Vol. 04, Iss. 3 (2026) 255-363, DOI: 10.61552/JME.2026.03.005

JME

Journal of Materials and Engineering

www.jme.aspur.rs

Research article

Deep Drawing of AZ31 Magnesium Alloy at Elevated Temperatures in Annealed Condition

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Keywords:

AZ31 magnesium alloys
Deep drawing
Annealing
Depth of forming
Thinning
Microstructural evolution

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Received: 22 May 2026
Revised: 23 June 2026
Accepted: 1 August 2026

ABSTRACT

The lower density and higher specific stiffness and strength of magnesium alloys make them appealing; nevertheless, the strengthening of the secondary phase and the lack of slip mechanisms reduce formability, particularly for the stronger magnesium alloys such as AZ31. Experiments examining the formability of AZ31 sheets in an annealed condition revealed that AZ31's improved plastic flowability causes the sheet's depth of forming to grow dramatically to 32 mm when the temperature is raised from 250 to 350°C. At 350°C, there was more thinning. A 350°C temperature, 8 kN blank-holding force, and 4 mm/min drawing speed are the ideal process conditions for hot deep drawing. The microstructural evolution demonstrates that twinning significantly accommodates plastic deformation of the AZ31 magnesium alloy at high temperatures. By overcoming the challenges of the reinforcing phases, this twinning deformation mechanism is triggered by heating and achieves improved forming properties.

1. INTRODUCTION

Apart from machining, metal joining, powder metallurgy, and metal casting, one of the most important operations for shaping materials is metalworking. However, shaping materials might be considered the initial metalworking, derived from the fundamental hammering of gold and copper [1]. It is critical, because the development of this technology is primarily responsible for industrial advancement. Fundamentally, the basic purpose of the metal forming process is to try to turn a metallic billet into products with the appropriate geometrical size and shape [2]. The shortage of petroleum resources is increasing the necessity for more research in the field of lightweight metals and their use in the aircraft and automotive industry. The deep drawing process is a key component of modern metal forming, transforming flat thin metallic sheets into three-dimensional products that serve a wider range of applications in a variety of industries [3]. The deep drawing process has acquired importance in today's manufacturing due to its potential in contributing to increased energy efficiency and production capacity [4, 5]. Deep drawing can be done on large or small batch quantities. The recent study of Jai Shiva Rao et al. [6] presents various sophisticated deep drawing methods created by researchers.

Lightweight sheet structures are progressively being used in the automotive, aerospace, and other related industries to minimize fuel consumption and pollutants. Magnesium alloys are popular because of their lower density, high stiffness and specific strength, excellent shock absorption and damping properties, superior machinability, thermal conductivity, and ease of recycling. However, because of the magnesium alloy’s thick hexagonal structure and few slip systems at ambient temperature, it results in low plasticity, limiting its usefulness. [7, 8]. Magnesium and related alloys are broadly utilised in industries such as automotive, aircraft, 3C (consumer electronics, communications, and computers), and biomedicine [9]. As per the European Commission report 2023, magnesium is primarily used in automotive (48%), packaging (23%), desulfurization (12%), construction (13%), and equipment for transportation (4%) [10]. Deep-drawn magnesium alloy products continue to have a wide range of uses, as represented in Fig. 1. A review by Babu et al. covers all elements of deep drawing magnesium alloys, including unique methods, factors impacting deep drawing performance, and obstacles [11].

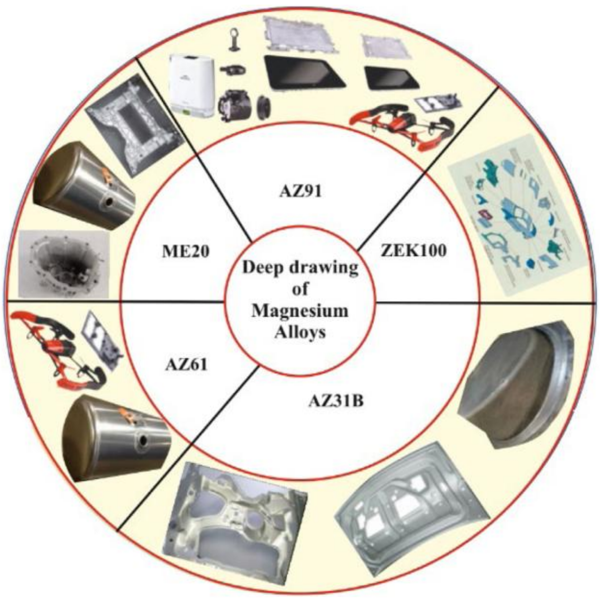

Fig. 1. Application examples of deep drawn products of magnesium alloy [11].

Research indicates that increasing the temperature activates slip mechanisms in magnesium alloy, leading to improved formability. When the temperature is very high, the grain's plasticity shall decrease [12]. Zhang et al. [13] discovered that magnesium and its alloys had outstanding drawing characteristics between 200 and 300°C. Sabat and Tam et al. [14, 15] discovered that when temperature increased, then the non-basal slip system’s critical shear stress reduced, while the non-basal slip system’s number grew, leading to enhanced flexibility.

Wang et al. [16] discovered that varying temperature gradients while stamping result in varying fracture locations. Feng et al. [17] discovered that AZ31B exhibits significant elongation at higher strain rates at the temperature of 25°C.

Stutz et al. [18] studied advances in the deep drawing of magnesium alloy. Their findings revealed that the material's microstructural evolution was dominated by dynamic recrystallization and twin creation. By adjusting the method, a 2.9 drawing ratio was obtained for the AZ31 magnesium sheet, outperforming standard materials at room temperature. Wang et al. [19] studied magnesium at raised drawing temperatures and varied drawing rates, as drawing ability is quite sensitive. When drawing speed grew, the drawing ability of the AZ31 decreased. Cao et al. [20] studied the heated deep drawing of an AZ31 sheet using DYNAFORM. The results showed that dynamic recrystallization of magnesium occurred completely when the forming temperature exceeded 423K, and material softening aggravated with the raise in temperature. Ghaffari Tari et al. [21] conducted experiments on AZ31B sheet deep drawing under different temperatures. They concluded that at greater punch speeds, tiny cracks form at the radius of the punch, increasing the likelihood of failure. Scanning electron microscopy is used to observe the fracture surfaces under each heat setting. It has been established that the mechanism of the fracture while deep drawing the AZ31B depends on temperature, which affects the active deformation process.

Yasuhide Nakayama et al. [22] studied the temperature and processability of AZ31 magnesium alloy’s deep drawing of a rectangular cup, concluding that the relationship between formability and blank size was estimated. According to their numerical simulation results, local heating of the die and punch increased the formability of deep drawings. Reddy et al. [23] developed an evaluation of LDR in deep drawing using a rapid determination technique. This technique is safe and gives an accurate estimation of LDR. Reddy et al. [24] conducted investigations experimentally and also simulations on the AZ31 alloy warm deep drawing. Their study resulted in higher formability at the elevated temperatures. It was found that LDR increased greatly with the rise in temperature.

Hui et al. [25] studied the deformation mechanisms of the blank holder region during heated deep drawings of the AZ31 magnesium alloy. Macroscopic and microscopic numerical simulations were carried out. They used EBSD analysis and multiscale modelling to study the deformation mechanisms, stress state, and also texture evolution during deformation. Their findings revealed that at the deformation commencement, the tension twins and basal slip started concurrently. Recently, Li et al. [26] examined the deep drawing performance of the AZ31 magnesium alloy. Their experimental results showed that when temperature increased, then maximum drawing force steadily decreased, and the drawing performance was ideal at higher temperatures. From the literature it was found that AZ31 magnesium alloy's warm deep drawing with annealing conditions is seldom available in the literature. Hence, the present study aims to investigate the deep drawing performance at elevated temperatures in the 250-350°C range on the AZ31 sheet specimens in annealed condition.

2. MATERIALS AND METHODS

2.1. Materials

AZ31 magnesium alloy sheets with a thickness of 1 mm served as the experimental specimen. They were made using the melting extrusion-rolling method. The chemical compositions of the material chosen are given below in Table 1. Annealing was done by keeping the samples in the muffle furnace till the temperature reached 300°C, with a holding time of 30 min and furnace cooling for one day. The circular blanks of diameter 140 mm were cut for the forming experiments.

Table 1. AZ31 magnesium alloy chemical composition in % of mass fraction

Element	Al	Zn	Mn	Si	Fe	Cu	Ca	Ni	Ti	Mg
Mass fraction [%]	2.84	0.94	0.34	0.0153	0.0025	0.0055	0.020	0.002	0.0216	**95.7**

2.2. Deep drawing experiments

Deep drawing studies were carried out utilizing a servo-electric hot-forming machine available at Defence Metallurgical Research Laboratory (DMRL), Hyderabad, India, as shown in Fig. 2. Servo-hydraulic control, with a programmable data acquisition technique, controls the force on the blank holder and the displacement of the punch. One actuator is responsible for the blank holding force, and another controls the movement of the punch. These experiments use a constant blank holding force. The experimental configuration includes the die, punch, and blank holder. The blank is heated utilising a three-layered thermocouple furnace. Each component contains thermocouples for recording and monitoring temperature. A chiller is provided to prevent overheating of the furnace and other components.

Initially, the furnace is turned on at temperatures ranging from 250°C to 300°C and 350°C. Before reaching these temperatures, a molybdenum-coated (Molykote, D-321R) 140 mm blank is placed between the die and blank holder, and the furnace is closed to ensure that the blank reaches the required temperature. The experiments are organized as follows. The punch is placed 1 mm away from the blank surface to maintain the temperature variation within specimen. Once the blank reaches the proper temperature, the specimen is maintained in this position for a duration known as the dwell time or wait time, while the blank is evenly heated. Forming starts at the end of the waiting period. The blank holder is then actuated by a servo-hydraulic controller actuator with an 8 kN BHF. The actuation system then moves the punch at speeds of 12 mm/min, 8 mm/min, 6 mm/min and 4 mm/min, respectively. By observing the movement of the punch, we may determine the amount of force required to make the cup. As the punch load decreases, the cup was formed without defects.

Fig. 2. Servo electric hot forming machine.

3. RESULTS AND DISCUSSIONS

3.1 Depth of forming at elevated temperatures

The cylindrical cups were drawn from a circular blank of AZ31 sheets with a 140 mm diameter and 1 mm thick. Several trials were made at a constant blank holding force of 8 kN and varying drawing speeds and temperatures, and the samples showed fracture at the drawing speeds of 12 mm/min, 8 mm/min, and 6 mm/min at the temperatures 350 °C and 300 °C, as shown in Fig. 3. There is less material transfer inside the plane flange area as a result of high drawing rates and high deformation speeds. This is likely to result in the sheet becoming too thin in a short amount of time, which eventually causes rupture. Hence, the next set of experiments were conducted at the 4 mm/min drawing speed at the temperatures of 250, 300, and 350°C. The deep-drawn cups at the three different chosen temperatures of 250, 300, and 350°C are shown in Fig. 4. The depth of the forming of the cups was measured using a vernier height gauge, as shown in Figure 5, and the comparison of heights of formed cups is shown in Fig. 6. The depth of forming obtained from the experiments is shown in Fig. 6, which represents that the change in temperatures has a significant influence on the deep drawing formability of the workpiece. As the temperature rises from 250 °C to 350 °C, the depth of forming value rises significantly and reaches a maximum of 32 mm at the forming temperature at 350 °C.

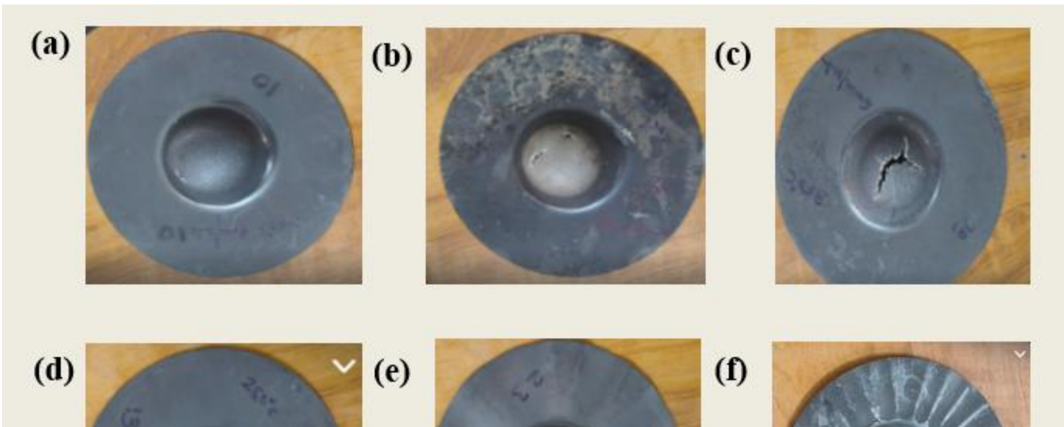

Fig. 3. Fractured deep drawn cups drawn at blank holding force of 8 kN, forming speeds were 12 mm/min, 8 mm/min, 6 mm/min at the temperatures (a-c) 350 ^{0}C, (d-f) 300 ^{0}C.

Fig. 4. Deep drawn cups drawn at the temperatures (a) 250 ^{0}C, (b) 300 ^{0}C and (c) 350 ^{0}C.

Fig. 5. Measurement of deep drawn cups using vernier height gauge (a) 250 ^{0}C, (b) 300 ^{0}C and (c) 350 ^{0}C.

Fig. 6. Comparison of depth of deep drawn cups in mm drawn at 250 ^{0}C, 21 mm, 300 ^{0}C, 30 mm and 350 ^{0}C, 32 mm.

3.2 Variation of thickness after deep drawing at elevated temperatures

As expected, the thickness goes on reducing from the sheet radius to the bottom of the dome. The results of thickness measured at various locations are shown graphically in Fig. 7. Warm forming of AZ31 reduces overall thinning and makes thickness distribution more uniform; at lower temperatures, domes show large localized thinning and early fracture, while at ~250–350°C, one can typically see reduced maximum thinning and smoother radial thickness gradients due to dynamic recrystallization and activated non-basal slip. AZ31 is HCP; at low temperatures only limited slip systems are active, resulting in localized necking and brittle fracture. Higher temperatures activate additional slip and DRX, increasing ductility and evening out thickness [25-27]. The dome apex or centre location '6' sees the highest biaxial stretch; flange-to-apex radial flow produces a monotonic thinning from flange to pole at all the temperatures. At higher temperatures, as the depth of forming is large, higher strain leads to higher thinning as seen in Fig. 7.

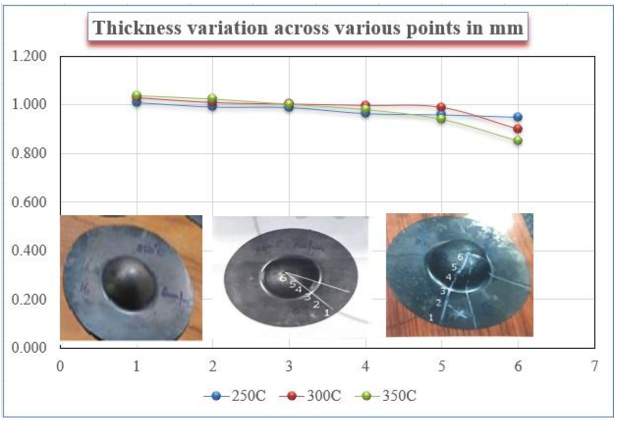

Fig. 7. Variation of thickness at different locations formed at two chosen temperatures.

3.3 Microstructural changes

The microstructures as received in rolled condition and after annealing are shown in Fig. 8. As received, material micrographs showing α–Mg grains with pronounced twins and partially recrystallized regions. After annealing, the micrograph shows equiaxed α –Mg grains with pronounced twins and uniformly recrystallized regions.

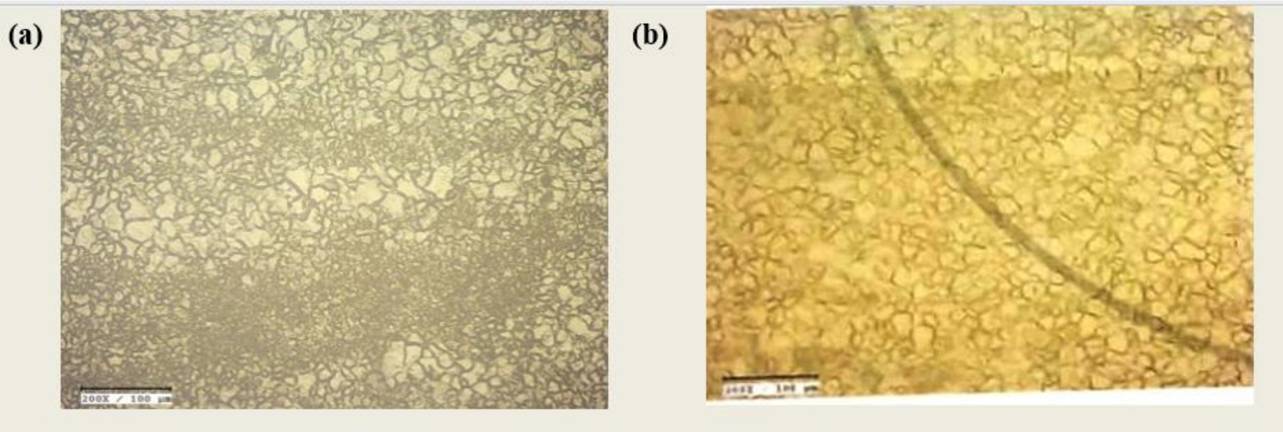

Fig. 8. Optical micrographs of AZ31 (a) As received in rolling condition, (b) After annealing.

Fig. 9 shows the optical micrographs of domes formed at the three different locations: the dome centre, the edge and the middle of the cup formed at the temperature of 250°C. The dome centre is the most strained region with biaxial tensile deformation. Microstructure reveals elongated grains of alpha Mg. Sporadic dynamically recrystalised grains are seen. A higher number of twins are seen, and at some places localised shear bands are seen, as in Fig. 9(a). Microstructure at the edge reveals a near-original as-rolled microstructure, i.e., an alpha Mg matrix with Mg-Al intermetallic occasionally seen. Not much recrystalisation is seen. Elongated alpha grains are observed as shown in Fig. 9 (b). In the middle of the cup, a plain deformation condition exists. Elongated alpha grains and, in some places, fragmented grains are observed. At some places of grain boundaries, recrystallisation is seen, as shown in Fig. 9(c).

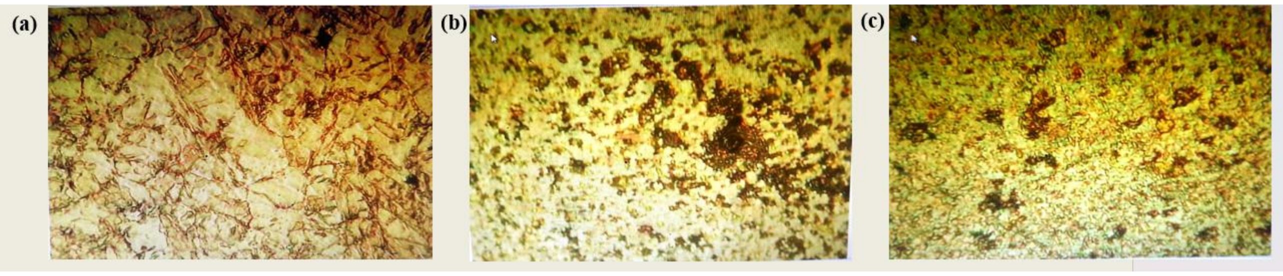

Fig. 9. Optical micrographs of deep drawn cups formed at 250 ^{0}C at various locations on the cup (a) Dome centre, (b) Edge and (c) Middle.

Fig. 10 shows the optical micrographs of domes formed at the three different locations: dome centre, edge and the middle of the cup formed at the temperature of 300°C. Here also dome centre is a highly strained region. Alpha Mg solid solution grains are seen with considerable dynamic recrystalisation. Residual deformed grains and occasional twins are seen. More or less uniform grain refinement with reduced twins. However, slip is dominant in this region, as given in Fig. 10(a). Balanced microstructure can be noticed. Edge is the low-strain region. Alpha Mg grains are seen with partial recrystallisation. Slight grain coarsening is also observed. A combination of original alpha grains of Mg and recrystallised grains of Mg is observed at the dome edge region, as shown in Fig. 10 (b). The dome's middle region is subjected to moderate strain. Fine equiaxed grains of alpha Mg with more or less uniform recrystallisation are observed. Intermetallic are seen at the Mg-Al interface as shown in Fig. 10 (c).

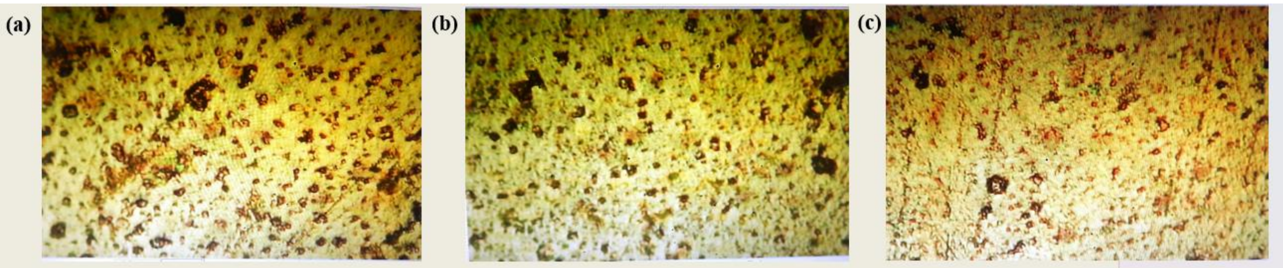

Fig. 10. Optical micrographs of deep drawn cups formed at 300 ^{0}C at various locations on the cup (a) Dome centre, (b) Edge and (c) Middle.

Fig. 11 shows the optical micrographs of domes formed at the three different locations: the dome centre, the edge and the middle of the cup formed at the temperature of 350°C. The dome is subjected to extensive deformation and this high temperature. Completely recrystallised equiaxed grains of alpha Mg are seen with minimum dislocation density, representing relieved stresses due to high deep-drawing temperatures, as shown in Fig. 11 (a). However, the problem of excessive softening and growth of grains may pose problems to the quality of deep-drawn cups. Balanced microstructure can be observed. Edge is the region subjected to the lowest strain and high temperature. In this area, grain growth of alpha Mg grains is predominant, resulting in coarser grains as in Fig. 11 (b). However, the internal stresses in this region are minimal. The dome's middle region is subjected to moderate strain. Completely recrystallised homogeneous grains of alpha Mg are seen with a few slightly coarsened grains as shown in Fig. 11 (c).

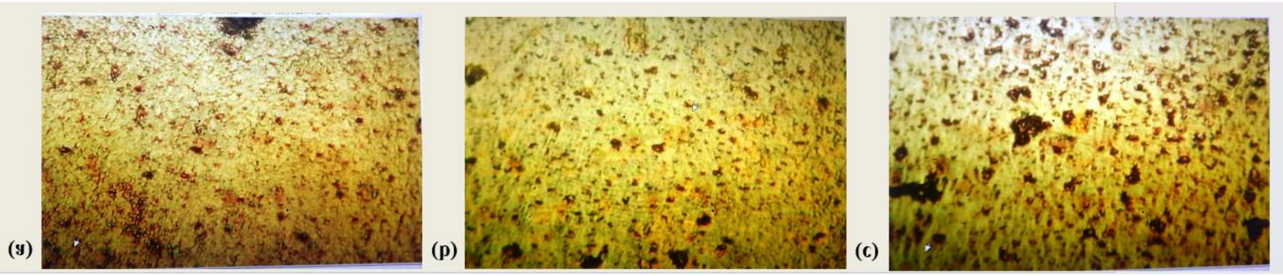

Fig. 11. Optical micrographs of deep drawn cups formed at 350 ^{0}C at various locations on the cup (a) Dome centre, (b) Edge and (c) Middle.

Summarizing, the microstructural analysis shows, initially, the AZ31 alloy consists of an alpha-Mg solid solution with Al-Mn intermetallic at some places. On a few occasions, Mg-Zn alloy also can be seen. Deep drawing of AZ31 alloy is difficult at ambient temperature because of the little slip systems of HCP crystal. At warm temperatures, the response of material improves but not to the required extent for obtaining dynamic recrystallization. When the drawing temperature is less than 250°C, not much significant difference is noticed between the microstructures of the corner and wall of the deep-drawn cup. But when drawing temperature is 300°C or more, dynamic recrystallization occurs at corners, improving toughness of material. Further intermetallic evolution occurs. Further, during deep drawing, different areas of the dome are subjected to the strains of varying severity. As deep drawing temperatures are less than 250°C, the response of the material for dynamic recrystallization is sluggish. At 350°C, higher depth of formation was observed. This could be because of the evolution of fine grains of alpha Mg rupturing intermetallic and the severity of deformation during deep drawing. An increase in deep drawing temperature released stored energy because of fracturing intermetallic and may enhance the depth of forming. Twin boundary crossing and the resulting refinement of grains could be the reason for the improvement of depth of forming with temperature. However, this discussion applies to deep drawing temperatures between 250°C and 350°C. Beyond 350°C, it may result in excessive coarsening and softening of grains, which may lead to early fracture, thus reducing the depth of forming.

4. CONCLUSIONS

This work presents the high-temperature deep drawing of AZ31 Mg alloy in an annealed condition. Deep drawing temperature ranges from 250 to 350°C, and the work is focused on depth of forming, thinning, and microstructural changes. It is concluded that deep drawing temperature significantly affects formability. A rapid increase in depth of forming is observed between 250°C and 350°C drawing temperature, and the peak value of depth of forming is 32 mm. At all temperatures, flange-to-apex radial flow results in a monotonic thinning from flange to pole; the dome apex or center position displayed the greatest biaxial stretch. The limited slip systems of HCP crystals make AZ31 alloy deep drawing challenging at room temperature. At a drawing temperature of 300°C, a higher depth of forming is possible due to the evolution of finer grains of alpha Mg rupturing intermetallic. Considerable dynamic recrystalisation is observed in the dome when deep drawing temperature is 300°C. But deep drawing at a temperature of 350°C witnesses slight grain coarsening. An increase in deep drawing temperature beyond 250°C releases the stored energy through (i) fracturing of intermetallic and (ii) twin boundary crossing, leading to grain refinement and, hence, an increase in depth of forming.

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