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End Milling of Biodegradable Magnesium Alloy (AZ 31) with Minimum Quantity Eco-friendly Cutting Fluids

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Abstract

Magnesium alloys are in focus of research in recent years as these are lightest structural material and biodegradable biomaterial. Mineral oil based cutting fluids adversely effect on both worker's health and environment during the machining process. To minimize the cutting fluid by effectively using it, minimum quantity cutting fluid (MQCF) came into existence. In this present work, the effect of cutting speed, feed rate and depth of cut on cutting force, feed force, workpiece surface roughness during end milling of AZ31 magnesium alloy with and without MQCF technique using eco-friendly cutting fluids bio-based cutting fluid (BCF). Results show that cutting force, feed force and workpiece surface roughness reduce during MQCF machining using BCF as compared to dry machining. Authors also study the surface morphology of the AZ 31 parent material and machined region materials with and without MQCF of eco-friendly cutting fluids using scanning electron microscope and non-contact 3D laser surface profilometer.

Key Words: Magnesium Alloy AZ31, end milling, machining force, surface roughness, minimum quantity cutting fluid, bio-cutting fluid

1. INTRODUTION

Magnesium is the third most abundant structural metallic element (2.33% by wt.) in the earth's crust coming after aluminum (8.23% by wt.) and iron (5.63% by wt.) [1-2]. Magnesium and its alloys have good physical and mechanical properties such as light weight, good damping properties, high strength-to-weight ratios, high stiffness-to-weight ratios and no pollution etc. [3]. Due to good strength to weight ratio, resistant to corrosion and lighter compare to steel materials, magnesium and its alloys are used as automotive and aerospace components worldwide [4]. Biomedical implants are the recent applications of the magnesium alloy [5]. Mass reduction consideration is one of the most prominent areas, which affect the fuel efficiency of the vehicles. Magnesium alloy AZ31 [density~ 1.8gm/cm^3] is almost one-fourth times lighter than structural metal like steel [density~8.05gm/cm3] and it is also lighter than aluminum [density~2.7gm/cm3].

Extraordinary good machinability is the unique attraction of the magnesium alloy. In the manufacturing process, workpiece surface finish, as well as dimensions and shape accuracy, are required, to adopt milling processes. Modern milling methods are used in both roughing and finishing operations.

In dry end milling operation, severe friction between tool-workpiece interface causes high heat generation leading towards lower workpiece surface finish. Therefore, cutting fluids are used to provide cooling, lubrication as well as removal of chip debris from the tool-chip interface. In conventional end milling, petroleum-based mineral oils are mostly used as cutting fluids. However, these types of cutting fluids have detrimental environmental effects as well as health hazards to operators [6]. Therefore, researchers have proposed minimizing the use of cutting fluids to reduce negative environmental effects. MQCF is a viable solution to reduce the amount of cutting fluid by a mixture of pressurized air and highly convective cutting fluid. Also, to reduce negative environmental effects eco-friendly bio-based cutting fluids are also explored by researchers [7]. The bio-cutting fluid overcomes environment as well as health-related issues.

Garcia and Ribeiro (2016) reported increase of tool life by 50% using MQF technique as compared to dry end milling of Ti-6Al-4V alloy [8]. Liu et al. (2011) confirms that the cutting force and cutting temperature depends upon air pressure and nozzle position of MQL technique [9]. Werda et al. (2016) investigated the influence of oil nature on the surface roughness of workpiece after end milling. They found that synthetic ester oil performed best in terms of surface integrity. However, fatty alcohols performed better in terms of tool life [10].

In the present work, the effect of depth of cut, feed rate and spindle speed on cutting force, feed force, workpiece surface roughness as well as their surface morphology during machining of biodegradable AZ31 magnesium alloy with MQCF technique using bio-cutting fluid (BCF) is investigated. For comparison, dry milling experiments were also conducted.

2. MATERIALS AND METHODS

The bio-magnesium alloy AZ31 plate with the dimension of 50mm×50mm×5mm was chosen as workpiece material due to its good machinability and bio-activity. PVCTIAlN coated carbide end mill (Make: Sandvik Coromant) was used as a milling cutter. The chemical composition of AZ 31 is illustrated quantitative composition in Table 1. Mechanical and thermal properties of AZ 31 magnesium alloy is shown in Table2. Table 3 shows detail of end mill cutter.

Table 1: Chemical composition of AZ 31 magnesium alloy

Element	Al	Zn	Mn	Fe	Ni	Cu	Mg
Wt.%	3.06	0.80	0.25	0.003	<0.001	0.001	Balance

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Table 2: Mechanical and thermal properties of AZ 31 magnesium alloy

Property	Value
Density	1.78 g/cm^3
Compressive yield strength	60-70 MPa
Ultimate tensile strength	235 MPa
Yield strength	125-135 MPa
Elastic modulus	45 MPa
Thermal conductivity	96 W/m ºC

Table 3: Details of end mill cutter

Property	Value
Diameter	6 mm
Flute helix angle	50°
Axial rake angle	13.5°

Table 4: Machining input parameters

Variable	Value
Spindle speed	90, 125, 180, 250, 355 rpm
Feed rate	40, 56, 80, 112, 160 mm/min
Depth of cut	0.10, 0.15, 0.20, 0.25, 0.30 mm
Cutting fluid	Ecoline bio-cutting fluid (Manufacturer: Cortec Co.)
MQCF type	Internal mixed MQCF
Air pressure	0.5 MPa (5 bar)
Cutting fluid flow rate	35 mL/h
Nozzle standoff distance	30 mm
Nozzle angle	45º

End milling experiments were carried out on the vertical milling machine (Make: Batliboi Ltd., Model: l BFV3) equipped with the commercial end milling cutter. Overview of MQCF machining experimental setup is shown in Fig. 1. Machining forces (F_x, F_y and F_z) were measured using piezoelectric quartz dynamometer (Make: Kistler, Model: 9272B) connected with a chart amplifier. Workpiece surface roughnesses were measured using a non-contact type 3D surface profilometer. Surface morphology of work piece was investigated using scanning electron microscope. Table 4 illustrates machining input parameter.

3. RESULTS AND DISCUSSION

In this section, results of machining forces, workpiece surface roughness and surface morphology of workpiece with MQCF and dry machining are discussed. All The end milling operations were carried out under both dry and minimum quantity of cutting fluids (MQCF) conditions.

Fig. 2 (a-c) shows the effect of depth of cut on cutting force, thrust force and radial force, respectively. From results, it is observed that with the increase in depth of cut, machining forces increases as expected. This is due to increase in material removal rate (MRR). To remove more material, high specific energy is required resulting in increasing machining forces. However, for depth of cut of 0.1mm, it is observed that forces are high as compared to other depth of cut. It is due to the fact that with a lower depth of cut, instead of shearing operation, ploughing between end mill cutter and workpiece take place, which causes higher friction and higher machining forces. Apart from this, MQCF milling show lower cutting force as compared to dry milling. This is due to Injection of MQCF mist in-between tool-workpiece interface. MQCF mist cools the generated heat and reduces temperature because of high lubricity of BCF and its better heat convection coefficient.

Fig. 1. (a) Overview of experimental setup, (b) workpiece

Fig.3 (a-c) shows the variation of cutting force, thrust force and radial force with respect to feed rate. It is observed that with the increase in feed rate, machining force increases. This is due to increase in shearing of workpiece material at the faster rate causing higher temperature and friction, which leads to increase in machining forces. Also, it is observed that MQCF with BCF is able to further reduce machining forces as compared to dry milling.

Fig. 4 (a-c) shows the variation of cutting force, thrust force and radial force with respect to spindle speed. With the increase in spindle speed, machining forces reduced as expected. This is due to more contact of the tool with workpiece per unit time. Therefore, while machining at high spindle speed, less time is available. Also, with the increase in spindle speed, tool-chip temperature increases causing thermal softening of the workpiece, which allows shearing with lesser forces.

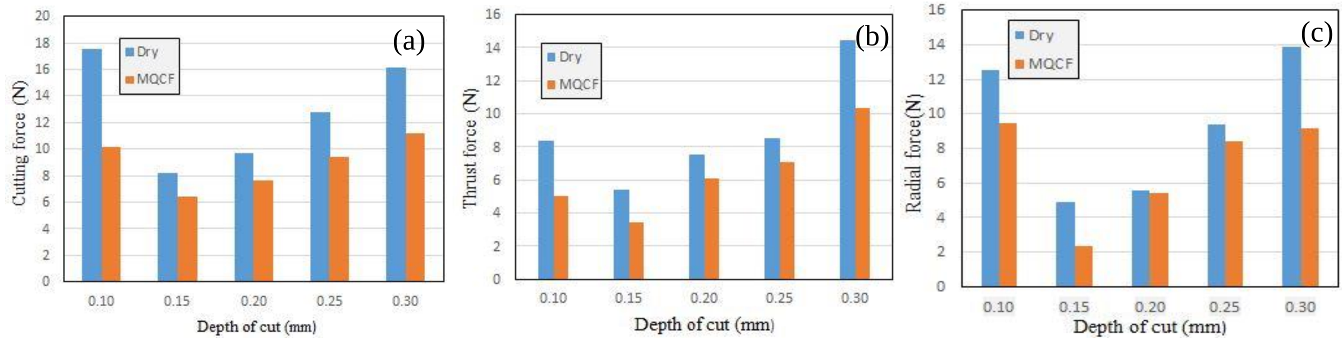

Fig.2. Effect of depth of cut on (a) cutting force, (b) thrust force and (c) radial force with MQCF and dry machining

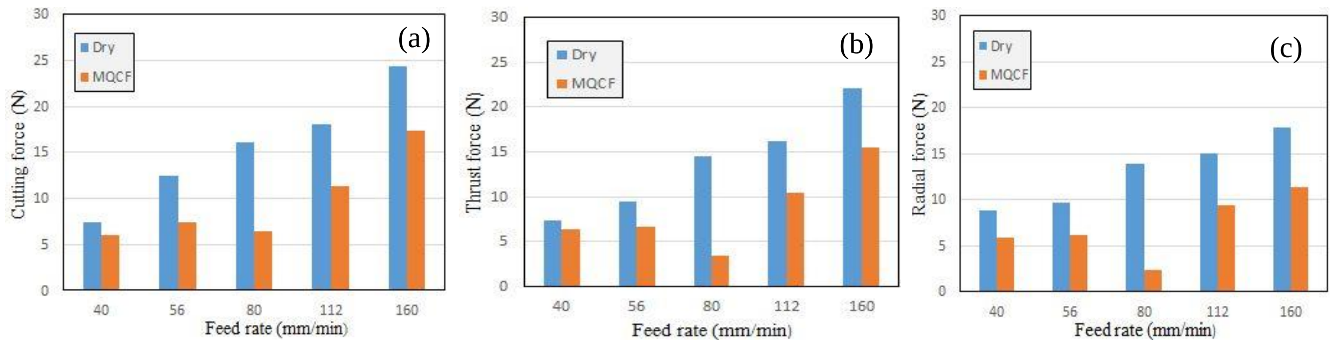

Fig.3. Effect of feed rate on (a) cutting force, (b) thrust force and (c) radial force with MQCF and dry machining

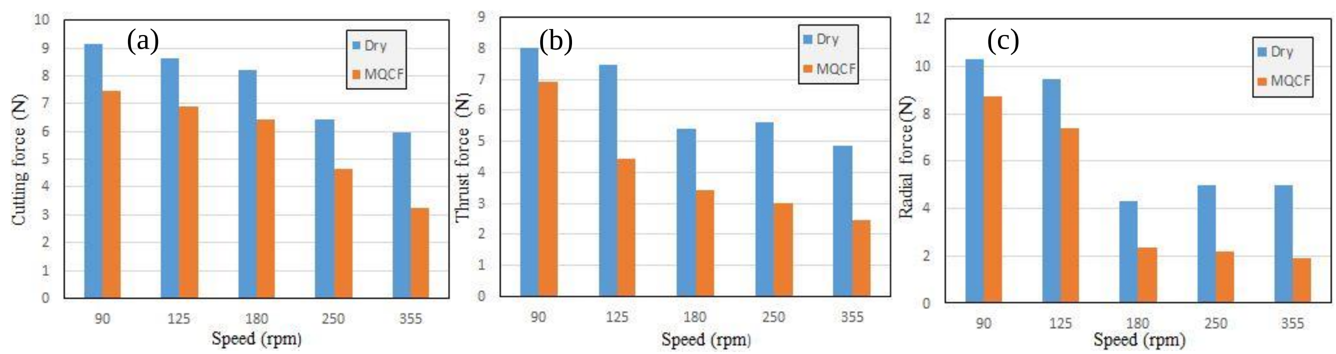

Fig. 4. Effect of speed on (a) cutting force, (b) thrust force and (c) radial force with MQCF and dry machining

Fig. 5. shows the surface morphology of end milled workpiece after MQCF machining. On the surface of the workpiece, cutting feed marks are observed. Also, number of pores are identified. Fig. 6 (a-b) shows the 3D surface profile of workpiece with dry and MQCF machining, respectively at the spindle speed of 355 rpm, feed rate of 80 mm/min and depth of cut of 0.15 mm. It is observed from the machined workpiece surface that in dry milled workpiece surface roughness is higher as compared to MQCF milled workpiece surface roughness. This is attributed to lesser machining forces in MQCF milling that leads to less tool vibration. This helps in lesser tool chatter, which results in better workpiece surface finish as shown in Fig. 6.

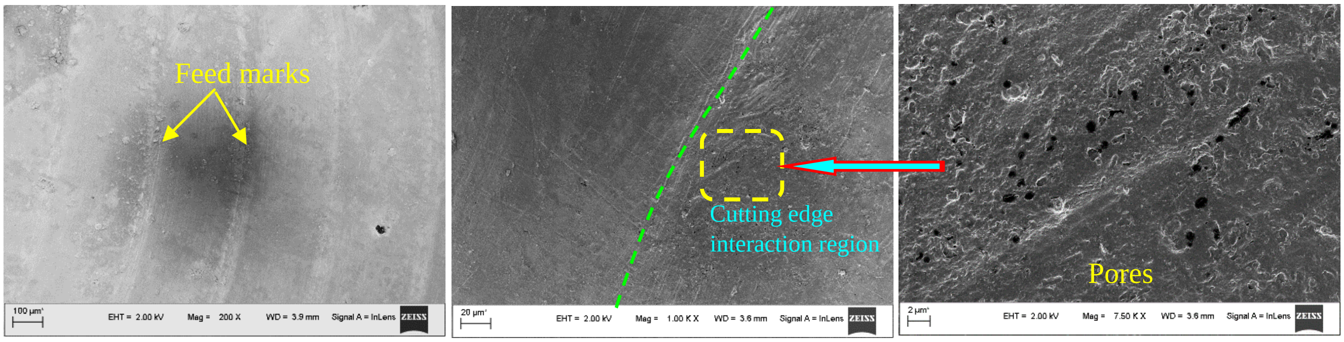

Fig. 5. Surface morphology of end milled workpiece after MQCFmachining

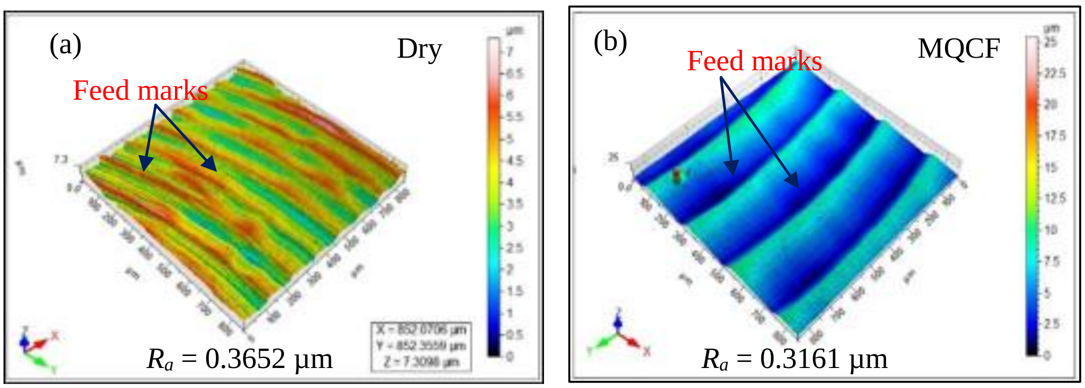

Fig. 6: 3D surface profile of workpiece with MQCF and dry machining, respectively at spindle speed of 355 rpm, feed rate of 80 mm/min and depth of cut of 0.15 mm.

4. CONCLUSION

Minimum quantity cutting fluid using eco-friendly bio-based cutting fluid end milling of AZ 31 magnesium alloy was carried out. For comparison, dry milling experiments were also conducted. The salient findings of this work are as follows:

- Cutting force, thrust force and radial force increased with increase in depth of cut as well as feed rate for most of the range.
- Cutting force, thrust force and radial force reduced with increase in spindle speed.
- The surface roughness of machined workpiece reduces with increase in spindle speed.
- In case of milling with MQCF using BCF, machining forces were reduced as compared to dry milling. This is due to better penetration ability of MQCF mist in-between tool-chip interface and better cooling as well as lubricating properties of BCF.

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