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ORIGINAL ARTICLE

Implications of the reduction of cutting fluid in drilling AISI P20 steel with carbide tools

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Abstract The machining of hardened steel is becoming increasingly important in manufacturing processes. Machined parts made with hardened steel are often subjected to high service demands, which require great resistance and quality. The machining of this material submits the tools to high mechanical and thermal loads, which increases the tool wear and affects the surface integrity of the part. In that context, this work presents a study of drilling of AISI P20 steel with carbide tools, analyzing the effects on the process caused by the reduction of cutting fluid supply and its relation with the tool wear and the surface integrity of the piece. The major problem observed in the tests was a difficulty for chips to flow through the drill flute, compromising their expulsion from the hole. After a careful analysis, a different machining strategy was adopted to solve the problem.

Keywords Machining · Drilling process · Cutting tools · Wear · Surface analysis

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1 Introduction

The machining of hardened steel is a topic of great interest for industrial production and scientific research. Some machine components are made of hardened steel materials and are required to function near their physical limits. Recent developments in machine tools as well as in process technology focus on cutting hardened steel and rapidly lead to an increased awareness of the industrial relevance of hard cutting [1]. One major problem of machining hardened steels is the tool wear caused by the hardness of the material [2]. Although hard machining avoids the shape and geometrical errors that could occur on a workpiece when subjected to heat treatment after machining and reduces the rework, it increases the thermal loads on the tool.

The heat generation and friction between tool and chip usually limit machining performance in metal-cutting operations [3]. Cutting fluids are customarily used to control the temperature in the cutting zone. However, the use of cutting fluids in machining processes has been questioned, due to some adverse effects which they cause. Prolonged contact of machine operators with cutting fluids may cause skin and respiratory diseases. Improper disposal of cutting fluids results in ground, water, and air pollution. In addition, the costs related to cutting fluids are higher than those related to labor and overhead. Thus, environmental and resource problems are forcing industry to implement strategies to reduce the use of cutting fluids in their production activities [4]. With this purpose, some alternatives have been sought to minimize or even avoid the use of cutting fluid in machining operations. Two of these alternatives are dry machining and machining with the minimum quantity of lubrication (MQL) [5, 6]. Among the processes in which these techniques are being applied is drilling.

Drilling is one of the most demanding machining processes because a completely machined geometry and surface are generated in one operation and usually postmachining is impossible. The demands in regard to diameter precision, straightness, and surface quality are enormously high. Tools must meet the requirements for diameter tolerances and shape–position tolerances [7]. In dry drilling, tool failure is a significant factor affecting productivity and manufacturing efficiency. Hence, one of the main objectives of cutting research is the assessment of tool wear and increasing tool life [8].

Beyond tool wear, the surface quality of the machined components plays a key role. The ability of a material to withstand severe conditions of stress, temperature, and corrosion depends on the quality of the surface generated during machining, which consequently determines the longevity and reliability of products made of these materials. The machined surface quality can be defined by two measures: surface topography and subsurface integrity. The surface topography can be measured using standard surface roughness measurement equipment, whereas the measurement of subsurface integrity is a complex task [9].

In a technology transfer from conventional machining with abundant lubricant to dry machining or with MQL, the thermal behavior tends to be more pronounced. Several studies [10–14] present results which show the tendency for a higher maintenance of the elevated temperatures in the cutting zone when dry machining is applied. These studies also indicate the tendency of lower temperatures using abundant fluid and intermediate temperatures applying MQL.

Previous works have shown good results for reducing or removing the cutting fluids in drilling processes. Rahim and Sasahara [12] conducted drilling experiments under different cooling and lubrication conditions such as air blow, vegetable and synthetic MQL, and flood. They used coated (TiAlN) carbide drills in the drilling of titanium alloy Ti-6Al-4 V. The researchers found that MQL gave comparable performance with the flood condition. Bhowmick et al. [10] also reported similar performance between MQL and flooded drilling in the machining of cast magnesium alloy AM60 using HSS drills. They used mineral oil in flood condition, and two types of MQL fluids, distilled water and a fatty acid-based. Heinemann et al. [15] demonstrated the effect of MQL on the tool life of coated and uncoated HSS twist drills. They performed deep-hole drilling experiments in plain carbon steel and found that a low viscous MQL oil with a high cooling capability gave rise to a notably prolonged tool life. Bhowmick and Alpas [16] studied the performance of diamond-like carbon (DLC)-coated HSS drills under MQL condition in the machining of an Al–6% Si (319 Al) alloy. Results were compared with drilling using conventional flooded coolant. They applied two types of DLCs (nonhydrogenated and hydrogenated) and distilled water as the MQL agent. The MQL cutting using either type of DLC coating reduced the drilling torque compared to dry drilling to a level similar to the performance under the flooded condition. Tasdelen et al. [3] made drilling experiments with MQL at different oil amounts, dry compressed air, and emulsion. The holes with 33-mm depth and 19-mm diameter were drilled with 155 m min^{-1} cutting speed and 0.11 mm rev^{-1} using indexable inserts. The tests showed that MQL and compressed air usage have resulted in lower wear both on the center and periphery insert compared to drilling with emulsion.

It is well established that the main problems in drilling when the cutting fluid supply is reduced or removed are the higher maintenance of elevated temperatures in the cutting zone and the difficulty for removing the chips from the hole [6, 17–19]. This second aspect is especially critical for drilling, since the cutting process is involved by the material of the piece. When the chip flow is compromised, it leads to packing and clogging of the chip and can cause the collapse of the tool [20–23]. It is also known that these problems are caused by the loss of the primary functions of the cutting fluids, which are lubrication, cooling, and transport of chips [6, 18, 19]. However, it is not clear what are the changes in the interface tool/piece/chip due to the loss of these functions and how they affect the tool wear and the quality of the machined surface. Therefore, in view of the complexity and extent of difficulties and different conditions in this type of change process, this work presents a study of drilling of AISI P20 steel with carbide tools, with different conditions for the application of cutting fluid. The main goal was to evaluate the effects on the process caused by the reduction of the cutting fluid supply and its relation with the tool wear and the surface integrity of the piece.

2 Experiments

2.1 Workpiece

The workpieces were prepared with AISI P20 steel and were hardened by heat treatment to obtain a final hardness between 36 and 38 HR$_c$. This steel is frequently used in the manufacture of molds and die cavities. The chemical composition is given in Table 1.

The workpiece dimensions were 250×80×60 mm. The distance between holes was 1.5 times the diameter of the

Table 1 Chemical composition of AISI P20 steel (% wt., ASTM)

C	Si	Mn	Cr	Mo	Ni
0.35–0.45	0.20–0.40	1.30–1.60	1.80–2.10	0.15–0.25	0.90–1.20

tool. In the dry tests, a drilling sequence was used with a distance between holes equal to three times the diameter of the tool using, however, two such cycles to complete the workpiece. Thus, at the end of the second cycle, the same distance between holes of 1.5 times the diameter of the tool was obtained. This strategy was applied in the dry tests to avoid thermal influences that could compromise the results of the experiment.

2.2 Tools

The tools used in the experiments were coated carbide drills, DIN 6537 K, provided by Walter AG Company. The diameter of the tools is 8.5 mm and they are coated with TiAlN. For the dry tests, some drill flutes were polished with an abrasive cloth to obtain a smoother flute surface and improve the chip flow. Figure 1 shows the standard tool used in the experiments.

2.3 Equipment

The experiments were performed on an Okuma Ace Center MB-46 VAE Vertical Machining Center, with maximum rotation of 15,000 rpm and power of 18.5 kW. A Universal stereoscope was used in wear analysis and measurements. The same equipment was used for an optical analysis of the texture of the machined surfaces. The surface roughness, R_a, parameter, was measured using a Taylor Hobbson 3+ surface roughness tester. To analyze the microstructures and to measure the depth of plastic deformations, a Nikon Optical Microscope Epiphot 200 was used. Microhardness tests were carried out with a Shimadzu HMV-2 microhardness tester to determine if there was any metallurgical alteration in the subsurface region of the machined material.

2.4 Experimental procedures

The cutting parameters used in tests were a cutting speed of 50 m min and a feed of 0.1 mm. The hole depth used was three times the diameter of the tool (25.5 mm). The tests were carried out for three different quantities of cutting fluids: (1) the application of fluid in abundance, (2) the MQL, and (3) a total absence of fluid. For the emulsion, a pressure of 3 bars was applied with a flow rate of 1,800 l h^{-1}. The oil used was Vasco 1000, in a concentration of 10%. In the MQL condition, the same pressure of 3 bars was used with flow rate of 10 ml h^{-1}. The MQL oil used was VASCOMILL MMS SE 1. Both oils were provided by Blaser Swisslube of Brazil.

The flow rate applied in MQL tests is the default value of the machine used in the experiments. Some of the first works dealing with MQL [24, 25] used to apply higher flow rates, up to 300 ml h^{-1}, but several studies showed that lower values tend to present similar performance. Bhowmick et al. [10] analyzed the average torque responses when MQL fluids were supplied at the rates of 10, 20, and 30 ml h^{-1}, and they did not find significant difference. Braga et al. [26] found similar results for tool wear using 10, 30, and 60 ml h^{-1} of oil. Therefore, the flow rate of 10 ml h^{-1} was fixed in this work.

Figure 2 shows the MQL system coupled to the machining center and also details of the nozzle position regarding the tool.

The quality surface analysis made in the holes was carried out near the beginning of the hole and near the bottom of the hole. The roughness measurements were made at three equidistant points for each depth (initial and final regions). Figure 3 shows the analysis depths and illustrates the roughness measurement positions.

Three repetitions were made for each condition of fluid application in order to get a satisfactory result. The end of tool life criterion adopted was a maximum flank wear ($VB_{máx.}$) of 0.2 mm or the occurrence of chipping. The tests were interrupted after 1,200 holes, even if the tool did not reach the end of life criterion.

For the application of fluid in abundance, the strategy of continuous drilling was adopted. And for the MQL and dry conditions, a pecking cycle was used, with an advance of 1.5 mm followed by retreat out of the hole. This procedure was used to facilitate the expulsion of the chip from the hole and to avoid crushing the chips and clogging the drill.

3 Results and discussion

3.1 Wear

The cutting parameters used in the tests were determined through the analysis of cutting performance during preliminary experiments. In these tests, no cutting fluid was

Type:	carbide drill ALPHA 2
Grade:	K30F
Standard:	DIN 6537K
Diameter:	8.5 mm
Coating:	TiAlN
N ° of edges:	2

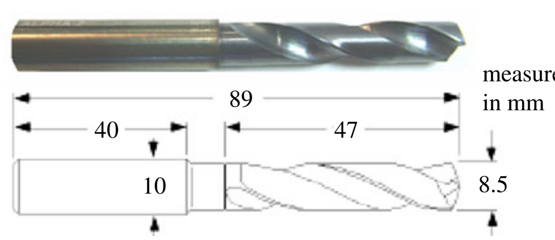


Fig. 1 Drill used in the experiments

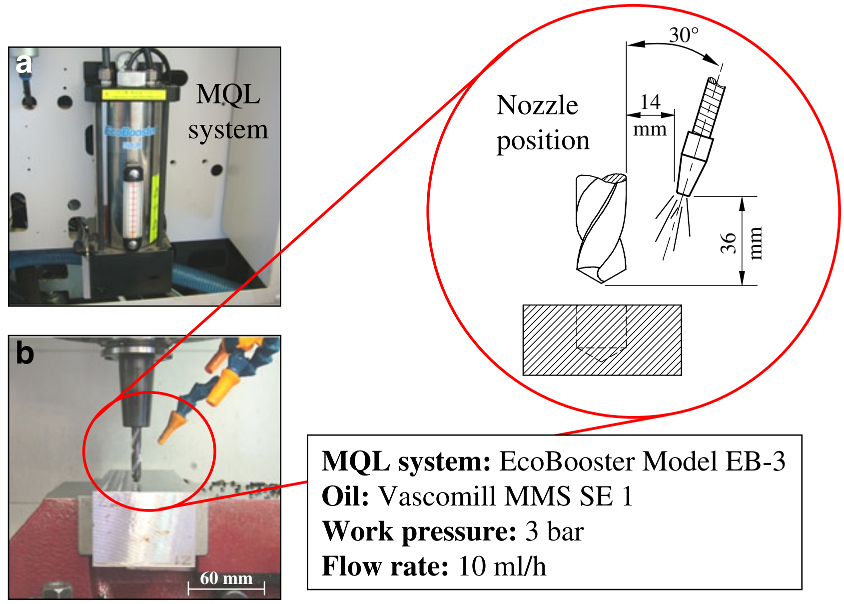


Fig. 2 MQL system (**a**) and application position (**b**)

applied, increasing the process severity, to facilitate the occurrence and observation of problems.

One of the main problems in dry drilling is the removal of chips from the hole. This problem was observed in continuous drilling using the cutting parameters v_c=40 m min^{-1}, f=0.10 mm, when the maximum number of drilled holes obtained was 129. In this condition, chip flow was difficult and obstruction of the drill flute occurred, as seen in Fig. 4a. Also, microchippings were observed in the margins and the consequent chip removal from the flute through the margin and land, as seen in Fig. 4b. The combination of these problems compromised the chip flow, causing the obstruction of the flutes and led to tool breakage.

To improve chip flow, the drill flute of some tools was polished with an abrasive cloth to obtain a smoother surface and, in this way, to facilitate the expulsion of the chip.

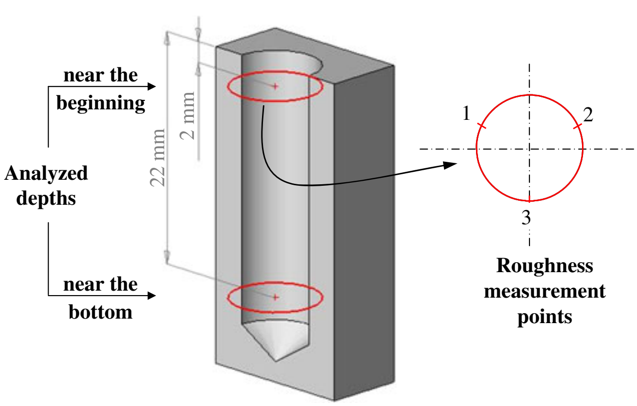


Fig. 3 Points of measurement

However, better results were not obtained and again microchipping occurred in the margins, as seen in Fig. 5.

An attempt to solve the microchipping at the margins was made, maintaining the same values of cutting speed and feed, but adopting a pecking cycle, with an advance of 1.5 mm without retreat out of the hole. The intent with this strategy was to improve the chip breakage and therefore enhance the chip flow. But again, good results were not obtained. The drill presented high adhesion of material in the flute and in the margin, and a high packing factor (clogging of the drill by the chips) was observed. Figure 6 illustrates this condition.

Therefore, a more detailed analysis of the chip formation was necessary. For this purpose, chip samples were prepared for metallographic analysis. Chips adhering to the drill flutes were removed and mounted in order to analyze their transverse section. This process started from the chip region near the top of the drill, and the analyzed depth increased successively by 1 mm after each analysis. Between 3 and 6 mm from the top, a higher packing factor was observed. This region is the same as that where the microchipping of the margins occurred. Figure 7a shows schematically the mechanics of cutting and shear zones, for a better understanding of the results presented in Fig. 7b, which shows the transverse section of the chip on the depth of 3 mm below the top of the drill.

Figure 7b shows the disordered packing of the chip and microwelding points as well as the different regions (smoothed and sheared) resulting from chip formation. After severe machining, the material removed can present several metallurgical alterations such as a high plastic deformation, a hardness increase, or a white layer formation. The sheared region resulted from the primary shear

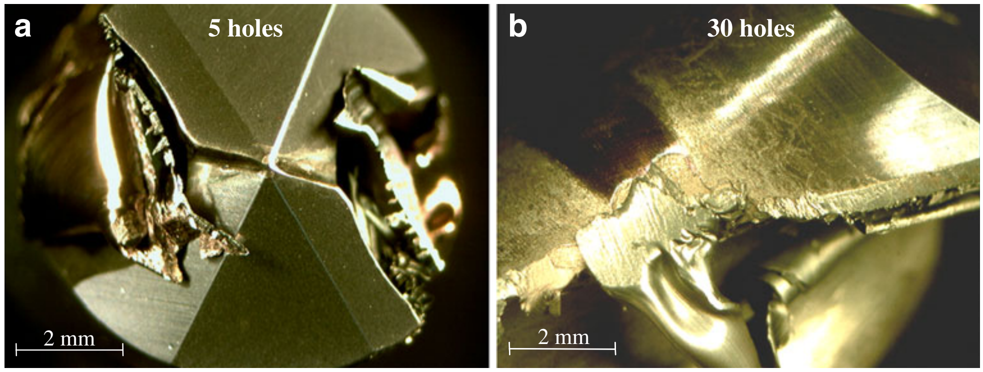


Fig. 4 Flute obstruction (**a**) and microchipping in the margin (**b**)

zone on cutting and, therefore, is submitted to severe strain hardening. The smooth region corresponds to the secondary shear zone, and the material is submitted to high compression and attrition against the tool face. Under severe conditions of pressure and temperature, this region can develop the so-called white layer, characterized by high plastic deformation and high hardness. Thus, smooth and sheared regions present metallurgical alterations that tend to increase the resultant hardness [28]. And this increase in hardness of the chip makes it more difficult to flow through the flutes on its way to removal from the hole.

The smooth and sheared regions, by having a high mechanical strength and due to the forces generated by compression and mechanical wear, tend to increase the heat generation. Thus, the three necessary conditions for the formation of a white layer on the chip are present: compression, friction, and high temperature [29]. The friction of the regions of high hardness with the hole wall creates difficulty for disposing of the chip, resulting in a volume increase, which compromises the chip flow out of the hole. The chip accumulation causes the obstruction of the flutes and the consequent tool breakage.

However, although this analysis has shown the occurrence of high compression and friction loads on the chip, it did not explain the cause of these problems. Then, a complementary analysis was made with a broken drill inside a hole. An external cylinder of material involving the hole with the tool and chip was removed from the workpiece. This cylinder was prepared for optical and metallographic analyses with a special cold cure resin that enabled transverse cuts of the cylinder in 2-mm-thick layers, maintaining the position of the tool and the chip inside the hole (see below). The aim of this analysis was to evaluate the chip formation and the interface tool/chip/piece and to investigate the cause of the elevated packing factor of the chip. Figure 8 illustrates the procedure and shows the top surface of the layer cut from approximately 1.5 mm below the top of the tool.

The layers were carefully analyzed and an unexpected cutting behavior was observed. Figure 8 shows that the chip has been cut by the margin, but these tool elements are not designed for cutting. The hypothesis raised for this case was that the wear of the drill corners would lead to a reduction of the tool diameter between the corners, and thus the diameter between the margins would be larger and the cutting of the material would be made by the margins. This difference between the diameters makes the margins the primary cutting surfaces of the drill and implies a change in the shear planes regarding the feed axis, transferring the primary shear plane, shown in Fig. 7a, to the margin. This change makes the chip flow toward the hole wall, instead of following the helical path along the flute. This results in intense friction with the hole wall and elevated compression loads on the chip, giving rise to the observed high packing factor of the chip and the microchippings in the margins.

These results explain the lower results for tool life in dry continuous drilling experiments. Based on these analyses, it was decided to change the drilling strategy in order to

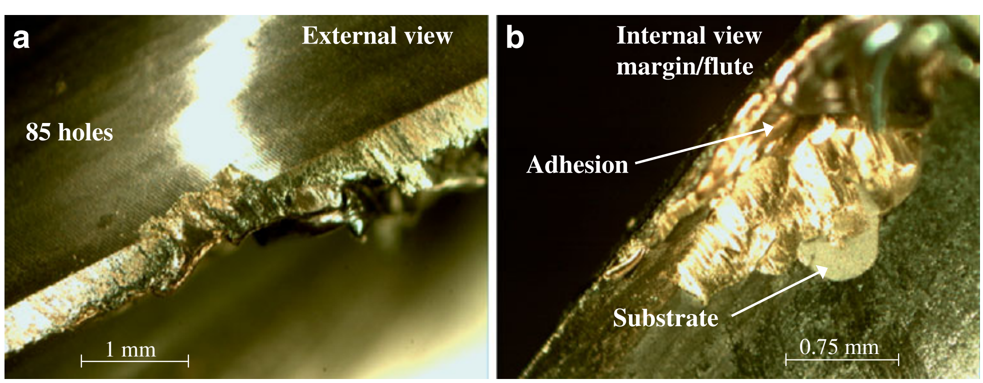


Fig. 5 Microchipping in the margin, external (**a**) and internal (**b**) view

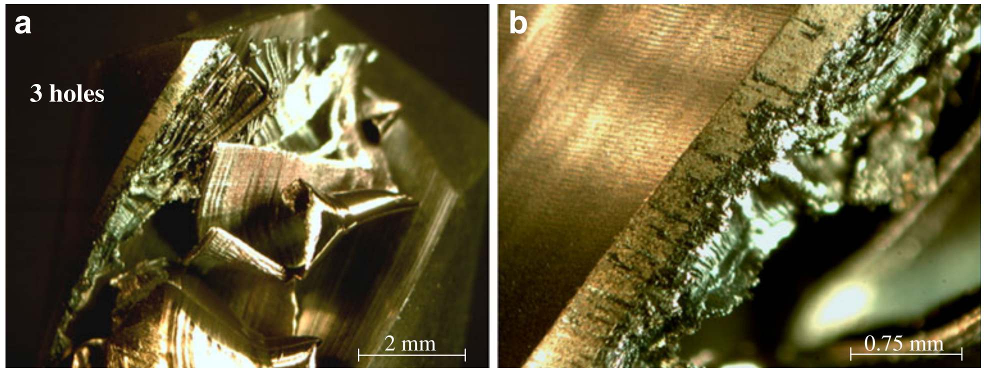


Fig. 6 High packing factor (**a**) and material adhesion (**b**)

facilitate the expulsion of the chips from the hole. Therefore, it was adopted as the pecking cycle with an advance of 1.5 mm followed by a retreat out of the hole. The retreat improved the chip expulsion from the hole, and in this way, the microchippings at the margins no longer occurred. However, this strategy increased the drilling time by about 150%. To compensate part of this loss of productivity, tests were made with the cutting speed of 50 m min^{-1}, which showed similar results to those obtained with 40 m min^{-1}. Thus, for the main experiment, the cutting speed of 50 m min^{-1} was adopted, and the pecking cycle for MQL and dry conditions was used. For processing with the emulsion, the tests were performed by continuous drilling in order to attain lower cutting times. With these definitions, the main experiment was carried out, and the results are presented below. Figure 9 presents the wear results from the experiments with v_c=50 m min^{-1}.

Drilling with the emulsion gave the worst result and the tools made 933 holes on average. For MQL tests, all three tools made 1,200 holes, but only one reached the end of tool life. For the other two, the test was interrupted by the criterion of 1,200 holes drilled. The dry drilling experiments presented the best results, because all tests were interrupted by the 1,200 holes criterion.

The worst results for the emulsion tests can be explained by the cooling of the machined material. The presence of the cutting fluid removes the positive effect of the heat in the cutting zone, which facilitates the material shear (lower resistance to cutting). That way, the cooled material presents greater strength, increasing the mechanical loads on the tool and, consequently, the tool wear. In the emulsion tests, also a high adhesion of material on the flank of the tools was observed, which leads to microchipping and tool failure. Figure 10 shows the material adhesion and the consequent microchipping.

The tools machined under MQL conditions also presented material adhesion on the flanks, but in lesser quantities than observed for the emulsion condition. In dry tests, it was observed that although material adhesion had occurred on tool flanks, when this material detached from the flank, it did not cause significant microchipping as was observed in the emulsion and MQL experiments.

3.2 Surface quality

The quality of machined components is currently of high interest, for the market demands mechanical components of increasingly high performance, not only from the stand-

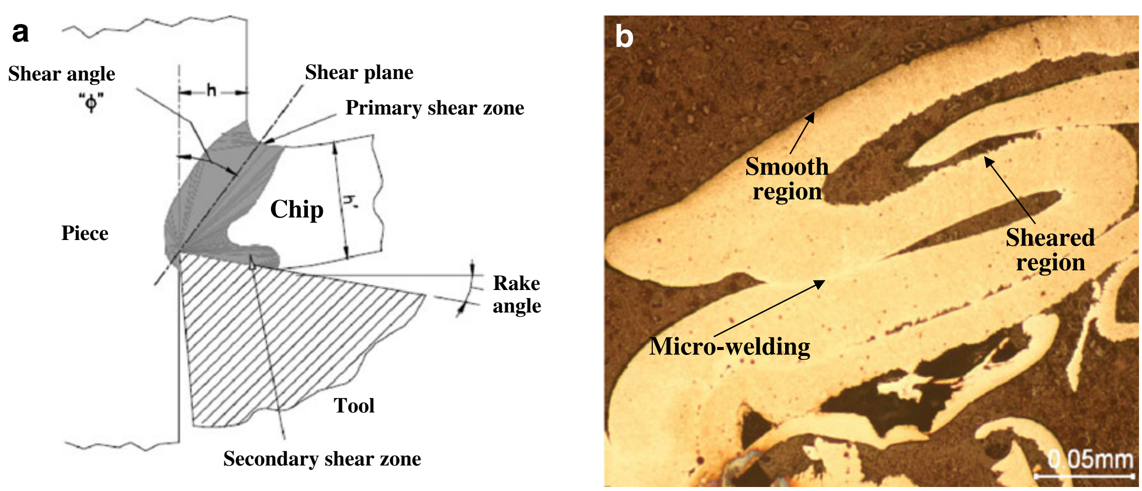


Fig. 7 Shear planes [27] (**a**) and the transverse section of the chip distant approximately 3 mm from chip region near the top of the drill (**b**)

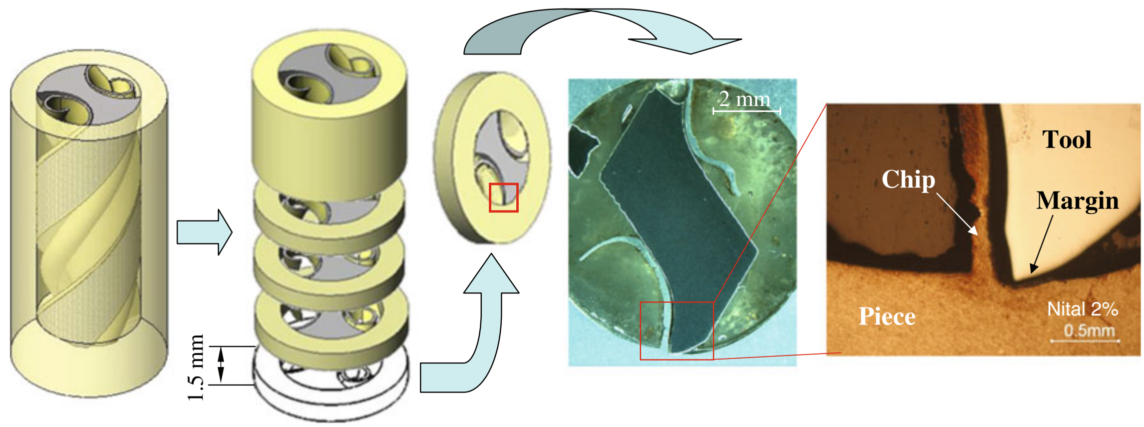


Fig. 8 Interface piece/tool/chip analysis

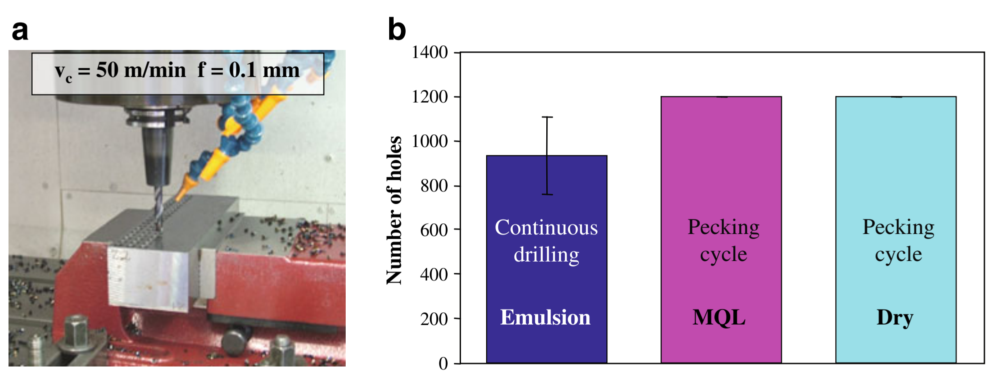
point of functionality but also from that of safety. Components are produced through operations involving the removal of material display surface irregularities resulting not only from the action of the tool itself but also from other factors that contribute to their superficial texture such as cutting speed, tool wear, feed, tool materials, tool geometry, etc. This texture can exert a decisive influence on the application and performance of the machined component [30, 31].

With the aim of facilitating the comparisons, in the surface quality analysis made for this experiment, one representative tool was selected and tested for each condition of fluid application that made 1,200 holes without attaining the end of tool life criterion. Figure 11 shows the values of roughness, R_a, measured near the beginning and the bottom of the holes, for each drilling condition.

Near the beginning of the holes, the dry tests gave the highest roughness values, while the lowest values were measured in holes machined with MQL. The elimination of cutting fluid tends to worsen the quality of the surface due to the larger friction forces and the increased detachment of material particle adhesions that are released from the tool [32]. For the emulsion condition, the fluid reaches the initial region of the hole, providing good cooling and lubrication, and for MQL condition, with the employment of the pecking cycle, the edge receives a microlubrication after each retreat, which reduces the attrition and produces lower roughness results. However, after about 1,000 holes, the results of all lubricant conditions tend to converge toward similar values. The friction caused by dry drilling is reduced while producing the holes due to the adjustments of the cutting edge, decreasing the roughness in the machined surface.

The MQL conditions also resulted in the lowest roughness values in the analysis made near the bottom of the holes. However, for this analysis condition, the emulsion tests presented a tendency toward larger roughness values, because the emulsion condition keeps the original cutting edge geometry for a greater time, causing the increased roughness. But after approximately 1,000 holes, the same tendency to similar values for all conditions is observed, as it was in the previous analysis. Texture and microhardness analyses made near the bottom of the holes showed, especially for dry condition, the occurrence of microwelding of the chip on the surface, which can be caused by elevated temperatures during machining resultant from the worn cutting edge. A worn cutting edge has its geometry changed, which reduces its cutting ability, hindering the shear of the material. With that, due to friction and the high temperatures generated in the process, parts of the removed material are welded onto the surface, providing a smooth aspect, which reduces the values of

Fig. 9 Picture of the drilling process (**a**) and wear results expressed in terms of the number of holes drilled (**b**)



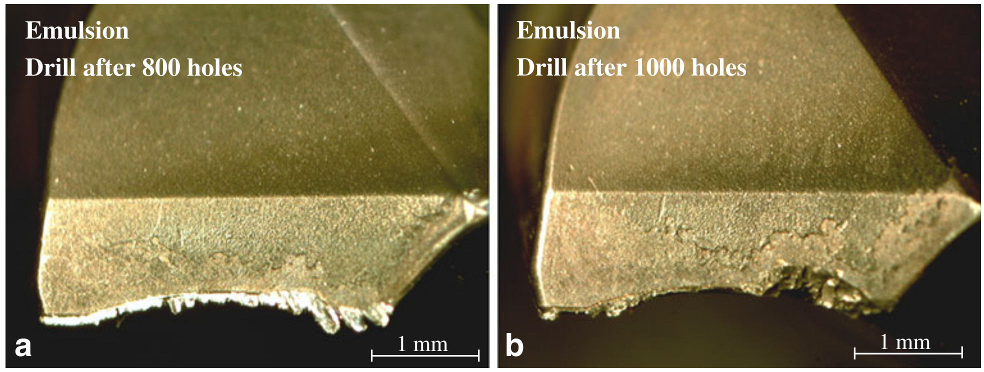


Fig. 10 Flank images with material adhesion (**a**) and microchipping (**b**)

roughness [33]. Figure 12 shows the surface texture of the first and last holes for the different fluid application conditions.

For drilling with the emulsion, the marks of the passage of the cutting edge can be seen, and in the first hole, there are deeper grooves which result in greater roughness values than in the last hole. The holes drilled with MQL presented a more homogeneous texture along the holes, especially in the last hole. For the MQL condition, the microlubrication associated with the facilitated material shear due to the temperature increase in the cutting zone reduces the cutting forces and allows the formation of a smooth surface. The holes obtained by dry drilling presented the worst visual aspect, with evidence of material adhesion along the holes and a smoothed surface in the final region of the holes, probably due to the occurrence of microwelding.

To complement this analysis, Fig. 13 illustrates the surface texture of the region near the bottom of the 1,200th hole with a larger zoom and also shows the average value of the microhardness measured on the surface of the hole for each condition. The measured values are approximately twice as large as the bulk material hardness, 390 HV on average. These results corroborate the hypothesis of the occurrence of microwelding, since the welded chip tends to be submitted to high thermal and mechanical loads, which can lead to the microhardening of the chip.

As mentioned previously, none of the tools analyzed for surface quality attained the end of life criterion, and the tests were interrupted after 1,200 holes drilled by each tool. However, wear analysis showed the maximum flank wear to be 0.15 mm for the tool used in the emulsion condition, 0.08 mm for the tool used under dry conditions, and 0.06 mm for the tool used in the MQL condition. Considering that the tool has a cutting edge radius of 0.05 mm, it can be stated that these wear values have a significant influence on the surface changes.

Beyond the surface region of the holes, the metallurgical alterations in the surface integrity were also studied. Surface quality influences characteristics such as fatigue strength, wear rate, corrosion resistance, etc. The fatigue life of a machined part depends strongly on its surface condition. It has long been recognized that fatigue cracks generally initiate from free surfaces. This is due to the fact that surface layers experience the highest load and are exposed to environmental effects. Crack initiation and propagation, in most cases, can be attributed to surface defects produced by machining. The surface of a part has two important aspects that must be defined and controlled. The first aspect involves the geometric irregularities on the surface, while the second aspect involves metallurgical alterations of the surface and the subsurface layer. The latter has been termed surface integrity [34].

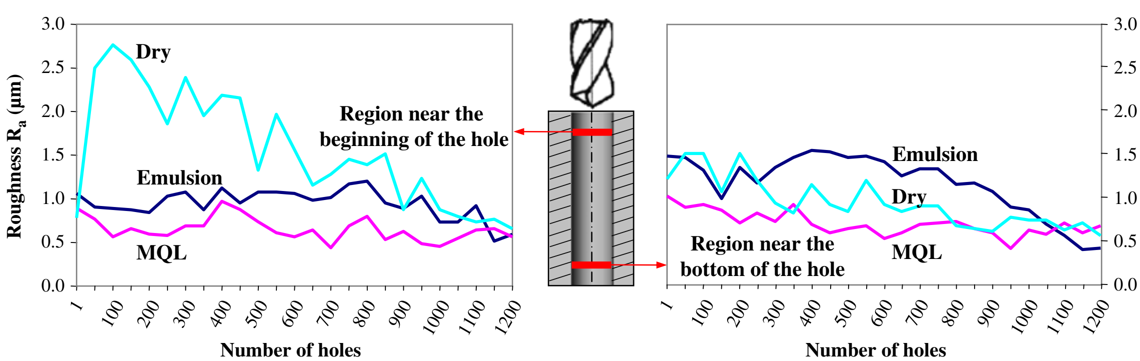


Fig. 11 Graphs of roughness R_a values measured near the beginning and near the bottom of the holes

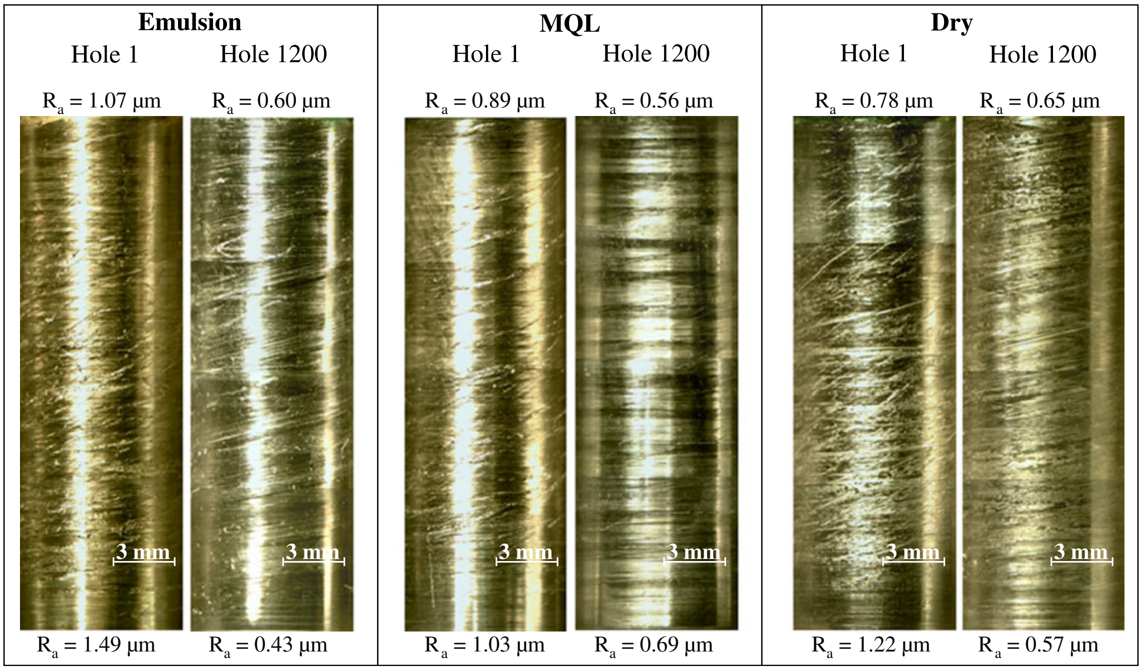


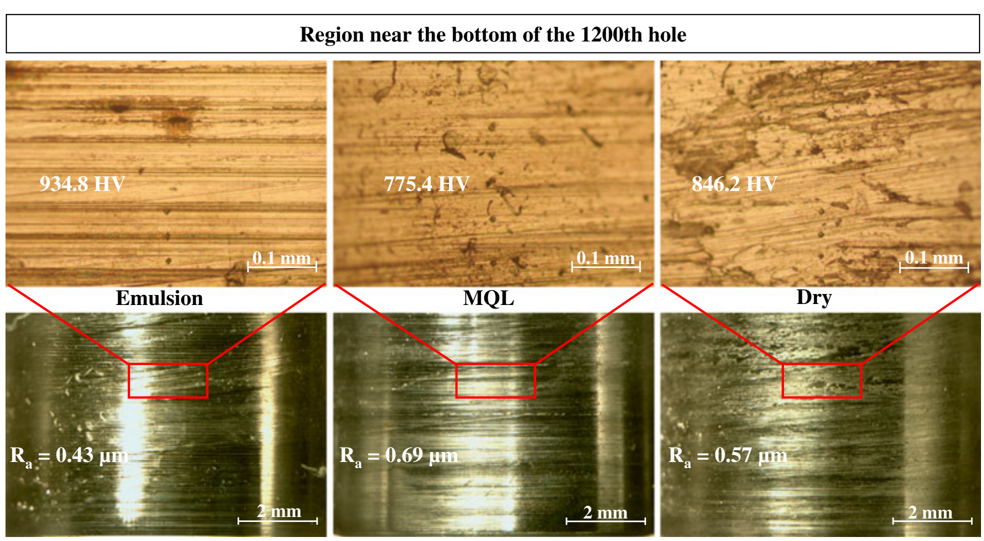
Fig. 12 Surface texture of first and last holes for the different fluid application conditions

Surface integrity analysis has great importance for surface quality characterization, due to its direct relation with the performance of the machined component. This characterization of the integrity can be performed by the evaluation of the alterations of the structure under the surface, as measurements of plastic deformations, micro-hardness, among others. Plastic deformations consist in the deformation and change of orientation of the grains near the surface of the material after the cutting. The measured values correspond to the vertical distance from the surface to the point in the microstructure without visible alterations.

Figure 14 presents the values of the plastic deformation measured near the beginning and the bottom of the first and last machined holes. Each value plotted in the graphs is the average value of the five maximum plastic deformations found in the analyzed region. The figure also shows metallographic images of the last hole surface for the different conditions tested.

For both analyzed regions (near the beginning and near the bottom), the measured deformation values were larger with the increase in the number of drilled holes due to the changed cutting edge geometry; this tends to increase the temperature in the cutting zone and, in turn, leads to the occurrence of higher deformations. It can also be observed that the measurements made near the bottom tend to be greater than those made near the beginning of the holes.

Fig. 13 Surface texture in the region near the bottom of the last holes



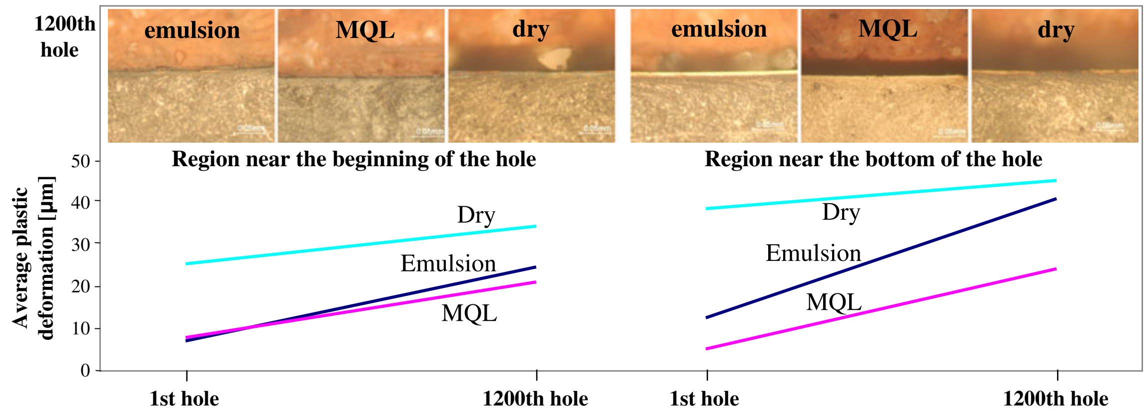


Fig. 14 Average plastic deformation measured near the beginning and near the bottom of the holes

This can be related to the greater difficulty of chip removal from the hole in the final region, increasing the contact between the chip and the piece, which causes the increase of heat generation and consequently higher deformation values.

Also, for the beginning and final regions, the dry tests resulted in greater plastic deformation, due to the process severity, because, as stated by the literature, this condition is characterized by higher maintenance of elevated temperatures in the cutting zone [6, 17–19]. Near the beginning of the holes, emulsion and MQL results were very similar, while near the bottom of the holes, the emulsion deformation results were larger. This difference is explained by the cutting strategy adopted for each condition. In the initial region, the fluid can reach the cutting zone for both conditions. However, in the final region, the continuous drilling employed in emulsion test impeded fluid access to the cutting zone, while in the MQL test, with the employment of the pecking cycle strategy, the edge receives a microlubrication after each retreat, which reduces the temperatures generated in cutting and results in lower deformations values.

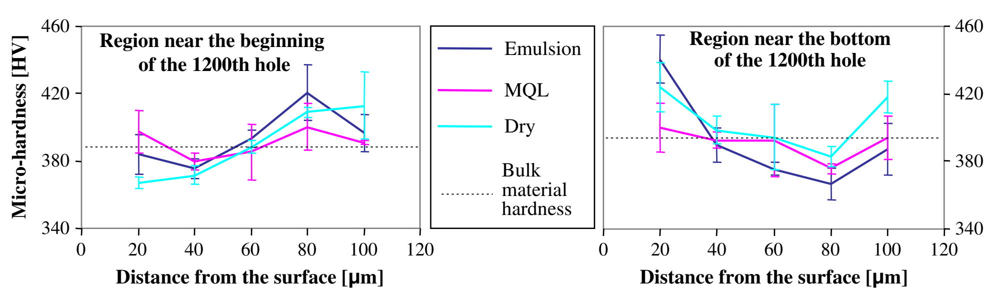
To complement the subsurface analysis, microhardness measurements were performed. Because of equipment limitations, the first possible distance for measurement is 0.02 mm from the machined surface. As seen in Fig. 15, which presents the microhardness measurements made near the beginning and the bottom of the last machined hole for the different fluid application conditions, the measured results presented a normal dispersion around the bulk material hardness, and no significant trend was observed.

4 Conclusions

The preliminary tests for the dry condition with continuous drilling presented great difficulty for chip flow through the drill flutes, generating a high chip-packing factor. These conditions led to obstruction of the flutes and the consequent tool breakage. After an analysis of the chip formation, it was concluded that the cutting was being done by the margins, instead of the principal edges, which changed the shear planes regarding the feed axis, and compromised the chip flow along the flutes. To resolve this problem, the pecking cycle was adopted, with a periodic retreat out of the hole. This strategy improved the chip flow and stopped the tool breakages. Thus, the main experiment was performed with continuous drilling for emulsion tests and with the pecking cycle for MQL and dry tests.

The surface quality analysis showed that, near the beginning and the bottom of the holes, the dry drilling condition generated greater values of the roughness on the machined surface due to the higher friction on the interface tool/chip/workpiece caused by the absence of the coolant and lubricant functions performed by the cutting fluid. The MQL application condition resulted in the lowest roughness values in both analyzed regions of the holes. Near the

Fig. 15 Surface microhardness versus the distance from machined surface



beginning of the holes, differently from what occurred in the region near the bottom, the emulsion tests presented a tendency toward higher values of roughness, because emulsion keeps the original cutting edge geometry for longer times and also cools the machined material, keeping its shear strength high and causing well-defined grooves due to the passage of the tool and the consequent greater roughness.

The microhardness measurements on the surface of the last holes, in the region near the bottom, resulted in values approximately twice as large as the bulk material hardness, which corroborates the hypothesis of the occurrence of microwelding, because applying high thermal and mechanical loads to the welded chip causes microhardening of the chip.

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