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Warm Hemming of Magnesium Sheet

John Carsley and Sooho Kim

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Magnesium sheet has received increasing interest for automotive body and closure applications. However, implementation of these applications faces many challenges involving room temperature formability. Hemming a closure panel with a magnesium outer panel will be difficult because of the sharp bend radius. Bending behavior of AZ31B-O at elevated temperatures was investigated to approximate the hemming of closure panels with acceptable surface appearance. Surface quality from small-radius bending was quantified as a function of temperature between 180 and 300 °C. Flanging with a 1.5 mm die radius yielded an acceptable surface quality at 210 °C and higher. Hemming required a minimum temperature of 270 °C for an acceptable surface condition with a 2 mm outer radius. The complex pattern of grain size and morphology of the deformed microstructure was documented with respect to the elevated temperature deformation behavior of Mg alloys. These results suggest that Mg can be hemmed at elevated temperatures with a small radius (~1½ times the sheet thickness) and therefore could be used for vehicle closures.

Keywords bending, deformation, magnesium, microstructure, hemming

1. Introduction

Magnesium has shown promise for reducing mass of automotive bodies and structures in order to improve fuel efficiency (Ref 1, 2). However, the use of sheet Mg for such applications has been deterred by high cost, lack of supply, and poor room temperature formability due to its hexagonal close packed crystal structure with few active slip systems. It is generally understood that Mg sheet can be made into useful shapes in the elevated temperature range 230-400 °C (Ref 3), where many more slip systems become active and other deformation mechanisms such as diffusion and dislocation climb are relevant. Investigations of warm stretching (Ref 1, 4, 5) and warm drawing (Ref 6) could lead to the production of closure panels and other structural applications of sheet Mg.

Aside from cost, supply and formability issues, Mg closure panel applications will be required to meet performance targets, i.e., structural stiffness, dent resistance, corrosion, durability, etc., as well as post-forming operations such as trimming, piercing, flanging, and joining. One particularly difficult challenge in the assembly process is the joining of inner and outer panels via flanging and hemming. In traditional assembly methods, outer panels undergo severe plane strain bending deformation in the flanging and hemming operations to achieve a crisp edge on the panel with desirable surface appearance (Ref 7).

The benchmark for hem quality is the flat hem condition typically exhibited by mild steel closure panels that are flanged with a die radius of 0.5*t*, where *t* is the sheet thickness. The outside of metal (OSM) bend radius along the hemline as seen by the customer is typically about 1.2-1.5 mm. This very sharp radius bending makes it difficult for competing materials to match the perceived quality of steel panels. In fact, aluminum faces two disadvantages when compared to steel. An aluminum outer panel is often thicker than steel by 25% or more in order to meet structural stiffness requirements, and age-hardenable aluminum tends to crack when hemmed to a flat condition. The traditional solution for aluminum panels is to flange with a die radius of 2*t* and to hem with a rope hem shape that leads to OSM radii between 2 and 3 mm. Customers perceive panels with these larger edge radii to be of lower quality and consequently rope hemming is becoming less and less acceptable to the product community. Two solutions for sharp hemming of aluminum are the retrogression method (Ref 8, 9) and roller hemming (Ref 7). Unfortunately, neither of these solutions by themselves will enable hemming of Mg panels.

For wrought Mg alloys, 90° bending at room temperature is limited to die radii of approximately 5-10*t* (Ref 3), which is unacceptable for automotive closure panel applications. However, smaller radius bending of Mg sheet can be accomplished by deforming at elevated temperatures. Chen and Huang (Ref 10) plotted minimum bend radius of AZ31 as a function of temperature and concluded that the minimum bend radius at 200 °C is about 3*t*. Emley (Ref 3) also suggested that 90° bending of AZ31B-O is possible at 290 °C with a die radius of 1*t*.

The purpose of the current study was to determine a temperature range that enables 90° flanging followed by 180° bending of AZ31B-O in a simulated hemming procedure. The surface condition of bend samples was examined for evidence of cracking and the microstructures were scanned in cross section for indication of unusual bending strain.

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John Carsley, and **Sooho Kim,** General Motors Research and Development Center, MC: 480-106-212, 30500 Mound Road, Warren, MI 48090. Contact e-mail: john.carsley@gm.com.

2. Experimental Procedures

2.1 Materials

Magnesium sheet AZ31B-H24, 1.3 mm thickness was chosen for this study. Most test samples were heat treated at 300 °C for 5 min to recrystallize the microstructure and simulate the condition of an outer panel after warm forming. Test sample coupons were sheared at 25 mm width along the rolling direction by 75 mm length along the transverse direction. The bend axis of each sample was parallel to the rolling direction, which should provide the condition most susceptible to crack initiation during bending (i.e., cracks should initiate and propagate along the rolling direction). Figure 1 shows the transverse—short transverse (T-ST) microstructures of this alloy in the as received H24 condition and after annealing at about 300 °C. The bend axis of all samples examined in this report is normal to the T-ST plane. After annealing, this alloy has approximately 168 MPa yield strength, 266 MPa ultimate tensile strength, and 20% elongation based on prior evaluation (Ref 11). Chemical composition is listed in Table 1.

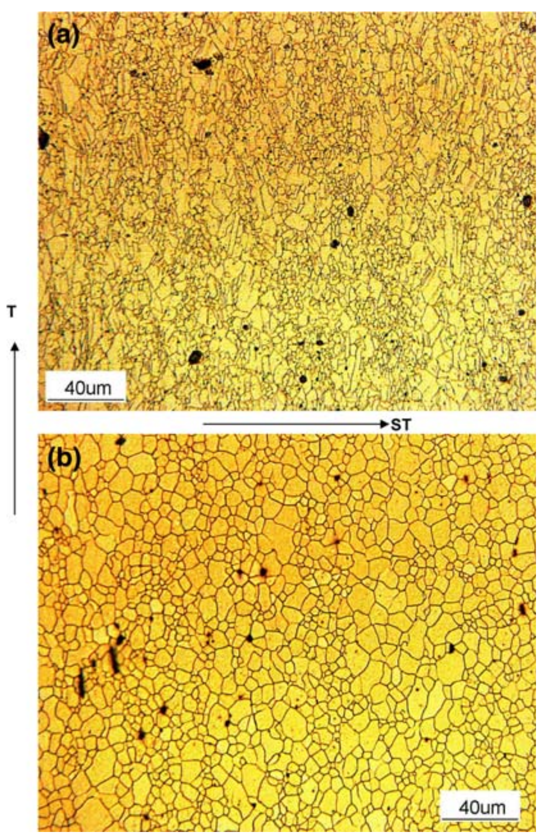

Fig. 1 Micrographs in the T-ST plane of (**a**) AZ31B-H24 (as received) and (**b**) AZ31B-O after annealing at 300 °C, gain size ~5.9 μm, grain aspect ratio ~1.17

Table 1 Chemistry of the AZ31B-H24 alloy

Al	Zn	Mn	Fe	Cu	Si	Ca	Mg
3.0	0.97	0.41	<0.005	<0.003	<0.1	<0.01	bal

2.2 Bending Tests

A heated press was used for bending test coupons at temperatures ranging from 180 to 300 °C. Figure 2 is a schematic of the test procedure including a Mg sample coupon, a control coupon, a flange tool, and a clamp tool. The press platens were heated to a set temperature with the tools and hammer to reach an isothermal condition. A sample coupon was positioned on the flange tool, extending approximately 12 mm over the 1.5 mm radius edge of the tool. The control coupon was also extended over the opposite edge of the flange tool such that a K-type thermocouple attached near the center of the control coupon width and was positioned near the edge, in the approximate vicinity where bending deformation occurred on the test coupon. Both coupons were clamped in place under a load of 130 tons and held until the temperature reading on the control coupon stabilized. The heat shields of the press were then opened and the hammer was used to bend the test coupon 90° against the flange tool as in Fig. 2b and the temperature during bending was recorded.

After flanging, several test coupons were flipped and repositioned on the flange tool, which then served as the hem anvil. An aluminum sheet (1.37 mm gauge) was positioned on these coupons to simulate the thickness of an inner panel. The clamp was lowered at an offset position as shown in Fig. 2d and temperature was allowed to stabilize as before. With a stable temperature on the control coupon, the flange was hammered to a flat hem condition with a 180° bend. In several cases, samples were hemmed over onto themselves without the aluminum inner panel in order to explore the most extreme bending situation with essentially a zero inside of metal (ISM) radius.

2.3 Surface Quality Rating

After flanging and hemming, the outer bend surface condition of each sample was examined and rated according to a standard procedure developed for aluminum alloys through a U.S. Automotive Materials Partnership (USAMP) project (Ref 12). In this procedure, the OSM surface conditions were rated from ***1*** to ***6*** according to the criteria listed in Table 2. A rating of ***1*** or ***2*** was considered acceptable while ***3*** or higher was not. Examples of surface quality ratings are displayed in Fig. 3 for several of the test samples.

2.4 Metallography

Several samples were chosen for microstructural evaluation and cross-sectioned normal to the bend axis to examine the surface curvature and the grain morphology in the bend region. Samples were cold mounted in epoxy, polished, and etched by brief immersion in acetic-picral. Initial attempts to hot, pressure mount samples in bakelite caused excessive twinning in the microstructure and were subsequently discarded. The cold, epoxy mounts, however, did a poor job of encasing the hem samples, which complicated the etching procedure. The acetic-picral rapidly etched the grain boundaries and collected in gaps between the edges of the samples and the epoxy mounts leading to over-etching and staining in many cases. The resulting microstructures displayed much staining at lower magnifications, but the grain conditions and observations of twinning at the higher magnifications were believed to be representative of bending deformation and not artifacts of the sample preparation techniques (Ref 11).

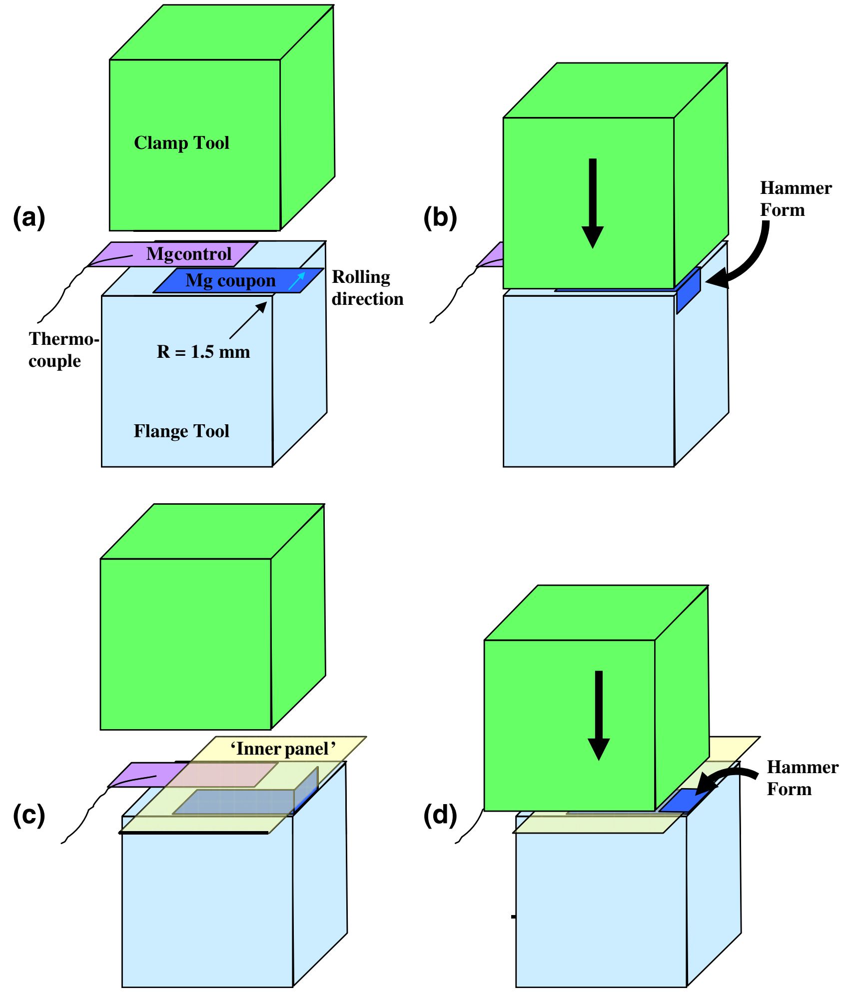

Fig. 2 Schematic of flanging and hemming test inside a heated press. (**a**) Mg coupon and thermocoupled control piece were positioned on the flange tool. (**b**) Samples were clamped and held until the temperature stabilized followed by 90° bending with a hammer over the 1.5 mm flange tool radius. (**c**) Flanged coupon was flipped and positioned with inner panel. (**d**) Clamp was applied offset and held until the temperature stabilized followed by 180° bending with a hammer

Table 2 Surface quality rating scheme for the outer bend surface (Ref 12)

1	No cracking, although mild to moderate orange peel is acceptable
2	No cracking, although heavy orange peel is acceptable
3	Crack initiation line (i.e., lines of localized thinning or crazing) parallel to the bend line or small cracks visible only with 3× magnification
4	Discontinuous cracks visible with the naked eye
5	Continuous crack along the entire bend line
6	Fracture through bend thickness (i.e., light passes through the crack)

3. Results and Discussion

3.1 Flanging

The bending temperatures reported were the initial stabilized values of the control coupon from the moment the heat shields of the press were opened until the samples were hammered to the final 90° or 180° position, which usually took several seconds. Hardness measurements were consistent for most of the heat-treated samples in this study (~66 HRF). They were softer than the as-received AZ31B-H24 (73.0 HRF) as expected, yet harder than AZ31B-O that was annealed at 450 °C (60.2 HRF) (Ref 11). This consistent hardness suggests that most samples were recrystallized with a fine grain microstructure similar to that shown in Fig. 1b.

3.1.1 Surface Quality. Surface quality was rated as a function of temperature in Fig. 4a for the flange samples (90° bend). Acceptable ratings (***1*** or ***2***) were observed for samples that were flanged at 210 °C or higher with the 1.5 mm die radius. This is consistent with Chen and Huang (Ref 10) who predicted a minimum bend radius of 3t at 200 °C. However, Emley (Ref 3) stated that 90° bending with a 1t radius required a minimum temperature of 290 °C. Below 200 °C, all samples cracked with this ~1t flange die radius.

There was one sample flanged at 245 °C with a questionable appearance that was rated ***3*** because there were crazing marks that were comparatively more severe than other samples with a ***2*** rating. Because this rating system is somewhat arbitrary and depends entirely on human judgment in the comparison of many samples, this condition may be acceptable under different circumstances. While these observations suggest that the minimum temperature for 90° bending was 210 °C, the upper

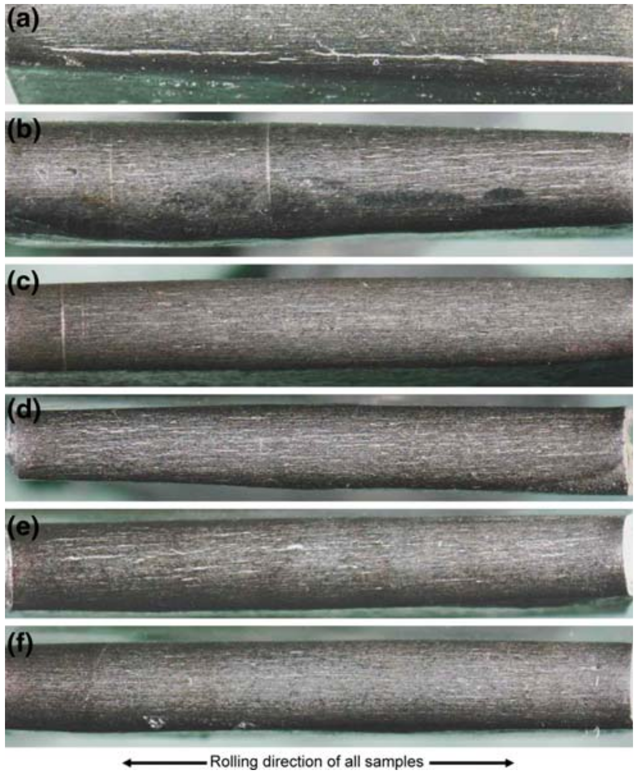

Fig. 3 OSM bend images for evaluating surface quality according to criteria in Table 2. (**a**) Flange sample with an unacceptable surface quality rating of ***5***. (**b**) Hem sample with a questionable surface quality rating of ***3***. (**c**) Hem sample with a very good surface quality rating of ***1***. (**d**) Hem sample (zero ISM radius) with an acceptable surface quality rating of ***2***. (**e**) Hem sample with an unacceptable surface quality rating of ***3***. (**f**) Hem sample with a very good surface quality rating of ***1***

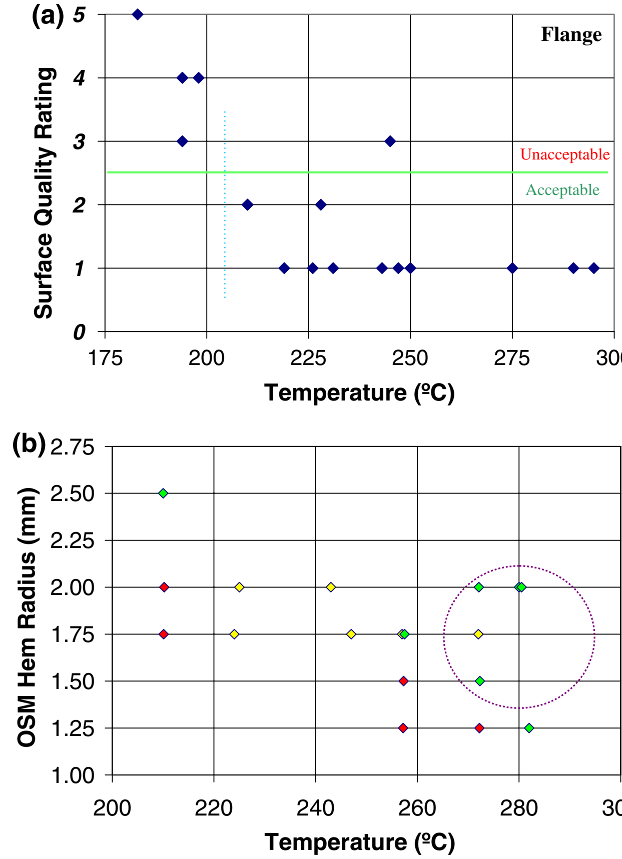

Fig. 4 Surface quality rating for (**a**) the 90° flange samples and (**b**) the 180° hem samples. ***1*** and ***2*** (*green symbols*) are acceptable while ***3*** (*yellow symbols*) and above (*red symbols*) are unacceptable

limit was not determined and very good quality was attained when the flanging temperature approached 300 °C.

3.1.2 Lower Temperature Bending. Below 200 °C, all 90° bend samples were unacceptable. Figure 5a and b shows a sample that cracked when flanged at 183 °C with a quality rating of 5, and a sample flanged at 194 °C with an unacceptable surface condition (rating of 3), respectively. A very interesting observation is the shear band deformation exhibited by the latter sample and magnified in Fig. 5c and d. AZ31B is known to exhibit shear banding in compression as shown in Fig. 5e for an unrelated study on hardness (Ref 11), and also as shown in the compressive region near the inner bend surface in Fig. 5d. This sample also deformed by shear banding under the tensile strain state near the outer bend surface (Fig. 5c). Shear bands were not observed in any of the bend sample microstructures that were deformed at higher temperatures, including the severe, zero ISM radius samples. Shear banding may be a deformation phenomenon restricted to lower temperatures for Mg sheet alloys.

3.2 Hemming

The 180° bend samples were more complicated and were grouped by OSM radius as well as by temperature as shown in Fig. 4b. Acceptable surface appearance was obtained when hemming at 270 °C or higher with a 2 mm OSM radius. Smaller radius hemming (1¾ mm) generally leads to unacceptable surface quality even when bending at up to 270 °C. It was difficult to control the outer radius of curvature because hemming by hammer did not consistently contact the flange at the same angle with the same force and number of strikes to complete each hem. OSM radii were measured with radius gauges that were only accurate to the nearest ¼ mm, and this small difference in radius can lead to a higher concentration of plastic deformation and localization along the outer surface that leads to visible imperfections.

Figure 6 shows the unetched cross sections of two samples that were processed identically except that the final OSM radius was smaller for one (1¾ mm) than for the other (2 mm). The surface quality rating of the smaller radius sample was an unacceptable ***3*** as seen in Fig. 3e, while the 2 mm radius sample had very good surface quality (see Fig. 3f). The surface markings on the 1¾ mm sample that caused the unacceptable quality rating were discontinuous separations or openings on the surface often called crazing or lines of localized thinning (not just orange peel) and can be difficult to capture in a cross-sectioned sample. However, the micrograph in Fig. 6a shows a 'cusp' on the OSM surface, just to the left of center. This cusp likely corresponds to one of the surface markings seen in Fig. 3e. Although this cusp is not a crack propagating into the sheet material and would not likely be visible on a painted panel, it is considered unacceptable for closure panels.

For a controlled-hemming procedure with consistent application of the hem steels and stable temperature control,

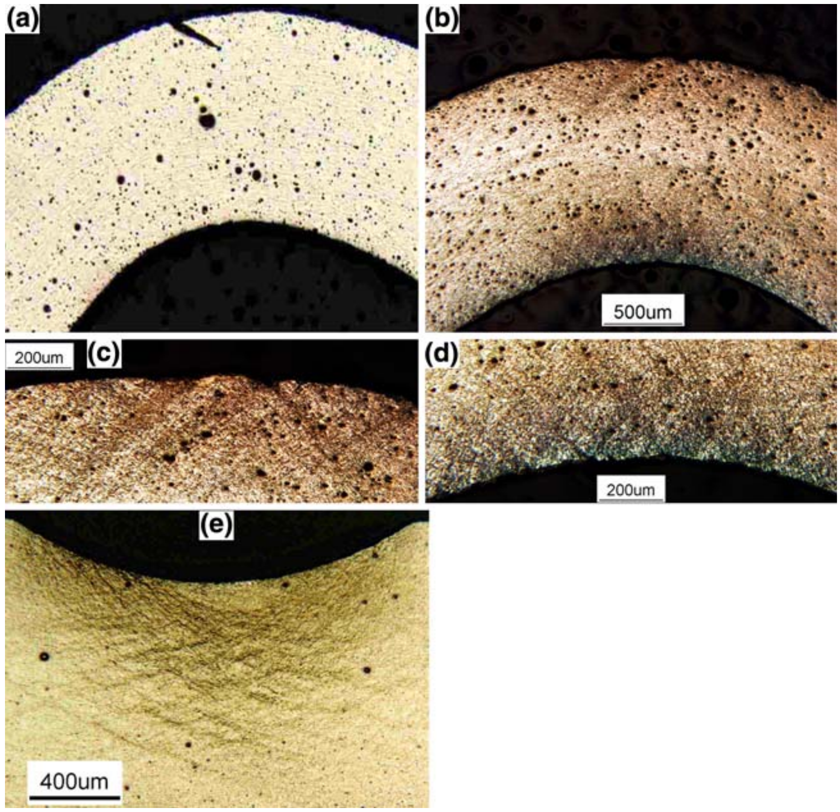

Fig. 5 (**a**) 90° bending at 183 °C with unacceptable cracking on the outer bend surface (rating of ***5***). (**b**) 90° bending at 194 °C with unacceptable surface appearance (rating of ***3***). (**c**) Shear banding deformation of the sample shown in (**b**) under tensile strain near the outer bend surface. (**d**) Shear banding of the sample shown in (**b**) under compressive strain near the inner bend surface. (**e**) Shear banding in AZ31B-O after the compressive deformation of a hardness test (Ref 11)

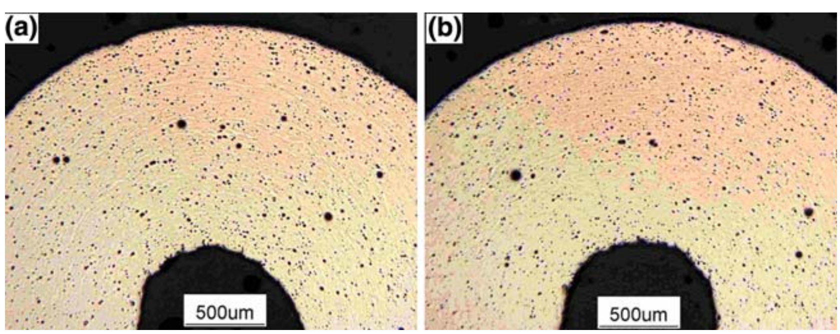

Fig. 6 Hem samples were deformed to 90° and then 180° under identical temperature conditions (~270°C). Sample shown in (**a**) had a smaller OSM radius of 1¾ mm and unacceptable surface quality rating of ***3*** (see Fig. 3e) compared to the good surface quality rating (***1***) of the sample shown in (**b**) with a larger OSM radius of 2 mm (see Fig. 3f)

acceptable surface appearance with a 2 mm OSM radius should be possible at and above 270 °C.

3.2.1 Zero ISM Radius. Figure 4b also includes samples that were hemmed without an inner panel, i.e., the metal was folded over onto itself with zero ISM radius to explore extreme bending deformation. The OSM radius gauge measurement for these samples was approximately 1¼ to 1½ mm. Even with this very small radius, good surface quality was observed on two of these samples at 272 and 282 °C. This appears to contradict the earlier observation that hemming with a smaller OSM radius (i.e., 1¾ vs. 2 mm) lead to an unacceptable condition by localizing strain and causing surface imperfections. However, when using a hammer to hem with an inner panel, it is possible and likely to slightly collapse the material into the gap between the inner and outer panels leading to strain concentrations and surface imperfections. Hemming without an inner panel should distribute the bending strain more uniformly and resist the local concentrations because the sample supports itself when hammered 180°.

Another zero ISM sample, however, was also hemmed at 272 °C, but with an unacceptable appearance. This observation reinforces the conclusion that ~270 °C is a lower bound for hemming AZ31B-O and surface quality is very sensitive to variation in process control.

Figure 7 is a cross section of the sample corresponding to Fig. 3d that was hemmed at 282 °C. This sample had a good surface quality rating of ***2*** and no cracks or cusps were observed on the OSM surface in Fig. 7, although there were discontinuous markings seen in Fig. 3d that might be considered orange peel. This micrograph illustrates the remarkable bending deformation that is possible with AZ31B-O sheet at the right temperature. While most closure panel applications do not require hemming without an inner panel, this severe situation identifies a lower temperature boundary of approximately 270-280 °C for small-radius hemming of Mg with good surface quality.

3.3 Bending Grain Structure

Perhaps the most interesting behavior of bending Mg sheet at elevated temperature is the changing grain structure around a sharp bend. Figure 8 shows the microstructure of a hem sample that was flanged at 295 °C and hemmed at 280 °C. This sample had a very good surface quality rating of ***1*** as seen in Fig. 3c with an OSM radius of 2 mm. The initial bending operation (90° flanging) used a die radius of 1.5 mm (ISM) as indicated in Fig. 8a, but the ISM radius was unconstrained in second bending operation (180° hemming). The changing grain structure illustrated in Fig. 8 was common and representative of all of the hem cross sections examined in this study.

The undeformed grain structure, similar to that shown in Fig. 1b, is a fine, equiaxed, uniform microstructure without twinning as seen in the lower part of Fig. 8b and in the central lower part of Fig. 8c. This structure is very similar to a narrow curved band of grains shown in Fig. 8d and e near the center thickness and slightly skewed to the left of the bend peak. Although technically not the neutral axis of the bend, this band of grain structure is referred to as the "neutral band" because it does not appear to have been altered by the bending deformation. Because this neutral band appears to be skewed to the left and might be symmetrical for the initial 90° bend, this deformation pattern may be a direct result of the flanging process when the die radius constrained the ISM surface. Bending strain during the subsequent hemming operation may have had little effect on this neutral band.

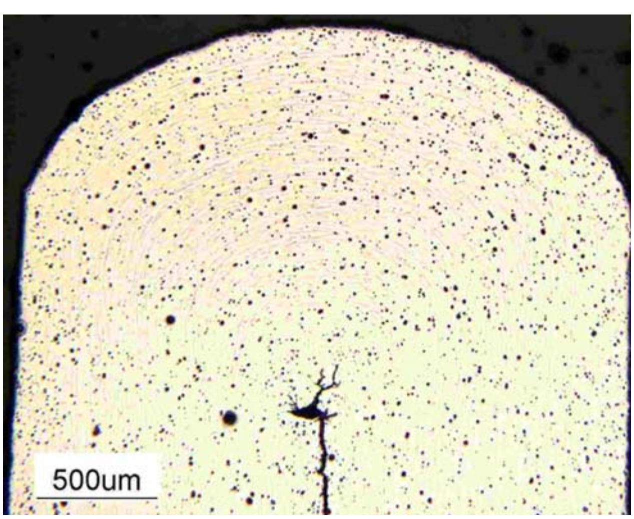

Fig. 7 Hem sample that was folded back onto itself without an inner panel to a zero ISM radius and an OSM radius of ~1.25 mm at a deformation temperature of 280-290 °C. The OSM surface quality was very good (rating of ***2***) without any evidence of cracking

Immediately above and below the neutral band, the grains have coarsened significantly and exhibit twinning deformation in the larger grains under tensile and compressive strain states, respectively. Figure 8f shows the upper portion of the neutral band adjacent to very course, twinned grains. Further above and below these course grains, near the OSM and ISM surfaces, the microstructure is less coarse, but still larger than the undeformed grain structure. And twinning is quite evident in the compressive region shown in Fig. 8g. In fact the distribution of twinned grains was not uniform, but almost appeared to be grouped into bands that may be precursors or 'shadows' of shear banding. For example, there are two small cracks shown in Fig. 8g that extend radially from curved ISM surface. There does not appear to be any twinning in the grains between these two cracks as indicated on the micrograph, but twins are evident in grains extending from these crack tips and in a curved-path connecting these tips.

Figure 8b shows a clear boundary between the flat, undeformed, fine grain region that was clamped in the tooling and the coarser, twinned grain structure that was affected by bending deformation. This boundary also exists on the flange side of the hem between the flat region and the bending region as shown in Fig. 8c. In the later case, the boundary is v-shaped with the fine microstructure in the center and coarse, deformed grains that extend from the compressive-strained inner surface and from the tensile-strained outer surface.

This complex grain structure of Fig. 8 has evidence of dynamic recrystallization, coarsening, and deformation by twinning that all may be dependent on strain path, strain distribution, temperature, and strain rate. While twinning is often considered a low-temperature mechanism, it has been documented as a dominant deformation mechanism up to 200 °C depending on the grain size and the strain rate (Ref 13). At higher temperatures of 325-400 °C, deformation is normally attributed to grain boundary sliding and to glide-controlled dislocation creep depending on both grain size and strain rate, without consideration of the twinning mechanism (Ref 14).

In the case of pure plastic bending, the neutral axis (na) that initially coincides with the centroid (c) tends to 'migrate' toward the ISM surface with decreasing radius (Ref 15) i.e., $r_c > r_{na} > r_{ISM}$. However, the "neutral band" in Fig. 8, which appears similar to the undeformed grain structure has a larger radius than the centroid. If this observation is correct, perhaps the outward migration of the neutral axis can be attributed to the tension-compression asymmetry of Mg alloys. AZ31 has lower yield stress, higher work hardening rate and greater elongation in compression than in tension at room temperature (Ref 16). Since yield strength and n-value both decrease with increasing temperature (Ref 10), the strength anisotropy of Mg alloys should be further explored at elevated temperature with respect to bending deformation. In addition, the decreasing n-value with temperature, may lead to non-uniform thickness strain (Ref 10) which could be associated with the complex grain structure observed in Fig. 8. Easton et al. (Ref 16) contend that the higher work hardening rate helps to more evenly distribute bending strain in Mg alloys, which could further improve hemmability if this behavior is consistent at elevated temperatures.

3.4 Manufacturing Issues

With conventional hemming procedures, hem adhesive is applied between the inner and outer panel flanges prior to 180°

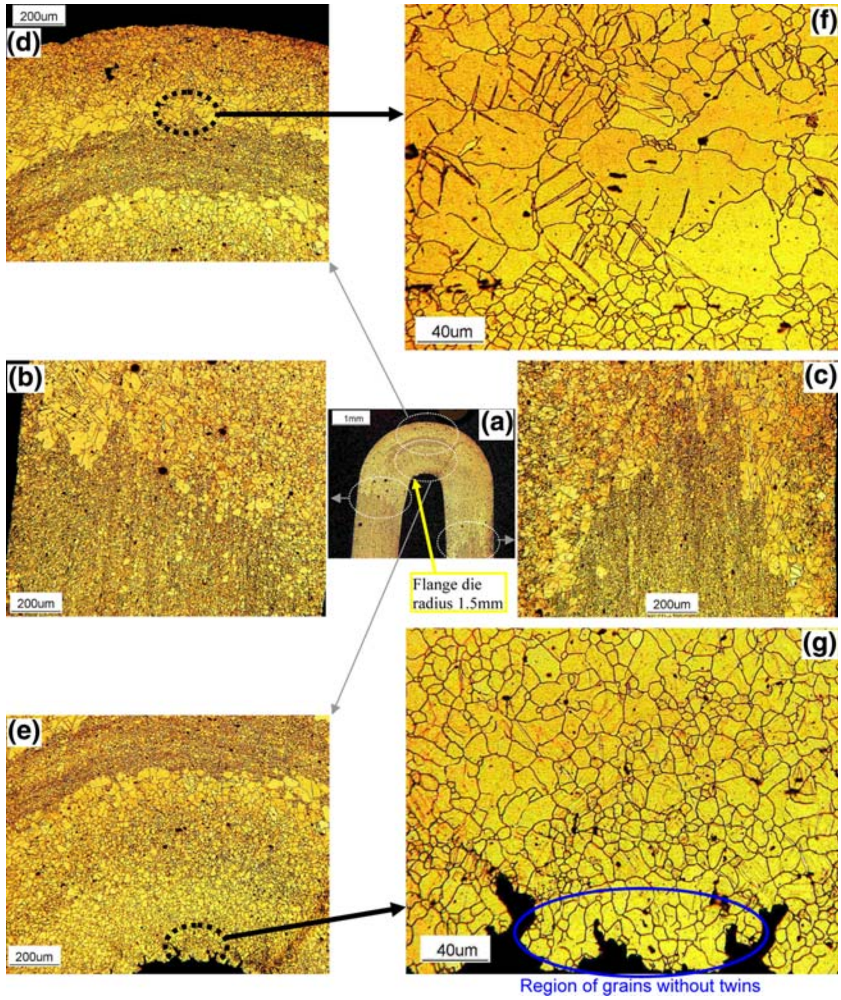

Fig. 8 T-ST Microstructure of the hem sample shown in Fig. 3c that was deformed near 280-295 °C and exhibited very high quality surface quality (rating of ***1***) with a 2 mm OSM radius

bending. This adhesive is necessary to secure the relative positions of the inner and outer panels during subsequent processing, and to prevent or inhibit corrosion during in-service performance. Adhesives used for steel or aluminum panels may not be suitable for Mg panels, and typical adhesives may or may not survive the temperature required for bending Mg. Methods must be developed to secure the panels and to provide corrosion protection. Full periphery, laser seam welding of the hem flange just after hemming might eliminate the need for an adhesive.

Hem equipment must be modified to locally heat the bending region of the Mg flange prior to hemming. Cartridge heaters could be inserted into the anvil and hem steels to heat the flange, or induction heating coils could be located around the periphery and scheduled to rapidly heat the Mg just prior to hemming. Other solutions could involve modifications to roller hemming procedures and equipment.

4. Summary

Future automotive mass reduction strategies may involve the fabrication of closure panels with Mg sheet alloys that require elevated temperature processing to attain the necessary formability. Assembly of these Mg closure panels will also likely require elevated temperatures to improve bendability during the flanging and hemming procedures. Small-radius bending of AZ31B was quantified as a function of temperature ranging from 180 to 300 °C, based on OSM surface quality. AZ31B-O, 1.3 mm gage was flanged (90° bend) with acceptable surface quality at temperatures as low as 210 °C with a flange die radius of 1.5 mm. Hemming (180° bending), however, required higher temperatures of at least 270°C to achieve an acceptable condition on the OSM surface. Some samples were hemmed at 280 °C with an outer radius of 1¼ mm (inside of metal radius approached zero) with good surface appearance.

Flanging and hemming AZ31B-O created unusual patterns in the grain structure and morphology around the bend when viewed in cross section. Regions subjected to bending strain appeared coarser than the base material near the surfaces and grain size increased toward the center thickness of the sheet. However, there appeared to be a "neutral band" of grains near the center that was similar in appearance (size and morphology) to the undeformed grain structure. The larger grains adjacent to this "neutral band" exhibited significant twinning even when bending occurred at 280 °C. Twins were also observed in the smaller grains of the compressive deformation region near the

ISM surface. This complex grain structure may be a result of several phenomena such as dynamic recrystallization, coarsening, twinning, dislocation plasticity, etc., occurring simultaneously under conditions of elevated temperature, complex and changing strain paths, and varying strain rates. These phenomena may also be influenced by the strength anisotropy of Mg alloys and its temperature dependent mechanical behavior.

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