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EXPERIMENTAL INVESTIGATIONS INTO THE DEFORMATION BEHAVIOR OF THIXO-MOLDED Mg AZ61L SHEET ALLOY

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Abstract

Deformation behavior and formability limits of thixo-molded Mg AZ61L alloy and regular Mg AZ61 alloy sheets (with similar chemical compositions except for Mn content) were experimentally investigated at elevated temperature. Tensile (uniaxial), hydraulic bulge (biaxial) tests as well as closed-die hydroforming tests were conducted to understand the material behavior at temperatures ranging from 25 °C to 300 °C and strain rates at 0.0013, 0.013 and 0.13 s^{-1}. It was found that flow stress and the maximum plastic strain increased with increasing temperature and decreasing strain rate. Closed-die warm hydroforming tests were also performed to determine the process window for the sheet alloy. Die cavity filling ratios and thinning of the sheet blanks were measured with non-contact optical photogrammetry. Results indicated that lower strain rates and higher temperatures increase formability, particularly above temperatures of 200 °C.

Introduction

Due in large part to the current state of the global economy along with concerns over global warming and going green, there has been an increasing quest to make vehicles more efficient. Utilization of lightweight materials such as aluminum and magnesium in automotive components is accepted as part of solution attempts to reduce fuel consumption and emissions. Depending on the choice of material, it has been known that the use of lightweight materials can lower the weight of vehicles 15-75% [1]. Mg, for example, is one the most promising materials in weight-saving efforts due to its low density of 1.74 g/cm^3 [2]. It is also reported that a 10% reduction in automotive body weight in turn can increase the fuel efficiency by as much as 8% [3]. However, the majority of the lightweight parts in the present vehicles are die castings, for mainly underbody structures and casings. Another realm of automotive components that can utilize lightweight materials to reduce weight is thin-gauge body and structural parts (sheet metal-based) that can be potentially fabricated using magnesium alloys to attain higher levels of fuel savings and emission reductions [4].

Despite the obvious advantages of lightweight materials, they have considerably lower formability at room temperature when compared to mild steel alloys. The formability of aluminum alloys at cold conditions is reported to be limited by its high alloy percentage [5] while the low formability of magnesium alloys at room temperature is known to be mainly caused by the limited number of slip systems in their hexagonal closed-packed (HCP) lattice structure and low tendency to twinning at ambient conditions [6]. To alleviate this problem, magnesium sheets should be formed at elevated temperatures below their recrystallization ranges, where the thermal activation of additional slip systems is realized [7–11]. Previous studies indicated that temperature levels of up to 350 °C for Mg AZ31 [12] and 200-250 °C for AZ31B and AZ61B [10] would increase the elongation. Furthermore, higher elongation could be obtained when low strain rate is used as these materials have intrinsically high strain-rate sensitivity, especially at elevated temperatures (i.e., strain-rate hardening, "m", increases 15 folds from room temperature to 200 °C for magnesium sheet) [7]. The strain-rate effect was shown to be less significant if the forming is carried out at lower temperatures [6]. On the other hand, lower strain rates lead to slow production rates. Thus, it is vital to find the optimum balance between production rate and strain-rate control. This optimization will require a complete understanding of the response of these materials at different temperature and strain-rate levels for accurate analysis and design of the forming processes.

The process of thixomolding takes advantage of the principle that magnesium, aluminum and zinc alloys become semi-solid between the liquidus and the solidus temperatures. Mechanical shearing of the semi-solid metal generates a thixotropic structure that allows these materials to be molded utilizing a process similar to plastic injection molding while eliminating the environmental impacts of die casting. Due to its similarity to injection molding of polymers, thixomolding is capable of creating parts with thin walls, superior surface quality, and be formed to virtually net shape. In addition, thixomolding allows for faster cycle rate, longer die life, and increased worker safety due to the lower temperature of the material. The resulting thixomolded magnesium microstructure characterized as primary Mg rich particles surrounded by rapidly quenched liquid (fully or partly amorphous) is believed to delay crack propagation during fracture, resulting in improved ductility [13]. The AZ61L alloy used in this study was manufactured by means of the Thixomolded-Thermomechanical Processed (TTMP) technique in which sub-micron grain size is obtained. This process also results in nanometer sized dispersoid generation in β phase in the alloy.

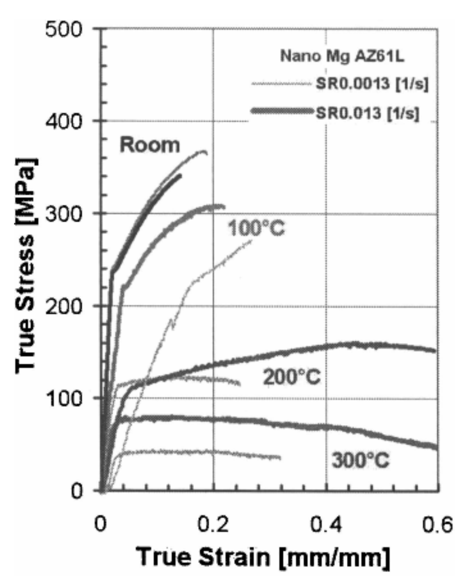
The main focus of this study was to understand the formability of thixo-processed Mg sheet material under uniaxial and bi-axial loading conditions at elevated temperatures. It was also intended to compare the mechanical properties of nano-structured Mg AZ61L alloy with the regular AZ61 alloy. One similar alloy, AZ31, was studied by the authors earlier, as well [14]. The following subsections cover the analyses of uniaxial (tensile), biaxial (hydraulic bulge), and closed-die hydroforming tests at different temperature and strain-rate conditions.

Material Characterization at Elevated Temperatures

Tensile Tests

Nanostructured thixomolded magnesium AZ61L alloy sheets (170x170 mm) with an initial thickness of 1.56 mm were provided by Thixomat (Thixomat Inc., Ann Arbor, MI). Tensile test coupons were prepared from the sheets according to the ASTM standard E8-04. To ensure a proper examination of anisotropy of the alloy, tensile coupons were prepared both parallel to the rolling direction and transverse to the rolling direction. A minimum number of three specimens was used to ensure the repeatability of the results at each testing condition.

Four different temperature levels (25, 100, 200 and 300 °C) and two different initial strain rates (0.0013 and 0.013 s^{-1}) were selected as test conditions. Figure 1 shows stress-strain curves obtained at each condition set for nano-structured and regular alloys. As expected, the flow stress values generally decrease with increasing temperature and/or decreasing strain rate. On the other hand, the effect of the strain rate on both flow stress and maximum strain becomes more distinct with increasing temperature. In addition to these effects, the direction in which load was applied had a strong bearing on total strain at failure. For higher temperatures (200 and 300 °C), consistently higher elongations were achieved for AZ61L alloy samples that were loaded parallel to the rolling direction (Figure 1a vs. 1b). When stress and strain values are compared for the alloys tested (Figure 1a versus 1c), it was noticed that both yield and tensile strengths did not differ significantly; however, AZ61L alloy exhibited considerably higher elongation especially at high temperatures (200 and 300 °C). However, at temperatures below 200 °C the samples showed less ductility. This is likely the result of the limited slip planes at temperatures below the critical temperature at which additional slip planes are activated.



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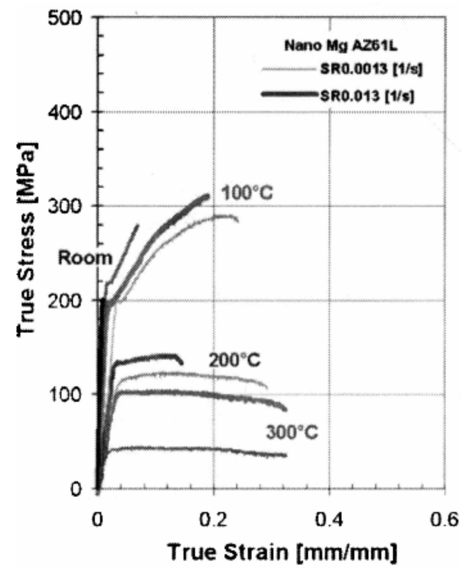

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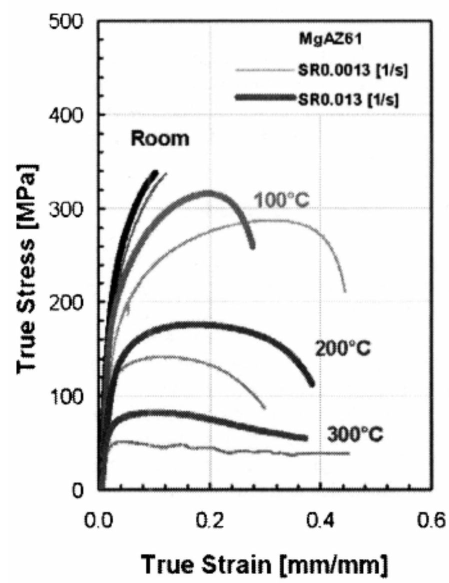

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Figure 1. Material flow curves obtained from tensile tests for (a) Nano-structured AZ61L (in rolling direction), (b) (in transverse direction), (c) regular Mg AZ61 (in rolling direction) alloys

The trend that lower strain rates result in increased elongation matches previous research [12]. This is more prevalent in the samples strained parallel to rolling direction than the samples strained in transverse direction. The maximum stresses on the samples before failure are consistent with the results of previous research along with the strain softening behavior at elevated temperatures for both strain orientations.

Hydraulic Bulge Tests

As sheet metal forming operations mostly involve a biaxial state of stress, the hydraulic bulge test is known to provide a more reliable stress-strain curve. Detailed comparison of the uniaxial and the biaxial test can be found in an earlier publication by the authors [15]. The hydraulic bulge test setup and its feedback control loop are presented in Figure 2. The test setup is composed of four major sub-systems: (1) a hydraulic system: pump and pressure transducer, (2) dies and inserts: upper and lower die with a bulge diameter of 100 mm and die corner radius of 6.5 mm; clamping and sealing mechanism between the two die halves using copper gaskets and 1,000 kN blank holder force provided by the Instron Satec 5596 machine, (3) heating system: cartridge and band heaters, temperature controller, and thermocouples to measure temperatures of the both dies.

The experimental setup is capable of conducting bulge tests at elevated temperatures approaching 400 °C. The heating of each die half was performed independently using separate sets of cartridge/band heaters and controlled with thermocouples attached to each die half. With PID control loop, the temperature deviation during the test was below 5 °C with respect to the set value. In addition, with a feedback control loop the strain rate can also be controlled based on the instantaneous dome height measurements.

Three bulge tests were performed for each case where temperature and strain rate were the main variables. During each bulge test, the internal pressure (P) and dome height (h) were continuously measured and recorded using a pressure transducer and either LVDT or laser sensor. The recorded pressure and dome height data were synchronized with the time step during the test. A schematic diagram of the bulge test setup, and the notation of parameters used in bulge test analysis are shown in Figure 3.

Both nano-structured AZ61L and regular AZ61 alloy sheet blanks were subjected to bulge tests at three strain rates (0.0013, 0.013 and 0.13 s^{-1}) and at four temperatures (25, 100, 200 and 300C). Under most conditions it would be expected that the location of rupture of the sample would be at the apex of the "dome". This is due to the fact that this location experiences the highest levels of straining and therefore would have the thinnest cross-section at time of rupture. On the contrary, Figure 4 illustrates that the location of rupture varies based on the temperature and strain rate used in the tests. Samples fractured in the die corner radius, also known as "shear fracture" typically at lower temperatures and/or higher strain rates. The fact that dome apex ruptures occurred at higher temperatures (at and above 200 °C) and lower strain rates indicates that both strain rate and temperature are highly important factors along with the R_c/t_o (die radius corner to initial sheet thickness ratio) and blank holder force (BHF) values.

Based on the observations on the fractured samples, some of the bulged samples did not achieve certain dome height value so that the spherical shape assumption for bulged shape was not valid. Similar observations were made for AZ31 [14] and some other aluminum alloys by the authors earlier. It is assumed that the problem is intrinsic to certain magnesium and aluminum alloys as authors did not experience such premature bulge height values for several other alloys and steels. Possible reasons and mechanisms for premature failure of the sheets are under investigation and therefore, stress-strain curves based on the hydraulic bulge test were not included here. Instead, the relations between strain rate, temperature and maximum dome height achieved are established based on the bulge test results and presented in Figure 5.

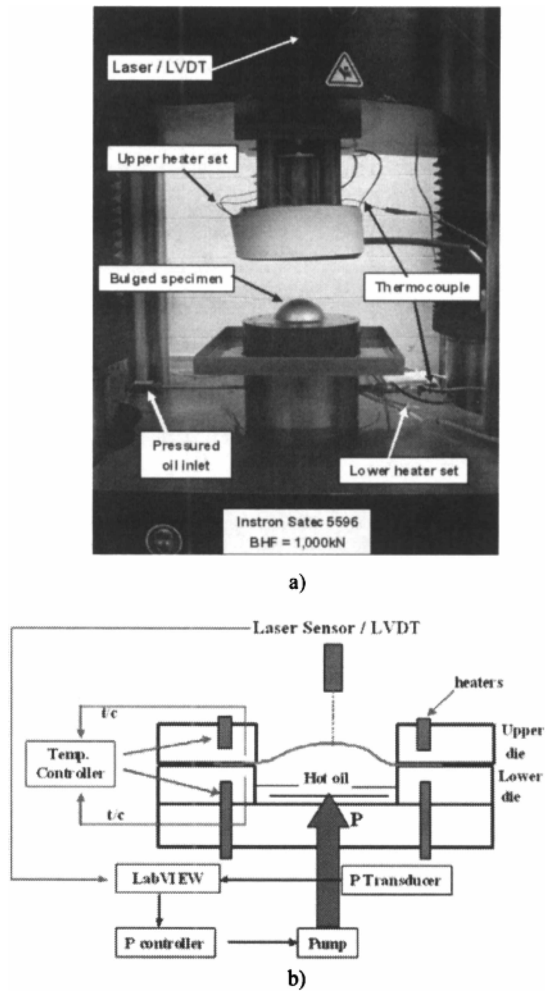


Figure 2. (a) Main components of the hydraulic bulge test setup, (b) feedback control loop.

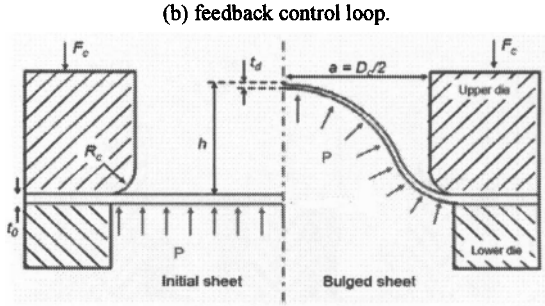
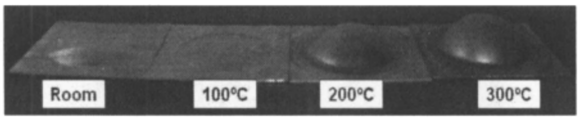


Figure 3. Schematic diagram of the hydraulic bulge test

In general, higher dome height, and therefore improved formability, was obtained when forming at higher temperatures and/or lower strain rates. As expected, higher pressure values were required to form the sheets at lower temperatures as compared to higher temperatures, a notable exception was observed for the samples at 25 °C, though. The noticeably lower pressure in the case of 0.13 s^{-1} strain rate at 25 °C is likely due to the fact that the samples ruptured early in bulging and therefore never had an opportunity to build as much pressure. Strain rate, in general, had an increased effect on required pressure at temperatures above 200 °C, with higher pressure levels being required at higher strain rates.



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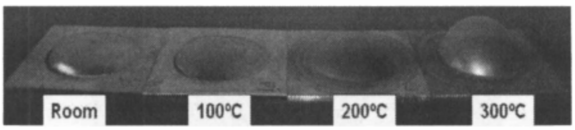

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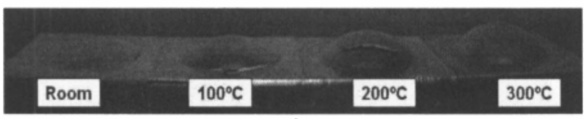

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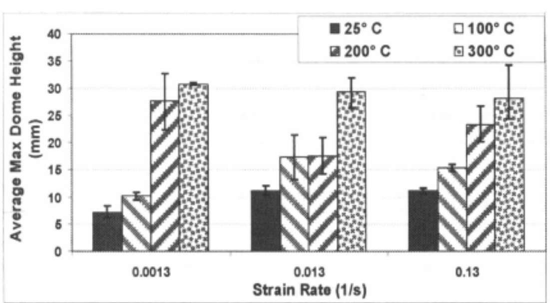
Figure 4. Bulged specimens at strain rate of (a) 0.0013 s^{-1}, (b) 0.013 s^{-1} and (c) 0.13 s^{-1}



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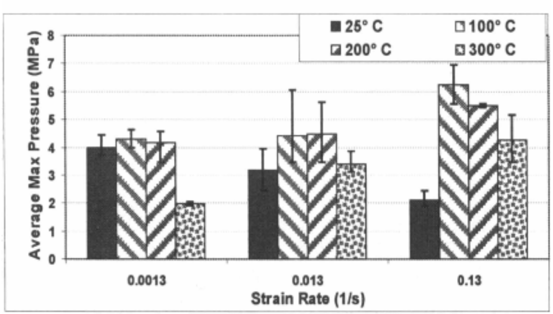

b)

Figure 5. Bulge test results for (a) maximum dome height, and (b) maximum pressure at different test conditions for hydraulic bulge test

As seen in Figure 5a relatively low dome height values obtained at room temperature and 100 °C imply that material flow curves at these temperature levels are well below 0.1 strain value. Contrarily, elongations for the sheets increased significantly at the 200 and 300 °C temperature levels. Examination of the bulge stress and strain graphs reveals the significant effects of temperature and strain-rate conditions. That is, the flow stress decreases and elongation increases with higher temperatures and/or lower strain rate. In addition, the effect of strain rate was observed to be more pronounced at the elevated temperature levels. These conclusions match with the previous studies on warm tensile tests available in the literature [6,12].

Figure 6 shows the optical microscopy analyses performed on the cross-section of bulged samples. Microanalyses showed that the zone under the blank holder (where no bulging effect is experienced) has different surface patterns when compared to that for deformed region.

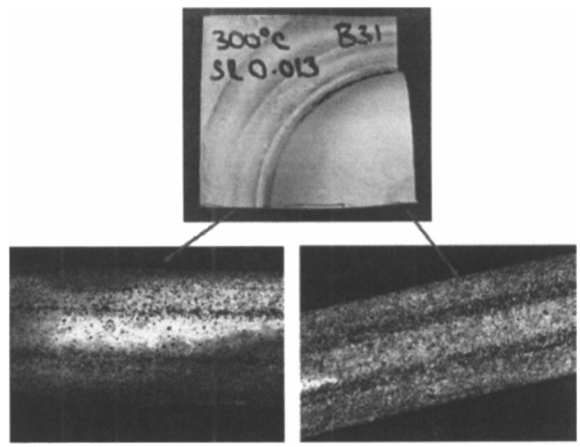

Figure 6. Optical microscopy for bulged samples from different locations at cross-section (test conditions: 300 °C, strain rate: 0.013 s^{-1})

Closed-die Warm Hydroforming Experiments

In order to assess the forming limits of the thixo-processed Mg alloy under warm hydroforming conditions, a set of closed-die hydroforming experiments was also conducted at different temperatures and maximum pressure values by using a non-axisymmetric die geometry as shown in Figure 7. Previous studies by Doege et al. showed that only a few seconds of flat contact between the blank and the die are sufficient for heating to temperatures of approximately 200 °C due to the high coefficient of thermal conduction and the low heat capacity of magnesium alloys [6]. In this study, the holding time was chosen to be approximately 10 minutes to assure a uniform temperature distribution (i.e., isothermal condition) on the die set and the pressurizing oil in the lower die cavity. The hydroforming pressure rate was set to a constant value of 0.22 MPa/s eliminating variability. Once the pressure reached the set values, the experiment was stopped and the hydroformed part was taken out of the die for thickness and profile measurements using micrometer and 3D non-contact photogrammetry system ARAMIS (GOM mbH, Braunschweig, Germany). Note that the rolling direction is along the long side of the formed shape. With this system, both 2D and 3D profiles were obtained, revealing the precise geometries of hydroformed parts as seen in Figure 7 for thinning and cavity filling analyses.

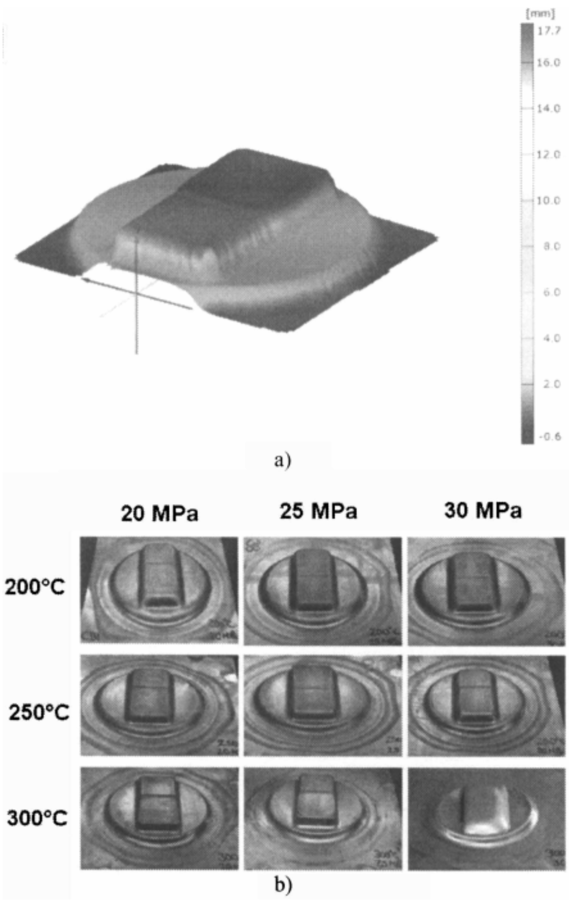

Figure 7. (a) Optical photogrammetry of closed-die hydroformed samples for cavity filling ratio calculation, (b) Closed-die formed samples at each condition set

First, the effects of the temperature and pressure levels were investigated. The closed-die hydroforming tests were conducted at 200, 250 and 300 °C with the pressure ranging between 20 and 30 MPa. This set of conditions was selected based on results of the tensile and bulge tests mentioned previously. The 2D profiles were then compared to the profile of the forming die to evaluate the percentage filling (cavity fill ratio). The cavity fill ratio is defined as the area under the samples profile geometry divided by the area under the die profile to create an unbiased evaluation of the total forming. Although its reason was not understood well, the cavity filling ratio tends to decrease with the increasing pressure level at 200 and 250 °C levels while there is an increase-increase trend pattern at 300 °C. Finally, at 300 °C forming temperature, it was even possible to form a quite small feature (groove) with cross-sectional dimensions of approximately 4 mm in width and 0.3 mm in height.

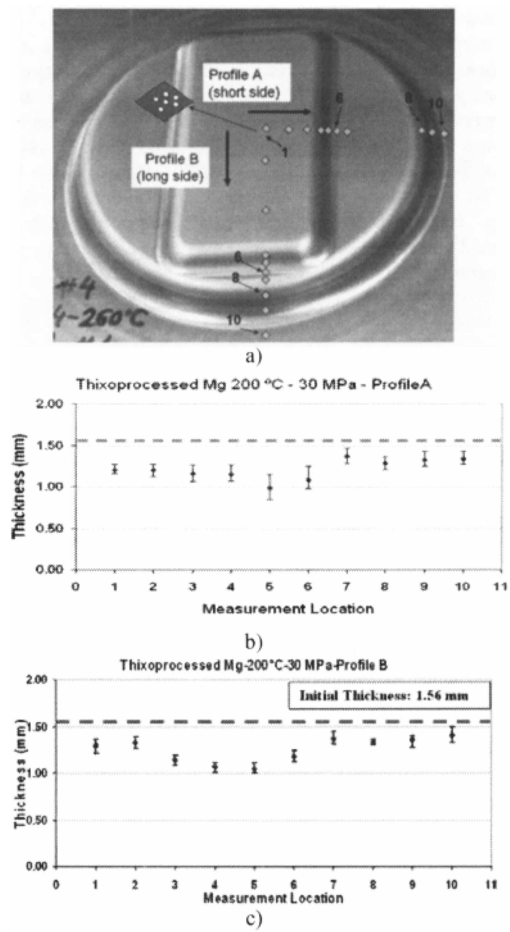

Figure 8. (a) Thickness measurements locations on the formed parts, (b) thickness variation along the transverse direction, (c) along the rolling direction for the closed-die hydroformed nano-structured Mg alloy sheet

In order to measure the thickness of the formed parts, the specimens were marked at ten locations in each direction, as indicated in Figure 8a. A measurement setup including a stationary pin and dial indicator with a spherical tip was used to increase the accessibility and accuracy of the measurement, especially in the corner regions. To minimize the bias based on instrument operator and other random errors, three operators made a minimum number of three independent measurements at each location along the sample profiles. As expected, the thickness values in both profile A (short side) and profile B (long side) decreased with an increase in forming pressure at the same temperature, and the maximum thinning location for each profile is at location #6 and #5, which are the most stretched zones of the blanks in each direction.

Conclusion

Uniaxial tensile and bulge tests were performed to investigate the formability of nano-structured Mg AZ61L and regular AZ61 alloys. It was shown that the nanostructed alloy differs from the regular version significantly in terms of elongation at higher temperatures (200, and 300°C). Strain softening behavior was also observed at elevated temperature levels. Strain rate did not affect both ultimate tensile strength and maximum elongations at room temperature and 100 °C, whereas a higher tensile strength was observed for the remaining temperature levels at the higher strain rate. Bulge test results, on the other hand, were not useful in terms of generating flow curves due to insufficient dome height value for bulged samples and premature failure during the bulging. It is assumed that the deformation characteristics (combined stress states in bulge test) and crystal structures played an important role in these results.

Acknowledgments

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