudden wear of the cutting edges of the drill, in such a way that the drill lives were significantly inferior to those of the other systems (see Table 5). In this way, the dry machining generally produced smaller average burr heights.

The burrs observed at the end of the holes were, in general, of type II (uniform) for the flooding and dry machining systems and of type I and III (crown and transient) for the MQL systems. Figure 8 illustrates these types of burr in the workpieces.

The dry machining generated burrs type II, however, without the formation of the "conical cap". These lids, observed in the machining with flooding systems, were easily removed (with compressed air or by rubbing a cloth). The remaining part of these burrs showed heights, on average, inferior to the burr heights for types I and III. Burrs type I (crown) presented height and thickness larger than the others, which hindered their removal. The top of these burrs had aspect similar to the teeth of a saw, with peaks and valleys. Therefore, the burr types observed at the end of the holes in the MQL systems, contributed decisively so that these systems generally presented average burr heights superior to the ones for the flooding and dry systems.



(a) (b)

Figure 8. Burrs observed at the end of the last holes machined. a) Burrs type II with formation of the "conical cap" for test 01, run B, flooding with mineral oil; b) Burrs types I and III for test 10, run C, MQL with mineral oil.

Conclusions

The height of the burr grows with the drills wear, and it grows practically exponentially after approximately 64% of drills life for the tests with v_c = 45 m/min, and 82% of wear for the tests with v_c = 60 m/min.

The cutting speeds of 45 m/min and 60 m/min produced relatively similar average burr heights for all the lubricant/coolant systems up to about 64% of drills life. However, after this value, the average burr heights for the speed of 45 m/min were practically twice those for 60 m/min.

For the lower cutting speed (45 m/min), the dry machining always produced the smallest average burr heights and the MQL system with vegetable and mineral oils generally produced the largest heights after 64% of drill life.

Burr formation is indeed linked to the capacity of the tool to continue cutting even after high wear levels, which is ensured by the application of the cutting fluids.

The burrs observed at the end of the holes were, in general, of the type II (uniform) for the flooding and dry machining systems, and of the type I (crown) and III (transient) for the MQL systems.

The burr type II with formation of the lid (conical "cap") only took place for the flooding systems.

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