Effect of Machining of Aluminium Alloys with Emphasis on Aluminium 6061 Alloy – A Review

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Abstract. Aluminium alloy is one of the most widely used engineering materials due to their relatively lower specific weight and corrosion resistance compared to steel. Besides, they are also relatively easier to machine. Aluminium alloys have been found to provide the highest degree of machinability compared to other lightweight metal such as titanium and magnesium alloys. Among every other type of aluminium alloy, the 6061 aluminium alloy has been used for general purposes due to some interesting attributes it possesses when compared to others. The investigation on the effect of machining condition on the corrosion of 6061 aluminium alloy has shown that the machining via electrical discharged provides better resistance to pitting corrosion than the diamond and carbide turning machine. Drilling, turning and cutting may influence the mechanical characteristics of the workpiece by producing hole opening around the low residual stresses and a small layer of extremely stressed material on the newly created surface, making it to become more prone to fatigue, crack propagation and corrosion at the stressed surface. The machining surface integrity has great influences on the fatigue lifetime of material since micro-cracks always initiate at the surface. The traditional machining techniques compared to the non-traditional or non-conventional techniques are more susceptible to the induction of poor surface integrity due to direct contact between the tool and workpiece which are characterised by several damage defects such as micro-cracks, surface hardening, roughness and residual tensile. This paper therefore provides an overview of the classes of aluminium alloys, their applications and machining of the alloys with a keen focus on 6061 aluminium alloy and exposition of various machining technique with both their beneficial and non-beneficial effects on the workpiece, tool life and the environment.

Keywords: Materials, Aluminium, Alloys, Machining, Corrosion

1. Introduction

Aluminium alloys are alloys which has aluminium as the major or predominant metal. The common alloying elements are zinc, silicon, magnesium, iron, copper, tin and manganese. These additional elements to aluminium enhance the workability, electrical conductivity, corrosion resistance and strength. Aluminium alloys have two main classifications, which are wrought alloys and casting alloys [1]. Both of these classifications of aluminium alloys are further subdivided into heat-treatable and strain hardenable alloys. Approximately 85 % of aluminium is used for wrought products such as extrusions, foils and rolled plate [2]. Cost-effective products are obtained from the cast aluminium alloys due to the relatively low melting point, although their tensile strengths are generally lower than wrought alloys. Al–Si is the most important cast aluminium alloy system with a high level of silicon ranging from 4 to 13 %. This level of silicon enhances the casting characteristics [3].

Aluminium alloys have been extensively used for the manufacture of engineering components and structures where corrosion resistance and lightweight is paramount. They have been highly useful to the manufacture aircraft components [4]. The surfaces of aluminium alloy will produce a protective oxide if it is not protected by anodizing or painted following the right procedures. For wrought alloy, the international alloy naming system had been widely accepted. The alloys are given a four-digit
number. The first digit depicts the main alloying elements; the second indicates a variation of alloy if it is not zero and the third and fourth identify the exact alloy in the series. Table 1 indicates the wrought alloys of aluminium series and their applications. A nomenclature similar to the naming of wrought alloys was adopted by the aluminium association for cast alloys. The second digit in the AA system unveils the minimum percentage of aluminium. For example, 160.x corresponds to a minimum of 99.60% aluminium while the digit after the decimal point usually with value 0 or 1, denote ingot and casting respectively. Cast alloys aluminium series are 1xx.x to 9xx.x. The alloying elements are minimum 99% of aluminium and alloyed with other elements such as manganese, copper, magnesium, zinc, silicon etc. [5, 6]. This review paper therefore provides an overview of the classes of aluminium alloys, there applications and machining of the alloys with a keen focus on 6061 aluminium alloy and exposition of various machining technique with both their beneficial and non-beneficial effects on the workpiece, tool life and the environment.

1.1. Classification of aluminium alloys based on application

Aluminium alloys are used for several applications such as marine, automotive, aircraft, gas and air cylinder, and many more.

- **Marine application**: Marine alloys are employed in the construction of boats and ships, other salts water-sensitive shore and marine applications. These alloys are 5052, 5059, 5083, 5086, 6061 and 6063 aluminium alloy. 6082, 6005A, 5183, and 4043 aluminium alloy are also employed in an offshore application and marine construction [7].

- **Automotive and aircraft alloys**: Aluminium alloys such as 6111 are extensively used for the exterior or body panels of automotive. The inner body panels use 5754 and 5083 Al alloys while the bonnets are manufactured from 6111, 6016 and 2036 alloys (Poznak et al., 2018). The body panels of trailer and truck are commonly made of 5456 Al. More so, the automotive frames are produced from 5754 and 5182 aluminium formed sheets, 6063 or 6061 extrusions. Crankcases and cylinder blocks are often made of aluminium 319 and 356 while aluminium 242 is also used but on rare occasion. Automotive wheels have been formed from 5xxx sheet or cast from aluminium 356.0. The 7xxx aluminium series are used for automotive chassis or body applications. Aluminium alloys 2xxx, 7xxx, and 6xxx have been employed in aircraft constructions for ages and are responsible for machining activities in these industries. The high strength-to-weight ratio and the ease of fabricating them for the replacement of substituting steel and cast-iron parts is a great advantage [8-10].

- **Gas and air cylinders application**: Aluminium alloys 6351 and 6061 are used widely in breathing gas cylinders used by underwater divers. The alloys used for this application exhibit good mechanical properties, good weldability and commonly extruded, which makes it one of the regularly used and general-purpose aluminium alloy [11].

| Table 1. Wrought alloys of Aluminium series and their applications [12, 13]. |
|---------------------------------------------------------------|
| **Wrought alloys of Aluminium Series** | **Elements alloyed with** | **Applications** |
|---------------------------------------|---------------------------|-----------------|
| 1000 Series                           | Minimum of 99 % Al        | They can be work-hardened. |
|                                       |                           | Areas of application are in Plate, foil, electrical conductors, aircraft components. |
| 2000 Series                           | Copper                    | They can be precipitation hardened. |
|                                       |                           | They found application in Aerospace, |
3000 Series  Manganese  They can be work hardened. Application in beverage can, rigid foil containers and decorative.

4000 Series  Silicon  Work-hardened forging, sheet, cladding, filter and rod.

5000 Series  Magnesium  Foil, rivets, rod, rocket cryogenic tanks, welding, marine, sheet and automobile component

6000 Series  Magnesium and Silicon  They can be precipitation hardened. Areas of application are automotive, sheets, marine, forgings and rod.

7000 Series  Zinc  They can be precipitation hardened. Thick plate, aerospace, forging.

8000 Series  lithium  Electrical wire, High temperature aerospace application

2. Machining of aluminium alloys

Machining is the process of removing the unwanted parts or materials from the bulk material or workpiece to create the shape and size of the final product [14]. The principal alloying elements in aluminium cast alloys such as magnesium, copper and zinc inflict some machining problems. Rake angles play an important function in the machining of cast alloys and tools with small rake angles can be used normally with minimal danger of damaging/burning the part or development of build up on the tools cutting edges. Alloys with silicon as the main alloying element require tools that possess larger rake angles. They are also more cheaply machined at relatively low feeds and speeds [15].

Most wrought aluminium alloys, on the other hand, have excellent machining performance and are well suited to multiple machining operations. A very good understanding of machining practises and designs is essential for free and quality machining of aluminium alloys. In machining of strain-hardenable alloys, there are formations of a continuous chip which must often be directed from the workpiece by tools with back rake angles and this prevents scratching of the finished surface with the work-hardened chips. The alloys are easily machined, although as a result of friction, the tool pressure is high. Good surface finishing is obtained by ensuring that the sharpness of the tools due to the gummy nature of the alloys. Cold working improves machinability, full-hard temper alloys are easily machined to a good finishing as compared to those annealed [16].

Heat treatable alloys can also be machined to a good finishing in the presence or absence of cutting fluid. However, cutting fluid is usually recommended for most cutting operations. Turnings usually take place as long and continuous curls, except the case of free machining alloys with chip breaking constituents. Heat treatable alloys are more easily machined in the heat-treated tampered condition than in the softer annealed solution or as fabricated [17].

2.1. General machining conditions of aluminium alloys
Power requirements: The power required for the machining of aluminium alloys are usually less than expected, based on their mechanical properties. Although the required cutting force for the machining of similar metals is often directly proportional to the tensile strength which is not necessarily true with dissimilar metals. The power requirements for machining are proportional to the cutting speed and force. More so, the loss of power in the gears and bearing of the cutting machine increases with speed. For the machining of aluminium alloys, power requirements decrease to some extent as the rake angles of the cutting tool is increased. The power requirements for cast 606 as measured using a cutter that posses single point tools with 0 and 20° rake angle ranges from 0.16 to 0.14 (kW/mm³/min) x10--4 or 0.20 to 0.50 hp/in.³/min. The higher the power rating, the bigger the cutting speed and cutting force [18, 19].

Cutting force: At low speeds ranging from 30 to 60 m/min, aluminium alloys cutting for can widely be varied. The speed rises momentarily to peak values many times above the normal. The cutting force at higher speeds increases slight during the machining of some aluminium alloys such as 2011-T3 alloy but decreases for most alloys [20]. The general effect of speed on cutting force is usually small. Increasing the cutting speed to about 300 m/min changes the cutting speed slightly. Above 300 m/min, the effect of speed is negligible. More heat is not produced as a result of the increase in speed, but the available time for removing the heat from the tool is shortened. Heat does not have any significant effect on the surface of high-speed tools until the speed is above 215 m/min. These tools can be used for speeds beyond this limit, but for long tool life, carbide tools are recommended [21, 22].

Cutting speed: The cutting speed for aluminium alloys is determined by the workpiece and the limits of the machine tools [23]. In experimental equipment and aerospace application, speeds up to 4600 m/min have been used. However, due to the limitation of caused by the spindle speed and the horsepower available, and also the parts dynamic balance, machining speed is rarely higher than 900 m/min and are often less than 300 m/min in some cases. In machining, cutting speed should be optimized to prevent time wastage and to reduce the temperature rise in the machined part [24]. When the cutting speed increases from 30 m/min to 60 m/min, there is the possible reduction of build-up edge formation on the cutter, chips are likely to break more readily and improved finishing [25].

Cutting depth: The depth of cutting should be as large as possible taking into consideration the part strength, power of machine tool, chucking equipment and the quantity of stock to be removed to reduce the possible number of cuts. Cutting force increase as the cutting depth increases [26]. The depth of the cut must be of limited value, to avoid distortion, slopping of the workpiece and unnecessary overloading of the machine. In roughing, the cutting depth can be as high as 6.35 mm for small work. It can be as high as 38.10 mm for large and medium work. However, the depth of cut less than 0.635 mm is often recommended at the opposite end in finishing [27]. At all time, all the cutting tools should be kept sharp and in good condition. The geometry of the tools must be carefully maintained within the required and standard requirement for aluminium alloys. Cutters are required to have the optimum flute numbers and standard spiral configuration for any application. In most applications, coarse spiral and a minimum number of flutes are more desired. Frictional heating and rubbing results from clogging and these can be reduced by ensuring that the flutes maintain a good surface finishing [28].

Feeds and speeds: Feed usually depends on the rigidity and strength of the machine, the workpiece and also on the desired finishing. Light feed ranging from 0.05 to 0.15 mm/rev is required for finishing cuts while rough cuts may employ a feed ranging from 0.15 to 2.03 mm/rev [29]. Correct feeds and speeds are required for any operation being carried out. High spindle speeds combined with slow feed rate can be seriously troublesome. Care must be taken in order not reduce feed below what is required especially when the cutter is tending towards or machining areas that require section changes. On pieces of equipment with multiple spindles, it is important to have enough net horse available to each of the spindles during heavy cuts [30].
- **Cutting fluids**: It is highly essential to have continuous and adequate flow or cutting fluid (mist or flood) properly directed at the cutting edge. It normally expected that the cutting fluid should start flowing before cutting. This is expected to continue until the cutter is separated from the part. Continuous fluid circulation is vital; to prevent airlock, which could consequently lead to local overheating. The usual cause of the defect is excessive heat which occurs directly or indirectly from frictional heat or lack of sufficient cooling. However, the cause of some problems may not be easily detected while some may require on-site analysis [31, 32].

- **Support and clamping methods**: The machine fixtures and support must be firm and have enough contact area and mass, to provide sufficient heat absorption capacity. The workpiece must be properly clamped to avoid part distortion or vibration. Any resulting deeper cuttings due to poor rigidity of the work could produce overheated areas. It is vital that the edge seal of the flat parts that being machine on vacuum chucks be positioned neatly the periphery to eliminate gapping and vibration at the outer edges [33].

2.2. **Challenges in the machining of Al 6061 alloy and remedies**

Aluminium 6061 is one of the most commonly used alloys of aluminium for general purposes. It can be precipitation hardened and it contains silicon and magnesium as its main alloying elements. It exhibits good mechanical characteristics, good weldability and usually extruded. Al 6061 alloy has a density of 2.7 g/cm³ and volume resistivity ranging from 32.5 - 39.2 nOhm.m. Aluminium 6061 alloy is not traditionally cast due to the low content of silicon which affects its fluidity. It can be cast suitably by employing a special centrifugal casting technique [34, 35]. Aluminium 6061 is used for the construction of aircraft structures such as wings due to its strength and corrosion-resistant ability. It is used in the construction of automotive parts and watercraft parts. Al 6061 alloy is also utilized in the construction of Tanks and the production of cans for beverages and food packaging [36].

The application aluminium 6061 alloys for screw machine, it has good machinability properties in the heat-treated T6/T6511 state. It can be difficult to break the chips from drilling and turning in the T6/T6511 temper state. Because of this, special machining method and chip-breaker, such as peck drilling, are employed to enhance chip formation. Another problem of machining aluminium 6061 alloy is the build-up edge formation on the tool materials due to the adhesion, especially in the dry machining of the alloy. This has been addressed by coating tungsten carbide tool with a diamond so prevent the adverse effect of the built-up edge on the surface of the workpiece. The cutting force with a diamond-coated tool was far less due to the high thermal conductivity of diamond. The coating prevents the work material from sticking on the rake surface of the end mill and this, therefore, reduces the force. The lesser cutting is also ascribed to the ability of the diamond to reduce friction [37].

Another challenge with the machining of aluminium alloy 6061 is the effects impose by the cutting parameters, in the end, milling on the wear mechanisms. In recent time, water base nano-fluids (WBNFs) were used for the minimum quantity lubrication during the machining of aluminium alloy 6061 as a substitute for the conventional oil-based lubricant. WBNFs have been found sustainable due to their ability to combine the high lubricating effect of nanoparticle and high cooling rate of water. The major wear mechanisms are adhesion and abrasion and attrition at micro-scale. The use of water-based TiO₂ nanofluid was found effective for edge integrity. Thus, the lubrication properties of nanoparticles integrated with high cooling rates of water are highly beneficial to the lubrication of aluminium alloy 6061 during machining process [38].
2.3. Various techniques for machining of Al 6061 alloy

The traditional technique for machining aluminium 6061 alloy and other aluminium alloys are Milling, Turning and Drilling. These are carried out using carbide cutting or diamond cutting machining tools and high-speed tools. Although this method of machining is still being used in most countries of the world, due to the clamour for sustainable and green manufacturing, non-traditional machining techniques have been adopted. Alloys, composite and ceramics can be machined via the non-traditional method with less damage, more complex shapes can be made, structures with low rigidity can be produced, and excellent surface finish at low cost and micro machined parts with tight tolerance can be obtained. Electrical Discharge Machining (EDM) and Laser Beam Machining (LBM) are further classified as a non-traditional thermal process of machining. Chemical Machining (CHM), Electrochemical Machining (ECM) is classified as Chemical and electrochemical process while Abrasive Jet Machining (AJM), Ultrasonic Machining (USM) are classified as a mechanical process [39, 40]. Unlike the traditional machining techniques, these do not require direct contact between tools and workpiece.

- **EDM of 6061 aluminium alloy**: EDM techniques removes unwanted material from 6061 Aluminium alloy by the action of electric discharge on the electrically conductive alloy regardless of the hardness [41]. High thermal energy is generated by electric discharge to remove materials by erosion. EDM process is carried out in a dielectric fluid with two electrodes. The tool is one of the electrodes in the geometry of the cavity to be produced, while the other electrode is the workpiece to be machined. Generally, the tool is negative while the workpiece is negative. The tool is fed in the direction of the workpiece in a carefully controlled path to produce the electrode’s shape. During the EDM process, the workpiece and the electrode do not make direct contact, which implies that the chatter and vibration are eliminated in the process. Due to the multipurpose nature of EDM, machining of complex or intricate shapes with the typical advantage in the production of die, mould, aerospace, surgical and automotive components from material which is tasking to a machine by conventional techniques [42]. It was discovered that the efficiency of EDM is influenced by discharge current, pulse on time, and pulse off time, arc gap, duty cycle, servo voltage, rotational speed and flushing pressure. However, researchers and scientists are carrying out their studies to improve the machining performance to the higher extent by implementing newer techniques, different machining conditions, different work materials, different electrodes and selecting optimum parameters [43].

- **ECM of 6061 aluminium alloy**: ECM is a machining technique where the anodic dissolution process is controlled at an atomic level of the workpiece that is electrically conductive through the electrolyte by a shaped tool. In this technique, the tool is the anode while the workpiece is the cathode. The electrolyte is pump in between the anode and the cathode; while direct current is made to flow throw the cell to dissolve the metal form the workpiece. Electrochemical Machining method has a wide scale of benefits such as high material removing rate, no stress concentration, excellent surface finish and long service life. ECM is a machining technique is largely used in automotive, aerospace, roller, gear, mould and dies industries. It is also used in the manufacture of surgical component [44]. The set up of ECM consist of the electrolyte tank, machining chamber, pressure gauge, control panel and the flow meter. A novel Hybrid Fuzzy-Artificial Bee Colony (ABC) algorithm was developed for multi-objective optimization of process parameters in electrochemical machining (ECM). The predicted values for the best performance is feed rate 0.89 mm/min, flow rate 9.64 L/min, voltage 24.88 volts, current 259 Amps, inter-electrode gap 0.176 mm, electrolyte concentration 204 g/L. Confirmation test results attested that good combination of machining parameters satisfy the real requirements of electrochemical machining of 6061Al/10%wt Al2O3/5%wt SiC composite [45].
• **AJM of 6061 aluminium alloy**: AJM is a machining process that carries air stream of high pressure with little abrasive particles to impinge the workpiece surface via a nozzle set for the removal of materials from the surface [46]. AJM has been used widely in various industrial machining application. The technology is not as such sensitive to material properties because it doesn’t cause chatter, the stress imposed on the workpiece is minimal, no thermal effect, flexibility is high and high versatility of machining. The few drawbacks are a messy working environment and likely generation of loud noise but have low initial investment cost [47].

• **LBM of aluminium and its alloys**: LBM is one of the extensively used non-conventional machining techniques that utilize an electro-thermal form of energy for material removal. Various operations such as drilling, milling and cutting can be carried out using LBM. Using the conventional techniques, machining of brittle and hard materials results in loss caused by high wear rate, making it highly expensive to machine such material. However, the LBM process which makes use of the thermophysical and optical properties of the material itself to machine them, exhibit better process performance efficiency compared to the traditional machining techniques (as the loss of material is very high) and other non-conventional methods. It is also a faster method of machining compare to other non-conventional techniques like the water jet abrasive machining. Although the investment cost of LBM is high, the operating cost is low [48].

• **Ultrasonic Machining**: Ultrasonic machining is used to perform grinding, milling and drilling operations via the delivery of high-frequency vibration to a tooltip buried in the abrasive slurry by booster [49, 50]. In USM, electrical energy of high frequency is converted to mechanical through transducer or booster combination and is transmitted to energy and amplifying device. The transmitted energy causes the vibration of the tool along its axis at a high frequency of usually above 20 kHz at amplitude ranging from 12 to 50 μm. A static load that is being controlled and power ratings of 50 to 3000 W is applied to the tools. A mixture of abrasive materials such as an aluminum oxide or silicon carbide suspended in water or other suitable carrier medium is pumped uninterruptedly across the gap between the work and the tool. The abrasive particles in the slurry impact the workpiece via the vibration of the tool to cause the removal of materials to inform of micro-chips. The process produces high precision machine parts because raw materials are not distorted. It allows for the machining of complex and no- complex shapes at fewer operations without the creation of burrs. However, the rate at which the material is being removed can be slow (low cutting speed) and it is not easy to drill deep holes in parts since the abrasive slurry will not reach the bottom of the hole effectively [51].

3. **Effects of machining condition on corrosion, fatigue and surface integrity**

The investigation on the effect of machining condition on the corrosion of 6061 aluminium alloy has shown that the machining via electrical discharged provides better resistance to pitting corrosion than the diamond and carbide turning machine [52]. Drilling, turning and cutting may influence the mechanical characteristics of the workpiece by producing hole opening around the low residual stresses and a small layer of extremely stressed material on the newly created surface, making it to become more prone to fatigue, crack propagation and corrosion at the stressed surface. It has been validated by numerous researches that machine affects high cycle fatigue due to the severity of operation which tends to affect the endurance limit [53]. The machining surface integrity has great influences on the fatigue lifetime of material since micro-cracks always initiate at the surface [54].

The traditional machining techniques compared to the non-traditional or non-conventional techniques are more susceptible to the induction of poor surface integrity due to direct contact between the tool and workpiece which are characterised by several damage defects such as micro-cracks, surface hardening, roughness and residual tensile [55, 56]. Besides the good surface finish and
accuracy of the non-conventional technique of machining, they are also without detrimental results such as a heat affected zone [57, 58].

4. Conclusions

The review on aluminium alloys applications and effect of machining, focusing on 6061 aluminium alloy and various machining techniques has revealed that 6061 aluminium alloy is one of the widely used aluminium alloys due to its resistance to corrosion, lightweight and good machinability. Milling, Turning and Drilling carried out using carbide cutting or diamond cutting machining tools and high-speed tools is the traditional method of machining. Although, these techniques of machining are still in use, for sustainable and clamour for green manufacturing, non-traditional machining techniques such as EDM, LBM, ECM AJM and USM. Alloys, composite and ceramics can be machined via the non-traditional method with less damage, more complex shapes can be made, structures with low rigidity can be produced, and excellent surface finish at low cost and micro-machined parts with tight tolerance can be obtained.

Although, it is more difficult to find spare parts for non-conventional machines but easier for conventional ones. More so, skilled operators who are experts in machining are required for the non-conventional tool because it is more complex to set up, unlike the conventional tool which can easily be set up without the assistance of professional. The traditional machining techniques are also more susceptible to the induction of poor surface integrity due to direct contact between the tool and workpiece which are characterised by damages and defects such as micro-cracks, surface hardening, roughness and residual stresses.

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