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Selective ablation of titanium nitride film on tungsten carbide substrate using ultrashort laser pulses

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Abstract

Many machining tools use coatings on their cutting surface to improve the machining process and increase its useful life. Due to damage or wear on the cutting edge, it is often desirable to remove this film for tool recovery. Doing this without damaging the base material is not easy due to the small thickness of the coating and because its hardness is much greater than that of the substrate.

In this work, the removal of titanium aluminum nitride (TiAlN) coating on tungsten carbide (WC) was done with the use of femtosecond laser pulses. Complete film removal was obtained without damage to base material using a fluency far below that of the film ablation threshold for a single pulse. A decrease in this threshold was obtained by applying a high number of overlapping pulses with a low fluency until the incubation effects reduced the film damage threshold to a value slightly below to that of the substrate. With this technique precise and clean results were obtained and are reported in this work.

Keywords: laser ablation; ultrashort laser pulses; thin film, selective ablation.

1. Introduction

Ablation of coatings is often necessary in applications where it is desired to eliminate the film layer on specific regions of a surface. For this, one of the most used methods is the selective laser ablation that is

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gaining space in manufacturing industrial processes [1]. In most cases, however, this ablation must be performed in a way that preserves certain specific characteristics of the materials. For this, nanosecond Q-switched lasers have proved to be inefficient, since the thermal effects from the ablation process produce diffusion of the materials between the layers and the substrate, generate the formation of layers of molten and resolidified material and a heat affected zone, with formation of crystalline phases different from those of the parent material. These effects are undesirable because they lead to physical and metallurgical modifications, which generally reduces the efficiency and characteristics of the product [2].

The use of ultrashort laser pulses avoids these problems, since it minimizes the formation of heat and is able to remove very small amounts of any kind of material [2, 3]. Layers of a few tens of nanometers can be removed per pulse, and the process can be repeated until all the coating material is removed. This process can have great precision and has been used in numerous applications [1-6], such as surface cleaning, object recovery, semiconductor masking, decontamination, and coating removal from cutting tools.

The difference between the physical properties of the film and the substrate determines the possibility of the process as well as its accuracy and complexity. If the material to be removed absorbs the wavelength of the laser and has a lower ablation threshold than that of the substrate, then the process is relatively simple and there is no need for rigid process control. The fluence of the laser pulse is adjusted to be slightly above that of the ablation threshold of the film and below that of the substrate. An excess of pulses on the surface of the substrate will not affect it. On the other hand, if the damage threshold of the coating is close to or greater than that of the substrate, then a more precise control must exist to avoid excessive damage to the base material.

One of the applications of selective removal of coatings is with cutting tools, where films are used to improve the machining process and increase its useful life. These coatings protect the base material, provide thermal insulation and faster heat conduction away from the cutting edge of the tool, as well as reduce friction and increase hardness at the machining interface. Often, however, the film wears out and damages itself in a certain location, and its removal with precision allows the recovery of the piece without the need of its replacement. A very common combination in the manufacture of inserts is the one that uses a tungsten carbide (WC) sintered substrate coated with a titanium aluminum nitride film (TiAlN), which has been well studied for Improvement of manufacturing processes [7, 8].

Here, machining inserts of this type were used for studies of film removal using femtosecond laser pulses. The objective is to control the removal without causing damage to the substrate allowing the preservation of this for future deposition of repair film.

2. Experimental Procedure

For the tests, machining WC inserts with a TiAlN film, model R210-14 05 12M-KM 1020, from Sandvik were used. This type of insert was chosen because it does not present the same elements in the composition of the film and the substrate, facilitating the control of the selective ablation process. EDS measurements showed an average film thickness of 2 µm.

Table 1 shows the composition measured for the insert used.

Table 1. Film and substrate composition of the machining inserts

Film	
Element	Relative concentration (% wt)
Ti	34.63
C	21.89
Al	19.82
N	14.62

Substrate	
Element	Relative concentration (% wt)
W	76.80
C	15.26
Co	3.19

The experiments were performed with a femtosecond Ti:Sapphire laser system (Femtopower Compact Pro CE-Phase HP / HR Femtolasers) that continuously generates pulses of 25 fs (FWHM), centered at 775 nm with 40 nm of bandwidth, maximum repetition rate of 4 kHz and maximum energy per pulse of 750 µJ.

The D-Scan method [9-12] was used to determine the film and the substrate ablation thresholds (F_{th}). This technique allows to quickly determine F_{th} as function of the number N of overlapped pulses, and thus the incubation factor S for the two materials. Several traces were etched in each material, using a 75 mm focal length lens, generating a focal diameter of ~ 15 µm. Energy of 94 µJ/pulse and overlaps ranging from 1 to 10^4 pulses were used. Figure 1 shows some of the traces obtained.

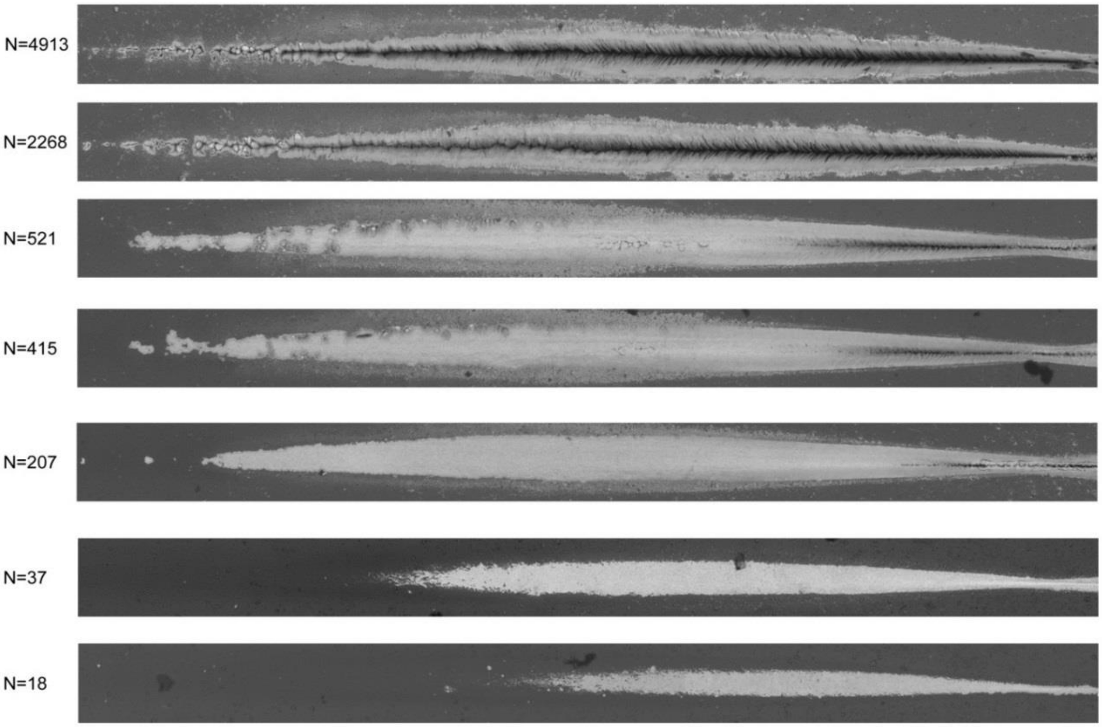

Fig. 1. D-Scan traces for N overlays from 4913 to 18 from top to bottom.

The measure of the greater width 2ρ_{max} of each trace provides the threshold fluency for each case through the equation [13]:

$$F_{th} = \frac{E_o}{e\pi\rho_{max}^2} \approx 0{,}117\,\frac{E_o}{\rho_{max}^2}, \qquad (1)$$

where E_0 is the pulse energy. The number of overlapping pulses, N, for each trace is given by [9]:

$$\mathrm{N} = \sqrt{\pi}\,\frac{f\rho_{max}}{v_y} \approx 1{,}8\,\frac{f\rho_{max}}{v_y}, \qquad (2)$$

where f is the repetition rate of the laser pulses, and v_y is the transverse translation speed of the sample relative to the laser beam.

The results obtained for each trace were placed on a log × log graph and a fit was made for each material, and the resultas are shown in Fig. 2 and

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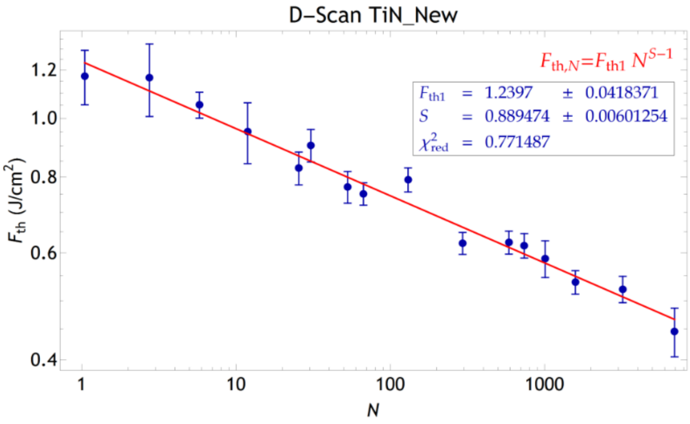

Fig. 2. Graph of the ablation threshold as a function of the pulses overlap for the TiAlN film obtained by the D-Scan method.

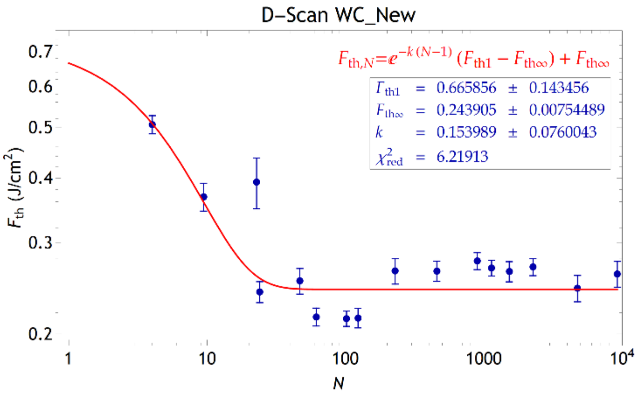

Fig. 3. Graph of the ablation threshold as a function of the overlap of pulses for the WC substrate, obtained by the D-Scan method

The best fits occurred with the expression $F_{th,N} = F_{th,1}N^{S-1}$ [14] for the film and with $F_{th,N} = e^{-k(N-1)}(F_{th,1} - F_{th,\infty}) + F_{th,\infty}$ [15] for the substrate. The first shows the metallic character of the film, and the second shows a behavior closer to a dielectric for the substrate.

From these graphs, a drastic reduction of the ablation threshold as a function of the number of overlapping pulses for the two cases is clearly seen. The substrate material, however, only begins to undergo the influence of the laser pulses after the removal of the protective film. If incubation effects, which decrease the ablation threshold, are considered for the film, many overlapping pulses with very low fluence can be used. These pulses will remove the film with an energy density below the one required to ablate the substrate with a few pulses, preserving the base material once the process ceases after the film is completely taken. Fig. 4 shows the region where the film ablation threshold is lower that the substrate threshold.

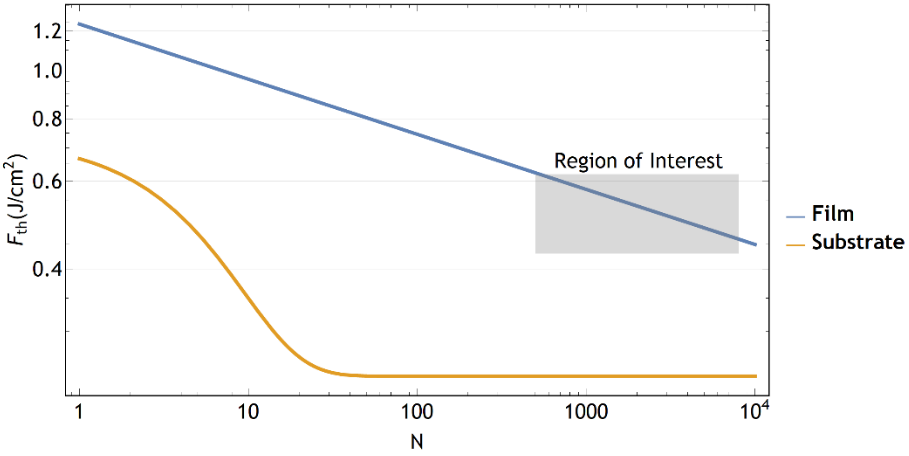

Fig. 4. Threshold fluence × N for the film and the substrate. The insert shows the region where the fluence is low enough to remove the coating but do not damage the substrate.

Based on the results shown in Figure 4, a density of energy of ~0.5 J/cm^2 was used for the removal of the TiNAl film. This fluence is less than half the threshold fluence for one pulse for the film, and below to the fluence threshold for one pulse for the substrate. After a great overlap of pulses with this fluency, the formation of LIPSS is observed and the continuity of this process leads to the complete removal of the film with insignificant damage to the substrate. Fig. 5 shows three tracks made with a 0.5 J/cm^2 fluency on the film deposited on the tungsten carbide. The colored traces represent the intensity of the EDS (Energy Dispersive Spectroscopy) lines of the materials elements. It is evident the almost complete elimination of Al and Ti in the trace region, even with the use of a fluency below the threshold fluency for one pulse.

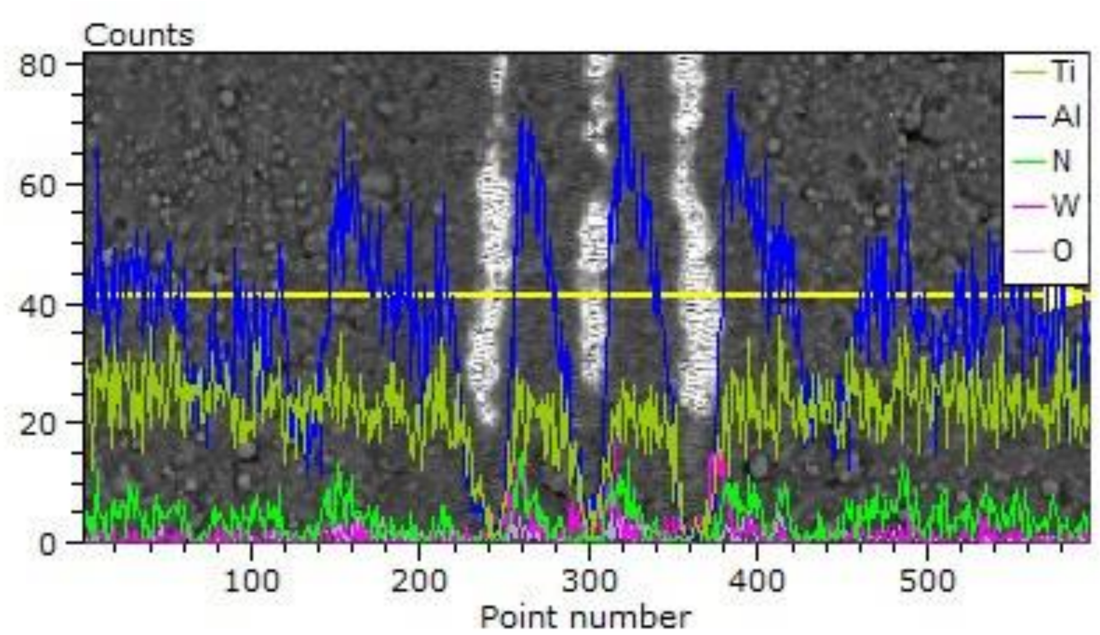

Fig. 5. Detail of the EDS analysis performed in a trace with N = 111, where it is possible to identify the decrease of the film components in the laser scanning region.

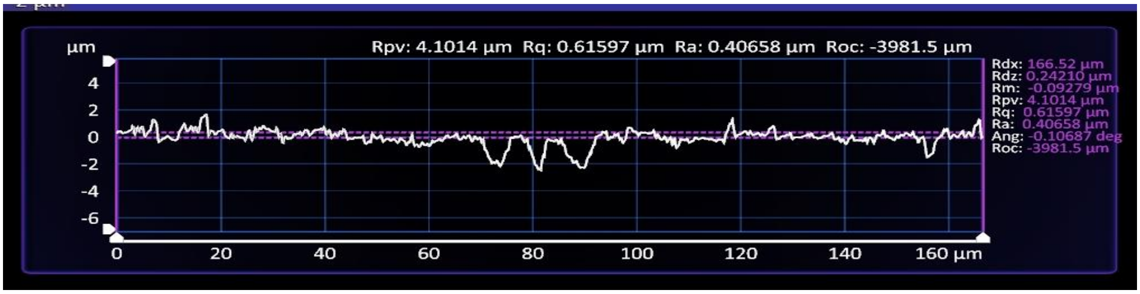

Fig. 6. Depth profile of the Fig. 5 traces measured by an optical profilometer.

The number of overlapping pulses for machining the traces of Fig. 5 is N ~ 111. This means an ablation rate of 18 nm per pulse, obtained from the traces 2 µm depth shown in Figure 5, which is low enough to remove the film with high accuracy and properly prepare finished substrate to a new layer of protective coating.

3. Conclusions

The incubation effects can be used to lower the film ablation threshold to a value below or close to the substrate threshold. This is achieved by using a large number of low-fluence pulses, which, in addition to reducing its ablation threshold, still remove subnanometric amounts of material per pulse. Thus, it is possible to obtain ablation with great precision and without damaging the substrate.

Acknowledgments

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