

Effect of Temperature Variation on Stresses in Adhesive Joints between Magnesium and Steel

Shardul Bhambure and Pankaj K. Mallick
University of Michigan-Dearborn

ABSTRACT

This study considers the thermal stresses in single lap adhesive joints between magnesium and steel. The source of thermal stresses is the large difference in the coefficients of thermal expansion of magnesium and steel. Two different temperature differentials from the ambient conditions (23°C) were considered, namely -30°C and +50°C. Thermal stresses were determined using finite element analysis. In addition to Mg-steel substrate combination, Mg-Mg and steel-steel combinations were also studied. Combined effect of temperature variation and applied load was also explored. It was observed that temperature increase or decrease can cause significant thermal stresses in the adhesive layer and thermal stress distribution in the adhesive layer depends on the substrate combination and the applied load.

CITATION: Bhambure, S. and Mallick, P., "Effect of Temperature Variation on Stresses in Adhesive Joints between Magnesium and Steel," *SAE Int. J. Mater. Manf.* 5(1):2012, doi:10.4271/2012-01-0771.

INTRODUCTION

Over the last two decades, there have been many focused projects in which individual groups of materials, such as advanced high strength steels, aluminum alloys, magnesium alloys and carbon fiber reinforced composites have been used to develop lightweight vehicles or vehicle substructures. Examples of these projects are ultra light steel auto body construction, aluminum-intensive vehicles, and magnesium frond end. While all these projects have produced significant results in light-weighting technology, and many of the materials and manufacturing technologies developed in these projects are being adopted in production vehicles, future lightweight vehicles will most likely be constructed using a combination of these materials. In such a scenario, joining of dissimilar materials becomes one of the critical design issues that must be addressed for safe and long term use of the vehicle structure. Currently, with steel as the principal material of construction, resistance spot welding is the most common joining technique used in the automotive industry. However, adhesive joining is also used in significant amount in the assembly of today's automobiles. Mechanical joining, such as bolting and riveting, and other joining methods are used in much smaller amounts. Since resistance spot welding and other welding techniques are either not suitable or not fully developed for non-ferrous materials, adhesive joining, either by itself or in combination with mechanical joining, such as riveting, will play a major role in vehicles in which multiple materials with dissimilar mechanical and thermal

characteristics will be assembled and joined to build the structure.

Adhesive joining is a well established technology and a large number of publications on stress distributions in adhesive joints between similar substrate materials already exist. A few publications on stress distributions in adhesive joints between dissimilar substrates are also available. Most of these publications consider stresses in the adhesive or at the substrate-adhesive interface due to mechanically applied loads. Due to unequal coefficients of thermal expansion of dissimilar substrates, thermal stresses may also arise in the adhesive joint due to temperature variation. Thermal stresses in the adhesive layer can be either beneficial or detrimental depending on whether they are additive or subtractive to the mechanical stresses created due to the applied load.

Deformations and stresses in the adhesive layer of single lap joints of Mg-Mg, steel-steel and Mg-steel substrate combinations under mechanical loading were reported in a previous paper [1]. This paper considers the effects of temperature variation on the deformations and stresses in single lap adhesive joints between Mg-Mg, steel-steel and Mg-steel. The thermal expansion coefficient of magnesium is nearly 2.2 times that of steel, and the thermal expansion coefficient of the adhesive is 2.2 times that of magnesium. Due to the mismatch in thermal expansion coefficients, thermal stresses are created as the operating temperature surrounding the joined substrates either increases or decreases from the ambient temperature. In addition to the

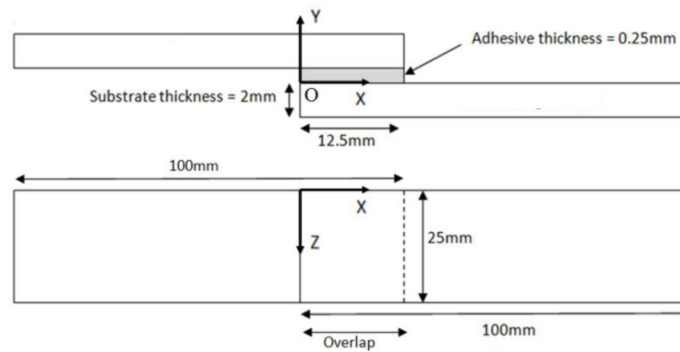


Figure 1. Front and top views of the single lap joint. The dimensions shown are at an ambient temperature of T_0 (23°C)

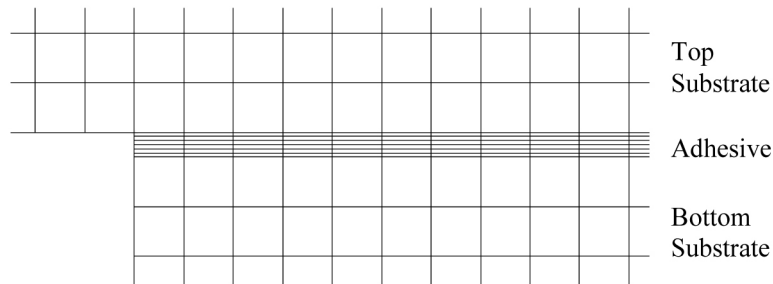


Figure 2. Mesh patterns in the adhesive and the substrates

thermal stresses created in the adhesive layer due to temperature differentials, there is another source of thermal stresses. The second source of thermal stresses is due to the shrinkage of the adhesive which occurs when the heat-curing adhesive is cooled down from its curing temperature to room temperature. It has been shown that adhesive shrinkage stresses are much smaller compared to the stresses due to thermal mismatch, especially at high applied loads [2, 3]. In this paper, only the thermal mismatch stresses are considered.

FINITE ELEMENT MODEL

The specimen dimensions used for the single lap joints are shown schematically in [Figure 1](#). The length and width dimensions of the substrates are 100 mm and 25 mm, respectively. Both substrates have a uniform thickness of 2 mm. The length of the overlap is 12.5 mm and the adhesive thickness is 0.25 mm. All of these dimensions are assumed to be at an ambient temperature T_0 of 23°C, which is considered the reference temperature. The temperature differentials, ΔT , considered in this study are +50°C and -30°C.

A three-dimensional linear elastic finite element stress analysis of the lap joint was conducted using Radioss, a commercially available finite element solver. [Figure 2](#) shows the mesh patterns in the adhesive layer and the substrates next to the adhesive layer. Modeling and meshing of the single lap adhesive joint was performed using Hypermesh. For the substrates, a fine mesh was used around the overlap region and a relatively coarse mesh was used toward their far ends.

All the elements used for the adhesive and substrates were eight-noded solid elements. The adhesive thickness was divided into six layers of elements and the element dimensions in the adhesive were 0.5 mm $\times$ 0.5 mm $\times$ 0.041 mm (thickness). The substrate thickness was divided into four layers so that the element thickness in the substrate was 0.5 mm.

BOUNDARY CONDITIONS

Two different boundary conditions were considered used in this study. They are described below. The temperatures of T_0 , $(T_0 + 50)^\circ\text{C}$ and $(T_0 - 30)^\circ\text{C}$ were applied in both cases, creating temperature differentials of 0°C, +50°C and -30°C, respectively. The temperature differential was applied to all the nodes, replicating a behavior of a controlled atmosphere around the joint.

- Both substrates are fixed at the far ends, as shown in [Figure 3\(a\)](#). Thus, the far ends of the substrates are constrained in all translations and rotations.
- The top substrate is fixed at its far end and the bottom substrate is free to translate at its far end only in the x-direction, as shown in [Figure 3\(b\)](#). A tensile load of 100N is applied at the far end of the bottom substrate.

In the case of Mg-steel joint, the top substrate is Mg and the bottom substrate is steel.

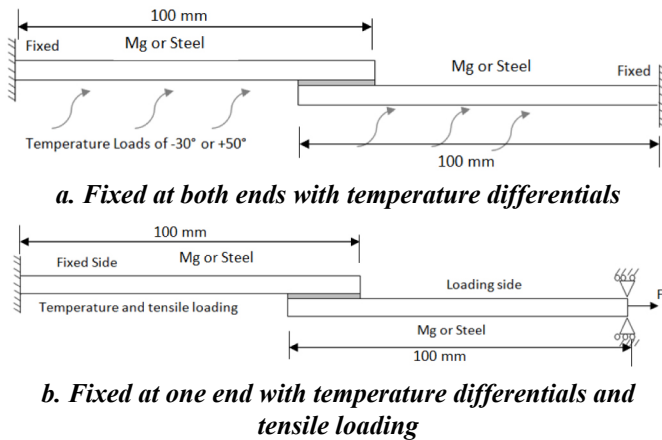


Figure 3. Boundary conditions used for thermal stress analysis

MATERIAL PROPERTIES

The material properties used for thermal stress analysis are shown in Table 1. Magnesium and steel were used as the substrates and an unfilled epoxy was used as the adhesive. As can be noticed in Table 1, the thermal expansion coefficient of magnesium is approximately twice that of steel and the thermal expansion coefficient of the adhesive is approximately five times that of steel. There may be variation of these properties with temperature, particularly for the adhesive; but this was not considered in this study.

Table 1. Material properties at 23°C

Material	Modulus of Elasticity (E) (GPa)	Poisson's Ratio (ν)	Density (ρ) (g/cm^3)	Co-efficient of thermal expansion ($1/^\circ\text{C}$)
Substrate				
1 Steel	207	0.29	7.87	12×10^{-6}
2 Magnesium	45	0.35	1.738	26×10^{-6}
Adhesive	1.4	0.45	1.01	58×10^{-6}

RESULTS

DEFORMATIONS DUE TO TEMPERATURE DIFFERENTIAL

Specimens with Both Far Ends Fixed

Since the specimen dimensions were specified at the reference temperature T_0 , there was, as expected, zero deformation for all three combinations of substrate materials at T_0 . However, with either the positive or the negative temperature differential, there were out-of-plane deformations, represented by the displacements in the Y-direction (Figures 4 and 5).

Figure 4 shows the deformation for Mg-Mg, steel-steel and Mg-steel joints with fixed far ends and a temperature

differential of $+50^\circ\text{C}$. The deformations are anti-symmetric for similar substrates (Mg-Mg and steel-steel). The deformation is larger for Mg-Mg joints than the steel-steel joint, which is due the lower modulus and higher coefficient of thermal expansion of Mg. For Mg-steel joints, the deformation is asymmetric and the magnesium side of the joint has a much larger out-of-plane deflection than the steel side. Since the far ends of the substrates are fixed, free expansion of the total length of the specimen is completely restricted, which creates a compressive loads at the far ends of the substrates. As the compressive loads are not collinear, a bending moment is developed at the joint, which causes large out-of-plane deformations shown in Figure 4.

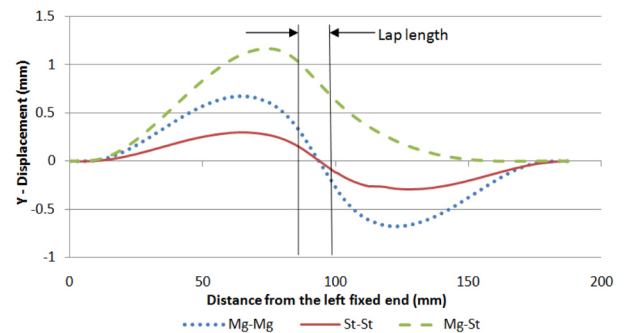


Figure 4. Displacement (Y-component) plots for Mg-Mg, steel-steel and Mg-steel specimens fixed at far ends for a temperature differential of $+50^\circ\text{C}$ (Scale factor 10)

The deformation plots for negative temperature differential of -30°C are shown in Figure 5. In this case, tensile loads are created at the far ends of the substrates, since the total thermal contraction of the specimen length was completely restricted. The bending moment developed at the joint due to the tensile thermal loads deform the substrates in directions opposite to the directions in the case of positive temperature differential. Since the negative temperature differential was smaller than the positive temperature differential, the out-of-plane deformation for the negative temperature differential (Figure 5) was smaller in magnitude than for the positive temperature differential (Figure 4).

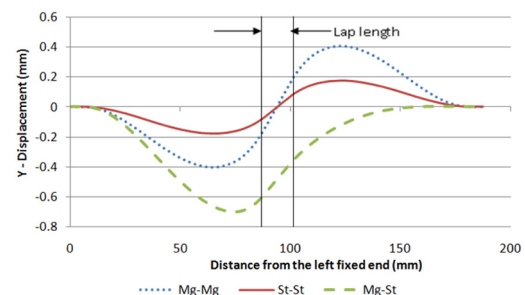


Figure 5. Displacement (Y-component) plots for Mg-Mg, steel-steel and Mg-steel specimens fixed at far ends, for a temperature differential of -30°C (Scale factor 10)