Laser removal of TiN coatings from WC micro-tools and in-process monitoring

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1. Introduction

Titanium nitride coatings are widely used in cutting tools for improving wear resistance and extending tool life [1–3]. These coatings are usually 2–3 μm in thickness and can have good adhesion to the substrate. However, when coated tools of this type need to be repaired, e.g. when faults arise in the coating process (unacceptable material composition/uneven thickness), or become worn-out due to machining, it is essential to remove coatings and subsequently recoat the repaired surfaces. The removal of thin coatings using thermal processes is a challenging task, as the thermal damage needs to be confined within the film thickness. It is difficult to remove these coatings mechanically due to their high hardness and good adhesion to substrates. Typically, removal of these coatings is performed using wet chemical processes [4–6]. Although this method is established in industry, it has some disadvantages including the requirement for processing of waste residue, uneven removal, long cycle time (in the order of hours) and most critically, environmental concerns. To overcome these problems, an alternative technique was explored in this paper using short pulse laser ablation. Laser removal of coatings or laser cleaning has attracted much attention in science and engineering [7–10] because of its advantages of high speed and selective removal over a small area. Additionally, the laser process does not produce hazardous chemicals. The excimer laser removal of thin films, oxides, ceramics and paints from various substrates [11–13] has recently gained increasing interest because of its ability to ablate a wide variety of materials in a well-controlled manner.

Commercially, hard coatings are mostly produced using either, chemical vapour deposition (CVD), physical vapour deposition (PVD) or plasma-assisted CVD or PVD [14–17]. A batch of these coatings when deposited over cutting tools may have some variation in thickness [18] and composition [19] (proportion of Ti and N). Irrespective of these concerns, the laser stripping process has the potential of becoming reliable and widely acceptable process if incorporated with an effective online monitoring system. Although the incorporation of such a system in laser decoating of micro-tools is yet to be reported, it must be mentioned that considerable effort has over the years been done in this area of research. Schubert et. al. [20] investigated the excimer laser removal of TiN and WC coatings from a steel substrate and its performance from an 8 mm diameter tool. Their investigation dealt with the application of the coating removal process on tools at the macro level. With minor damage to the substrate during the process, such tools can still be useful. It should be noted that Schubert et. al. [20] work was based on a steel substrate which exhibits different thermal and optical properties compared to carbide substrate which is to be used in this study. Of concern in the current study is on the application of
the process on tools at the micro-level. For such tools, typically the 0.5 mm diameter tool considered in the current study, the coating removal process is comparatively more crucial and challenging since any minor damage to the substrate (due to increase in number of pulse) makes the tool unusable. Hence, the aim of the current research was to investigate the excimer laser removal of TiN from coated tungsten carbide (WC) micro-milling tools. The feasibility of using probe beam reflection and laser plume emission spectroscopy for online monitoring of TiN decoating from coated micro-tools was also explored. Process monitoring and control is important because of the critical nature of the process.

2. Experimental procedure, results and discussion for laser decoating

The samples for decoating were cutting tools typically used for micro-milling of hardened material. The tools, as depicted in Fig. 1, were of 0.5 mm diameter, 1 mm flute length with two flutes; and the shank of the tool was 3 mm diameter and 35 mm long. These (WC) flat end mills were obtained in uncoated condition from UNION TOOLS and was coated with 2 μm thick TiN coating by closed field unbalanced magnetron sputtering ion plating [21].

The decoating trials on the micro-tools made use of a GSI IPEX 848 excimer laser with an output wavelength of 248 nm, pulse duration of 16 ns and maximum energy of 550 mJ. The experiments were carried out at room temperature and atmospheric pressure. A rectangular output laser beam was passed through an aperture mask to obtain a region of uniform fluence and then imaged onto the target using a fused silica lens. In doing so, care was taken to minimise damage to substrate materials during laser decoating process. Precisely controlled pulsed laser decoating conditions were conceived as an important requirement for a complete removal of a coating without damaging the substrate. To identify process conditions, pilot tests were started on flat plates of tungsten carbide substrate that were coated with TiN coating. Process development was then extended to the TiN coated WC micro-tools. The two experimental stages carried out are discussed in the next sections; and in each case, the laser decoated samples were analysed using scanning electron microscopy (SEM), elemental energy dispersive spectroscopy (EDX) and a white light optical interferometer (Wyko NT1100) to characterise the laser decoating properties.

2.1. Stripping of TiN coating from a flat plate substrate

Before performing laser stripping on actual micro-tools, and also to minimise or avoid any damage to the tool material, initial experiments were carried out on flat plates. The experiments served to check the viability of the laser stripping process and to predict the laser process parameters that will give best performance. Flat WC plates (similar material to the cutting tool) of 50 x 50 x 10 mm³ with 2 μm thick TiN coating (coated under identical conditions to the micro-tools) were used as the workpiece. An experimental setup as illustrated in Fig. 2 was used to perform laser stripping on the flat plates. The lens used was a cylindrical lens of focal length 200 mm. An aperture mask of 4 mm by 4 mm was used and the distance between optics was arranged to obtain beam geometry of 4 mm by 0.2 mm over the workpiece surface, with 0.2 mm dimension along the scanning direction.

The experiments on the flat plates were in the first instance carried out using a stationary laser beam to evaluate the ablation threshold. Then linear tracks were performed by moving the workpiece. A combination of various laser decoating parameters (fluence, number of pulses and frequency) were investigated in order to identify the resulting ablation depths, which were measured using a Wyko white light optical profiler.

The resulting change in ablation rate (μm/pulse) of the TiN coating and WC substrate with respect to laser fluence, F is shown in Fig. 3. As shown in Fig. 3, the ablation rate strongly depends upon the laser fluence.

The ablation rate d can be related to the threshold fluence Fr by equation 1, which is Beer-Lambert’s law [22], where z is the effective absorption coefficient.

\[ d = \frac{1}{z} \ln \left( \frac{F}{F_r} \right) \]
By fitting the experimental results in Fig. 3 to equation (1) an ablation threshold of 1.62 J/cm² for the TiN coating and 2.36 J/cm² for the WC substrate were found. This suggests that fluence values greater than 1.62 J/cm² and less than 2.36 J/cm² should be applicable for the safe removal of the coating without substantial damage to the substrate. Above the ablation thresholds the ablation rate increases rapidly for both the coating and substrate.

Using the established ablation threshold values as reference, further experiments this time with a moving beam were carried out on the flat plates for various parameters of fluence, frequency and speed in order to identify the best parameters for quality removal of 2 μm thick TiN coating along a linear laser track. Fig. 4 shows the variation of ablation depth (μm) with laser scanning speed for a constant fluence of 2 J/cm² and a pulse repetition rate of 25 Hz. As can be seen from the figure, the required ablation depth of 2 μm is obtainable at a speed of 0.02 mm/s. This combination of parameters (fluence = 2 J/cm², frequency = 25 Hz and speed = 0.02 mm/s) was hence considered as the best operating condition for the removal of the 2 μm thick TiN coating from the WC substrate. Under these conditions the optimal number of pulses per spot was calculated from Eq. (2) to be 250.

\[ N_m = \frac{L_m \times v_m}{S_m} \]  (2)

where, \( N_m \) is the number of pulses given per spot in the scanning direction, \( S_m \) is the scanning speed of the moving laser beam (mm/s), \( L_m \) is the spot size in scanning direction of the moving laser beam (mm) and \( v_m \) is the frequency of the moving laser beam (Hz).

Figs. 5(a) and (b) show the ablation depth and surface morphology, respectively, of the laser stripped linear track over TiN coated WC flat plate. While Fig. 5(a) indicates the achieved ablation depth of 2 μm for the established best operating condition. The achieved surface roughness was 0.35 μm Ra.

2.2. Stripping of micro-tools

Having established the optimal parameters for the decoating TiN from flat plates, the experimental process was then extended to stripping of TiN from the coated WC micro-tools. The workstation used for micro-tool stripping process had three translation axis and one rotational axis. As shown in the Fig. 6 the tool was held in a chuck and aligned, such that the axis of rotation of the tool and the central axis of the laser beam were exactly perpendicular to each other. In this experiment the tool was rotated at 10 rpm.

The micro-tool stripping experiments were carried out using the established parameters obtained in flat plate stripping. The laser beam size of 4 mm by 0.2 mm, similar to the one used in the flat plates stripping experiments was used in the micro-tool stripping experiments. This beam size was to ensure that the tool flute body is fully under laser irradiation. On the other hand, it would also reduce uneven heat accumulation; and moreover, the edge effect that may be produced due to the small overlaps of multiple tracks [23] can be eliminated thus reducing the chance of producing ripples over the surfaces. The vital parameter towards a complete and effective stripping of the 2 μm thick TiN coating from the micro-tool is the total number of pulses, \( N_t \), through which the coating can be removed; and this can be evaluated from...
the equation 3.

\[ N_t = \frac{n}{C^2 T} \]  

where \( n \) is the frequency (Hz) and \( T \) is the total time (s) which is defined by equation 4.

\[ T = \frac{T_1}{C^2 n} \]  

where \( T_1 \) is the time (s), taken for one revolution of the tool with a constant rotational speed and \( n \) is the total number of revolutions, through which the tool has to rotate during the process. \( n \) can be evaluated from the equation 5.

\[ n = \frac{N_m}{N} \]  

where \( N_m \) is the total number of pulses per spot, which as established from the flat plate stripping experiment (this was 250 in the case considered) and \( N \) is the number of pulses over a region for one revolution of the tool, which is defined by Eq. (6).

\[ N = \frac{L}{S} \]  

In Eq. (6), \( L \) is the spot size in feed direction (mm), \( v \) is the frequency (Hz). The optimal values for these parameters as established also from the flat plate stripping experiment are 0.2 mm and 25 Hz, respectively. \( S \) is the linear scanning speed (mm/s) of the laser beam over the micro-tool and is defined by equation 7.

\[ S = \frac{C}{T_1} \]  

where \( C \) is the circumference (mm) of the 0.5 mm diameter micro-tool and \( T_1 \) is the time (s), taken for one revolution of the tool.

From calculations using the combination of eqns. (3–7) a value of \( N_t = 1950 \) was obtained. The total number of pulses of 1950 should be suitable for removing 2 \( \mu \)m thick TiN coating from a 0.5 mm diameter micro-tool, at a fluence of 2 J/cm\(^2\), constant rotation speed of 10 rpm and a pulse repetition rate of 25 Hz. Laser stripping experiment was carried out using the calculated parameters and for comparison, surface morphologies of the tool before and after laser stripping are shown in Figs. 7(a) and (b), respectively. Even in high magnification the decoated tool showed excellent edge definition. Moreover the cutting edges after stripping were of comparable quality to those on a new tool.

The surface finish of the decoated tool (measured using Wyko white light optical profiler along the shank of the tool) was found to be in the range of 0.3–0.33 \( \mu \)m Ra (which is very close to the one obtained after decoating a flat plate). The corresponding ranges for the uncoated and coated surface were 0.15–0.18 \( \mu \)m Ra and 0.2–0.22 \( \mu \)m Ra, respectively. It is important to mention at this point that the measured surface roughness value of the decoated tool was well within the permissible range [24] reported for high speed machining.

To confirm the complete removal of the TiN coating, elemental EDX analysis was performed on the micro-tool surface before and after stripping. Fig. 8(a) shows the spectrum taken on the surface of the cutting tool before decoating which is rich in Ti and N. The EDX spectrum taken after stripping is shown in Fig. 8(b), which clearly indicates the removal of the TiN by the absence of any peak related to Ti. The large peaks of W and C confirm that the underlying layer has been exposed.

3. Online monitoring of laser coating removal process

Once the best parameters for stripping the TiN coating from micro-tool have been established, two online monitoring systems were developed using probe beam reflection (PBR) and laser plume emission spectroscopy (PES).

![Fig. 7. Surface morphology of the decoated micro-tool (a) before and (b) after decoating (decoating parameters: fluence=2 J/cm², frequency=25 Hz, rotational speed=10 rpm, total number of pulses per position=250 and number of pulses=1950).](image)
3.1. Online monitoring using probe beam reflection system

In order to understand the laser coating removal process and for process quality control, an in-process probe beam reflection diagnostic system was developed based on probe beam reflection (PBR). Fig. 9 shows a schematic representation of the experimental setup for probe beam reflection system.

The PBR monitors the change in the intensity of the reflected light source [25] from a material surface. This change in intensity of the reflected light source (during laser stripping) can be calibrated and the laser stripping process can be monitored and subsequently controlled. In this experiment, a CW HeNe laser with a wavelength of 632.8 nm and a beam diameter of 3 mm was used as a light source. The HeNe laser beam was focused by a BK7 lens (focal length 20 mm) approximately normal to the surface of the micro-tool within the imaged excimer laser spot. Since the excimer laser beam was wide enough, the HeNe laser beam was focused at end of the flute (taper shank) where the tool surface is uninterrupted. This was to avoid the scatter of HeNe laser beam which could have resulted if it was to be focused on the tool flute. The reflected light from the tool surface was then focused using another BK7 lens (focal length 15 mm) into an Osram BPX65 photodiode in order to increase measurable intensity. The output signal from the photodiode was then recorded using a LeCroy Waverunner digital storage oscilloscope and used for monitoring the stripping process. During the laser stripping process, the change in reflected intensity of the probe beam and the corresponding signal in the photodiode were monitored for each pulse.

Fig. 10 shows the change in normalised reflected intensity of the material for various numbers of pulses per spot and fluence. The pulse per spot is the actual number of pulses delivered in one spot, rather than the total number of pulses (1950) that is scattered over the circular tool. In the Fig. 10 the y-axis with values of 1 and 0 corresponds to the normalised reflected intensity of TiN and WC, respectively. Prior to the start of decoating process, the photodiode showed reflected intensity values corresponding to F (intensity value corresponds to TiN). As the laser decoating process begins, the reflected intensity sharply increases for the first few numbers of pulses per spot, which is possibly due to the removal of any contaminants or dust over the TiN surface. As the laser decoating process continues, the reflected intensity starts to decrease rapidly with increase in number of pulses per spot. Once the reflected intensity reaches close to G (intensity value of 0), it was assumed that the TiN coating was removed and the laser pulse should be stopped to avoid any damage for the WC substrate.

As seen from the Fig. 10, for fluence values greater than threshold fluences (2–6 J/cm²), the rate of change in reflected intensity increases with increase in laser fluence. For a fluence of 2 J/cm² it takes approximately 250 pulses per spot to bring the reflected intensity from 1 to 0 which corresponds to complete removal of TiN coating. This supports the findings in section 3.1 (for a fluence of 2 J/cm², 250 pulses per spot is required to remove the TiN coating). The number of pulses per spot required to remove the coating reduces from 250 for a fluence of 2 J/cm² to 90 and 50 for a fluence of 4 J/cm² and 6 J/cm², respectively. These values also reflect the findings in Fig. 3, from which it should take approximately 222, 80 and 44 pulses per spot for removing the 2 μm thick TiN coating with a fluence of 2, 4 and 6 J/cm², respectively. As seen from the Fig. 10, the change in reflected intensity was very low for fluence less than 1.5 J/cm² even after 800 pulses per spot (A and B in Fig. 10). This confirms the minimum ablation threshold of 1.67 J/cm² for effective removal of TiN coating as discussed in Section 3.1.

3.2. Online monitoring using laser plume emission spectroscopy (PES)

During the laser stripping process, the laser pulse which incindent the surface of the tool produced a plasma plume [26].
This gave rise to bright emissions, which extended up to a few millimetres from the surface of the tool. It is often the case that this emission contains information regarding the molecular species and atoms in the plasma plume. This information was used for distinguishing the spectra produced during the irradiation of TiN coating and WC substrate. As shown in Fig. 11, for the plume emission spectroscopy (PES) the probe beam and photodiode in the PBR system were replaced by an Ocean Optics HR4000 spectrometer. Accessing the elemental spectra, was done through the use of a fused silica lens (focal length 100 mm), with which the scattered emission was imaged at 45° onto an optical fibre, which in turn was coupled to a spectrometer. In order that the excimer radiation was eliminated from the sensor, a UV filter (< 360 nm cut-off) was positioned before the fibre.

The spectra produced by the scattered plasma radiation for each pulse was recorded with the spectrometer and Fig. 12 (a) and Fig. 12 (b) show the results recorded at 150 and 1950 pulses, respectively which correspond to approximately 20 and 250 pulses per spot. Following the discussion in Section 3.2, relating to ablation characteristics, it was deduced that these spectra characterise the TiN coating and the WC substrate. From the literature [27], the emission peaks in Figs. 12(a) and (b) were identified to be of titanium, nitrogen, tungsten, cobalt and carbon.

Fig. 10. Change in reflectivity with the number of pulses per spot for different laser fluences.

Fig. 11. Schematic illustration of the experimental setup of the plume emission spectroscopy (PES) system for online monitoring of coating removal.

Fig. 12. Emission spectrum of the TiN coating and WC substrate recorded after 20 and 250 pulses per spot, respectively.
575.25 and 585.40 nm. However, due to the relatively low intensity of nitrogen peaks, the titanium emission peaks seemed to have dominated over the nitrogen peaks. In contrast, in Fig. 12(b), an emission spectra rich in tungsten and few peaks of cobalt and carbon is shown. Tungsten emission as can be seen from the figure occurred at wavelengths of 388.14, 406.99, 410.27, 421.93, 429.46 and 498.25 nm while cobalt and carbon traces were found at 374.55 and 505.21 nm, respectively. These spectra gave a fair idea of the change of elemental composition with increase in number of pulses. This indicates that the online information obtained during laser processing can be exploited to control the number of pulses required for removing the coating irrespective of the coating thickness and compositions. However, the PES method needs further research towards the generation of standard spectra that could be compared to spectra obtained with the ablation process.

4. Conclusions

A novel method of removing TiN coatings from WC micro-tools has been successfully demonstrated using an excimer laser. The coating is removed without noticeable damage to the base material. The process is more environmentally friendly compared to conventional chemical methods. The ablation threshold of TiN and WC were found to be 1.62 and 2.36 J/cm², respectively. The best decoating parameters for 0.5 mm diameter TiN coated micro-tools were found to be a fluence of 2 J/cm², a frequency of 25 Hz and applying 1950 pulses. Two online monitoring systems for decoating of TiN coating were established using probe beam reflection and plume emission spectroscopy. Both systems have the potential to be used for controlling the laser stripping process of TiN from WC coated micro-tools. The PBR method enables a general assessment and removal depth monitoring of the decoating process while the PES can be exploited to shed light on the elemental composition of the surface. The PES is found to be interesting because in practice most coatings are multi-component and multi-layered and also contain a thin bonding layer. Thus, PES presents opportunities for selective removal of layers, or using the layer structure to track decoating process. The challenge for the plume emission spectroscopy system is the need to have a reliable information base for identifying the element emission peaks. While the utility of the probe beam reflection method is that it is easier to calibrate and implement without recourse to databases.

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