

CHARACTERIZATION OF THE PHENOMENA THAT AFFECT THE SURFACE INTEGRITY IN HARD PART TURNING WITH PCBN TOOL

Clarianne Natali de Campos

Federal University of Santa Catarina, Florianópolis – SC
clarianne.campos@gmail.com

Denis Boing

Sandvik Coromant R&D, Stockholm, Sweden
denis.boing@gmail.com

Rolf Bertrand Schroeter

Federal University of Santa Catarina, Florianópolis - SC
rolf.schroeter@ufsc.br

Abstract. High performance components in mechanical systems need to have an adequate level of surface integrity in order to reach the required performance, the fatigue life or prevent premature failure. Among these, transmission components stand out, which are typically finished by grinding and/or hard turning using PCBN (Polycrystalline Cubic Boron Nitride) tools. Despite the advantages of hard turning it is known that this is a thermomechanical process, a characteristic that creates conditions for changes in surface integrity, such as microstructural alterations and modification of the residual stress profile in the surface layers and subsurface of the components. Evaluating industrial applicability of hard turning two main tooling concepts are used: standard solutions (e.g., use of ISO inserts) typically rely on cutting speed to achieve adequate levels of productivity, with such a choice having the highest incidence of thermal effects. On the other hand, solutions that improve productivity by increasing the feed rate and reducing the cutting speed cause an increase in the contact area between the tool and the workpiece and, consequently, the greater the effects of mechanical loads on the process. In this perspective, the present work aims to evaluate the influence of different cutting parameters on the phenomena perceived in the surface integrity in the hard turning of AISI 4340 steel (60 HRC) with PCBN tool. For this, three distinct sets of parameters were defined that, theoretically, can generate different responses in the machined surfaces: a solution that foresees the increase of cutting speeds, another that uses low cutting speeds and high feed and cutting depth and a last solution with recommended parameters for finishing hardened steels. For this, turning tests were carried out with AISI 4340 steel with PCBN tools. The machined workpieces and after the metallographic procedure were evaluated with the aid of optical microscopy and scanning electron microscopy (SEM). From the analyses, it is expected to observe that the use of high cutting speeds promoted the elevation of the temperatures of the tool-workpiece interface, inducing, thus, thermal phenomena. With the increase in feed and depth of cut and reduction in cutting speed and, with the consequent increase in the contact area of the tool, greater will be the levels of plastic deformation and mechanical phenomena incident on the surface. Finally, with the use of finishing conditions, both thermal and mechanical phenomena will coexist, given the levels of deformation generated and temperatures reached in the process.

Keywords: surface integrity; hard part turning; cutting parameters; industrial solutions.

1. INTRODUCTION

High performance components in mechanical systems need to have an adequate level of surface integrity in order to reach the required performance, the fatigue life or prevent premature failure. Among these, transmission components (e.g., shafts and bearings – hardness between 58 to 62 HRC) stand out, which are typically finished by grinding and/or hard turning using PCBN (Polycrystalline Cubic Boron Nitride) tools.

There are several definitions of hard part turning, but the most commonly used is the one that describes the machining of materials with a hardness greater than 45 HRC or when the hardness of the machined material is greater than 50 HRC. Despite this reference, most automotive transmission components have a surface hardness of 60-63 HRC.

The advantages of applying hard part turning are the high production rate, the greater flexibility of the process, the possibility of machining without fluid lubricating coolant and the potential generation of compressive residual stresses in the layers below the surface of the machined component (Klocke, Brinksmeier and Weinert, 2005). On the other hand, it is known that the hard turning is a thermomechanical process, a characteristic that creates conditions for changes in surface integrity, such as microstructural alterations and modification of the residual stress profile in the surface layers and subsurface of the components (Guo, Warren and Hashimoto, 2010; Shen et al., 2015).

Evaluating industrial applicability of hard turning two main tooling concepts are used: standard solutions (e.g., use of ISO inserts) typically rely on cutting speed to achieve adequate levels of productivity, with such a choice having the highest incidence of thermal effects. On the other hand, solutions that improve productivity by increasing the feed rate and reducing the cutting speed cause an increase in the contact area between the tool and the workpiece and, consequently, the greater the effects of mechanical loads on the process.

Although the literature specialized in hard turning usually describes incidents on the surface integrity in a homogeneous way, without a greater detail or understanding of their characteristics, thermal and mechanical effects have different origins and promote different effects on the manufactured component (Liao et al., 2019). In case of surface integrity changes due to mechanical nature these are the result of a process called Severe Plastic Deformation (SPD), in which the grains are deformed and fragmented by the high tension induced by the mechanical load, resulting in breakage of the original grains or an elongated subgrain structure, with reorientation along the shear direction by the dynamic recovery mechanism (Li et al., 2007).

However, thinking about this same process, but now in a condition in which the temperature gradients increase, changes by thermal phenomena can be observed, such as phase transformation and regions of high hardness on the surface. For this to occur, the temperatures must be high enough to reach the temperature of recrystallization of the material and generating the nucleation of new grains by accommodation by displacement of highly deformed grains, forming equiaxed grains with well-defined boundaries. This mechanism is called dynamic recrystallization (Hosseini and Klement, 2021). And when considering the combination of these phenomena – thermomechanical condition, the changes perceived in the surface integrity will originate both from a severe plastic deformation governed by dynamic recovery, and from dynamic recrystallization due to increasing temperatures. It is important to note that the changes generated by the combination of these effects will depend on the process parameters and the characteristics and properties of the machined material (Liao et al., 2021; Hosseini and Klement, 2021).

In addition to these changes in the microstructure of the material, the combination of thermal and mechanical effects can also cause the modification of the microhardness profile and residual stresses. Regions with higher levels of hardness in the boundary layer can form and cause the propagation of cracks on the surface, which can lead to premature failure of a component subjected to dynamic stress cycles (Hosseini and Klement, 2021; Schwach and Guo, 2006).

Regarding the residual stresses generated, as previously mentioned, the hard part turning can generate compressive residual stresses in the layers below the surface, what is favorable for fatigue performance. However, when thermal effects are more predominant than the mechanical ones, the thermal expansion induced by the temperature gradient between the rapid heating of the surface of the part and the cooling of the layers below it promotes the induction of tensile residual stresses, which are not beneficial for a component that will be subjected to high fatigue cycles, causing premature failures (Liao et al., 2021; Chaudhari and Hashimoto, 2016; Sales et al., 2020).

Thus, understanding how thermal and mechanical phenomena, alone and in combination, influence the integrity of the surface, mainly in the hard part turning allow optimizing the final conditions of the surface integrity of this type of machining, so that components of high performance are obtained.

Reinforcing the importance of such analysis, Guo, Warren and Hashimoto (2010) concluded that white layers can reduce fatigue life by up to eight times compared to surfaces free of white layers resulting from the machining of AISI 52100 steel.

In the case of hard turning, despite the mechanical nature of the process, due to the high temperatures developed in the cutting region, limiting heat dissipation and severe plastic deformation with a phase transition in the workpiece, it can be said that phenomena of a thermomechanical nature occur in this type of machining (Niaki et al., 2020).

The occurrence of white layers in the machining of hardened materials proves that metallurgical processes can be induced by their respective chip formation mechanisms. In the case of hard turning, the greatest amount of heat is generated in the chip formation area, with a large part being dissipated through them. However, portion of the heat is inevitably absorbed by the part and this, when associated with mechanical effects, can induce transformations beyond the white layer itself, which can directly compromise the fatigue life of the manufactured component, making it necessary to better understand these phenomena.

In summary, the surface integrity phenomena are very sensitive to the type of energy that governs the process and understanding them in a deeper way allows the process parameters to be adjusted to enhance the performance of the machined component. However, as pointed out, the literature typically evaluates the surface integrity in a generic way without investigating the root cause of the transformation, which makes it difficult to optimize the process that takes these specificities into account. Thus, in this perspective, the present work aims to evaluate the influence of different cutting parameters on the phenomena perceived in the surface integrity in the hard turning of AISI 4340 steel (60 HRC) with PCBN tool.

2. METHODOLOGY

The experiments were carried out in a ROMI Horizontal Turning Center, model GL240. The main data of the machine tool are: spindle motor with 15 kW of power, rotation range between 4 and 4500 rpm, tool holder tower with 12 positions, plate diameter of 210 mm with a hydraulic drive of maximum pressure of 23 kgf/cm², external tool holder section 20 x

20 mm and numerical control GE Fanuc model 0i-TD. The courses on the X and Z axes are respectively 180 mm and 400 mm. And for the tests, a plate with hydraulic closing of three hard jaws with a maximum pressure of 45 bar was used (Fig. 1).

The pieces were designed to promote a continuous cut, and the geometry adopted in this research was based on the work of Diniz and de Oliveira (2008). As shown in Fig.1, to minimize shocks and avoid chipping at the entrance and exit of the tool, chamfers were made along the external and internal diameters of the part ($0.5 \text{ mm} \times 45^\circ$). The tools were mounted in a tool holder (code PSKLN-2020K-12) and fixed with a combination of top clamp and center pin in order to promote high insert rigidity and, consequently, avoid chipping during machining.

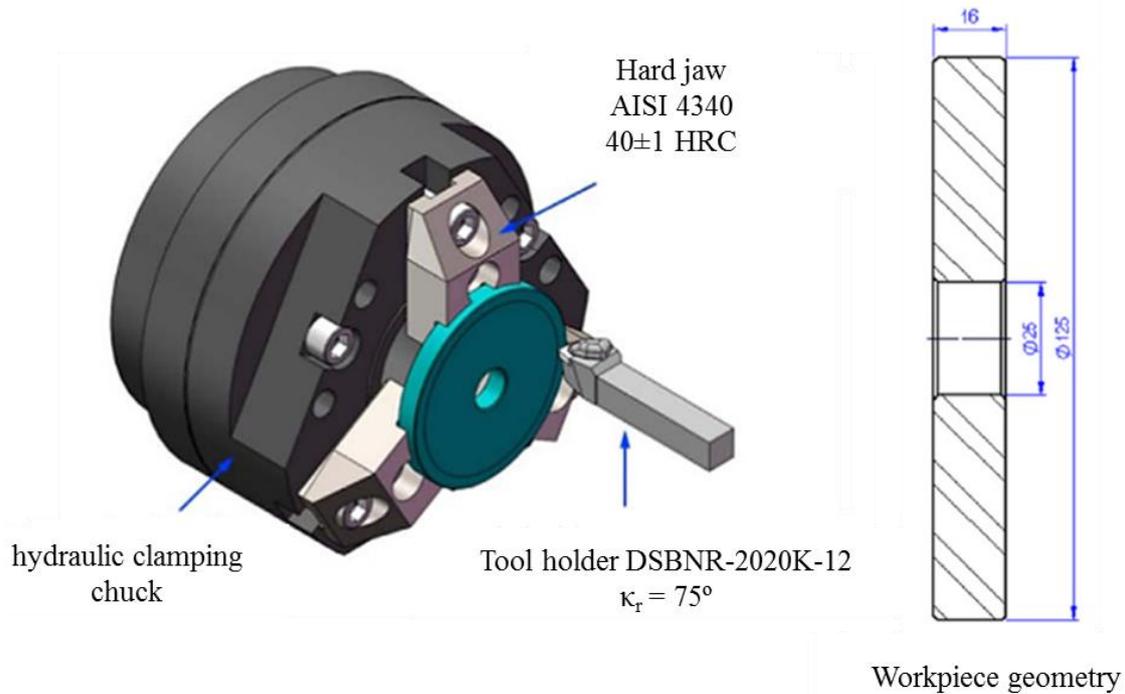


Figure 1. Clamping system and workpiece geometry.

For the tests, AISI 4340 hardened steel was used, with a hardness of 60 HRC, whose chemical composition is found in Tab.1.

Table 1. Chemical composition.

Steel	C	Mn	P	Si	Ni	Cr	Mo	V
AISI 4340	0,4	0,6	0,02	0,2	1,7	0,76	0,2	-

The experiments were performed with PCBN tools (SandvikCoromant® class 7025 or ISO H20, code SNGA 120408 S01030A). The tools have a low CBN content (60%) with bimodal grain distribution (1 and 3 μm) in Ti(C, N) and Al ceramic binders. In addition, they present high edge strength due to the inhibition of the formation of borides, such as TiB₂, together with the PCBN sintering process. These properties help to prevent chipping and fracture of the edge, promoting a beneficial situation for the machining of materials with a high fraction of carbides in the microstructure (Sandvik, 2022).

After fixing the part in the machine tool, the surface to be machined was prepared with a pass with a specific tool. The purpose of this procedure was to create a reference surface to minimize axial runout of the workpiece after clamping. The tools were then replaced with the cutting edges for the final test. The tests were performed without the use of cutting fluid.

In order to understand how the different thermal and mechanical phenomena, together or separately, influence the behavior of the surface integrity, the cutting parameters were selected (Tab. 2), then, to induce such types of energy.

Table 2. Cutting parameters used in the tests.

	v_c (m/min)	f (mm/rev)	a_p (mm)
Mechanical	80	0,2	0,5
Thermomechanical	180	0,08	0,5
Thermal	350	0,08	0,2

Thus, for the mechanical condition, the defined parameters are intended to induce plastic deformations in the material; thermal, with the increase in cutting speeds, there is a consequent increase in temperature gradients at the chip-tool interface; and, finally, in the thermomechanical condition, the induction of both phenomena is desired.

To evaluate the microstructural changes, the specimens were cut using waterjet machining. Subsequently, to eliminate possible edge rounding, the sections obtained were submitted to a cutting machine with an abrasive disc. It is important to note that during this stage, refrigerant fluid was used and it was possible to control the cutting parameters, avoiding exposure of the surface to severe thermal changes. In addition to the cuts to eliminate rounding, the sample was again sectioned to facilitate the metallographic procedures. For this analysis, the sample from the region close to the inner diameter was selected. Figure 2 exemplifies the analyzed region of the specimen.

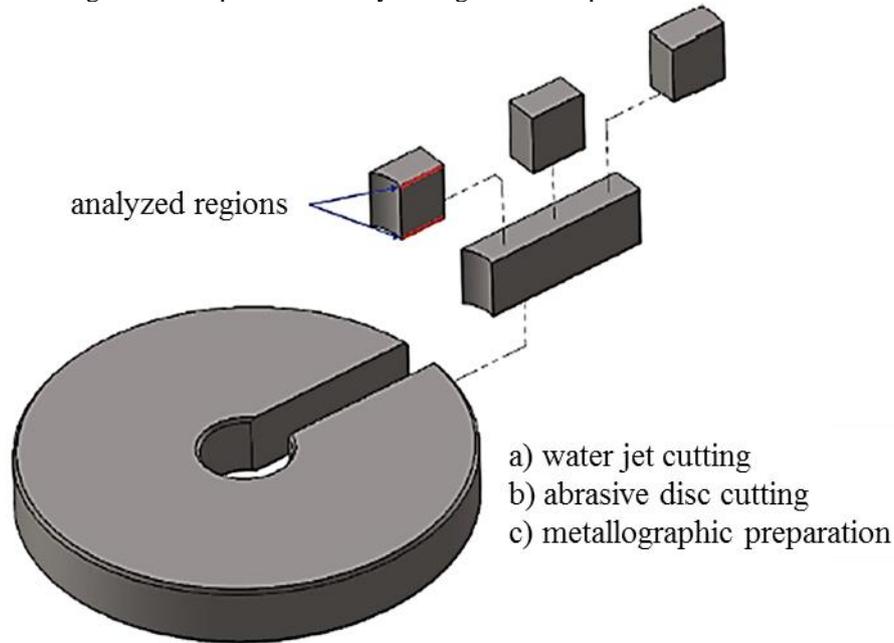


Figure 2. Procedures for sectioning the sample and regions selected for analysis.

To avoid the edge rounding that may occur during the metallographic process, the sample was initially covered with aluminum foil and embedded with thermosetting epoxy resin, a material indicated for this purpose.

With the samples already prepared, they were etched with Nital 3% for approximately 15 seconds. The evaluation of the microstructural changes was performed with the aid of a Hitachi® Hightech Scanning Electronic Microscope (SEM), model TM3030 Tabletop Microscope.

3. RESULTS AND DISCUSSION

After performing the tests and obtaining the micrographs referring to the machined surfaces, an analysis is proposed taking into account the different phenomena that can promote changes in the layers below the surface: mechanical, thermomechanical and thermal.

So, Fig. 3 refers to the surface machined under conditions that promote changes of a mechanical nature.

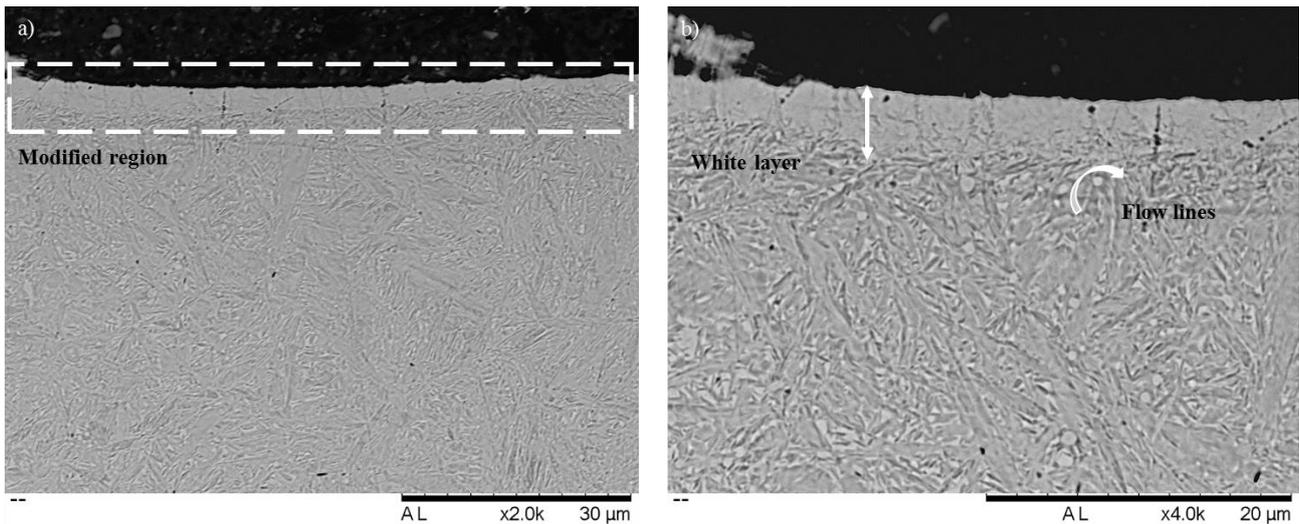


Figure 3. Microstructural changes observed for the mechanical condition.

Thus, it is possible to see in Fig. 3a a region modified as a function of the machining process, in which the layer closest to the surface has a more significant change. And, just below this range, it is also possible to notice that deformations were generated, while the substrate remained unchanged.

Due to the fact that parameters were used that aim to induce mechanical phenomena, it can be said that the identified changes are correlated to the plastic deformation generated in the machining process, given that increasing the feed values (f) and reducing the cutting speeds (v_c), the greater the contact of the cutting tool with the surface to be machined.

In Fig. 3b the mechanical effects can thus be better described. In the outermost layer, as commented, it presented a higher level of alteration, being able to observe a more significant level of grain deformation. Although one cannot rule out the incidence of some level of thermal energy, it is possible to observe the presence of martensite in this region, which is an indication to rule out the occurrence of phase transformation. In addition, just below this region, it is possible to identify the presence of flow lines oriented in the direction of advance of the cutting tool, another indication of the effects of plastic deformation in the machined region. According Imbrogno et al. (2018), this is a common phenomenon is the formation in the drag direction of the material that represent the paths of the grain deformation displacements that occur in the direction of the movement of the cutting tool in relation to the workpiece.

By increasing the cutting speed (v_c), reducing the feed (f), and adapting the parameters to those employed in finishing operations on hardened steels, it was intended to generate thermomechanical phenomena on the surface and in the layers below it. The micrographs referring to this condition are shown in Figure 4.

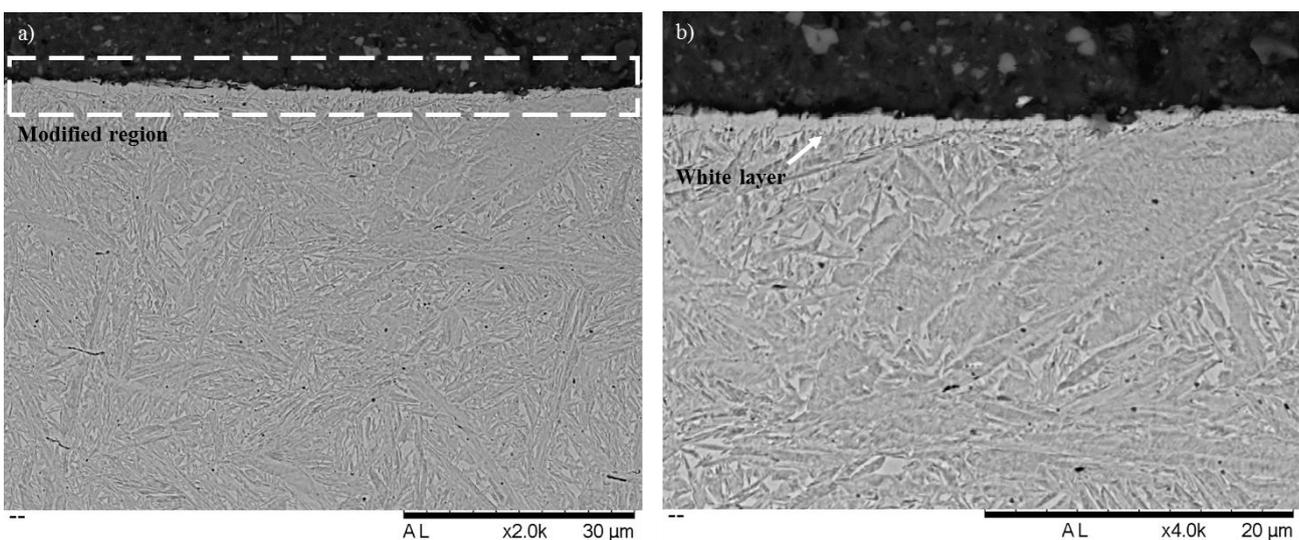


Figure 4. Microstructural changes observed for the thermomechanical condition.

For the thermomechanical condition, a very narrow region that was subjected to alteration is observed, which is less than $2 \mu\text{m}$. However, it is possible to observe the formation of a white layer on the machined surface, however it is not

possible to identify whether it is of mechanical or thermal origin or a combination of both. It is worth noting that the tests were performed with a PCBN tool that has higher thermal conductivity, which may be associated with the small altered region.

Similar behavior was identified for the thermal condition, as seen in Fig. 5.

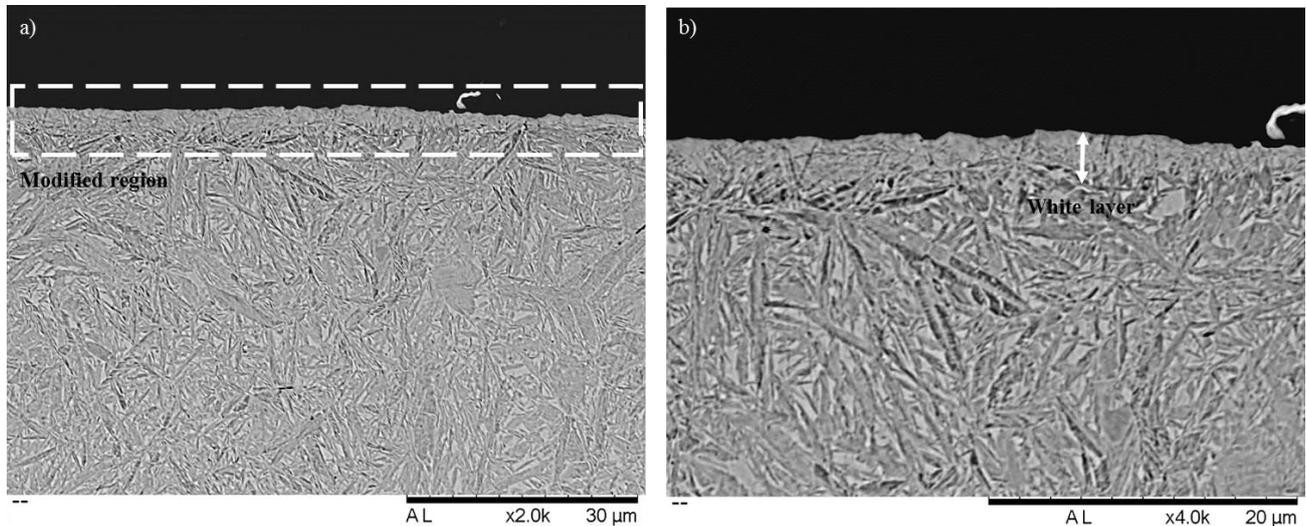


Figure 3. Microstructural changes observed for the thermal condition.

For the thermal condition, the formation of a thicker altered layer was verified when compared to the thermomechanical one. However, it was not possible to identify which phenomenon is linked to this change. Associated with this, the use of a PCBN tool, due to its properties, contributed to the fact that thermal phenomena were not so perceptibly observed.

4. CONCLUSION

The tests carried out aimed to identify, for limit conditions, the phenomena that affect the condition of the surface and the layers below it in the hard turning.

Thus, it was possible to perceive that for the three conditions analyzed – mechanical, thermomechanical and thermal – changes were promoted in the surface of the machined material. It was also confirmed, for the mechanical condition, that the observed phenomena are directly related to plastic deformation, such as grain deformation and flow lines.

On the other hand, for the thermomechanical and thermal conditions, the altered regions were smaller and it was not possible to conclude about the incidence or not of thermal energy in the process, to the point of promoting a phase transformation, for example, given the higher thermal conductivity of the PCBN tool.

Finally, it is important to emphasize the need to deepen the study with the use of more advanced techniques, which allow a greater expansion of the field of analysis, in order to understand the real phenomena that affect the surface and the layers below it, and in which proportion they occur and influence the surface integrity in the hard part turning.

5. ACKNOWLEDGEMENTS

This work was funded and supported by FAPESC (Foundation for Support to Research and Innovation of the State of Santa Catarina), Sandvik and Capes (Coordination for the Improvement of Higher Education Personnel).

6. REFERENCES

- Chaudhari, R. G., Hashimoto, F., 2016. Process controls for surface integrity generated by hard turning. *Procedia CIRP*, Vol. 45, p. 15-18.
- Diniz, A. E., Oliveira, A. J. de., 2008. Hard turning of interrupted surfaces using CBN tools. *Journal of Materials Processing Technology*, Vol. 195, p. 275-281.
- Guo, Y. B., Warren, A. W., Hashimoto, F., 2010. The basic relationships between residual stress, white layer, and fatigue life of hard turned and ground surfaces in rolling contact. *CIRP Journal of Manufacturing Science and Technology*, Vol. 2, p. 129-134.
- Hosseini, S. B., Klement, U., 2021. A descriptive phenomenological model for white layer formation in hard turning of AISI 52100 bearing steel. *CIRP Journal of Manufacturing Science and Technology*, Vol. 32, p. 299-310.

- Imbrogno, S. et al., 2018. A physically based constitutive model for predicting the surface integrity in machining of Waspaloy. *Materials & Design*, Vol. 152, p. 140-155.
- Klocke, F., Brinksmeier, E., Weinert, K., 2005. Capability Profile of Hard Cutting and Grinding Processes. *CIRP Annals*, Vol. 54, p. 22-45.
- Li, J. G. et al., 2007. A microstructural investigation of the surface of a drilled hole in carbon steels. *Acta Materialia*, Vol. 55, p. 1397-1406.
- Liao, Z. et al., 2019. Grain refinement mechanism of nickel-based superalloy by severe plastic deformation - Mechanical machining case. *Acta Materialia*, Vol. 180, p. 2-14.
- Liao, Z. et al., 2021. Surface integrity in metal machining - Part I: Fundamentals of surface characteristics and formation mechanisms. *International Journal of Machine Tools and Manufacture*, Vol. 162. p. 103687.
- Niaki, A. et al., 2020. Machinability and surface integrity characterization in hard turning of AISI 4320 bearing steel using different CBN inserts. *Procedia Manufacturing*, Vol. 48, p. 598-605.
- Sales, W. F. et al., 2020. A review of surface integrity in machining of hardened steels. *Journal of Manufacturing Processes*, Vol. 58, p. 136 – 162.
- SandvikCoromant, 2012. Hard part turning. 18 Jun. 2022.
<https://coromantstrgprod.blob.core.windows.net/files/sitecollectiondocuments/downloads/global/brochures/en-us/c-1040-225.pdf>.
- Schwach, D. W., Guo, Y. B., 2006. A fundamental study on the impact of surface integrity by hard turning on rolling contact fatigue. *Journal of Fatigue*, Vol. 28, p. 1838-1844.

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.