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COB-2019-2173 SAE 4340 STEEL TURNING WITH LASER TEXTURED INSERTS AND TiAlN COATED

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Abstract. *The goal of this work is to compare, through tool-life tests and surface finishing of the workpiece machined in SAE 4340 steel turning, surface modified carbide inserts of ISO S grade by means of laser texturing and blasting (commercial process), and then coated with TiAlN (Titanium Aluminium Nitride). The results showed a better average performance in the life tests of the blasted textured inserts, and a better finishing of the turned workpiece with the use of TiAlN coating, for both the sandblasted and laser textured substrate in relation to the uncoated tool. The TiAlN coated blasting textured tool had a life tests performance of approximately 3800 percent over the uncoated tool. Compared to the laser textured tool the increase was approximately 200 percent. Adhesion tests of the coatings, Rockwell indenter test, showed, qualitatively, a higher delamination of the TiAlN coating deposited on the laser textured carbide substrate.*

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

1. INTRODUCTION

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 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.

Thus, the main justification for this work is to contribute with new investigations and provide data that will give technical support in the viability of the use of this new technology, of surface texturing of cutting tools using laser beam in comparison to the commercial process that uses blasting in the modification surface of coated cutting tools.

2. EXPERIMENTAL PROCEDURES

2.1. Tool-life tests

In these tests, laser-textured and microblasted cemented carbide inserts ISO S 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 SAE 4340 steel.

The performance of the inserts will be evaluated based on turning length from the SAE 4340 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.

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.

Dry 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 $\gamma_0 = -2^\circ$, clearance angle $\alpha_0 = 5^\circ$, inclination angle $\lambda_s = 0^\circ$ and side cutting edge angle $\kappa_r = 45^\circ$. The workpiece material used was SAE 4340 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 $\lambda = 510$ nm, pulse duration $\tau_p = 30$ ns, focus diameter $d_f = 30$ μ m, 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 Oerlikon-Balzars. Figure 1 shows the difference between the blasted and textured TiAlN coated laser tools. The texturing lines for the TiAlN-laser tool are clearly observed.

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

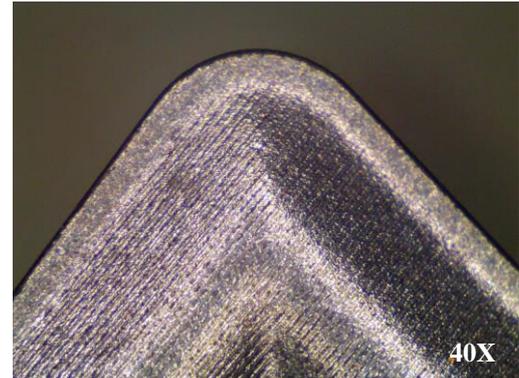


Figure 1. Detail of the rake face tools of TiAlN-blasted (left) and TiAlN-laser (right)

2.2. Roughness assessment

Two roughness parameters, i.e. arithmetical mean roughness R_a and maximum roughness R_z , were determined using roughness tester Mitutoyo SJ-210, tip radius $2\ \mu\text{m}$, tip angle 60° , cut-off $0.8\ \text{mm}$, measuring speed $0.25\ \text{mm/s}$ 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 $\gamma_0 = -2^\circ$, clearance angle $\alpha_0 = 5^\circ$, inclination angle $\lambda_s = 0^\circ$ and side cutting edge angle $\kappa_r = 45^\circ$. The workpiece material used was SAE 4340 steel in the form of a round bar with an external diameter $50.8\ \text{mm}$ and length of $113\ \text{mm}$.

In the tests the arithmetical mean (R_a) and maximum (R_z) roughness of the machined surface were obtained with three measurements for each tool tested with scanning at 120° 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. Adhesion tests of the coatings - Rockwell indenter test

The goal of this test was to evaluate qualitatively the adhesion of TiAlN deposited on cemented carbide tools after they have been textured by laser and blasted. The test consists of indenting the rake face of the tools, causing delamination of the coating around the indentation, later delamination is evaluated by optical microscopy.

The experiments were carried out following the VDI 3198 (1991) standard, using a durometer Mitutoyo model Durotwin with load of $150\ \text{kgf}$ ($1471\ \text{N}$), diamond Rockwell C conical penetrator, angle of 120° and curvature radius of $0.2\ \text{mm}$. The analysis of the results was based on the markings obtained after the indentation.

They were visualized and evaluated using a Zoom 645T-Koye stereomicroscope with $100\times$ enlargement, and also by *MountainsMap*[®] software 8th version.

3. RESULTS AND DISCUSSIONS

3.1. Tool-life tests

Figure 2 shows the results obtained in the tool-life tests. The worst performing tool was uncoated, with a life of only 0.13 m of machining, equivalent to three passes. The tool with the best average performance in the life tests was the TiAlN coated tool with blasted textured substrate, with a mean life of 5.02 m, equivalent to 100 passes.

It can be seen from the results obtained in Fig. 2 that the use of TiAlN coating for both the blasted and laser-modified substrates significantly increases the life of the cutting tool compared to the uncoated tool.

Coatings of ternary composition such as TiAlN, which in addition to having high hardness at room temperature, about 3000 HV, have high hot hardness, which helps to slow the wear of the cutting tool.

TiAlN ternary coating is also more efficient in blocking the heat transfer to the substrate because during the cutting process, especially at high temperatures, a tribo-oxidation occurs on the tool surface, resulting in the consumption of the coating constituent elements for formation of protective oxide films, such as Al_2O_3 , with high chemical and thermodynamic stability (Endrino *et al.*, 2007).

Thin coatings such as TiAlN are not able to block the heat dissipated to the tool substrate. Necessarily, they act as a thermal resistance, which decreases the heat transferred to the substrate (Bunshah, 2001), in this way they retard the softening of the tool substrate and also significantly increase the wear resistance.

TiAlN is a “*thermally activable*” coating with temperatures that optimize its performance in the range 800-825 °C (Fox-Rabinovich *et al.*, 2005; Kalls *et al.*, 2006; Endrino *et al.*, 2006 and Coelho *et al.*, 2007), that is, there is a need for high temperatures during cutting so that TiAlN can be activated, forming Al_2O_3 oxides, which probably alter the tribological interaction between the tool and the part.

Probably, the temperatures developed in this test would be close to the TiAlN oxidation range, allowing the formation of Al_2O_3 , forming a thermal barrier to heat propagation to the substrate and promoting greater lubricity between tool and workpiece, delaying wear, consequently, increasing the life of TiAlN coated carbide substrates.

In the evaluation of the performance of the tested substrates, blasting and laser, it is observed that the TiAlN-blasted tool had an average performance superior to the TiAlN-laser tool.

The TiAlN coated blasting textured tool had a life tests performance of approximately 3800 percent over the uncoated tool. Compared to the laser textured tool the increase was approximately 200 percent.

Subsequent analyzes through coating adhesion tests, Rockwell C indentation test, will be carried out to better understand the behavior of the tools, and in this way, try to justify with greater clarity the performance of the tools in the life tests.

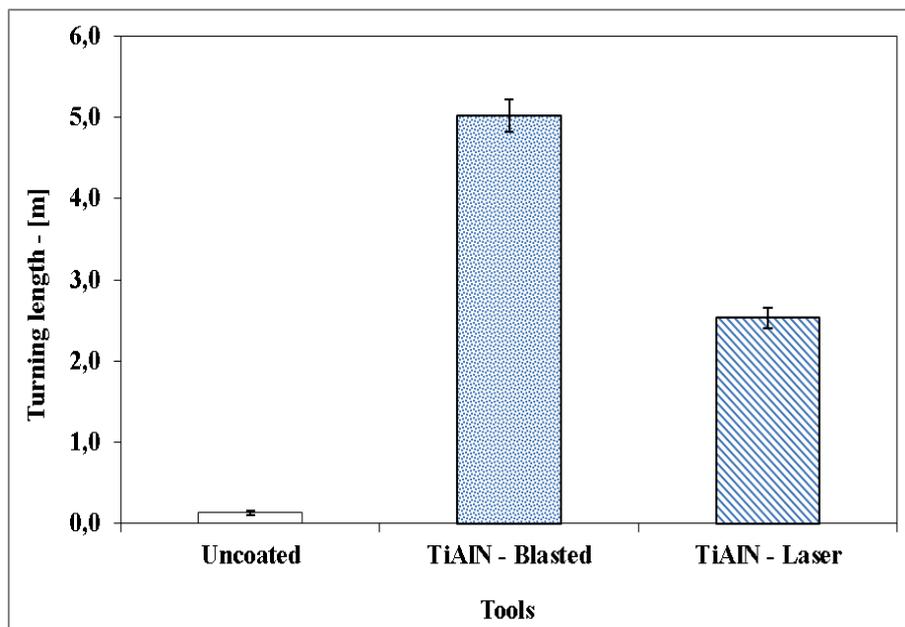


Figure 2. Life tests on dry turning SAE 4340 steel

3.2. Roughness assessment

Figure 3 shows the results obtained in the roughness tests of SAE 4340 steel in dry 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) and maximum roughness (Rz) 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. Possibly 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. Probably, 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. Possibly, 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.

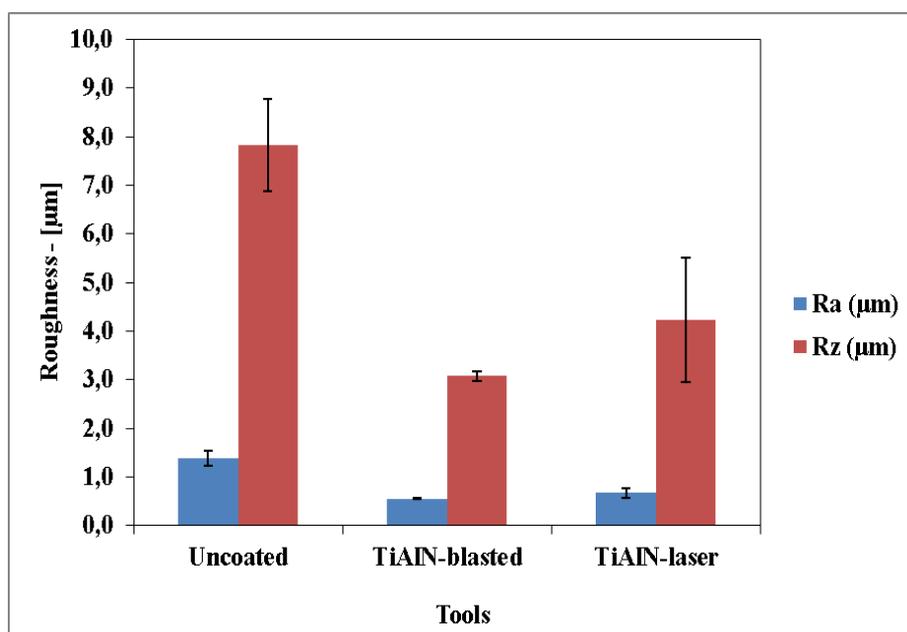


Figure 3. Roughness testing of SAE 4340 steel in dry turning

3.3. Rockwell indenter test

Indentations by the Rockwell C indenter with quasi-static load of 150 kgf were carried out on the rake face of the cemented carbide tools. In both microblasted and laser textured tools, delamination of the TiAlN coating occurred. However, the tool with laser texture showed bigger areas of delamination of the coating around the indentations, as shown in Fig. 4. Figure 4 shows a large area of delamination of the TiAlN coating deposited on the laser texturized tool, exposing the cemented carbide substrate (WC-Co).

Probably the delamination of TiAlN deposited on the surface of the laser textured tool caused the formation of high hardness abrasive particles. These hard particles of TiAlN coating, when ripped off and dragged during the machining process, resulted in premature flank wear of the tool, leading to its inferior performance in life tests compared to the blasted texture tool, which justifies the results obtained in the Fig. 2.

The tool with blasted texture also shows delamination of TiAlN, however, the area of delamination is effectively smaller, as shown in Fig. 5.

Tool manufacturers use hard particles for blasting the surface of the tools, claiming that the residual stresses are reduced and thus the tool life is increased. The correlation between coating adhesiveness and residual stresses was studied by (Sprute *et al.*, 2014), who found a strong influence of not only the residual stresses of the multilayer and monolayer coatings, but also the residual stresses of the substrate on the adhesiveness of the coatings. Harder substrates and higher compressive stresses improve adhesion.

The smaller area of delamination of the TiAlN coating on microblasted evidences its greater adhesion on cemented carbide substrates and its greater capacity to support loads before cracking and delaminating.

With respect to coating detachment/delamination of the deposited on substrates with laser and blasted textures, possibly, occur different forms of degradation of the coating TiAlN.

Figures 6 and 7 showed images, rendered in *MountainsMap*[®] version 8 software, of only two indentations, one on the laser textured substrate and the other on the blasted textured substrate, in order to try to characterize the fragmentation of the coating.

It is observed that in Figure 6, with laser texture, the fragmentation of the coating apparently is discontinuous, the delamination occurs by isolated breaking of several smaller coating plates, probably, the ripples caused by the laser ablation tensile stresses the surface and subsurface of the substrate asymmetrical shape, which would cause poor adhesion of the TiAlN coating.

In Figure 7, with blasted texture, TiAlN fragmentation apparently occurs continuously, with a smaller area of degradation, the blasting particles propelled symmetrical compression stresses, which probably positively influenced TiAlN anchorage on the tool substrate.

The prior considerations regarding the form of delamination of the TiAlN coating deposited on the laser textured and blasted substrates are only superficial. Continuing this analysis would require the observation of the indentations by scanning electron microscopy, to observe possible microcracks in the surface of the studied substrates, and also an analysis using x-ray diffraction in order to verify the occurrence of change of phase in the components of the carbide substrate, mainly of tungsten carbide.

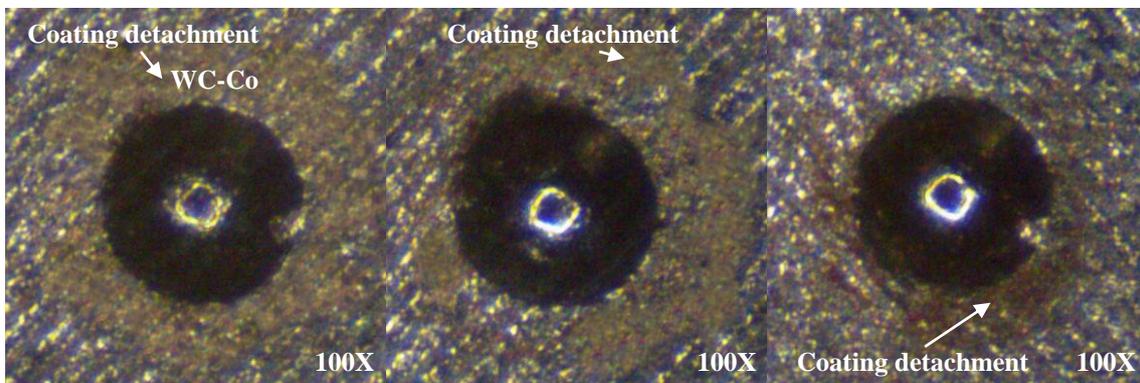


Figure 4. 150 kgf indentations on laser textured TiAlN coated substrate

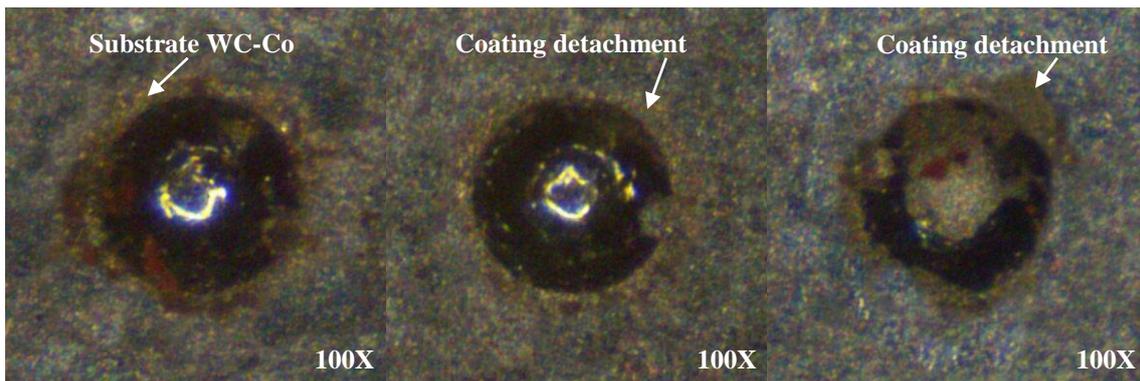


Figure 5. 150 kgf indentations on blasting textured TiAlN coated substrate

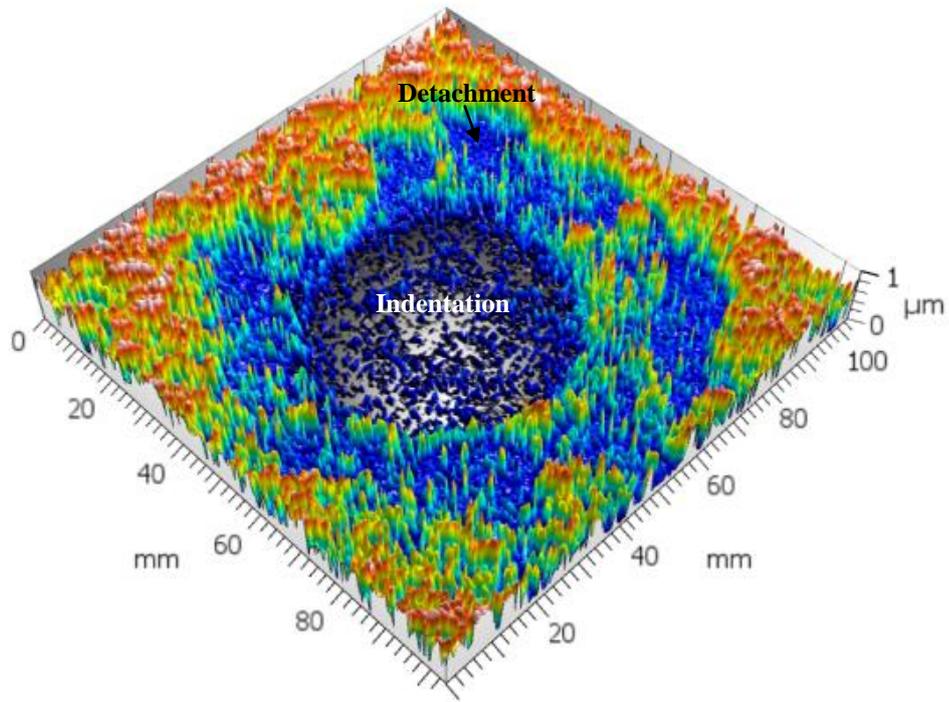


Figure 6. Laser textured and TiAlN coated substrate indentation, *MountainsMap*[®] image

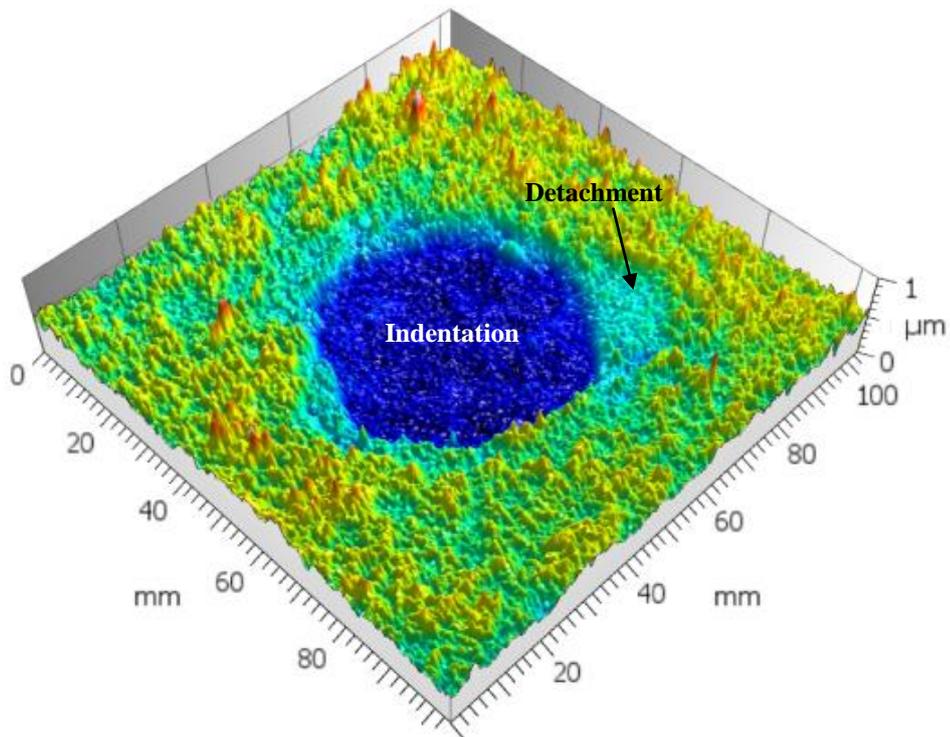


Figure 7. Blasted textured and TiAlN coated substrate indentation, *MountainsMap*[®] image

4. CONCLUSIONS

In this study, two types of surface textures were fabricated on the WC/Co carbide substrate: (i) texture fabricated by a laser beam, specifically, laser ablation using a HyBrID copper laser source (ii) texture fabricated by blasting (commercial process), and the textured samples were then deposited with TiAlN coating. The performance capabilities of the different surface textures, laser and blasting, were measured in terms tool-life tests, with measuring the average flank wear of the tool, surface roughness (R_a and R_z) of the machined surface, SAE 4340 steel, and adhesion test, *Rockwell* indenter test. The following conclusions are obtained:

- ✓ In the tool-life tests, TiAlN coating significantly increased turning length over uncoated tool for the cutting conditions used in this work;
- ✓ The TiAlN coated blasting textured tool had a life tests performance of approximately 3800 percent over the uncoated tool;
- ✓ Considering the results obtained in this work, for the cutting conditions used, it is observed that the blasted texturing of substrates of coated cutting tools, allows a performance in average superior to the substrate laser;
- ✓ The use of ceramic coatings, more specifically TiAlN, for the given cutting conditions, enables smaller average and maximum roughness of the turned surface in relation to the uncoated tool;
- ✓ Thin coating adhesion test, *Rockwell* indenter test, showed qualitatively that the TiAlN-coated blasted textured carbide insert has smaller film delamination areas than the TiAlN deposited on the laser textured carbide insert.

5. ACKNOWLEDGEMENTS

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