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Research Article

SEM and EDS Characterisation of Layering TiO_X Growth onto the Cutting Tool Surface in Hard Drilling Processes of Ti-Al-V Alloys

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Scanning electron microscopy (SEM) has been used to identify and analyse the secondary adhesion effect precursors formed during the dry drilling processes of Ti-6Al-4V alloy over the rake face and flute of the drilling tools. Subsequent analysis with energy dispersive spectroscopy (EDS) was enabled to distinguish its compositional characteristics. Thus, according to the EDS obtained data, a stratified multi built-up layer (MBUL) composed by TiO_x is formed over the rake face of the tool. Furthermore, this multi-layer adhered allows initially the built-up edge (BUE) development close to the edge of the tool by a mechanical adhesion mechanism. In a second step, it is responsible for the formation of a thicker secondary BUL which avoids the chip flow, and it provokes the tool collapse. These mechanisms are different from those observed in the dry machining of other alloys such as steels, nickel-based alloys, or aluminium alloys.

1. Introduction

Nowadays, light alloys, mainly aluminium and titanium-based alloys, are wide and commonly applied for building structural components of aircrafts and aerospace vehicles, due to the excellent relationship weight/cost/mechanical properties [1–7]. Generally speaking, said components must be hardly controlled in all their aspects in order to guarantee a perfect behaviour in service [8–10]. Most of the functional properties of the aerospace alloys are influenced by the changes in the surface integrity due to the manufacturing processes. Because of this, the surfaces finishing have to respond to high quality requirements [5, 8, 9]. Thus, manufacturing processes must be carefully designed and carried out in order to avoid both dimensional and geometrical deviations [5, 11].

On the other hand, aeronautical parts production usually involves different types of material processing operations. Because of assembly necessities, one of the most common of such operations involves removal material processes, particularly, drilling [3, 11].

Cost-effectiveness objectives force to work with low cost cutting tools, using standard commercial cutting tools, if possible, applying high performance feeds and cutting speeds, and maximising the duration of the tool. The most common procedures for enlarging the tool life take account of the use of cutting fluids, habitually playing a double role: on one hand, coolant, diminishing the cutting temperature; on the other hand, lubricant, decreasing the friction effect in the tool-workpiece interface. However, environmental laws recommend avoiding to cut fluid because most of them have a nondesirable environmental impact and/or can cause damage to human health [12, 13]. Thus, although these fluids can increase tool life, the current dominant trend in machining processes consists in avoiding their use [12, 14, 15]. Because of this, dry or near to dry based on the use of the minimum quantity of lubricant (MQL)-machining processes are designed and carried out [3, 14–20]. As a consequence of all that, high research efforts are currently being made in order to optimise tool life in highly aggressive conditions. Firstly, some of these research lines are focused on the particular analysis of the tool life influence variables in order to have a solid evaluation criterion.

Tool life is commonly evaluated through parameters defined from criteria based on tool wear for a specific machining process. Thereby, tool wear can be considered as a first reference of tool life [19, 21, 22]. So, cutting tool wear study is one of the most relevant analysis that can be made in order to characterise tool life and, as consequence of this, to predefine cutting conditions for obtaining a high degree of optimisation in a cutting process.

Different mechanisms can be responsible for the tool wear in a determined cutting process. Usually, those mechanisms do not act separately, but furthermore, their combination is multiplied synergically [19, 21–23]. However, in order to know the importance of each mechanism, it is necessary to study each one of them separately.

In this work, scanning electron microscopy (SEM) has been used for both analysing and identifying secondary adhesion mechanisms that are taking place when an aeronautical titanium alloy is machined. Special severe cutting conditions have been applied. Thus, titanium alloy has been dry machined with TiN-covered tools. Special attention has been paid to the built-up layers formed during the dry drilling processes of Ti-6Al-4V alloy. A further analysis with energy dispersive spectroscopy (EDS) has been made in order to reveal its compositional characteristics. Previously, a review of the main secondary adhesion wear mechanism reported by different researchers has been achieved. The differences between these mechanisms have been also exposed.

2. Secondary Adhesion Wear of Cutting Tools

Adhesion wear is one of the mechanisms that operate in a wider range of cutting temperatures [21, 23]. This kind of tool wear can be produced by two different ways. On one hand, direct adhesion wear is caused by the incorporation of tool particles to the chips by the action of the forces developed in the interface tool-machined material. On the other hand, secondary (also called indirect) adhesion wear is caused by the incorporation of fragment of the workpiece material to the tool. When these fragments are removed, they can drag out tool particles causing tool wear, not only by the loss of tool material but also by the abrasion process due to the friction of those particles with the tool rake face when they are dragged by chip.

Figure 1 plots the intensity of tool wear, δ (arbitrary units), as a function of the cutting temperatures, T, for the two different adhesion wear forms. As it can be deduced from the observation of this figure, the intensity of indirect adhesion wear is higher at lower temperatures. So, it can be expected that indirect adhesion be revealed in the first instants of the machining process. On the other hand, at medium and high temperatures both effects show similar intensities although in the cases where indirect adhesion is produced the direct adhesion is hardly observed [23].

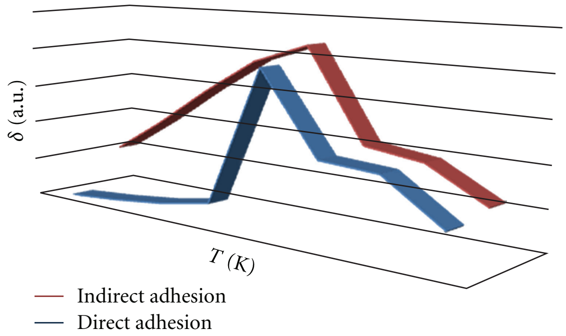


Figure 1: Indirect adhesion wear of cutting tools (arbitrary units) as a function of cutting temperatures.

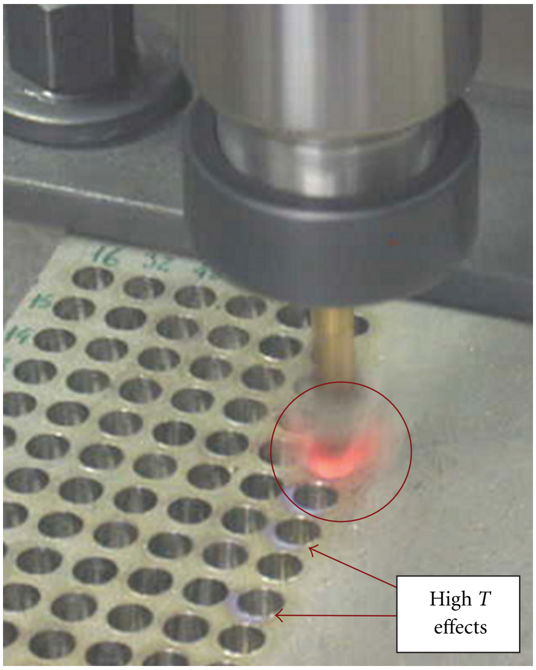
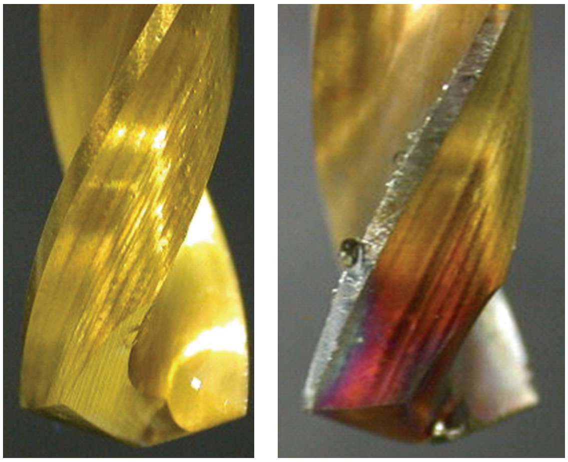


Figure 2: Ti chips combustion during a dry drilling process. Notice the coloured circles around the holes caused by the high cutting temperatures.

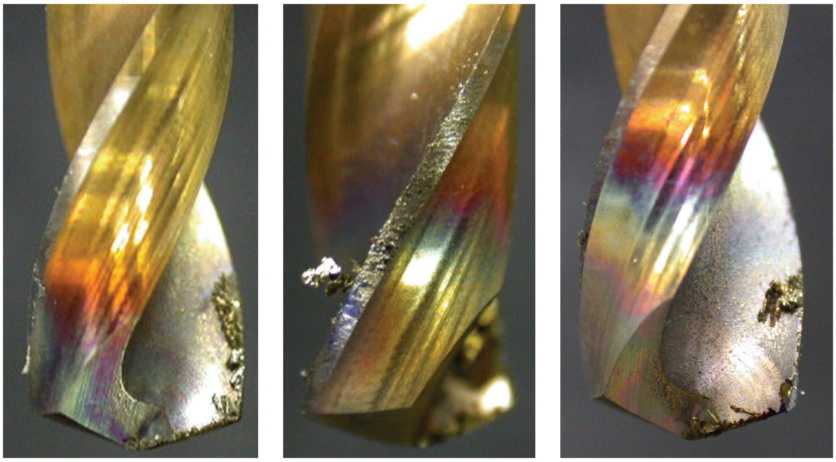
Indirect adhesion can be localised in two zones of the cutting tool: the tool edge, giving rise to built-up edge (BUE), and the tool rake face, giving rise to built-up layer (BUL) [22, 24]. Results reported in the research works on the origin of BUL and BUE revealed that BUL and BUE formation mechanisms are usually different depending mainly on both tool and workpiece materials. Thus, thermal conductivity of tool material is specially related with temperature-based adhesion effects. In effect, low thermal conductivity can produce a high increase of temperature in the chip-tool interface giving rise to changes in the material properties and favouring the adhesion. On the other hand, thermal and mechanical properties of workpiece material are critical in the secondary adhesion mechanisms. In effect, some of previous investigations about secondary adhesion in machining processes of different materials have stated the influence of the worked material on these phenomena.

So, when carbon steels or stainless steels are machined, a mechanical adhesion process takes place in the edge zone, giving rise to a BUE formation [22, 24]. This BUE grows and when it reaches a critical size, then it can be plastically extended onto the tool rake face forming a BUL [24, 25]. Compositional features of BUL and BUE did not show differences in these materials. In these cases, BUL and



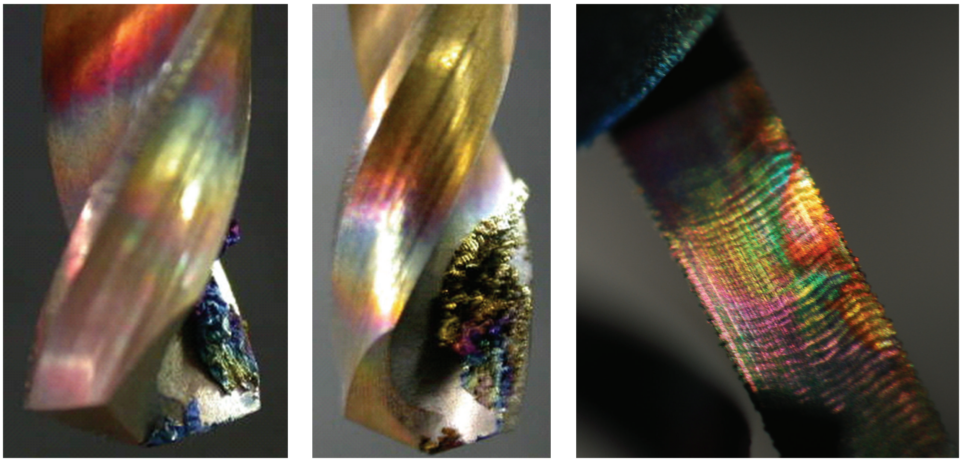
(a) (b)

Figure 3: (a) Drilling tool as received. (b) Drilling tool after drilling five holes at 30 m/min.



(a) (b) (c)

Figure 4: Evolution of the drilling tool after (a) eight, (b) ten, and (c) fourteen drills at 30 m/min.



(a) (b) (c)

Figure 5: Aspect of the drilling tool after (a) sixteen and (b) seventeen holes at 30 m/min. (c) Chips collected after dry machining of Ti-6Al-4V alloy.

Figure 6: Tool blocking caused by the accumulation of material in the chip flow zone.

BUE are wear precursors in the way that has been above commented.

However, in the dry machining of Inconel 718, although similar observations about the BUL and BUE composition can be deduced from the study included in [26], BUL is presented as a protective coating which avoids tool rake face wear, at least in the first instants of machining. In a similar way, the development of BUL and BUE has been observed in other nickel-based alloys [27, 28]. However, the machining process of Ni-based superalloys, such as Hastelloy C-22HS, only built-up edge was observed [29].

Protective layers developed onto the tool rake face have been also detected during machining process or Ca/O/S-rich steels. In these cases, a mixed diffusion-air reaction film formed onto the tool rake face can act as a protective BUL against wear [30–32].

When aluminium alloys are dry machined, the secondary adhesion wear mechanisms change, especially in that related to the BUL and BUE formation. In effect, in the machining processes of different aeronautical aluminium alloys (UNS A92024 and UNS A97050), BUE depends on the BUL formation [33–37]. Thus, BUL is quickly formed by a thermo-mechanical process: first, high local temperatures provoke a softening of aluminium matrix; second, aluminium is compressed onto the rake face and hot adhered to it; intermetallic particles have a higher melting point that Al and they remain in a solid state, being dragged out with chip [34]. Thus, BUL composition is close to pure aluminium. Once the built-up layer is formed, initial cutting conditions (tool material and geometry) change, and built-up edge is formed by mechanical adhesion with a composition very close to the composition of the alloy [34–36]. Later, when BUE reaches a critical size, it can be extruded over the tool rake face giving rise to a secondary BUL with similar compositional features that alloy. BUE-BUL evolution to high thicknesses promotes the pulling out of the adhered material, and, as a consequence of this, tool particles are swept away [33]. The influence of the tool material was also studied in those processes. Obtained results allowed concluding that when tool is covered by a refractory coat (e.g., TiN), BUL is quicker formed [18]. Some similar observations have been made by other authors on these and other aluminium alloys in different dry machining processes [14, 38–40]. On the other hand, the influence of the material thermal state was studied in [33, 37]. In these studies, a comparative analysis of the machining performance of UNS A92024 alloy in TO and T3 temper state was achieved. Results showed that TO state favours BUL-BUE formation. The surface finish of the machined pieces diminished in these cases.

All above commented states that it is necessary to analyse individually the secondary adhesion wear mechanism for each material or, at least, for each group of materials.

In particular, it is very difficult to find references about the BUL and/or BUE formation mechanisms in the machining process of titanium alloys. Only some works identify built-up edge in the dry cutting of Ti alloys, but without an analysis of the formation mechanism and without an identification of the possible built-up layer development [22, 41, 42].

So, in [43–46], tool wear mechanisms in different machining processes of Ti alloys were studied, analyzed, and identified by using SEM and EDS techniques. However tool wear was not evaluated. Reported results revealed that adhesion is one of the main tool wear mechanisms when Ti alloys are machined. Nevertheless, the adhesion effect formation is not characterized. In particular, it is very relevant that BUL is not identified, and only BUE is considered as precursor of the tool material leakage.

Some tool wear evaluations have been made in particular machining processes of Ti alloys. Thus, in the particular case of turning, in [2, 4], flank wear/cutting edge wear was evaluated. Results included in these papers showed that majority of the tool failure mechanisms were due to flank face wear and excessive adhered material on the flank edge. However, BUL was not identified and adhesion mechanism was not characterized.

On the other hand, in the case of dry drilling of Ti alloys, in a previous work, tool wear mechanisms were identified by using SEM and preevaluated by SOM techniques. BUE was identified as a precursor of the tool material leakage [3].

All previously commented reveals that it is necessary to study the BUL and BUE formation mechanisms in the particular case of the dry machining of Titanium alloys. Because of this, in this work, the main objective has been the characterization of those mechanisms in the dry cutting of Ti alloys and its differences with regard to the BUL and BUE formation mechanisms in the machining processes of other alloys. So, in this paper, the tool edge or flank fractures stay out of the aims of this work.

3. Experimental

Ti6Al4V sheets (thickness from 8 to 16 mm) were dry drilled using TiN-covered WC-Co drills. It must be noticed that although TiN coatings are not good heat conductor, this kind of tool material was employed because these Ti alloys are currently drilled as a part of fibre metal laminates (FML) structures in the airship-building industry. FML contains

(a) (b) (c)

Figure 7: Different drills showing tool wear. Notice the zones with loss of TiN coating.

carbon fibre and, commonly, these materials are dry drilled with TiN covered tools [47].

Drilling tests were carried out in an EMCO VMC-300 CNC Machining Center, equipped with a SM-810 Siemens Numerical Control. In these tests, cutting speeds from 10 to 50 m/min and feeds from 0.01 to 0.2 mm/rev were applied. Cutting speeds range is defined by the cutting conditions of FML, although it is necessary to advise that, generally, Titanium alloy is the controling material in the machining operations of CF/Ti FMLs. The cutting process was monitored by combining the use of a digital camera for visual inspection in the CNC machine tool, with a stereoscopic optical microscope (SOM) for visual observation in lab after removing the tool from the tool holder. SOM analysis were carried out using a Nikon SMZ800 microscope. These visual inspections were achieved each 1, 2, 5, and 10 holes.

Additionally, the surface microstructure of the cutting tools after drilling was deeper studied by applying scanning electron microscopy (SEM) techniques through a QUANTA 200 and JEOL 800 electron microscopes. Moreover, the compositional features of the adhered material to the tool surface and the compositional changes of the tool material after working were analysed by energy dispersive spectroscopy (EDS) techniques, using an EDS analysers LINK 10000 and EDAX attached to the cited microscopes, respectively. SEM and EDS have been successfully used for similar studies in other alloys [34, 35, 48].

4. Results and Discussion

As it has been aforementioned, TiN-coated tungsten carbide tools are not good thermal conductor. This fact is especially relevant when dry machining processes are carried out [3, 49]. Because of that, heat energy is quickly and continuously accumulated in the tool-chip contact zone, and, consequently, temperature also increases quickly and continuously in the tool-chip interface. In the dry drilling processes, the heat transmission can be seen even more obstructed in the inside of the holes, giving rise to a higher increase of the temperature in the cutting zone [3, 47]. This increasing is critical when titanium-based alloys are machined because titanium is highly reactive in presence of oxygen when temperature is higher than 750 K [3]. In these conditions, small volumes of Ti can have a combustion reaction, as it occurs in the case of the Ti alloy chips, Figure 2. Effects of high temperature can be also observed in the characteristic dark blue-magenta circles around the holes in

Combustion of titanium is simply an quick exothermal oxidation reaction. The titanium oxidation reaction effects must also be detected in the tool surface. In effect, after some few drills (the exact number depends mainly on cutting speed), tool rake surface and drill flute appear coloured. Figure 3(a) shows a TiN-covered WC-Co drilling tool as received, before being used in a dry drilling process of Ti6Al4V alloy. The changes in this cutting tool after five drills at 30 m/min can be observed in Figure 3(b). In effect, the surface closer to the tool bottom seems to be turned blue and magenta in a similar way that the zones around the holes in the workpiece. This fact is more intense and extensive when cutting speed is increased. All this can drive to take into consideration the possibility of a deposition of titanium oxide onto the rake face and the flute of the drilling tool. This fact was observed by Cantero et al. in [3], but it was not explained.

On the other hand, when the drills number is increased, an iridescence process seems to take place onto the tool surface. Figure 4 shows the evolution of the drilling tools after eight (a), ten (b), and fourteen drills (c) at 30 m/min. As it can be observed in this figure, the tool is iridised in a higher surface as the number of drills is increased. On the other hand, external face of the drill is also coloured.

It must be also noticed that a higher amount of workpiece material seems to be adhered to the tool edge and to the drill flute as the number of holes is increased. So, it can be supposed that iridescence (or, even initial coloured effect) which perhaps may be related to the titanium oxide formation is the precursor of the secondary adhesion effects,

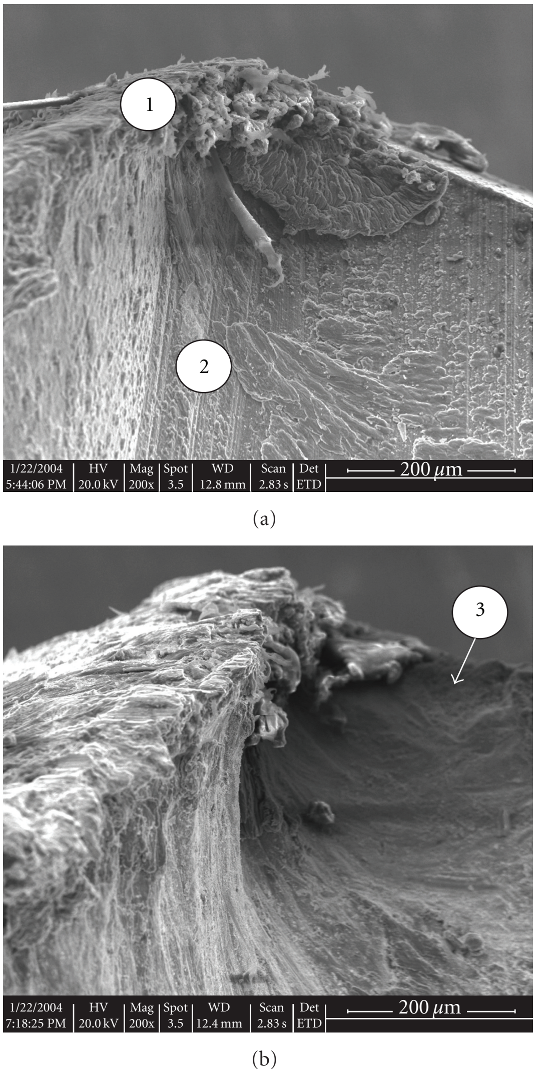


Figure 8: SEM images of the coloured zone close to the sharp end of two drills after (a) 25 holes and (b) 30 holes. Cutting speed, 20 m/min.

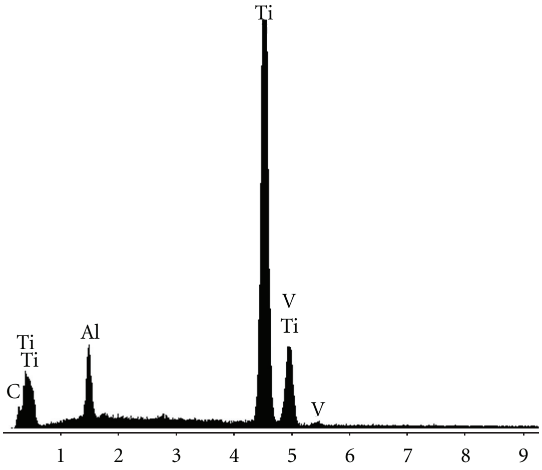


Figure 9: EDS microanalysis of the adhered material marked as 1 in Figure 8.

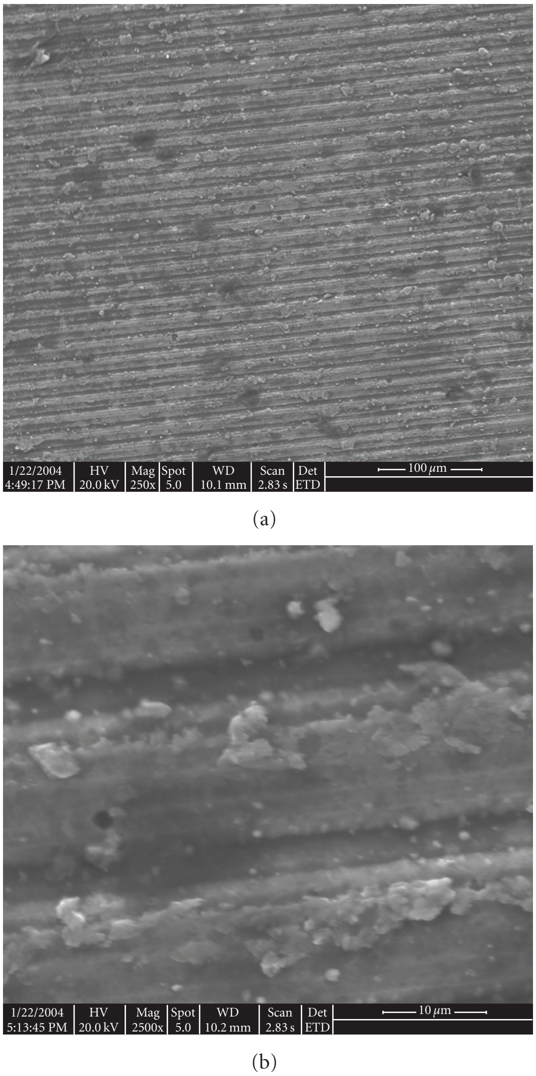


Figure 10: Enlarged SEM images of the zone marked as 2 in Figure 8. Notice the film superposition.

and it facilitates their formation. Additionally, initial traces of abrasive particles can be distinguished onto the flute surface.

A higher intensity in those adhesion effects can be appreciated in the macrographs included in Figures 5(a) and 5(b), acquired on a drill for a higher (16, 17) number of holes. In particular, the amount material adhered on the flute surface has grown, and it shows an iridescence similar to that shown by the tool surfaces. This makes to think that titanium chips combustion must also show similar signs. In effects, Figure 5(c) includes samples of the chips collected after dry drilling process of the Ti-6Al-4V alloy.

On the one hand, when material adhered in the drill flute grows to a critical size, it can obstruct the way of the chip flow giving rise to the tool blocking, as it can be observed in Figure 6. On the other hand, when adhered material is removed by the chip flowing in the tool rake face, particles of the tool can be dragged out. In the case analysed in this

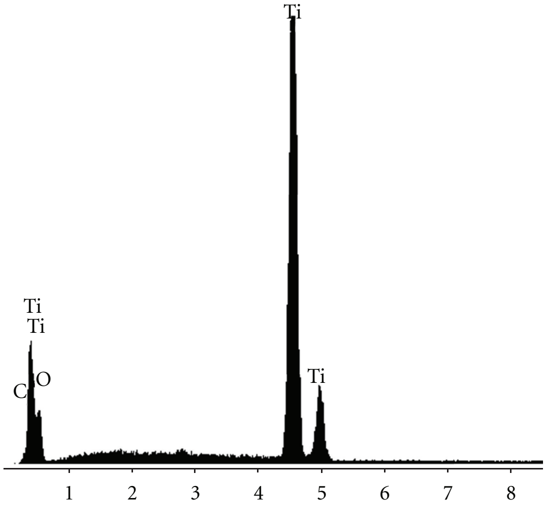
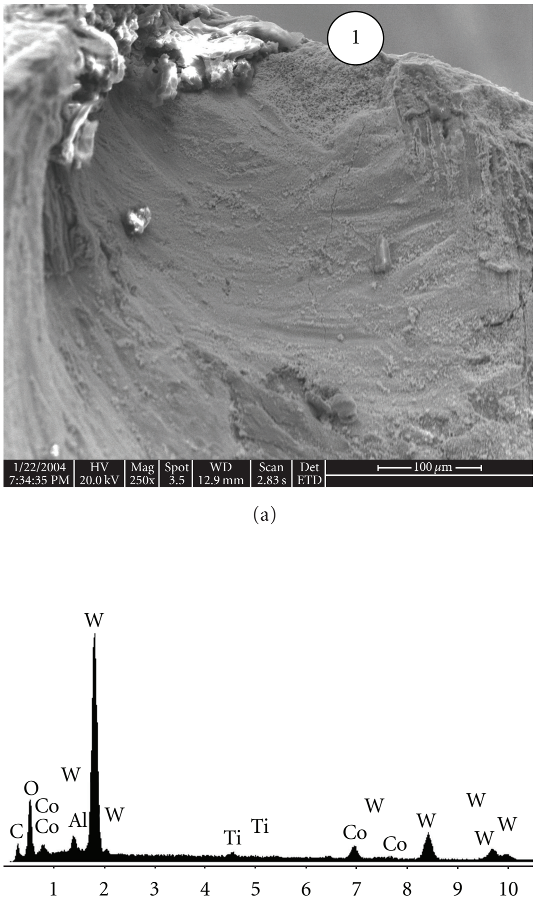


Figure 11: EDS spectrum acquired on the surface showed in the SEM image pictured in Figure 10.

work, this fact involves a loss of TiN coating, causing a more intense tool wear, Figure 7.

Hypothesis about titanium oxides developed during the drilling process by the metal oxidation reaction and its influence in the geometrical, microcompositional and microstructural tool changes can be studied by applying scanning electron microscopy (SEM) techniques combined with energy dispersive spectroscopy (EDS) analysis [34, 48]. In this sense, changes in different zones of tool surface were characterised by SEM and EDS. Figure 8 includes SEM images of the coloured zone close to the sharp end of two drills after working at 20 m/min (Figure 8(a) after 25 holes; Figure 8(b) after 30 holes). Looking at this figure, it can be observed that tool surface is clearly coated in the studied zone. On the other hand, a high accumulation of material can be detected in the tool tip. As it has been aforementioned, this material is adhered after the coloured coating is formed and its adhesion is promoted by the presence of that film, which impedes the well flowing of the chip. An EDS microanalysis of this adhered material, marked as 1 in Figure 8, revealed that its composition is the same as the alloy, Figure 9. This fact allows concluding that, as it had been supposed, chip material (workpiece material) is directly adhered in this zone. It is necessary to take into account that EDS included in Figure 9 has been obtained in both average and spot forms in different points of the zone. So, this spectrum is representative of the microcompositional characteristic of the adhered material in the edge zone (BUE).

Coming back to the coating detected in the flute, marked as 2 in Figure 8, enlarged SEM images of this zone have been included in Figure 10. Looking at this figure, it can be also appreciated that this layer is formed by a superposition of different films. In the measurement range of the SEM microscope, all seems to indicate that each individual film has approximately a similar thickness, Figure 10(b). These stratified films have been detected in the different tests developed, and the images included in Figure 10 are representative of the BUL observed in the tool rake face.



(a)

(b)

Figure 12: (a) SEM image of the coloured zone close to the sharp end of a drilling tool after working 35 holes at 20 m/min. (b) EDS analysis in the point marked as 3 in Figure 8(b) and in the one marked as 1 in Figure 12(a).

Compositional features of these stratified layers have been analysed by using EDS techniques. Figure 11 plots a characteristic EDS spectrum acquired as in spot as in average form on the surface recorded in Figure 10(a). As it can be observed in this spectrum, the multilayer formed onto the tool surface can be considered mainly composed by titanium oxide. In the same way as the other spectra, this is a representative spectrum of the MBUL.

According to the above commented, it can be supposed that titanium oxide films are formed because of the cutting temperatures in the cutting zone, which are sufficiently high for provoking the titanium oxidation reaction [3]. Initially, a very thin layer is formed, over which other layers are deposited step by step giving rise to the so-called multi built-up layer (MBUL) as a new form of the adhesion effect known as built-up layer (BUL), with a mechanism of formation very different of that identified in other alloys [24–45]. This stratified titanium oxide multilayer disposition originates the iridescent appearance of the tool surface by two combined effects: first, the own oxide colour and, secondly, the prism effect of the multithin films.

On the other hand, these coatings modify the tool surface, and they provoke the final adhesion of the alloy material to the different zones of the drill (Figure 5). Thus, it can be responsible for the chip flow block which can produce the final collapse, Figure 6. On the other hand, secondary adhesion processes can provoke tool wear, as it can be distinguished in Figure 7.

The loss of TiN coats in the drill can be distinguished in SEM images included in Figures 8(b) and 12(a) (acquired in a tool after drilling 35 holes). EDS analysis in the point marked as 3 in Figure 8(b) and in the one marked as 1 in Figure 12(a) have revealed that, in effect, the composition is similar to the composition of the tool nucleus, WC-Co. Figure 12(b) plots a representative spectrum recorded on these zones, and it has been acquired in the same way as all those aforementioned. This fact states the tool wear once the adhered material is removed as it was previously demonstrated in other works [3]. Thus, according to [3, 43, 45, 47], when MBUL, BUE, and secondary BUL are removed, it carries on the TiN coating which covers the tool causing a loss of tool material.

5. Conclusions

Secondary adhesion tool wear is mainly related to the built-up edge (BUE) and built-up layer (BUL) formation and its later elimination by the chip. The analysis on the results reported in research works focused on the origin of BUL and BUE has revealed that BUL and BUE formation mechanisms depend strongly of the workpiece material. In this analysis, a lack of studies about adhesion tool wear in the machining processes of titanium alloys has been detected.

Scanning electron microscopy (SEM) combined with energy dispersive spectroscopy (EDS) analysis has allowed to study the adhesion effects that help the tool wear in the dry drilling of Ti-6Al-4V alloy. The first steps of these mechanisms are notably different from those observed in the machining of other alloys, such as steels or aluminium alloys.

Previous observation allows distinguishing iridescence onto the tool surface in the previous stage to the material accumulation which provokes the final tool blocking. SEM analysis of the iridescence zone reveals that this effect is caused by multi-built-up layers (MBULs). Subsequent analysis by EDS was enabled to determinate that those layers are formed by titanium oxides which are developed thanks to the titanium combustion favoured by cutting temperature. Light dispersion by MBUL and the own colour of titanium oxides containing films cause the iridescence.

In a second step, the multilayer adhered avoids the chip flow giving rise to a secondary material adhesion in the chip flow channel and in both the tool edge and the sharp end of the drill. EDS analysis of the adhered material reveals that it has a composition similar to the workpiece alloy. Thus, MBUL is responsible for the secondary BUL and BUE formation. When secondary BUL and/or BUE are removed and dragged out by the chip, then tool wear is clearly detected in form of a loss of TiN coating.

Finally, the accumulation of material in the edge, the sharp end, and the flute of the drill cause the tool collapse.

Acknowledgments

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