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Evolution of Microstructure and Texture in AZ31 Alloy Subjected to Gas Forming

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In this study, AZ31 sheets were subjected to gas forming using a stepped geometry die and employing two different temperatures (400°C and 450°C) and exposure times (60 s and 120 s). Microstructural examinations revealed that the density of the mechanical twins may be taken as indicative of the progress of recrystallization together with the relative grain size. Although gas forming was successfully applied, the severe residual texture inherited from the initial material was found to persist and was little affected by the operating conditions and the multiaxial stress state of the process.

INTRODUCTION

Magnesium alloys, although one of the most promising candidates to employ for weight-saving purposes, mostly have, like AZ31, inferior mechanical properties and deformation capacity as compared with their rival, aluminum alloys. This handicap can be overcome through design via employing appropriate geometries, which still lead to considerable weight reductions in various applications. Nevertheless, several inherent deficiencies of magnesium,[1] like low deformation capacity and severe texture development, cannot be overcome via design. Remedies in such cases may be sought in alloy compositions[2] or heat-treatment/processing procedures.[3,4]

Following this line of thought, less conventional processes such as gas forming in a female die,[5,6] and the ones based on high-strain-rate superplasticity are being developed[7–9] for materials like magnesium that cannot be successfully formed into complex shapes easily. In the case of magnesium alloys, the operational window for these processes must also take into account the insufficient number of slip systems and the contribution of twinning to deformation to achieve the desired deformation capacity.

Solute solution magnesium alloys such as AZ31 develop a crystallographic texture[10,11] during deformation that cannot be healed by an otherwise useful recrystallization. The response of the solid-solution and the precipitate-containing alloys of magnesium to static and dynamic recrystallization may be different in terms of both kinetics and residual texture. AZ31-like alloys may be expected to give a weaker texture if deformed under a multiaxial stress state such as gas forming.

In the case of magnesium, when high temperatures around 400°C are employed for deformation, activation of all deformation systems including twinning, as well as fast dynamic recrystallization, are ensured, leading to industrially usable deformation levels. The most frequent twins in magnesium are known as "extension" and "contraction" twins, i.e., {10–12} ⟨10–1–1⟩ and {10–11} ⟨10–1–2⟩ twins, rotating the twinned regions by 86.3° and 56°, respectively.[12,13] The relatively thin (≤1 μm) and lenticular types represent the compression twins with less mobile boundaries, whereas the tensile twins are wider and possess greater boundary mobility.[14]

Nucleation of dynamic recrystallization has been said to take place more readily at compression twins or shear bands as compared with that at tension twins or grain boundaries.[15,16] The deformation rate has been reported to be a determining factor in their formation, with the extension twins being more affected than the contraction twins.[17] Thus, their relative densities in magnesium alloys may be taken

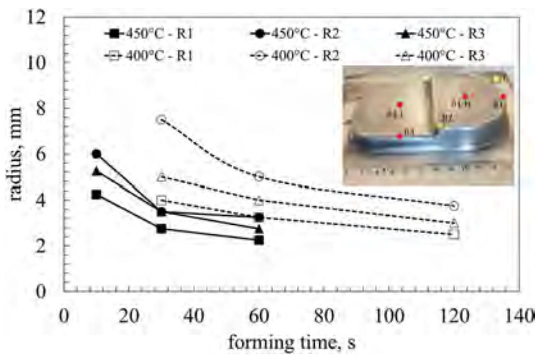

Fig. 1. Fillet radii measurements from the gas-formed part and the coded sampling locations.

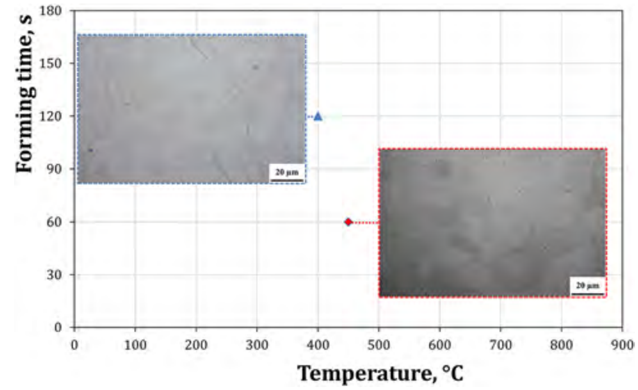

Fig. 2. The Microstructure of the region labeled as F.

as good indicators when making comparisons in different cases, e.g., deformation and progress of recrystallization.

The purpose of the present work can be expressed as observation on the microstructural evolution and texture during the high-temperature fast gas forming of AZ31 alloy toward an understanding on whether the multiaxial stress conditions of the process improve deformation while lessening the final texture.

MATERIALS AND METHODS

The commercial as-received AZ31B sheets having an average equiaxed grain size of 10–15 μm and a thickness of 0.75 mm were used.

Gas-forming operations were conducted using a stepped die geometry that has two different depths, 12 mm and 20 mm, and a 2500-kN electro-hydraulic press machine that is suitable for tests up to 1000°C. Boron nitride was applied onto the upper blank surface to reduce friction. The forming gas, argon, at a constant pressure of 2.5 MPa was used without heating because of its negligible thermal capacity. Gas-forming experiments were conducted under two sets of conditions, namely, 400°C/120 s and 450°C/60 s.

The tools were heated at the test temperature before the test and kept at that temperature during the whole forming process by a closed-loop controller. Samples for metallographic characterization mechanically cut from each region representing different strain conditions were prepared via conventional metallographic methods. They were also employed for EBSD using a SEM (ZEISS SUPRA 50 VP) equipped with INCA software.

RESULTS AND DISCUSSION

Analysis of Gas-Formed Parts

A gas-formed part is shown in Fig. 1 consisting of a highest plateau corresponding to a greater level of deformation and therefore a longer dynamic recrystallization period as compared with the shallower plateau.

Point F in Fig. 1, clamped between the blank-holder and the die, was subjected during the process to the same temperature and time conditions as the other regions of the blank. The samples taken from location F were considered to have gone through the same thermal cycle of the deformed regions but with a negligible strain, and they were thus taken to represent the over-annealed state of the already recrystallized as-received sheet.

During the process, the sheet freely expands first in the shallow, and then in the deepest, die cavity.[17] The two processing conditions gave the same forming trends in terms of reduction in fillet radii and thinning of the initial sheet material (Fig. 1). For example, the minimum measured thickness values were 0.30 ± 0.02 mm and 0.31 ± 0.02 mm under the test conditions of 400°C/120 s and 450°C/60 s, respectively.

Metallographic Analyses

The different regions indicated in Fig. 1 correspond to decreasing amount of deformations as a result of the die geometry, the strain level being in the following order: R1 > R2 > (R1-H) > R3 > R3-L > F. Region F is considered not to have been subjected to deformation and, therefore, representing the grain growth for the as-received sheet. Figure 2 represents the microstructure of region F for the two sets of conditions.

A few twins with less than 1 μm thickness in these regions have been interpreted as compression twins as their morphology fits,[15] and they were attributed to the clamping forces exerted on these locations.

Upon contact with the die, the deformation in the flat R1-H and R3-L regions stop and the material undergoes annealing for the remainder of the time elapsed until completion of the shaping. The microstructure of such regions is given in Fig. 3.

Figure 4 shows the microstructure of the regions R1, R2, and R3, representing an increasing amount of deformation during gas forming. It can be seen from Figs. 3 and 4 that the microstructure mostly

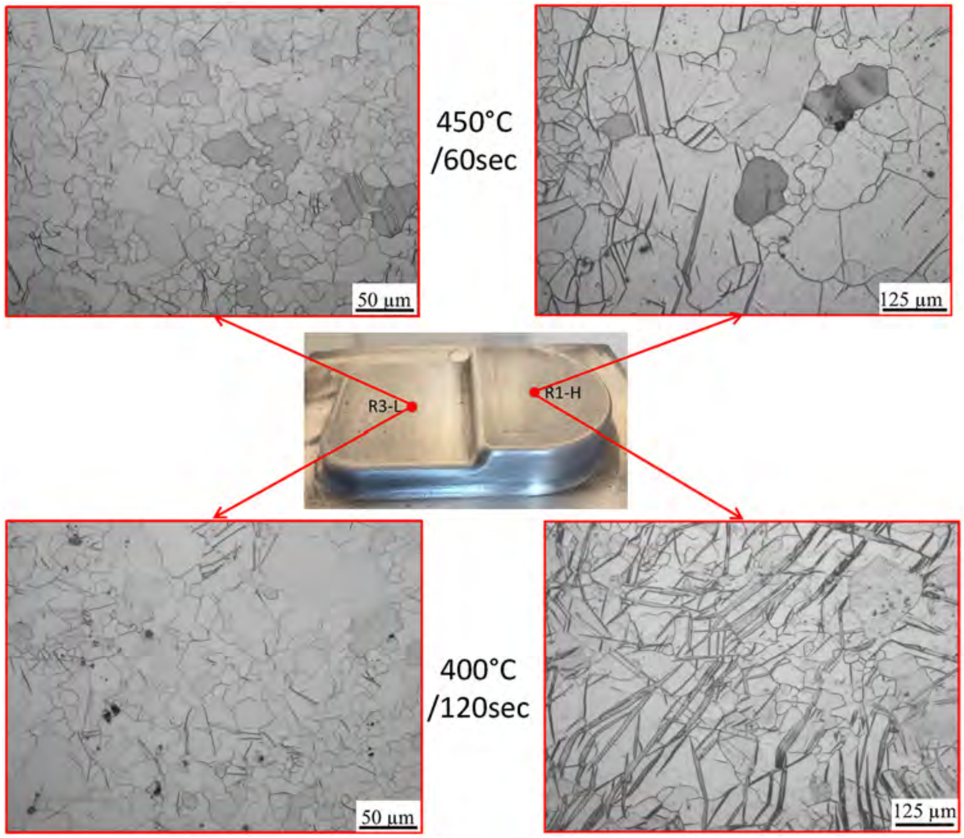

Fig. 3. Microstructure of the regions labeled as R1-H and R3-L under the two explored conditions.

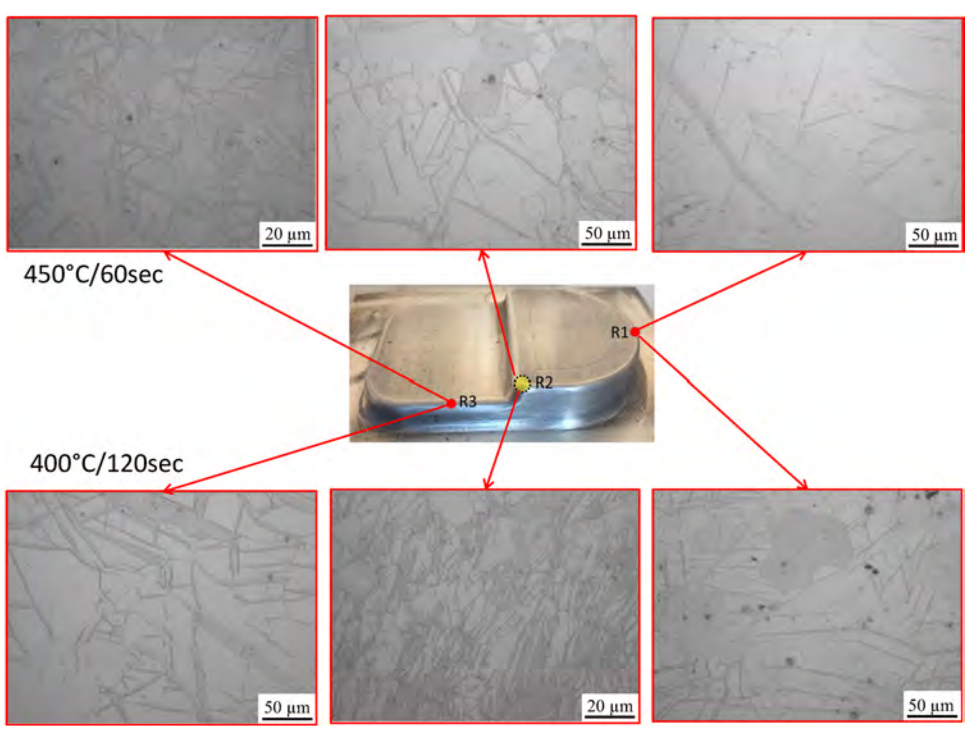

Fig. 4. Microstructure of the regions representing an increasing amount of deformation during gas forming (R1, R2, and R3) under the two explored conditions.

contains tensile twins, whereas very few, if any, compressive type exist, as characterized based on their observed thickness.

The twins observed should be regarded as either the ones that had just formed at the final moments of the deformation or as those that had formed somewhat earlier but had not yet been annealed out during dynamic recrystallization. Regardless of the location, the population of twins appeared greater in the samples processed at 400°C as compared with those at 450°C.

At the highest temperature employed (450°C), at locations where deformation was greater (R1 and R2), the twin population seemed to be less. This may be interpreted as twins being consumed as nucleation sites during dynamic recrystallization, expectedly at a greater rate at higher temperature. It can also be said that, in regions where deformation stopped earlier, as in the region R3-L, the twins appeared to be finer as opposed to R1 where some large twins still existed. It is difficult to explain conclusively the readily observed twin population difference in regions that correspond to different strain levels over the completion of deformation. A possible explanation may be that in the R1 location (where deformation stopped later), the twin formation had become progressively more difficult as a result of the increasing texture as the deformation developed further.

When microstructures from the equivalent locations were compared, the samples from the higher temperature process showed a more advanced

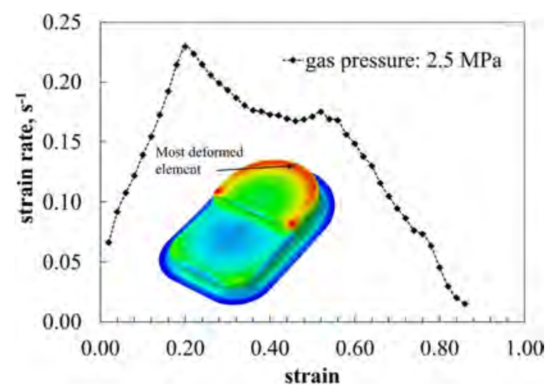

Fig. 5. Strain rate evolution in the point experiencing the highest strain rate during the simulated gas-forming process at constant pressure and 450°C (Ref.,17 reprinted with permission).

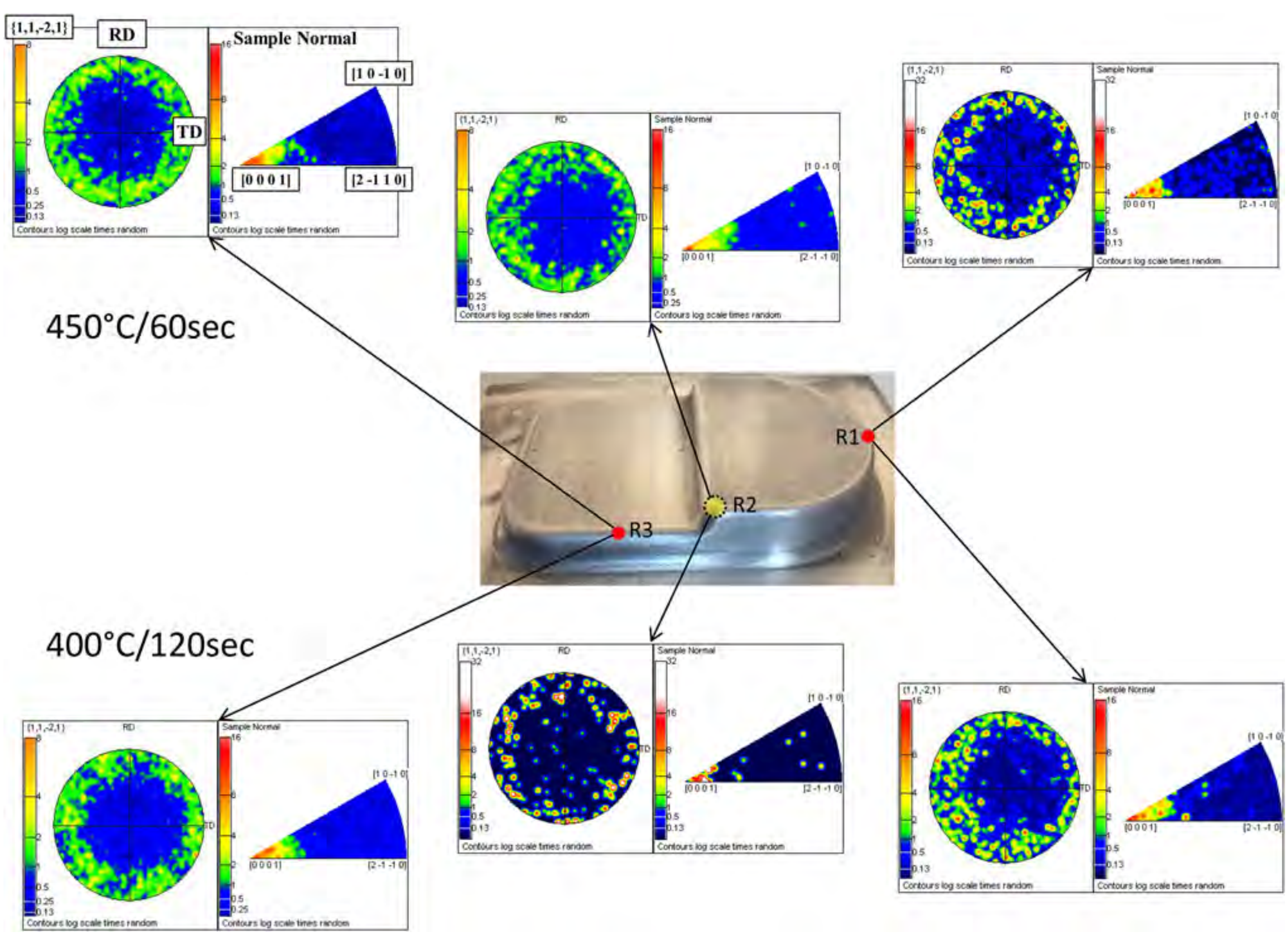

Fig. 6. EBSD figures confirming the existence of the basal texture in the gas-formed samples.

dynamic recrystallization as indicated by their larger grain sizes and much lower twin densities. It was also noticeable from the samples of both processing temperatures that the grain sizes seemed somewhat smaller in regions where the deformation stopped earlier, and a higher number of surviving twins was observed. This may be attributed to some degree of grain boundary sliding (GBS) at the initial stages of gas forming while the grain size was still sufficiently fine, which then stopped when grain size increased. The contribution of GBS to deformation has been reported for the same alloy with an equivalent grain size and at comparable deformation rates even at lower temperatures.[11] Thus, the formation of twins was somewhat delayed while GBS, at least partially, provided the necessary deformation. This scenario is in need of support in terms of low strain rates for these locations. Indeed, the simulation results of the strain rate evolution from the previous work[17] given in Fig. 5 indicated that, when forming the blank using the pressure of 2.5 MPa, even if the strain rate in the most deforming element reaches the maximum level of 2.3×10^{-1} s^{-1}, at the initial stage of deformation, it is close to 5×10^{-2} s^{-1}.

The work by Carpenter et al.[18] supports the possibility of GBS in the AZ31 sheet being an active mechanism of plastic deformation across strain rates from 10^{-4} to $10^{-1} s^{-1}$ at 450°C. Admittedly, however, a would-be conclusive evidence for GBS, e.g., some void formation at least at triple junctions of the grains, was not observed.

This fact was attributed to the small contribution of an envisaged GBS that had been accommodated without the formation of voids. EBSD plots given in Fig. 6 showed the existence of a strong basal texture in the samples.

CONCLUSION

Microstructural observations highlighted that the formation of twins extended to high deformation temperatures employed in this study. This finding is particularly interesting as twinning provides an important addition deformation mechanism in magnesium, otherwise known as a material of low deformation capacity resulting from the hexagonal crystal structure.

Berge et al.[19] in their study on an equiaxed AZ31 alloy at 200°C and 250°C reported that mechanical twins did not form at all. This seemingly contradicting result as compared with the readily observable twins in all samples presented here may be related to a finer initial grain size of the material employed in their study, being about half the grain size of the sheet employed here, thus, prohibiting twin formations.

Twins were readily observable after high-temperature forming, and relatively speaking, some were even consumed as nucleation sites in the process of dynamic recrystallization, expectedly at a greater rate at the higher deformation temperature.

The EBSD results confirmed the existence of a basal texture in the material after the forming processes. Thus, it may be concluded that the solid solution alloys of magnesium can still possess a severely textured structure even after a multiaxial deformation process despite the expectations. If texture is to be lessened, this conclusion emphasizes the necessity of precipitates that would act as nucleation sites during dynamic recrystallization even in shaping methods involving multiaxial deformation.

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