Production of wide shear-rolled magnesium sheet for part forming

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Keywords: Magnesium, Asymmetric Rolling, Texture, Formability

Abstract

In recent years the process of shear rolling has seen considerable study, particularly for heavily textured materials such as magnesium. The goal of this work has been to produce sheet with greater formability for industries such as automotive and aerospace. To date, almost all work on asymmetric rolling has been carried out on small strips that are not large enough to produce parts. The current work will discuss scaling-up of the shear rolling process to generate wider sheet. A mill at the Magnesium Elektron North America plant was modified to allow shear rolling at a ratio of 1:1.35 on sheets up to 36" wide. AZ31B and ZEK100 sheets of size 36"x72" were shear rolled and demonstration automotive parts have been formed by Superform USA.

Introduction

Magnesium alloys are strong and lightweight, making them very attractive to the automotive and aerospace industries, with a density approximately two thirds of that of aluminum and one fifth of steel. It could therefore provide significant weight savings in applications for these industries. Magnesium alloys are utilized in various applications in cast form, but sheet material has not gained wide acceptance in modern engineering solutions. A significant hindrance to the greater use of magnesium sheet is the poor low temperature formability. In general magnesium sheet is either superplastically formed at elevated temperatures or hot deep drawn. Both processes are more expensive compared to room temperature matched die deep drawing, as is currently employed for steel sheet. Forming of sheet components at temperatures below 200°C simplifies the lubrication system needed for deep drawing, as oil can be used. Above this temperature, solid state lubricants such as boron nitride and graphite are used that require specialized cleaning routes to remove them. Oils can be removed with a simple degreasant such as an alkali dip, which saves time and energy costs.

Production of more formable magnesium sheet has been approached in a variety of ways. Examples include Equal Channel Angular Processing (ECAP)[1, 2], Equal Channel Angular Rolling (ECAR)[3, 4], 'cross-roll rolling'[5], and asymmetric or shear rolling[6-8]. Asymmetric rolling is considered to be the only viable method to produce sheet on a commercial scale and therefore has been the focus of the current work.

Asymmetric, or shear, rolling introduces shear into the sheet during the rolling process by having one roll moving faster than the other. This can be achieved either by having independently driven rolls, or by having differently sized rolls on a single drive. Shear rolling has been shown to provide more homogeneous deformation through the thickness of the sheet, along with grain refinement and texture changes[9-14]. These factors are expected to increase the formability of the sheet.

Two alloys were chosen for this study: AZ31B (Mg-3wt%Al-1wt%Zn-0.3wt%Mn) and ZEK100 (Mg-1wt%Zn-<1wt%Rare Earths-<1wt%Zr). Initial trials were carried out on a small laboratory scale shear mill. This had bottom and top roll diameters of 229 and 76mm respectively, giving a shear ratio of 3:1[15]. This work lead to the modification of a 48 inch mill at Magnesium Elektron to enable shear rolling. This mill has a bottom roll of diameter 367mm and a top roll of diameter 495mm, giving a shear ratio of 1:1.35. Initial trials on this mill were carried out on 10 inch wide strips to gain a greater understanding of the material behavior at different rolling conditions. The best processing parameters were selected following biaxial testing to assess the formability of the 10 inch wide sheets. Wider sheet was rolled using these parameters. Rolling wider sheet was more complex than the smaller strips; some issues were anticipated while others were not. The focus of this paper is the engineering challenges arising from shear rolling wide magnesium sheet, and the solutions that were implemented to overcome them. Finally, demonstrator parts were formed to demonstrate the viability of shear rolled sheet.

Experimental Materials and Procedure

<u>Modification of Mill at Magnesium Elektron</u>

A smaller scale industrial mill (known as 8-Mill, see Figure 1) based at MENA was modified to allow shear rolling. 8-Mill has a single drive motor, and thus the conversion to shear rolling required different diameter rolls. The maximum shear ratio that could be carried out on 8-Mill was limited by the design of the mill. The small roll could be no smaller than the chocks in which it is held and the top backup roll could be raised no higher than the top of the screw, limiting the size of the large upper roll. This resulted in a maximum shear ratio of 1:1.35 via the installation of rolls with diameters of 367mm and 495mm. To achieve the higher position of the upper roll, a new spindle was engineered with universal couplings, that replaced the old wobbler joints, to accommodate the steeper angle of operation created in shear mode.

It was known from previous shear rolling that the effect of one roll moving faster than the other caused a curl in the exiting sheet. Therefore, a stripper plate arrangement was designed for the mill to ensure that material exited horizontally. This will be discussed further in the results section.

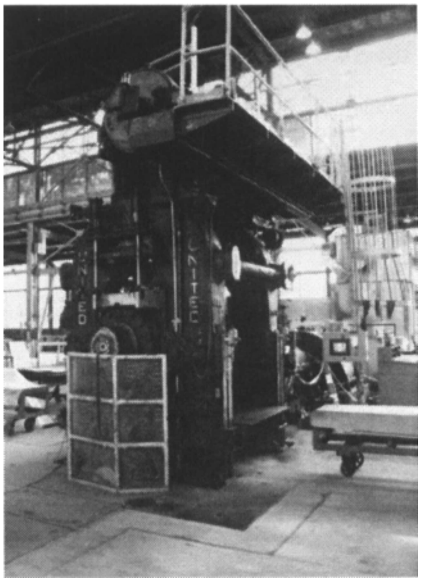

Figure 1 – 8-Mill

Rolling

Magnesium Elektron supplied commercially rolled sheet for these trials. Both AZ31B and ZEK100 were direct chill cast and rolled from slab down to the feedstock gauge of nominally 2.5mm.

The best rolling conditions for formability were found from the previous work on smaller strips. Lower processing temperatures performed better and this was used for the wider sheet. The conditions chosen were 250°C with 10% reduction. It was intended to carry out the rolling without lubrication. This was to allow maximum friction between the rolls and the material, presumed to cause the maximum amount of shear during rolling. However, as will be discussed later, this was not practical, and lubrication had to be used.

Analysis

Samples for optical microscopy were cut from the rolled sheet and mounted and polished using standard metallographic techniques. An acetic-picral etch was used to reveal the grain structure and imaging was carried out on an Olympus GX51 microscope.

Samples for X-ray diffraction (XRD) analysis were cut from the rolled sheet and polished down to the centreline for texture analysis. A 4-axis diffractometer was used with a cobalt x-ray source, and pole figures were measured for the (0002) reflections.

Elevated temperature biaxial testing was carried out using proprietary equipment at Oak Ridge National Laboratory. A spherical punch of diameter 100mm was used to deform a 138mm diameter disc held in a 103mm inner diameter ring. The material and the ring were heated in a furnace prior to deformation. A speckle pattern was applied to the disks with paint, and with the use of two cameras, a three dimensional strain map was collected during the tests. The final dome height at fracture was used as the measure of formability for the current study. More complex analysis will be shown in further publications.

Results and Discussion

Initial Trials

Ten inch wide pieces were rolled on 8-Mill to find suitable conditions for rolling the wider sheet. Samples from a selection of these sheets were tested for biaxial formability (see Figure 2 for an example of a tested sample) and the best performing were selected. Table 1 shows the dome heights of the samples that were studied. It can be seen that rolling at a lower temperature led to greater dome height. Therefore, 250°C was chosen as the rolling temperature for further work.

Table 1 – Biaxial dome heights of 10" wide strips shear rolled on 8-Mill

Alloy	Temperature (°C)	Reduction (%)	Dome Height (mm)
AZ31B	250	10	21.3
		50	26.7
	425	10	22.5
		50	16.0
ZEK100	250	10	44.3
		50	43.7
	425	10	40.5
		50	33.8

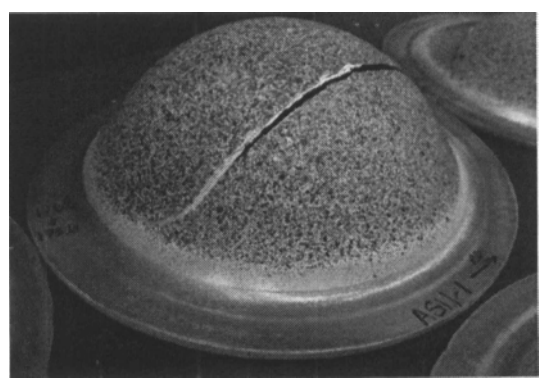

Figure 2 – Example of a biaxial test sample

Wide Sheet Rolling

The arrangement of the stripper plates is shown in Figure 3. It was anticipated that the material would increase in length on the side of the fast roll, and thus curl downwards. This had been observed in previous trials and therefore the stripper plates were designed such that the lower plate was positioned very close to the roll to ensure the material did not wrap around the roll. The top stripper plate was put in place to avoid the sheet buckling upwards. By forcing the sheet though the slot, it was thought that a flatter sheet would be produced. Therefore, the upper plate was not positioned as close to the roll (see Figure 4). An entirely new exit table was designed that incorporated the stripper plates and bracing bars to enable shear rolling, see Figure 3.

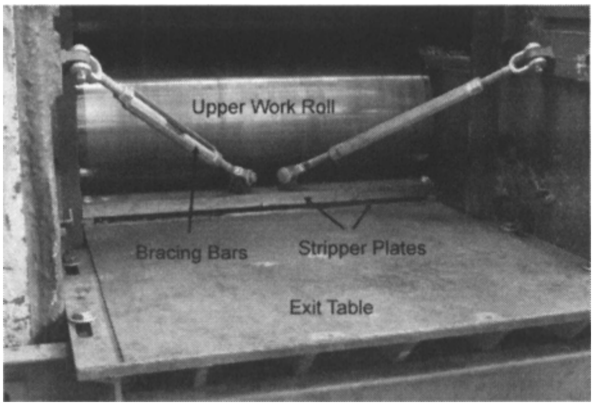

Figure 3 – Exit side of the mill showing the stripper plate arrangement

It was found during rolling that the material did not behave entirely as expected. In many cases, the material curved upwards. This caused problems with the stripper plates and certain sheets came into contact with the plate edges when they exited the mill. Figure 5 shows the end of one sheet that slightly contacted the stripper plate; a small section of the sheet was removed. Figure 6 shows the extreme case of this behaviour when a sheet caught on the stripper plate so badly that it was ripped into 3 pieces. Therefore, it can be seen that the positioning of the stripper plates is critical in a shear rolling mill. This is more complicated for a wide mill as the plates need to be supported across the length. The material itself also seems more prone to catching on the plates as there is a greater chance that some small portion may deviate far enough to touch the edge of the stripper plate.

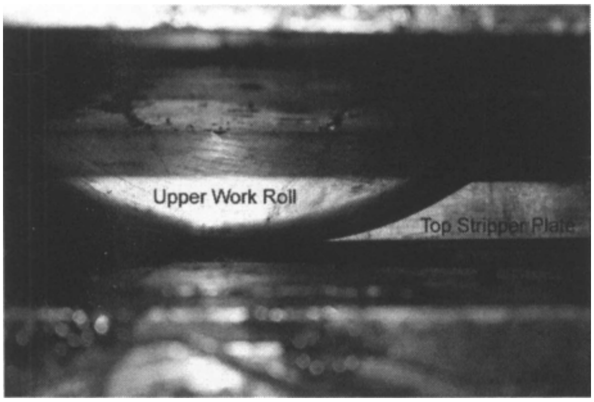

Figure 4 – View from the side of the mill showing the alignment of top roll and stripper plate

The stripper plates needed to be shaped carefully and fitted less than 200μm from the roll surface. This was achieved by placing a sheet of paper between the plate and the roll, pushing the plate in to touch and then removing the paper. Ideally, both plates would be positioned this close to the rolls. However, the upper roll is not stationary during a rolling campaign; not only is the gauge intentionally changed for different rolling passes, but the majority of mill stretch in the system, the elastic stretch of the rolling mill due to separation forces, causes movement of the top work roll. Therefore, a shear mill designed from scratch should have the top stripper plate attached to move in conjunction with the top work roll; this is not generally possible for modifications to existing mills.

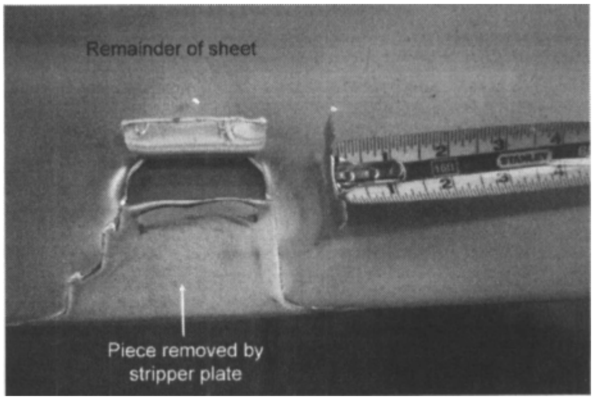

Figure 5 – Photograph of a sheet that contacted the stripper plate (the piece removed was placed back where it belonged to show the damage)

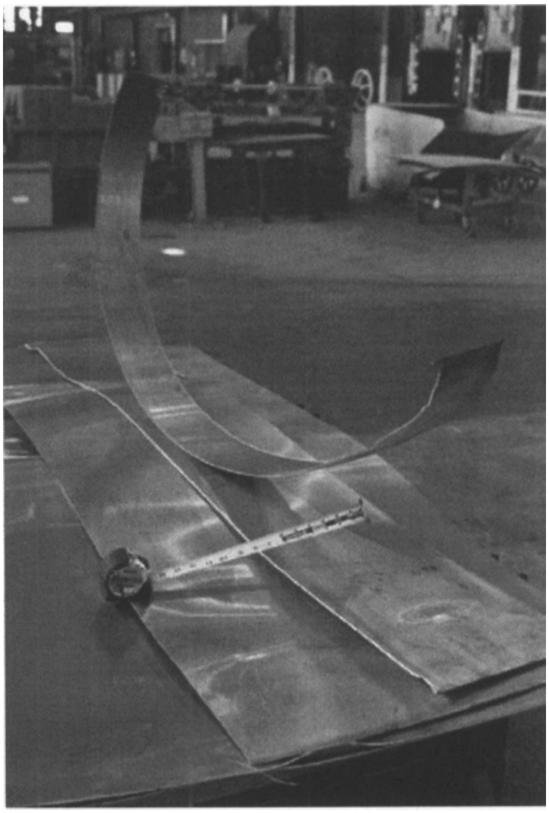

Figure 6 – Photograph of a sheet that caught in the stripper plate and split into three pieces

As well as causing problems with the stripper plates, the curl of the sheet raised questions about the effect of shear rolling. It was expected that the fast roll would stretch the surface of the sheet further than the slow moving roll, leading to a downward curl in the sheet. However, in most cases it was seen that the sheet curled upwards. The exact cause of this is unknown but two theories have been put forward. The first is that the sheet is simply sticking to the upper roll and is being bent after it has exited the roll gap, putting an opposite curve into the sheet. The second is that there is a difference in friction between the two rolls. At the very start of rolling this is unlikely as the rolls were ground to exactly the same finish. However, after several passes are carried out build-up of magnesium and magnesium oxide on the rolls occurs. The amount of build up is likely to be different on the upper and lower rolls due to the speed that each roll is travelling and the contact length. This will change the friction coefficient between the roll and the material, which will alter the forces on the sheet, causing a variation of the total shear.

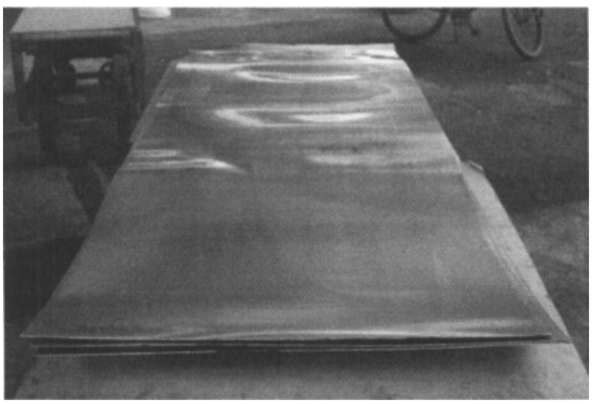

Figure 7 – Photograph of rolled sheets showing the difference in shape control along the length

The first sheets were rolled with no lubrication. It was thought that this would apply more shear to the material, due to higher friction, and thus create 'better' sheets. However, after a few sheets had been rolled, the material started to 'chatter' very badly through the roll bite, with alternating regions of sticking and slipping, as a result of pickup on the rolls. This produced very uneven surface and was expected to give inconsistent amounts of shear deformation. For this reason, lubrication was used for the remainder of rolling. While there may have been more slipping at the roll surface, and consequently less shear applied to the metal, the overall quality was much better and more consistent. Shape control was also helped by the application of lubricant, in its role as a coolant of the rolls. Figure 7 shows a typical example of the type of problem that was encountered. The leading edge of the sheet is shown in the foreground. It can be seen that there was a clear line between good, flat material at the start and poorly shaped/warped material at the end. The initial good section is approximately one revolution of the rolls, and it is thought that heating from the material is responsible for the change in shape. Rolling hot sheet results in a thermal profile across the rolls, getting hotter nearer the centre line of the mill. The expansion of the rolls at the center will lead to buckling in the sheet if not countered. 8-Mill was not equipped with any shape control mechanics. This issue is more a problem with rolling wide, thin sheet than any specific effect of shear rolling, as longer rolls are more prone to shape control problems, which in thin gauges manifest as buckles and waves in the sheet. However the use of coolant minimized these issues by cooling the rolls during processing.

<u>Microstructure and Texture</u>

An overview of the microstructure and texture is shown here to demonstrate that the wide shear rolling caused the same changes as were seen previously in smaller strips. This evolution will be analyzed in more detail in later publications.

Figure 8 and Figure 9 show the microstructure at the centre line of the AZ31B and ZEK100 sheets respectively. It can be seen that the behavior of the two alloys under the same conditions was quite different. The AZ31B had a smaller grain size than the ZEK100 and many more twins. The grains in the ZEK100 appear to be much more elongated than the approximately equiaxed grains in AZ31B. This indicates that more dynamic recrystallization occurred in the AZ31B. However, the presence of many twins in AZ31B shows that it still contained a significant amount of stored work.

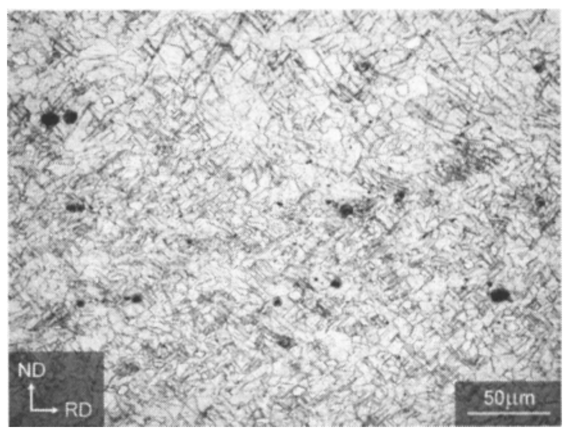

Figure 8 – Microstructure of 36 inch wide shear rolled AZ31B sheet

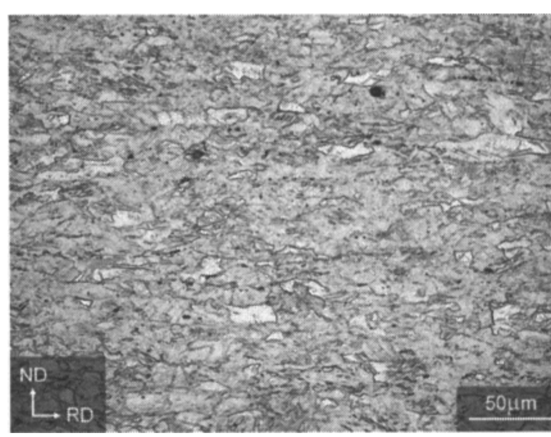

Figure 9 – Microstructure of 36 inch wide shear rolled ZEK100 sheet

The textures of the two alloys are shown in Figure 10 and Figure 11. Again, a significant difference was seen between AZ31B and ZEK100. The distinctly different textures have been seen previously and are responsible for the disparity in mechanical properties. The texture seen in AZ31B was typical, with a split of the basal poles about the normal direction, tilted towards the rolling direction. There is an asymmetry of the split, which may be due to the shear rolling but is too small to be truly significant. The texture in the ZEK100 was also a split basal, as already seen in AZ31B, but with significant spreading in the transverse direction and much weaker intensity.

The microstructure and texture of the wide sheets processed on 8-Mill were comparable to the 10 inch wide sheets. This demonstrated that shear rolling could be scaled up to wider sheet, and will give the same microstructural and textural effects.

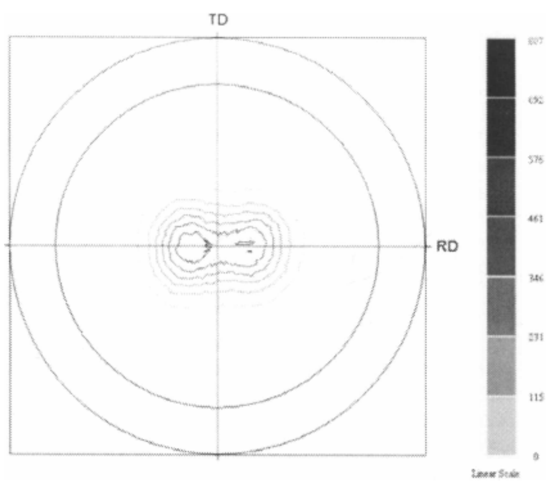

Figure 10 – 0002 pole figure for AZ31B

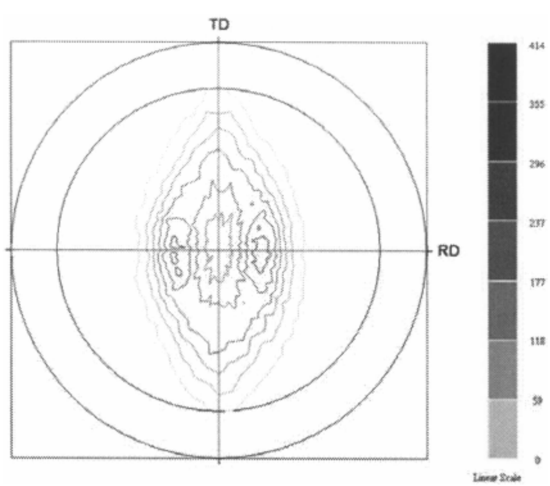

Figure 11 – 0002 pole figure for ZEK100

Formed Parts

Demonstration parts were formed at Superform USA. The part chosen was a section of the firewall for the Panoz Abruzzi. This was chosen as it is a reasonably large part (using a blank approximately 24x28 inches), with a variety of different strains experienced in different areas. An example of a formed part is shown in Figure 12. The parts were formed in a two stage process, consisting of a deep draw followed by pneumatic coining (superplastic forming). Both AZ31B and ZEK100 formed successfully; it was observed that the ZEK100 could be formed faster than the AZ31B, which split at higher forming speeds, see Figure 13.

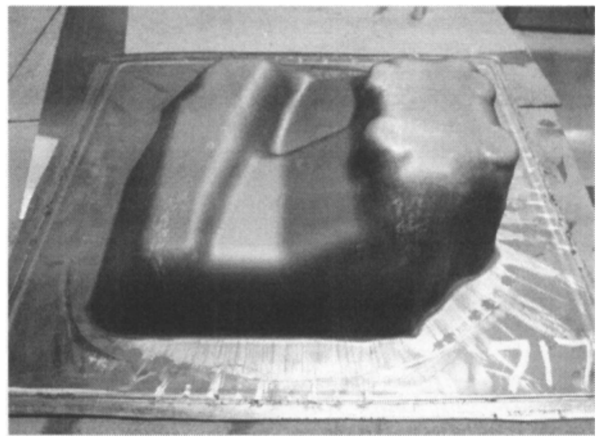

Figure 12 – Photograph showing a part formed at Superform from shear rolled ZEK100

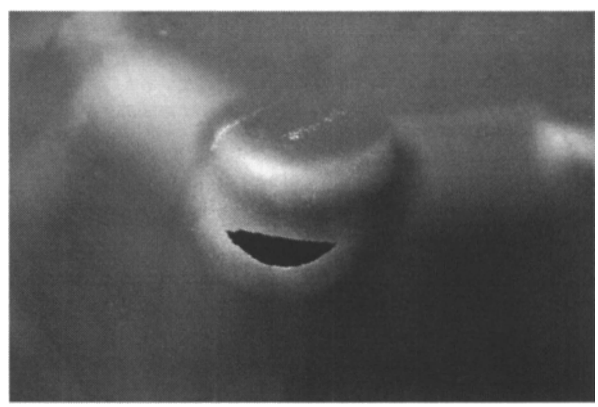

Figure 13 – Photograph showing the failure of an AZ31B shear rolled sheet formed at a faster rate

Summary

Wide sheets of AZ31B and ZEK100 have been successfully shear rolled and the following conclusions were drawn.

- Frictional effects during shear rolling are complex and often act opposite to that expected
- Stripper plates both top and bottom are required on the exit side of the mill
- The stripper plates must be positioned closely and accurately with respect to the rolls
- Lubrication was necessary to ensure successful rolling, but may also have decreased the amount of shear experienced by the material
- Microstructure changes were the same in wide sheet as in smaller strips
- Texture evolution during rolling was the same in wide sheet as in smaller strips
- Automotive parts were successfully formed from shear rolled material

Acknowledgements

This work was carried out in collaboration with Oak Ridge National Laboratory, in part, under sub contract 4000092046 as part of the American Recovery and Reinvestment Act through the Department of Energy. Also, this research through the Oak Ridge National Laboratory's High Temperature Materials Laboratory User Program was sponsored in part by the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program. Thanks go to those staff members at Oak Ridge National Laboratory that contributed to the research program.

Thanks also go to Superform USA for help with part forming.

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