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Article

Study of Tool Wear Process in the Dry Turning of Al-Cu Alloy

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Abstract: Light alloys machining is a widely implemented process that have usually used in presence of cutting fluids to reduce the wear impact and increase tool life. However, current environmental protection policies require their elimination in order to improve process sustainability. This fact forces to work under aggressive cutting conditions, producing adhesion wear that affects the integrity of the part surface. This study describes cutting tool wear mechanisms in machining of UNS A92024 samples under dry cutting conditions. EDS analysis showed the different composition of the adhered layers, while roughness was also positively affected by the change of the cutting geometry produced in the tool.

Keywords: tool wear, aluminum alloys, adhesion, turning

1. Introduction

Aluminum is one of the easiest materials to find in the transport industry. Many parts of the aeronautical and automobile industry use this material to manufacture [1, 2]. For this reason aluminum production rates have been increased in the last ten years, reaching up to 75% and increasing worldwide [1].

Since 1930s the most used aluminum alloy series in the aerospace sector are 2xxx, 7xxx and 6xxx. These kind of alloys present excellent mechanical properties and good corrosion resistance [3]. Particularly, UNS A92024 is widely used for structural parts in different aircraft programs. These parts usually have high surface integrity requirements and though, need to be machined using different machining processes. Despite aluminum alloys are usually considered easy to machine materials, an increase of the material ductility produced by the amount of copper within the alloy - up to 4% in A92024 [4]- decreases its machinability [5, 6], mainly due to the increase in the contact length of the tool/chip interface, which increases cutting forces, temperature and so, tool wear.

Although lubricants could reduce the tool wear ratio, dry machining is being considered as an ecofriendly technique in several industries. Therefore, the study of wear and control mechanism is crucial to increasing process efficiency. Due to the low melting point, diffusive wear and superficial plastic deformation wear mechanisms are difficult to find in the tool after machining aluminum, being the main wear mechanisms abrasion and adhesion [7-9]. Abrasion is supposed to be produced by hard particles from the precipitates or particles from the cutting tool [10], while the adhesion mechanism is caused by the interaction between tool and workpiece, which produces a high contact pressure that facilitates the transfer of particles from one surface to another [11]. Under this scenario, a layer known as Built-Up Layer (BUL) appears as a welded layer of pure aluminum on the tool, transferred from the metal matrix. This layer, added by a thermomechanical process, modifies the friction behavior by changing the contact pair from WC-Co (tool material)-aluminum to aluminum-aluminum [12], facilitating the mechanical adhesion mechanism. After that, a secondary BUL, formed by a mechanical process is extruded, giving place to a secondary aluminiun layer in a cyclical process,

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forming a Multi-BUL or MBUL [3]. The material that composes this MultiBUL is transferred from the chip to the tool. This is the reason why this MBUL composition is close to the original alloy, not pure aluminium. In addition, a part of adhered material is accumulated in the cutting edge, being usually called Built-Up Edge (BUE). BUE can modify the rake face characteristics by increasing the rake angle and so, modifying the chip formation [13-14] and its contact with the tool surface, also modifying the coefficient of friction [12]. However, the adhered material is unstable and may detach or descend to the primary adhesion, vanishing, re-growing or breaking [6]. In both cases (BUL and BUE), tool particles can be dragged [15-16], producing continuous morphological changes at the tool edges [17]. This cyclic behavior can weaken the cutting edge, breaking it gradually or finally fracturing it completely [18-19]. Therefore, this type of wear is dynamic, with successive layers of welded material, hardened or bonded and then extruded, dragged or removed by mechanical actions.

This phenomenon, which is only observed in the case of carbide tools, generally leads to the formation of a false cut or overlapped cut [18, 20]. This also produces an increase in the radius of the cutting edge, worsening the surface quality of the part. For this reason, the only solution seems to come given by the reduction of the adherence. The industrial options are the use cutting fluids, that allow to reduce friction in the tool/chip interface, or the use of Poly-Crystalline Diamond (PCD) coated tools. Both options can reduce the adhesion, but not eliminate it altogether [21, 22].

This problem opens a field of technical interest little explored in the scientific bibliography, especially with regard to the formation of BUL/BUE in the first moments of machining and the study of the secondary adhesion process and its effects on the parts quality.

This paper presents an experimental work in order to analyse the previously exposed hypothesis, by determining the behavior of the dry turning of Al-Cu alloy at high cutting depths. For this purpose, the wear found at different machining time is quantified. The wear mechanisms are studied through the composition of the adhered layers. Finally, the effect of the adhered layers and their geometry on the surface roughness of the part is evaluated.

2. Materials and Methods

Dry horizontal turning of UNS A92024-T3 (Al-Cu) aluminum alloy cylinders was carried out with a CNC Lathe EMCOturn 242 (EMCO, Hallein, Austria), with 13 kW power and EMCOtronic TM02 numerical control. The cutting parameters used in the experiments are shown in Table 1. In order to study the evolution of the tool wear, several tests have been performed at different machining times. The cutting speed was set at 100 m/min and feed rate at 0.1 mm/rev. These parameters have been selected providing the minimum roughness values in previous works [17, 19]. The tool used was an uncoated WC-Co neutral tool with a general-purpose chip-breaker ISO DCMT11T308 [23], from SECO Tools. The main geometrical data are represented in Figure 1. Selection of this cutting geometry comes given by its extensive use for machining aluminium alloys [24-26]. The experiments were filmed using a Motion Pro X4 (Redlake, Cheshire, CT, UCA) high-speed camera, at a capture frequency up to 8k fps.

Table 1. Cutting parameters

Cutting Speed (*Vc*) [m/min]		100	
Feed (*f*) [mm/rev]		0.10	
Deph of cut (*d*) [mm]	0.5	1.0	2.0
Cutting time (*t*) [s]	0.5 - 1 - 5 - 10 - 15 - 30 - 60 - 120		

The rake and the flank face of the tools were observed by using a Nikon SMZ800 stereoscopic optical microscope (Nikon, Tokyo, Japan) with a 5 MPx Optikam B5 (Optika, Ponteranica, Italy) digital camera. Tool wear was measured through image filtering and digital measuring with Perfect Image v7 software (Clara Vision, Verrières le Buisson, France). The affected area of the rake face was automatically recognized by filtering color pattern, taking 3 measures for the analysis (Figure 1). Similarly, ten thickness measures were taken at the flank face, using the ISO 3685 standard as a reference (Figure 1).

Some of the machining conditions were specifically studied by obtaining the cross-section of the tool, Figure 1). So, the tool was cut using a wire electro discharge machine ONA PRIMA E25 (ONA, Durango, Spain). Then, the sections were slightly grinded and studied in a metallographic microscope Nikon Epiphot 200 (Nikon, Tokyo, Japan). Also, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) have been used in order to characterize the section and the entire tool. For this purpose, a FEI QUANTA 200 (ThermoFisher Scientific, Hillsboro, OR, USA) with EDAX Phoenix (Phoenix, EDAX, Mahwah, NJ, USA) have been used. Finally, the surface finish of the part was measured in terms of average roughness values (Ra) with a Mahr Perthometer M1 roughness measure station (Mahr Metrology, Göttingen, Germany).

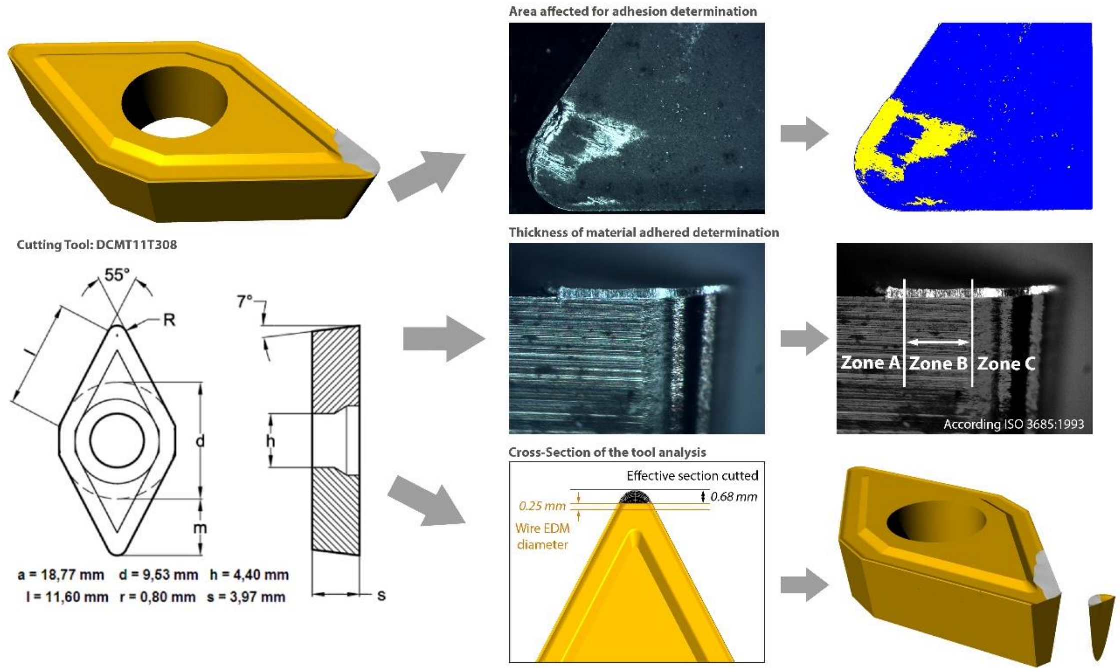

Figure 1. Experimental proposal for adhesion evaluation

3. Results and discussion

3.1. Evolution of tool wear

High speed videos were used to analyse the first instants of machining. A change in chip surface was observed in the first 0.05s, Figure 2.

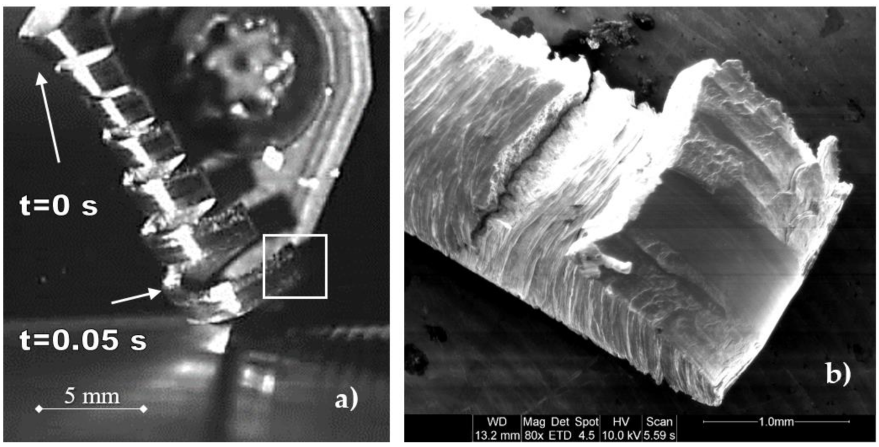

Figure 2. (a) High speed filming frame, where the chip formation in the beginning of machining is observed, (b) SEM image from the chip surface

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Initially, the chip surface was bright and smooth, with no marks of cracks in the contact zone, cutting edge and rake face, and did not present any deformation or irregularity. When adhesion started, the surface changed reducing the contact area and leaving part of the chip without support during its formation, producing cracks and marks on its external surface. For this reason, it is reasonable to think that the development of the adhered material is almost instantaneous, being the more important mechanical component of the wear process, being in accord with some studies [3, 6].

For a longer machining time, visual inspection analysis is shown in Figure 3. The width of the affected area is related to the depth of cut, increasing the contact length between the chip and the rake face. This area generally increases over time, mainly due to the material softening produced by the high process temperatures. In the first instants, and until the BUE was completely extruded over the tool, the temperature increased, softening the aluminum matrix and easing its adhesion to the tool [6]. This fact changes the contact-pair to aluminum-aluminum, facilitating the adhesion of the second layer, BUL [12].

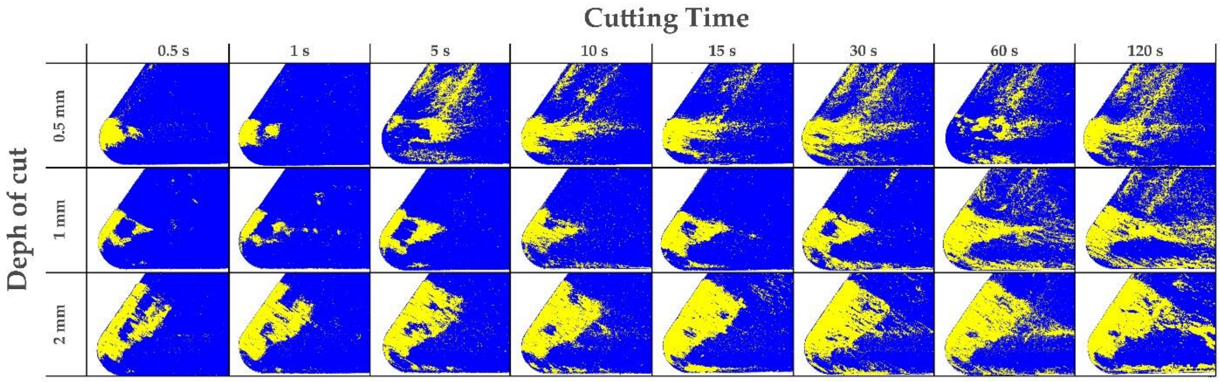

Figure 3. Secondary adhesion wear evolution in the zenith plane, evaluated with phase contrast analysis

However, this process is dynamic. Particles of the adhered material are dragged by the chip, temporarily decreasing the affected area (Figure 4). This effect is more significant for the lower cutting depths. An increase in chip rigidity may affect its extrusion over the tool, fact that has high relevance in the wear behavior [6, 17, 19].

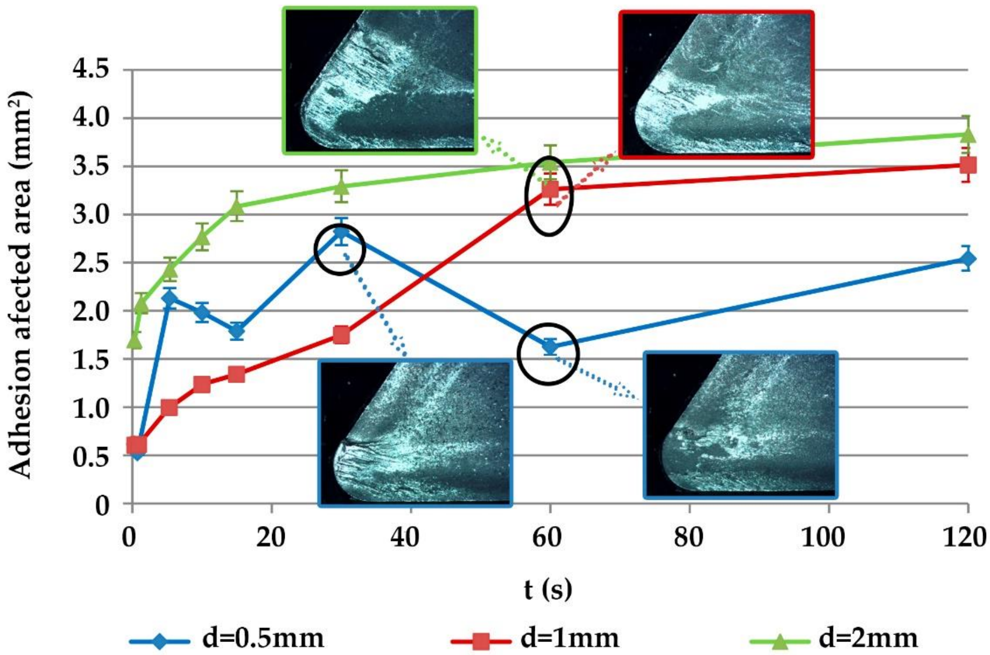

Figure 4. Secondary adhesion affected area as a function of cutting time

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Similarly, the thickness of the adhered material increased with cutting time, which behaved in the same way as the area affected by the adhesion, Figure 5. The BUL thickness values fluctuated over a stable value, which means that the volume of the adhered material increased as it happened in previous studies [17].

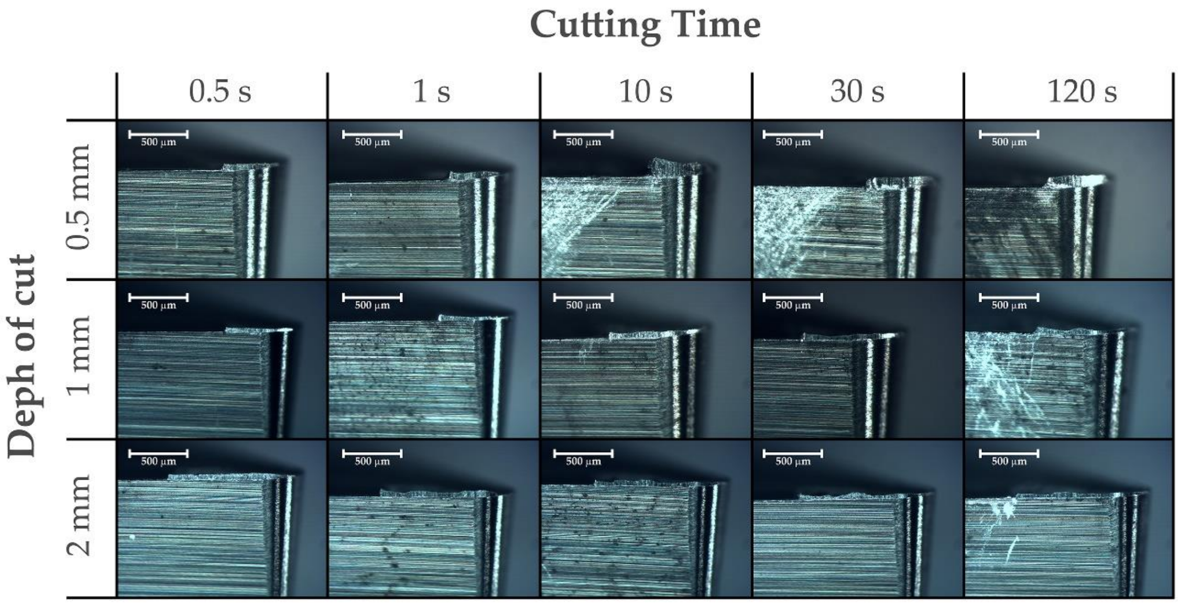

Figure 5. Evolution of the adhered material over the rake face, from a vertical plane projected on the clearance face

However, this analysis showed a high variability on the morphology of the material adhered to the cutting edge, that could be related with the changes produced in the force density in the lateral sense of the chip fluency. This variability suggested the study of alternative statistical parameters to the average value. For this reason, the standard deviation of the thickness data at each edge was studied, showing a repetitive pattern for the entire cutting depth, Figure 6. This fact proved that the dynamic behavior of the adhesion is more repetitive than expected, and it could be normalized for different cutting depths (d).

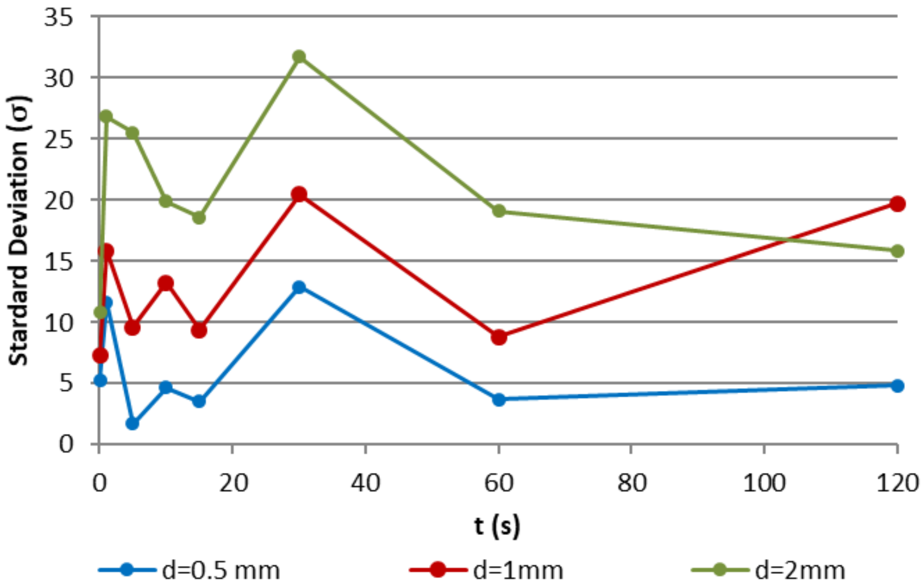

Figure 6. Standard deviation evolution of the thickness of the adhered, as a function of cutting time

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3.2. Wear mechanism

The composition of the adhered layer is affected the cyclic mechanism. An example of this can be observed in the SEM analysis over the rake face (Figure 7), that revealed three layers with different thicknesses that have slight changes in their composition. The first one, marked in orange in Figure 7, is a thin layer with lower Cu content than the nominal alloy. The second one is thicker, but the amount of Cu in its composition has not been as expected from the alloy specifications (4% Cu), indicating that both layers were adhered by thermomechanical processes.

Initially, friction between the tool and chip increases the temperature in the contact area. This fact smooths the aluminium matrix in this area, almost melting it and obtaining a thin layer where the interstitial particles are removed by the chip, being only the aluminium matrix adhered to the upper part of the rake face. This first layer changes the fictional behaviour of the contact area, gradually decreasing the cutting temperature, but also improving the transfer between the tool and chip. For this second step, the process is similar, but it is easier to obtain Cu particles at the surface. This thermo-mechanical adhesion continued up to a thickness where the mechanism changes to mechanical adhesion, caused by the extrusion of the adhered material over the first and second layers.

Finally, the top layer of adhered material has shown the same Cu content than the nominal alloy (4%). This stratification of the adhered material was also previously observed in some studies [3, 6, 19].

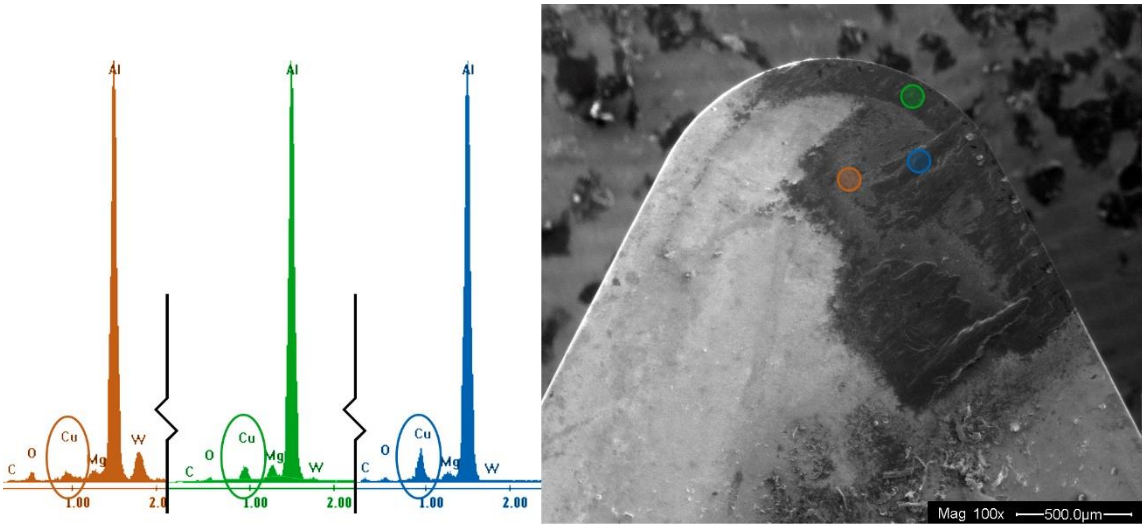

Figure 7. SEM/EDS of the tool after 10s machining at Vc=100 m/min, f=0.1 mm/rev, d=1 mm

This stratification is given on the rake face, following the chip fluency direction (Figure 8c). The cross section shows how the different layers of material overlapped until the chip breaker is filled, Figure 8a. This material looks distributed unevenly around the edge of the tool, creating a BUE and over the rake face forming a MBUL, where it has been possible to identify the interface between the layers. In this case, the friction is completely different; being Al/Al instead of Al/WC-Co. This fact also could vary the output of the chip [12].

In addition, the adhered material has changed the initial geometrical conditions. Although the rake angle increased (modifying the shear angle and the chip fluency), and consequently changing the wear mechanism to abrasion, the most important change occurred at the edge of the tool. BUE changes the positioning angle of the edge (Figure 8b), directly affecting the surface integrity of the machined part.

According to the literature, mechanically adhered materials are unstable and could detach and drag some parts of the tool [27]. In fact, it emerged from some of the tools studied that allowed it to be studied in Figures 4 and 5. When the adhered material is dragged outward, some parts of this material continue to adhere (Figure 9 show this effect).

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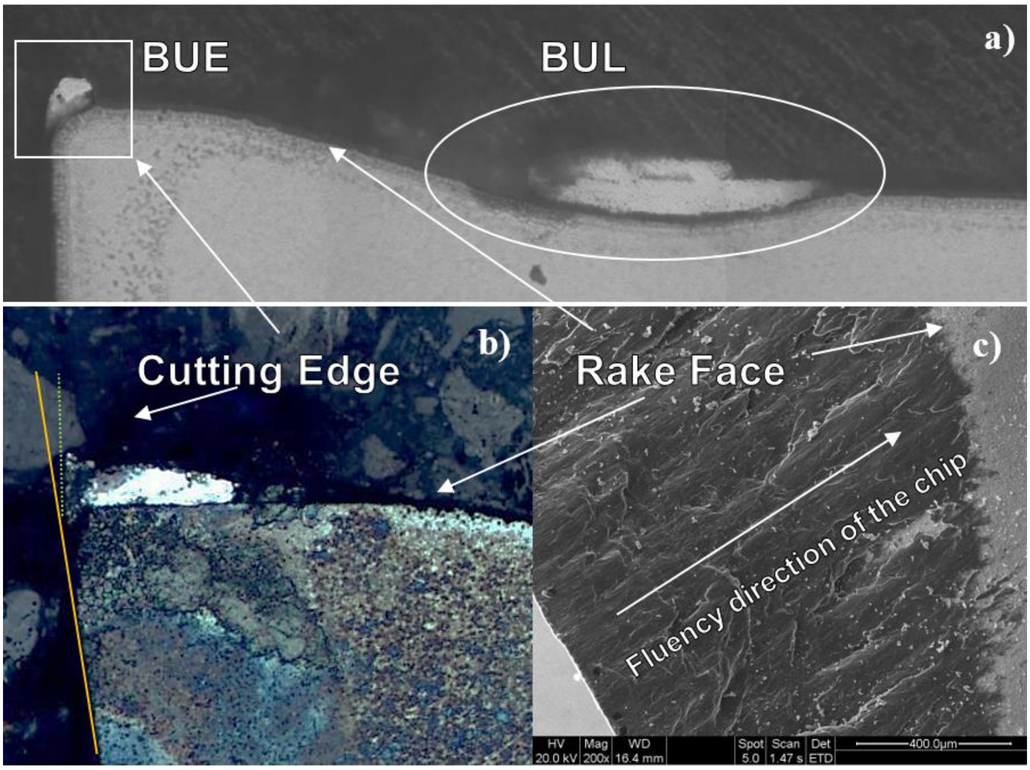

Figure 8. a) Cross section of the tool. b) Overlapped layers of adhered material. c) SEM of stratified structure of adhered material

As can be observed in the Figure 9, there is a fracture in the area close to cutting edge. There was a non-uniform detachment during machining.

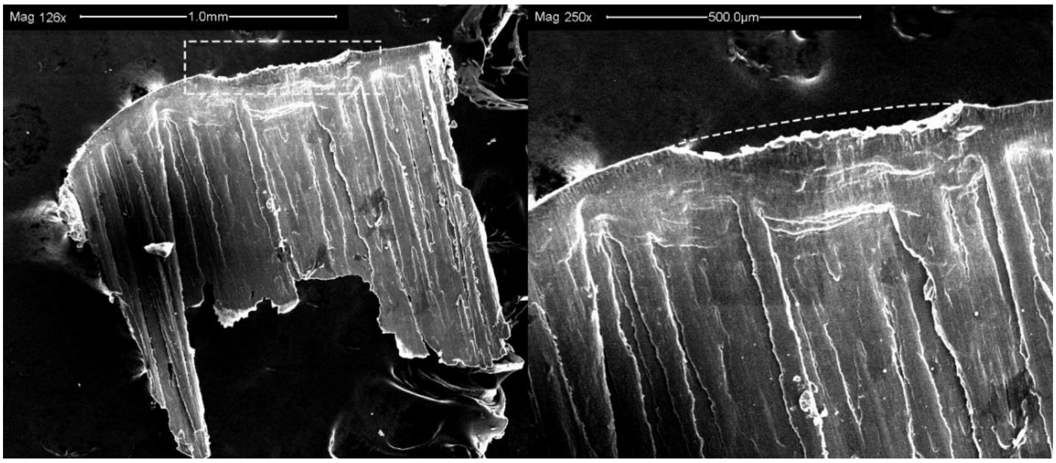

Figure 9. Scanning electron microscopy of the detached adhered material

In the other side (reverse, Figure 10), there are cracking morphologies in the direction of chip fluency. They may be produced by the temperature changes during the chip extrusion and the MBUL deposition. The EDS analysis shows a composition close to the aluminium alloy, suggesting that the first layer responsible for the appearance of marks on the chip (primary BUL) do not easily detach. Additionally, the crack on the MBUL surface generally contain small spheres with W and Cu as main components. This spheres seem to be part of the intermetallic alloy mixed with tool particles, that could cause synergistic behavior of the two main wear mechanism: adhesion and abrasion.

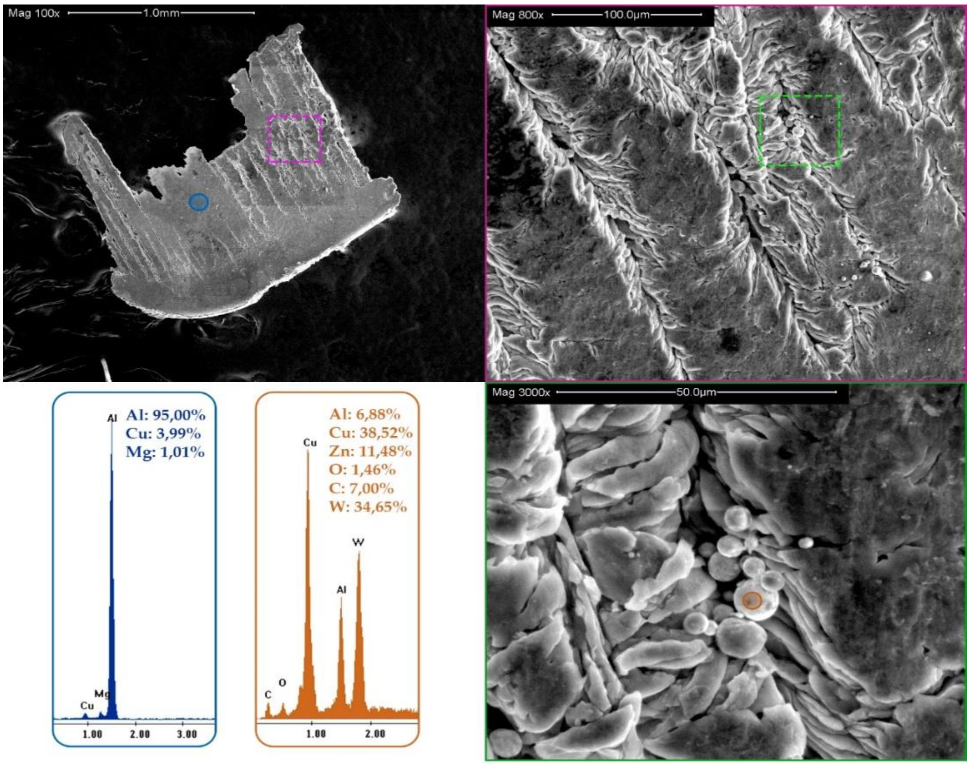

Figure 10. Analysis of the reverse face of the adhered material

3.3. Relation of tool wear and surface quality

The instantaneous formation of the adhered material changes the tool geometry and frictional behavior, favoring tool wear. As the secondary adhesion occurred during the machining time (Figure 11.c) the main position angle of the cutting edge is modified [3, 8, 16], leading to a variation of the Ra [11, 28-29]. In the case of aluminium alloys, Ra can decreased with machined length, that is to say, surface integrity improves as machining time increased (Figure 12). However, this decrease has been accompanied by strong oscillations, caused by the cyclic adhesion and drag process explained above.

Thus, as the adhered material increases, the height of the roughness value decreases, and so, Ra decreases. It is exposed in Figure 11.d, where the real height of the roughness is lower than the theoretical one. Nevertheless, when a part of adhered material is carried out, as explained above, the height of the roughness increases again, and the Ra suffers a slight increase. This behaviour explains the oscillations observed in Figure 12.

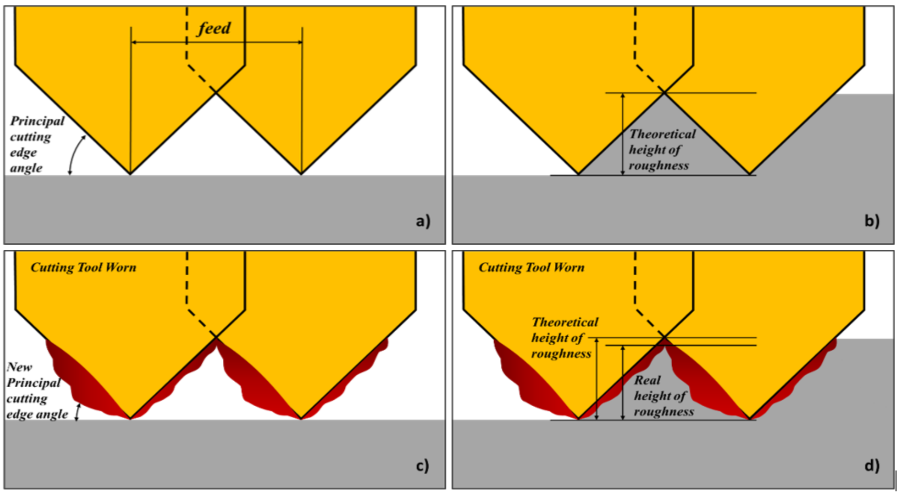

Figure 11. Tool wear effect on the surface roughness

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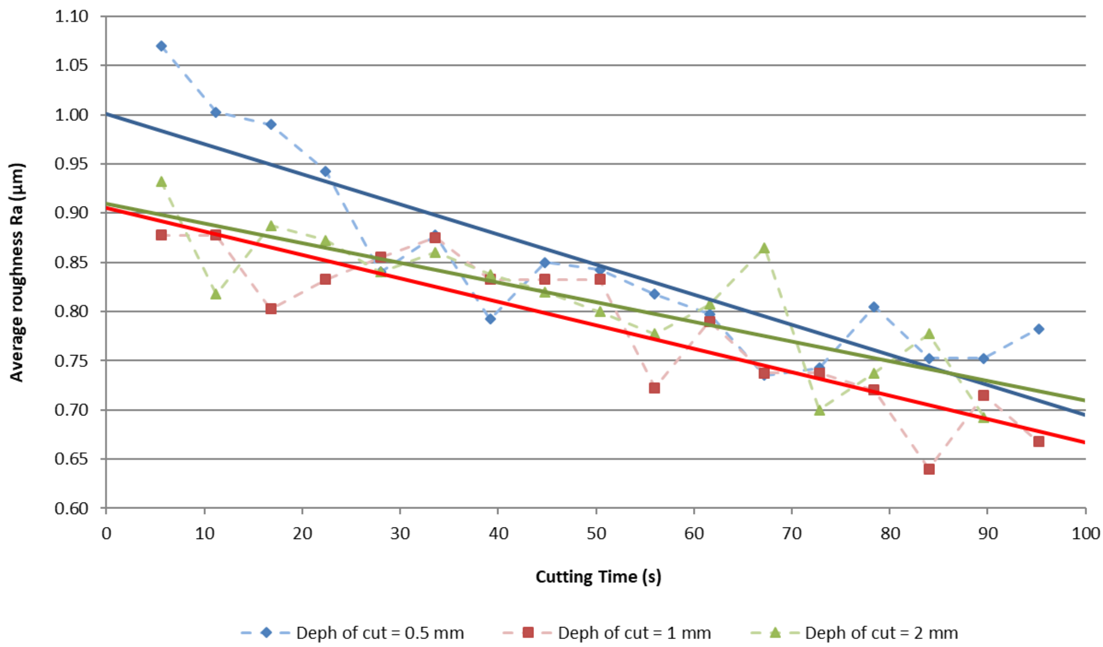

Figure 12. Ra evolution in function of the machining length (Vc=100 m/min; f=0.1 mm/rev)

The behavior of Ra is highly influenced by the adhered material, but the influence is different depending on the adherence process. If one studies the statistical correlation between Ra and the two phenomena of secondary adhesion (BUE/BUL), it is possible to see that the material adhered in rake face (BUL) controls the dependence of Ra (Figure 13). The correlation between the thicknesses of material adhered on cutting edge is around 40% for a cutting depth of 2 mm, being worse for the rest of cutting depth. Therefore, the correlation between area affected by adhesion and Ra is around 50%, but depending on the depth of cut it can be very high. In the case of 2 mm depth is about 86% and in the case of 1 mm about 95%.

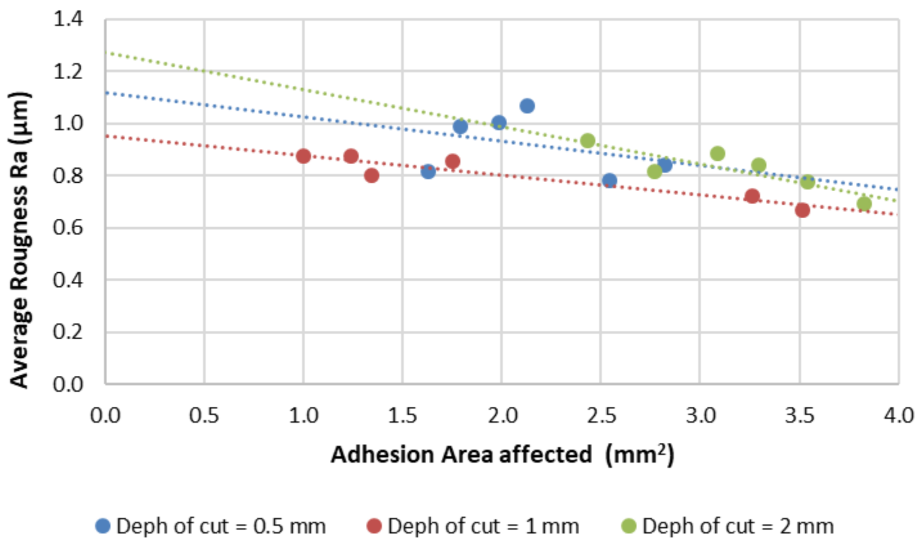

Figure 13. Evolution of Ra in function of area affected by adhesion for each depth of cut

This means that when the tool is highly affected by adhesion in the rake face, forming BUL, the Ra decreases by the geometric effect explained before. So, the general trend is to decrease the Ra, but this trend is not constant along the time, because the tool material that is removed during the cyclical process produce mechanical cracks that weakens the tool, leading for longer times to a worse surface quality.

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4. Conclusions

This paper studied the wear mechanism of the tool after machining the aluminum-copper alloy UNS A92024 under dry conditions. The main wear mechanism is adhesion, that presents in some situations abrasion phenomena.

Secondary adhesion wear is an instantaneous process. In 0.05 seconds a layer of material adhered to the rake face is formed. This layer has very low thickness and low Cu content, due to the thermo-mechanical process, fact that changes the tribological behavior of the cutting tool.

This adhered material increases with the cutting time, forming a BUL on the rake face and a BUL over the cutting edge. However, this formation is unstable, being a part of it dragged with the fluency of the chip.

When the adhered material is dragged out, it removes particles from the cutting tool material, in form of tungsten carbide (WC) spheres. The cyclicity of the process causes that the adhered material increases over time and forms a Multi-Layer Adhered (MBUL), giving rise to a modification in the tool position angle of the tool.

The geometrical modification in the cutting tool causes positive changes in the machined parts, by decreasing the surface roughness (Ra). In addition, the material adhered to the rake face is the most affected by Ra.

However, if the adherence process is cyclic and the tool material is removed, the tool is weakened in each cycle.

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Conflicts of Interest: The authors declare no conflict of interest.

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