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Full Length Article

Effect of aluminum content on machining characteristics of AZ31 and AZ91 magnesium alloys during drilling

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Abstract

Magnesium (Mg) and its alloys are now becoming the promising choice for various structural applications due to their low density and high specific strength compared with other light metals such as aluminum and its alloys. Among all Mg alloys, AZ (aluminum and zinc) series is the most widely used alloy system for various structural applications. But, machining of magnesium and its alloys involves certain issues due to their brittle nature and risk of inflammability unlike other nonferrous metals. Particularly, alloys with considerable amount of secondary phase may exhibit different machining characteristics during metal cutting operations. In the present study, two AZ series alloys AZ31 and AZ91 were selected and drilling operation was performed to assess the effect of the secondary phase amount and distribution on machining characteristics. Drilling operation was carried out at different sets of process parameters and cutting forces were obtained and the chips which have been produced during drilling were analyzed. From the results, it can be clearly understood that the presence of secondary phase ($Mg_{17}Al_{12}$) has a significant influence on cutting forces. Increase in cutting speed has reduced the required cutting force and load fluctuations in all the cases.

Keywords: Light metals; Magnesium; Drilling; AZ series; Cutting force; Compounds

1. Introduction

Magnesium and its alloys are now gaining wide popularity as promising materials for light weight structural applications. The density of magnesium (1.74 g/cc) is lower compared with aluminum (2.7 g/cc). High specific strength and good damping properties make Mg alloys as best suitable candidates for energy efficient load bearing structures [1,2]. Fuel consumption can be reduced by using components made of Mg alloys in automobile and aerospace industries. Among the wide variety of Mg alloys, AZ series (aluminum and zinc) alloys are the most widely available and used in the manufacturing industry [2,3].

Machining is one of the basic manufacturing processes usually found in fabrication of components and structures. Machining of Mg alloys is complex compared with the other non-ferrous alloys. The inflammable nature and formation of flank built-up (FBU) at higher cutting speeds are the common issues associated with machining of Mg alloys [4,5]. However, by using appropriate cutting tools and combination of process parameters, complexity in machining of Mg and its alloys can be reduced with the present existing knowledge. Friemuth and Winkler [5] have reported the possibility of chip ignition during turning at higher cutting speeds and also suggested the need of lower cutting forces for better machinability of Mg and its alloys. It has been clearly brought out by a few studies that the chip temperature during turning of AZ31 Mg alloy is increased with increase in cutting speeds [6,7]. At higher cutting speeds during turning, appearance of FBU due to adhesion of work piece material to the cutting tool was another observation reported by Tönshoff et al. [4,8]. Very recently, Birol Akyuz [9] has studied the machining characteristics of AZ series alloys during turning and reported that AZ91 showed lower cutting forces compared with AZ21 alloy. However, the effect of aluminum content on machining characteristics of AZ series alloys during drilling was not reported yet. In the present study, two AZ series Mg alloys, one with lower amount of aluminum

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(AZ31) and one with higher amount of aluminum (AZ91) were selected and the cutting forces during drilling was investigated. The chips were analyzed and the effect of process parameters such as drill bit cutting speed and feed rate on the cutting forces and chip formation was investigated.

2. Experimental details

AZ31 Mg alloy sheets (2.75%Al, 0.91%Zn, 0.001%Fe, 0.01%Mn and remaining being Mg) and AZ91 Mg alloy sheets (8.67%Al, 0.85%Zn, 0.002%Fe, 0.03%Mn and remaining being Mg) of size $100 \times 50 \times 5\ mm^3$ were purchased from Exclusive Magnesium, Hyderabad, India. AZ31 Mg alloy sheets were produced from a billet by hot rolling process and AZ91 Mg alloy sheets were produced by die casting method. Mechanical properties of these received materials are shown in Table 1. The alloys were then characterized by X-ray powder diffraction (XRD, D8 Advanced, Bruker, USA) method with CuKα radiation (step size 0.1). For the microstructural observations, the samples of size $10 \times 10 \times 5\ mm^3$ were cut and metallographically polished using different graded emery sheets followed by polishing using alumina and diamond paste (1–3 µm particle size). The samples were cleaned in ethanol and dried before each polishing step to remove residues resulted from the previous polishing step. Chemical etching was done using a picric acid reagent (comprised of 5 g of picric acid, 5 ml acetic acid, 5 ml distilled water and 100 ml ethanol), then rinsed with ethanol and dried in hot air. Microstructural observations were carried out using a polarized optical microscope (Leica DMI5000M, Germany). Microhardness measurements were carried out by Vickers indentation method (MHT-Smart, Omnitech, India) by applying 100 g load for 10 sec. Particularly for AZ91 Mg alloy; indents were placed on α-phase, β-phase and α + β regions to assess the hardness variations at different regions.

Machining experiments were conducted using a vertical milling machine. A twist drill bit made of high speed steel with 6 mm diameter was used in the present study. The work piece was fixed on a dynamometer (Kistler 9403, Switzerland) which was fixed on the work table of the milling machine as shown in Fig. 1. Drilling was carried out at 45, 235 and 450 tool rotational speeds (rpm) and 10, 15 and 30 feed rates (mm/min) and holes were produced on the work pieces. No lubricant was applied during the machining. Cutting forces were recorded continuously with the help of the dynamometer. The measurement of cutting forces was started a few seconds before the drill bit touched the work piece and continued up to a few seconds of machining for all the samples. After drilling, chips were carefully collected and the morphology was observed for every set of parameters for both the AZ31 and AZ91 alloys.

Table 1
Mechanical properties of AZ31 and AZ91 Mg alloys used in the present study.

Material	UTS (MPa)	YS (MPa)	% elongation
AZ31 Mg alloy	255	220	14
AZ91 Mg alloy	225	185	3.5

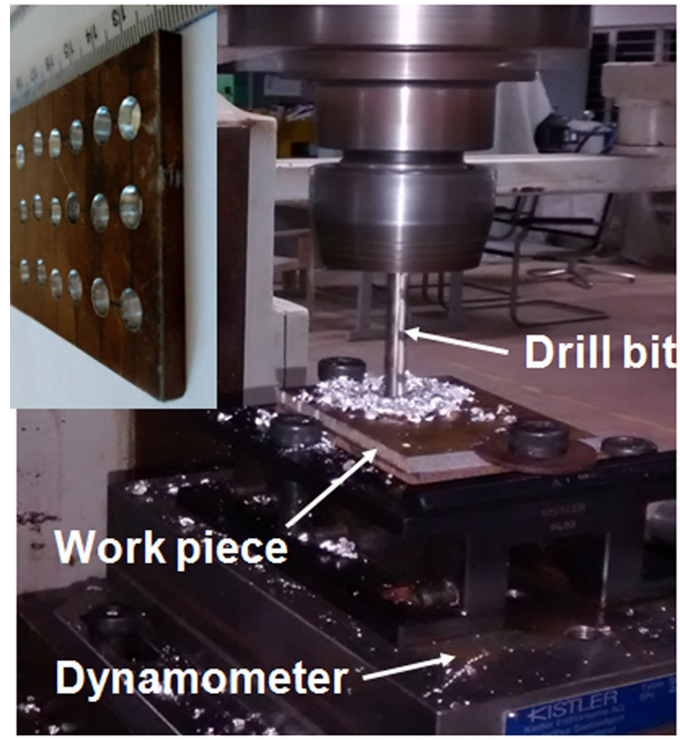

Fig. 1. Photograph showing drilling and the sample after drilling.

3. Results and discussion

Fig. 2 shows the XRD patterns of starting materials. Appearance of peaks corresponding to β-phase ($Mg_{12}Al_{12}$) was found to be prominent for AZ91 sample in which Al content is more compared with AZ31. Fig. 2 shows the optical microscope images of AZ31 and AZ91 samples. From the metallographic observations, the average grain size was measured by linear intercept method as 19 µm and 161 µm for AZ31 and AZ91 respectively. Usually, β-phase is invisible in AZ31 compared with AZ91. But the appearance of β-phase is inevitable in AZ91

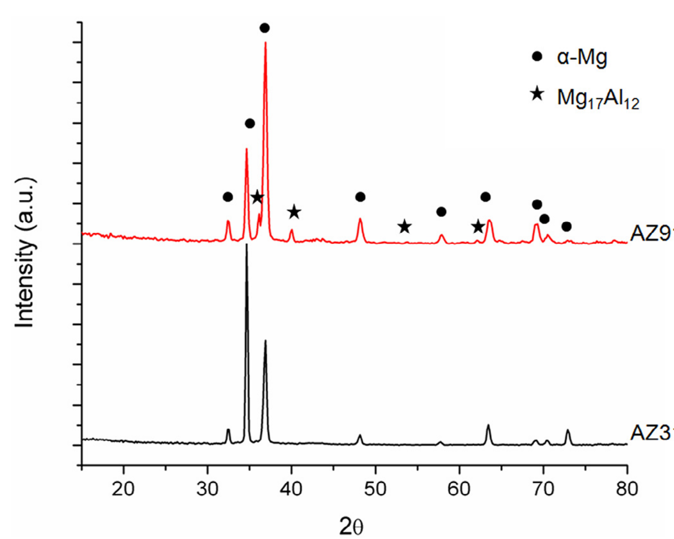

Fig. 2. XRD patterns of AZ31 and AZ91 Mg alloys.

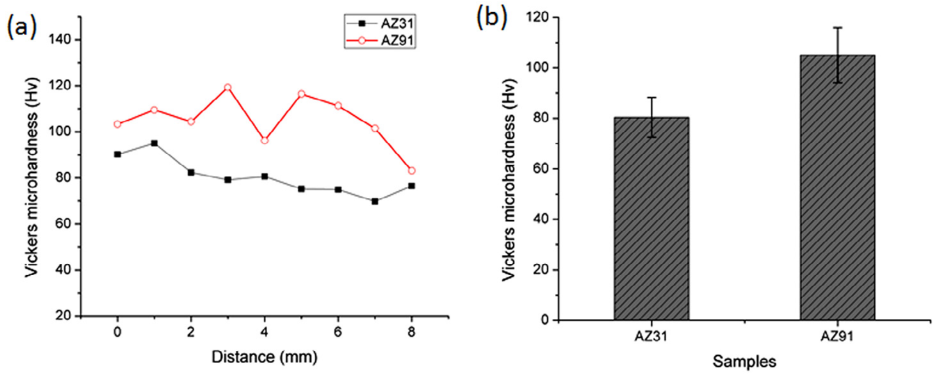

Fig. 3. Optical microscope images of the samples: (a) AZ31 Mg alloy and (b) AZ91 Mg alloy.

as shown in Fig. 2b. In Mg–Al alloy system, the maximum solubility of Al is limited to 1% at the room temperature and forms a solid solution (α-phase) of Mg and Al [1]. If Al content is increased more than 1%, the excess Al then forms $Mg_{17}Al_{12}$ phase and appears at the grain boundaries as shown in Fig. 2b. A combination of both α and β phases results lamellar structure at the interface as indicated by the arrows in Fig. 2b. Therefore, AZ91 Mg alloy exhibits a variation in material properties at microscopic level due to the presence of different phases (regions of α, β and α + β phases).

Fig. 3 shows the hardness measurements of the samples. Since a compound of Mg and Al ($Mg_{12}Al_{12}$) is present in AZ91 Mg alloy and exhibits higher brittleness and imparts high hardness to the matrix material, the range of the hardness distribution was found to be more (Fig. 4a) for AZ91 and also the average hardness was observed as significantly higher compared with AZ31 (Fig. 4b). Fig. 5 shows the micrographs of hardness indents placed at different regions of the samples. It is clear from these micrographs that the indent diagonal lengths are smaller when placed on β phase (33 µm) compared with the indents placed on the other regions (48 µm and 36 µm on α-region and α + β region respectively). The regions of α + β phases also exhibited higher hardness similar to that of β phase. These lamellar regions of α + β phases behave like laminate composites and promote hybrid behavior (combination of both hardness and toughness) as usually found in the composites. Therefore, the hardness of α + β region was also higher compared with α region.

The morphologies of the chips obtained at different process parameters are shown in Fig. 6. As feed is increased from 10 to 30 mm/min, continuous chips were resulted during drilling of AZ31at all the speeds compared with AZ91. In AZ series Mg alloys, solid solution of Mg–Al (α-phase) is a soft phase compared with the secondary phase (β). Therefore, in AZ91 Mg alloy, the presence of β-phase at the grain boundaries influences the machining characteristics [3,10]. The chip continuity also depends on the uniformity of the chemical composition within the work piece. AZ91 contains regions of different phases such as α, β and α + β phases. Therefore, discontinuous chips were formed for AZ91 compared with AZ31. Usually at the higher cutting speeds, the heat generation is more and therefore continuous chips arise during the machining. The force required to plastically deform the metal is also decreased with the increase in cutting speed. No chip ignition was observed during machining and also there was no indication of adhesion of work piece material to the drill bit in the present study. That indicates the generated heat is insufficient at the adopted cutting parameters which did not promote chip adhesion to the cutting tool.

From the cutting force analysis (Fig. 7), it can be clearly seen that the increase in cutting speeds led to decrease the cutting forces which is true as per the theory of metal cutting [11]. However, Birol Akyuz [9] reported increased cutting forces

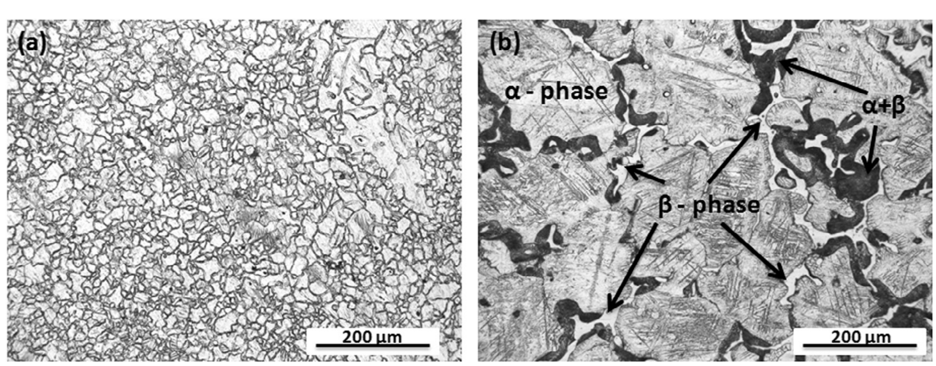

Fig. 4. Microhardness of the samples: (a) hardness distribution and (b) average hardness.

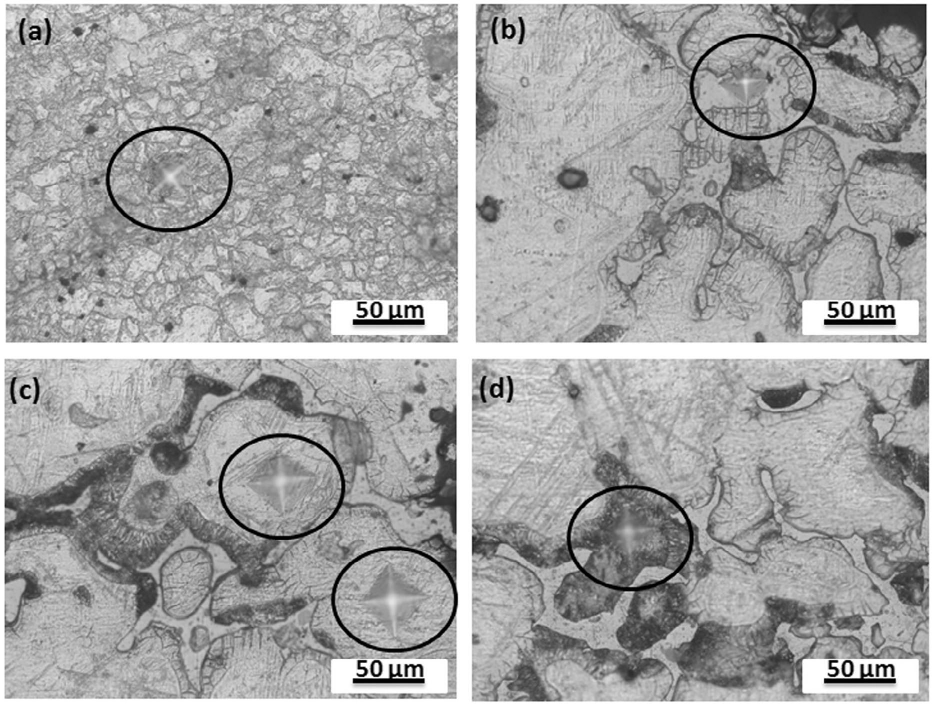

Fig. 5. Optical microscope images showing microhardness indents at different regions on the samples: (a) AZ31, (b) AZ91 β-phase, (c) AZ91 α-phase and (d) AZ91 α + β region.

during turning of AZ series Mg alloys with increase in cutting speeds due to the formation of FBU at the cutting edges of the cutting tool. The machining process (drilling) in the present study is different compared with turning and also no FBU was observed. Therefore, the cutting forces were decreased. For all the cases, AZ91 was recorded with higher cutting forces compared with AZ31. It is contradictory with what earlier reported by Birol Akyuz [9]. Of course, it is true that the formation of FBU certainly influences the machining characteristics. Therefore, the machining which is free from FBU gives different cutting characteristics as observed in the present study. For lower feed (10 mm/min), increase in drill bit rotating speed found to produce a starting hike in the cutting force and then a sudden drop followed by a gradual increase. As the feed rate was increased to 15 mm/min, increase in cutting speed did not show considerable sudden hike and drop during the initial stage of drilling. Interestingly, as the feed rate was increased to 30 mm/min, increase in cutting speed has caused negligible hike and drop at the initial stage of the drilling.

Usually, the removing of material is initiated as soon the drill bit touches the work piece surface. The two cutting edges OA and OB, as shown in Fig. 8 during drilling, remove the material as the rotating drill bit further advances into the work piece. More amount of material is removed and correspondingly the required cutting force also is increased. Once the cutting edges OA and OB of the drill bit completely enter the hole and the diameter of the hole is reached to the diameter of the drill bit, a relief on the drill bit leads to decrease the cutting force. Then the material removal rate is constant throughout the drilling and therefore approximately uniform cutting forces are recorded as observed in Fig. 7. AZ31 is a wrought alloy and AZ91 is as cast alloy. The tensile strength of wrought AZ31 Mg alloy is higher compared with cast AZ91 Mg alloy (Table 1). Even though the hardness was measured to be higher for AZ91 alloy compared with AZ31 alloy, when the nose of the drill bit has touched the surface of the work piece, necessary force to initiate the plastic deformation and to cut the material was increased in order to remove the material from AZ31 alloy. Therefore, the cutting force was found to be increased at the beginning of drilling. Interestingly in all the cases, AZ31 samples have shown higher increment and drop at the beginning of drilling compared with AZ91. This behavior can be related with the mechanical properties of both the alloys. Tensile strength and yield strength were more for AZ31 compared with AZ91 which made the required cutting force to increase to initiate the metal removal from AZ31 compared with AZ91. However, hardness was also found to be played an important role when the drill bit completely enters into the work piece and therefore the cutting forces were observed as more for AZ91 in all the cases during the drilling except at the initial stage.

The mean cutting force ($F_{z\ mean}$) during drilling of AZ31 and AZ91 at different speeds (Fig. 9) indicated that the AZ91 required higher cutting forces compared with AZ31. The presence of more amount of hard and brittle phase in AZ91 compared with AZ31 has increased the mean cutting force during drilling. In AZ91 Mg alloys, secondary phase which appeared at the grain boundaries in the form of a network like structure opposes the cutting tool movement compared with the matrix and hence the requirement of force is increased to cut these hard phases when cutting tool traveling through the grain boundaries. Similarly, α + β region which is similar to lamellar composite of α and β phases exhibits higher hardness and therefore the required force to remove material at α + β region is also

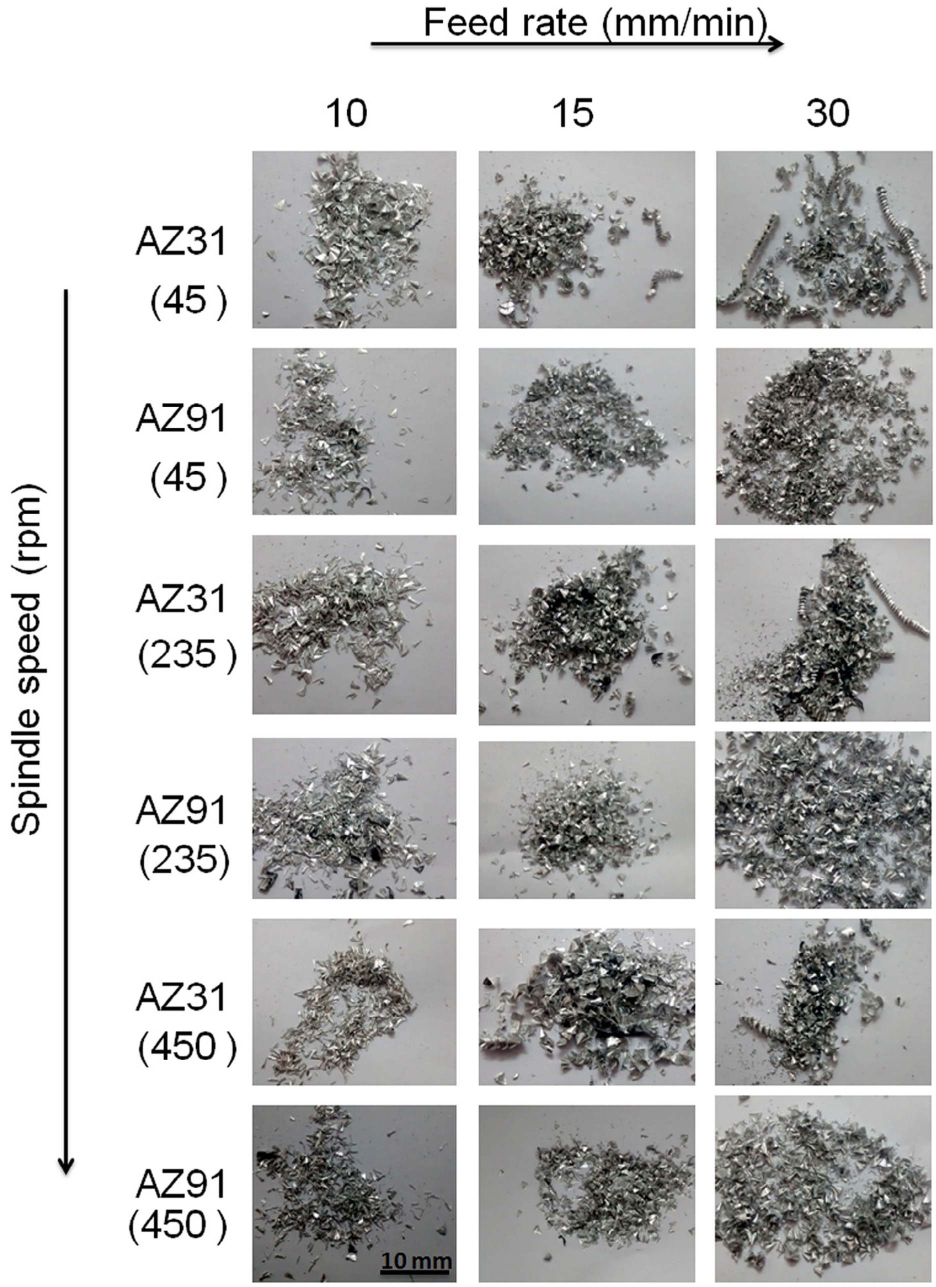

Fig. 6. Photographs of the chips of AZ31 and AZ91 resulted at different cutting parameters.

increased. Hence, it can be understood that there are two different regions which require higher cutting forces compared with α phase in AZ91 Mg alloy during drilling. Since AZ31 Mg alloy is a solid solution of Mg and Al (α phase) with negligible amount of β phase, compared with AZ91, lower mean cutting force ($F_{z\ mean}$) was observed for AZ31 Mg alloy. The difference in the cutting forces between AZ31 and AZ91 was found to be increased as the cutting speed was increased from 45 to 450 rpm. But the mean cutting force was observed as reduced for all the samples as the drill bit rotating speed was increased. From these results, it can be observed that more heat was generated due to the increased cutting speed and therefore required force to initiate plastic deformation and further to remove the material was reduced. But risk of chip ignition and adhesion of work material to cutting tool are the two issues that usually arise with the higher cutting speeds. Therefore, optimum cutting speeds are suggested to reduce the cutting forces as well as to avoid the risk of chip ignition. Therefore, from the present study, it can be understood that the secondary phase play an important role in altering the machining characteristics of AZ series Mg alloys during drilling. The higher amount of Al leads to produce discontinuous chips and the required cutting force also is increased with Al content. Without any risk of chip ignition and work material adhesion to the drill bit, dry machining of AZ31 and AZ91 Mg alloys can be performed up to higher speeds of 450 rpm.

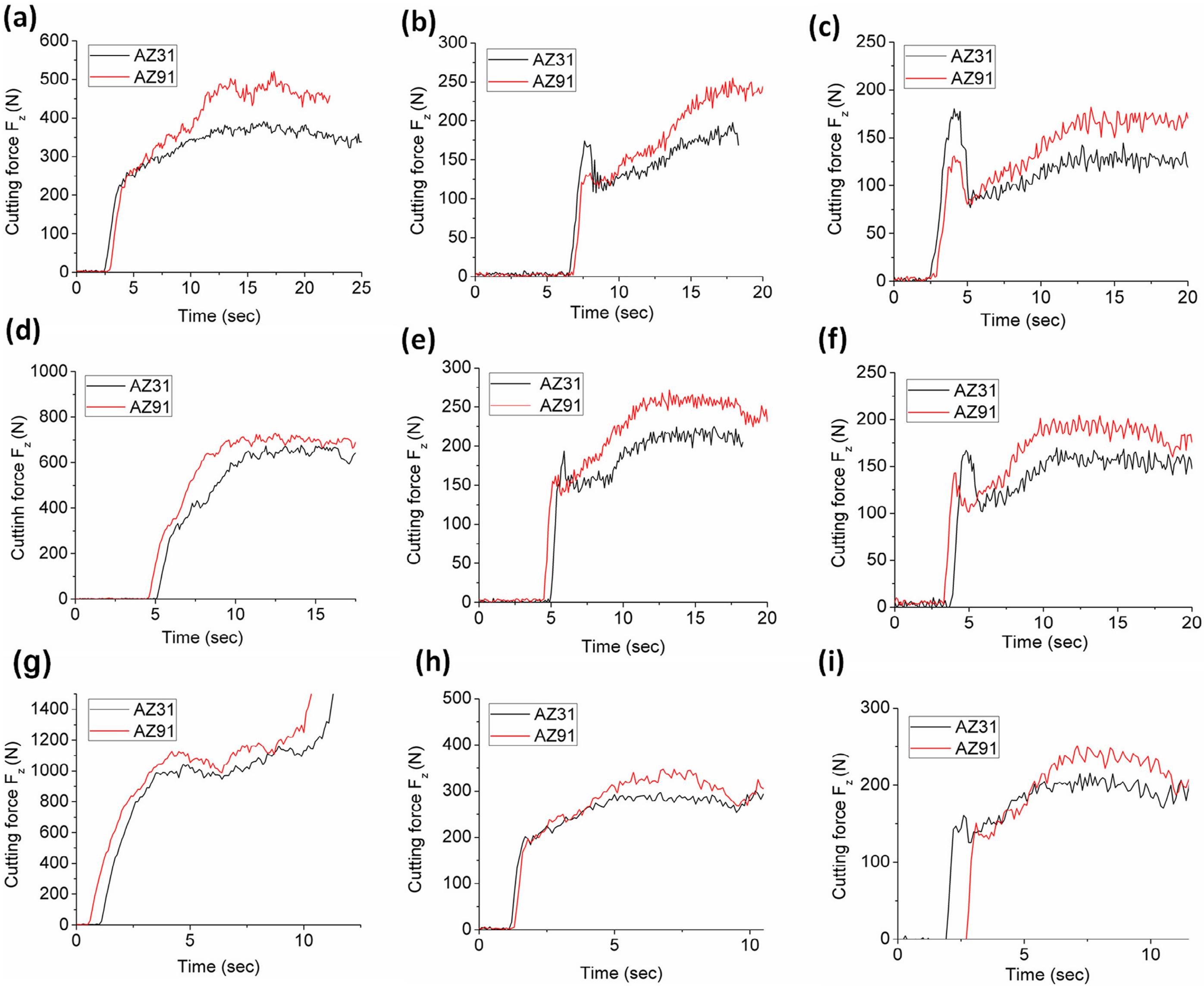

Fig. 7. Cutting force (F_z) resulted in drilling of AZ31 and AZ91 at different cutting parameters: (a) 45 rpm and 10 mm/min, (b) 235 rpm and 10 mm/min, (c) 450 rpm and 10 mm/min, (d) 45 rpm and 15 mm/min, (e) 235 rpm and 15 mm/min, (f) 450 rpm and 15 mm/min, (g) 45 rpm and 30 mm/min, (h) 235 rpm and 30 mm/min, (i) 450 rpm and 30 mm/min.

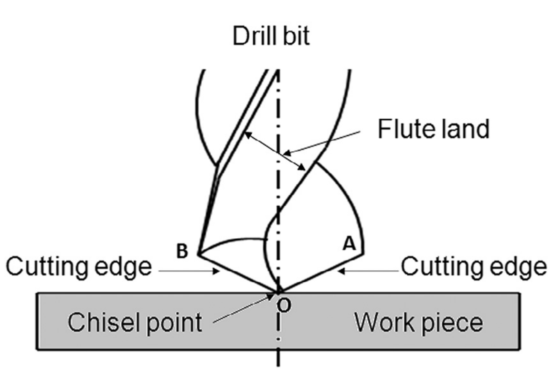

Fig. 8. Schematic representation of drilling.

4. Conclusions

Machining characteristics of AZ31 and AZ91 Mg alloys were investigated during drilling and the following conclusions can be drawn from the present study:

1 Presence of regions with different phases in AZ91 gave more variations in hardness compared with AZ31 alloy.
2 Discontinuous chips were produced from AZ91 at all the process parameters which can be attributed to the combination of soft and brittle regions that belong to α and β phases respectively.
3 Cutting forces were reduced for AZ31 at all the parameters compared with AZ91 due to the presence of uniform α phase compared with AZ91 alloy.
4 Hence, it can be understood that the presence of more aluminum in the form of $Mg_{17}Al_{12}$ secondary phase produces

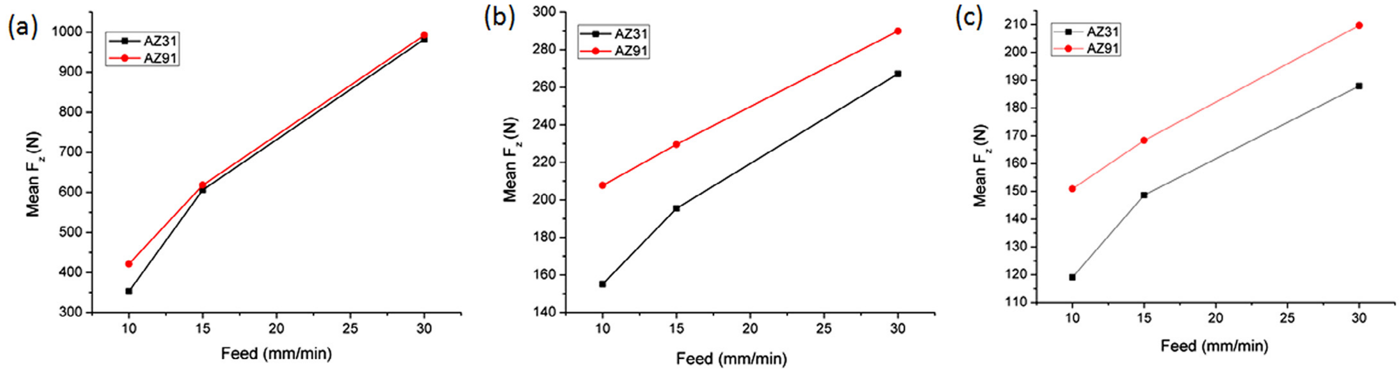

Fig. 9. Mean cutting force ($F_{z\ mean}$) resulted during the drilling of AZ31 and AZ91 with 10, 15 and 30 mm/min feed rate with: (a) 45 rpm, (b) 235 rpm and (c) 450 rpm.

discontinuous chips and significantly influences the machining characteristics by promoting higher cutting forces.

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