Journal of the Brazilian Society of Mechanical Sciences and Engineering (2018) 40:15
https://doi.org/10.1007/s40430-017-0922-6

TECHNICAL PAPER

Effects of cryogenic cooling on the surface integrity in hard turning of AISI D6 steel

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Received: 14 September 2017 / Accepted: 19 December 2017 / Published online: 11 January 2018

Abstract

Methods able to enhance surface integrity of machined components have been one of the emerging areas in manufacturing engineering, and a technique that has been providing satisfying results in the last years is cryogenic machining. Besides promoting surface integrity improvement, it is considered an alternative to the use of conventional cutting fluids, which is in accordance with the latest global trends for sustainable means of production. In this sense, replacing grinding operation, which uses large volumes of conventional cutting fluids, by hard turning assisted by liquid nitrogen, for example, could be a good choice. The aim of this work was to investigate the effects of cryogenic cooling on the surface integrity of quenched and tempered AISI D6 tool steel after turning operation. Dry and cryogenic turning trials with polycrystalline cubic boron nitride tools were performed and the results of surface integrity (surface roughness and topography, microhardness and residual stresses, as well as the modified microstructure of the deformed layer) were analyzed for comparison. The results showed that cryogenic cooling played an important role in modifying the workpiece surface integrity, providing low values of surface roughness (similar to those obtained in grinding operations), as well as higher values of surface microhardness and compressive residual stresses as compared to the dry condition.

Keywords Cryogenic cooling · Hard turning · AISI D6 steel · Surface integrity · PCBN tools

1 Introduction

D-type tool steels are the most highly alloyed cold work steels. The high volumetric fraction of hard carbides gives to these steels an excellent wear resistance, which is a demanded characteristic for deep-drawing and cold forming dies. If long production runs are necessary, AISI D6 steel with high carbon and chromium content is an appropriate grade to be taken into account for meeting these demands. However, according to Roberts et al. [1], high-carbon and alloyed tool steels are considered difficult-to-cut materials, mainly if they are in hardened state. Because of their characteristics of high hardness and deformation resistance combined with high abrasiveness, high cutting tool wear rates are usually a great problem when machining these alloys. Because of that, several steps of machining operations usually characterize the manufacture of dies before and after heat treatments of quenching and tempering, which make the process time-consuming. Finishing operations usually include grinding and polishing. Klocke and Kuchle [2] mention that these

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abrasive finishing processes usually induce tensile residual stresses on the machined surface, which are not beneficial to the dies in terms of fatigue strength. For this reason, to maximize the die lifetime in many high-stress cold forming applications, it is common to use the shrink fitting technique. Lee et al. [3] described the method that consists of inserting the die into a compressive stress ring, which applies a pretensioning on its external surface, inducing compressive stress on its inner surface. Despite its effectiveness, it is considered a costly and time-consuming procedure. Furthermore, grinding and polishing operations are expensive and cause high environmental impact because they normally use large volumes of conventional cutting fluids. According to Shokrani et al. [4], although conventional cutting fluids provide technical benefits, great problems are still associated with the use of them on shop floor such as, the cost of maintenance and disposal, and problems associated with the worker's health. They usually present chemical elements such as, sulfur, phosphorus and zinc, and some of them are toxic to the human being and not biodegradable. For these reasons, Meza et al. [5] claimed that the implementation of less costly and time-consuming, and sustainable procedures on shop floor is a major concern nowadays.

In this regard, an alternative that has been used is to replace grinding with dry hard machining using polycrystalline cubic boron nitride (PCBN) or oxide ceramic inserts. AISI 4340, 8640 and 52100 steels with martensitic microstructure have been extensively machined accordingly, even at cutting speeds higher than 150 m/min. Oliveira et al. [6] stated that both cutting tool materials, PCBN and oxide ceramic, have been used in continuous and interrupted cutting achieving machining times over 50 min. The reason why dry machining these hardened steels is based on the fact that the high temperatures generated during the process would help to soften the workpiece material, facilitating the chip formation. In spite of that, high temperatures can accelerate the cutting tool wear and provoke workpiece distortions, besides modifying the workpiece surface and subsurface in many respects.

In this context, many attempts have been made to improve the tribological conditions at the tool – workpiece interface and reduce the impact on the human health and on the environment. In this sense, techniques that use metallic and non-metallic nanoparticles added to the base fluid (called nanofluids) have been investigated [7, 8].

Other practice that has given successful results in machining of hard-to-cut materials in the last 20 years is the use of liquefied gases as cutting fluids. Shokrani et al. [4] reported that by using super-cold medium, such as liquid carbon dioxide (LCO_2), liquid nitrogen (LN_2), liquid helium and others, it is possible to obtain better results in terms of cutting temperature, cutting force, and surface integrity as compared to the dry condition or by any other known cooling medium. In this case, liquid nitrogen (LN_2) is the most commonly used liquefied gas because it is considered environmentally friendly and non-toxic. Uehara and Kumagai [9] were the first to use the term "cryogenic machining" to denominate the technique of using liquefied gases as coolant in machining, though there are inconsistences in identifying at what point on the temperature scale refrigeration ends and cryogenics begins [10].

Machining induces surface and subsurface modifications, usually called surface integrity. Field et al. [11] defined the term "surface integrity" as the various aspects of a machined surface including roughness and topography, microhardness, residual stresses and microstructure, which can directly influence the functional performance of the components. In this case, as described before, cryogenic machining can provide better results as compared to dry, near-dry or wet machining.

Cryogenic cooling is able to diminish surface roughness in a range of materials. Klocke et al. [12] reported a significant surface roughness reduction after cryogenic turning a third-generation gamma titanium aluminide in comparison with dry and near-dry machining. Pusavec et al. [13] showed reduced values of Ra after turning Inconel 718 under cryogenic condition. Turning AISI 52100 bearing steel, Umbrello et al. [14] found Ra values 35% lower for cryogenic machining in comparison with dry condition. Usually, the better performance of cryogenic cooling is attributed to its ability to keep cutting temperatures down and, consequently, reduced tool wear rate. However, it seems that cryogenic cooling is able to make the workpiece surface brittle, leading to the breakage of the feed marks' ridges. According to Kaynak et al. [15], improved surface quality in cryogenic machining is due to the fact that under this condition, much smoother surface topography is obtained as compared to dry, MQL, and flood cooling conditions, in which the feed marks are much more visible. As the main parameter used in machining for evaluating roughness is based on the vertical deviations of the roughness profile from the mean line, it is expected that the average roughness value (Ra) under cryogenic will be lower than under dry condition.

After machining, it is noted that a thin layer is formed below the workpiece surface presenting different mechanical properties in comparison with the bulk material. Kaynak et al. [15] explained that this phenomenon occurs because the material close to the cutting edge is plastically deformed and dragged in the cutting direction, leading to work-hardening of the deformed layer. Because of that, the hardness on the surface is higher than that in the bulk material. During or after the plastic deformation, if the cutting temperature increases to the workpiece material's restoration point, the effect of the work-hardening will be weaken. According to Quan and Ye [16], plastic deformation at low temperature results in increased work-hardening. Since cryogenic machining reduces the cutting temperature remarkably, it is expected that the surface microhardness under this condition will be higher than under dry machining. It is also important to highlight that, as described by Kaynak et al. [15], the thickness of this layer depends on many parameters, such as the mechanical properties of the workpiece material, cutting parameters, cutting tool geometry, and cooling conditions.

It is well known that the functional performance of a machined component is very determined by the state of its surface and subsurface. The plastic deformation provoked by the cutting tool on these regions can also induce residual stresses usually called "machining-induced residual stresses". Brinksmeier et al. [17], based on previous investigations, reported the influence of the machining process on the workpiece surface integrity in terms of residual stresses and hardness, and provided a comprehensive understanding based on destructive and nondestructive tests for evaluating surface integrity of machined components.

According to Guo et al. [18], the influence of residual stress can be either beneficial (if it is compressive) or harmful (if it is tensile), depending on its magnitude, pattern, and distribution. M'saoubi et al. [19] reported that the nature of the residual stresses will be influenced by many parameters, including lubricating and cooling conditions. Compressive residual stresses on the surface and subsurface are expected to contribute for improving fatigue resistance of the machined components. Bicek et al. [20] showed that cryogenic cooling is effective in generating a machined surface layer with compressive residual stresses. The explanation is based on the fact that cryogenic machining is able to greatly reduce thermal stress inducements as compared to dry machining, promoting higher compressive stresses on the surface and subsurface.

For all the aforementioned reasons, both in technical and sustainable aspects, it is believed that cryogenic cooling can be an excellent alternative to the conventional methods of refrigerating and lubricating machining operations. The technique is not extensively spread in the industry yet and one reason for that can be the lack of more detailed studies and information on economic questions, but it is a subject for other investigation.

In this paper, the concern is about how the surface integrity of hardened AISI D6 steel is modified after being turned under dry and cryogenic conditions. In this case, surface roughness, microhardness and residual stress were the main analyzed variables. Additionally, SEM analyses of the machined surface and subsurface were performed for a more comprehensive understanding about the phenomena involved.

2 Materials and methods

The following is a description of the materials, equipment and experimental procedure adopted in this investigation.

2.1 Workpiece

For the turning trials, two round bars (127 mm diameter and 133 mm length) of quenched and tempered AISI D6 tool steel were used as workpieces. The microstructure of the material is composed of coarse hard carbides embedded in a martensitic matrix (Fig. 1) with an average hardness of 57 HRC (633 HV).

2.2 Cutting tools

PCBN inserts with low content of CBN and ceramic phase (Sandvik grade 7015 or ISO H15, code SNGA 120412 S01030A) were used as cutting tools [21]. According to Sandvik [22], 7015 grade contains 50% of CBN fine grains in a single ceramic binder and a PVD TiN coating. The low CBN content guarantees better performance in turning of hard materials [23]. It is also important to highlight that the inserts have a microgeometry with a 0.1 mm negative land, a chamfer angle of 30° and a round edge of 0.025 mm. The tool holder was PSBNR-2525 M 15. When the insert is attached on the tool holder, the following macrogeometry is established (see Table 1).

It is important to emphasize that due to its microgeometry, in which a 30° chamfer is present throughout the cutting edge, the effective rake angle becomes − 36°. This is a very important detail, mainly because the depth of cut applied in this investigation was equal to the chamfer land length (0.1 mm). This fact will remarkably influence on the deformed layer obtained after the turning operation.

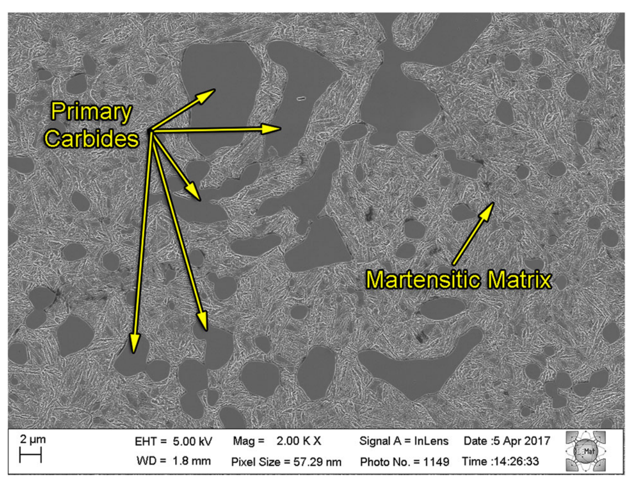

Fig. 1 Workpiece material microstructure showing primary carbides (darker regions) embedded in a martensitic matrix

Table 1 Cutting tool macrogeometry

Position angle, κ_r	Nose angle, ε_r	Lateral position angle, κ'_r	Main clearance angle, α_o	Wedge angle, β_o	Rake face angle, γ_o	Edge inclination angle, λ_s
75°	90°	15°	6°	90°	− 6°	− 6°

2.3 Experimental setup

The experiments were performed in a Romi Centur 30D CNC lathe with 9 kW of power and maximum speed rotation of 4000 rpm.

A liquid nitrogen supply system were built and set up on the lathe in order to deliver liquid nitrogen to the cutting zone. The system consists of six main parts: air supply hose; LN_2 Dewar container; cryogenic needle valve; vacuum insulated cryogenic hose; manifold and frame. Figure 2 shows an overview of the experimental setup.

The system works as follows (see Figs. 2, 3): Compressed air is pushed into the LN_2 Dewar container through the air supply hose. Since the Dewar container is completely sealed, its internal pressure is increased and kept at 1.8 bar by means of two relief valves located at the top of the container. This increased pressure impels LN_2 towards the manifold through the vacuum insulated cryogenic hose. As soon as the liquid nitrogen reaches the manifold, it is driven to the rake, flank or both faces of the cutting tool (Fig. 4) by means of two needle valves and two flexible copper tubes 3/32 inch (2.38 mm) of inner diameter.

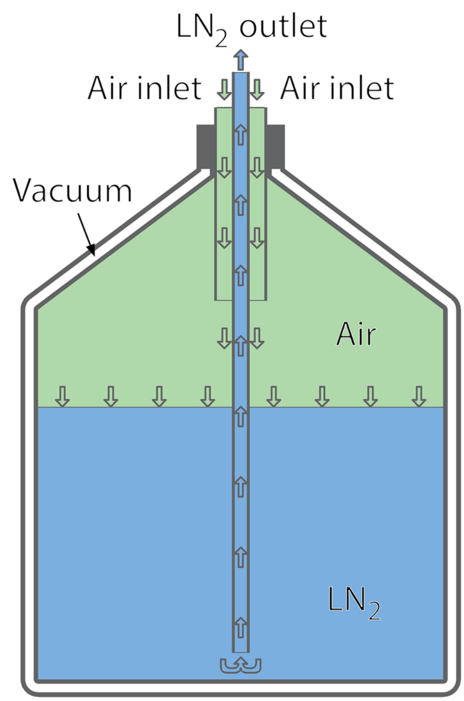

Fig. 3 Schematic drawing showing the working principle of the Dewar container

2.4 Experimental procedure and analyses

Information on recommended cutting parameters for machining AISI D6 tool steel is not easy to find, even in catalogs. As reference, it was used the paper published by Yallese et al. [24]. In this work, quenched and tempered

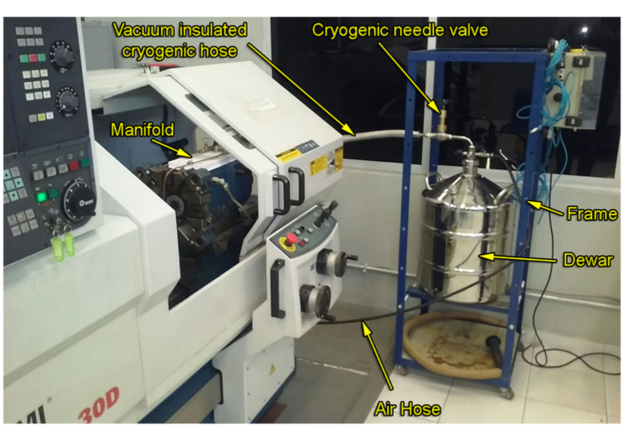

Fig. 2 Experimental setup

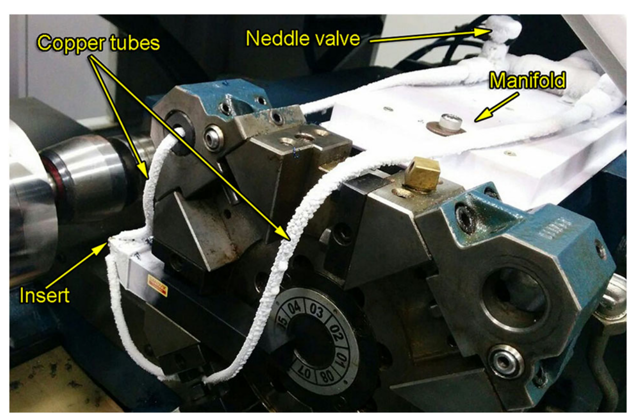

Fig. 4 Copper tubes positioned on the rake and flank faces

AISI D3 steel (60 HRC) were turned with PCBN 7020 at 180 m/min for around 15 min under dry condition. Based on this previous investigation, the following cutting parameters were adopted in the present study: cutting speed

(v_c) = 170 m/min, feed rate (f) = 0.1 mm/rev and depth of cut (a_p) = 0.1 mm.

In order to prevent cutting edge chipping while turning, the workpiece was positioned as shown in Fig. 5.

Cutting tests at four different cutting conditions were performed as follows:

- Under dry condition (DRY).
- With LN_2 applied on the tool rake face (RF).
- With LN_2 applied on the tool flank face (FF).
- With LN_2 applied on both tool faces (RF/FF).

Each abovementioned cutting condition was used for machining along a feed length (L_f) equal to 25 mm in the sequence shown in Fig. 5. It is important to highlight that for each cutting condition a fresh cutting edge was used.

The needles valves were kept completely open during the trials with LN_2.

After the turning trials, average roughness (Ra) was measured on each machined length (related to each cutting condition) at ten different positions on the circumference of the workpiece. For this purpose, a Taylor Hobson Surtronic 25 portable roughness tester was used which a cut-off of 0.25 mm and an evaluation length of 1.25 mm. These parameters are in accordance with the ISO 4288 standard (RSm range between 0.04 and 0.13 μm).

After the roughness measurements, a sample of each machined length was removed from the workpiece for microscopy analyses. The aim of these analyses was to investigate how each cutting condition influenced on the workpiece surface and subsurface layer. The samples were removed with a precision cutter and an Isomet diamond wafering blade (152 mm of external diameter and 0.5 mm of thickness) to prevent thermal damage to the workpiece material. After metallographic preparation, the samples were analyzed in a SEM FEG Zeiss Auriga 40.

The microhardness of the machined surface was measured in a MV2000A Pantec digital microhardness tester. In this case, five vickers microhardness indentations were performed applying a load of 50 gf for 15 s.

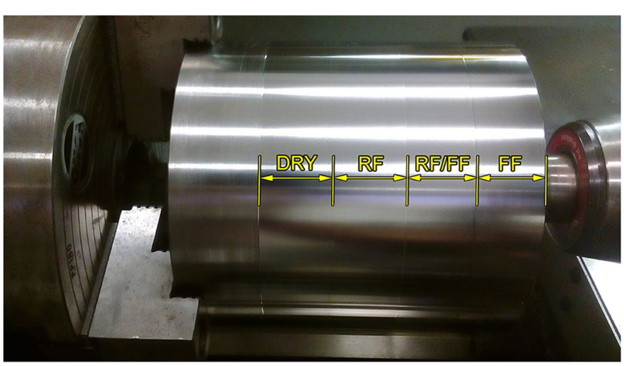

Fig. 5 Machining trials for surface roughness evaluation

Residual stresses were evaluated with a MAXima XRD-7000 Shimadzu X-ray diffractometer. In this case, residual stresses were measured ten times in axial and circumferential directions.

3 Results and discussion

Results and discussion obtained in this investigation follow below.

3.1 Roughness

Figure 6 shows the mean values of Ra (arithmetical mean roughness) obtained after turning under the conditions DRY, FF, RF, and RF/FF. It is noted that the cryogenic cooling provided mean roughness values notably lower than those obtained under dry condition.

Based on these results, it is noted that cryogenic cooling was effective in reducing the workpiece surface roughness in comparison with the dry condition, which is in accordance with other similar investigations, as reported by Kaynak et al. [15]. Pusavec et al. [13] also found lower values of Ra after machining Inconel 718 under cryogenic condition in comparison with the dry condition. Umbrello at al. [14] found values of Ra very similar to those obtained in the present investigation after turning AISI 52100 with PCBN inserts under dry and cryogenic conditions. In this case, the values of the applied cutting parameters were very similar to those applied in the present work (cutting speed = 150 m/min and feed rate = 0.075 mm/rev) and the obtained values of Ra were around 35% lower for the cryogenic condition in comparison with the dry condition.

Figure 7 presents the values of average roughness, Ra, in the "N" System, according to ISO 1302:2002 standard [25] and Whitehouse [26].

The classification presented in Fig. 7 is based on the application of the component according to its surface

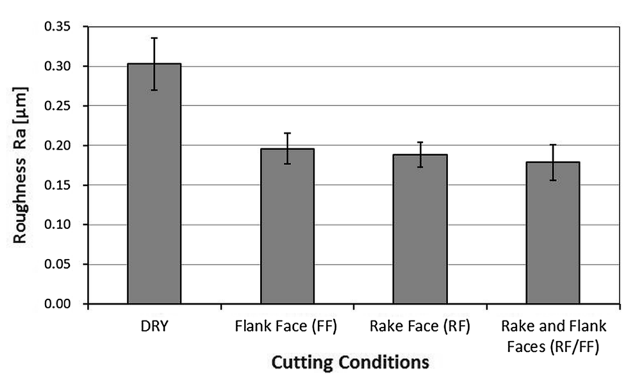

Fig. 6 Arithmetical mean roughness values (Ra) for each cutting condition

Roughness Grade Number	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12
Ra (μm)	0.025	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.3	12.5	25	50
Machining Operation			GRINDING		HARD TURNING							

Fig. 7 Roughness grade numbers according to [25] and [26]

roughness [26]. It is noted that hard turning process is normally able to provide roughness values corresponding to the grades N5, N6, and N7. Analyzing the obtained values of Ra in the present work for the cryogenic condition, and comparing them to those showed in the Fig. 7, it is noted that the values obtained for each cutting condition [Ra = 0.20 μm (FF); 0.19 μm (RF) and 0.18 μm (RF/FF)] are within the grade N4, which is normally obtained in grinding operations. This means that it would be possible to eliminate finishing operations, like grinding, if LN_2 was used as coolant when machining quenched and tempered AISI D6 steel. The same situation would not be possible if dry machining was used since the average value of Ra obtained under this condition was 0.30 μm, corresponding to the grade N5. Umbrello et al. [14] obtained similar results after machining AISI 52100 steel.

An explanation to comprehend why cryogenic condition is able to provide lower values of roughness than dry condition is related to the tool wear. Kaynak et al. [15] cited investigations in which the authors reported that the reduced values of roughness when machining under cryogenic condition would be related to the lower values of flank tool wear. However, in the present investigation, this was not an evidence that could be identified. As the machining time was not so long, the values of flank wear corresponding to each cutting condition were very similar, as can be seen in Fig. 8.

Figure 9a–d show samples of the roughness profiles obtained for each cutting condition. The respective values of R_z are also presented in the figures.

Overall, higher peak-to-valley distances are noted in the profile corresponding to the dry condition in comparison with the other conditions (cryogenic conditions). It is well known that conventional machining processes, like turning, produce periodic roughness profiles on the machined surface called feed marks. In this investigation, feed marks were clearly identified for the dry condition, as can be seen in Fig. 9a. In this case, it is even possible to see that the peak-to-peak distances are equal to the applied feed rate, 0.1 mm/rev. Whereas for the cryogenic conditions, the feed marks were somehow hidden by other marks, as can be seen in Fig. 9b–d. For these cutting conditions, it is harder to identify clearly the value of the applied feed rate. An appropriate variable that is used to quantify disturbances in the original roughness profile is the RSm parameter (it represents the average peak-to-peak distance). In machining operations that produce periodic feed marks, like turning, the value of RSm will normally be very close to the applied feed rate. In this investigation, the obtained value of RSm for the dry condition was 0.1001 mm, which is practically the value of the feed rate used in the trials ($f = 0.1$ mm/rev).

Figure 10a–d show SEM images of the resulting surface after machining under each cutting condition and its respective values of RSm. It is noted that the DRY condition resulted in feed marks that are clearly defined, with RSm practically equal to the feed rate used in the turning trials. Whereas, after machining under the conditions FF, RF and RF/FF, the resulting feed marks are not so evident, presenting values of RSm lower than the applied feed rate, mainly after the tests with liquid nitrogen delivered on the rake face of the cutting tool (RF and RF/FF).

Oliveira et al. [23] reported to have observed non-periodic roughness profile at the beginning of the cut after dry machining high-chromium white cast iron. In this case, the high quantity of carbides in the workpiece material was considered as the main responsible for this result. According to the authors, carbides close to the machined surface are sheared by the action of the cutting tool during the chip formation, producing an irregular surface topography with big sheared carbides, which disturbs the surface roughness profile. However, at the end of the cutting tool life, a periodic roughness profile was observed. In this case was suggested that the modification of the cutting tool geometry, due to the flank and crater wear and then the high temperatures developed in consequence of that, became the carbides smaller and more distributed along the workpiece surface and subsurface. However, in the present work, the phenomenon of carbide fragmentation was not verified. In this case, the pattern on the surface and subsurface was that shown in Fig. 13.

Bordin et al. [27] presented results of surface roughness and topography images after turning Ti6Al4V produced by additive manufacturing under dry, wet and cryogenic conditions. They concluded that due to the lower plasticity of the material induced by lower cutting temperatures under cryogenic condition, the machined surface was wavier with the presence of jagged feed marks in comparison with the results obtained for wet and dry conditions. The authors affirmed that the plasticity of the machined alloy was noticeable reduced, limiting its capacity to be deformed by the tool nose, as happened under dry and wet conditions. A similar situation may have occurred in the present investigation. Under cryogenic

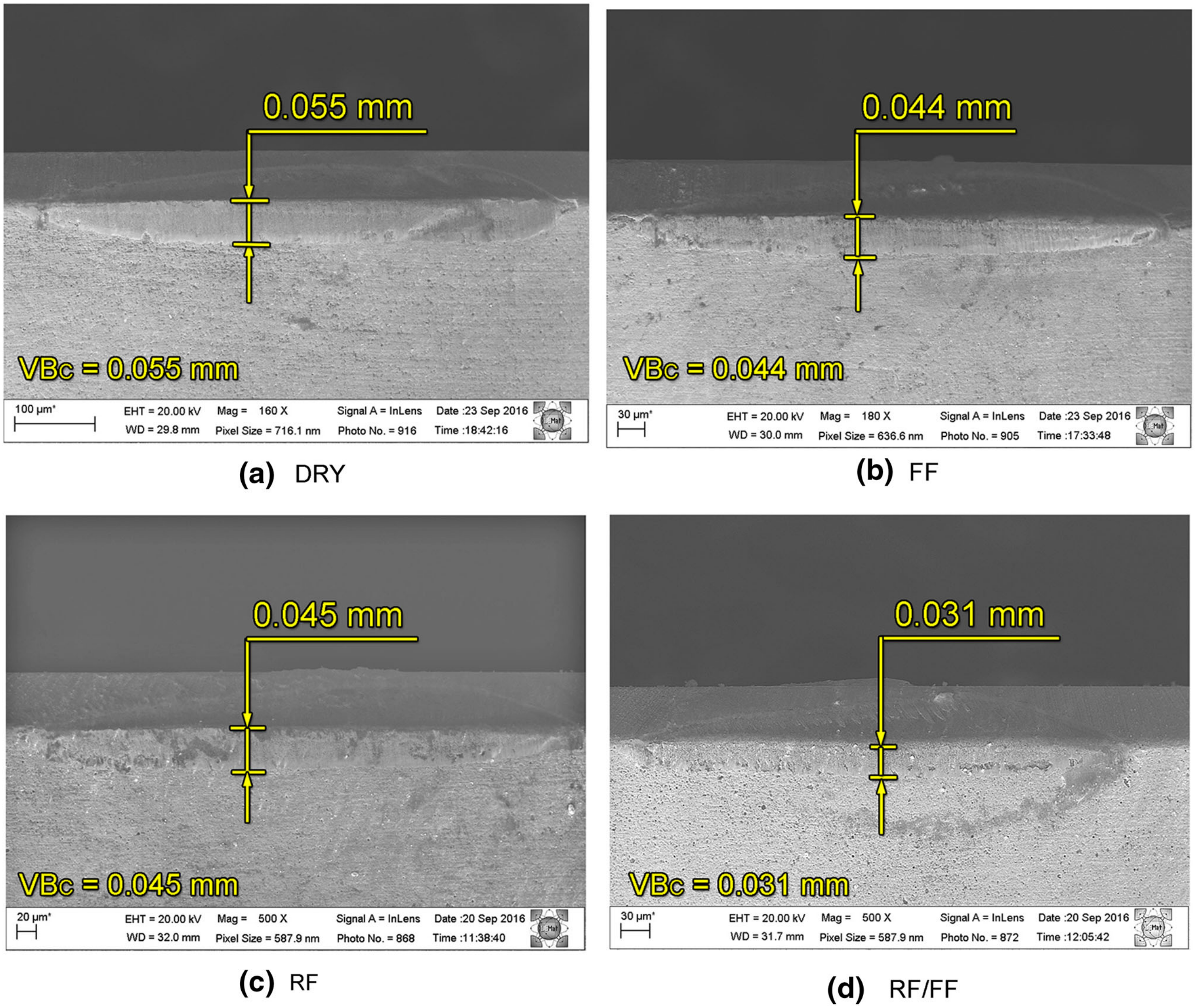

Fig. 8 Flank wear corresponding to each cutting condition

condition, the workpiece material on the surface and subsurface became more brittle and, by the action of the cutting tool, the ridges of the feed marks were fractured, reducing the peak-to-valley heights. It was possible to verify the ability of LN_2 in making the workpiece material brittle when the chips were collected and analyzed (see Fig. 11). Figure 11 shows that, when LN_2 was applied, the chips tended to be fractured, mainly when LN_2 was positioned on the rake face of the cutting tool (conditions RF and RF/FF). In these situations, the extremely low temperature of the LN_2 is able to make the chips brittle, breaking them during the process of formation. This phenomenon has already noted by Hong et al. [28] when machining low carbon steel under cryogenic condition. Under the conditions DRY and FF, this effect was not so pronounced, producing more tangled chips.

As the measured roughness parameter (Ra) is dependent on the peak-to-valley heights, that is, it is an amplitude parameter, it is not a surprise that the values of roughness obtained for the cryogenic condition were lower than those obtained for the dry condition.

3.2 Microhardness

Figure 12 shows the workpiece surface hardness obtained for each trial condition.

At first, as already expected, it is noted that the surface material became harder in comparison with its as-received condition (633 HV). Besides, it is noted that the cryogenic cooling promoted higher values of surface hardness as compared to the dry condition. It was verified an increase of around 8% for the conditions FF and RF and 19% for the condition RF/FF.

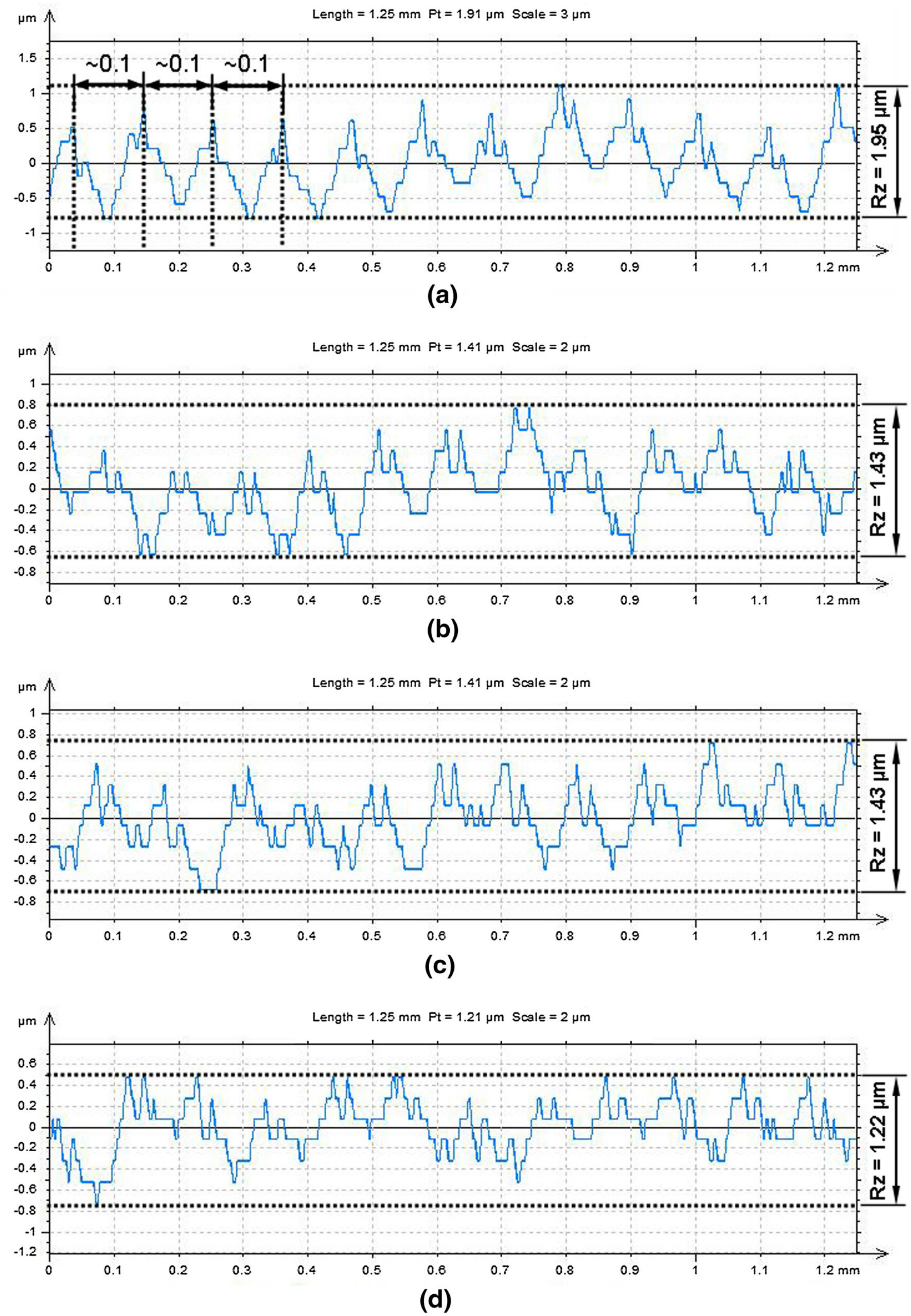

Fig. 9 Original roughness profiles for the conditions: **a** DRY; **b** FF; **c** RF and **d** RF/FF

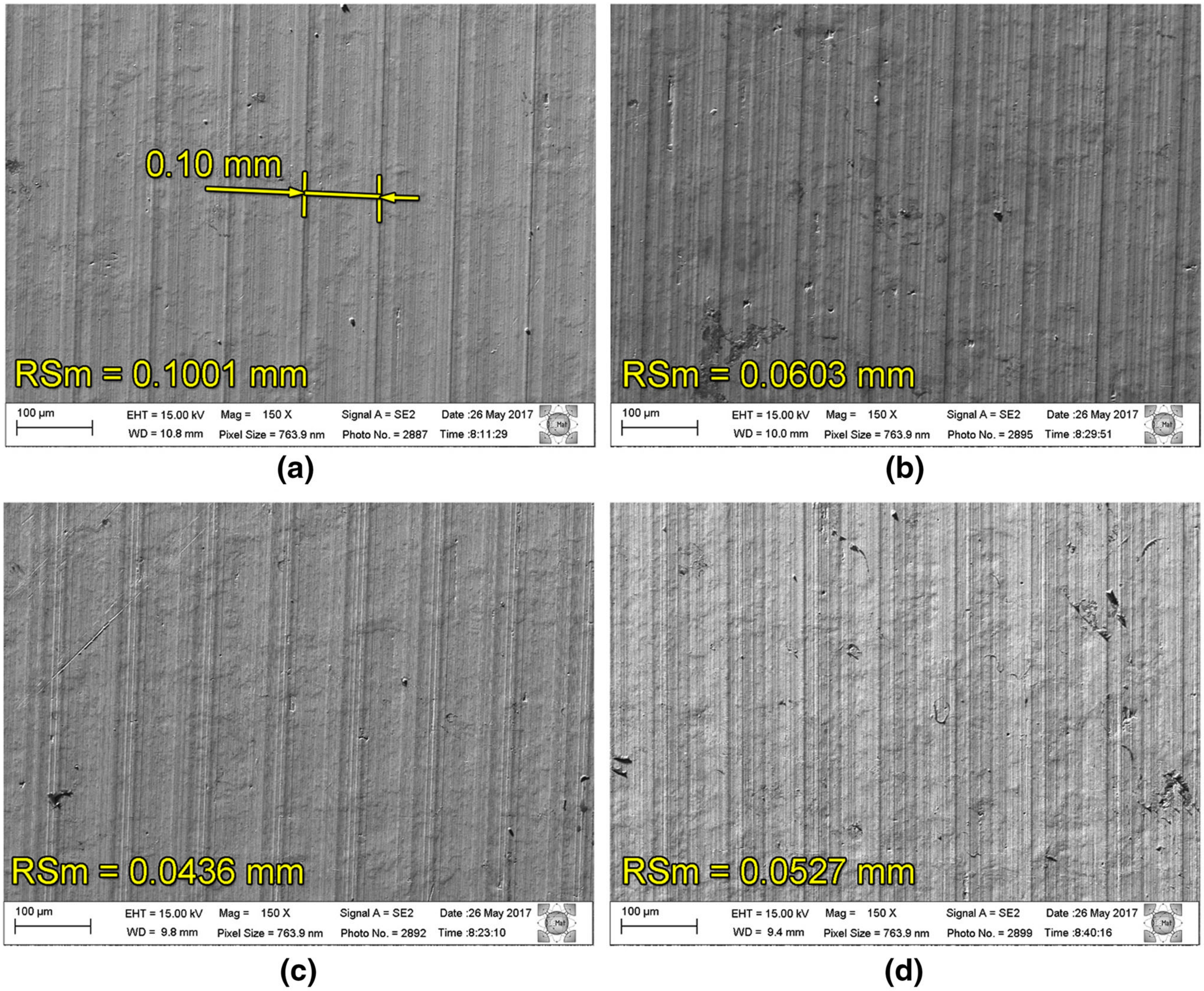

Fig. 10 Surface topographies after machining under the conditions: **a** DRY; **b** FF; **c** RF and **d** (RF/FF)

In this investigation, as shown in Fig. 13, it was detected the presence of a modified layer beneath the machined surface. However, it was not found evidences, in terms of microstructural alterations, that could explain the differences in the hardness showed in Fig. 12. It was only verified that the material on the surface was deformed in the cutting direction and downwards due to the cutting tool action, causing the alignment of the tempered martensitic laths. Defining the thickness of these deformed layers is difficult because there is no evident border between these layers and the bulk material.

Figure 14 shows a big carbide that was pushed into the bulk material, deforming the tempered martensitic matrix around it. Certainly, this mechanical deformation plays an important role in increasing both surface hardness and residual stress. It was verified this phenomenon for all cutting condition.

After machining Inconel 718 with cemented carbide inserts under cryogenic cooling, Pusavec et al. [13] obtained higher values of surface hardness as compared to the dry condition. Kaynak et al. [29] obtained similar results after machining NiTi alloys. Bicek et al. [20] reported an increase from 10 to 15% in the surface hardness after machining AISI 52100 steel under the cryogenic condition as compared to the dry condition.

It is well known that the machining process and the cooling condition have a remarkable influence on the surface hardness. The plastic deformation on the workpiece surface and subsurface, induced by the cutting tool action, creates a thin hardened layer that comprises these regions and makes them harder than the as-received workpiece material. However, if the temperature rises up to the material's restoration point, the effect of work-hardening can weak. Kaynak et al. [15] reported that at lower

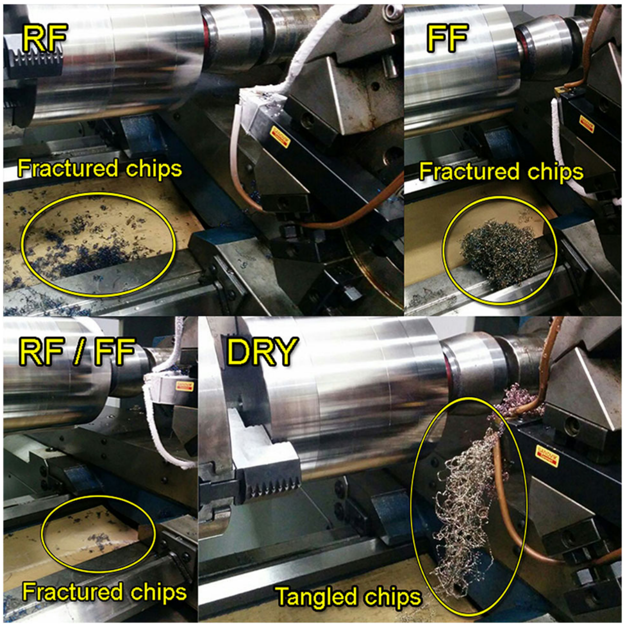

Fig. 11 Types of chips obtained for each cutting condition

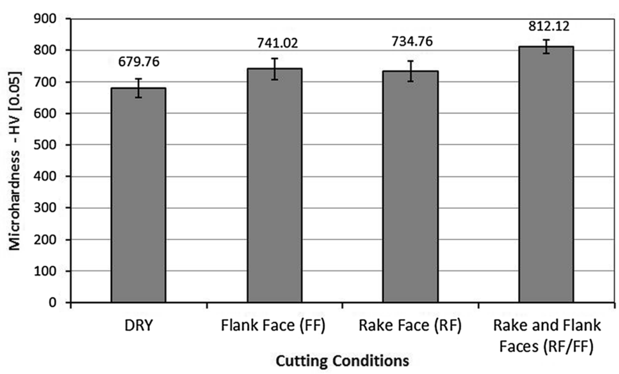

Fig. 12 Workpiece surface hardness after turning trials under each cutting condition

temperatures, as in the case of cryogenic cooling, this mechanical hardening is intensified because of the fact that the cutting temperature is kept at much lower levels, not allowing the material's restoration at the same intensity as occurs for the dry condition.

A smaller grain size is expected on the workpiece surface and subsurface if the cryogenic cooling is able to maintain the cutting temperature below the recrystallization temperature of the workpiece material. Umbrello et al. [14] verified a grain refinement in the modified surface layer of AISI 52100 steel samples after machining under dry and cryogenic conditions in comparison with the bulk material. However, they observed the presence of more refined grains for the cryogenic condition with higher values in the surface hardness.

3.3 Residual stress

Figure 15a, b show the average values of residual stresses measured on the machined surface in the axial and circumferential directions, respectively. It is important to highlight that these values are an average of ten measurements performed automatically by the X-ray diffractometer.

It is noted that only compressive residual stresses were detected regardless of the cutting condition and direction of analysis. This result can be comprehended analyzing the Figs. 13 and 14, in which is evident the presence of a thin deformed layer on the machined surface for all cutting conditions. Besides, the cryogenic condition provided higher values of compressive residual stress as compared to the dry condition.

Pusavec et al. [13] presented residual stress curves after turning Inconel 718 under different cutting conditions (dry, MQL, cryo and MQL + cryo). The authors reported that, because the cryogenic cooling is more effective in reducing the cutting temperature, it induces lower tensile stresses on the workpiece surface and higher compressive stresses in the subsurface as compared to the MQL and dry conditions. Bicek et al. [20], after machining AISI 52100 steel under dry and cryogenic conditions, also found values of compressive residual stresses higher for the cryogenic machining.

The results showed that both the turning operation and the type of cooling influence the induced residual stress. The mechanical deformation is one among other agents able to generate residual stress on the machined surface and subsurface and, it is verified that reducing the thermal effect during the machining process can help to generate higher surface and subsurface compressive stresses. Thus, it would be possible to understand the results of compressive residual stress obtained for all cutting condition in this investigation, with higher values for the cryogenic cooling as compared to the dry condition.

4 Conclusions

The present study investigated the surface integrity of quenched and tempered AISI D6 tool steel after turning operation with PCBN inserts under dry and cryogenic condition. In this last case, LN_2 was applied on the rake face (RF), flank face (FF) or on both faces (RF/FF) of the cutting tool. Surface roughness, microhardness and residual stress were the main output variables studied. From the experimental results, the following conclusions could be drawn:

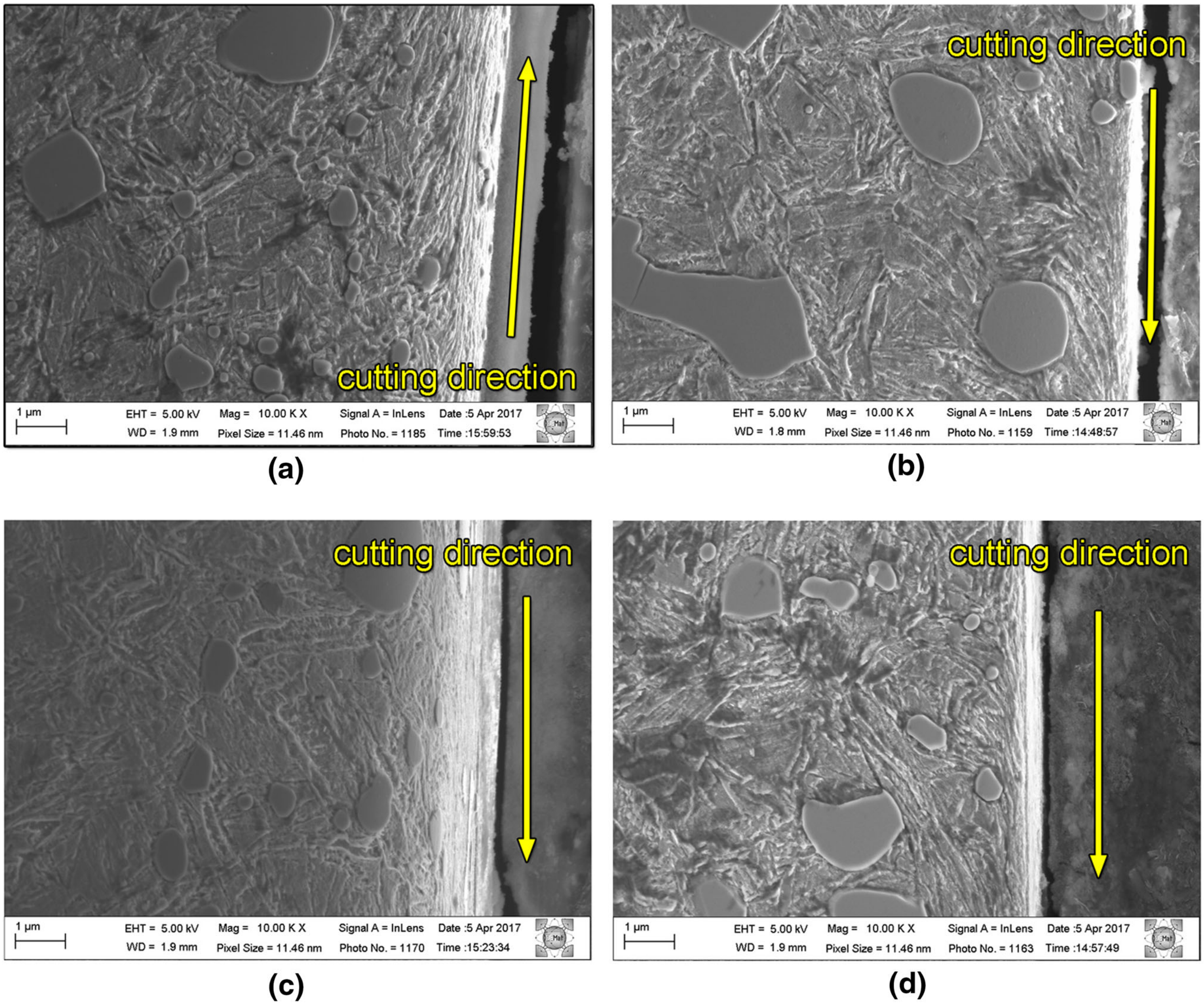

Fig. 13 SEM images of the cross section of the workpiece showing the modified layer after machining under: **a** DRY; **b** FF; **c** RF and (RF/FF). The arrows represent the cutting direction

- It was not verified major differences among the conditions RF, FF and RF/FF regarding the average roughness (Ra).
- Liquid nitrogen was able to reduce the surface roughness in comparison with the dry turning of hardened AISI D6 steel. On average, the Ra value was around 1.6 times lower for the cryogenic condition as compared to the dry condition.
- The values of surface roughness obtained under cryogenic conditions (FF, RF and RF/FF) were within the roughness grade number N4, which is normally obtained in grinding operations.
- It was verified that after dry machining, the roughness peaks were kept somehow upright, what gave a more regular roughness profile and, consequently, larger values of Ra compared to the cryogenic condition. Whereas, cryogenic cooling, by extremely refrigerating the workpiece surface, became it more brittle than when dry machining. Hence, the combination of brittleness with a cutting tool with an extremely negative effective rake angle, promoted the fracture of the roughness peaks, diminishing the peak-to-valley distance, which reduced the Ra value. In this case, the obtained values of Ra were within that one possible to obtain in grinding operations, which suggests that cryogenic turning of hardened AISI D6 steel could eliminate the need of finishing operations like grinding.
- When liquid nitrogen was applied on the rake face, the chips presented more fractured as compared to the dry condition and to the condition in which liquid nitrogen was applied on the flank face only. These evidences

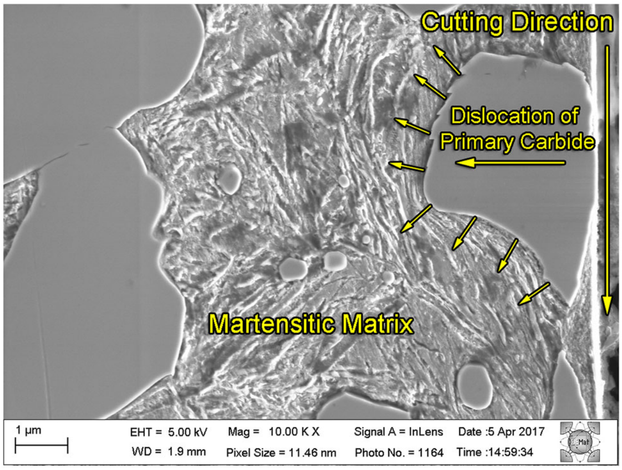

Fig. 14 Deformed martensite near the machined surface promoted by the dislocation of a primary carbide due to the cutting tool action

show that liquid nitrogen was able to make the surface of the workpiece brittle.

- Because of the work-hardening, regardless of the cutting condition, the hardness of the workpiece surface after the turning operation was higher than that of the as-received material.
- Liquid nitrogen was able to provide higher values of surface hardness as compared to the dry condition. It was possible to verify an increase of around 8% for the conditions FF and RF and 19% for the condition RF/FF.
- Cryogenic turning provided values of compressive residual stresses higher than under the dry condition. It was noted that, in general, the stronger the cooling condition on the workpiece (DRY > FF > RF > RF/FF), the higher the values of residual stresses. As it is well known, compressive residual stresses play an

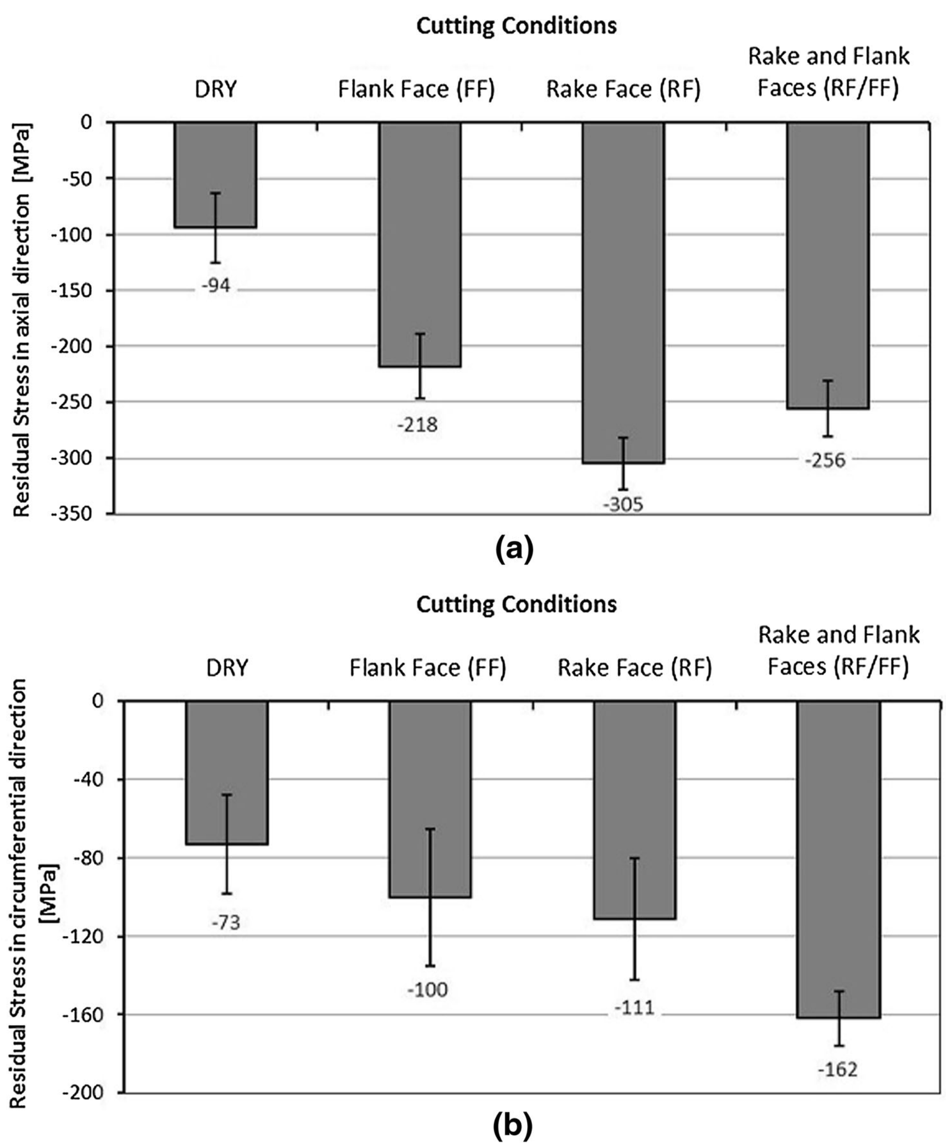

Fig. 15 Residual stresses values: **a** measured in the axial direction and **b** measured in the circumferential direction

important role in increasing the fatigue strength of the machined components and significantly help to reduce nucleation and propagation of cracks on the machined surface, increasing the service life of the component.
- The values of residual stresses in axial direction were higher than those in circumferential direction. This fact unveiled that the deformation in the feed direction was stronger than in the cutting direction.

Finally, this investigation provided important technical results, proving that cryogenic machining of hardened steels may be an alternative to be regarded in the seek for more sustainable means of production. By analyzing the many papers published on cryogenic machining, it is very clear that this technique is effective in many aspects. However, results of investigation on the cost–benefit ratio of using this technique are still scarce in the literature, which is certainly a great field of study to be explored.

5 Future work

At the beginning, research involving hard turning was focused on materials with wide applications in bearing, gearbox and mold industries in order to replace grinding process. These materials imposed moderate difficulty to PCBN cutting tools and the main objectives were to determine appropriate PCBN grades and cutting parameters for specific conditions. The experimental results typically showed advantages in favor of hard turning, such as the generation of compressive residual stresses and the possibility of cutting these hard materials under dry condition. However, machining materials with martensitic microstructure with high volumetric fraction of carbides such as, tool steels, white cast irons, and high-speed steels is a big challenge. Thus, alternative methods to overcome these challenges have been investigated. In the present work, cryogenic cooling using liquid nitrogen was investigated in hard turning of AISI D6 cold work tool steel regarding surface integrity. Results showed improved surface integrity as compared to the dry cutting. On the other hand, information on the optimum flow rate and pressure of liquid nitrogen for different cutting conditions and workpiece material is still unclear. At the Manufacturing Laboratory of the Federal University of Rio Grande do Norte, for example, investigation on the consumption of liquid nitrogen for different applications has been conducted since the beginning of 2017. The aim is to study the optimum liquid nitrogen flow rate for different machining demands. Another investigation that has been performed at this lab is related to the chip – tool interface temperature during hard turning under cryogenic condition. Thus, there is still a vast amount of information that can be obtained from cryogenic machining investigation to make this sustainable technique feasible for industrial applications and, why not, for the machining of common steels and of other common engineering materials.

Acknowledgements The authors would like to thank CAPES for granting scholarship to Welber Leadebal Jr. The Graduate Program in Mechanical Engineering at UFRN. The Department of Physics at UFRN for providing the LN_2 used in this investigation. Professor Álisson Rocha Machado for donating the PCBN inserts and the AISI D6 bars used in this study and Sandvik Coromant for donating the toolholder.

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