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ORIGINAL ARTICLE

Machining of aluminum alloys: a review

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Abstract The use of aluminum alloys in manufacturing industry has increased significantly in recent years. This is because primarily to their ability to combine lightness and strength in a single material. Concomitant to this growth, the machining of aluminum alloys has enormously increased in volumetric proportions—so that the chip volume represents up to 80 % of the original volume of the machined material in certain segments of the industry, like aerospace. In this context, knowledge of the characteristics of machinability of aluminum alloys is essential to provide industry and researchers with information that allows them to make the right decisions when they come to machining this fantastic material. The purpose of this review is to compile relevant information about the characteristics of machinability of aluminum alloys into a single document.

Keywords Aluminum alloys · Cutting forces · Cutting temperature · Surface integrity · Cutting tools · Cutting fluids

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1 Introduction

Aluminum (Al) is the third most abundant metal in the earth's crust and in its natural form is combined with oxygen and other elements [1]. It has a face-centered cubic (FCC) structure, has high ductility at ambient temperature, and is relatively easy to machine [2]. Compared to other engineering metals, aluminum has a low melting temperature about 660 °C [3]. Since around 1886, when Al alloy was first produced by the Hall-Heroult method of electrolytic reduction, aluminum production rose from just over 45,000 tons to more than 25 million tons today [4]. A good reference of the growth of aluminum production is its application in the automotive industry. Figure 1 illustrates the growth of the quantity of aluminum used per vehicle over the last 50 years, an eightfold increase, and according to Ducker Worldwide cited by Drive Aluminum (http://www.drivealuminum.org/vehicle-uses/passenger-vehicles), today figures are about 180 kg per passenger vehicle with an estimation of 70 % increase up to 2025 (or 250 kg per vehicle).

After production, aluminum can be found in the primary state or in the form of alloys with other chemical elements. Primary aluminum is produced by electrolysis of aluminum oxide (alumina) at a temperature range of 950 to 980 °C (the

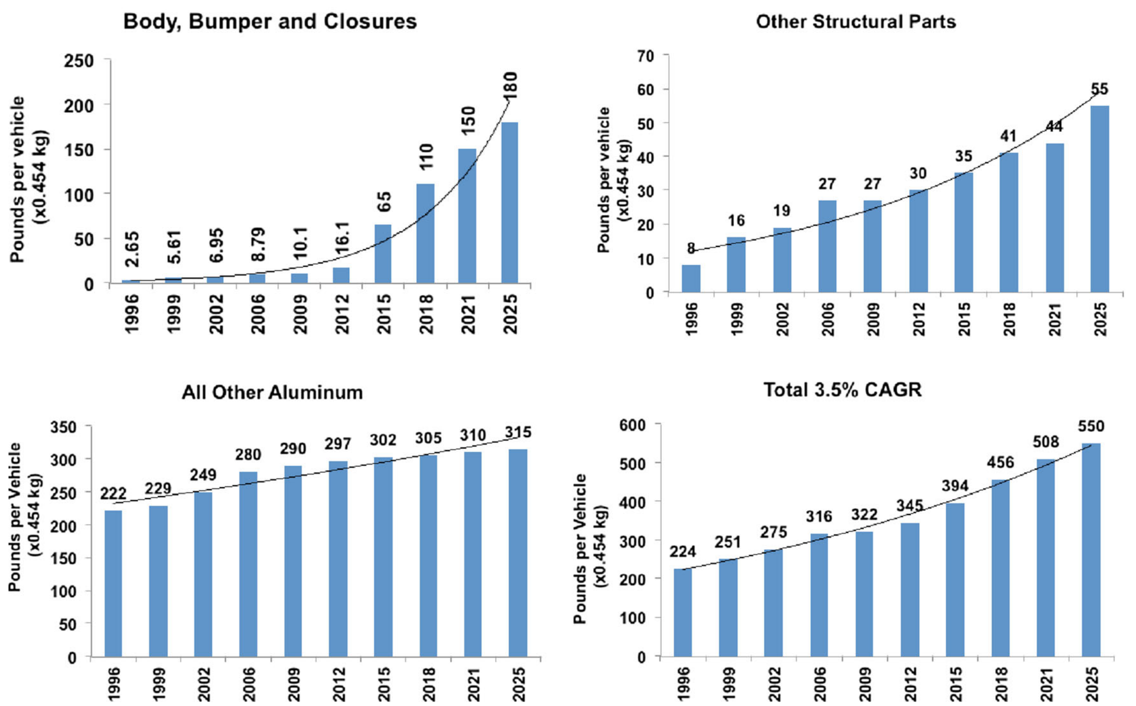

Fig. 1 Average use of aluminum in the car industry [5]

Hall-Héroult process) [6, 7]. Alloys can be formed through reaction with chemical elements such as copper, zinc, manganese, silicon, magnesium, iron, etc. to give primary aluminum new mechanical properties [8].

Aluminum alloys have been employed in aircraft construction since 1930, mainly those of classes 2xxx, 7xxx, and 6xxx [9, 10]. These alloys are responsible for most of the machining activities in the aerospace and automotive industries [11, 12], since they present a high strength-to-weight ratio and can advantageously substitute steel and cast iron in the fabrication of parts [2, 13]. Their low weight reduces the environmental impact caused by energy consumption [14]. Among the main applications of aluminum alloys are the fabrication of car wheels, panels, and structures using 6061 alloy [11], pistons, brake discs, brake drums, and piston sleeves using SiCp (silicon carbide hard particle) or Al_2O_3p (aluminum oxide hard particle) reinforced 6061 aluminum alloy [15] or aluminum-silicon alloys containing up to 20 % Si [16]; aircraft structures made of 7050-T7451 aluminum alloy [17]; fittings, gears, and shafts made of 7075-T6 aluminum alloy [18, 19]; skin of aircrafts made of 2024-T3 aluminum alloy [20]; and rocket chamber made of 2014 aluminum alloy [21]. In addition, Bishop et al. [22] and Ozcatalba [23] reported out that sintered aluminum alloys, due to their high strength-to-weight ratio and specific characteristics, are attractive materials for the automotive industry. Other applications are distributed in the civil construction; in electrical, electromechanical, electronic, and packaging industries [24]; and in the production of nanostructures of high mechanical strength and thermal stability, as is the case of 6061-T6 aluminum alloy [25].

2 Different workable alloys

Aluminum alloys are divided into workable alloys, i.e., those that undergo hot or cold mechanical working process, and cast alloys, i.e., where the final shape of the part is obtained by casting process. To classify workable and cast alloys, the Aluminum Association uses numerical designations that identify the class, the main alloying element, and modifications of the alloy within the class [3, 6]. Table 1 exemplifies the designation system adopted for workable aluminum alloys. Cast aluminum alloys are classified by a similar process.

Compared to ferrous alloys, aluminum alloys are generally considered to have good machinability. However, their ductility is responsible for increasing the machining forces, for poor surface finish and difficult chip control, while the high contents of silicon in aluminum-silicon alloys are responsible for the high wear rates of cutting tools [26].

3 Characteristics and properties of aluminum and its alloys

Aluminum alloys have about one third of the density and modulus of elasticity of steels, high thermal and electrical conductivity, high corrosion resistance [5], high friction coefficient, excellent formability, low melting point, high magnetic neutrality, and a wide range of possible surface treatments [8, 27]. Table 2 presents some of the physical and mechanical properties of several aluminum alloys and different materials for comparison.

Table 1 Main series of workable aluminum alloys according to the Aluminum Association [3]

Series	Main alloying elements
1XXX	Commercially pure aluminum >99 % purity (non-heat treatable)
2XXX	Copper (heat treatable)
3XXX	Manganese (non-heat treatable)
4XXX	Silicon (non-heat treatable)
5XXX	Magnesium (non-heat treatable)
6XXX	Magnesium and Silicon (heat treatable)
7XXX	Zinc (heat treatable)
8XXX	Other elements
9XXX	Not used

The mechanical properties of aluminum alloys, particularly hardness and strength, are markedly improved by precipitation of the elements in heat-treatable aluminum alloys and by hardening in mechanically workable alloys [9, 34–36]. Lee et al. [37] claim that the 6061 aluminum alloy, a typical AlMgSi (aluminum-magnesium-silicon) alloy, is an age-hardening alloy that can be strengthened appreciably by heat treatment. The aluminum alloys of the 2XXX, 6XXX, and 7XXX series stand out among the group of heat-treatable alloys, while the aluminum alloys of the 1XXX, 3XXX, 4XXX, and 5XXX series, such as the 1100-H12, 3003-H12, and 5052-H12 alloys, stand out among the group of mechanically workable alloys [38].

Another way to increase mechanical strength, stiffness, and wear resistance is by adding oxides, carbides, and nitrides to the aluminum matrix, such as Al_2O_3p, SiCp, or TiN (titanium nitride), in various proportions [6, 18, 30, 39]. The aluminum matrix composites, such as SiCp, Al_2O_3p, aluminum silicates, and graphite [40], possess light-specific density, high strength, low coefficient of thermal expansion, good wear resistance, high module of elasticity, low ductility, and high thermal conductivity [41, 42] and can enable an unreinforced aluminum with higher modulus, lower thermal expansion coefficient, improved tribology characteristics, and higher hardness.

The designations indicating the treatments to which alloys are subjected are as fabricated (F), annealed (O), strain hardened (H), solutionized (W), and thermally treated (T). Numbers after the letter indicate a specific treatment [8]. For instance, H1—only strain hardened, H2—strain hardened and partially annealed, T1—cooled from a high-temperature forming process and naturally aged to a stable condition, and T2—cooled from a high-temperature forming process, strain hardened, and naturally aged to a stable condition [27].

4 Machinability of aluminum alloys

To understand machining is essential to be familiar with the chip formation process, very well discussed by Trent and Wright [26] in their masterpiece *Metal Cutting Principles*. When ductile materials (such as aluminum) are machined, a large chip-tool contact area is formed and the chip thickness ratio is high which contribute to augment cutting forces, machining power, and heat generation and generate long and stringy chips as well as poor surface finishing. On the other hand, the shear strength is relatively low which even with large chip-tool contact areas, machining aluminum is considered relatively easy. This item will present and discuss the main response machining parameters, which are relevant to understand the behavior of aluminum alloys in machining. The following aspects will be covered: forces and stresses, power consumption, temperature, surface integrity, recommended cutting tools, tool wear, and cutting fluids and chip control. In each topic, the viewpoints of several researchers

Table 2 Mechanical properties of some aluminum alloys and a free-machining steel [17, 28–33]

Alloy	Ultimate strength (MPa)	Yield strength (MPa)	Elongation % (50 mm)	Hardness
6061 (L)	365	342 (0.2 % off)	11.5	HV121 (200 g)
6061 (T)	352	326 (0.2 % off)	12.4	HV125 (200 g)
6061 SiCw (silicon carbide whisker) (L)	608	454 (0.2 % off)	2.3	HV167 (200 g)
6061 SiCw (T)	418	353 (0.2 % off)	1.8	HV179 (200 g)
6061 5 % SiCp (L)	371	347 (0.2 % off)	11.2	HV128 (200 g)
6061 5 % SiCp (T)	347	331 (0.2 % off)	9.5	HV132 (200 g)
6061 10 % SiCp (L)	378	352 (0.2 % off)	10.7	HV134 (200 g)
6061 10 % SiCp (T)	354	336 (0.2 % off)	8.6	HV138 (200 g)
7050-T7451	510	455 (0.2 % off)	10	HV162 (200 g)
2011-T3	379	296 (0.2 % off)	10	BHN 95
SAE12L14: steel	613	414	10	BHN 67

L longitudinal direction, *T* transversal direction, *HV* hardness Vickers, *BHN* Brinell hardness number are presented, raising the main problems and indicating right decisions to have the process under control.

4.1 Forces and stresses in the machining of aluminum alloys

Cutting forces in the machining of aluminum alloys are usually low compared to those of ferrous alloys due to their lower mechanical strength, which may generate 70 % lower specific cutting pressures than in the machining of steels [43]. However, it should be noted that this difference is minimal among aluminum alloys and depends on their chemical composition and physical properties [44–46].

Any thermal or mechanical treatment or even the addition of chemical elements that increase the hardness and mechanical strength of an aluminum alloy reduce the chip-tool contact area and may thus reduce the machining forces [26, 47, 48]. This reduction will, of course, compensate the effects of the increase in mechanical strength and the reduction in contact area. In some aluminum alloys, hard particles in proportions of up to 15 % vol. and aging processes, provided the latter do not cause coalescence of the precipitates, may reduce cutting forces by at least 10 % [11, 48]. Increasing the cutting speed normally reduces the machining forces, regardless of the strength of the aluminum alloy [11, 49, 50], since the shear stress in the primary shear zone and in the flow zone at the secondary shear region decreases with increasing cutting speed due to an associated increase in cutting temperature [51–53]. Although high cutting speeds contribute to lowering machining forces, in high-speed cutting (HSC), excessive increase in deformation rates may increase the machining forces [2, 54–56] (Fig. 2).

Other situations that may lead to augmented machining forces with increasing cutting speeds are excessive flank wear due to the presence of hard particles in the Al alloy [18]. This is in agreement with Lahres et al. [57] during the dry milling of the AlSi10Mg casting alloy where sticking of the workpiece material to the tool's cutting surface was pronounced. However, this problem may be minimized by the application of minimum quantity lubrication or oil-jet lubrication [58].

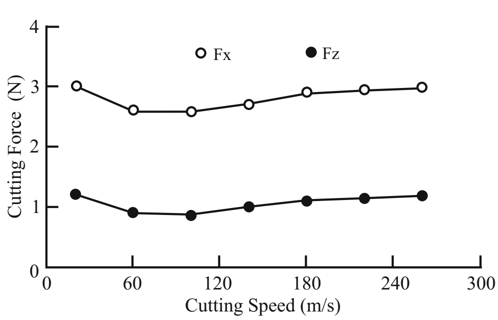

Fig. 2 Cutting force variation with cutting speed [54]

Increasing the feed rate and/or depth of cut increases the areas of the primary and secondary shear planes, hindering the shearing of the material and increasing the machining forces [19, 49, 50]. Even so, the stresses on the secondary shear plane may be about 30 % lower than those on the primary shear plane, since higher temperatures occur in the former [53].

Tool geometry, particularly rake angle and nose radius as well as the geometric changes caused by wear and by built-up edges (BUE), strongly influences the machining forces of aluminum alloys. An increase in the rake angle, whether through the fabrication process or the presence of a BUE, reduces chip-tool contact in the interface region, which in turn reduces the machining forces [59, 60]. Shankar et al. [25] reported signs of strain hardening in the interface region with reduction of the rake angle when machining 6061-T6 aluminum alloy. This may be the cause of the increase in cutting resistance in response to a diminishing rake angle. Cutting edges with large radius generate small rake angles at the beginning of cutting—at which moment the cutting forces increase [61]. Flank wear can generate excessive machining forces, as reported by Tang et al. [17] during the milling of aluminum alloy 7050-T7451, since flank wear increases the workpiece-tool contact area (Fig. 3).

When machining aluminum alloy, flank wear can be reduced, surface finish improved, and machining forces minimized by improving the sharpening technique of cutting edges [16] or by reducing the surface roughness of the diamond coating (CVD, chemical vapor deposition) tools after polishing [62]. Coated or solid diamond cutting tools, due to their high hardness and low chemical affinity for aluminum, and hence low adhesiveness, contribute to reduce machining forces, as reported by Roy et al. [61] when machining of pure aluminum with several types of tool materials: (1) as received, (2) TiC (titanium carbide)—CVD, (3) TiN—CVD, (4) Al_2O_3 (aluminum oxide)—CVD, (5) AlON (aluminum oxynitride), (6) TiB_2 (titanium diboride)—PVD, and (7) diamond—HFCVD (hot filament chemical vapor deposition) (Fig. 4).

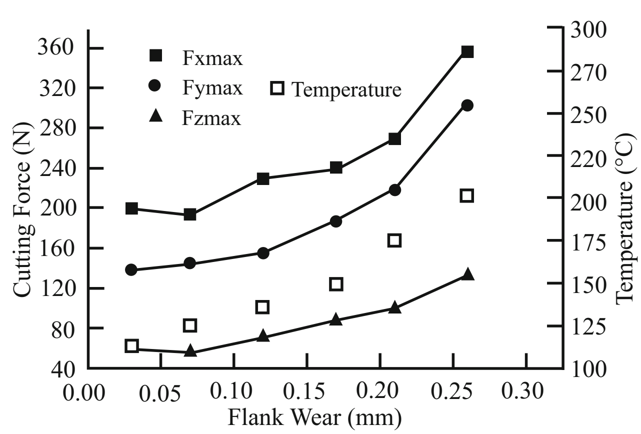

Fig. 3 Effects of flank wear on cutting forces and temperature in milling of aluminum alloy 7050-T7451 [17]

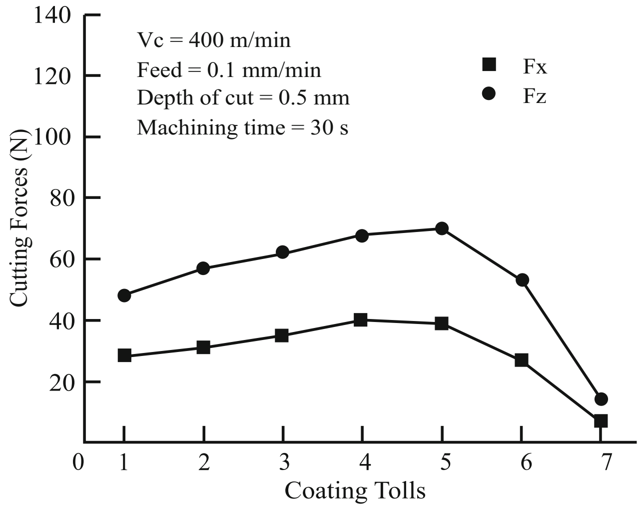

Fig. 4 Behavior of the cutting forces generated by different cutting tools in turning of aluminum [61]

4.2 Power generated when machining aluminum alloys

The cutting forces generated when machining aluminum alloys is about one third of that when machining steel; conversely, the energy required is much higher due to the need to operate at extremely high cutting speeds [43]. However, the specific cutting energy is very low because large volumes of material are removed due to the high feed rates and cutting speeds employed in order to achieve higher productivity [2, 54, 55]. Rao and Shin [63] confirmed these results during high-speed face milling of 7075-T6 aluminum alloy.

The specific cutting energy tends to increase as the hardness and mechanical strength of machined materials increases and decreases as the feed rate and cutting speed increase, since the former increases the material removal rate while the latter decreases the cutting force. This behavior was confirmed by Ng et al. [19] in the orthogonal cutting of 7075-T6 aluminum alloy (Fig. 5).

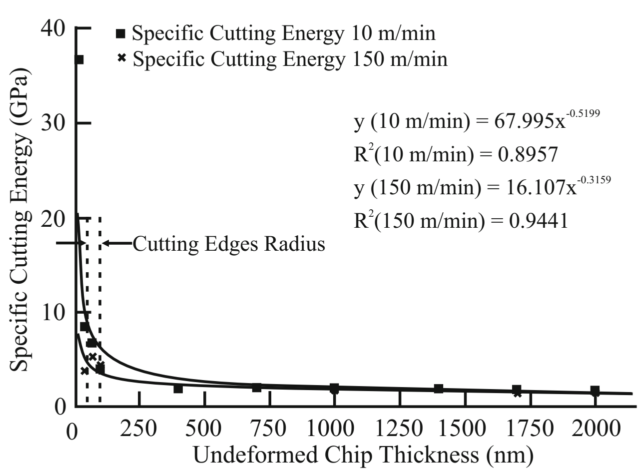

Fig. 5 Effect of undeformed chip thickness and cutting speed on specific cutting energy of an aluminum alloy [19]

The cutting power depends on the loads on the shear planes, which in turn depend on the mechanical strength and on the presence of free-cutting elements in the alloys, in addition the cutting conditions employed [52]. Increasing the cutting speed (it promotes sufficient softening of the alloy and prevents sticking in the cutting region), the rake angle, and the hardness up to a given value, as well as adequate lubrication, tends to reduce the cutting power. Oil-jet cooling or even the presence of free-cutting elements such as Pb (lead), Bi (bismuth), In (indium), or Sn (tin) in proportions of 0.10 to 1.0 % wt., combined with adequate cutting speeds in aluminum alloy drilling, can result in a significant reduction of the power since they promote lower adhesiveness and facilitate chip removal [64].

The cutting power tends to increase with increasing feed rates and the machined length, since the machining forces tend to increase in both situations—in the latter due to the increase in tool wear. This situation was reported by Braga et al. [65] when drilling aluminum alloy with 7 % wt. Si.

4.3 Temperature generated when machining of aluminum alloys

Cutting temperature is not a major problem in the machining of aluminum alloys, because their low melting point is not able to alter the mechanical properties of cutting tools [66]; in other words, it is not able to cause high tool wear rates [67], although tool life is still controlled by the cutting temperature [68]. However, an increase in cutting temperature to a given level may generate microstructural alteration, residual stresses in the surface layer, tolerance errors, and distortions and accelerate tool wear and sticking of the work material onto tool edges [67]. Higher temperatures can also increase the ductility of the material, which produce longer chips [23] and promote chemical interaction between aluminum and the tool coating material to promote inter-atomic diffusion [61]. According to Yousefi and Ichida [54], the heat generated increases the cutting temperature as the cutting speed increases. This may approach the melting temperature of the work material, depending on the mechanical properties of the aluminum alloy [69]. Workable aluminum alloys with silicon contents varying from 5.5 % wt. to 12 % wt. have recorded temperatures from 350 to 750 °C in several machining processes [70, 71]. Tang et al. [17] observed a significant increase in residual stress on the surface of machined parts due to increased flank wear resulting from the elevation of the machining temperature.

The highest cutting temperatures are obtained in the machining of aluminum alloys with higher mechanical strength—workable or cast [72, 73]—preferentially situated in the secondary shear zone, in regions distant from the cutting edge [17]. Moreover, in the combined presence of high mechanical strength; percentages of Si, SiCp, and Al_2O_3p varying from 10 to 20 %; and high cutting speeds, cutting temperatures tend to rise abruptly [53, 73] as the hard particles produce intermittent friction against the tool surface [26]. The cutting speed generally increases the machining temperature because it increases the shear plane deformation rate [52, 65]. An increase in the feed rate, provided it does not cause an excessive increase of the effective chip-tool contact area—which generates greater heat dissipation between the tool—workpiece interface—contributes to the elevated temperature [53]. Figure 6 illustrates this behavior.

On the other hand, in the drilling of 2024-T351 aluminum alloys (finite element simulations), Nouari et al. [68] observed that although the feed rate increased, there was no tendency for stabilization of the temperature at the chip-tool interface (Fig. 7). This is likely due to the increase in machining forces and changes in thermal conductivity and chip morphology, which are common occurrences in the drilling process.

Alteration of tool geometry such as wedges with large rake (e.g., 10^0–25^0) and clearance angles up to given levels (e.g., 4^0–7^0), low friction coefficients, and the presence of free-cutting elements such as lead (0.17 % wt.) inhibit excessive increase of machining temperature since these conditions facilitate chip flow over the tool rake face [26, 64, 74]. It has been found that increasing the cutting speed improves the action of free-cutting elements by facilitating their melting, which improves their chip lubrication, removal, and embrittling effects [64]. However, tool geometric changes such as those caused by flank wear increase the cutting temperature since they increase the shear plane cutting forces and favor the appearance of a third source of heat between the clearance surface and the machined workpiece [17, 52].

Although the cutting temperature is lower comparing with work materials like alloyed steels, titanium and nickel alloys, for instance, the thermal conductivity of aluminum and its alloys is higher, then the heat generated spreads quickly for the whole workpiece body and increases its temperature at sufficient values to promote warping, depending on the workpiece fixture system. Aiming to eliminate this undesirable effect, the cutting fluid with high coolant ability needs to be applied at high flow rates in order to maintain the wok material at a few Celsius degrees above the room temperature. This problem is rather common when milling at high cutting speeds with PCD (polycrystalline cubic diamond) tools, for example, in engine heads, blocks, and transmission cases, among others.

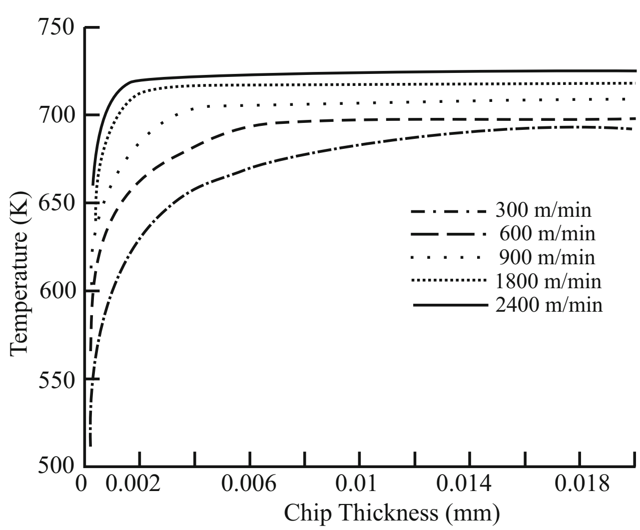

Fig. 6 Influence of chip thickness and cutting speed on the temperature in the secondary shear zone for 7075-T6 aluminum in a half immersion up-milling [53]

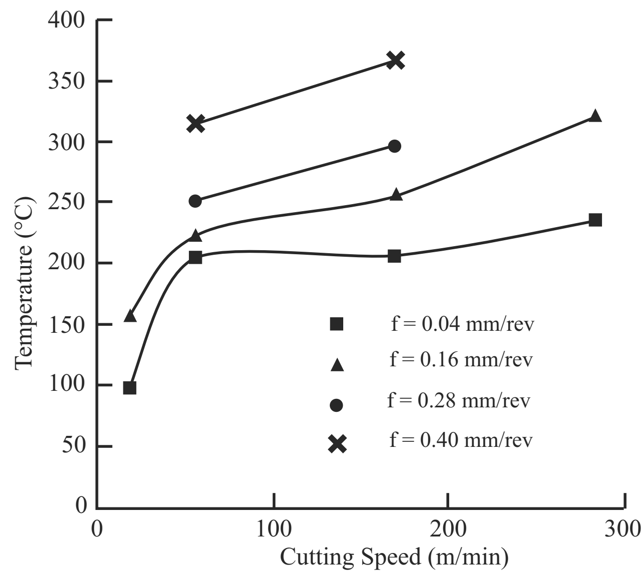

Fig. 7 Influence of the feed rate and cutting speed on the temperature in drilling of the AA 2024-T351 [68]

4.4 Surface integrity in the machining of aluminum alloys

In the machining of aluminum alloys, the main limiting factor of the material removal rate (feed rate and depth of cut) can be the surface integrity [75–78]. Normally, surface roughness in the machining of aluminum is considerably influenced by the alloy's hardness and microstructural characteristics [79, 80]. Generally speaking, the higher the hardness of the machined alloys, the lower their surface roughness [11, 73, 81], since hardness reduces sticking on the tool's cutting surface. However, when hardness is the result of hard particles embedded in the aluminum matrix, e.g., proportions of 20 % vol. SiCp [18] and 15 % vol. SiC and 12 % wt. Si [50], there may be BUE formation and random pullout of hard particles from the matrix, which adhere to or scratch the machined surface [43]. The high chemical affinity of aluminum alloys for materials such as TiC, TiN, TiB_2, Al_2O_3, and AlON causes the machined material to accumulate on the surface of the tool. This tends to worsen the surface roughness of this material during machining due to the constant release of particles adhering to the surface of the machined workpiece [61]. This occurs in the dry, flood cooling, and MQL (minimum quantity lubricant) conditions [58].

The undesirable effects of ductility and BUE on the surface finish of aluminum alloys, i.e., high roughness values and large burrs, can be minimized by selecting suitable cutting tools and conditions such as high cutting speeds, diamond-based tools with low chemical affinity to aluminum [57, 61], intense use of cutting fluid, large rake angles, low feed rates, and larger tool nose radius [74, 82, 83]. These situations favor chip flow on the cutting tool surface and inhibit the formation of BUE [84]. However, Hamade and Ismail [2] do not recommend the use of high cutting speeds in the drilling of aluminum alloys because they may increase the material's ductility as a result of rising temperatures, which may cause clogging of the drill grooves. Ciftci et al. [84] observed when machining aluminum alloys with high SiCp contents, also observed poor surface roughness at higher cutting speeds due to flank wear and the release of hard particles. This behavior is strongly dependent on the size and distribution of the hard particles.

The addition of about 0.5 % wt. of a suitable free-cutting element to aluminum alloys, such as tin or bismuth, combined with high cutting speeds has proved effective in reducing surface roughness values during machining since this combination embrittles the chip and facilitates its sliding over the tool surface [85]. However, cutting fluid has proved more effective in reducing surface roughness values than the addition of free-cutting elements [64] (Fig. 8).

Another common problem in the machining of aluminum alloy is warping, as mentioned when discussing the cutting temperature (item 4.3). This occurs mainly in the milling of very robust or thin-walled workpieces, as in the case of aircraft components and engine cylinder blocks. There are no scientific reports available to address the cause or propose solutions, thus representing a challenge for professionals in this area. However, it is not difficult to imagine that the problem is caused by excessive loadings associated with high temperatures. Therefore, measures to reduce cutting loads and machining temperature should help in minimizing or eliminating the problem. Warping can also depend on other factors such as the alloy's properties and geometry, the tool material, and especially the type of operation and the cutting conditions employed.

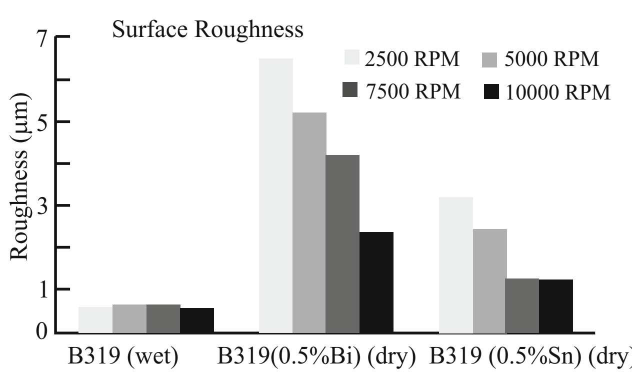

Fig. 8 Effect of drill speed and lubricant condition on the surface roughness of modified aluminum alloys [64]

4.5 Cutting tools for machining of aluminum alloys

The tools employed for machining aluminum alloys range from high-speed steels, straight grade (K) of cemented carbides (mainly fine grained) due to its low chemical affinity for aluminum, which considerably improves the surface finish, and diamond-based tools [43]. The latter tool considerably reduces the adherent layer accumulated on the tool edge in the chip flow direction [86]. K10 grade is recommended for turning, milling, drilling, and boring of silicon aluminum alloys [87]; K20 for interrupted cutting with abrupt temperature changes; and K01 for cutting aluminum alloys with abrasive particles [88]. Liew et al. [35] assert that the K20 grade is widely used in the machining of aluminum and other nonferrous metals. In their cutting tests on the aluminum alloy Al 2014-T4, they used cutting tools with a rake angle of 6°. Today, the new ISO 513 [89] standard designates the letter N, instead of K, for the class of these cemented carbide tools used in the machining of non-ferrous aluminum alloys. Thus, the aforementioned K01, K10, and K20 tools are now designated N01, N10, and N20, respectively.

Cutting speeds varying from 600 to 800 m/min and rake angles from 6° to 20° can be employed in the turning of aluminum alloys without hard particles and with cemented carbide tools. Toropov et al. [87] used K10 with rake angles of −5°, 0°, 5°, 10°, and 20° and a cutting speed of 800 m/min during turning of Al6061-T6 (magnesium and silicon aluminum alloys). The two latter angles showed smaller burr height than the three formers.

Rake angles of 0° to 7° and cutting speeds of 20 to 450 m/min are recommended for aluminum alloys containing about 12 to 15 % vol. of hard particles (SiCp and Si), regardless of the type of tool material [26]. Manna and Bhattacharayya [50] performed turning tests with a maximum cutting speed of 225 m/min in the Al/SiC (12 % wt. Si and 15 % vol. SiCp) using an uncoated tungsten carbide K10 (now N10) with a rake angle of 5°. Coelho et al. [72] performed drilling and reaming with a cutting speed between 37.7 and 75.4 m/min using natural diamond, PCD, and K10 (N10) in aluminum alloy with 7 % wt. Si; 2.8 % wt. Si and in the reinforced MMC (metal matrix composites) wrought aluminum alloy, AA2618 (15 % vol. SiCp). Ciftci et al. [84] performed turning tests in the Al-2014 alloy matrix composites containing 8 and 16 % vol. SiCp using K10 (N10) inserts (5° rake angle) and cutting speeds ranging from 20 to 80 m/min. Kamiya and Yakou (2008) [90] carried out turning tests with a maximum cutting speed of 1.5 m/s using K10 (N10) carbide cutting tool inserts with 5° rake angle in the aluminum alloy 4032-T651 (11.5 % wt. Si) and Al 12 % wt. Si.

Tools with positive geometries and deep flow grooves, such as helical drills with helix angles of about 40° to 48° and point angles of 118° to 140°, should be used for drilling aluminum alloys in order to facilitate chip flow and prevent material from sticking to the drill's rake face [43, 67, 68]. Hamade and Ismail [2] reported that standard twist drills with a helix angle of approximately 30° are used in drilling hard aluminum alloys and high (quick) helix drills having helix angles of approximately 40° are used for drilling lower strength aluminum alloys. Wain et al. [91] used a HSS (high-speed steel) twist drill with 118° point angle and 37.5° helix angle for the drilling of casting aluminum alloy A319 (6 % wt. Si). Dasch et al. [70] have chosen two-flute, high-helix, 118° point angle HSS drills and three-flute, 30° helix, 130° point angle of carbide drills to conduct drilling tests in the cast aluminum alloy B319 (6.5 % wt. Si). Dasch et al. [64] used a drill with three-flute, 30° helix, 130° point angle, solid carbide drills for drilling of aluminum alloy containing 5–7.5 % wt. Si.

Diamond-based tools have proved to be very efficient in the machining of aluminum alloys in general and can reach cutting speeds exceeding 600 m/min [26, 87]. For machining of high-mechanical-strength aluminum alloy even without hard particles, usually a rake angle of 0° is used [92]. Polycrystalline diamond (PCD) tools are more suitable for machining alloys containing 10 % vol. to 20 % vol. of ceramic particles or Si contents varying from 12 % wt. to 21 % wt. because they are resistant to thermally activated wear mechanisms [16, 93], since they can reach a three to fourfold increase in hardness than ceramic particles such as SiCp [94] and can be about fourfold harder than a cemented carbide tool (K10). Moreover, the thermal conductivity of cemented carbide tools is about fourfold lower than that of PCD tools, thus generating higher cutting temperatures [72].

In view of the need for more complex tools that cannot be manufactured by the conventional solid diamond tool fabrication methods, diamond-coated tools—due to their high hardness at high temperatures, low friction coefficient, low adhesiveness, high thermal conductivity, and chemical stability—have been identified as promising technologies to improve the machinability of aluminum alloys. These latest tools minimize BUE, abrasive wear, and cutting forces and provide good surface finish as well as enhance tool life [15, 70, 95]. Yoshikawa and Nishiyama [96] used K10 or K20 (today N10 or N20) cemented carbide (rake angle 6°) as a substrate for diamond layer (CVD) for turning aluminum alloys with 12 % wt. Si and 18 % wt. Si using a cutting speed of 600 m/min. Itoigawa et al. [97] used a sintered diamond tool with 0° rake angle and a K10 (N10) grade of carbide tool with 5° rake angle for turning aluminum-silicon alloy (AlSi5) at a cutting speed ranging from 200 to 800 m/min. The latter showed a specific force smaller than the former. These results could be an indication that the rake angle is an important variable here.

Chattopadhyay et al. [98] used several cutting tool materials with different tool surface qualities in dry turning of an aluminum alloy. They reported that the HFCVD (hot filament chemical vapor deposition) diamond-coated tool had the lowest level of deterioration although it did not produce the best surface quality. This corroborates once again that the low chemical affinity of diamond with the aluminum alloy is the prevailing factor in improving the machinability.

Nanocrystal diamond coatings are more resistant and cause less adhesion of material to the cutting surface than microcrystal coatings, since they present lower roughness, lower stress concentrations, lower crack propagation ability, and higher adhesiveness to substrates due to random grain growth. In addition, they can provide similar levels of surface roughness as those of solid PCD in the machining of aluminum alloys with silicon contents of about 18 % wt. [99]. Other types of coatings that have ensured good machinability of aluminum alloys containing silicon are TiN/TiCN (titanium carbon nitride) coatings with a hardness of about 3000 HV250 [100]. Karakas et al. [101] during milling of Al-4 % Cu/B_4Cp composites (20 vol%. B_4Cp: boron carbide hard particle and 80 vol% Al-4Cu) used the following tools: (a) uncoated K20 (N20), (b) K20 (N20) triple-coated (TiCN + Al_2O_3 + TiN) CVD, and (c) K20 (N20) double-coated (TiN + TiAlN, titanium aluminum nitride) CVD. All these tools with a rake angle of 0° were tested under a maximum cutting speed of 286 m/min. The cutting tool (b) showed the lowest levels of flank wear.

Due to their high affinity (solubility) for aluminum alloys, ceramic tools containing nitrides such as TiN, TiAlN, CrN (chromium nitride), Si_3N_4 (silicon nitride), and Ti [61, 67] are not recommended for machining aluminum alloys, since they encourage adhesion and the formation of BUE [12, 60].

4.6 Tool wear when machining of aluminum alloys

The greatest problem of cutting tool wear occurs in the machining of aluminum alloys containing hard particles (Al_2O_3p, SiCp, and Si) [67]. With other alloys, even using less resistant tools such as high-speed steel, a good tool life can be attained at a cutting speed of about 300 m/min [26].

The intermittent contact of hard particles against the cutting surface causes high machining temperatures that lower the resistance of cutting tools thereby accelerating adhesive and abrasive wear mechanisms [26]. The disintegration of tool particles occurs next to the cutting edge. Normally, the proportion of hard particles of silicon carbide in workpiece matrices varies from 10 to 20 % of the alloy volume [18] and its hardness can be about 1.5-fold higher than that of a K01 cemented carbide tool [88]. This will drastically lower the machinability of aluminum alloys. Narahari et al. [102]

reported that the amount of SiCp has a significant effect on the cutting tool performance and also affects the initial rapid flank wear, even when using PCD tools. Coelho et al. [72] reported high levels of flank wear in the drilling of aluminum alloys containing hard particles of silicon and silicon carbides using PCD tools (Fig. 9).

Flank wear rate increases with the size and proportion of Si precipitates and hard particles (Al_2O_3p and SiCp) in the matrix of aluminum alloys [85, 96]. However, soft matrices that facilitate the release of precipitates produce less wear [43]. The control of silicon particle size and distribution in the matrix of cast aluminum alloys depend on the cooling rate [75].

The low melting point of aluminum and its alloys leads to relatively low machining temperatures, thus practically inhibiting the development of thermally activated wear mechanisms or processes such as diffusive wear, superficial plastic deformation by shearing at high temperatures, and plastic deformations of the cutting edges under high compressive stresses [26, 52].

The type of wear that prevails in a specific machining operation depends on the tool material, the machined workpiece, and the cutting conditions employed. Flank wear is common when machining alloy and is normally developed by adhesive and abrasive wear mechanisms [18, 61]. This behavior was also observed by Sreejith [58]. Abrasive wear mechanism is caused by the presence of hard particles in the cutting region, which may originate from the matrix containing hard precipitates or from the cutting tool itself, when hard particles are detached by attrition wear mechanism. The combination of high cutting speeds and high SiCp contents of about 15 % vol. may accelerate the process of flank wear to levels above that acceptable in K10 cemented carbide tools [47] (Fig. 10). However, the use of diamond-based tools rather than the straight grade of cemented carbide (WC-Co) or coatings of the types TiC, TiN, Al_2O_3, AlON, and TiB_2 can significantly reduce adhesion on the clearance surface, thus reducing flank wear [57, 61].

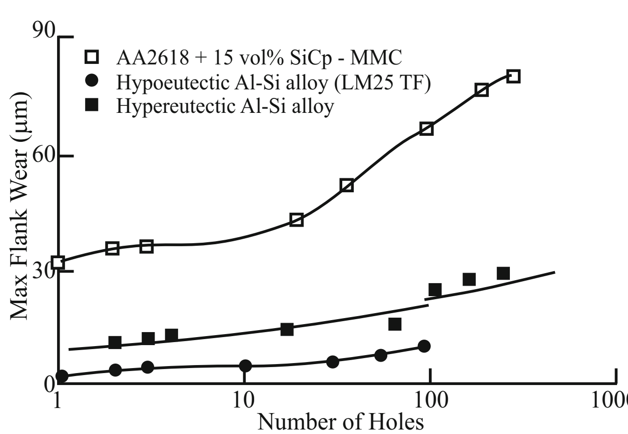

Fig. 9 Flank wear evolution when drilling Al-Si alloys and MMC using PCD tipped drills [72]

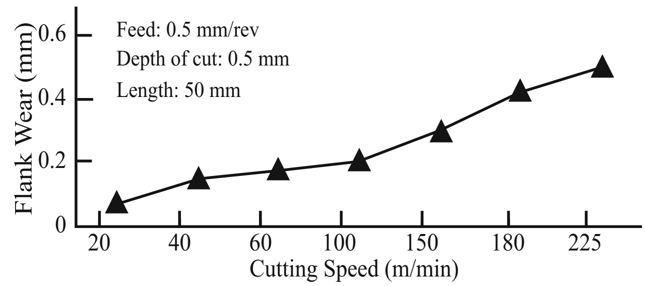

Fig. 10 Influence of cutting speed on flank wear in turning A356 alloy with K10 carbide tool [50]

Although flank wear is the main type of wear observed when machining aluminum alloys, there are reports of crater wear and notch wear when machining pure aluminum containing 12 % wt. Si using TiC- and TiN-coated carbide tools [61]. Liang et al. [99] reported these failure modes when machining of aluminum A390 alloy containing 18 wt% Si using PCD tools. Ciftci et al. [84] reported similar failure modes and notching in single point continuous turning of 2014 Al (16 % wt. SiCp) using cubic boron nitride (CBN) with 0° rake angle. All of these failure modes can be associated with adhesive and abrasive wear mechanisms [103]. Albeit rare, Roy et al. [61] reported wear of chemical origin accelerated by the increase in machining temperature at high cutting speeds in the machining of pure aluminum containing 12 % wt. Si using Al_2O_3, AlON e TiB_2-coated tools, with erosion of the coating due to the transfer of material at the chip-tool interface [104]. Ng et al. [75] carried out face-milling tests using cemented carbide tools with 0.05 mm also with 0.30 mm of flank wear with the minimum flank wear the machined surface was clean, however, with the worn tool workpiece material smearing was observed on the machined surface. According to the authors, this phenomenon is generated because the increase of the cutting edge radius of the carbide tool as the flank wear progresses. However, when face milling with PCD tools, they did not found smearing phenomenon even with a large flank wear land. Smearing is a side flow effect when there is a lateral flow of work material due to improper tool geometry, cutting parameters, tool wear, or all of these actuating together.

Unexpected peeling off (delamination) of coating materials due to high friction coefficients at the chip-tool interface at high cutting speeds have been reported as the main failure of coated tools in the machining of aluminum alloys [99]. Peeling off occurs as a result of low adhesion between the coating and substrate, which is not able to resist the force of friction at the chip-tool interface. One way of preventing this problem is to use diamond coating or solid diamond tools with extremely fine grains [99] and bigger rake angles. These will generate lower cutting forces in the interface region [105]. In drilling, catastrophic drill failure due to sticking and accumulation of material in the drill grooves causes increased torque and temperature. This is the predominant factor leading to the destruction of cutting tools [70].

Wear rates when machining aluminum alloy can be reduced by adding free-cutting elements, improving the cutting conditions, and using suitable tool material and applying adequate lubrication/cooling. Mills and Redford [106] suggest the addition of copper, tin, bismuth, and lead associated with low cutting speeds and feed rates. Dasch et al. [64] used Pb and Sn contents of 0.09 % wt. and 0.02 % wt., respectively, in drilling 319 alloy with 6 % wt. Si to increase the drill productivity by about ninefold. However, the use of cutting fluid produced greater increase in productivity, i.e., about 100-fold. Hamade and Ismail [2] recommended cutting speeds lower than 15 m/min and feed rates of less than 0.3 mm/rev to drill aluminum-silicon alloys with high silicon contents using high-speed steel drills. For turning operations, Manna and Bhattacharyya [50] suggested using cutting speeds of about 60 to 100 m/min and feed rates of 0.5 mm/rev to minimize flank wear. Kannan and Kishawy [18] obtained a reduction in flank wear of approximately 50 % with a coated cemented carbide tool by reducing the cutting speed from 240 to 60 m/min when turning A356 aluminum alloy (20 % vol. SiCp).

Liang et al. [99], when machining aluminum-silicon alloy A390 (18 % wt. Si) using the following tools: (1) uncoated WC—6 wt% Co (cobalt) insert, (2) WC—6 wt% Co insert, coated with ~35 μm nanostructured diamond film, and (3) polycrystalline diamond cutting, reported lower levels of flank wear with the latter two tools. Karakas et al. [101] during milling of aluminum alloy (20 % vol. B_4Cp) with (1) uncoated K20 (N20), (2) uncoated K20 (N20) + triple coating of (TiCN + Al_2O_3 + TiN) CVD, and (3) K20 (N20) + double coating of (TiN + TiAlN) CVD always found lower levels of flank wear with the latter tool regardless of the cutting speed used.

4.7 Cutting fluid in the machining of aluminum alloys

Cutting fluids prevent excessive heating and sticking to the cutting surface (lubrication/cooling) when employed in the machining of Al alloys. They also prevent flank wear and spalling, reduce the surface roughness of the workpiece, improve machining accuracy, protect the surfaces against oxidation and corrosion, and facilitate the release of chips from the tool's rake face [58, 61, 67, 107]. Due to the easy release of chips enhanced by the cutting fluid, Dasch et al. [64] reported a considerable reduction in torque when drilling of aluminum alloy (ductile matrix) with 7.5 % wt. Si hard particles. Kannan and Kishawy [18] and Jayal et al. [108] used cutting fluids and recorded reduction of flank wear in the machining of aluminum alloys (ductile matrix) containing 20 % vol. SiCp and up to 18 % wt. Si, respectively, due to the lubrication and cooling capacity of the cutting fluid which ensures for better control of the machining temperature. In view of the various benefits of cutting fluid, Yoshimura et al. [86] and List et al. [104] suggested that aluminum alloys with high levels of ductility should not be dry machined. Braga et al. [65] during drilling of aluminum-silicon alloy used soluble oil at a concentration of 4 % with a flow rate of 2.4 m^3/h.

Both the cooling and lubrication action of cutting fluids contribute to reduce sticking and accumulation of material on the cutting surfaces, as Sreejith [58] observed in the machining of 6061 aluminum alloy, since the former reduces softening of the material and the latter diminishes friction on the cutting surface [49, 59], thereby reducing flank wear, machining forces, and torque in the machining of soft aluminum alloys or even alloys containing hard particles such as 20 % vol. SiCp [18, 70].

Although dry machining is not recommended, lubrication and cooling characteristics can be applied economically by the minimum quantity lubrication (MQL) method [84, 97, 109, 110], with a flow of 10 to 60 ml/h of cutting fluid. This cutting fluid may be emulsion or synthetic ester. For example, with EP (extreme pressure) additives, applied at an air flow rate of 72 m^3/h and a pressure of 4.5 bar [65, 75], Sreejith [58] found lower wear rates when turning of 6061 alloy with MQL than with oil-jet lubrication, while Kishawy et al. [66] reported lower flank wear when milling A356 aluminum alloy with the MQL method (Fig. 11).

Greater dimensional accuracy and heat exchange can be achieved by spraying a mist of oil film on water (OoW) on the machined surface [97]. However, authors like Klocke et al. [111] do not consider the application of MQL in drilling processes advantageous. Nevertheless, there are signs that this depends on the cutting conditions. Kelly and Cotterell [67] drilled 5080 aluminum alloy and reported a reduction of the feed force with MQL at a high cutting speed and low feed rate conditions, while flood coolant application yielded better results than MQL at lower speed and high feed rate conditions.

Other ways to improve the machinability of aluminum alloys, i.e., minimize sticking to the cutting surface of the tool, even with small amounts of cutting fluid, would be by using tools with a low friction coefficient such as diamond and by adding free-cutting elements that substitute the flow zone, such as 0.5 to 1 % wt. of In, Pb, and Bi, mainly for

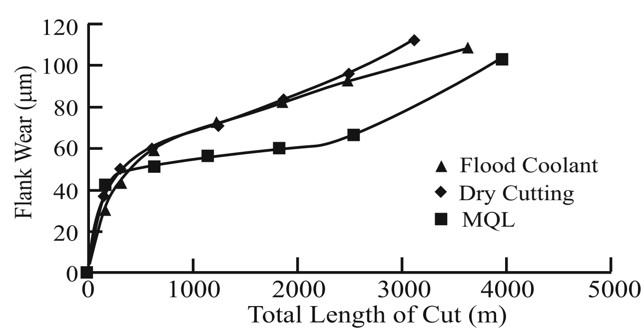

Fig. 11 Flank wear behavior when milling A356 aluminum alloy with uncoated carbide inserts under different lubrication/cooling conditions (v_c = 5000 m/min) [66]

aluminum alloy with high silicon contents, e.g., higher than 7.5 % wt. Si [64, 68, 70, 84]. Although high cutting speeds applied to alloys with high Si contents promote greater tool wear, they are an important factor for the efficiency of free-cutting elements, since they increase the machining temperature and facilitate melting of these elements at the chip-tool interface.

As for the type of cutting fluid, mineral oil emulsion (soluble oil), and synthetic fluid, specially formulated fluids are recommended for continuous cutting with high-speed steel tools and mineral oil emulsion and synthetic fluid for cemented carbide tools. In the case of milling, tapping, and drilling, both with carbide and high-speed steel tools, mineral oil or synthetic oil is recommended [67]. In micro-milling of 6061-T6 aluminum alloy, Chern and Chang [112] used mineral neat oil. However, in continuous cutting of highly abrasive alloys such as those containing 10 % vol. or 20 % vol. SiCp, a 20 % concentration of water-based emulsion with 5 % sulfur and 6 % phosphorus additives has shown good results [18]. Kerosene applied at high cutting speeds was used to obtain a good mirror polish in milling [83]. To facilitate chip removal in drilling, 2 to 8 % water-soluble oil is recommended and applied at a volume of 330 cm^3/s and a pressure of 44 KPa [107].

4.8 Chip control in the machining of aluminum alloys

Chip controlling is a major problem when machining of aluminum alloys [11]. This highly deformable material produces continuous thick chips, which are difficult to break up [26]. These continuous chips in the form of long ribbons can become entangled in the workpiece and impair its surface quality [67]. In drilling, they can cause production stoppages as a result of drills breaking due to clogging of their grooves [26, 107].

Tool geometry and type of coating, cutting conditions, and workpiece mechanical properties strongly influence the chip formation process when machining of aluminum alloy [52]. Softening heat treatments of aluminum alloys tend to produce more continuous chips [24]. The presence of high silicon contents in aluminum alloys, such as 12 % wt. Si, tends to produce shorter, fragmented, and more curved chips [61, 107]. Lower cutting speeds and rake angles, high feed rates, and depth of cut improve chip control, because the chip becomes more brittle due to its greater thickness and lower curvature radius [49]. A more effective chip breaking can be achieved when machining with tools made of materials such as WC + 6 % Co (K10) and TiC, TiN, Al_2O_3, AlON, or TiB_2 coatings which exhibit a greater chemical affinity for aluminum than diamond [61, 112].

As stated earlier, measures to improve chip control may impair other characteristics of machinability, such machining force, surface finish, and tool wear. Therefore, any measure adopted for effective chip control should benefit other machining characteristics. In this context, Kelly and Cotterel [67] suggested using sharpened tools with large rake angles, polished rake faces, and control of the cutting speed. Trent and Wright [26] recommended the addition of alloying elements such as copper, which promote the formation of short segmented chips in aluminum alloys. Dasch et al. [64] suggested the addition of up to 5 % wt. of free-cutting elements such as lead, bismuth, tin, or antimony, which can embrittle the chip due to their low solubility in the aluminum matrix at elevated temperatures encountered at higher cutting conditions. The cutting conditions, in some situations, may worsen chip control.

5 Final comments and remarks

Machining of aluminum and its alloys is not usually a difficult task. Major problems are encountered only in alloys containing high Si contents (above 7.5 % wt.) or hard SiCp or Al_2O_3p particles. Normally, the forces are relatively low, as are the cutting temperatures and energy consumed, providing high productivity. The greatest challenge may be to achieve good chip control, tight dimensional tolerances, good surface finish, and minimal warping. These problems are usually a consequence of the high ductility of this material and its tendency to stick to the surface of cutting tools. This is also responsible for a common problem in the drilling of these materials, which stick to the surfaces of the drills, particularly of high-speed steel and cemented carbide (but much less on drills coated with PCD), clogging their grooves, increasing the torque, and possibly leading to tool failure.

The correct choice of cutting tools, cutting conditions and lubrication, and cooling systems is essential for a successful operation. The most recommended tools are high-speed steel, N grade of cemented carbide, and synthetic diamond—PCD (both solid and coating). The latter presents the lowest coefficients of friction against aluminum (0,2) and therefore the fewest problems with sticking. The recommended geometries are highly positive, depending on the alloy and the process. The wear type is normally flank wear, but crater wear may also occur or even notch wear in some alloys containing hard particles. The predominant wear mechanisms are adhesion (attrition) and abrasion, the latter occurring due to the presence of hard particles in the aluminum matrix or originating from the tool itself, pulled out by attrition. The use of cutting fluid in the form of flood cooling or MQL will favor all the machining parameters of the material.

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