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Developing ShEER as a Method for Sheet Metal Manufacturing

September 2024

Brandon S. Taysom

U.S. DEPARTMENT OF ENERGY

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Abstract

Shear Enhanced Eccentric Roiling (ShEER) is a novel sheet manufacturing technique that aims to superimpose and control hydrostatic and deviatoric stress paths during rolling. In this research, we attempt to use ShEER to form and enhance the properties of low-ductility highly anisotropic materials such as magnesium.

Summary

ShEER is a rolling technology based upon pilgering. It is desired to use ShEER to fabricate plates or sheets of magnesium, which otherwise has poor formability. A few different modeling approaches were considered, and a FEM analysis via LS-Dyna was selected due to computation time and remeshing capabilities. Initial experiments were performed, which showed the ability to process aluminum with ease, yet magnesium failed unless extremely light forming passes were taken. Modeling of aluminum showed that ShEER resulted in slight formability benefits as compared to traditional rolling. Extending this modeling to magnesium is difficult due to the differences in magnesium arising from its crystal structure and texture anisotropy that is developed during processing.

Acknowledgments

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Acronyms and Abbreviations

FCC – Face Centered Cubic (crystal structure)

FEM – Finite Element Modeling

HCP – Hexagonal Close Packed (crystal structure)

Mg - Magnesium

ShEER – Shear Enhanced Eccentric Rolling

SPH – Solid Particle Hydrodynamics

SPP – Solid Phase Processing

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1.0 Introduction

The general purpose of this research is to develop ShEER as a method for rolling low ductility sheet materials, such as magnesium. ShEER is a new PNNL technology and has not been applied to attempt to process magnesium. The aim is to produce defect/crack free sheets of magnesium with large reductions (>80%) in a single step, and improved formability over conventional sheet. If successful, this could allow for the reduction or elimination of rare earth elements in magnesium sheet alloys, reduce the embodied energy, and enable widespread adoption of magnesium alloys.

1.1 Background

Many common metals such as Aluminum and Iron have an FCC crystal structure. This relatively symmetric structure results in a large number of slip planes for most materials at room temperature, and this allows for a reasonable amount of plastic deformation before failure.

In contract, Magnesium has a HCP crystal structure. HCP is very anisotropic and results in limited slip planes at room temperature. Due to this, magnesium alloys have limited ductility and formability at room temperature and adopt a severe texture when deformed. This results in a large asymmetry between tensile and compressive deformations in magnesium, with compressive deformation resulting in rapid hardening and a lower total elongation before failure (see Figure 1). Unfortunately, plate rolling is a primarily compressive process. As such, plate rolling usually has limited rolling reductions [1-2], or needs highly-alloyed or hot magnesium in order to activate more slip planes to enable to requisite ductility [3].

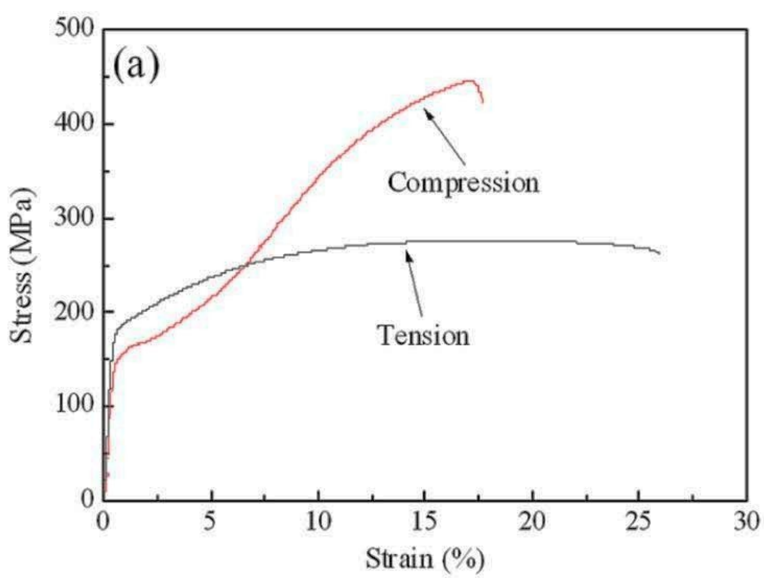

Figure 1. Stress-Strain curve for magnesium, highlighting the difference between pure tensile and pure compressive deformation.

1.2 Pilgering

Pilgering is a method to produce seamless tubing. Pilgering starts with a hollow billet on a tapered mandrel. Specialized tapered cams rotate back and forth as the billet and mandrel is feed in. The cams incrementally squeeze the billet between a smaller and smaller profile and the tapered mandrel, producing a small tube as the end result. The deformation of pilgering occurs in two dimensions with extrusion occurring in the third dimension, and texture can be controlled by a large degree based upon the thinning of the wall vs thinning of the circumference [4].

1.3 ShEER

ShEER is a new technology that is based upon pilgering but creates plates instead of tubes [5]. In ShEER, a thick plate or flat ingot is feed back and forth between two roller cams. The cams slowly reduce the thickness of the plate as it successively passes back and forth. In ShEER, the plate width is held constant in one dimension, with rolling deformation occurring primarily in a perpendicular dimension, and the plate extruding out the 3rd dimension.

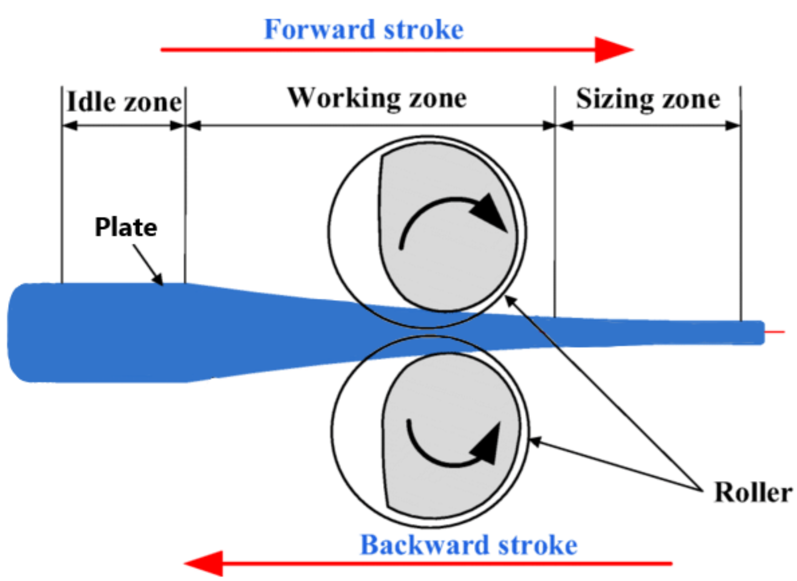

Figure 2. Side-profile schematic of the ShEER process.

2.0 Research Results

The approach for this research was to use SPH/FEM modeling to understand the stress state in the working zone. From there, the cam and stroke profile can be altered to affect the aforementioned internal stress states of the metal. The cam-stroke-FEM process can be iterated to obtain stress states that result in enhanced ductility. Thereafter, cams can be fabricated to perform ShEER in line with optimized simulation conditions, with process-data-informed updates to the model thereafter to streamline the process.

2.1 Initial FEM modeling

At the outset of the project, SPH and FEM were both considered as candidate modeling methods. FEM was chosen due to the manageable strains (<10's), whereas SPH has a much higher solve time but is needed in the case of very large strains (>>10's) such as in friction stir welding. Aluminum was initially modeled instead of magnesium due to its ease of use and robust preexistent materials models. FEM in Abaqus was attempted (see Figure 3) but was quickly abandoned due to the severe mesh distortion and inability to re-mesh well.

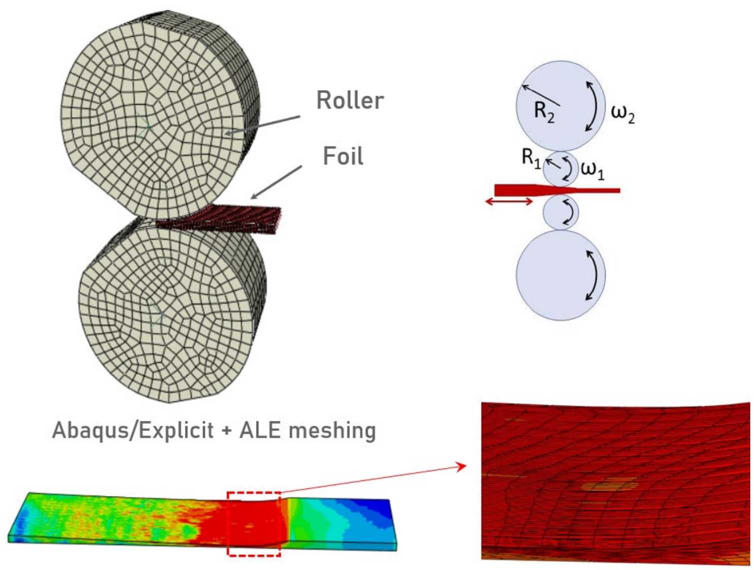

Figure 3. Side-profile schematic of the ShEER process as modeled in Abaqus, showing severe mesh distortion under a reduction ration of 80%.

Due to the mesh distortion, the FEM analysis was switched from Abaqus to LS-Dyna, a simple rolling case was modeled (see Figure 4) and re-meshing into favorable ratio elements easily occurred. Using this approach, eccentric cam rolls were able to be used to model the ShEER process (see Figure 5).

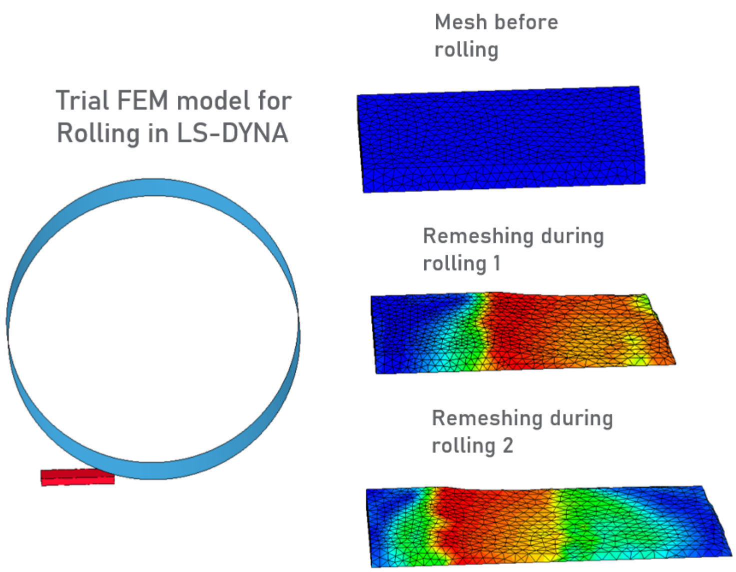

Figure 4. LS-Dyna significantly improved remeshing capabilities.

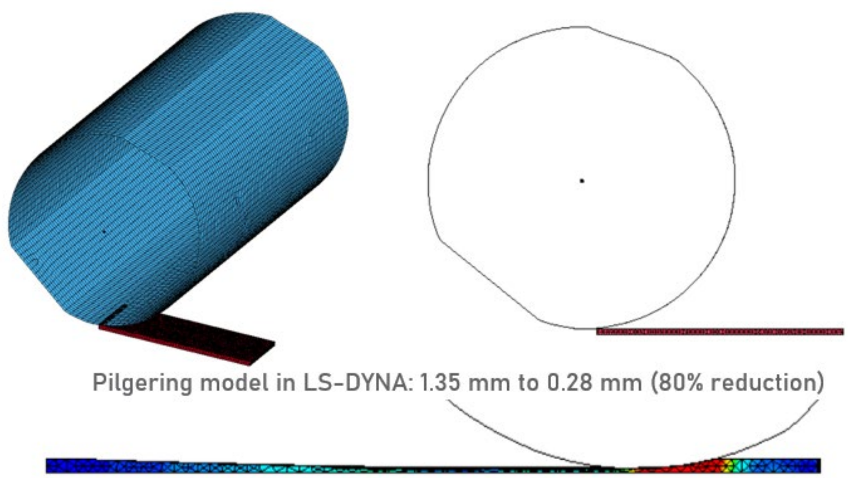

Figure 5. LS-Dyna was able to stably model one and two-passes of the ShEER process.

2.2 ShEER Experiments and FEM Analysis

With the FEM model executing properly, attention was shifted to using PNNL's Stanat pilger mill to produce ShEER plates. Aluminum 6061 rolled quite successfully down to a reduction of about 70%, although some asymmetry occurred in the produced plate due to roller wear (see Figure 6). In contrast, magnesium AZ31 brittle failed under the same conditions, (see Figure 6) and was only successful rolled by dropping the roll reduction down to ~10%.

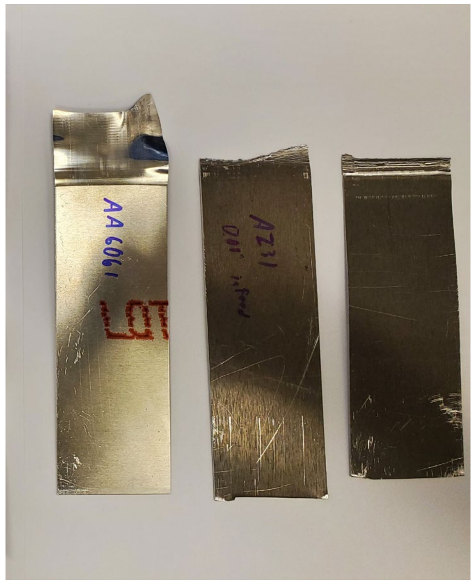

Figure 6. Plates rolled by ShEER. Left – Aluminum 6061, showing a thinned section at the top. The side protrusions are due to the roller having been previously slightly damaged. Middle and Right – AZ31 magnesium, which after any notable amount of rolling catastrophically failure into broken off slivers.

Due to the difficulties encountered in processing magnesium, a second analysis was again done in LS-Dyna. In this case pilgering was compared to regular rolling in aluminum. As shown in Figure 7 for the given analysis conditions in AA 6061, ShEER provided a minor reduction in the damage criteria due to a more uniform and lower peak strain of the process, but overall minimum strains were comparable.

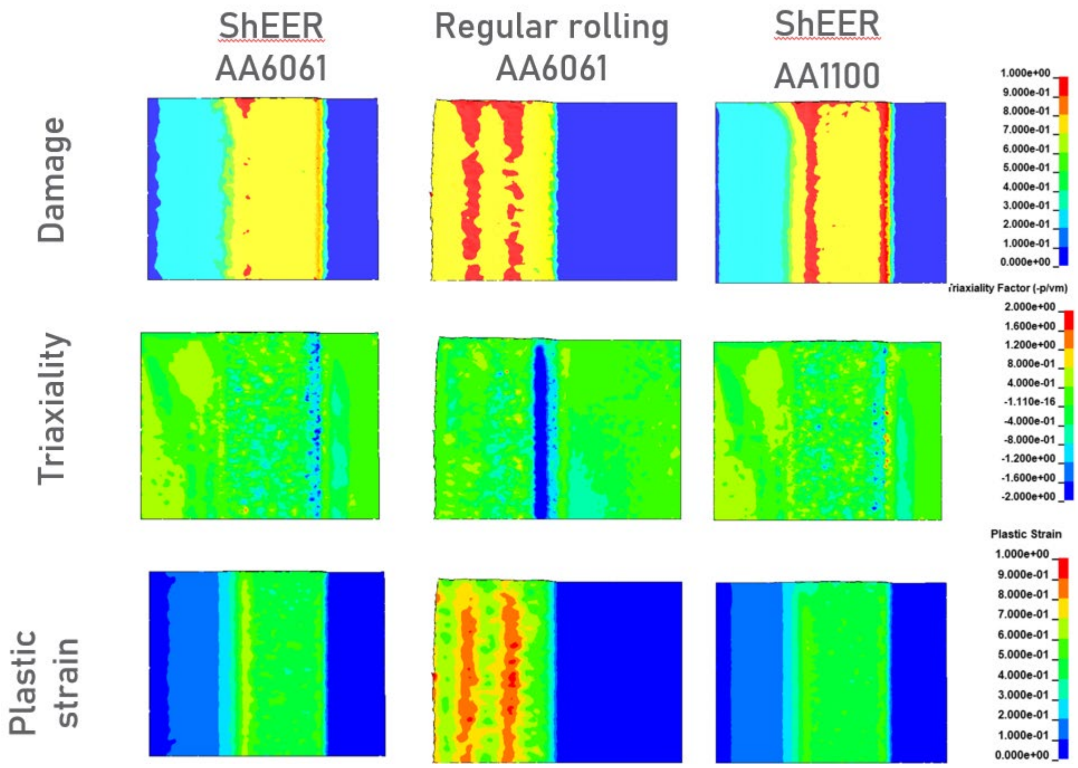

Figure 7. Damage, triaxiality, and plastic strain shown in ShEER and conventional rolling

2.3 Magnesium Modelling

All FEM programs require accurate underlying constitutive laws and materials data to give proper results. Without such data, the FEM model may produce a solution, but the solution might be wildly inaccurate with no way of knowing in what way it is inaccurate.

Unlike linear-elastic FEM, SPP FEM utilizes strains well past the yield point. “Failure” can be recognized by the softening of the hardening curve. Once this happens, further deformation occurs there preferentially which leads to rapid cracking and failure. Knowing when this occurs is key to accurate failure modeling. In a 1D scenario this can be seen by the stress-strain curve (Figure 8 – Left), whereas for 2D and 3D scenarios a more full yield loci is needed. (Figure 8 – Right). For metals such as AA 6061 which are isotropic and well researched, these phenomena are reasonably well understood.

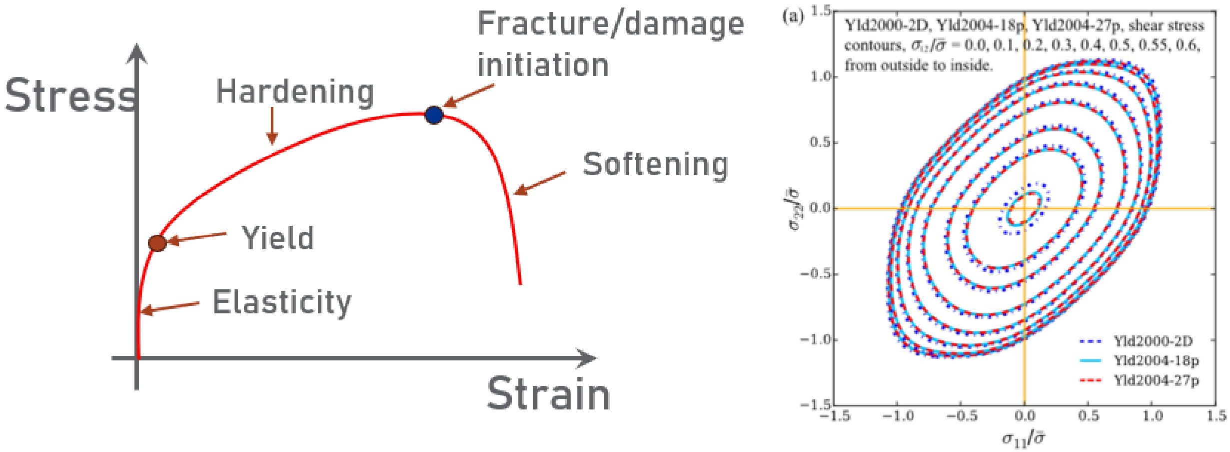

Figure 8. Left – Stress-strain curve showing the onset of fracture/damage. Right – 2D stress-loci of an isotropic material showing successive yield stresses after plastic strain increments.

In contrast to aluminum, magnesium is HCP which gives rise to very different textures developed in compression vs tensile. Both the texture developed prior to deformation, as well as how it is deformed further, affect the future stress. This is shown in the 2D strength profile at various strains, which is quite asymmetric compared to an FCC metal (Figure 9).

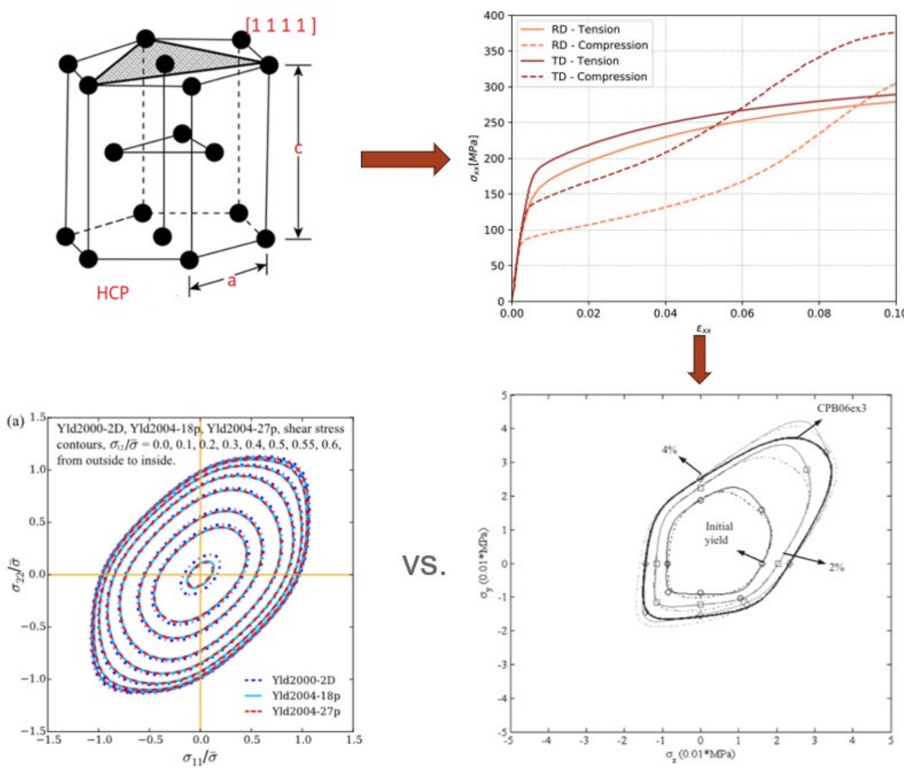

Figure 9. Asymmetry of HCP structure leads to different tensile and compression load paths. These result in very anisotropic multi-dimensional stress development in response to strain.

3.0 Conclusions and Future Work

ShEER was used as a forming method able to make large reductions of area in aluminum, but in this research we were not able to achieve the desired single-pass reductions of magnesium. The desired path of using modeling to inform cam and stroke profile was not realized in this project. The following paths may be suitable to advancing this technology toward the desired goals.

The first route is primarily experimental. Here, a variety of cam designs would be used on a forgiving material such as aluminum, with the goal of determining what cam designs and processing conditions result in high ductility, and which lead to premature failure. Using this as a baseline, work would first be done on a more ductile (i.e. highly alloyed) magnesium, before moving onto a more difficult alloy.

A second approach is to substantially improve the state of the art of magnesium deformation modeling, and then use that to inform cam and stroke profiles. First, accurate yielding and hardening data and models are needed for HCP materials such as magnesium, with material decks suited to the specific alloy. Second, the path-dependent texture development needs to be understood, which is interrelated with the first objective. Not only the current strength of the material is important, but how the material got there – the strain history, accumulated deformation, and most importantly the texture of the material. This is necessary for prediction of deformation past yielding which is present in rolling. Third, edge crack initiation models are needed. Cracking is a nucleation based failure mechanism, and once cracking starts further cracking occurs preferentially along existing cracks. Understanding when cracking may start is key to avoiding developing edge cracks in the first place. Once these three phenomena are better understood, useful modeling can be performed dictating the cam profile and stroke profile of the ShEER process to enable rolling of limited ductility metals such as magnesium.

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