PNNL-27920

Self-Pierce Riveting (SPR) Process Simulation, Analyses, and Development for Magnesium Joints

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Pacific Northwest National Laboratory
Richland, Washington 99352

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Executive Summary

In 2012, the U.S. government issued a Grand Challenge entitled, “EV Everywhere” (EV – Electric Vehicle). The vision is by the year 2022, to produce a Plug-In Electric Vehicle (PEV) that is as affordable and convenient as gasoline powered vehicles are today. In order to reach this vision, a Grand Challenge Blueprint was released in 2013 which describes a number of specific goals. One of the goals is to “Eliminate almost 30% of vehicle weight.” This includes reducing the weight of the body structure by 35%, 25% for the chassis and suspension, and 5% reduction in the weight of materials used for the interior. One of the specific efforts recognized as critical and necessary to achieve the EV Everywhere targets is to provide solutions for cost effective joining and corrosion protection of multi-material structures. This was the motivation for the research described in this paper. Self-Pierce Riveting (SPR) is a mechanical joining technique that is similar to traditional riveting but does not require pre-drilled holes. This is done by driving a rivet through the top layers of material and upsetting the rivet in the lower layer, without piercing the layer, to form a durable joint. The leak proof SPR joint has higher strength compared to spot welding and will replace spot welding in many applications.

When SPR is used to join two sheets of Mg alloy AZ31, at room temperature, the resulting joint shows visible signs of cracking on the bottom, or tail-side, of the riveted joint. In addition, microcracks are observed to originate near the end of the rivet and extend out to the cupped deformation region. In automotive applications such SPR joints reduce the structural integrity of the joint and increase the likelihood for corrosion to initiate and penetrate at this location. Such joints would be unacceptable. However, with proper heat input, successful Mg SPR joints are achievable. It was demonstrated that with sufficient heat, the Mg sheets had enough ductility to produce SPR joints with no tailside cracking. With assistance from a FEM-based SPR process simulation tool, accelerating the process parameter development in terms of heating mechanisms and the associated riveting parameters in achieving the desired rivet quality is possible.

The purpose of the SPR project is to provide a reliable mechanical joining technology for Mg joint applications and to enable the success of mechanical fastening of Mg by assisting the Mg SPR process development and cycle time through rivet process simulation and experimentation. This will be achieved by providing actual SPR joint performance data of Mg/Mg and Mg/dissimilar metal joints, so that more accurate data is applied to the overall structural design, and by developing process windows to provide design recommendations/guidelines for effective Mg SPR joining.

As the automotive industry continues to improve vehicle performance by utilizing lightweight metals, joining of these alloys becomes increasingly more important. Today the Self-Pierce Riveting (SPR) process is a proven high-speed mechanical joining technology for sheet material components, especially for materials that are difficult to weld such as aluminum (Al). For magnesium joint applications, however, there are limitations in the use of SPR due to its low ductility at room temperature. In this paper, improvements to the Mg SPR process have been developed using an in-line pre-heating system that allows the joining of Mg-to-Mg or Mg-to-Al sheets. A Finite Element Model (FEM) developed at PNNL, helped define the process parameters necessary to form joints without tail-side cracking. The sheet temperature at the joint location proved to be the most critical parameter in preventing material cracking. Additional models, with experimental validation, have defined optimized rivet geometries for specific Mg sheet thicknesses. Further developments in automating the heating and joining process for production rates, as well as optimizing the rivet material are on-going.

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Stanley Engineered Fastening, Inc. ("*Stanley" - formerly known as Emhart Teknologies)* is an international leader in the application of SPR for aluminum sheet joining. They desired to add high-rate mechanical joining of magnesium sheet products to their list of global solutions. In 2013 funding was awarded from the U.S. Department of Energy for the Pacific Northwest National Laboratory to collaborate through a Cooperative Research and Development Agreement (CRADA) with *Stanley* to develop and demonstrate the ability to use SPR technology to join multiple sheets of Mg or Mg to Al. Such development would enable SPR joining technology to be used in attaching Mg structures to similar and dissimilar metals.

In this study, a validated FEM-based simulation tool for heat-assisted SPR process of Mg alloys was developed that included both temperature-dependent material properties and transient temperature measurements. It was a coupled thermal-mechanical finite element mode using the commercial FE software, LS-DYNA, to simulate the piercing and clinching processes. The model was validated through comparison with actual joint cross sections obtained using the same rivet/die geometries with and without heating. The model was then used to conduct a series of parametric studies to examine the effects of different riveting parameters including sheet temperature, rivet material and die design. Optimized forming parameters were then used to produce SPR joints of Mg-to-Mg and Mg-to-Al alloy sheets that exceeded the joint acceptance criteria. In addition, experimental joints were produced using Al alloy rivets that reduced galvanic corrosion effects when compared to the existing steel-based rivets used throughout this study.

Because of increased pressure from government agencies and consumer advocate groups to produce safer, more durable, fuel-efficient vehicles, automotive original equipment manufacturers (OEMs) are investigating Mg for use in the major structural sections of vehicles. Mg components offer a potential weight reduction of approximately 50% when substituted for the higher-density or lower-strength steel materials conventionally deployed in vehicles. Historically, poor joining methods for Mg components have limited their applications in vehicles. Over the years, a variety of joining technologies have been introduced into the automotive industry to achieve lightweight vehicle goals. SPR is potentially a viable method for joining similar and dissimilar metals involving Mg. SPR is a low-energy consumption joining process with relatively low initial capital equipment cost. Because SPR is a mechanical joining process, the joint formation process involves large plastic deformation at the rivet tail end to ensure a mechanical interlock between the rivet material and the bottom sheet material. However, Mg alloys have low ductility at room temperature; thus, conventional SPR processing typically causes rivet tail end cracking. These cracks can be detrimental to the rivet performance in terms of static strength, fatigue strength, and corrosion performance.

This project is focused on developing and enabling the SPR process for joining Mg components in new vehicle applications to reduce vehicle weight through efforts established in a Cooperative Research and Development Agreement between PNNL and Stanley Engineered Fastening. This project aims to eliminate or substantially address key technical barriers in using SPRs in Mg-joining applications by using an integrated modeling and experimental approach. Barriers include tail-side cracking of Mg sheet or castings due to the lack of ductility at room temperature; lack of desired joint properties including corrosion at the joint; and lack of acceptable processing parameter windows. Further, the project will explore alternative/non-conventional rivet metals similar to the materials being joined to minimize the galvanic potential in the joint and an alternative joining method (i.e., adhesives) that may further promote joining of Mg. Initial work focused on the development of a numerical tool used to develop reliable Mg

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riveting process parameters through modeling and provide guidance in the development of joining process windows.

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Acronyms and Abbreviations

CRADA	Cooperative Research and Development Agreement
DOE	Department of Energy
PNNL	Pacific Northwest National Laboratory
SEM	scanning electron microscopy
SPR	self-pierce riveting
UTS	ultimate tensile strength

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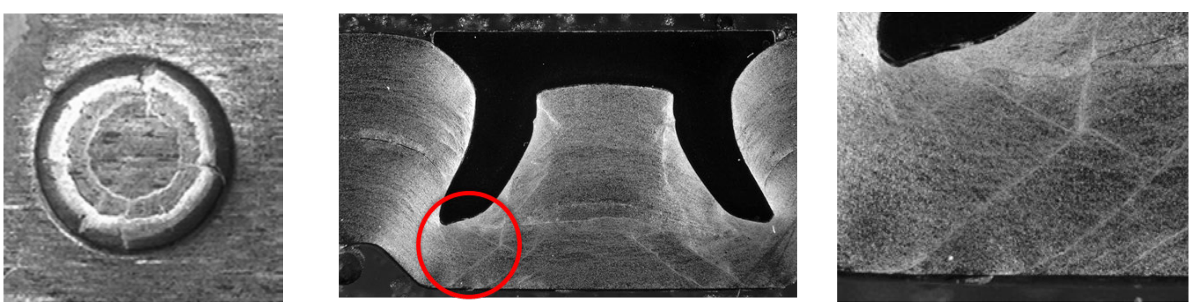
1.0 INTRODUCTION

In 2012, the U.S. government issued a Grand Challenge entitled, “EV Everywhere” (EV – Electric Vehicle). The vision is by the year 2022, to produce a Plug-In Electric Vehicle (PEV) that is as affordable and convenient as gasoline powered vehicles are today. In order to reach this vision, a Grand Challenge Blueprint was released in 2013 which describes a number of specific goals. One of the goals is to “Eliminate almost 30% of vehicle weight.” This includes reducing the weight of the body structure by 35%, 25% for the chassis and suspension, and 5% reduction in the weight of materials used for the interior. Further weight savings will be realized in the drive system which will have compounding weight reductions, lighter vehicles require smaller and lighter components) [1].

Manufacture of future automobiles will integrate a combination of lightweight materials including carbon fiber composites and metal alloys such as high strength steel, aluminum and magnesium. Magnesium is the lightest structural metal and has been the focus of much research in the last 10 years to expand its use in automotive applications [2]. One of the specific efforts recognized as critical and necessary to achieve the EV Everywhere targets is to provide solutions for cost effective joining and corrosion protection of multi-material structures. This was the motivation for the research described in this paper. Self-Pierce Riveting (SPR) is a mechanical joining technique that is similar to traditional riveting but does not require pre-drilled holes. This is done by driving a rivet through the top layers of material and upsetting the rivet in the lower layer, without piercing the layer, to form a durable joint.

In Figure 1 an example is shown where a SPR was used to join two sheets of Mg alloy AZ31 at room temperature. The resulting joint shows visible signs of cracking on the bottom, or tail-side, of the riveted joint. In addition, microcracks are observed to originate near the end of the rivet and extend out to the cupped deformation region. In automotive applications such SPR joints reduce the structural integrity of the joint and increase likely hood for corrosion to initiate and penetrate at this location. Such joints would be unacceptable.



(a) **(b)** **(c)**

Figure 1: An example of a room temperature SPR joint of AZ31 magnesium sheet. (a) external cracks on tailside, (b) microcracks extending from the bottom of the rivet out toward the deformed sheet surface, and (c) with the same region in the red circle magnified.

With proper heat input, successful Mg SPR joints are achievable. In Figure 2, SPR was used to join two Mg sheets heated to 250 °C. The heat was applied to the sheets using an industrial heat gun. This

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demonstrated that with sufficient heat, the Mg sheets had enough ductility to produce SPR joints with no tailside cracking.

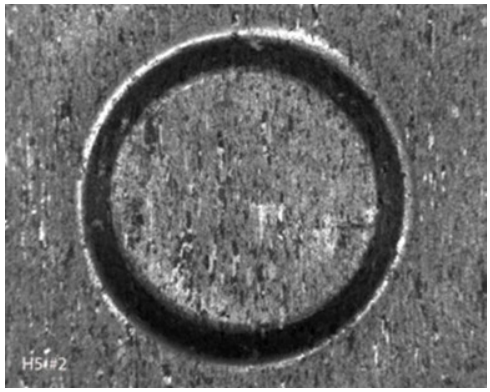

Figure 2: Successful SPR Mg joint.

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2.0 MOTIVATION, GOALS and MILESTONES

Since the practical challenges of applying the traditional SPR technique to join Mg sheets lie in the tendency of tail-side cracking due to the intrinsic low room temperature ductility of Mg, many heat-assisted methods have been attempted experimentally to circumvent this difficulty. For example, Durandet et al. [3] demonstrated that AZ31 to AZ31 crack-free joints can be produced at sheet temperatures above 200°C at the time of rivet insertion. They used a laser assisted method to heat the bottom sheet to the desired temperature before the piercing process. However, variable surface conditions, different sheet thickness, heating mechanisms and riveting die setup can greatly influence the resulting rivet quality in terms of the degree of tail clinching and tail cracking. A FEM-based SPR process simulation tool can help accelerate the process parameter development in terms of heating mechanisms and the associated riveting parameters in achieving the desired rivet quality.

Stanley Engineered Fastening, Inc. (“*Stanley” - formerly known as Emhart Teknologies)* is an international leader in the application of SPR for aluminum sheet joining. They desired to add high-rate mechanical joining of magnesium sheet products to their list of global solutions. However, it was well known that Mg alloys have poor room temperature ductility due to the limited number of slip systems in their hexagonal close packed crystal structure [4-5]. Therefore, a heating mechanism was required that could rapidly heat the Mg to temperatures adequate enough to enable the sheet(s) to deform and avoid cracking during the riveting process. If this could be achieved, then SPR of Mg sheets would also be a viable method for joining Mg sheets as well as dissimilar metal alloys such as Mg-to-Al sheets. In 2013 funding was awarded from the U.S. Department of Energy (D.O.E.) for the Pacific Northwest National Laboratory to collaborate through a Cooperative Research and Development Agreement (CRADA) with *Stanley* to develop and demonstrate the ability to use SPR technology to join multiple sheets of Mg or Mg to Al. Such development would enable SPR joining technology to be used in attaching Mg structures to similar and dissimilar metals.

FEM-based process simulation has been demonstrated as a useful tool in reducing costs and improving production efficiencies related to industrial-process development and optimization. This numerical method has been used to investigate various aspects of the SPR process over the past twenty years. A basic FE model to calculate the setting forces, displacements, and deformations was developed by King [6]. Numerical simulation of the SPR process was then extensively covered by Hahn and Dolle [7] and Westgate et al. [8]. They suggested that 2D models were sufficient for the early design assessment, and 3D models were required to predict the stresses accurately and to refine the design. Stromstedt [9] performed FE analysis of SPR lap shear joint specimens. Iyer et al. [10] performed 3D FE analysis to evaluate the load induced local distributions of relative slip, contact pressure and bulk stress in joints. The riveting process has also been numerically simulated [11-12] with commercial FE package such as LS-DYNA, where a 2D axisymmetric model with implicit formulation is used to simulate the SPR joining of AA 6060 alloys in both the T4 and T6 conditions.

In this study the overall goal was to develop a process to produce Mg SPR joints that met the standard test criteria for joint strength. In addition, to aid in the development of the SPR process, it was the goal of the project to develop and validate a FEM-based simulation tool for predicting the performance of heat-assisted SPR process of Mg alloys. The model should include both temperature-dependent material properties and transient temperature measurements. In this work, such a model to simulate the piercing and clinching SPR processes was developed. The model coupled thermal-

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mechanical finite element modeling using the commercial FE software LS-DYNA. The model was validated through comparison with actual joint cross sections obtained using the same rivet/die geometries with and without heating. The model was then used to conduct a series of parametric studies to examine the effects of different riveting parameters including sheet temperature, rivet material and die design. A complete review of the PNNL model results is available in Soulami et al. [13].

Specific project Goals and Milestones to develop, enable and evaluate the progress in developing the SPR process for joining magnesium components to reduce vehicle weight are listed below in Tables 1 and 2.

Table 1: Project Goals and Project's Technology Development Assessment.

	GOALS	TECHNOLOGY DEVELOPMENT ASSESSMENT	Achieved? Yes/No
	Provide a reliable mechanical joining technology, incorporating localized heating into the SPR process for magnesium joint applications.	**Create Mg SPR joints with no tail side cracking.**	**Yes**
	Enable the success of mechanical fastening of Mg by assisting the Mg SPR process development and cycle time through rivet simulation and experiments.	**Develop a numerical modeling tool to perform parametric study on process parameters (geometries, temperature, rivet material)**	**Yes**
	Enhance existing SPR technology through joint optimization when joining Mg similar/dissimilar joints	**Produce Mg SPR joints with a minimum target joint strength of 1.5 kN * t (substrate thickness in mm)**	**Yes**

Table 2: Project Milestones

	MILESTONES	Complete?
	Submit journal article to Journal of Materials Processing Technology on the numerical tool used to predict SPR joint performance of magnesium materials.	Yes
	Characterize SPR joint performance in terms of fatigue.	Yes
	Provide design guideline recommendations for effective SPR joining of magnesium.	Yes

3.0 EXPERIMENTAL PROCEDURE

3.1 Mechanical Properties

In the first phase of this research, elevated-temperature material properties of the AZ31B-O material were obtained from uniaxial tensile tests conducted using a geometry designed to accurately measure the flow stress as a function of strain and strain rate [14]. The tensile test specimen geometry was 25.4 mm long by 6.4 mm wide. The transition radius from the grip section to the gage is 1.6 mm. The specimens were shoulder loaded. The 3-weight percent Al, 1 weight percent Zinc, AZ31 alloy in the "O" temper was obtained from Magnesium Elektron North America.

Stress versus strain curves at four temperatures (200 ^{o}C, 250 ^{o}C, 300 ^{o}C and 350 ^{o}C) and two constant strain rates ($5.0x10^{-3}$ sec^{-1} and 5.0 sec^{-1}) were generated. Mechanical testing was performed in an air atmosphere inside a servo-hydraulic Instron tensile testing machine equipped with a box-type furnace. Once the samples were placed in the furnace and raised to the test temperature as quickly as possible, the samples were then held at the test temperature for 20 minutes. Specimens were tested using a computer-controlled, stepper-motor driven uniaxial testing machine. The tests were conducted at the desired constant strain rate to failure. Once completed, the samples were removed and measured for total elongation along the gage length.

3.2 Transient Sheet Temperature Profiles

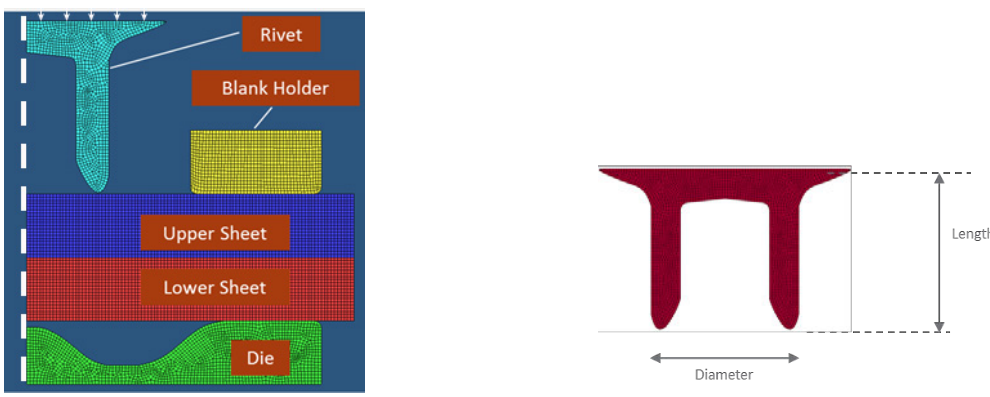
In addition to the temperature dependent materials mechanical properties, the transient temperature profiles of the heated Mg sheet during the SPR process were also very important. It was necessary to determine the maximum temperature, the heating rate, and the sheet to sheet heat transfer rate. To measure these, a set of heating/cooling experiments were carried out wherein the AZ31B-O sheet was instrumented with a set of thermocouples on both the heating side and the back side of the heating source (industrial heat gun). The sheet was heated up and then cooled in the ambient air, with the transient temperature profile monitored. Similar tests were then conducted with two sheets stacked up to determine the amplitude of the cooling rate after the heat source is removed. Knowing that the piercing process occurs within 1.5 to 2 second, we were able to estimate the sheet ductility reduction during this time due to transient temperature changes.

3.3 Finite Element Model Description

As introduced above, the model developed uses explicit finite element analyses using the commercial FE package, LS-DYNA, to simulate the heat-assisted SPR process for Mg alloys. Coupling the thermal-structural analysis with temperature-dependent elastic-plastic constitutive equations was adopted to describe the material behaviors during the piercing process. Taking advantage of the geometry symmetry of the SPR process, an axisymmetric model was developed as shown in Figure 3.

The model includes two Mg sheets to be joined, rivet, and tools (i.e., die and blank holder). A uniform vertical displacement was applied to the top part of the rivet. The rivet comes into contact with the upper sheet, deforms it, and pierces through until it locks into the bottom sheet and pushes the tail material into the corners of the die. The die and the blank holder are fixed in all degrees of freedom. The rivet and Mg sheets to be joined are deformable materials whose mechanical properties and constitutive behaviors are measured and/or discussed further in this section. Initial thermal boundary conditions were also applied to various parts of the SPR model. The initial temperatures of the rivet, die, and blank holder were set to 25°C for all simulations; while the temperature of the Mg sheets varied from case to case. Four-node linear elements with a stiffened-based hourglass control were used to simulate the deformable parts, i.e., the sheets and the rivet. A uniform element size of 0.1 mm x 0.1 mm was used to discretize the Mg sheets to capture the extremely large deformation and local material failure due to piercing. The modeling tool was integral to understanding the role of the heating mechanism, the rivet material and geometry, and die geometry to achieve successful joints [12].

The SPR process parameters depend on its application. Therefore, for a given combination of material and thicknesses to be joined, the optimum rivet geometry and die shape need to be identified in order to obtain the desired joint strength. Compared to aluminum SPR used in automotive manufacturing, the SPR process should not exceed 1.5 to 2 seconds. Given our sheet thicknesses, rivets geometries, and die geometries, a strain rate of approximately 5/s is required for the sheet material deformation during the SPR process.



(a) (b)

Figure 3: Description of the axisymmetric model for the SPR process. (a) schematic drawing and (b) rivet dimensions.

3.4 Heat-Assisted SPR Process Development

A custom designed induction heating system was constructed and then tested at PNNL. With functional testing complete, the system was sent to *Stanley* in Chesterfield, MI where it was integrated into a fully functional SPR C-frame system. The induction coil was calibrated for heating the Mg and/or Al sheets to be joined. The sheets were then heated for 1 to 4 seconds, depending on material and gage thickness. The heated sheets were then riveted using the semi-automated SPR system in Stanley's development and testing laboratory. Pictures of the SPR C-frame and the induction heating coil are shown below in Figure 4.

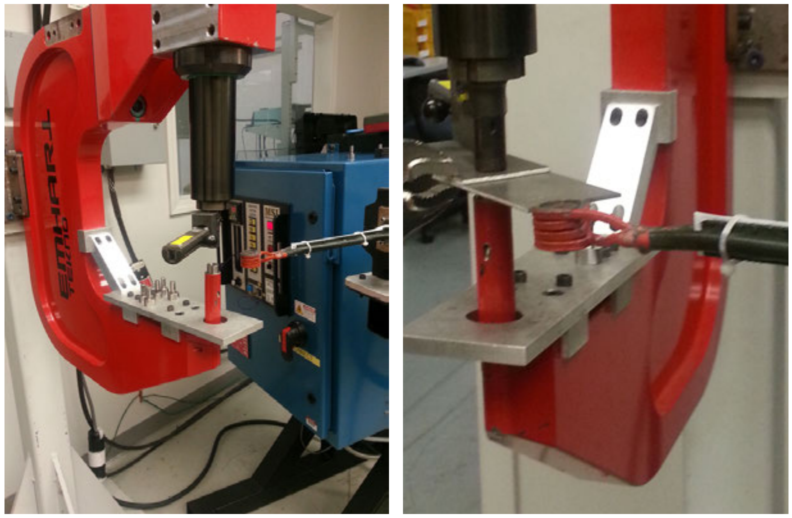


Figure 4: Self Pierce Riveting system with integrated heating supply. *Stanley* SPR C-frame with PNNL's custom built induction heating system and (b) induction heating and Mg SPR joining.

3.5 Process Development - Lap Shear Testing

In order to evaluate the effectiveness of the heated SPR process, lap-shear samples were produced and tested. An example of a SPR joined lap-shear sample is shown below in Figure 5a. The lap-shear tension test setup is shown in Figure 5b, with load applied in a vertical "north-south" orientation with respect to the photograph.

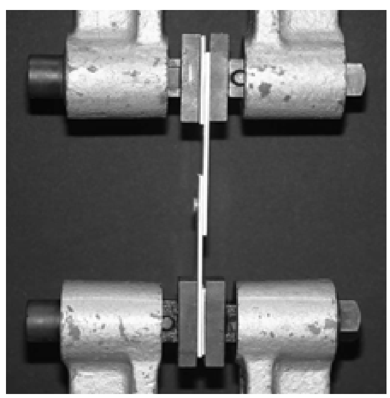


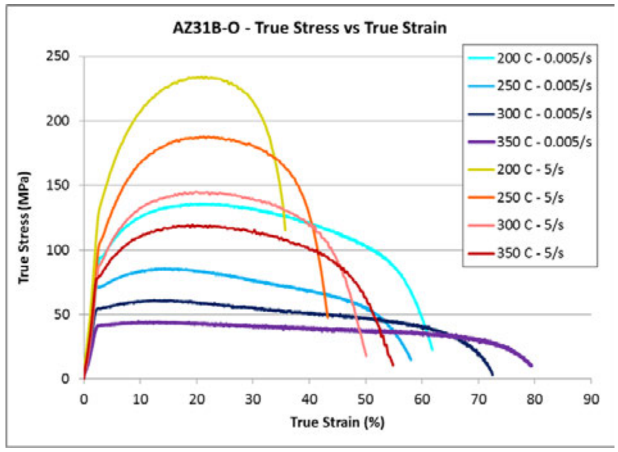
Figure 5: Mg-Mg lap-shear sample prepared for testing. Typical test sample geometry used in process evaluation at PNNL for lap-shear tension test configuration.

4.0 RESULTS AND DISCUSSION

4.1 Phase 1 – Predictive Model Development

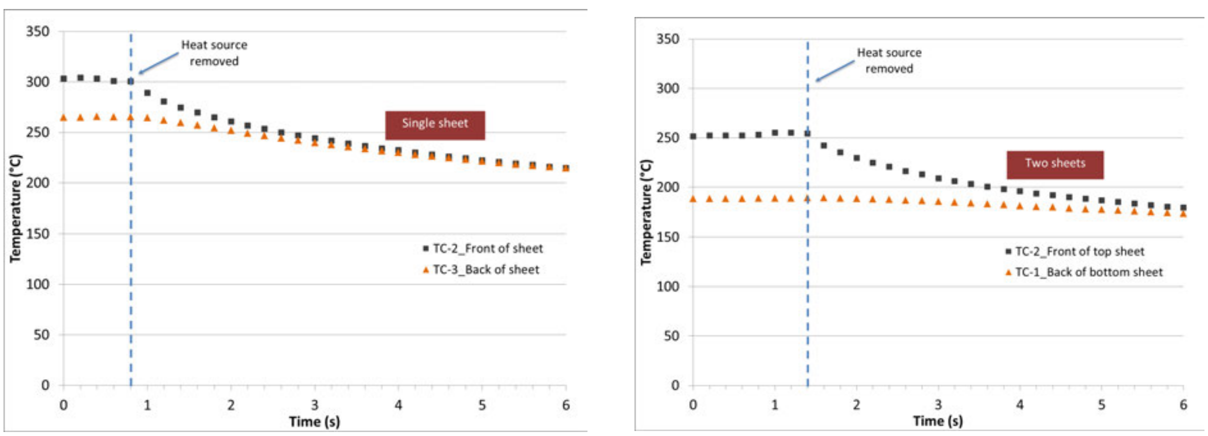
The Phase 1 objectives to build the predictive modeling tool required both temperature dependent mechanical properties and thermal conductivity results for the Mg sheets. In Figure 6 the results for the mechanical testing data are shown. The true stress vs. true strain results are plotted for the AZ31B-O sheet for the strain rates and temperatures described in Table 1. The results show that the flow stress of AZ31B-O has positive strain-rate sensitivity at a given temperature. On the other hand, a significant drop in the strain to failure was observed when the strain rate increased from 0.005 to 5/s. At a constant strain rate, temperature increase resulted in a lower flow stress, softening the material, with a significant improvement in ductility. As expected the ductility increases with temperature and the stress components (yield strength, flow stress, and ultimate strength) increase with increasing strain rate.

In addition to the temperature dependent mechanical properties, the transient temperature profiles of heated Mg sheet during the SPR process are also very important. To measure these, a set of heating/cooling experiments were carried out wherein the AZ31B-O sheet was instrumented with a set of thermocouples on both the heating side and the back side of the heating source (industrial heat gun). The sheet was heated up and then cooled in the ambient air, with the transient temperature profile monitored. It was necessary to determine the maximum temperature, the heating rate, and the sheet to sheet heat transfer rate. Figure 7(a.) shows the measured temperature history of the front and the back sides of a single sheet, and the results indicate a maximum 40 ^{o}C temperature difference between the front and back of a single sheet with the sheet reaching a nearly uniform temperature after 1.5 seconds of heat source removal. Similar tests were conducted for a two-sheet stack. The results indicate a maximum 40 ^{o}C temperature difference between the front and back of a single sheet with the sheet reaching a near equilibrium temperature after 1.5 seconds. For the two-sheet stack, the peak temperature reached 250 ^{o}C and the variation between the top of the upper sheet and the bottom of the lower sheet (190 ^{o}C) is 60 ^{o}C. Continuous heating of the two-sheet stack reached an equilibrium temperature of approximately 250 ^{o}C after 4 seconds of heating. The results also indicate that the heat loss during the piercing process is not significant since the piercing cycle, which consists of heating the sheet, bringing the die and rivet and piercing, takes less than 2 seconds. Hence the starting sheet temperature for the SPR simulations are set to vary from room temperature to ~ 300 ^{o}C in the process simulations assuming that the follow-up time between the SPR machine and the removal of the heating source is within 4 seconds.



(a)

Figure 6: Tensile stress-strain curves for AZ31B-O Mg at quasi-static and intermediate strain rates and different temperatures.



(a) **(b)**

Figure 7: Experimental results of the temperature profile and cooling rates. (a) Single-sheet of AZ31B and (b) Two-sheet stack of Mg AZ31B.

With the above data established, the preliminary model design was built. The rivet design had a nominal diameter of 5 mm as shown in Figure 3(b). Rivet lengths and rivet-tip shapes were varied for different cases. Multiple die designs were investigated in the parametric studies [12], but the flat bottom die shown in Figure 8 was the primary design used throughout the results described in this report**.** Figure 8 also shows the initial model geometry and the predicted joint generated using the Stanley die design riveted at an assumed 200 °C. When the strain was predicted, as in Figure 9, the model described higher strains at the rivet tail and near the bottom of lower sheet, consistent with experimental observations as described above in Figure 1. Increasing the temperature about 50 ºC higher should reduce the strains and likelihood of failure.

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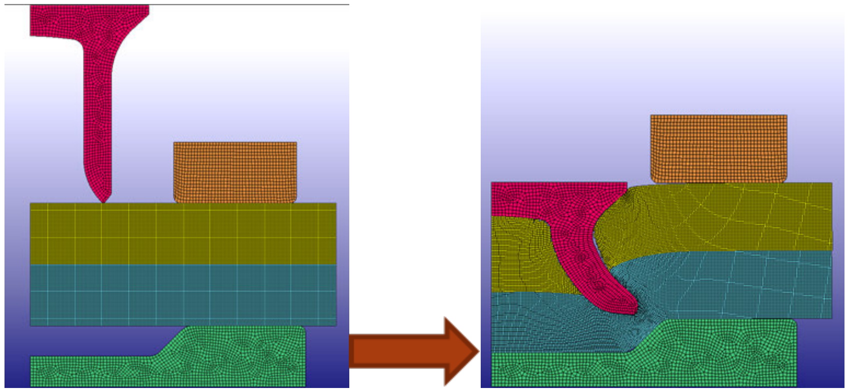


Figure 8: Schematic descriptions of the SPR model processing results using an axisymmetric die design and rivet used to predict joint efficiency with Stanley's flat bottom die and rivet geometries (T = 200 oC, 2 mm to 2 mm AZ31).

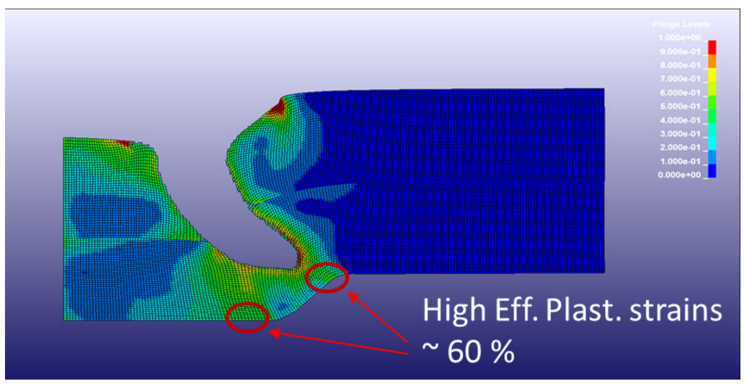


Figure 9: Effective Plastic Strain Contours (T = 200 oC, 2 mm to 2 mm AZ31).

4.2 Phase 2 - Process Simulation Verification

In Phase 2 of the project, the SPR process simulation procedure described above was validated through comparison with SPR joints, made at 200 °C and at room temperature, using Stanley Engineered Fastening geometries, flat bottom die. Figure 10 shows the comparison with an experimentally validated SPR cross section. Very good agreement was observed between the FEM predicted joint geometry and the actual cross section of the joint made by at Stanley's R&D center using a 2 mm to2 mm AZ31B sheet stack up. In Figure 11 the Load – Displacement data used to set the type of rivet, shown in Figure 10, were measured experimentally and compared to the model predictions. The model slightly under predicted the loads, but the overall comparison for the Mg-to-Mg joints was good.

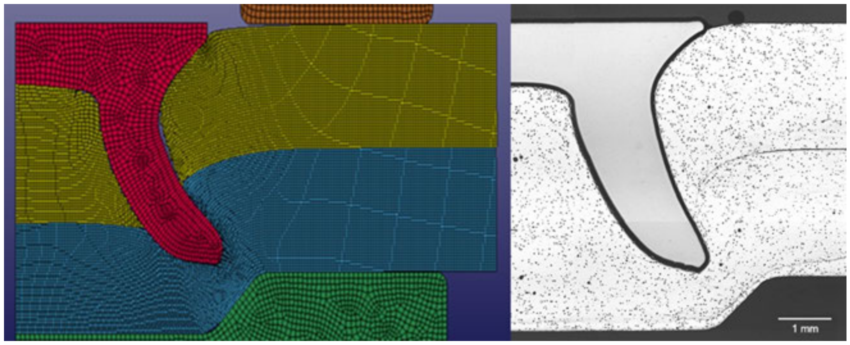


Figure 10: PNNL's FEM Model compared to actual joint testing conducted at T = 200 oC, 2 mm to 2 mm AZ31.

Additional model-process validation was achieved through experimental samples produced using a variety of die designs, rivet designs and temperatures. Metallographic samples were prepared and examined for cracks and measured for penetration and rivet engagement (Figure 12). Cracking was observed when heating only reached 180 ºC. Lap-shear samples were then prepared for mechanical and corrosion testing.

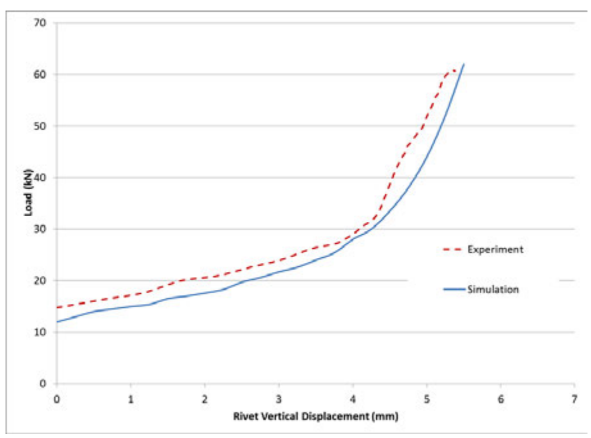


Figure 11: Load-Displacement data for a rivet set at T = 200 ºC, using 2 mm to 2 mm AZ31sheets.

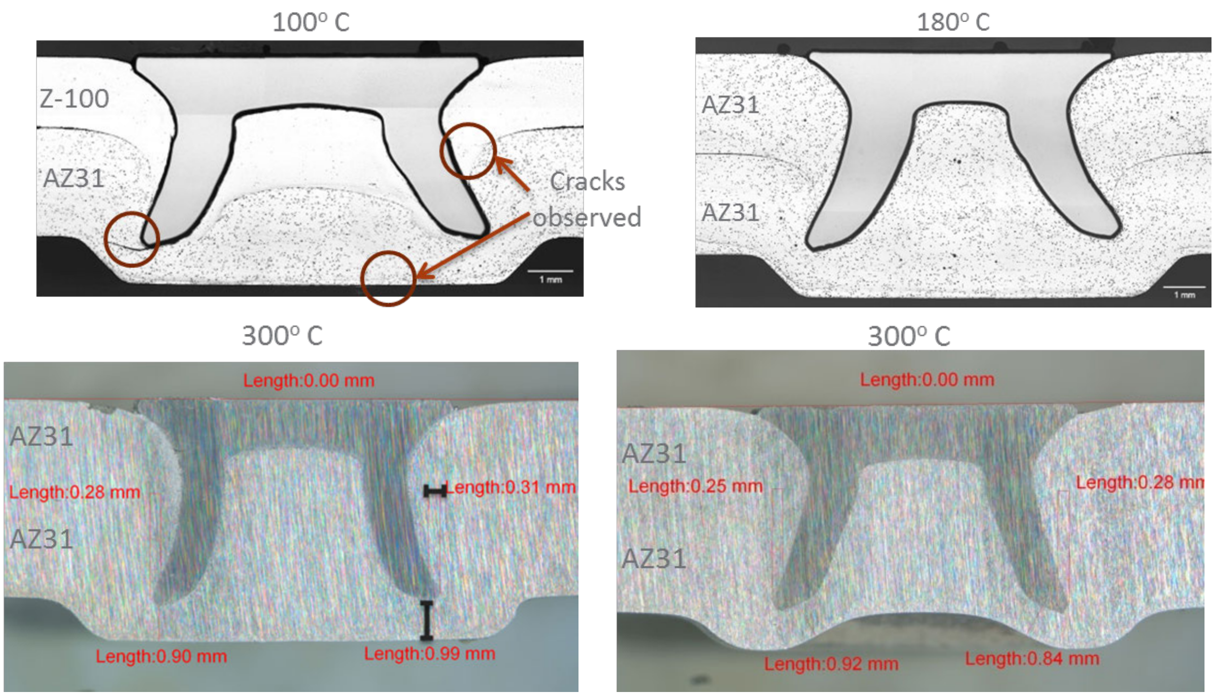
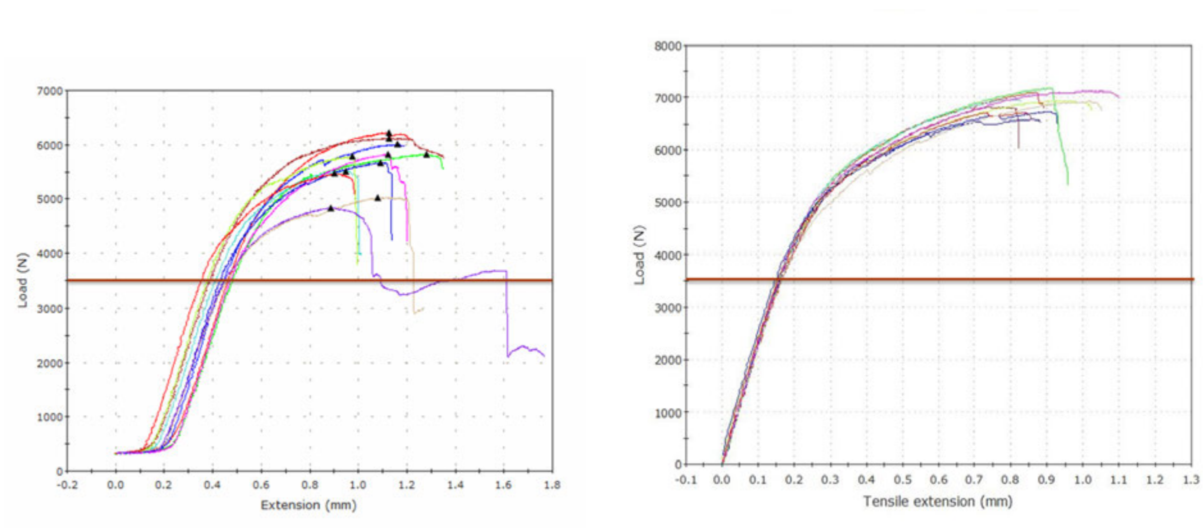


Figure 12: Heat-assisted SPR cross-sections prepared at a series of temperatures and die designs.

The target performance criteria for the Mg SPR lap-shear joints was a minimum joint strength of 1.5 kN * t (t, minimum sheet thickness). Figures 13a and 13b provide examples of the load-extension results for both the preliminary joints (Figure 13a) and the joints used in the final development phase (Figure 13b). Note that both sets of SPR joints produced exceeded the target joint strength, indicated by the red line at 3,500 N, but that the consistency of results is vastly improved for those joints produced under more repeatable, optimized conditions in the final phase. For the 2 mm to 2 mm AZ31B-H24 joints formed, the lap-shear joint strength was well in excess of the target criteria with a result of approximately 6,900 N when tested at room temperature and using an optimized rivet design.



(a) (b)

Figure 13: 2 mm to 2 mm Mg-Mg sheet lap-shear test results. (a) Initial joints formed at 250-300 ºC and (b.) results from the final joints produced under optimized, consistent induction heating conditions.

The lap-shear fatigue results are shown below in Figure 14. As expected, superior fatigue performance was observed for the AZ31 2 mm to 2 mm joints compared to the AZ31 1mm to 2mm joints. The same 2 mm to 2 mm joints behaved similarly to the Al to Al 5182-O joints, with the exception that at the higher load amplitudes, the Al 5182-O joined sheets had slightly better fatigue performance than the Mg joints. The overall behavior is quite similar, with the Mg joints actually outperforming the Al at higher cycles.

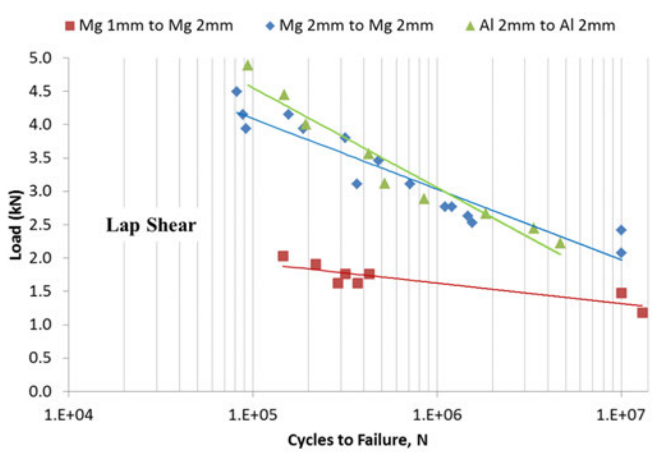


Figure 14: Lap-Shear Fatigue results for Mg-to-Mg and Mg-to-Al sheet SPR joints.

4.3 Evaluation of Dissimilar Metal Sheet Joining

The axisymmetric FEM modeling tool previously developed was used to predict the loads required to form a SPR joint using 2 mm Al 7075 joined to 2 mm Mg AZ31 at a temperature of T = 250 ºC. The

[redacted]

predicted results for the Al on top and the Mg sheet on the bottom are shown below in Figure 15. Experimentally the same joint was prepared and is compared to the model prediction. The joint produced had no tail-side cracking observed and compared very well to the model. This provides additional confidence that with proper material property data, the model can be used to evaluate a variety of joint materials and configurations.

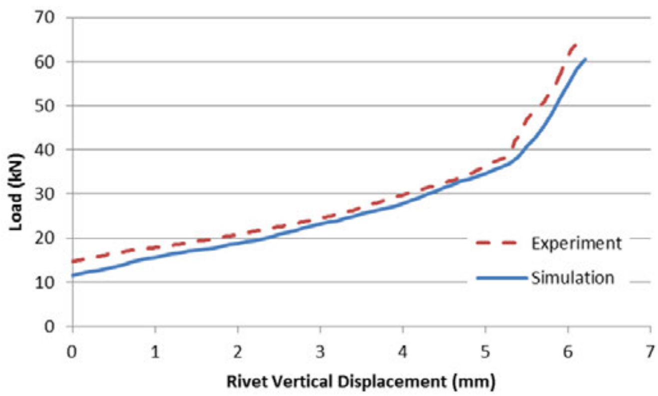


Figure 15: Load vs. Rivet Vertical Displacement for 2 mm Al 7075 joined to 2 mm Mg AZ31B formed at 250 ºC.

The lap-shear tests for the same Al-Mg joint exceeded the joint strength criteria; however, there was an unusual amount of variability in the resulting data (Figure 16). Although the joint strength target was achieved, it was suspected that due to the susceptibility of Al 7075 alloy to thermal instability, possible slight variation in the heat input was attributed to the inconsistent joint strength results.

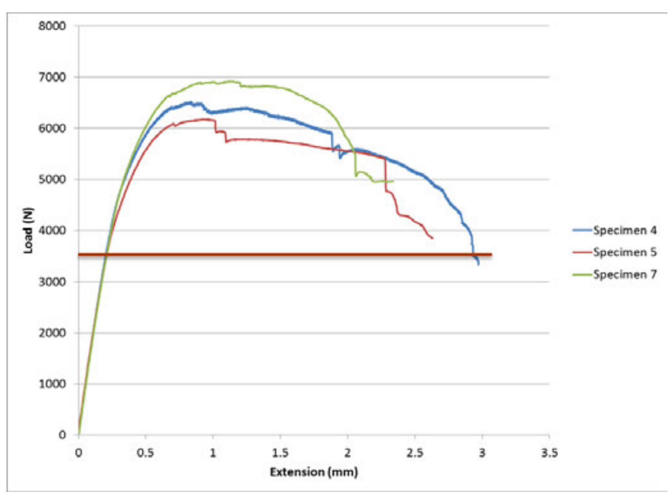
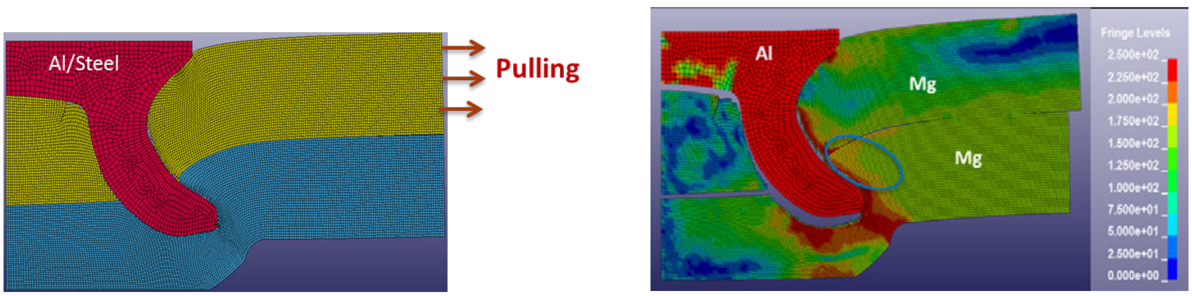


Figure 16: Load vs. Extension for the 2 mm Al 7075 joined to 2 mm Mg AZ31B formed at 250 ºC.

[redacted]

4.4 Novel Rivet Materials for Magnesium and Aluminum Sheet

Currently, work is on-going to develop a series of lightweight rivet alloys that would minimize galvanic corrosion between the aluminum and/or magnesium sheets. This effort has been limited to lap shear simulations performed on Mg-to-Mg SPR joints comparing carbon steel and aluminum rivets. After simulating the SPR joining, the die and sheet holder were removed, and adequate boundary conditions applied on the remaining parts to simulate lap shear (Figure 17). As expected, the predicted joint strength was higher for the steel rivets as compared to the Al 5182-O rivets and this was again verified experimentally (Figure 18). Further work to develop rivets from lightweight alloys which have an adequate combination of strength and ductility is underway. In addition, PNNL and Stanley are developing design guidelines for successful Mg SPR joining.



(a) (b)

Figure 17: The lap shear deformation model results. (a) Model applied to an Al 5182 rivet joining two sheets of 2 mm Mg AZ31B formed at 250 °C and (b) the resulting Von Mises load contours for the SPR joints formed.

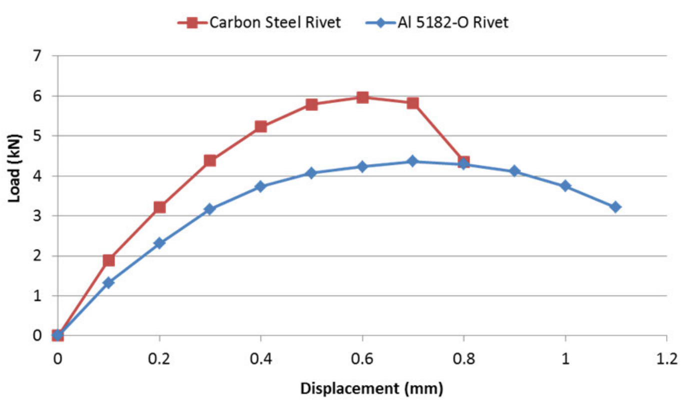


Figure 18: Load vs. Displacement for 2 mm to 2 mm AZ31 sheets SPR joined using both Al 5182-O and carbon steel rivets.

5.0 CONCLUSIONS

Successful technology development was demonstrated using an integrated solution using a combined modeling/experimental approach. Magnesium self-pierce riveting was accomplished using conventional rivets and dies in conjunction with a custom heating mechanism. Based on results from the predictive modelling, the use of a heating system was necessary to produce mechanically sound magnesium joints. Both joints of Mg-to-Mg and Mg-to-Al sheet were demonstrated to exceed the threshold minimum strength using the heated SPR technology.

Sheet material constitutive behaviors were implemented into a modified FEM LS-Dyna model using thermo-mechanical experimental data. Good agreements were found between the predictive simulations and the experiments with respect to the deformed rivet and the Mg sheets. A real time data comparison between the recorded load vs. rivet displacement during SPR experiments and prediction also showed a good match. Parametric studies on rivet length, sheet temperature, and cooling rate were also conducted. The modeling tool identified a temperature range of 200 to 350 °C for SPR of Mg/Mg sheet using conventional rivet materials and die geometries. In addition, the SPR modeling tool demonstrated that medium carbon steel rivets yield the best results in terms of shape of the rivet inter-lock, distance between the tip of the rivet and the tail free surface, and filling of the die.

Die geometries were investigated and the model predictions showed that flat dies resulted in a better locked rivet compared to pip ‘contoured’ dies. With optimization of rivet design and uniform processing, more repeatable and improved strengths were demonstrated. The FEM modeling tool was key to understanding the roles of sheet deformation along with the rivet and die geometry on joint integrity.

Stanley Engineered Fastening recognized the power of the predictive numerical modeling tool, integrating sheet material properties and physical measurements with the rivet and die designs to optimize the SPR development process. Technology transfer via collaboration between PNNL and Stanley included transfer of the modeling tool, development of processing parameters, and processing equipment necessary to achieve successful Mg SPR joining.

With the integration of the custom designed induction heater into a full-scale SPR system at Stanley Engineered Fastening, induction-heated Mg-Mg SPR joints within target cycle time of 3 seconds were successfully demonstrated. In addition, joints of Al 7075 to Mg AZ31 were also achieved.

The PNNL modeling tool was validated against experimental results. It was used to confirm that the interlock of various rivet/joint combinations could be accurately predicted. In addition, it was demonstrated for the first time that a numerical modeling tool could be used to integrate material properties of both the rivet and joined sheets, together with the rivet and die designs, to predict and optimize the SPR process. The minimum target joint strength of 1.5 kN * t (substrate thickness in mm) was achieved for both think and thick sheets of Mg as well as Mg-Al joints. The results indicate that the model was able to accurately simulate the SPR process and, therefore, can be used as a tool to accelerate the joining process development.

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