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Microstructural characterisation of material adhered over cutting tool in the dry machining of aerospace aluminium alloys

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Abstract

In this work, scanning electron microscopy has been used in order to identify the effects of adhesion on the dry turning processes of different aerospace aluminium alloys. Analysis with energy dispersive spectroscopy allows distinguishing different composition characteristics between built-up layer (BUL) and built-up edge (BUE) formation in the processes we studied. A preliminary hypothesis on the formation of BUL and BUE, taking into consideration the temperature in the region of initial deformation has been formulated. According to this hypothesis, BUL formation is preceded by a process of incipient fusion, which releases intermetallic particles. Once BUL has formed initial cutting conditions change enabling BUE formation by mechanical adhesion. Additionally, the evolution of BUL and BUE with the time of machining has been also studied.

Keywords: Tool wear; Adhesion wear; BUE; BUL; Aluminium alloys

1. Introduction

In machining processes, cutting tool life is commonly measured trough parameters defined from criteria based on tool wear [1]. So, tool wear can be considered as a first reference of tool life. Because of this, cutting tool wear study is one of the most relevant analysis that can be made in order to reach a high degree of optimisation in a cutting process [1,2].

Different mechanisms can be the responsible of the tool wear in a determined cutting process [1–3]. Usually, those mechanisms do not act separately but, furthermore, their combination is multiplied sinergically [3]. However, in order to know the importance of each mechanism, it is necessary to study each of them in a separate form.

Adhesion wear is one of the mechanisms that operates in a wider range of cutting temperatures [2]. This kind of tool wear can be produced by two different ways. On the 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 [3]. On the other hand, indirect adhesion wear is caused by the incorporation of fragment of the workpiece material to the tool [1,4]. When this fragments are removed, they can drag out tool particles causing tool wear.

Indirect adhesion can be localised in two zones of the cutting tool [4]:

1. The tool edge, giving rise to the formation of built-up edge (BUE).
2. The tool rake face, giving rise to the formation of built-up layer (BUL).

From the results reported in the research works on the BUL and BUE formation mechanisms, it can be concluded that BUL and BUE formation mechanisms can be different depending mainly on both tool and workpiece materials [4–7].

In this work, scanning electron microscopy (SEM) has been used in order to identify the effects of adhesion on the dry turning processes of different aerospace aluminium alloys, such as AA2024 (Al–Cu) and AA7050 (Al–Zn) alloys. Subsequent analysis with energy dispersive spectroscopy (EDS) enabled us to distinguish different composition

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characteristics between built-up layer (BUL) and built-up edge (BUE) formation in the processes we studied. According to these differences, built-up layer is formed practically in the beginning of the turning process and its composition is very similar to pure aluminium. On the other hand, built-up edge is formed later and there are not remarkable differences between its EDS spectrum and those acquired on the alloys.

Starting from these facts, it can be able to formulate a preliminary hypothesis on the formation of BUL and BUE, taking into consideration the temperature in the region of initial deformation. According to this hypothesis, BUL formation is preceded by a process of incipient fusion, which releases intermetallic particles. Once BUL has formed initial cutting conditions change enabling BUE formation by mechanical adhesion.

Additionally, the evolution of BUL and BUE with the time of machining has been also studied. The analysis by SEM and EDS of the tool surface after longer times of turning have revealed that BUE is growing until it reaches a critical thickness. After this, BUE is plastically deformed by the action of the forces that are present in the process. As a consequence of this, BUE can be extended over the rake face of the tool and BUL can be hidden.

2. Experimental

This work reports on a part of the results of different Research Projects between AIRBUS Spain, SL and the Materials Technology Research Group of the University of Cadiz, Spain. In some of these projects collaborates the Manufacturing Engineering Research Group of the Spanish University of Distance-Learning, placed in Madrid. These projects are focused on the optimisation of the machining of different alloys commonly used in the aerospace industry, mainly aluminium alloys.

Following the line of the aforementioned, the workpieces used in our experiments were cylindrical bars (150–200 mm long with diameters between 80 and 120 mm) of AA2024 and AA7050 alloys. The composition of this alloys was analysed by ICP. Table 1 contains the mass percentage of the main elements in both alloys.

One of the objectives proposed in the above commented projects is the optimisation of machining processes, not only from the viewpoint of the industrial cost-effectiveness, but also from ecological and environmental considerations.

Thus, machining processes carried out in this work were performed taking into consideration the use of environmentally friendly technologies [8–10]. Because of this, the employment of cutting fluids, which could give rise to healthless and toxic waste products has been avoided. So, dry machining processes were carried out. In this work, only the results from the study on the dry turning process are reported.

The cylindrical bars of the both alloys were horizontally dry turned in an EmcoTurn-242 CNC Lathe equipped with an Emcotronic TM02 Numerical Control (Fig. 1). Cutting speeds from 40 up to 200 m/min, and feeds from 0.05 up to 0.3 mm/rev were applied. Cutting depth was maintained at 2 mm in all the experiments.

The preliminary tests did not last longer than 10 s in order to analyse the mechanism of formation of the adhesion effects. Longer tests were after carried out in order to study the evolution of those effects.

The tools employed were TiN covered WC–Co turning inserts with ISO KCMW 11T308 FN M-identification.

Tool geometry is indicated in Fig. 2.

The cutting process was monitored by using a NIKON 4500 Coolpix Digital Camera.

Once the tests were completed, the surface of the tools were examined by scanning electron microscopy (SEM) through a QUANTA 200 or JEOL 800 electron microscopes (Fig. 3).

Additionally, the material that had adhered to the tool surface was analysed by energy dispersive spectroscopy (EDS) by using an EDS analyser EDAX or LINK 10000 attached to the cited microscopes (Fig. 3).

SEM and EDS techniques have been also employed for studying the alloys microstructure. As it will be shown, the alloy composition and microstructure has an special relevance in the formation of built-up edge and built-up layer.

Table 1
Composition of machined alloys (mass%)

	AA2024	AA7050
Cu	4.00	2.00
Zn	0.25	6.00
Mg	1.50	2.30
Mn	0.60	0.10
Si	0.50	0.12
Fe	0.50	0.15
Ti	0.15	0.06
Cr	0.10	0.04
Zr	Traces	0.10

3. Results and discussion

3.1. Alloys microstructure

Fig. 4 shows SEM images of different zones of the surface of a sample of the AA2024 alloy. As it can be appreciated in this figure, three types of intermetallic particles can be distinguished dispersed onto its surface.

So, looking at Fig. 4(a), it can be observed a first type of particles accumulated in a zone of the surface. SEM analysis made on these particles revealed that they are formed by a β-phase of (Al,Cu). On the other hand, particles placed more dispersedly onto the alloy surface were also observed (Fig. 4(b) and (c)). The compositions of these are different that those shown in Fig. 4(a). Thus, particles in Fig. 4(b) were identified by EDS as Al(Cu,Fe) precipitates, and particles marked in Fig. 4(c) as (Al,Fe) precipitates.

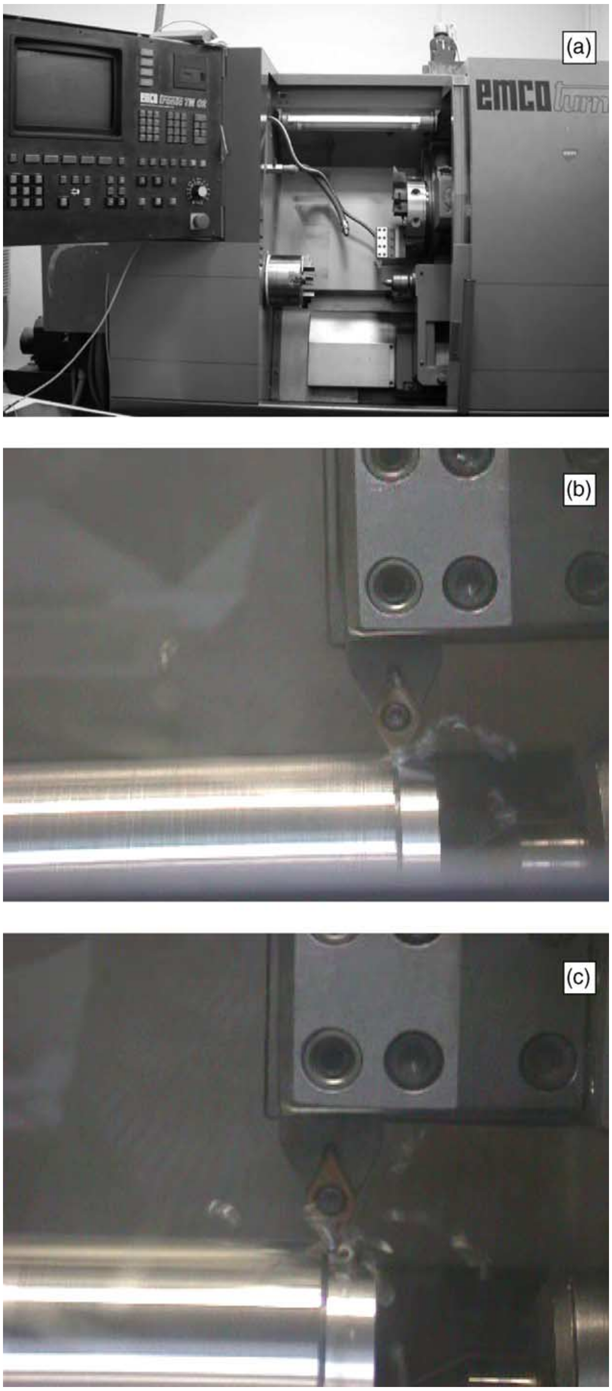

Fig. 1. (a) CNC Lathe used in the turning tests, (b) and (c) frames of the turning process. Notice the zone of the tool affected by the chip formation and flow direction.

All these intermetallic particles have a melting point much higher that pure aluminium. Therefore, if the alloy reach temperatures close to this last, particles cannot be affected and only the metallic matrix will change. This is a very important appreciation, as it can be seen later.

In the same way, alloy AA7050 was also analysed. Fig. 5 shows SEM image of a zone of the surface of a sample of this

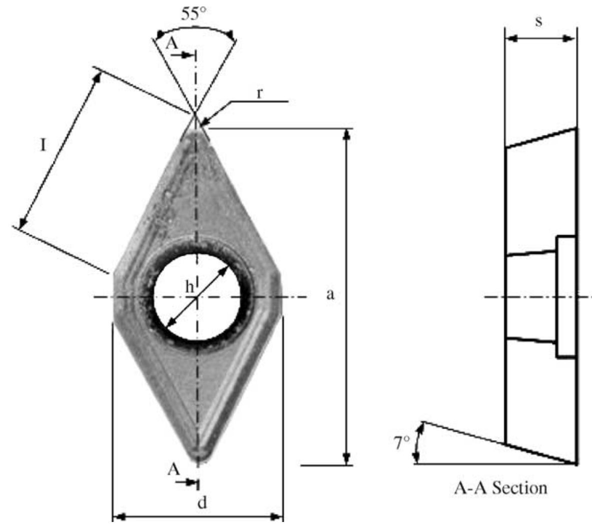

Fig. 2. Tool geometry. Parameter values: $a = 18.77$ mm; $h = 4.40$ mm; $r = 0.80$ mm; $d = 9.53$ mm; $s = 3.97$ mm; $l = 11.60$ mm.

alloy. Again, three types of particles can be distinguished with different morphology and composition.

So, in Fig. 5, it can be noticed the existence of spherical (1), globular (2) and acicular (3) particles. EDS analysis made on them revealed that spherical particles are formed by (Al,Cu,Mg); globular particles are formed by a β-phase of (Si,Mg); finally, acicular precipitates are formed by (Al,Cu,Zn).

As in the case of the AA2024 alloy, all these intermetallic compounds have a melting point much higher that pure aluminium and it will be so relevant in this study.

3.2. Short duration tests

As it has been aforementioned, short duration dry turning tests were carried out in order to identify the mechanisms, which are responsible of the formation of BUL and BUE.

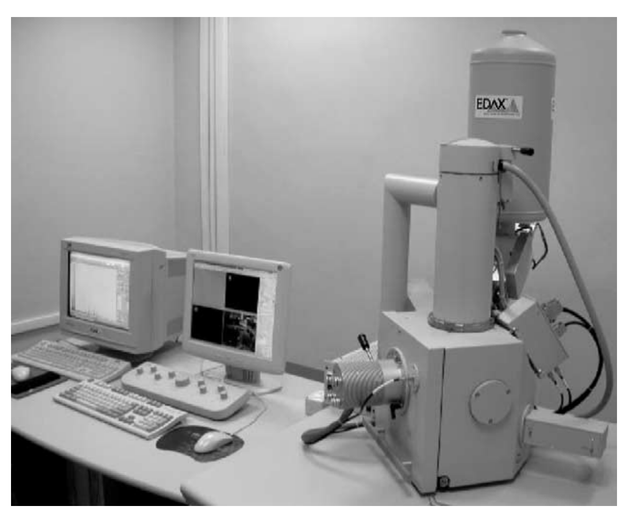

Fig. 3. SEM and EDS equipments used in the experimental stage of this work.

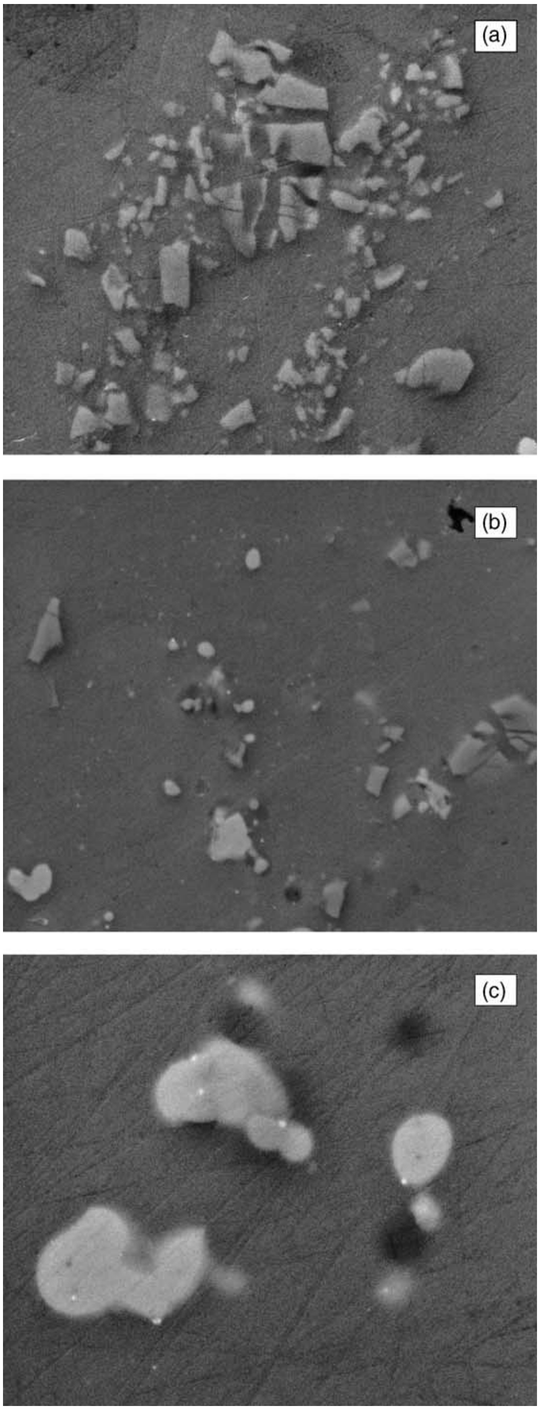

Fig. 4. SEM images acquired on the surface of a sample of the AA2024 alloy. Intermetallic particles identified by EDS as (a) β-(Al,Cu), (b) (Al,Cu,Fe), and (c) (Al,Fe).

Fig. 6(a) includes a SEM image of a TiN covered tool after turning during 10 s a cylindrical bar of AA2024 alloy at 85 m/min and 0.1 mm/rev. The transfer of material from the machined sample to the tool surface can be clearly distinguished in this figure.

In agreement with [4], two zones of transferred material can be appreciated. In the first one, the workpiece material

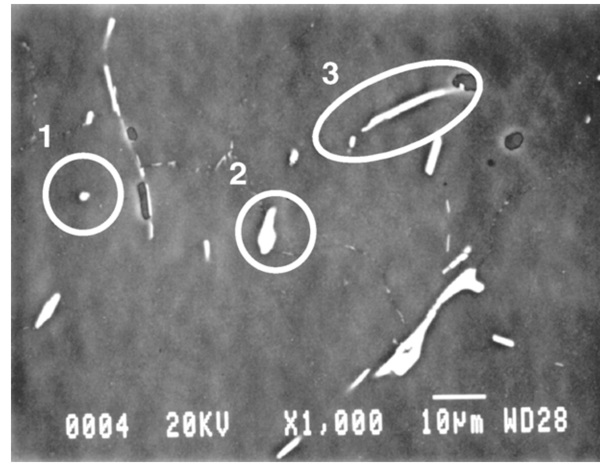

Fig. 5. SEM image acquired on the surface of a sample of the AA7050 alloy. Intermetallic particles identified by EDS as (1) (Al,Cu,Mg), (2) β-(Si,Mg), and (3) (Al,Cu,Zn).

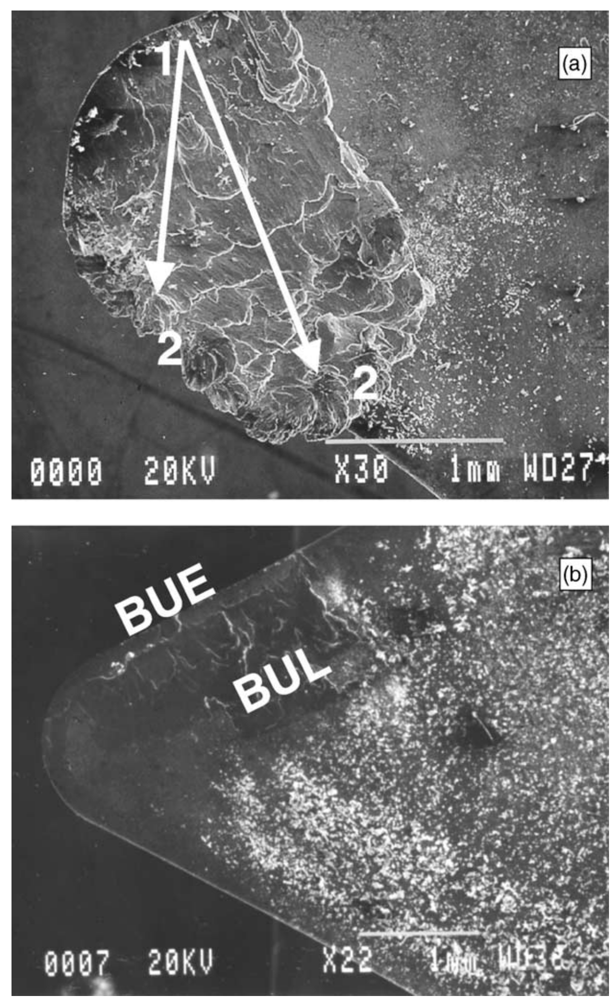

Fig. 6. (a) SEM image of a TiN covered tool after a 10 s turning process of a cylindrical workpiece of AA2024 alloy (cutting parameters: v = 85 m/min and f = 0.1 mm/rev) and (b) SEM image of a TiN covered tool after a 10 s turning process of a cylindrical workpiece of AA7050 alloy (cutting parameters: v = 170 m/min and f = 0.1 mm/rev).

is accumulated close to the tool edge, giving rise to built-up edge (BUE), whereas, in the second, it is extended on the rake face of the tool, giving rise to the so-called in [4] built-up layer (BUL).

In a first observation, a multi-layer deposition form of the workpiece material can be suggested by the SEM image of Fig. 6(a). However, the thickness does not decrease progressively in the chip flow direction, marked by an arrow from 1 to 2 in this figure. As it was demonstrated in [5,6] a single roughness analysis of the adhered material permit verifying that fact. So, as regards as [5,6], in the nearest zones to the tool edge a much higher metal seems to be accumulated, while thickness of the layer is almost constant on the rake face of the tool. In agreement with [4] this finding can be explained as if the layering increase of thickness was stopped and a change in the mechanism seems to be produced.

Similar considerations can be made after analysing the SEM image of a TiN covered tool after turning during 10 s a cylindrical bar of AA7050 alloy at 170 m/min and 0.1 mm/rev (Fig. 6(b)).

Fig. 7 shows SEM images enlarging the boundary between the two regions assigned to BUL and BUE effects in Fig. 6.

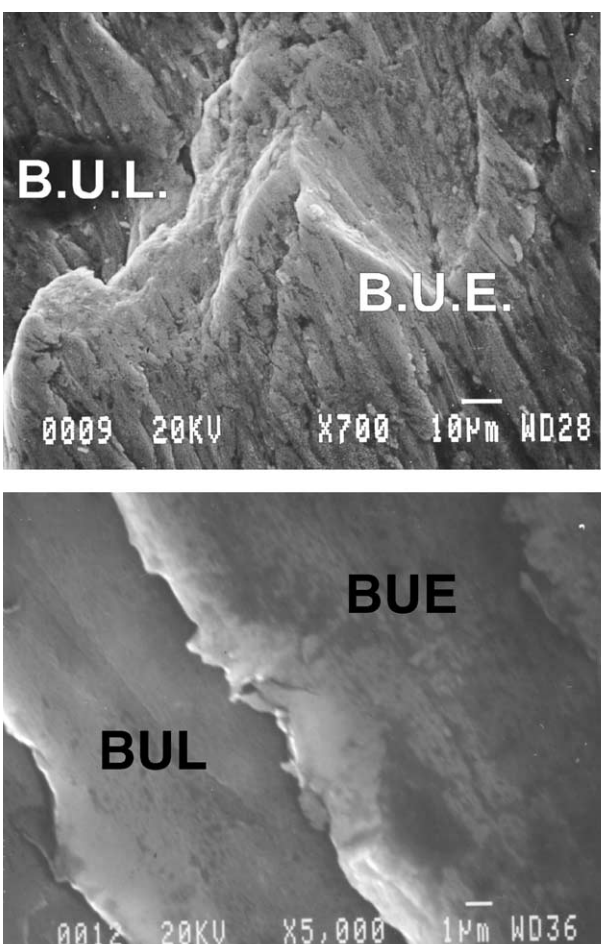

Fig. 7. SEM images enlarging boundary zone between BUL and BUE (a) AA2024 and (b) AA7050.

As it has been commented in the experimental paragraph, similar turning tests has been carried out at different cutting speeds and feeds. The results obtained are in the same way that the discussed above.

However, in [4], where machining processes of steels are studied, BUL and BUE are considered two forms of the same effect.

So, BUL is defined as a plastic extension of BUE, which is initially formed.

On the other hand, as it was commented, shorter duration experiments were carried out in order to analyse the development sequence of BUL and BUE.

Fig. 8(a) shows the SEM image of the rake face of a TiN covered tool insert employed in a 1 s dry turning test of a sample of AA2024 alloy at 80 m/min. An initial metal accumulation associated to the BUL formation can be observed.

Fig. 8(b) can be even clearer. This figure corresponds to a TiN covered tool after a dry turning process of AA7050 during 0.1 s at 127 m/min. Looking at this image can be observed as built-up edge is not yet formed and only built-up layer can be detected.

This fact reveals that BUL is formed before that BUE and, therefore, built-up layer cannot be considered as a plastically extended BUE.

An enlarged image of the zone corresponding to BUL in Fig. 8(b) is presented in Fig. 8(c). Notice as, in the working conditions, BUL formed is practically electron-transparent.

Once determined the formation sequence of adhesion effects, an EDS analysis of both zones has been carried out in order to distinguish the microstructural differences between BUL and BUE.

Fig. 9 plots the EDS spectra acquired on zones corresponding to BUL (a) and BUE (b) in Fig. 7(a). As a reference, an EDS spectrum acquired on a sample of the AA2024 alloy is also plotted (Fig. 9(c)).

From the comparison of the spectra plotted in Fig. 9, it can be concluded that the intensities of the Fe and Cu peaks in the BUL (Fig. 9(a)), are much lower than those observed for the same elements both in the BUE and the alloy (Fig. 9(b) and (c)). Similar spectra have been found in the different cutting conditions analysed. This is a first evidence of the dissimilar nature of these two regions.

In the same way, Fig. 10 plots the EDS spectra acquired on zones corresponding to BUL (a) and BUE (b) in Fig. 7(b). As a reference, an EDS spectrum acquired on a sample of the AA7050 alloy is also plotted (Fig. 10(c)).

From the comparison of the spectra plotted in Fig. 10, it is possible to establish similar conclusions than those realised for the AA2024. Notwithstanding, it must be remarked that, in the case of the alloy AA7050, the EDS spectrum corresponding to BUL, Fig. 10(a) is very close to the corresponding to pure aluminium. Also, in this case, similar spectra have been found in the different cutting conditions analysed.

The compositional differences stated above could be related with a loss of intermetallic particles during the BUL growth. Thus, in the case of AA2024 alloy there is a notable

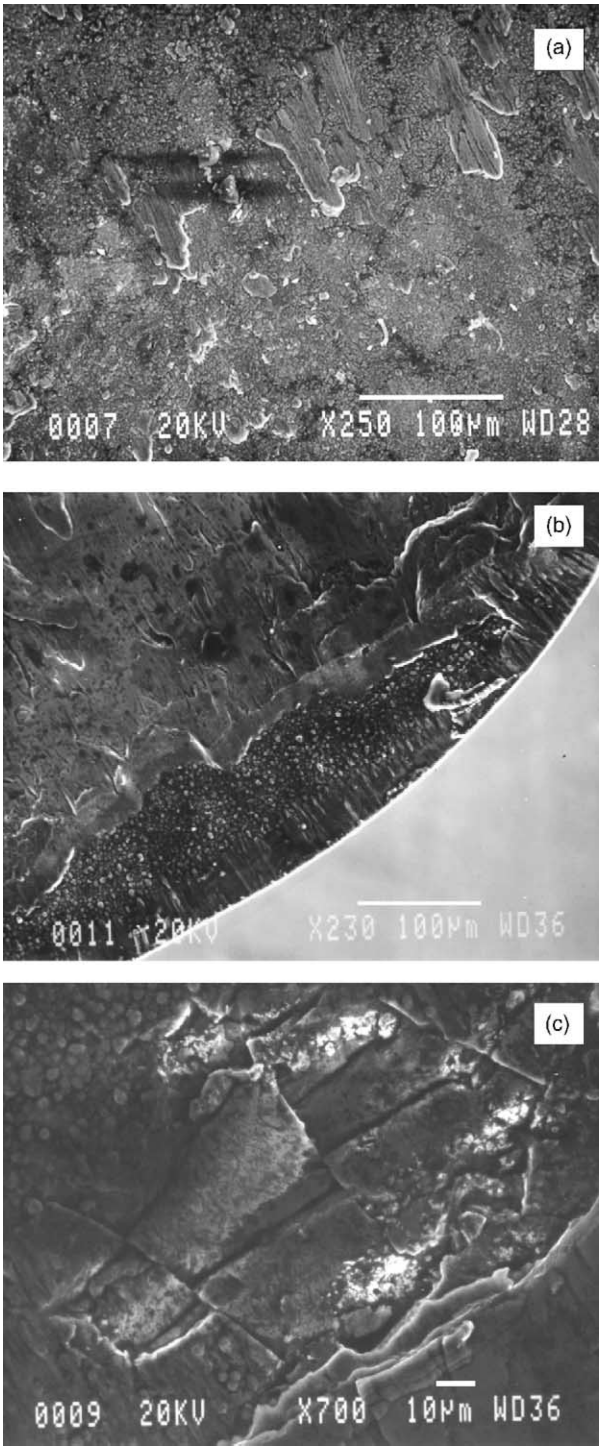

Fig. 8. (a) SEM image acquired on the rake face of a tool after 1 s turning process of the AA2024 alloy, (b) and (c) different magnifications of images acquired on the rake face of a tool after 0.1 s turning process of the AA7050 alloy.

decrease of Cu and Fe-rich particles, while in the case of AA7050 alloys, almost can be considered disappear the content in Cu and Zn.

An explanation of these findings can be made from considerations based on the temperature in the machining process.

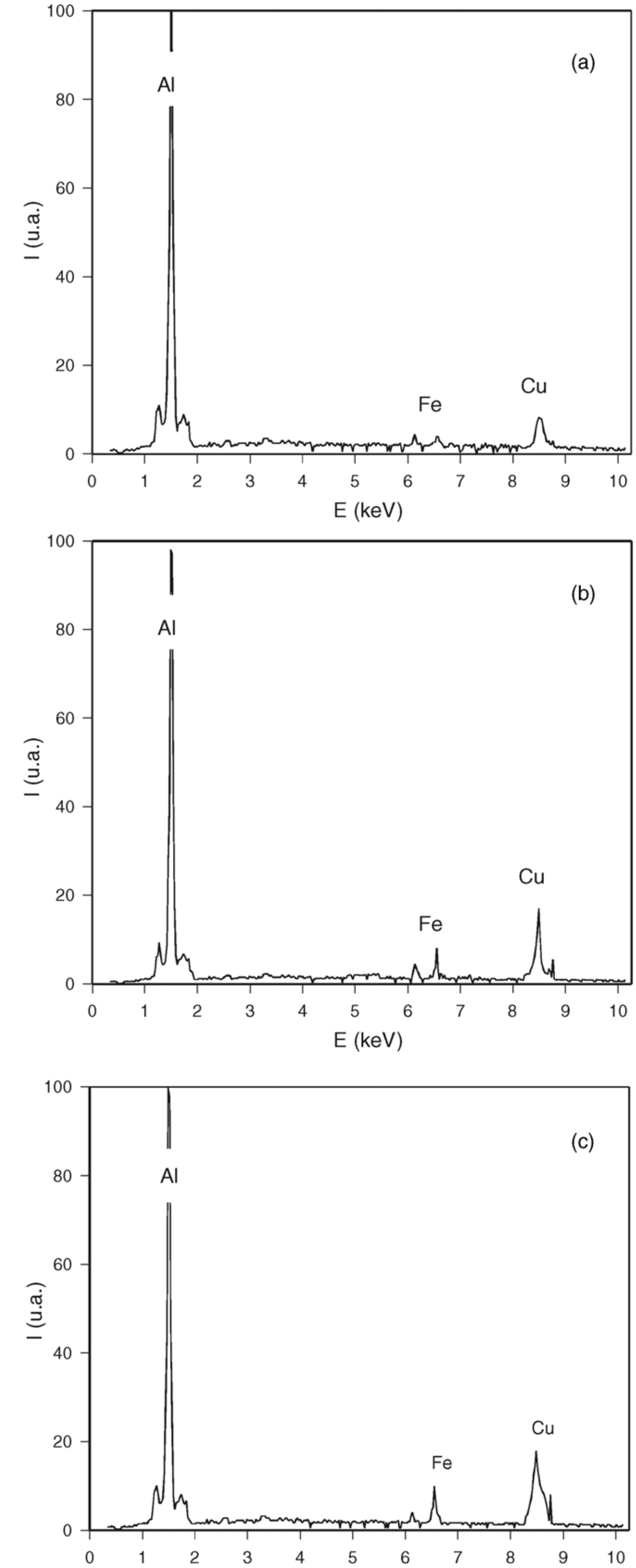

Fig. 9. EDS spectra acquired on (a) BUL, (b) BUE, and (c) alloy (machined material: AA2024; EDS analyser: LINK 10000).

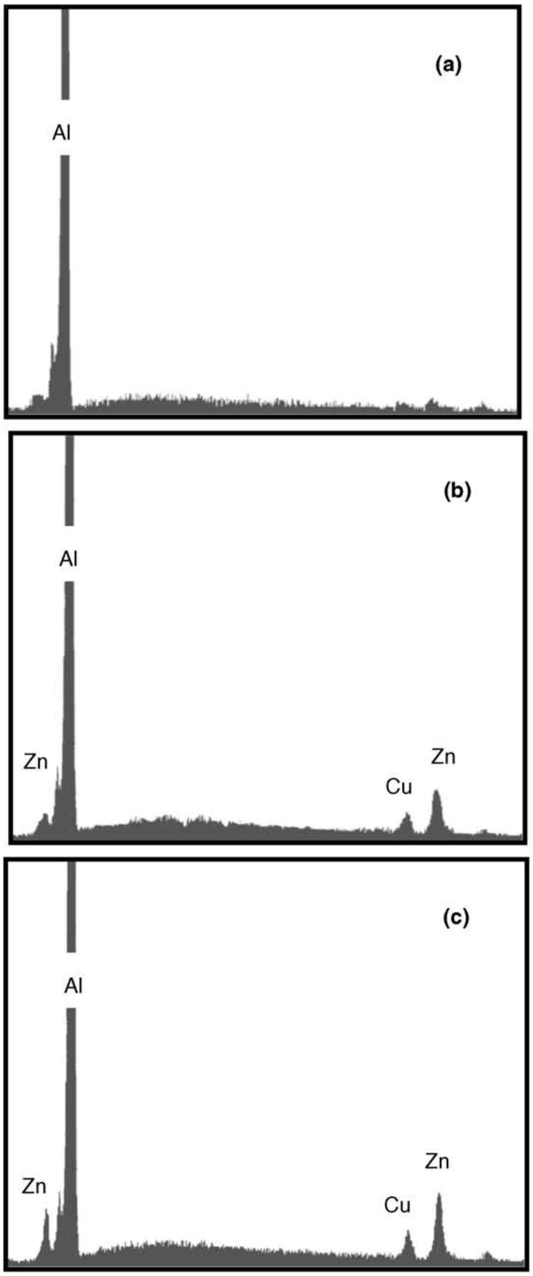

Fig. 10. EDS spectra acquired on (a) BUL, (b) BUE, and (c) alloy (machined material: AA7050; EDS analyser: EDAX).

According to [5,11], in the dry turning process of these alloys, in the rake face of the tool temperatures around 750 °C are reached in the initial stages of the cutting process. These temperatures cause the incipient melting of Al matrix in the alloy, which flows on the rake face of the tool [11]. The compression force over the rake face combined with the visco-plastic state of the aluminium allows welding it on the tool surface. Moreover, under these conditions the metallic chips drag off the solid intermetallic particles, which have a much higher melting point as it was commented in Section 3.1.

A situation like this was shown in [7,12] when calcium enriched resulphurised steel calcium was machined. The calcium-rich intermetallics in the alloy have al lower melting point than the Fe matrix. Thus, in this case, these inclusions are the responsible of the adherent layer formation.

Returning to the aluminium alloys here studied, once the BUL is developed in the first instants of machining, the Al accumulated on the tool surface reduces its initial hardness and increases its thermal conductivity. As a consequence of both processes the temperature reached during the next steps of the cutting process decreases [13,14]. This avoids the incipient melting of the bulk of the alloy and, so, the increase of the thickness of BUL.

Due to this, the workpiece material will remain in the zones close to the edge forming the BUE by mechanical

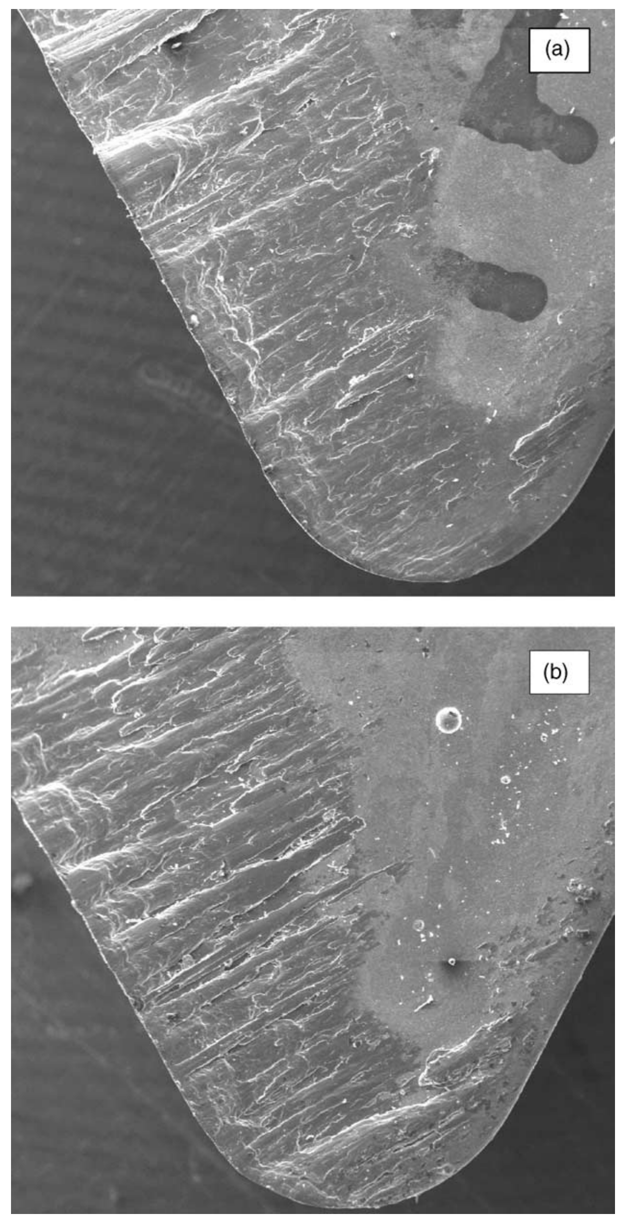

Fig. 11. SEM images acquired on different TiN covered inserts after dry turning 175 mm of AA7050 bars (a) $v = 43$ m/min and (b) $v = 64$ m/min.

adhesion, which explain its composition close to that of the machined alloy.

As summary, BUL and BUE are formed by different causes and it is reflected in the microstructural differences detected through the SEM and EDS analysis. Thus, BUL is caused by thermo-mechanical mechanism, while, once BUL is formed, BUE is developed by mechanical adhesion processes.

3.3. Longer duration tests

As it has been mentioned in the experimental paragraph, longer duration dry turning tests were carried out in order to identify the evolution with the time of machining of BUL and BUE. In this study, bars were completely horizontal dry turned although it involves different machining time due to the different cutting parameters applied.

When the time of machining is higher, a change can be observed in the morphology of the adhered material onto the tool surface.

In effect, as it can be observed in Fig. 11, no thickness differences can be appreciated after longer dry turning tests. Furthermore, two levels can be differentiated. On the one hand the original BUL onto the rake face, and over it, other metallic layer can be distinguished. The EDS acquired on this layer revealed that its composition is very close to the alloy and BUE. Moreover, no thickness differences can be remarked between the material adhered close to the edge and the rest adhered on the rake face.

Therefore, this can be considered a plastic extension of BUE in a similar way that occurs with the dry turning of steels [15]. As a consequence of this, BUL is hidden.

So, it can be concluded that BUE is growing until a critical thickness and, once reached, it is plastically extended over the BUL due to the action of the mechanical forces that are taking place in the cutting process, presenting a similar appearance to the BUL formed when steels are machined.

4. Conclusions

SEM and EDS analysis of TiN covered tool inserts using in short duration dry turning tests revealed that two adhesion effects are produced by the action of different mechanisms.

So, BUL is caused by thermo-mechanical mechanisms and its formation is preceded by a process of incipient fusion of the metallic matrix, which releases intermetallic particles. The compression force over the rake face combined with the visco-plastic state of the aluminium weld it onto the tool surface.

Once BUL has been formed, initial cutting conditions change enabling BUE formation by mechanical adhesion.

Analysis after longer turning times revealed that BUE is growing until it reaches a critical thickness. After this, BUE is plastically deformed and it can be extended over the rake face of the tool. Because of this original BUL can be hidden and the surface analysis can show an appearance similar to that shown by a tool surface after dry machining of steels.

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