Chapter

Machining of Al-Cu and Al-Zn Alloys for Aeronautical Components

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Abstract

Machining operations are chosen by aircraft manufacturers worldwide to process light aluminum alloys. This type of materials presents good characteristics in terms of weight and physicochemical properties, which combined with a low cost ratio making them irreplaceable in aircraft elements with a high structural commitment. Conventional machining processes such as drilling, milling and turning are widely used for aeronautical parts manufacturing. High quality requirements are usually demanded for these kinds of components but aluminum alloys may present some machinability issues, basically associated to the heat generated during the process. Among others, surface quality and geometrical deviations are highly influenced by the condition of the cutting-tool, its wear and the cutting parameters. Consequently, the understanding of the relationship among the process parameters, the quality features and the main wear mechanism is a key factor for the improvement in the productivity. In this chapter, the fundamental issues of drilling, milling and turning are addressed, dealing with the relationship between cutting parameters, wear phenomena and micro and macro geometrical deviations.

Keywords: aluminum, drilling, milling, turning, cutting tool, tool wear

1. Introduction

Aluminum is considered a valuable material thanks to its lightness (around a third of copper and steel density), its mechanical properties and its resistance to corrosion. This highly malleable material presents an excellent thermal and electrical conductivity. It is also a magnificent light reflector that gives to it an attractive natural appearance. Furthermore, neither magnetic nor toxic, this metal is 100% recyclable, increasing its value even as a waste. In fact, its recycling offers powerful economic incentives [1, 2]. It should be noted that around 70% of the 761 million of tons of aluminum produced since 1886 continue in use [3].

The large number of chemical elements that can be alloyed to pure aluminum allow to find a suitable aluminum alloy for every industrial case. The different compositions help to enhance some of the mechanical properties, as is shown in **Table 1**.

Nonetheless, these alloys easily respond to hardening mechanisms, reaching strengths up to 30 times higher than the pure aluminum strength [4, 5]. For these

Al +	Cu	• Increased strength and hardness • Combined with Mg produces a heat treatable alloy
	Zn	• Increased strength and hardness • Possibility of stress corrosion • Combined with Mg produces a heat treatable alloy
	Si	• Good corrosion resistance • Combined with Mg produces a heat treatable alloy
	Mn	• Increased resistance to corrosion
	Mg	• Increases strength and hardness • Good corrosion resistance • Increased weldability

Table 1.
Main alloying elements used in aluminum alloys.

reasons, the variety of applications for aluminum is constantly increasing, being an essential part of our life.

Particularly, transport industry absorbs more than a quarter of the produced aluminum, being applied to any type of transport. Cast alloys are widely used in the automotive industry while forging alloys predominate in the aeronautic field.

This material is indispensable for the aeronautic industry since its origin, due to the high influence on the total weight of the aircraft. It is estimated that each ton of weight reduction in the structure of an airplane, considering an average weight of 80 kg per passenger, luggage on board included, results in an increase of 12 passengers per flight [6]. Likewise, the weight of the aircraft is directly proportional to fuel consumption as well as operational and maintenance costs, especially in landing gear consumable elements [7].

Consequently, light materials such as titanium-based alloys, composite materials and aluminum alloys are the most common choices for the structural elements of this sector. Despite nowadays it seems to be a trend trying to replace aluminum alloys by composite materials, forged aluminum alloys or some of its variants 2xxx (Al-Cu) and 7xxx (Al-Zn) series are still strategic materials for most of the structural parts (**Figure 1**) [8]. Their choice ensures a wide scope and a predictable in-service behavior [6]. That's why, 82% of the structure of a Boeing 747 aircraft and 70% of a Boeing 777 are made of this type material [1, 4].

Aeronautical parts have specific characteristics. They are designed to increase their strength and reduce their weight as well as to be integrated in the aircraft using assembly operations.

In the case of aluminum machining, the cost is significantly influenced by the machinability problems, which are basically associated with the heat generated during machining due to the deformation of the crystal lattice and the friction between the chip and cutting-tool [9].

The study of machining processes and the theory of metal cutting dates back to F.W. Taylor, who published "On the Art of Metal Cutting" in the early 20th century [10]. Since then, the scientific/technical advances have been spectacular, among the most noteworthy milestones are: new materials and tool coatings, automation of the machine tool, increasing the process accuracy and its monitoring, among others.

The most common operations are milling and turning to shape the component, while drilling is mainly used to prepare assembly operations. These processes keep in common the material removal in order to give the desired shape and dimensions, that is, to add value to the workpiece.

Due to the widespread use of forging alloys, it is common to find parts with a high Buy to Fly ratio (BtF). The BtF defines the relation between the weight of the

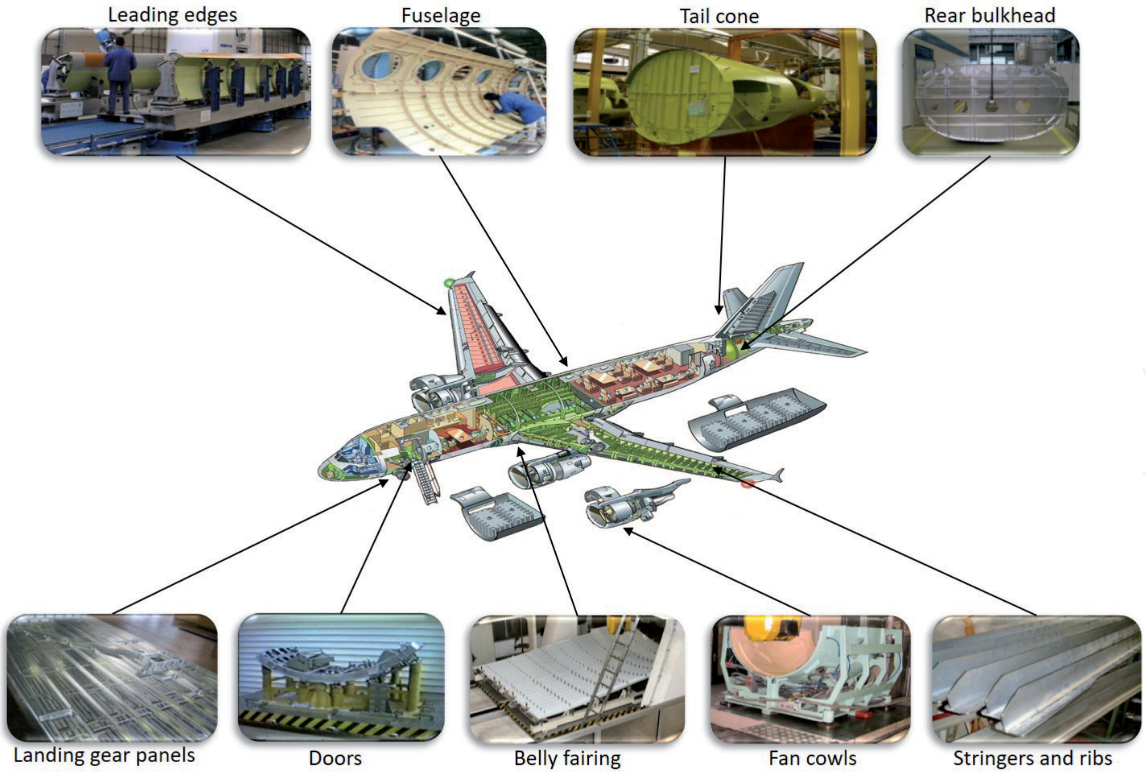

Figure 1.
Structural parts manufactured in aluminum in an A319 aircraft.

purchased raw material and the weight of the part that finally flies [8, 11], which means that most of the raw material is removed transforming it into chips during the machining operation. In fact, milling of monolithic parts can achieve up to 12: 1 BtF. Such high BtF factors will affect the primarily cost, weight, and performance of the part.

In summary, the aeronautical components start from a large volume of raw material, in which is necessary to remove the excess of material. Depending on the geometry and function of the component, various machining processes can be used, standing out the drilling, milling and turning processes. The correct control of these machining processes allows to obtain high quality parts, as those demanded in aeronautics.

1.1 Chapter scope

In the following sections, the main characteristics of these machining processes are presented based on a literature review. The text analyzes when and how each machining is used, covering the parameters and the cutting-tool wear effects on the quality of the produced components. This text is illustrated with examples extracted from experimental campaigns performed by the authors of this chapter.

All the experimental work and most of the literature find is focused on the two main Al series which characteristics are shown in **Table 2**.

2. Drilling of aerospace aluminum alloys

Aircrafts are subjected to a wide temperature ranges during their service, being able to reach up to 40°C while operating in airports and temperatures below –50°C when flying. This wide gradient implies that the structural joints must be designed to withstand stresses in a wide thermal gradient. Therefore, the joint

Identification	Aluminum Association	AA2024	AA7475	AA7050	AA7075
	UNS	A92024	A97475	A97050	A97075
	ISO	AlCu4Mg1	AlZn5.5MgCu(A)	AlZn6CuMgZr	AlZn5.5MgCu
Composition	Si	≤0.5	≤0.1	≤0.12	≤0.4
	Fe	≤0.5	≤0.12	≤0.15	≤0.5
	Cu	3.8–4.9	1.2–1.9	1.9–2.5	1.2–2.0
	Mn	0.3–0.9	≤0.06	≤0.1	≤0.3
	Mg	1.2–1.8	1.9–2.6	2.0–2.7	2.1–2.9
	Cr	≤0.1	0.18–0.25	≤0.04	0.18–0.28
	Zn	≤0.25	5.2–6.2	5.9–6.9	5.1–6.1
	Ti	≤0.15	≤0.05	≤0.06	≤0.2
	Al	Rem.	Rem.	Rem.	Rem.
Properties	Density (kg/m^3)	2.78	2.81	2.83	2.81
	Melting point (°C)	500–638	477–635	490–630	475–635
	Thermal conductivity (W/m°C)	121–151	163	157	130
	Thermal expansion (um/m°C)	23.2	23.2	24.1	23.6
	Young's Modulus (GPa)	73	72	72	72
	Percent elongation (%)	6–20	12	10	11
	Ultimate tensile strength-UTS (MPa)	440–495	531	495–550	525–570
	Heat treatment	T3, T4, T361, T6, T81,T861	T7651	T74	T6, T651, T73

Table 2.
Most frequent aeronautical aluminum alloys designation, compositions and technical properties [5].

must be made with rivets, while the use of welded joints is not certified. Because of this, drilling is one of the prior machining operations in the assembly of aerospace components [11, 12].

Drilling operation have a direct impact on the performance of the riveted joint, affecting mainly its dimensional compatibility with the part to join and the joint fatigue behavior, being particularly important in airframes parts. For this reason, drilling is monitored measuring the thrust force and the torque produced during the machining. Afterwards, some quality parameters such as roughness, burr formation or roundness, are usually measured to ensure the quality of the obtained hole [13–15].

This quality is usually affected by different factors, including the correct the selection of the cutting parameters, movements of the operator during the machining, incorrect chip removal, marks produced by the cutting-tool due to uncontrolled vibrations, as well as imperfections in the drilling angles [16].

Uncontrolled vibrations can be reduced by using automatic drilling machines or by reducing the length of the cutting-tool, decreasing the deflection of the tip and improving the roundness cylindricity of the hole [16]. However, the main problems of aluminum drilling are roughness, burr formation and cutting-tool wear, which are related mainly to the machining parameters [17].

Additionally, fatigue behavior is highly influenced by the roughness, even more than by residual stresses, so their control becomes a critical task. A higher roughness on the hole surface reflects deeper machining marks, scratches and gauges that may work as stress concentration points, increasing the possibilities of crack propagation by magnifying the stress on the part at the assembly point [18].

2.1 Influence of the drilling parameters

Drilling is an axial machining operation where the cutting-tool rotates and penetrates perpendicular to the surface to be drilled at the same time, **Figure 2**.

It is governed by two main parameters: tangential cutting speed (V) and linear feed rate (F). V is usually provided by the tool manufacturer, in function of the cutting-tool material. From V and the tool diameter (D), the spindle speed (S) can be calculated by using Eq. (1):

$$S = \frac{V}{\pi \cdot D} \tag{1}$$

Similarly, F depends on the feed per tooth (f_z), the number of cutting tooth (Z) and S. This parameter can be calculated using Eq. (2):

$$F = f_z \cdot Z \cdot S \tag{2}$$

Both parameters have a direct impact on the quality of the hole, and though on the quality of the joint.

In a general way, lower values of roughness are obtained when low cutting speed and feed-rate are used [17, 19]. Higher spindle speed brings longer chips that

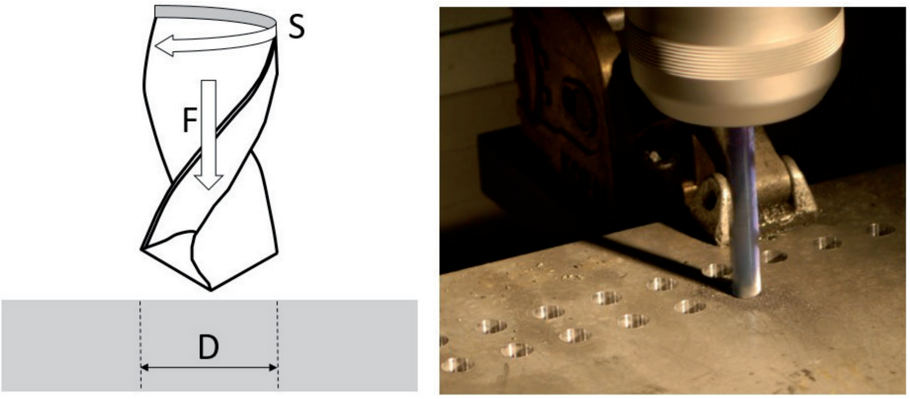

Figure 2.
Drilling scheme and image of a drilling process.

curl inside the hole, producing marks on its surface [19]. Other way to improve the roughness results it to use high point and helix angles [20], but in this case, diamond coatings should be considered to increase wear resistance [17]. Similarly, higher-feed rates increase thrust force and though the wear behavior, while an increase of the cutting speed slightly reduces the thrust forces.

Cylindricity and perpendicularity errors rise by increasing feed-rate and depth of cut, but cutting speed have a different effect in both of them. Low cutting speed reduces roundness error but it also peaks the perpendicularity error, so the optimum value should be selected depending on the part requirements [21].

Probably, the most relevant phenomenon in the drilling of aluminum alloys is the burr formation. Burrs in aluminum are usually classified as type "A", uniform along the hole [22]. They are related to the aluminum ductility (10–12% elongation), affected by the drill geometry (point angle, helix angle, diameter, web thickness and chisel edge) and the process parameters (F, S). Low feed-rates are recommended to reduce burr height, especially near the exit of the cutting tool [22], while a proper cutting speed can interact on the burr thickness. Additionally, large point angles minimize burr height [19]. If the selection of the suitable parameters cannot avoid burr appearance, deburring operations before riveting and assembly are performed. They depend on the burr height, being mandatory when it excess 0.3 mm.

Finally, the dimensional accuracy is mainly related to the helix angle. Larger helix angles increase it [20]. However, it should be considered that oversized holes are common and low cutting speed and high-feed rates can also increase its deviation from the nominal value [19], mainly due to adhesion wear mechanism.

Aluminum alloys are usually machined under dry conditions using tungsten carbide (WC-Co) tools but more aggressive parameters can be selected depending on the lubricating conditions. Carbide tools increase the process efficiency in terms of wear behavior [14] but they may have an impact on the hardness and the cylindricity whereas parameters need to be carefully selected to not increase the tool wear due to thermal effects.

When liquid lubricants are used, they should be placed inside the working area, but as drilling edges work inside the material, the chips produced inside it are constantly removed upward, forcing the lubricant to be evacuated from the place of action and reducing its cooling effect [16]. For this reason, the most adopted lubricating option to avoid this problem it to project the cutting fluids trough the cutting-tool, creating an internal lubrication.

Wear control is essential to obtain the expected quality parameters, affecting the diameter, the roughness and burr height. As example of the aforementioned, **Figure 3** shows different graphs analyzing the diameter, the roughness, the burr and cutting forces evolution in the dry drilling of AA7475 alloy.

It can be observed a diameter reduction produced by the heat effect on the expansion of the hole during the drilling operation. A slight opposite trend can be found for the thrust force due to the loss of cutting edge capacity, reduced by wear effects. Similarly, burr height easily grows over 0.3 mm, the maximum value permitted, forcing deburring operations as long as the tool wear increase. At last, Ra values present a high variability, indicating the presence of dynamic problems or a poor chip evacuation, as well as the alternate effects of the secondary adhesion wear mechanism. However, they are far from 3.2 μm, the maximum value allowed for metal alloys.

2.2 Advanced drilling techniques

Drilling of aluminum components is sometimes performed in multiple materials at the same time such as stacks or laminates. For this reason, different advanced

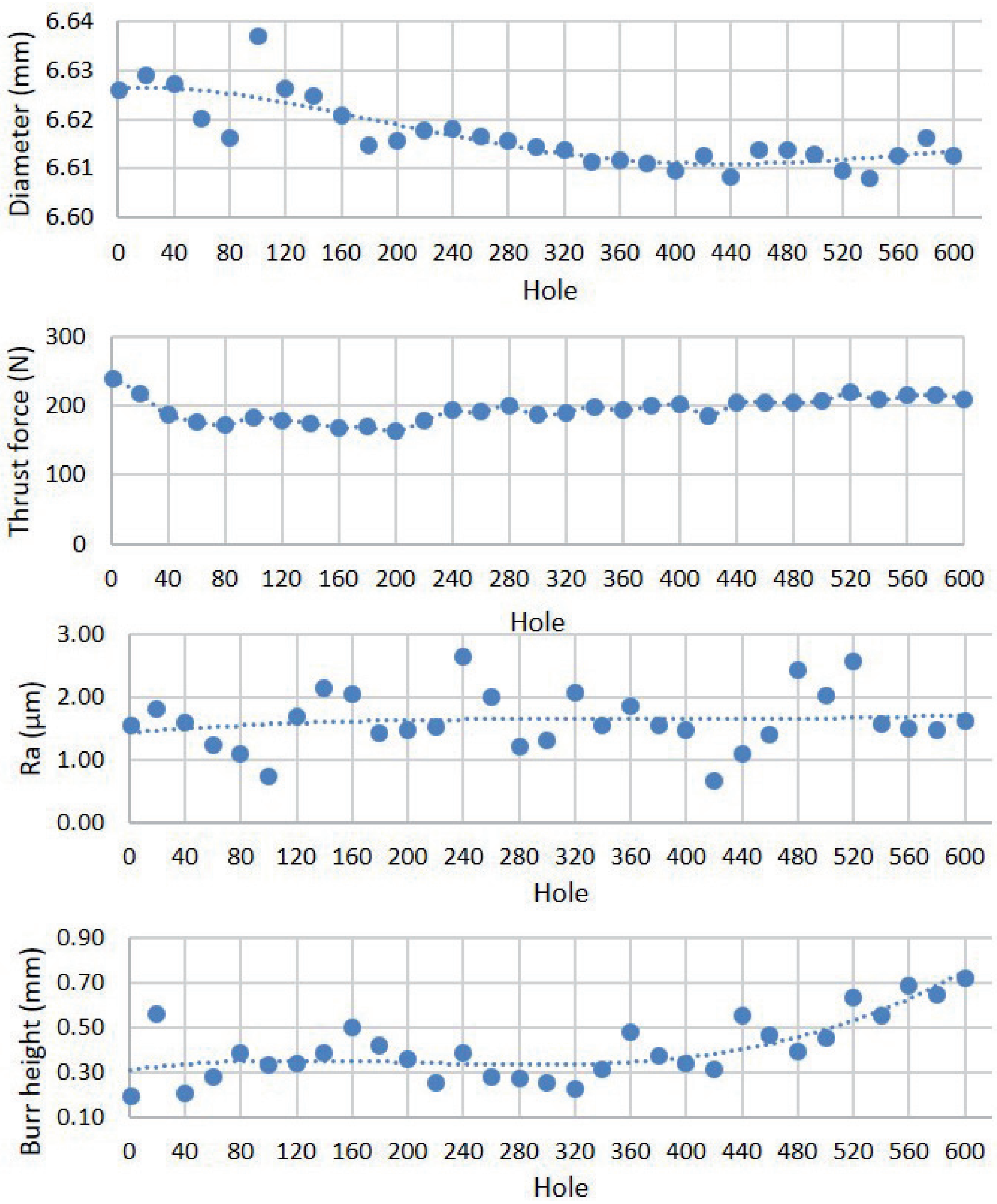

Figure 3.
Diameter, average roughness, burr and cutting forces evolution in the dry drilling of a AA7475 alloy drilled using a double-lip 6.6 mm diameter cutting-tool, S = 4800 rev/min and F = 1085 mm/min.

drilling techniques are used to improve the quality of the hole and avoid possible defects derived from them.

- Orbital Drilling (OD) is a technique where the hole is produced using a milling-tool instead of a drill bit. The cutting tool generates an orbital path to create the hole instead of an axial one. This technique is usually limited to 40 mm depth to reduce the possible vibration produced during the operation, which may decrease the hole quality as well as the cutting-tool life [23]. Moreover, cutting forces are lower than the obtained in conventional drilling, increasing the option of robots and machines that can be used in this operation [24]. It also drops the thermal effect of the machining, by its discontinuous cut and the short chip produced, that is also continuously removed reducing the need of lubricants [25]. This technique is quite useful when stacks of aluminum and titanium are drilled.

- Vibration Assisted Drilling (VAS) is a technique that combines the drilling operation with an impose high frequency vibration on the tool. It reduces the cutting forces, the burr formation and it increases the breakability of the chip, which increases the surface quality and reduces the dimensional error and the wear behavior [26, 27]. This technique includes peck drilling, where the amplitude and the frequency are higher and created by the alternative axial displacement in the machining center. VAS is a common technique for aluminum and fiber composite stacks drilling.

3. Milling of aerospace aluminum alloys

Milling of aluminum in the aeronautical industry is used to produce light components with a high accurate dimension. This operation creates slim parts or monolithic parts. Peripheral milling is performed in the first type to adjust the final dimensions of preformed sheets. Otherwise, monolithic parts come from a rough stock of aluminum and up to the 95% of the material can be removed [28], as it was mentioned before. For this reason, milling of aeronautic alloys selects the most aggressive parameters, so the material removal rate is as high as possible.

The quality of these type of parts is verified trough the surface quality and the dimensional accuracy [29] and both types involve at some point of the operation, a low stiffness situation were deflection and vibration, including chatter issues, may appear severally affecting their final quality. Consequently, low stiffness becomes determinant to select the machining parameters and reduce wear behavior. Additionally, this process has to consider residual stresses produced and released during the milling as well as the temperature achieved, especially to meet the precision targets [30].

In contrast to drilling, the continuous release of chip and cooling effect of inconstant contact favor manufactures to recommend high speed machining parameters. This option reduces the wear mechanism and increase the process efficiency. Nevertheless, high speed combined with low rigidity makes easier the appearance of chatter. These vibrations can arise due to the system excitation at the natural frequency response of the cutting-tool or the workpiece or due to the amplification of the displacements caused by the forces and the lack of stiffness [31, 32]. In these cases, the cut is unstable creating an un-constant chip thickness, which is afterwards reflected on the surface quality [33, 34]. Similarly, the static deflection produced by the forces involved in the process leads to over or under cuts, affecting the final dimension of the parts [35, 36]. These facts enhance the importance of the workholding to ensure the final quality of the parts.

Therefore, different workholding and fixture devices had being designed to increase the part stiffness. Most of them change their position during the operation to ensure the maximum rigidity of the complete system all over the operation [37]. It is common to combine them with active damping actuators to attenuate vibrations [38]. The better clamping system, the more aggressive the parameters will be and the higher the efficiency of the process.

Regarding the parameters and tool path selection, analytical approaches can be useful to reduce defects on the part and in-process issues. Simulations must include an accurate model of the material and a system that allows them to consider the continuous material removal, which will update the rigidity behavior of the part [39].

For the particular case of tool path and strategies, virtual twins' developments are common since they allow to predict the part behavior and improve the operation [40].

3.1 Influence of the milling parameters

Milling is a machining process where a rotary cutting-tools is used to remove material. The tool advance into a work piece varying the direction on one or several axes, **Figure 4**. This operation is defined with the same cutting parameters proposed in the expressions that govern drilling operation, Eqs. (1) and (2), including a radial feed rate.

Conventional milling strategies are prone to generate undercut while climb milling is usually related to overcut [37]. Symmetric tool paths are selected to compensate the effect of residual stresses in the part deformation [41] as well as to reduce in-process deflection. Similarly, particular tool paths may be designed to increase the part stiffness during the cutting operation [42].

In terms of parameter selection, higher cutting speeds and lower axial depths of cut reduce the cutting forces and though the deflection [35, 36]. High cutting speeds also have an impact on the temperature of the process. When high cutting speeds are used, the chip formation mechanism changes to a near to adiabatic process. In this situation, the chip takes a relevant role as a heat exchanger, evacuating most of the heat generated and keeping the workpiece and cutting-tool relatively cold. This fact directly influences the cutting force components, as is shown in **Figure 5**. The force in the feed rate direction is reduced up to 50% from 600 to 750 m/min, the high speed machining range for aluminum. The other force component is kept almost constant and proportional to the feed rate.

Roughness is also proportional to the feed-rate, directly increasing with it. Nevertheless, the adhesion wear mechanism can produce alterations in the geometry of the cutting-tools, improving the surface quality with the machining time, as is shown in **Figure 6**.

Milling operations are usually performed in different steps, roughing and finishing, as a consequence burr formation is less significant than in drilling operations. However, deburring operations may be included in the same process if the tool wear considerably increases, having direct impact on the burr height, **Figure 7**.

The cutting tools recommended for aluminum milling have the following characteristics. Very sharp edges to minimize adhesion and to perform a smooth cut. Two-lip cutting tools, with low helix angles (25°-30°) and long pitches to facilitate the evacuation of large chip flow rates [43, 44]. In order to reduce dynamic instabilities, lower than 5 length-to-diameter ratios (L/D < 5) are recommended.

Whereas the choice between integral or insert tools depends on the application, rounded inserts are more stable if they work with a considerably larger radial (20–60% diameter) than axial paths (2–8% diameter) [45] while integral

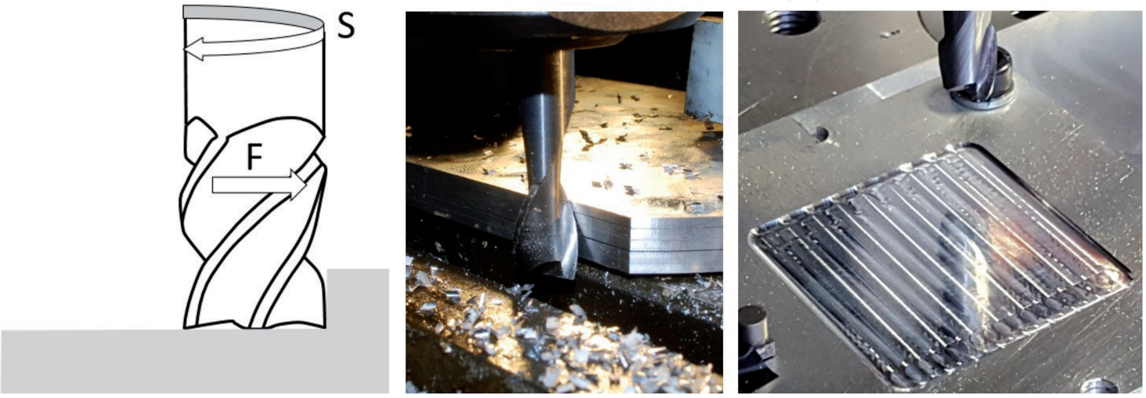

Figure 4.
Milling scheme and image of milling processes.

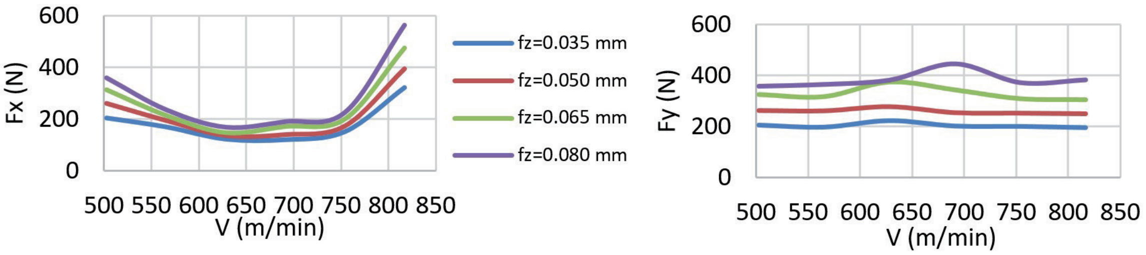

Figure 5.
Evolution of the cutting force components, obtained during the milling of a AA2024-T3 alloy, as a function of the cutting speed and the feed rate. Axial depth of cut is kept constant at 10 mm.

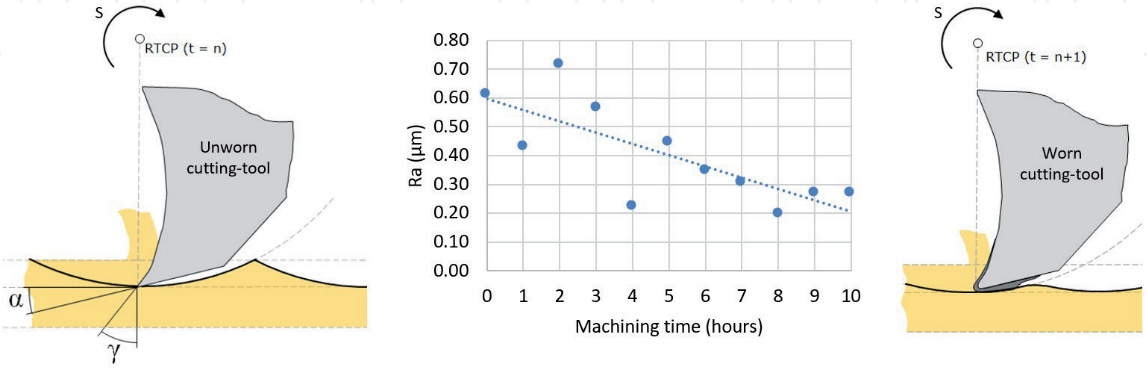

Figure 6.
Roughness average evolution during the milling of an AA2024-T3 alloy.

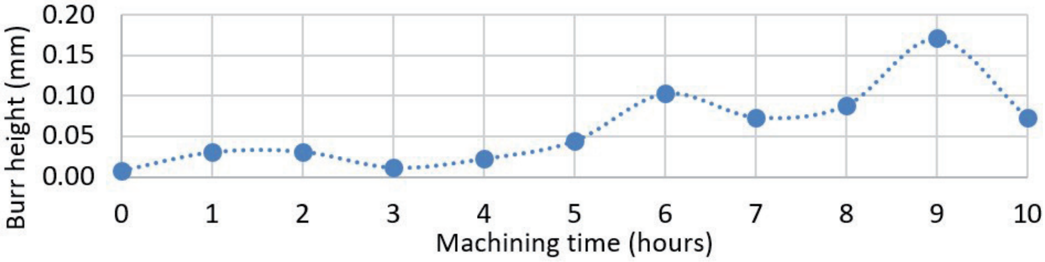

Figure 7.
Burr height evolution during the milling of an AA2024-T3 alloy.

cutting-tools, with both flat and toroidal tips, work much better laterally, with axial depth of cut between (50–150% diameter). However, these depths of cut also depend on the conditions described in the previous paragraph [45].

3.2 Advanced milling techniques

Nowadays there is a great interest in the machine intelligence. In this sense, different monitoring solutions are available to control the process. This measure allows to control the system state and with an adaptive control system, auto-regulate the cutting parameters.

For instance, an increase of the part vibration can be detected through the cutting forces or the acoustic emission frequency analysis will lead to a decrease of the surface quality, if it is detected on time and there is a model governing the case, the correct parameters can be changed so the situation is inverted [46].

Similarly, distance sensors are used to act on the depth of cut, so when the distance recorded is not in the expected range the system automatically modifies the depth of cut improving the dimensional accuracy [47, 48].

Finally, the cutting power and the cutting force signals can provide information about the tool wear or the process temperature improving the dimensional accuracy. It should also be considered that the variation on the cutting parameters can extend tool life slightly decreasing the material removal rate but increasing the process efficiency.

4. Turning of aerospace aluminum alloys

Despite turning processes are mainly applied in aerospace to critical elements, such as connecting bolts for gates and actuators built of titanium alloys, several non-critical elements are made of aluminum, as shafts, fasteners and spacers. These parts are also evaluated in terms of roughness, roundness, parallelism deviation and residual stresses to define their in-service behavior, but their requirements are less stringent than those for critical structural parts.

Turning is the simplest machining process, so its use is also essential to obtain preliminary results that may give an initial approximation to more complex processes like drilling and milling. That's why, this operation is commonly used to define the machinability of the alloys as well as the tool wear behavior in orthogonal or oblique cutting configurations, therefore its importance.

Several studies about the turning of aluminum alloys identify the importance of cutting parameters on the micro geometrical properties of the generated surfaces, evaluating them in terms of roughness average (Ra) [49]. Few of them correlate the residual stresses and machining of aluminum alloys [50], but the induced residual stresses are in all cases compressive not having a negative effect on the part. Finally, the roundness is usually measured from the parallelism deviation, since it is a relevant feature that can affect the in-service behavior.

4.1 Influence of the turning parameters

Turning is the most suitable machining process to create revolution surfaces by using a cutting-tool. This operation has two main movements to set the dimensions, one along the Z axis of the stock (F) and another, along the X axis, where the depth of cut (d) is set. At the same time, the tangential cutting speed is produced by the rotation of the part (S) cutting the part. These three actions are represented in **Figure 8**.

Regarding the cutting parameters, they are defined by the same expressions that govern drilling and milling operations, but in this case, D is the diameter of the cylindrical part. Turning cutting-tools work with just one cutting-edge, simplifying Eq. (2) in Eq. (3), where f is the feed per revolution:

$$F = f \cdot S \tag{3}$$

These parameters have a direct impact on the micro and macro geometrical deviations as well as on the tool wear. Generally, better Ra results are achieved when low feed-rates and high cutting speeds are applied during short machining times (**Figure 9**).

Ra is also affected by the machining time (**Figure 10**). It gradually decreases due to the adhesive wear [51]. This mechanism modifies the initial tool geometry, due to the material adhered to the rake and clearance faces, that reduces the edge position angle [52]. This fact decreases the height of the peaks created in each step, producing a smoother surface, in a similar way that was exposed for milling.

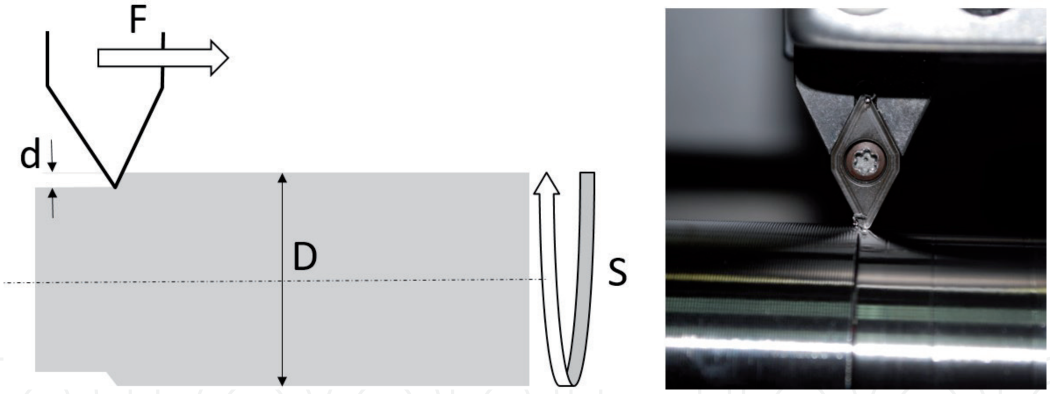

Figure 8.
Turning scheme and image of a turning process.

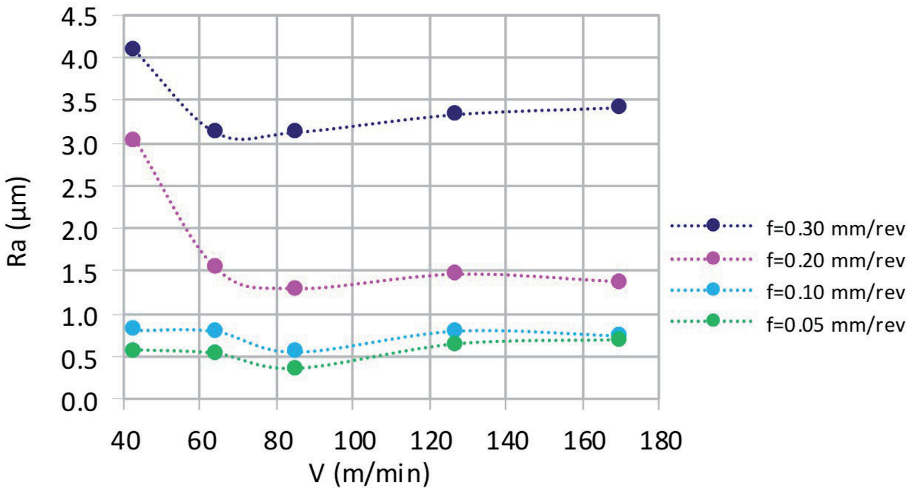

Figure 9.
Ra as a function of the cutting speed in the dry turning of AA2024-T3, depth of cut 1 mm and machining time 10 s.

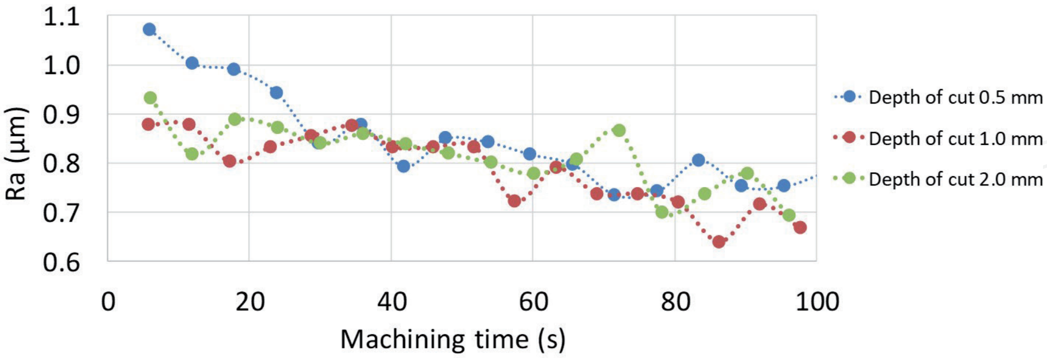

Figure 10.
Roughness average evolution in the turning of AA2024 as a function of the depth of cut.

Shape quality criteria for turning parts include roundness and parallelism deviations (*PD*). However, *PD* is easier to measure so its analysis is more usual [53, 54]. This criterion is also affected by the cutting parameters as is shown in **Figure 11** [55]. High cutting speeds achieve higher precision, while the feed rate has a combined effect in the deviations. The alloy used affects the machine dynamics, for instance the UTS of AA7475 (531 MPa) compared to AA2024 UTS (440 MPa) increase the deviation. For this reason, parametric surfaces are used to find the minimum *PD* by selecting the better cutting parameters.

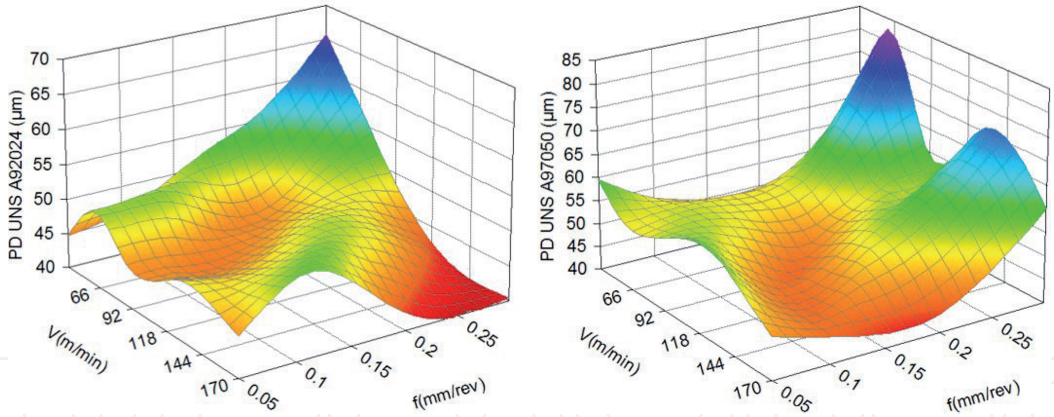

Figure 11.
Parametric surface PD (f,v) for AA2024 (left) and AA7050 (right).

Finally, as in the previous machining processes, the current trend in the machining of Al alloys is to minimize or eliminate the environmental impact reducing or avoiding the use of cutting fluids (dry turning) [56–58].

However, both turning and dry turning can have a negative impact on the in-service behavior of the parts or components manufactured, by reducing the functional performance of the process through the loss of the quality or the surface integrity [51, 56, 59]. Dry machining also has an impact on the wear behavior affecting the macro geometrical properties of the machined elements, in terms of dimensions or shape tolerances.

5. Cutting-tool wear in the machining of aluminum alloys

In the previous sections, the main machining techniques applied in the machining of aluminum aerospace alloys have been explained. For each machining process, it was indicated the influence of cutting-tool wear in the quality features of the machined parts. For this reason, it is relevant to explain the wear mechanisms that take place in the machining of aluminum alloys.

When the cutting-tool penetrates the part, it causes a compressive plastic deformation, which intensity can exceed the bond energy in certain planes, leading to shearing or sliding elements along planes. At the same time, the elastic recovery of the chip and the tribological interaction between the part-chip-tool provoke an exchange of heat that may thermally affect the tool properties. This change of properties or tool wear may be produced by different wear mechanism but all of them lead to possible changes in the cutting forces or in the dynamic stability of the process modifying, as a consequence, the properties of the surface generated [60–63].

The most common wear mechanism of aluminum alloys machining is secondary adhesion. This phenomenon takes place due to the temperature achieved in the process, the thermal conductivity (between 120 and 165 W/m°C) of the part-tool combination and the selected cutting speed. This mechanism, as well as the temperature and parameters associated, has been deeply studied for ferrous materials. Nevertheless, these studies are not directly applicable for softer materials such as aluminum. The high plasticity of this material favor chipping or notch wear for low cutting speeds [61, 62, 64].

Secondary adhesion appears divided in to two well-located phenomena, the Built-Up Edge (BUE) is located close to the cutting edge and the Built-Up Layer (BUL) is placed on the rake face [60, 65], as it is shown in **Figure 12**.

This adhesion process appears in different steps, which are represented in **Figure 13**. At the beginning of the machining process, a layer of material is adhered on the rake face of the cutting-tool, creating a BUL due to a mechanic-thermic effect of the cutting mechanism. Once it is formed, the cutting-tool geometry changes, promoting the growth of the adhered material over the cutting edge (BUE), which grows up to a critical thickness. Once this critical thickness is reached, BUE is mechanically extruded along the rake face, increasing the thickness of BUL and forming an adhered multilayer of material [66, 67].

Both the BUL and the BUE can disappear, be detached and be rebuilt, causing the gradually breaking of cutting-tool particles that are removed by the chip flow. This is therefore, a dynamic mechanism with successive layers of chip material welded and hardened. This cyclic behavior may change a gradual wear into a full weakening and even into the complete fracture of the tool [66, 67]. **Figure 14** shows the previous instants to the detachment of the adhered material, enriched with cutting-tool (WC-Co) elements in the machining of AA2024 alloy. This fact may also be favored by a weak edge or other types of tool wear, such as abrasion and diffusion.

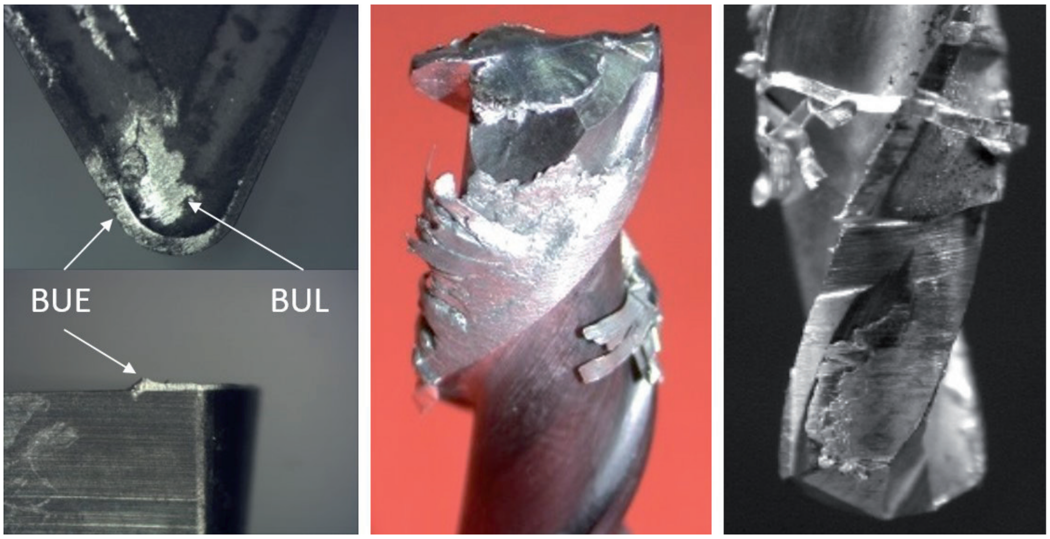

Figure 12.
Secondary adhesion in turning insert, milling and drilling cutting tools.

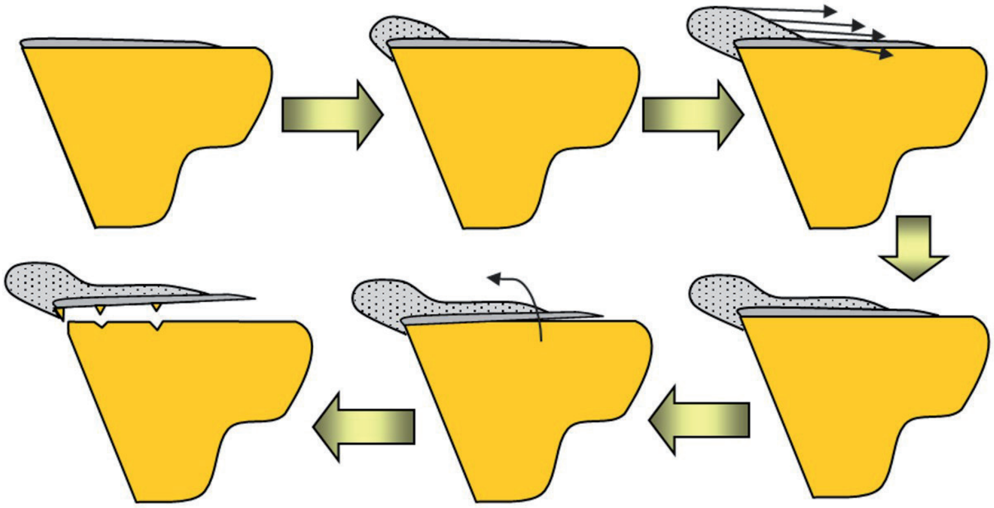

Figure 13.
Scheme of the secondary adhesion mechanism.

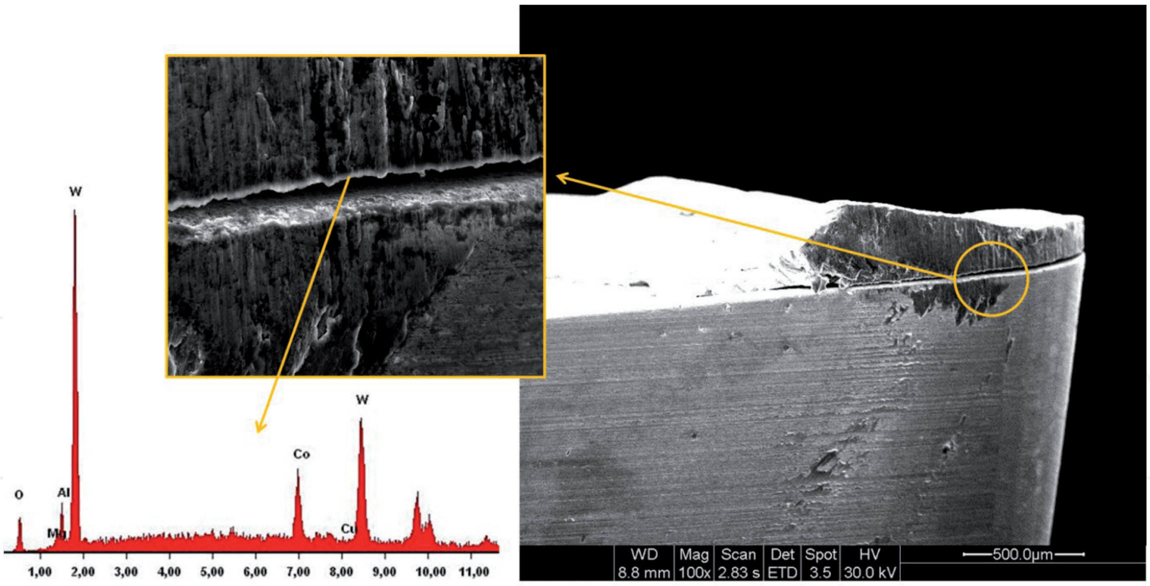

Figure 14.
Detachment of adhered material in the dry turning of AA2024.

If the temperature achieved is low the adhesion is not very significant, no matter if the chips are long or short. Otherwise, when a critical temperature is reached, other types of wear mechanisms such as diffusion may appear, increasing the synergy effect previously described [68, 69].

6. General remarks

The use of aluminum alloys, mostly forged, remains essential to build aircrafts. Al-Cu and Al-Zn are the most used alloys due to their excellent physicochemical-cost ratio properties. They come as raw material as sheets, blocks or cylinders that have to be drilled, milled or turned, in order to give them a final geometry.

Drilling, milling and turning are complex machining processes whose fundaments are based on the theory of metal cutting. The drilling process is fundamental in the manufacture of aircraft for the assembly of the structures using rivets. For specific applications with high quality requirements, OD and VAS techniques are used. Milling produces light components with a high accurate dimension, being mainly applied to monolithic parts that present deflection, overcuts, residual stresses and part deformation issues if the parameters are not properly selected. Turning generates surfaces of revolution, used to manufacture non-critical elements as shafts, fasteners and spacers.

The parameters that governs the machining processes, mainly cutting speed and feed rate, are highly related to the quality features usually required in aeronautics, surface quality, burr formation, macro geometrical deviations, form errors, etc. Generally, feed rate increase cutting forces and roughness while the effect of the cutting speed is related to thermal phenomenon and its influence depends on the machining regime. Feed rate selection usually comes with an agreement between different quality criteria and the process efficiency and high cutting speeds are the best choice whenever they are possible. Finally, both affects the tool wear produce by the secondary adhesion mechanism creating a BUL/BUE, which affects the macro and micro geometrical deviation. However, these effects can be diminished in different ways, using advanced tool coatings or projecting harmful cutting fluids in the cutting zone. In more advanced systems, machine intelligence is commonly used to look for adaptive control responses that auto-regulate the cutting parameters after the measure of the system state.

Conflict of interest

The authors declare no conflict of interest.

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