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EFFECT OF SURFACE TEXTURE TOOLS AND MINIMUM QUANTITY LUBRICATION (MQL) IN TURNING OF AISI 1045 STEEL

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Abstract. Laser surface texturing has become popular method in recent years, its application results in several benefits in different fields, such as machining. In machining, laser texturing can increase the life of cutting tools by increasing the adhesion of ceramic coatings on the substrate. In addition, the ordered texture of the surface can change the interaction between the tool and the workpiece in the cutting zone, both for dry and for cutting fluid machining. The goal of this work is to compare through tool life tests and surface finishing of the machined part in dry turning of AISI 1045 steel and with application of wet cutting fluid and MQL (Minimum Quantity Lubrication), surface modified carbide inserts of ISO P grade by means of laser texturing and blasting, and then coated with TiAlN (Titanium Aluminium Nitride). The results showed a better performance in the life tests of the blasted textured inserts, and a better finish of the turned part with the use of the TiAlN coating, both for the sandblasted and laser textured substrate in relation to the uncoated tool. The application of cutting fluid by MQL proved to be efficient in life tests, increasing the tool life, exceptionally, in the TiAlN-sandblasted tool. In surface finishing tests, measuring the average arithmetic roughness (Ra), the application of MQL was not efficient. The superficial characterization by SEM (Scanning Electron Microscopy) showed that the TiAlN-laser tool suffered an early detachment of the coating, which probably justifies its poor performance in life tests.

Keywords: *Turning, SAE 4340 Steel, Laser, TiAlN*

1. INTRODUCTION

Currently, it is essential for the metal mechanic industry to carry out machining operations that offer the best technologies in order to increase productivity and reduce manufacturing costs. These technologies include the use of more flexible equipment that cover a wider range of machining operations, new materials for cutting tools, tool substrates with oriented textures, use of ceramic coatings, lubrication/cooling means, among others.

Ceramic coatings composed of transition metal carbides or nitrides such as TiC (Titanium Carbide), TaC (Tantalum Carbide), NbC (Carbide Niobium), TiN (Titanium Nitride), TiCN (Titanium Carbonitride) and TiAlN (Titanium Aluminium Nitride) provide wear protection, heat resistance, corrosion resistance, good adhesion to the substrate, exhibit high hardness and are applied in mechanical components, cutting tools such as optical and decorative coatings (Suh *et al*., 2003).

Because of the wide industrial applicability of coatings, there is a growing need to understand the fundamental properties of these hard films, and how they act to protect a surface.

The study of coatings has a multidisciplinary aspect, as it involves the knowledge of their chemical, physical and tribological properties (Santos, 2002).

The difference in performance of coated and uncoated cutting tools is a result of the interaction between these properties, which probably modify the chip-tool interface region, increasing the performance of the coated tool. In the need to understand how coatings modify the performance of cutting tools, it is important that the coating be analyzed in both machining tests and in tests that may characterize its morphology, microstructure and especially its adhesion to the substrate.

The performance of the coating deposited on the surface of the tool to withstand constant changes in the mechanical and thermal stresses of the machining process will depend, in particular, on a good adhesiveness on the substrate. Adequate adhesion of the coating is very important as the insufficiently tacked coating tool may behave worse than the uncoated one. The formation of hard and abrasive particles, resulting from the premature destruction of the coating, accelerates the wear of the surfaces that are in contact (Lima *et al*., 2005).

Hence the importance of having new deposition processes available, better control of the deposition process, the supply sources of the coating materials, substrate materials with properties that offer less discrepancy with coating properties and even techniques that can physically modify the substrate without significantly altering its mechanical properties to improve the adhesiveness at the substrate/coating interface. The development of tool substrates having properties compatible with the coating properties may be a good alternative to improve the adhesiveness of the coating on the substrate. However, it should be noted, for example, that an increase in the hardness of the substrate to approach the hardness of the coating, thus obtaining less discrepancy between these properties, may cause a somewhat undesirable effect on the substrate, which is the their tenacity (Leyland and Matthews, 2000). This may be undesirable in cutting tools for machining, especially in intermittent cutting, where the tools constantly suffer from impacts on the part and demands for compression and traction as they enter and leave the part, respectively. A good option to approximate the substrate properties of the tool and the coating without adversely affecting the tool's toughness is to modify the properties of the substrate only in regions close to the interface with the coating (Sun *et al*., 1995).

Within this context a currently widespread medium is surface laser texturing. In recent years, laser texturing has been presented as a competitive option for hole production and/or alteration of the previous surface texture of the surface (Low *et al*., 2001). Examples are present in the aeronautics industry, which has employed this technique in turbine (vane) components, in the combustion chamber (Corfe, 1983), and in microtechnology, where the problems of permanent lubrication of miniaturized components due to the minimal amount of lubricant and the difficulty of confining it to contact surfaces is a challenge (Blatter *et al*., 1999; Watanabe *et al*., 2000).

In machining processes, laser texturing is used to improve the adhesion properties of hard coatings on cutting tool surfaces. In the process of laser texturing, a laser of short pulses and of high repetition rate causes a texture resulting from the formation of liquid pools. After the solidification of these puddles, nanostructures are formed that allow a better anchoring of the coating. In this process the simultaneous cleaning and texturing of the substrate can take place, the material receives an additional amount of energy to melt superficially. Macroscopically, the roughness of the surface increases, generally due to the formation of craters from the melting and ablation of the material (Lima *et al*., 2005), which probably can contribute to increase the adhesiveness of the coating on the substrate. This means of modifying the substrate texture of cutting tools by means of laser beams in order to improve the adhesion of coatings is relatively new in machining, and still needs many investigations since few published works in the area. Due to its potential, it is observed that it is a very promising alternative to improve the adhesiveness of coatings in cutting tools.

Another relevant research front in machining in recent years is cutting fluids and their application forms, since they are technically indispensable in the machining of various materials. However, they can harm the environment and also the health of the machine operator. Consequently, the interaction between textured tools and the use of cutting fluids and their application form is another interesting topic to be researched in the machining area.

The use of cutting fluid is significant in any machining operation to cool the cutting tool and workpiece surface, and/or lubricate the tool-part interface, and promote chip removal from the cutting zone. Recently, many researches have focused on lubrication with minimal amount of lubricant or cutting fluid (MQL or MQF) among the various existing methods in the application of a coolant/lubricant (Said *et al*., 2019).

The MQL/MQF reduces the use of refrigerant/lubricant by pushing a mixture of compressed air and cutting fluid into the cutting zone in reduced amounts, on average up to 50 ml/h. For certain machining operations, such as milling with tools with diameters greater than 40 mm, this quantity can be greater than 150 ml/h for a short period of time (DGUV, 2010). The MQL/MQF method proves to be appropriate in machining, as the application of a fine mist of cutting fluid with compressed air in the cutting zone meets the needs of a "green" machining, with an ecological and economical solution (Kamata; Obykawa, 2007; Pervaiz *et al*., 2019; Said *et al*., 2019).

Thus, the main justification for carrying out this work is to contribute to new investigations and provide data that will provide technical support in enabling the use of surface texturing of cutting tools using a laser beam with the application of a minimum amount of lubricant.

At first, the contribution of this work was intended to evaluate the performance of ISO P grade carbide inserts blasted and coated with TiAlN (Titanium Aluminum Nitride) used commercially, and laser textured and coated carbide inserts of ISO P grade TiAlN through tool life tests and surface finish tests of the machined part in AISI 1045 steel turning with MQL application, dry machining and cutting fluid wet.

The tool substrate/coating conjugate was also evaluated by means of confocal laser and scanning electron microscopy tests.

2. EXPERIMENTAL PROCEDURES

2.1. Tool-life tests

In these tests, laser-textured and microblasted cemented carbide inserts ISO P grade coated with TiAlN were used. The objective of these tests is to check which insert, according to the cutting conditions of Tab.1, give the best combination for the turning AISI 1045 steel.

The performance of the inserts will be evaluated based on turning length from the AISI 1045 steel workpiece, until it reaches the end-of-tool-life criterion based on the medium flank wear, VB_B = 0.3 mm, using a Zoom 645T-Koye stereomicroscope flank wear measurement.

The life tests were carried out dry, wet and MQL for three tools tested - uncoated, sandblasted and coated with TiAlN, and laser and coated with TiAlN. The cutting fluid used was Rocol Ultracut 250 HW applied by wet and MQL. In the MQL application, a Quimatic V nebulizer with a flow rate of 50 ml/h and a pressure of 6 bar was used, with only one injection nozzle inclined at 45º in relation to the rake face of the tool. In the wet application, the flow was 20 l/min.

In order to guarantee statistical reliability, each test was repeated three times (test and two replicas) and the average results were considered in the analyses.

Turning tests were carried out on a CNC lathe Diplomat Logic 195 VS equipped with a commercial tool holder having the following geometry: rake angle γ_0= -2º, clearance angle α_0= 5º, inclination angle λ_S= 0º and side cutting edge angle κ_r= 45º. The workpiece material used was AISI 1045 steel in the form of a round bar with an external diameter 50.8 mm and length of 113 mm.

Laser ablation on the cemented carbide surface was carried out using a hybrid copper laser source, which delivers a laser beam with a wavelength λ= 510 nm, pulse duration τ_p =30 ns, focus diameter d_f= 30 µm, repetition rate f_r= 13.8 kHz and high beam quality $M^2 \approx 3.5$. The hybrid copper laser source was developed by the Photonics Division of the Institute of Advanced Studies of the General Command of Aerospace Technology (IEAv-CTA).

Following laser ablation, an TiAlN layer was deposited on the cemented carbides surfaces using an industrial PVD (Physical Vapor Deposition) installation.

The tools used were manufactured by Sandvik, specification CNMG 12 04 08 H13A. The TiAlN coated and blasted tool was prepared by Oerlinkon-Balzers. In this step, scanning electron microscopy (SEM), model MEV Jeol JSM-7000F, was also used to characterize the wear and surface analysis of the tools.

Table 1. Cutting conditions used in tool-life tests.

Conditions	Value
Cutting speed [m/min]	200
Feed rate [mm/rev]	0.5
Depth of cut [mm]	2.0
Turning length [mm]	50

2.2. Roughness assessment

Two roughness parameters, i.e. arithmetical mean roughness Ra, was determined using roughness tester Mitutoyo SJ-210, tip radius 2 µm, tip angle 60°, cut-off 0.8 mm, measuring speed 0.25 mm/s and applicable standard ISO 4287.

Dry turning tests were carried out on a CNC lathe Diplomat Logic 195 VS equipped with a commercial tool holder having with geometry: rake angle γ_0= -2º, clearance angle α_0= 5º, inclination angle λ_S= 0º and side cutting edge angle κ_r= 45◦. The workpiece material used was AISI 1045 steel in the form of a round bar with an external diameter 50.8 mm and length of 113 mm.

In the tests the arithmetical mean (Ra) roughness of the machined surface were obtained with three measurements for each tool tested with scanning at 120º from each other.

The cutting conditions used in the roughness tests are shown in Tab. 2.

Table 2. Cutting conditions used in roughness assessment.

Conditions	Value
Cutting speed [m/min]	200
Feed rate [mm/rev]	0.1
Depth of cut [mm]	1.0
Turning length [mm]	50

2.3. Morphological analysis of the substrate/coating conjugate

For the morphological analysis of the substrate/coating conjugates of the tools, optical and confocal laser microscopy tests were performed. The objective of the optical microscopy test was to characterize the surface of the conjugates regarding the macroscopic differences existing in the laser and sandblasted textures. The equipment used in this analysis was a Zoom 645T - Koye stereomicroscope. The Confocal Laser Microscopy test aimed to study in a more realistic and precise way the surface characteristics of textured and coated tools, using a Zeiss Axio Imager 2 optical microscope coupled to a Zeiss LSM 700 laser scanning system, equipped with diode laser (405 nm) and EC PLAN-NEOFLUAR 40x0.75 objective lens. The images were generated from mosaics of 5x5 images totaling a scanning area of 800x800 µm. With the images obtained, it was possible to compare the topography of the tools by measuring the roughness amplitude parameters (Sq, Sa and Sz) and amplitude distribution or statistical parameters (Ssk and Sku), shape variation, irregularities and induced changes by laser and sandblasted texturing. Confocal laser microscopy was performed at the Regional Center for Technological Development and Innovation (Crti-UFG).

3. RESULTS AND DISCUSSIONS

3.1. Tool-life tests

Figure 1 shows the results obtained in the life tests of the tested tools. The tool with the worst performance was the uncoated one, both dry and with the application of wet cutting fluid and MQL.

The tool with the best performance in the life tests was the TiAlN coated tool with blasted substrate, both dry and with the application of wet cutting fluid and MQL.

In the evaluation regarding machining with cutting fluid, it is observed in Figure 1 that the use of spouted and MQL increased tool life, with greater emphasis on the TiAlN-blasted tool.

The application of cutting fluid, by wet and MQL, modified the cutting zone, particularly the secondary shear zone in machining, causing a decrease in friction at the chip-tool interface and in the heat generated, enabling an increase in life of the tool.

As for the behavior of the tested substrates, sandblasted and laser, it is observed that the TiAlN-blasted tool had a much better performance, both dry and with spouted and MQL application, in relation to the TiAlN-laser tool. The justification for this result may lie in the adhesion of the TiAlN coating on blasted and laser substrates.

Figure 2 shows images of the rake face of the TiAlN-laser tool. The images clearly show the early detachment of the deposited TiAlN coating. The premature detachment of the TiAlN coating on the laser-textured tool may be related to different degrees of brittleness of the coating, its elasto-plastic properties, the internal residual stresses of the deposited film and even a low adhesiveness of the deposited film on the metal substrate hard with laser texture.

A low adhesiveness of the coating on the substrate clearly interferes with the tools behavior during cutting, as the delamination of the layer leads to premature contact of the substrate carbide with the workpiece. In addition, coating fragmentation generates hard and abrasive particles that interact with the part-tool tribological system, which can further accelerate tool wear (Neves *et al.*, 2006).

Figure 3 shows the TiAlN-blasted and TiAlN-Laser tools after end of life. The images clearly show marked flank wear on the tools. Flank wear is considered to be the most common form of wear that occurs on machine tools. It is even a preferable form of wear as it indicates a predictable and stable tool life.

Flank wear occurs mainly due to wear mechanisms by abrasion and attrition, caused by hard elements such as carbides present in the workpiece material or even by the early detachment or delamination of the coatings used, TiAlN in this study.

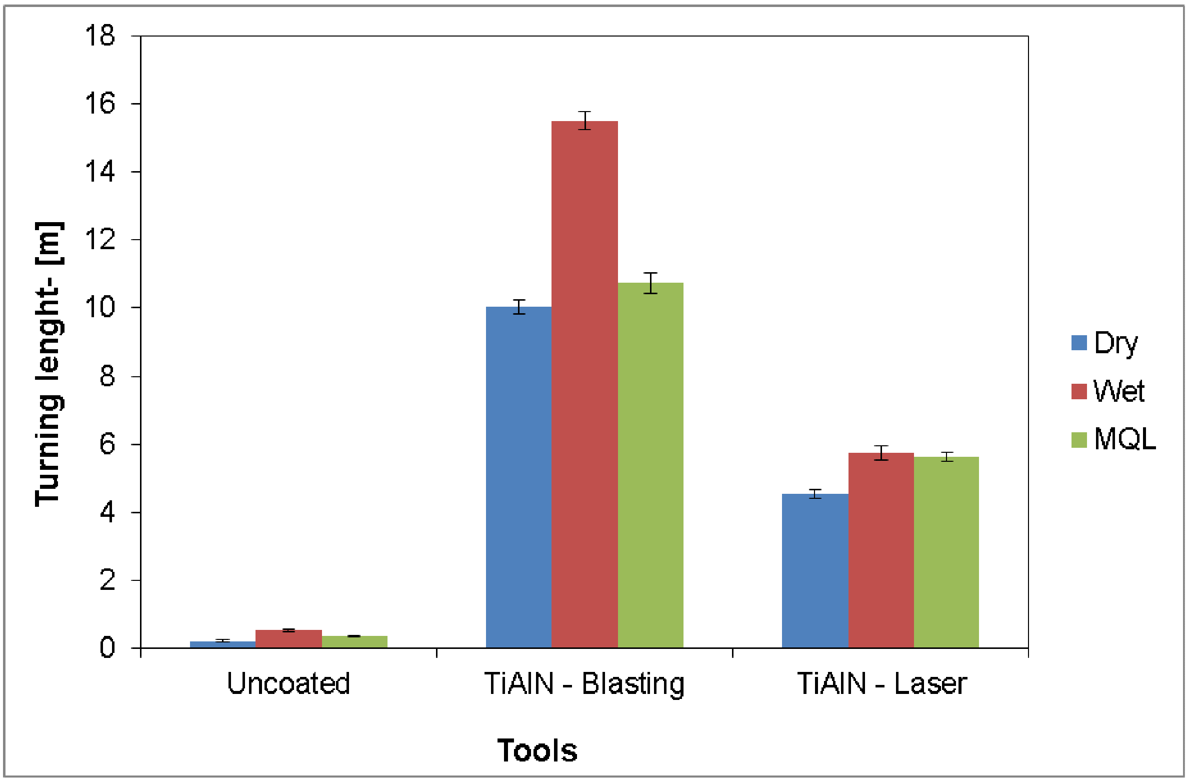

Figure 1. Life tests in turning of AISI 1045 steel.
(Cutting conditions: vc= 200 m/min, f= 0.5 mm/rev and ap= 2.0 mm)

Figure 4 shows, by SEM, an area plastically deformed in the flank wear region of the TiAlN-blasted tool, the presence of micro grooves and part material adhered to the tool, clearly characterizing the performance of the wear mechanisms by abrasion and attrition, whose the last one has as a remarkable characteristic the adhesion and the material dragging of the part during the machining.

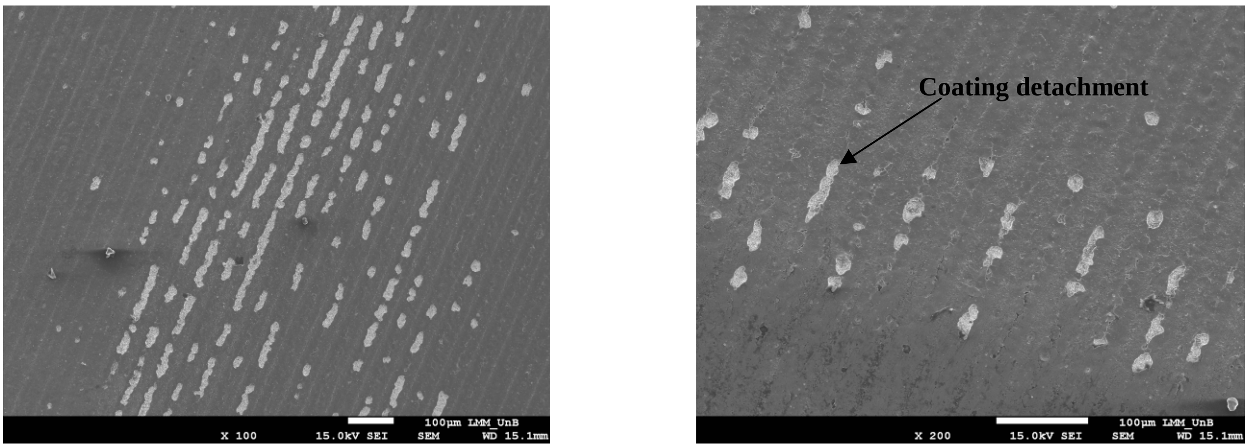

Figure 2. SEM rake face of the TiAlN-laser tool.

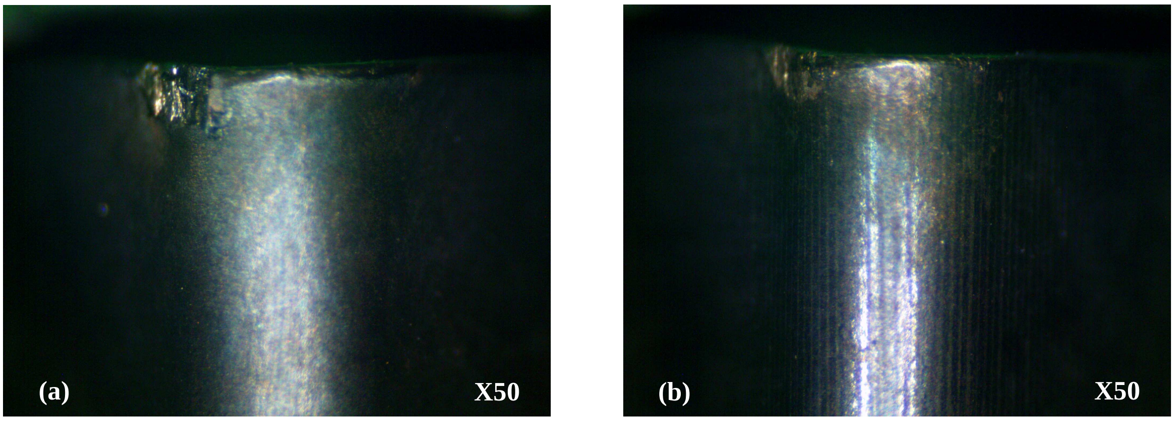

Figure 3. Images of tool flank wear at end of life: (a) - TiAlN-blasted and (b) - TiAlN-laser.

Abrasion and attrition wear mechanisms were also predominant in uncoated and TiAlN-laser tools.

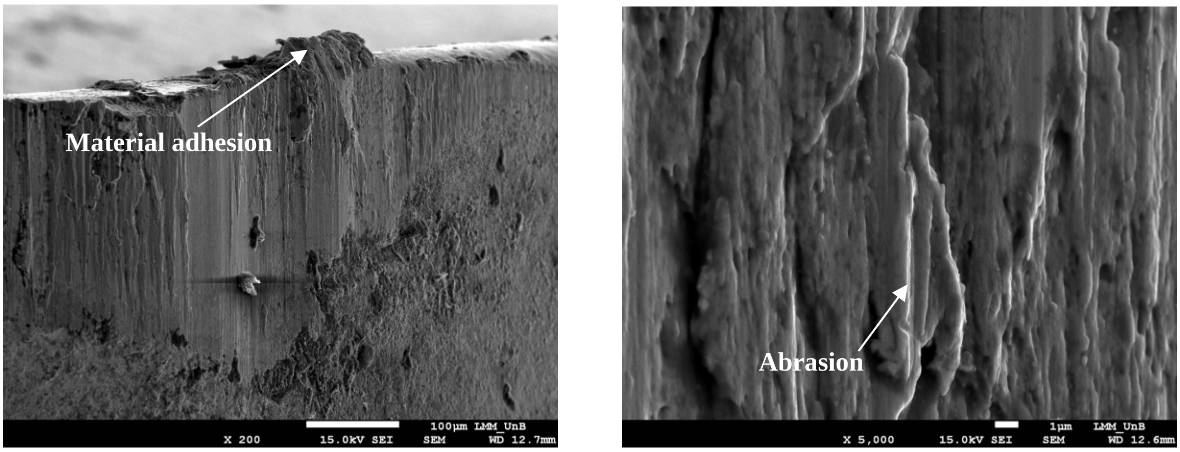

Figure 4. SEM image of flank wear of a TiAlN-blasted tool.

3.2. Roughness assessment

Figure 5 shows the results obtained in the roughness tests of AISI 1045 steel in turning using the tools - uncoated, TiAlN-blasted and TiAlN-laser. In general, the results show that the use of the TiAlN coating significantly affects the arithmetical mean roughness (Ra) values of the turned surface.

As mentioned in the previous item 3.1, TiAlN coating during machining undergoes oxidation forming mainly aluminum oxide on the tool surface. This formed oxide acts as a solid lubricant during workpiece machining. The presence of aluminum oxide on the tool surface, decrease machining forces, thus enabling a better finishing of the machined workpiece (Endrino *et al*., 2007).

It is clear from the results shown in Fig. 3, that the use of the TiAlN coating modifies the tool/workpiece interface since it interferes directly in the areas of the primary and secondary shear planes, reducing friction. With the reduction of the friction, the tendency is that there is a decrease of the micro irregularities formed in the machined surface, improving the finishing.

When comparing the TiAlN-laser and TiAlN-blasted tools, it is observed that there is no statistical difference between them. Modifying the texture of the tool substrate, laser or sandblasted, does not alter the dynamics of the cutting process. The micro-irregularities formed on the surface of the turned workpiece did not change significantly in its roughness values.

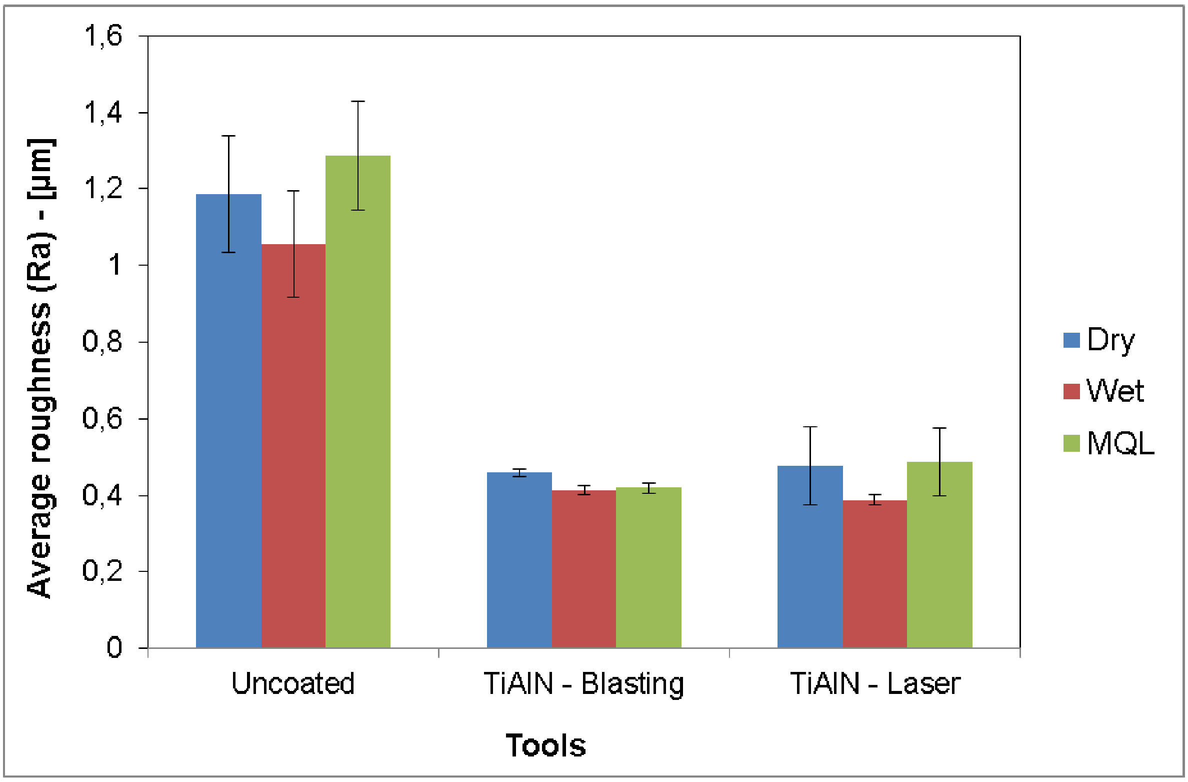

Figure 5. Roughness testing of AISI 1045 steel.

3.3 Optical and Confocal Laser Microscopy

For the morphological analysis of the substrate/coating conjugates, optical and confocal laser microscopy tests were performed. Figure 6 shows images of the texture of the exit surface of the tested tools: TiAlN-blasted and TiAlN-laser. With the use of a stereomicroscope one can see the difference between the sandblasted and laser textures of the tools used. In sandblasted tools there is no macroscopic ordering of the texture, like the parallel arrangement of lines visualized in the TiAlN-laser tool. This differentiated ordering between the coatings was probably crucial for the performance of the tools in the life tests. Essentially the ordering of the texture in the laser tool was ineffective, the premature degradation of the coating leads to the formation of "microchips" of TiAlN coatings with a hardness of approximately 3000 HV. These TiAlN "chips" then become part of a tribological system, probably causing abrasive wear to three bodies: workpiece, tool and the TiAlN "chips" as an interfacial element. The TiN "microchips" are pressed against the workpiece and the tool at the same time, causing microcracks and, mainly, wear micro grooves on the tool flank, as seen in Fig. (4).

Figure 6. Detail of the rake face tools of TiAlN-blasted (left) and TiAlN-laser (right).

Figures (7) and (8) shows the results of confocal laser microscopy tests for the TiAlN-blasted and TiAlN-laser tools. Images were acquired by laser scanning through confocal microscopy, after scanning the images were treated using

MountainsMap® 8.2 software. In the images it is possible to clearly see that the sandblasted texture is random, while the laser texture has a notoriously ordered distribution of peaks, which can probably change the contact conditions at the chip-tool interface, and occasionally modify the life of the tool.

Table 3 shows the measurement results of the roughness amplitude parameters (Sq, Sa and Sz) and statistical distribution parameters (Ssk and Sku), obtained in the laser scanning of the tools surface by means of confocal microscopy. Basically, laser texturing caused a decrease in the Sa and Sq amplitude parameters of the tool surfaces, which may contribute to a decrease in the average roughness of the machined workpiece. As for the asymmetry (Ssk), the texture distribution is moderately skewed, with a kurtosis above 3 for all textures of the tested tools.

Table 3. Amplitude and statistical parameters.

Tool	**Sa (µm)**	**Sq (µm)**	**Sz (µm)**	**Ssk**	**Sku**
TiAlN-blasted	1,221	1,505	13,729	-0,698	3,245
TiAlN-laser	0,959	1,305	16,748	-1,620	7,203

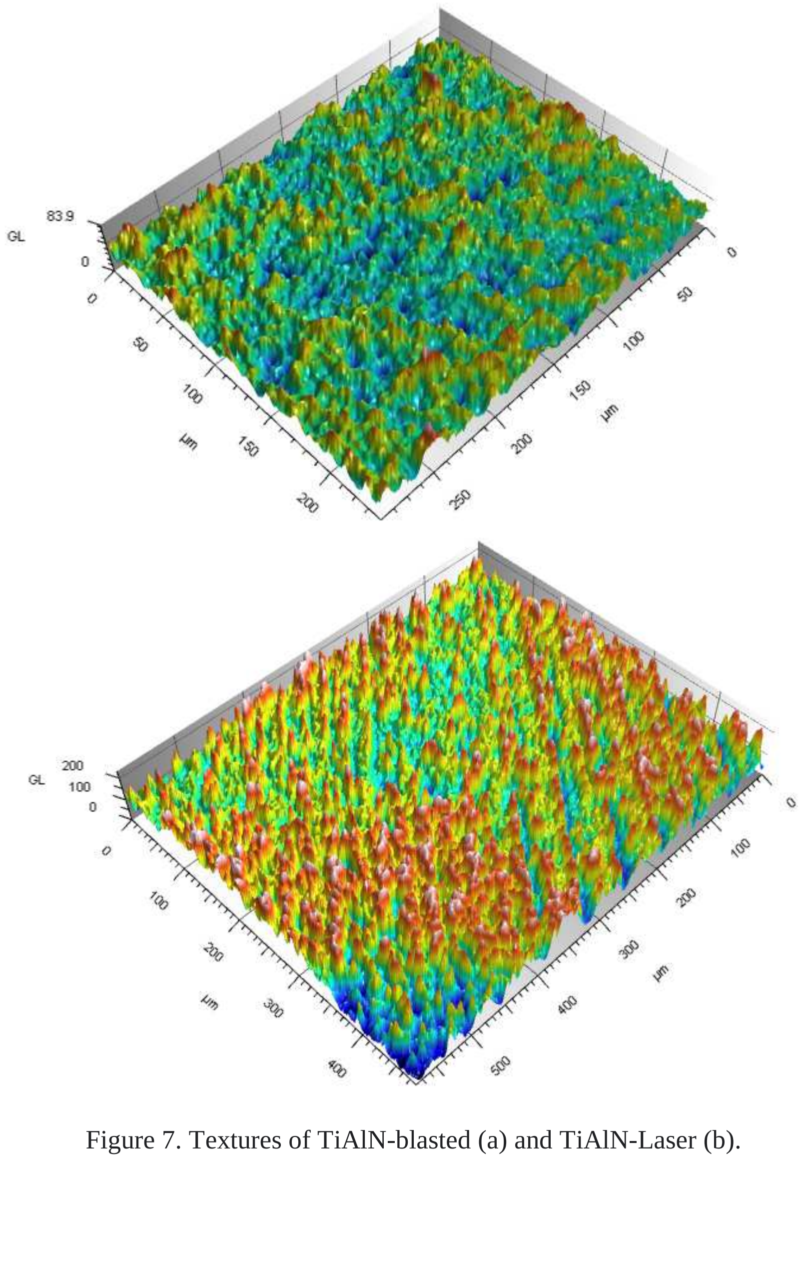

Figure 7. Textures of TiAlN-blasted (a) and TiAlN-Laser (b).

4. Conclusions

In this study, the surfaces of carbide inserts were textured: (i) by laser beam, specifically, laser ablation using a source of CuHBr (Copper and Bromine Hydride), and (ii) sandblasting (commercial process), subsequently textured inserts were coated with TiAlN. The performance of different textures, laser and sandblasting, were tested in tool life tests and machined surface finish in the dry turning of AISI 1045 steel and with application of wet cutting fluid and MQL. The different textures were also characterized using optical and confocal laser microscopy. According to the results previously presented and discussed, the following conclusions were reached:

- ✓ In the life tests, the TiAlN coating significantly increased the turned length compared to the uncoated tool, both dry, with wet and MQL application;
- ✓ The TiAlN-blasted tool showed the best result in life tests, followed by the TiAlN-laser tool;
- ✓ Probably the premature detachment of TiAlN deposited on the laser textured substrate was the main factor for its low performance in life tests;
- ✓ The use of TiAlN reduced the mean arithmetic roughness (Ra) of the turned surface in relation to the uncoated tool;
- ✓ The application of wet cutting fluid and MQL increased tool life compared to dry machining, exceptionally for the TiAlN-blasted tool;
- ✓ The application of wet cutting fluid and MQL did not significantly alter the surface finish of the turned surface compared to dry machining.

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