FRICITION STIR SPOT WELDING OF AM60 MAGNESIUM ALLOY TO DP600 STEEL

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ABSTRACT

The feasibility of friction stir spot welding of AM60 magnesium alloy to DP600 steel is examined. A tungsten-rhenium alloy tool is used to spot weld overlapping sheets of 1.2 mm thick base material, configured with the Mg-alloy sheet on the top and steel sheet on the bottom. The influence of welding parameters (tool rotation speed and welding time) on the joint microstructure and overlap shear fracture load is examined. Mechanical testing indicates that the fracture occurs through the Mg-alloy material in the upper sheet and not the bonded interfacial region.
INTRODUCTION

The demand for weight reduction in automotive applications is driven by the need for increased fuel economy and improved vehicle performance. This has lead to an increased use of advanced high strength steels, such as dual phase steel and transformation induced plasticity steels. Lighter base materials also provide significant reductions in weight compared to steel during automobile manufacture and this explains the driving force for the increased use of magnesium alloy base materials for automotive component manufacture. The incremental replacement of steel by Mg-alloys in a variety of applications will inevitably demand a technique for joining this dissimilar combination of materials.

Currently resistance spot welding is generally used in automotive material steels, and is feasible for joining of Mg-alloy materials as well [1]. However resistance spot welding is not feasible for dissimilar welding of steel to Mg-alloy due to their widely differing material properties and the limit solubility of Mg in Fe [2]. Friction stir spot welding is the natural competitor to resistance spot welding, and has been demonstrated to be feasible for both steel [3] and Mg-alloy [4] base materials.

During friction stir spot welding joints are produced by plunging and retracting a rotating tool comprising a pin and a shoulder into and out of the sheets being joined, leaving a keyhole region. Plasticized material formed at the periphery of the keyhole during the spot welding operation facilitates joint formation between the contacting sheets. No research papers have been published concerning dissimilar friction stir spot welding, particularly on joint mechanical properties when steel and Mg-alloy materials are involved.

Joints produced between dissimilar Al alloys during friction stir welding are characterized by the formation of microstructures comprising intermingled lamellae of the adjoining base materials [5-8]. The formation of a joint between the two materials depends on the formation of an intermixed zone at temperatures near the solidus of the materials, and involves the viscous flow of plasticized material immediately adjacent to the rotating tool and dynamic recrystallization [6-8]. Since the high temperature material properties of steel and Mg alloys differ so greatly, this mechanism of intermixing is precluded during dissimilar friction stir spot welding of these materials [9,10].

In the present work friction stir spot welding of AM60 magnesium alloy to DP600 dual phase steel is examined, where the AM60 sheet is the top layer. The intent of this configuration was to examine the feasibility of producing a joint via the extrusion of steel material from the bottom sheet into the AM60 layer during tool penetration, which has been referred to as the development of a ‘hook’ structure [11]. The failure loads and fracture mechanisms of dissimilar joints were examined with different tool rotation speeds and welding times.

EXPERIMENTAL

The 1.2 mm thick AM60 material thixomolded material had a microstructure comprised primary α-Mg grains surrounded by α-Mg plus Mg17Al12 eutectic, and had a chemical composition of 93.5%Mg, 6%Al, and 0.5%Mn, all in wt%. The DP600 steel was 1.2 mm thick and had a microstructure consisting of martensite islands in a ferrite matrix. The steel sheets had a chemical composition of 0.1%C, 1.523%Mn, 0.195%Mo, 0.197%Cr, 0.156%Si, and were Zn coated. Details of the base material microstructures are available elsewhere [3,12].

The friction stir spot welding equipment used in the present study provided tool rotational speeds of 2000 and 3000 RPM, while a servomotor provided axial loads up to 12 kN. The friction stir pot welding tool was machined from W-25Re alloy. The spot welding tool had a shoulder diameter of 10 mm, a pin diameter of 4 mm and a pin length of 1.6 mm. Plunge rate during welding was 1.25 mm/s, with a minimum penetration of the pin by 0.4 mm into the lower steel sheet. When the rotating pin was fully penetrated into the overlapping sheets the welding cycle was extended by incorporating a dwell time of 0.5 or 2 seconds. The tool rotational speed remained constant while axial force and torque decreased during the dwell period. Due to machine compliance the rotating tool penetrated further into the upper sheet during the dwell period. At the end of any selected dwell period the rotating tool was retracted.

During spot welding the tool penetration (displacement) was measured using a linear transducer with an accuracy of ±0.01 mm while the axial load and torque were measured using a JR3 six-axis load cell, which was coupled to a data acquisition system. The key parameters (axial force, torque, rotational
speed, pin displacement, shoulder and pin temperature) were logged on a desktop computer during all spot welding trials.

Joint mechanical properties were evaluated by measuring the fracture load during overlap shear testing using a loading rate of 1 mm/minute. All mechanical test specimens had dimensions 25 mm x 75 mm, and a minimum of five samples was tested for each welding condition. Great care was taken to make sure that co-planar alignment was maintained during mechanical testing of all test samples. Mechanical testing was halted on two samples and the partially failed specimens were examined using SEM microscopy. During metallographic examination the test sections were etched using 3 vol.% nital solution for 3 seconds which preferentially etched the AM60 material.

RESULTS

An optical macrograph of the AM60/DP600 sheets friction stir spot weld using 3000 RPM and a 2 s dwell time is shown in Figure 1. The axial forces during spot welding caused an annulus of DP600 material to be extruded around the pin and displaced into the upper sheet of AM60 magnesium during spot welding. The location marked Region A was examined using SEM, see Figure 2. During penetration of the tool pin, DP600 steel was extruded and displaced upwards around the pin and flowed into the upper sheet of AM60 magnesium. The horizontal interface between the sheets remained unbonded following spot welding. Bonding between the materials only occurred along the interface formed by the DP600 material vertically displaced into the AM60 sheet, and no crevices or gaps could be observed along this interface. EDX analysis of the bonded interface in Figure 2 suggested the formation of a mechanical bond between Mg and Fe, and no intermetallic phases were detected at the interface.

Figure 1 – Optical micrograph of friction stir spot welded AM60/DP600 sheets produced using 3000 RPM and 2 s dwell time.

Figure 2 – SEM micrographs from Region A in friction stir spot welded AM60/DP600 sheets produced using 3000 RPM and 2 s dwell time.
The fracture loads during overlap shear testing of spot welds produced using 2000 and 3000 RPM with dwell times from 0.5 to 2 s are shown in Figure 3. Increasing the tool pin penetration resulted in a larger volume of DP600 material being displaced into the upper AM60 sheet, which increased the bonded area between the two materials.

Figure 3 – Fracture loads during overlap shear testing of dissimilar AM60/DP600 spot welds produced using tool rotation speeds of 2000 to 3000 RPM, and dwell times from 0.5 to 2 seconds. Error bars indicate one standard deviation above and below the average value.

Several eutectic phases containing Mg and Zn were found embedded within the AM60 top sheet and outlining grain boundaries in Region A, see Figure 4. During the spot welding process, the Zn coating on the surface of the DP600 steel formed eutectic phases when it contacted the Mg in the upper sheet of AM60 at high temperature. EDX analysis of eutectic phases shown in detail in Figure 4 indicates these regions are consistent with Mg+MgZn eutectic.

Figure 4 – SEM micrographs of Mg-Zn eutectic phases in friction stir spot welded AM60/DP600 sheets produced using 3000 RPM and 2 s dwell time. EDX analysis from location B was: 54.3% Mg, 44.9% Zn and 0.8% Fe, all in wt%.

During mechanical testing, the fracture in all samples propagated through the AM60 magnesium alloy material. A micrograph of a partially failed mechanical test specimen made using 2000 RPM and 2 s dwell time is shown in Figure 5. The fracture propagated entirely through the AM60 material in the upper sheet. It is also apparent that there is much less DP600 material vertically displaced into the AM60 sheet when using 2000 versus 3000 RPM during welding (see Figures 1 and 5) when a constant dwell time of 2 s is applied. There is no indication that the Mg+MgZn eutectics formed near the bonded region have an influence on the fracture during mechanical testing. It should be noted that a significant number
of tungsten-rich particles originating from the spot welding tool were entrained in both of the sheets of the dissimilar joint.

![Image of SEM micrographs](image_url)

Figure 5 – SEM micrographs from the bonded region in a partially failed AM60/DP600 dissimilar friction stir spot weld made using 2000 RPM and 2 second dwell time. EDX of Location C was: 97.6% W, 1.2% Mg, 1.2% Fe, all in wt%.

**DISCUSSION**

It has already been shown that increasing the tool rotation speed or dwell time during friction stir spot welding will result in higher tool penetration during the dwell period [13]. The relationship between fracture load and bonded area in friction stir spot welded sheets is well understood [3,14]. As a result, it is not surprising that the highest fracture loads were obtained using 3000 RPM and a 2 s dwell time, since these conditions are also expected to have the largest bonded areas of the three conditions tested.

The displacement of material from the lower sheet to the upper sheet during dissimilar friction stir spot welding has already been observed during welding of Al 6111 aluminum alloy to AZ91 magnesium alloy [15]. During Al/Mg dissimilar friction stir spot welding, the formation of α-Mg plus Mg₁₇Al₁₂ eutectic controls the peak temperature obtained during spot welding and the material properties of the final joint. For example, it was shown that even a small quantity of α-Mg plus Mg₁₇Al₁₂ eutectic has a detrimental effect on mechanical properties of Al/Mg alloy dissimilar joints [14]. In the case of AM60/DP600 dissimilar spot welds there is no eutectic formed at the interface, and the sheets are bonded by a mechanical joint which interlocks the two sheets together. The Zn coating on the DP600 base material facilitates the formation of a Mg-Zn based eutectic near the bonded region, however this eutectic does not influence the fracture mechanism or failure load during mechanical testing. These eutectic regions did not play a role during fracture since eutectics were not aligned and located away from the fracture initiation point.

The microstructure of the eutectic regions was primarily globular, with some regions organized into lamellae, see Figure 4. This microstructure suggests that the Mg+MgZn eutectic melted during spot welding, which would indicate that the temperature in this region exceeded 325°C [2]. The majority of testing during friction stir spot welding has indicated that the peak temperature is limited by either the solidus of the alloy in question or by spontaneous melting of intermetallic particles contained in the as-received base material [16]. It is also well known that the temperature gradients produced at a sliding interface during friction stir spot welding may exceed 1000°C/mm [17,18]. Based on these findings, one might expect that the peak temperature during AM60/DP600 dissimilar friction stir spot welding would be close to the peak temperature during spot welding of AM60, namely 500°C [12]. This readily accounts for the formation of melted Mg+MgZn eutectic material in the welded joint.

As in the case of friction stir seam welding of steel alloys, tool wear is a major concern during friction stir spot welding of dissimilar AM60/DP600 materials. To address the issue of tool wear, polycrystalline cubic boron nitride (PCBN) tools have been developed for friction stir spot welding of...
steels which could survive over one hundred trials without noticeable degradation [19]. It is apparent from Figure 5 that some degree of wear has occurred during testing using the W-25Re tool material, however the mass loss could not be detected over the limited number of tests. Since some degree of wear has also been observed during friction stir seam welding using PCBN tools [20], further study is needed to examine the cost to benefit ratios and longevity of different tool materials.

CONCLUSIONS

Friction stir spot welding of AM60 magnesium alloy to DP600 steel is feasible using a tungsten-rhenium alloy tool with the sheets oriented with AM60 as the upper sheet. A mechanical bond was formed by displacing the lower sheet of DP600 material into the upper AM60 sheet. The overlap shear fracture loads of the joints were tested for joints produced using settings from 2000 to 3000 RPM, and dwell times of 0.5 to 2 s. The highest joint fracture loads were obtained when the highest tool rotation speed and dwell time were used, and fractures occurred consistently through the AM60 upper sheet. The Zn coating on the DP600 base material facilitated the formation and melting of Mg+MgZn eutectic, however the presence of this material did not influence the fracture propagation during mechanical testing.

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REFERENCES