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Machining of Aluminum alloys: a review

Jammula Praneeth[1], Narraa Naveen [2]
[1,2]Mechanical Engineering, Anurag Engineering College, Kodad

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 proportionsso 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, forces, Temperature, Machinability***

I. INTRODUCTION

Aluminum Alloys can be machined rapidly and economically. Because of their complex metallurgical structure, their machining characteristics are superior to those of pure aluminum. The micro constituents present in aluminum alloys have important effects on machining characteristics. Nonabrasive constituents have a beneficial effect, and insoluble abrasive constituents exert a detrimental effect on tool life and surface quality. Constituents that are insoluble but soft and nonabrasive are beneficial because they assist in chip breakage; such constituents are purposely added in formulating hstrength free-cutting alloys for processing in high-speed automatic bar and chucking machines.

In general, the softer alloys and, to a lesser extent, some of the harder al-c alloysare likely to form a built-up edge on the cutting lip of the tool. This edge consists of aluminum particles that have become welded to the tool edge because they were melted by the heat generated in cutting. Edge buildup can be minimized by using effective cutting fluids and by employing D tools with surfaces that are free of grinding marks and scratches he most difficult to machine because hard particles of free silicon cause rapid tool wear. Alloys containing more than 5% Si will not finish to the bright machined surfaces of other high-strength aluminum alloys, but will have slightly gray surfaces with little luster. Chips are torn rather than sheared from the work, and special precautions (such as the use of lubricant-containing cutting fluids) must be taken to avoid the buildup of burrs on cutting edges.

II. CLASSIFICATION OF ALUMINUM ALLOYS

Cast, wrought, strain hardenable, and heat treatable is the four major classifications of aluminum alloys. Machinability groupings are also used. Cast alloys containing copper, magnesium, or zinc as the principal alloying elements impose few machining problems. Tools with small rake angles can normally be used with little danger of burring the part or of developing buildup on the cutting A edges of tools. Alloys having silicon as the major alloying element require tools with larger rake angles, and they are more economically machined at lower speeds and feeds.

A. Aluminum Alloys

1) *Wrought Alloys:* Most wrought aluminum alloys have excellent machining characteristics; several are well suited to multiple operation machining. A thorough understanding of tool designs and machining practices is essential for full utilization of the free-machining qualities of aluminum alloys.
2) *Strain-hardenable alloys (*including commercially pure aluminum) contain no alloying elements that would render them c hardenable by solution heat treatment and precipitation, but they can be strengthened to some extent by cold work. In machining, a continuous chip is formed that must be directed away from the work piece by tools with generous side and back rake angles, thus preventing scratching of the finished D surface with the work-hardened chips. These alloys machine easily, although tool pressures are high as a result of high friction. To obtain good surface finish, sharp tools are mandatory because the alloys are gummy. Machinability is improved by cold working; alloys in the full-hard temper are easier to machine to a good finish than those in the annealed condition.
3) *Heat-Treatable Alloys:* Most of the alloys of this group contain fairly high percentages of alloying elements such as copper, silicon, magnesium, and zinc. They can be machined to a good finish with or without cutting fluid, but a cutting fluid is recommended for most operations. Turnings usually occur as long, continuous curls, except for the free-machining alloys,

which contain chip-breaking constituents. Heattreatable alloys are more machinable in the heat-treated tempers than in the softer asfabricated or annealed solution.

4) *Machinability groupings:* for aluminum alloys are useful in specifying tool forms. For this purpose, alloys are classified into five groups: A, B, C, D, and E, in increasing order of chip length and in decreasing order.

III. 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 Table 1 [1, 2] exemplifies the designation system adopted for workable aluminum alloys. Cast aluminum alloys are classified by a similar process.

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

Table 1: Series Workable Aluminum alloys according to aluminium association

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 [3].

IV. 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 [4], high friction coefficient, excellent formability, low melting point, high magnetic neutrality, and a wide range of possible surface treatments [6, 7]. Table 2 presents some of the physical and mechanical properties of several aluminum alloys and different materials for comparison.

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 [8, 9,10]. Lee et al. [11] claim that the 6061 aluminum alloy, a typical AlMgSi (aluminum-magnesium-silicon) alloy, is an agehardening 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 [12].

Another way to increase mechanical strength, stiffness, and wear resistance is by adding oxides, carbides, and nitrides to the aluminum matrix, such as Al2O3p, SiCp, or TiN (titanium nitride), in various proportions[8,9,10].

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 [5]. 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 [6].

V. MACHINABILITY OF ALUMINUM ALLOYS

To understand machining is essential to be familiar with the chip formation process, very well discussed by Trent and Wright [13] 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 are presented, raising the main problems and indicating right decisions to have the process under control.

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 [14]. However, it should be noted that this difference is minimal among aluminum alloys and depends on their chemical composition and physical properties [15, 16].

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. 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 %[17,18].

A. Cutting Force and Power

Increasing the cutting speed normally reduces the machining forces, regardless of the strength of the aluminum alloy [11, 17, 18], 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 [19,20]. Although high cutting speeds contribute to lowering machining forces, in high-speed cutting (HSC), excessive increase in deformation rates may increase the machining forces (fig1)

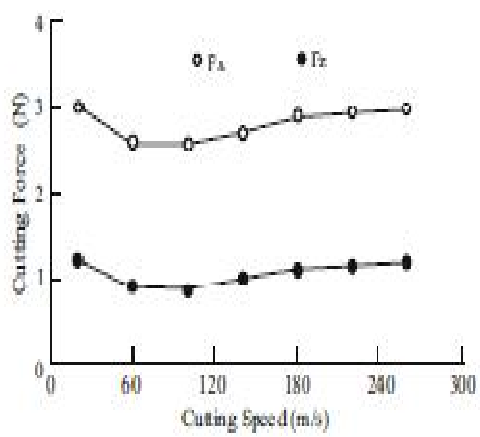

Figure 1: Cutting force with cutting speed variation

The cutting force, and therefore the power, required to machine aluminum is less than might be expected on the basis of its mechanical properties. Although the cutting force required to machine similar metals is often in direct proportion to tensile strength, this proportion is not necessarily valid with dissimilar metals. For example, the common mechanical properties of 2017-T4 aluminum alloy and of hot-rolled low-carbon steel are quite similar. cutting force required in turning aluminum is only about 35% of that required in turning low-carbon steel• Consequently, as shown in Fig. 2, the number of cubic millimeters of metal that can be removed per minute per unit kilowatt expended is approximately three times as great for aluminum alloy 2017-T4 as for hot-rolled low-carbon steel of closely similar tensile strength.

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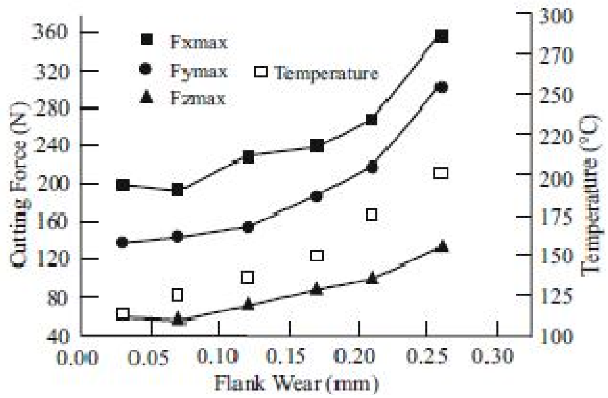

Figure 2: Effects of Plank wear on cutting forces and temperature in milling of al alloy 7050-T7451

B. Power generated when machining aluminum alloys

Cutting temperature is not a major problem 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[21]. 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[22,23]. 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.

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.

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[24].

C. Temperature generated when machining of aluminum

lem in the machining of aluminum alloys, because their low melting point is not able to alter the mechanical properties of cutting tools in other words, it is not able to cause high tool wear rates, although tool life is still controlled by the cutting temperature[24,25].

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. Higher temperatures can also increase the ductility of the material, which produce longer chips 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

D. 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. The latter tool considerably reduces the adherent layer accumulated on the tool edge in the chip flow direction.

K10 grade is recommended for turning, milling, drilling, and boring of silicon aluminum alloys; K20 for interrupted cutting with abrupt temperature changes; and K01 for cutting aluminum alloys with abrasive particles. 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[27-29] 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. [28] 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.

VI. CONCLUSION

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 Al2O3p 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, an 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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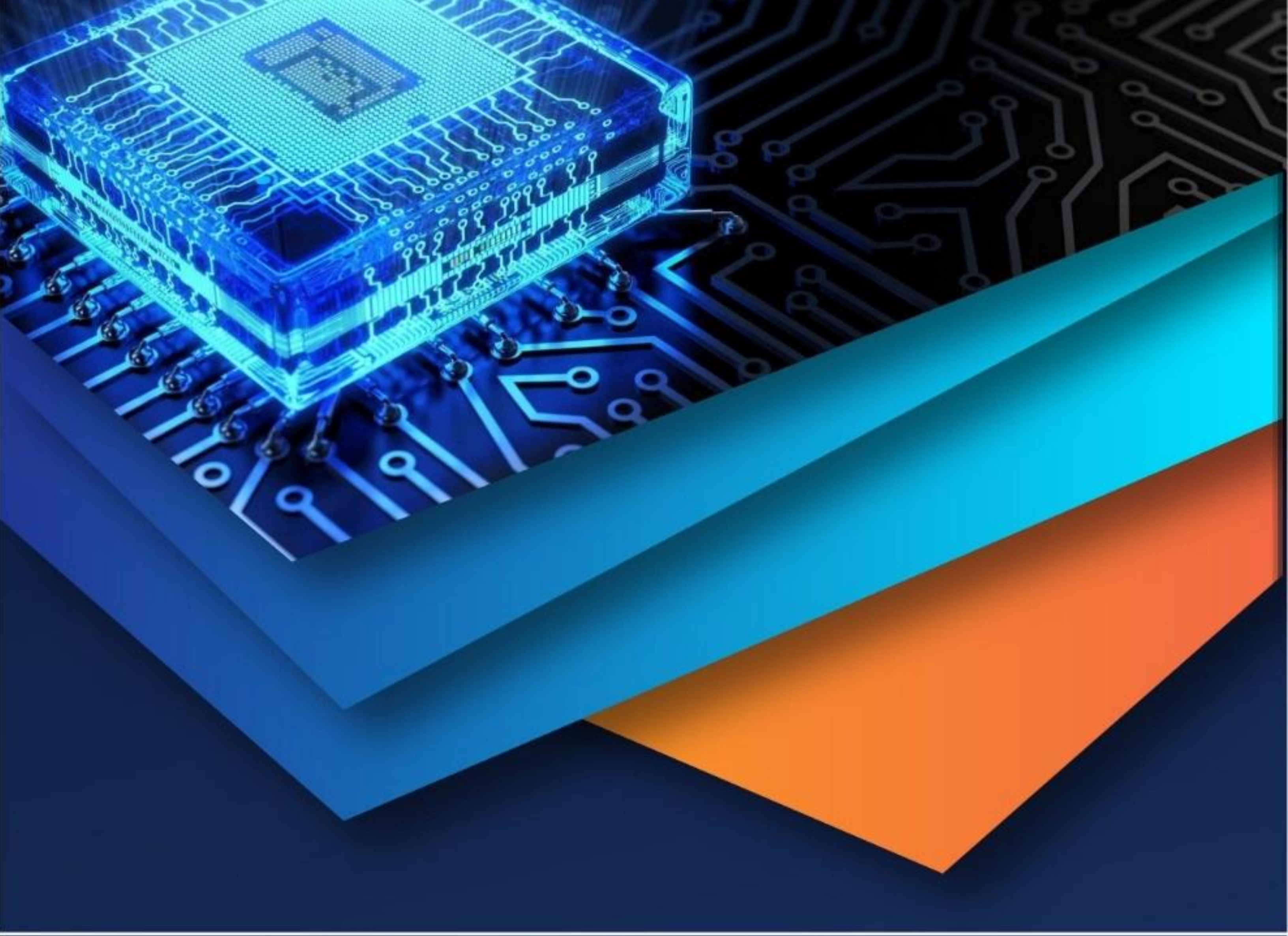

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