PLASTICITY-BASED WELDING DISTORTION ANALYSIS OF THIN PLATE CONNECTIONS

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ABSTRACT

In autobody assembly, thin-wall, tubular connections have been used for the frame structure. Recent interest in light materials, such as aluminum or magnesium alloys, has been rapidly growing for weight reduction and fuel efficiency. Due to higher thermal expansion coefficient, low stiffness/strength, and low softening temperature of aluminum and magnesium alloys, control of welding-induced distortion in these connections becomes a critical issue. In this study, the material sensitivity to welding distortion was investigated using a T-tubular connection of three types materials; low carbon steel (A500 Gr. A), aluminum alloy (5456-H116) and magnesium alloy (AZ91C-T6). An uncoupled thermal and mechanical finite element analysis scheme using the ABAQUS software program was developed to model and simulate the welding process, welding procedure and material behaviors. The predicted angular distortions were correlated to the cumulative plastic strains. A unique relationship between distortion and plastic strains exists for all three materials studied. The amount of distortion is proportional to the magnitude and distribution of the cumulative plastic strains in the weldment. The magnesium alloy has the highest distortion sensitivity, followed by the other two materials with the steel connection having the least distortion. Results from studies of thin-aluminum plates show that welding distortion can be minimized by reducing the cumulative plastic strains by preventing heat diffusion into the base metal using a strong heat sink placed directly beneath the weld. A rapid cooling method is recommended to reduce welding distortion of magnesium tubular connections.

KEYWORDS

T-tubular connection, cumulative plastic strains, angular distortion, magnesium alloy, mitigation technique

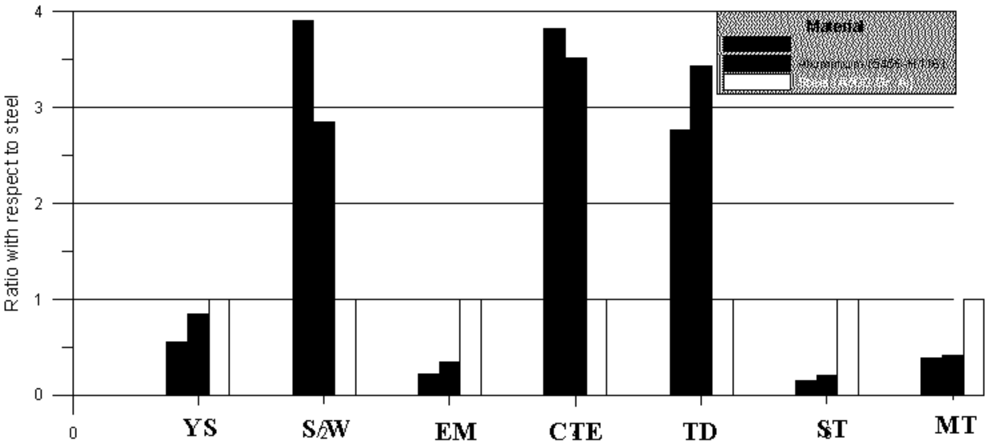
1. Introduction

Driven by the need to minimize vehicle weight, improve fuel efficiency, and use more environmentally friendly materials [1], automakers are showing increased interest in incorporating magnesium into the production of next generation vehicles. Compared to other materials, magnesium has the highest strength per weight ratio that makes its use a viable option. However, the high thermal expansion coefficient and lower strength/stiffness at the elevated temperature usually result in more severe welding distortion. Figure 1 shows normalized comparisons of the influential thermal and mechanical properties of steel, aluminum and magnesium alloys.

In welding T-tubular connections, distortion is usually a dependent function of welding parameter, welding sequence and material property. The highly non-linear characteristic behaviors of the welding process and the material responses make it difficult to quantify the amount of distortion based on the material comparisons along. The finite element analysis (FEA) modeling scheme, which incorporates complex physical phenomena such as moving arc source with finite heat distribution, material softening, strain relaxation due to melting, filler addition, and temperature dependent material properties, was used to investigate the distortion sensitivity in this study

It has been reported by many researchers that there exists a unique relationship between the cumulative plastic strains and distortion due to welding [2-4]. In this study, this unique relationship was demonstrated by comparing the cumulative plastic strains and the amount of angular distortion in the welded T-tubular connection of three different materials.

In welding distortion sensitive magnesium alloys, distortion control plans must be considered during the design stage. Several distortion mitigation techniques, such as application of auxiliary heating, rapid cooling heat sink, external restraint, or any combinations, have been studied and reported. Preventing the welding heat from diffusing into the base metal has been found the most effective distortion control technique. Passing air-water mixture flow through the internal tube is recommended for welding magnesium tubular connections.



YS: Yield strength, S/W: Strength/weight ratio
EM: Linear elastic modulus, CTE: Thermal expansion coefficient
TD: Thermal diffusivity, ST: Softening Temperature MT: Melting temperature

Figure 1 Comparison of thermal and mechanical material properties

2. Finite element analysis

The finite element analysis (FEA) method incorporated an uncoupled scheme for separate thermal and mechanical analyses. Since the plastic work generated from the plastic deformation during welding is insignificant comparing to the magnitude of the arc heat source, it is reasonable to separate the two analyses without comprising the numerical accuracy. This uncoupled numerical scheme enables the ability to verify thermal analysis and calibrate the heat input by temperature measurements and weld nugget analysis prior to the mechanical analysis. In this study, the experimental weld nugget area and shape was used to calibrate the heat input for the aluminum tubes. The weld nugget areas obtained from detailed FEA modeling of mockup models were used to calibrate the heat input for other two materials.

Once the heat input calibrated, the thermal analysis of T-tubular connection was performed to simulate the gas metal arc welding (GMAW) process and a practical welding sequence obtained from a welding procedure data source. Temperature fields at each time increment over the entire welding and weldment cooling off periods were calculated and saved. The mechanical analysis retrieves the temperature data at each time increment for a elasto-plastic iterations. The plastic strain increments generated at each time step are cumulated and saved. The final cumulative plastic strains interact with the connection rigidity resulting in the final state of residual stresses and weldment distortion in the connection. An equilibrium condition between the incompatible cumulative strains and the connection rigidity exists. The incompressibility condition among the three principle plastic strain components must also exist.

Figure 2 shows the FEA model for the T-tubular connection composed of two rectangular aluminum tubes with the cross-sectional dimensions of 100mm×60mmx2mm. Welding parameters and the cross-sectional dimensions of the connections were taken from the design data source. The magnesium connection maintains the same exterior dimensions as the aluminum tubes, but the wall thickness is increased to 3.3mm to provide an equivalent bending rigidity. For the steel connection, the cross-sectional dimensions, including the wall thickness, remain unchanged. The 2.0 mm wall thickness is required to avoid melting through in accordance with the recommended welding specification for a GMAW process in welding A500 Gr.A steel. This minimum wall thickness is usually required to prevent local wall crippling of the thin tube in service.

Thermal analysis

Welding parameters for each material were summarized in Table 1. The orientation of welding sequence is followed from #1 to #4 as shown Figure 2. Leg length of fillet and the width of butt weld were 5mm and 8mm, respectively. Between each sequence, arc was turned off for 5 seconds to change the weld position. After the final weld, there was a cooling period of 147 seconds.

Table 1. Welding parameters for GMAW

Material	Weld Type	Sequence	Power(W)	Weld Speed (mm/sec)	Arc Efficiency
AZ91C-T6	Butt	#1, #2	2900	11.7	0.7
	Fillet	#3, #4	2700	11.7	0.7
5056-H116	Butt	#1, #2	2900	11.7	0.7
	Fillet	#3, #4	2700	11.7	0.7
A500 Gr A	Butt	#1, #2	5000	11.7	0.7
	Fillet	#3, #4	5000	11.7	0.7

In 3D analysis with coarse mesh, heat applied should be calibrated to ensure if heat input is reasonable. The calibration was performed under the assumption that heat input be reasonable when a molten region matched with the design size of welds. The calibration was done using simple and coarse-meshed plate with the same size of elements in 3D T-tubular connection using double ellipsoidal moving heat source model [5]. A factor achieved from the calibration was 1.7 for all cases, which meant that there was heat loss due to coarse mesh scheme.

The heat with calibration factor was applied in 3D T-tubular connection model. Figure 3 shows the temperature map during arc's moving in case of magnesium alloy. By incorporating the user-subroutine calculating the maximum peak temperature, the size of weld bead was monitored with plotting the maximum peak temperature contour. For each material, all thermal properties were dependent on temperature except for density. In order to consider the effect of phase transformation, latent heat was employed as well. Tag welds were also considered at both ends of each weld sequence. The effect of deposition of weld metal was not incorporated in thermal analysis, but in mechanical analysis by using MODEL CHANGE in ABAQUS as shown in Figure 3.

Temperature was calculated and saved over entire weld time. For aluminum connection, temperature history at some locations compared with design source data. Very good agreement was observed. It was assumed that the reasonable temperature profile for other materials would be achieved under the same calibration procedure done in aluminum connection. Mechanical analysis retrieved temperature history calculated from thermal analysis.

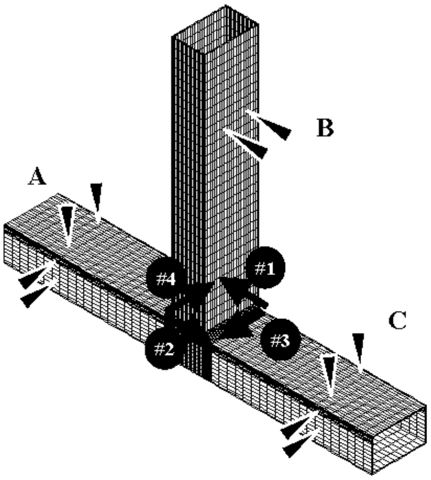


Figure 2 T-connection configuration

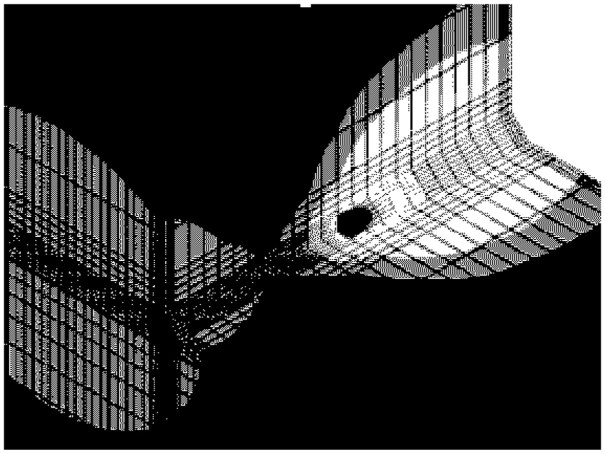
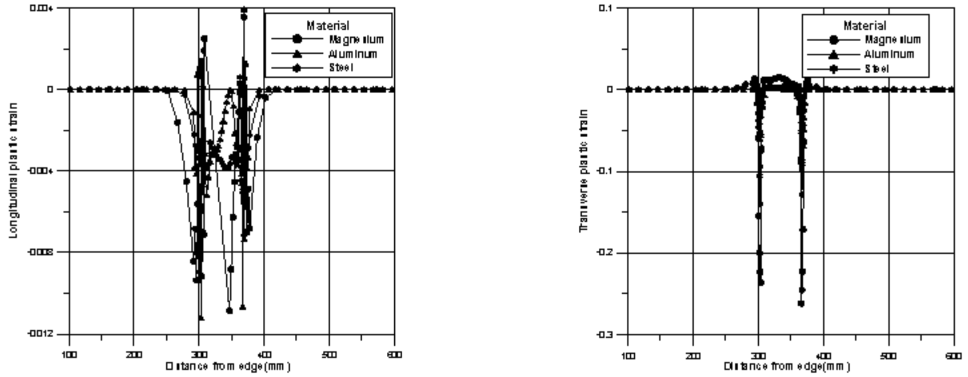


Figure 3 Temperature map during welding

Mechanical analysis

Elasto-plastic analysis to calculate the distortions was performed with temperature obtained from thermal analysis, and boundary conditions presenting the fixture restraint as shown in Figure 2. During four weld sequences, boundary conditions, A, B and C remained as unchanged. After cooling period, C and B were eliminated sequentially under the additional restraints on A region to avoid rigid body motion. Before starting the first weld sequence, element groups associated with filter metal deposited on fillet and butt were deactivated except for element groups of tag welds, and then subset of element group were activated right before an arc passed through it. For three different materials, the cumulative plastic strains were saved and carefully post-processed because it was believed that they contained important information figuring out distortion pattern. At the center of fillet weld experiencing quasi-steady-state, the cumulative longitudinal and transverse plastic strains for three materials were plotted along the top surface of under frame related with boundary condition A and C as shown Figure 4



a) Longitudinal b) Transverse

Figure 4 Cumulative plastic strain distributions

As can be seen in Figure 4, magnesium alloy shows the widest plastic zone and largest magnitude of plastic strain in longitudinal and transverse directions, and aluminum follows next. Especially, more significant difference is shown in transverse plastic strain associated with shrinkage on the top surface of under frame. If distortions were closely associated with the cumulative plastic strains, it might be said that higher transverse plastic strain would result in more shrinkage on top surface and angular distortion of T-tubular connection.

For three materials, the calculated displacements associated with angular distortion were plotted and compared as shown in Figure 5. It is shown that magnesium alloy has the largest angular distortion, and is followed by other two materials. The smallest distortion is observed in steel connection. It can be said that the amount of distortion is proportional to the magnitude and distribution of the cumulative plastic strains.

From results of distortion analysis, it can also be said that magnesium alloy has relatively high distortion sensitivity compared to others. Therefore, more careful distortion control can be necessary in the fabrication of magnesium alloy connections.

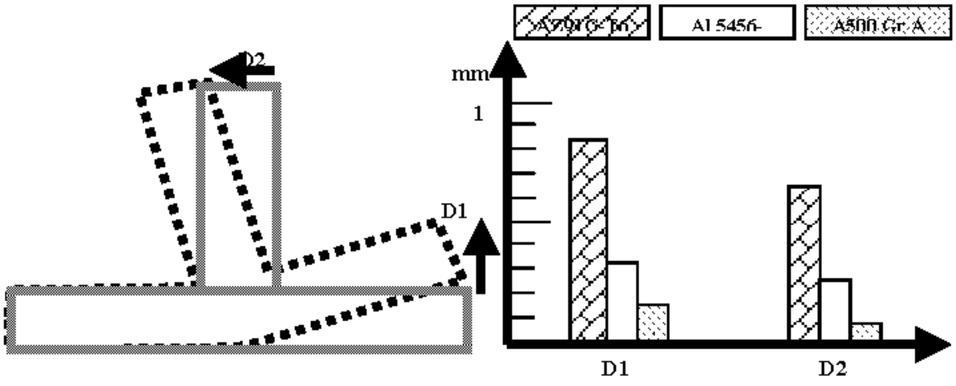


Figure 5 Comparison of angular distortion for materials tested

3. Mitigation technique

In case that material has high distortion sensitivity just like magnesium alloy, distortion should be controlled during welding, or after welding. It was observed that plastic strains might be cumulative not only temperature gradient, but also softening of material, and most of cumulative plastic strains might be caused by mainly the softening of material [6]. In order to control the softening of material, temperature near weld region should be reduced by some rapid cooling methods.

Han [6] simulated the effect of auxiliary heating and heat sink on the cumulative plastic strain as shown Figure 6. Only with auxiliary heating, there was no significant change of the magnitude of plastic strain. On the other hand, heat sink gave significant reduction of magnitude and distribution of plastic strains. Based on proportional relation between the cumulative plastic strain and distortion, heat sink may effectively mitigate distortion induced in T-tubular connection with magnesium alloy, which may not experience significant metallurgical phase transformation associated with embrittlement of nugget and HAZ just like steel. One of mitigation scheme for T-tubular connection is under investigation by OSU welding design group. Figure 7 represents the basic concept of the mitigation technique with heat sink providing a rapid cooling on weld region. Considering the geometry configuration of T-tubular connection, air and water mist is forced to flow through into the under frame of T-connection. This mist will take away heat from a weld region, and results in cooling the weld region, which may reduce the cumulative plastic strains and distortion..

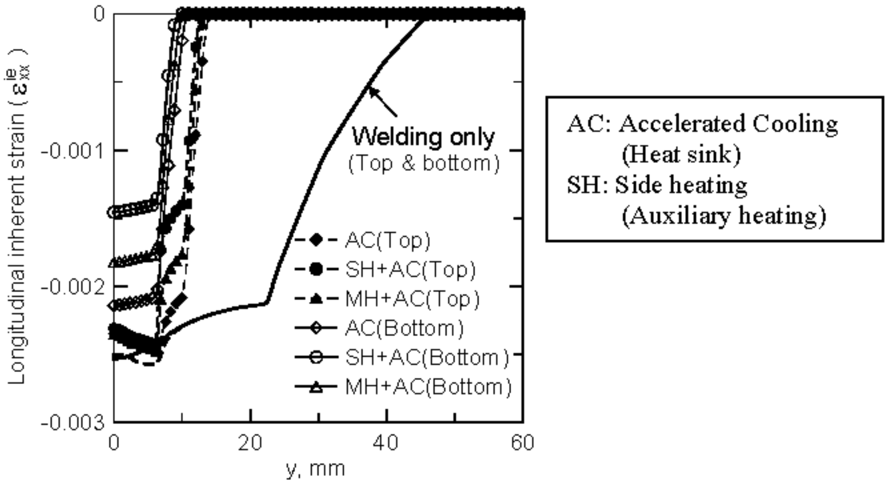


Figure 6. Longitudinal plastic strain distribution under thermal management for butt weld [6]

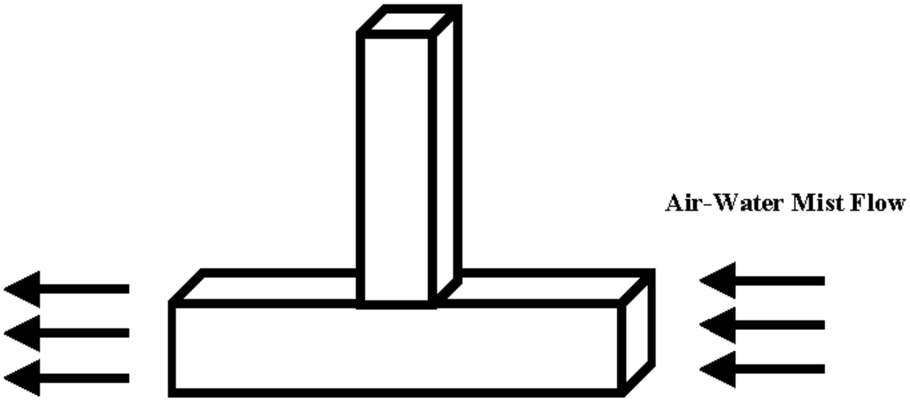


Figure 7 Concept of mitigation technique for T-tubular connection

4. Conclusions

Based on the results of analysis, we can conclude the followings.

(1) The unique relation between cumulative plastic strains and distortion exists
(2) Magnesium alloy has higher distortion sensitivity than aluminum and steel.
(3) In fabrication of magnesium alloy based T-connection, distortion control plan may be necessary.
(4) Based on the mechanism generating the cumulative plastic strains, heat sink with air and water mist may be effective way to reduce distortion of T-tubular connection for magnesium and aluminum alloys.

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