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Effects of drill microgeometry and cooling supply in the surface integrity

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ABSTRACT

Purpose: The objective of this paper is to investigate the effect of drill microgeometry and cooling supply in the surface integrity of machined holes. The changes in the holes surface and subsurface due to differences on tools features were presented.

Design/methodology/approach: Two types of carbide drills with differences in microgeometry and internal/external cooling were used in the machining of SAE 1045 steel. The surface integrity of the holes was evaluated in terms of surface and subsurface quality. The holes surface was examined using optical microscopy (texture) and roughness measurement. The subsurface analysis included plastic deformations, and micro and nanohardness.

Findings: The differences in the cooling supply and drills microgeometry showed influence on surface integrity results. The drill type with internal cooling and improved microgeometry produced holes with a smoother surface and subsurface changes of lower magnitude. The most influent feature of microgeometry was the margin thickness. The drill with a thicker margin presented better results, mainly due to friction reduction.

Practical implications: The performed investigations could be useful in the industrial practice and give the information for tool selection in drilling of SAE 1045 steel, which is very used in mechanical components industry.

Originality/value: The paper shows the importance of analysing the effect of differences of tools features in surface integrity, which is often neglected, but has great influence on the components performance, mainly under severe mechanical and thermal loads. This work also presents the benefits in surface integrity due to drills microgeometry improvement.

Keywords: Machining; Plastic deformations; Hardness

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Drilling process is widely used in automotive, aerospace and aircraft industries. Although modern metal cutting methods improve in manufacturing industry, including electron beam machining, ultrasonic machining, electrolytic machining and abrasive jet machining, conventional drilling still remains one of the most common machining processes [1]. Drilling may appear to be a simple process, but it is in fact deceptively complex. In contrast to most other machining processes, such as milling, turning and grinding, the cutting edges work inside the workpiece volume. Chips must be removed upwards through the bore, interfering with lubrication and cooling [2]. Furthermore, drilling is one of the most demanding machining processes because a completely machined geometry and surface are generated in one operation. The demands in regard to diameter precision, straightness and surface quality are high. Tools must meet the requirements for diameter tolerances and shape-position tolerances [3]. Therefore, tool selection plays an important role in the process.

Cutting tool management includes the appropriate choice and use of cutting tools, as well as continuous monitoring of unwanted phenomena on cutting tools during the period of cutting, e.g. breakages, intensive wear and overload of the cutting edge [4]. Another important element to be monitored is the surface quality of the parts.

Surfaces analysis is not limited to a numeric value allocation to parts surface conditions. Identify and assign functional values that will influence performance when the part is at work condition is the main factor to be considered [5]. The surface of a part has two important aspects that must be defined and controlled. The first aspect are geometric irregularities on the surface, and secondly the metallurgical alterations of the surface and the surface layer. This second aspect has been termed surface integrity [6]. The surface integrity is a measure of the quality of the machined surfaces, interpreted in function of elements that describe the structure of the surface and the substratum of the material. Generally it is defined by the metallurgic, chemical and topological properties of the surfaces, as surface roughness, microstructure, microhardness variations and changes in the residual stresses [7].

The quality and performance of a product is directly related to surface integrity achieved by final machining [8]. It is known that the quality of surface generated during machining is influenced by a large number of process, tool, machine and work material dependent parameters. These include cutting parameters, tool material and features, cooling methods, stiffness of machine and cutting tool system, etc. [9, 10]. The geometry of the tool plays a critical role in achieving the desired surface finish producible on the machined surface and in controlling the chips (i.e. breaking the chips into small and acceptable shapes and forms) [11]. All these factors have influence on the heat generation in the machining process.

Most of the energy in the cutting process is largely converted into heat. This heat is generated by plastic deformation and friction at the tool-chip and the tool − workpiece interfaces [12]. During the drilling process, the most important factor affecting the cutting tool performance and workpiece properties is the cutting temperature that emerges between the drill and the chip. The cutting temperature directly influences the hole sensitivity (hole diameter, perpendicularity and cylindricity), surface roughness and tool wear [13]. Since materials properties, such as shear strength and hardness, are influenced by temperature, the physical natures of metal removal process are highly dependent on temperature [14]. Thus, the wear of the major flank of the drills is the dominant mechanism limiting tool life with worn drills raising the prospect of introducing damage into the workpiece [15].

Efforts have been made to investigate the relationships among the machining process parameters, the nature of the surface alterations produced and their effect on product's functional performance [12]. The performance, longevity and reliability of machined components during their service are most dependent on their machined surface quality [16, 17]. Factors such as fatigue creep and stress corrosion cracking, which cause failure of the mechanical components, start to affect the component surfaces, and these failure extensions highly depend on the surface integrity of the component [10]. Good surface integrity is especially important in various engineering applications requiring high reliability and resistance to failure [18]. Therefore, it is essential to gain better understanding how the machining process affects the functional behaviour of machined parts to minimize failure during service.

This paper aim to analyze the surface integrity of holes machined with carbide tools in drilling of structural steel, using two types of drill with same diameter, but with particular differences between themselves, such as with or without internal cooling and difference on the tool margin thickness, allowing to analyze the effect of friction area between the margins and the workpiece in the surface integrity of the holes.

2. Experiments

2.1. Workpiece

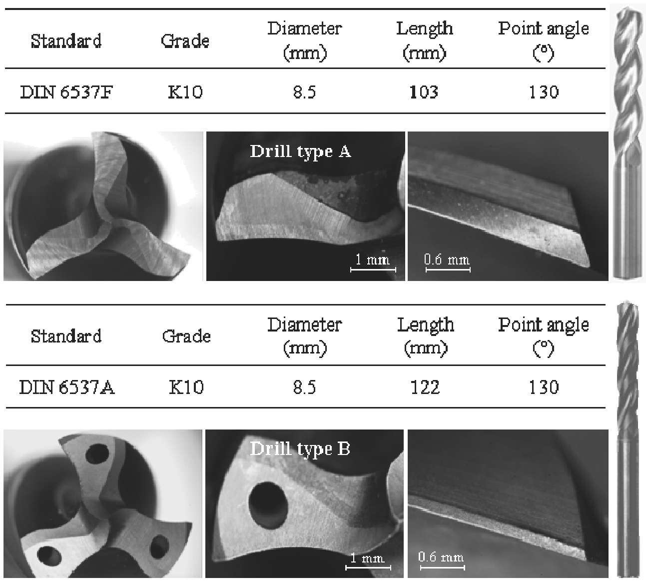
The workpieces were prepared with SAE 1045 steel, hardness 180 HV. The workpiece dimensions were 60 x 35 x 50 mm and the distance between holes was 1.5 times the diameter of the tool. Table 1 shows the chemical composition of the workpiece material.

Table 1.
Chemical composition of the steel used during the experiments, in % of weight

C	Mn	P_{max}	S_{max}
0.45	0.60	0.0396	0.0105

2.2. Tools

Two types of carbide twist drills were used in the experiments, both uncoated, with different geometries, one with external cooling and one with internal cooling. Figure 1 shows the tools used in the experiments.



Standard	Grade	Diameter (mm)	Length (mm)	Point angle (°)
DIN 6537F	K10	8.5	103	130

Standard	Grade	Diameter (mm)	Length (mm)	Point angle (°)
DIN 6537A	K10	8.5	122	130

Fig. 1. Tools used in the experiments

As shown in Figure 1, the tools have different geometries, such as the thickness of the margins, respectively 0.125 mm for drill type A and 0.375 mm for drill type B.

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 optical analysis of the texture of 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 and nanohardness measurements were made using a Micro Materials NanoTest 600 Nanoindenter. The parameters used in nanohardness measurements were indentation depth of 1800 nm, loading speed of 5 mN/s and initial load of 0.1 mN.

2.4. Experimental procedures

The tests were carried out with new and worn tools, and two repetitions were made for each condition of test. The worn tools used in the experiments presented a maximum flank wear ($VB_{max.}$) of 0.2 mm. The cutting parameters used in tests were cutting speed of 70 m/min, feed of 0.066 mm and the depth of the holes was three times the diameter of the tool (25.5 mm).

For all tested conditions was applied fluid in abundance, with pressure of 3 bar and flow rate of 1800 l/h in external cooling, and 145 l/h in internal cooling tests. The oil used was Vasco 1000, in a concentration of 10%. The oil was provided by Blaser Swisslube of Brazil Ltda.

The quality surface analysis made in the holes was carried out near the beginning, 2 mm depth, and near the bottom of the hole, 22 mm depth.

3. Results and discussion

Surface roughness plays an important role in parts accuracy and service life, which is affected by many factors [16]. The most common way to evaluate the surface is through the analysis of the surface roughness and texture of the hole. The below results present the effect of the machining conditions as well as the effect of the drill geometry and characteristics.

Figure 2 presents the graphs of R_a roughness values measured near the beginning and near the bottom of the holes machined using new and worn tools.

Comparing the regions near the beginning and near the bottom of the holes it can be seen that there is no significant variation for both types of drill, for new or worn tools. However, the wear of the tools caused an increase in roughness, what can be explained by the rounding of the tool's corners, which makes larger grooves in the passage of the drill, as can be seen in Figures 3 and 4. The drill B provided lower roughness due to internal cooling, allied to the effect of the smaller margin thickness and corner, reducing the friction between the tool and the holes wall, as well as in the cutting region, resulting in the reduction of temperature.

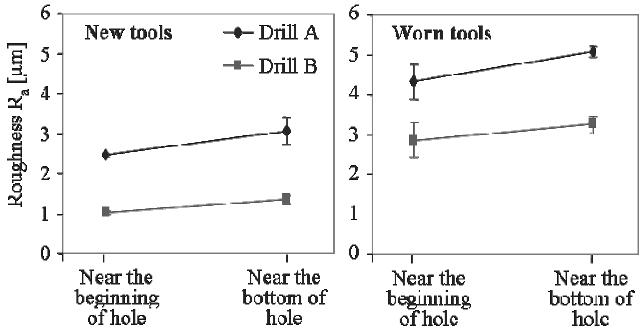


Fig. 2. Roughness obtained with new and worn tools

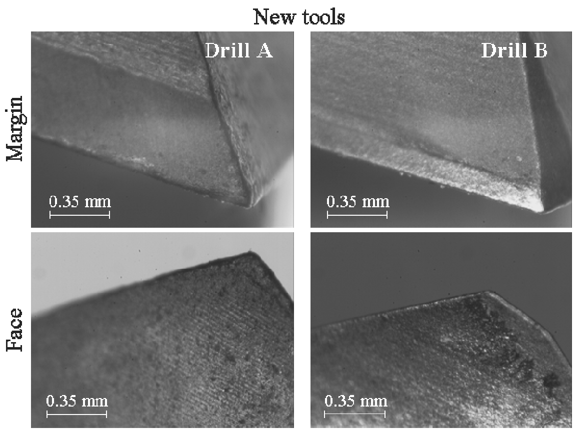


Fig. 3. Photos of the new tools, with detail of the corner edge

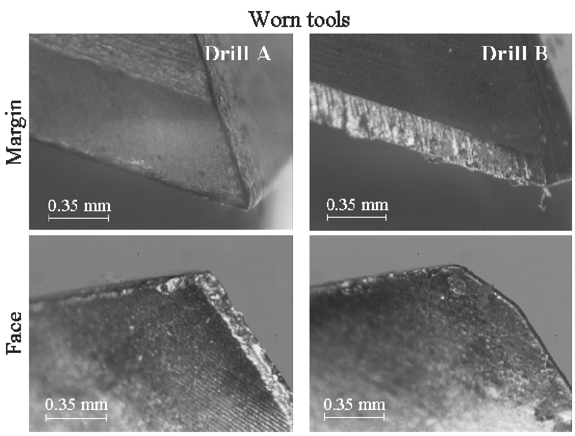


Fig. 4. Photos of the worn tools, with detail of the corner edge

The analysis of surface topography was complemented by texture analysis, performed in each test condition, as shown in Figures 5 and 6. Through these analyses the obtained values of roughness can be qualitatively understood.

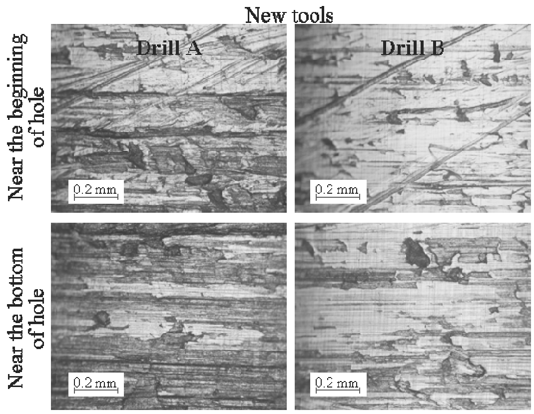


Fig. 5. Surface texture of holes machined with new tools

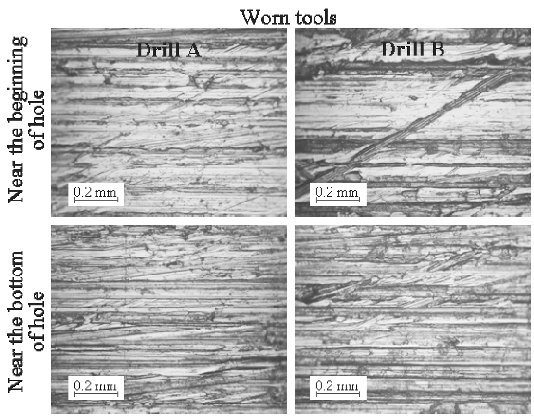


Fig. 6. Surface texture of holes machined with worn tools

Analyzing the images it can be observed that surfaces generated with worn tools present deeper grooves, what explain the higher roughness values measured for worn tools. The texture of holes made with drill B is smoother than that machined with drill type A, what also is in agreement with the lower roughness obtained with drill B.

Due to the increasing demand on the mechanical properties of parts manufactured by machining, the focus given to the topography of the surface should be extended to the transformations that occur in the layers under the surface, e. g., to the surface integrity [6]. As the main cutting edges of the drill follow a helical trajectory, analysis in the radial direction of the hole is needed to facilitate a more complete interpretation of the phenomena occurring at the tool/workpiece interface during drilling and thus to enable better understanding of their implications for surface integrity [15].

The main threats to surface integrity come from the plastic deformation of the workpiece during the machining process [8]. The subsurface microstructural deformation caused by machining consisted of deformed grain boundaries in the direction of cutting, elongation of grains and surface cavities. Plastic deformation is a phenomenon usually associated with the highly localized surface heating caused by severe machining (i.e. high feed rates or large depths of cut), or worn tools [19].

Figure 7 shows the graphs of measured plastic deformations in holes machined with new and worn tools. The measurements were made near the beginning and near the bottom of the holes, and the depth (measured in the radial direction of the hole) of the plastic deformations was quantified as the distance from the free surface of the workpiece to the depth beneath the surface where no more plastic deformation is visible on the micrographs. Each value plotted in the graphs is the average value of the five maximum plastic deformations found in the analyzed region.

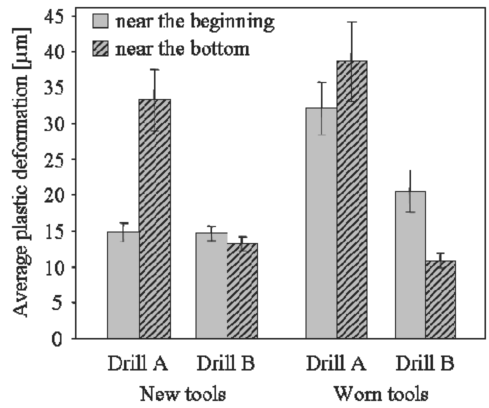


Fig. 7. Plastic deformations with new and worn tools

The results shows that drill B caused lower plastic deformations than drill A, except near the beginning of holes made with new tools, which results are statistically equal for both types. One hypothesis for this result indicates that the cutting fluid applied by the internal cooling of the drill B reduces the friction and consequently the temperature on the cutting region, which reduces the heat flow to the piece and causes lower plastic deformations. The minor thickness of the margin of drill B also contributes to decrease the friction between the tool and piece, since the interface area is smaller, reducing the heat generation and the formation of plastic deformations.

Considering the effect of the tools wear, for both drill types the worn tools caused higher plastic deformations than new tools near the beginning of the holes and no significant variation near the bottom of the holes.

Analyzing the results along the depths of the holes, different results were obtained. For new tools, drill A resulted in plastic deformations near the bottom of the hole approximately twice higher than near the beginning. The drill B, also in new condition, did not caused significant variation along the hole depth. The worn tools presented an opposite behavior, since drill A presented results statistically equal near the beginning and near the bottom, while drill B resulted in higher plastic deformations near the beginning than near the bottom of the hole.

Especially intriguing are the results of drill A in new condition and drill B in worn condition. Drill A presented higher plastic deformations near the bottom, while drill B showed higher results near the beginning of the hole. The drill A result is expected because near the bottom the chip flow is more difficult, what increases the friction between the chip and the piece, causing higher generation of heat and larger plastic deformations. The drill B result does not follow this trend. A study of Kwong et al. [15] can explain this result. They showed that the interaction between the tool margins and the workpiece can cause material from the surface to plastically deform in the radial direction of the hole by a dragging mechanism. According the authors the extent of the interaction is dependent on the time that the margins of the drill are in contact with the workpiece material (walls of the hole) and the intensity of the associated friction phenomena. Consequently the material near the beginning of the hole is exposed to interaction with the margins for longer time than that near the bottom, allowing for a larger cumulative dragging effect. Thus, a triangular plastic deformation distribution might be expected to describe the volume of material drag caused during the drilling operation.

Another possible explanation for this result is the taper of drill B, which is significantly higher than drill A. The taper causes increasing friction between the margins and the hole along the drill length, being lower the friction near the top of the drill. Therefore, this contact difference is larger for drill B, causing higher friction near the beginning of the hole, which can lead to larger plastic deformations.

To summarize, it's possible to notice a trend for each tool, independent from its life condition. The drill A (external emulsion, greater margin thickness) increased the average plastic deformation when comparing near the beginning with near the bottom of the hole, for both new and worn tools. As for drill B (internal emulsion, minor margin thickness), the values tend to decrease when comparing near the beginning with near the bottom of the hole.

To better understand the analyzed regions, it is useful to observe images of typical plastic deformations found in the samples, in Figures 8 and 9.

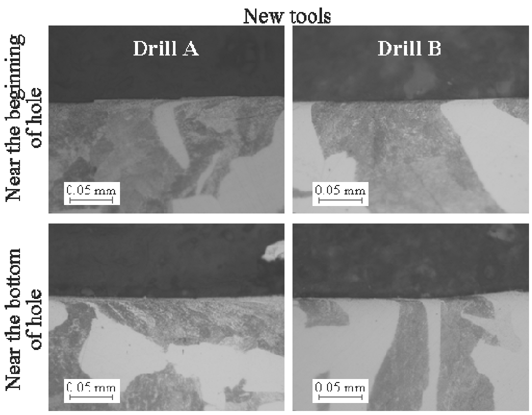


Fig. 8. Micrographic images of holes machined with new tools

One way to evaluate the effect of plastic deformations in the machined surface is the hardness measurement. Hardness evaluation belongs to the basic tests of mechanical properties of materials. There is a relationship between the hardness and other material's characteristics, e.g. a tensile strength [20]. To perform these tests, the microstructural constitution of the workpieces was considered.

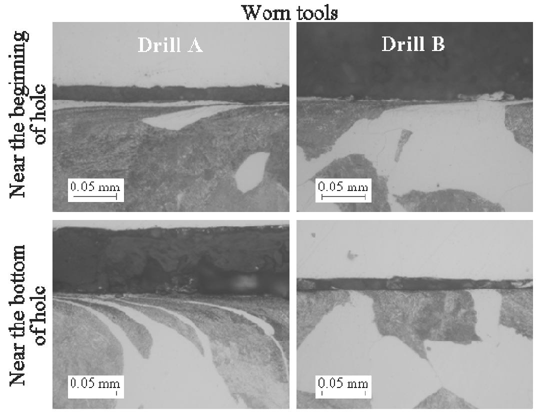


Fig. 9. Micrographic images of holes machined with worn tools

The SAE 1045 is basically a ferrite-pearlite steel. Ferrite is the softest phase of steel, which can practically be called carbon free iron. The pearlitic microstructure consists of pearlite phase dispersed in a softer matrix of ferrite. Pearlite is not a homogeneous phase, it consists of layers of ferrite and cementite (iron carbide). It is well established that pearlitic microstructures are affected directly by %C content in the material. As the %C content increases, higher pearlite content in the material can be produced. Increasing % pearlite in the steel enhances the strength but sacrifices the toughness of the material [21].

Due these differences in mechanical properties of ferrite and pearlite phases, microhardness tests were performed on each phase. Figures 10 and 11 show the measurements results.

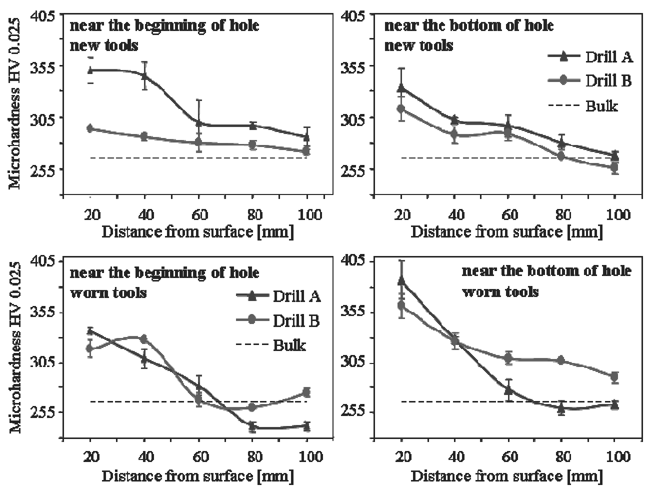


Fig. 10. Microhardness results for pearlite phase

In general, the subsurface close to the machined surface present high values of microhardness and these values decrease with an increase in the depth until they stabilize and reach the hardness value of the bulk material [19]. Work hardening of the deformed layer beneath the machined surface causes higher superficial hardness than the average hardness of the bulk material. The higher hardness generated is mainly due to the cutting plastic deformation, corner radius extrusion and the severe friction between the tool flank and machined surface [16].

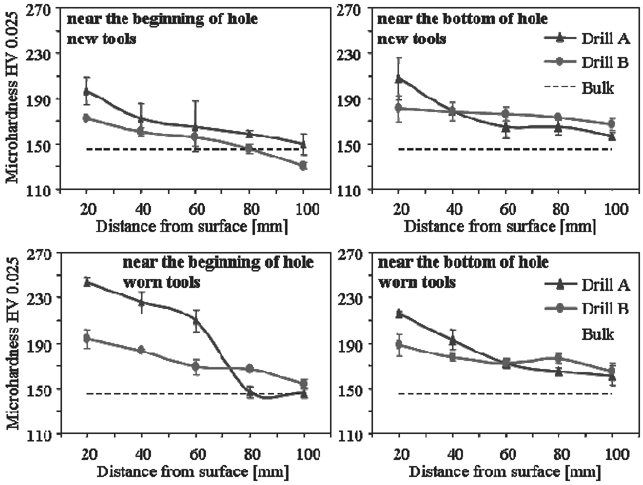


Fig. 11. Microhardness results for ferrite phase

The average bulk hardness measured in pearlite phase was 265 HV, while for ferrite phase the average bulk hardness obtained was 145 HV. Through the analysis of microhardness it can be observed that values decreased with the increasing of distance from the surface, tending to bulk hardness. The results show no significant differences between drills A and B, neither between the regions near the beginning and near the bottom of holes.

As observed in the other analysis, the effect of the tool corner and margin thickness, as well as the different fluid applications had a significant impact on the microhardness results. The higher heat generated by the tools with thicker margin and no internal cooling generated higher plastic deformations, therefore, increasing the microhardness present on the deformed surface.

As for the tool condition, there was no significant difference between the near the beginning of hole for new and worn tools, however near the bottom there was an increase of the hardness for worn tools in the pearlitic regions. Nevertheless, the ferritic region presented no significant change on the measured hardness between near the beginning and near the bottom of the hole.

Nanohardness tests also were applied. The measurements were performed on the surface, near the beginning of the hole, and on the radial direction of the hole, also near the beginning of the hole. Figure 12 presents the results.

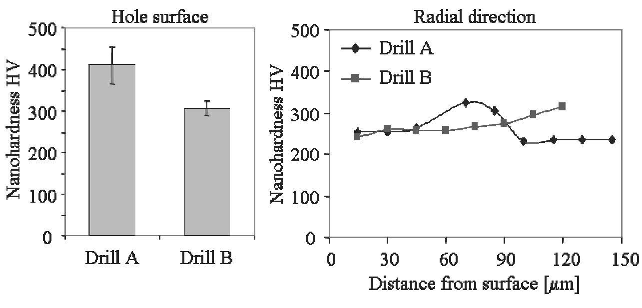


Fig. 12. Results of nanohardness measurements

The effect of the material plastic deformation on the surface nanohardness increasing, caused by the effect of the grain hardening, was more pronounced on the drill A, which showed higher plastic deformations, matching the earlier presented results. As for the radial direction measurements, the results matched the observed for the microhardness, with slight differences.

4. Conclusions

The application of internal fluid reduced the heat generation in the contact zone between tool and workpiece, by granting a better lubrication and thus, friction reduction, which contributed to reduce the surface roughness as well as smoother texture.

It was observed that the margin thickness has a relevant effect on the results, explained by the reduction of the friction between the margin and the hole wall, generating less heat and minor roughness, smoother surfaces, less plastic deformation and consequently minor hardness variation on the deformed regions.

Due to the adhesion present on the tool corner and cutting edge as well as the roundness of the corner, the worn tools presented higher surface roughness, irregular surfaces and higher plastic deformations.

The effect of the depth of the hole was more evident for the tool without the internal cooling (drill A), associated to the difficulty of transport of fluid in the bottom of the hole and thus, more generated heat, when comparing to the beginning.

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