Magnesium Technology *Edited by A. Lou*
TMS (The Minerals, Metals & Materials Society), 2004

FRICTION STIR WELDING OF MAGNESIUM AM60 ALLOY

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ABSTRACT

An investigation has been carried out on the friction stir welding of magnesium alloy, AM60. Casting samples have each been welded and their mechanical properties were presented. The microstructure and defect formation were conducted by optical and scanning electron microscopes. More attention was paid to failure mode of welded pieces near joined area or so-called thermo-mechanical affected zone under tension and voids formed during friction stir welding. In addition, the effect of FSW processing parameters and casting thickness on the mechanical properties will be presented. At the end, a cost analysis using friction stir welding for magnesium application on the Ford GT vehicles will be presented.

INTRODUCTION

The use of magnesium has grown considerably in the past ten years, and continues to rise in the automotive industry. This is mainly attributed to the lightness of magnesium - one-third lighter than aluminum, three-fourths lighter than zinc and four-fifths lighter than steel. Magnesium also has the highest strength to weight ratio of any of commonly used metals. Moreover, many other advantages of magnesium, e.g. good castability, high die casting rates, electromagnetic interference shielding properties, parts consolidation, dimensional accuracy, and excellent machinability promote its utilization in the automotive industry. For example, die cast magnesium components which have been used for applications include instrument panel crosscar beams, door inners, transmission housings, pedal brackets, integral seat frames and wheel hub cover components. Equipped with these characteristics, magnesium provides opportunities for the automotive industry where weight reduction, fuel economy, and environmental friendliness of vehicles are increasingly demanded to a great extent.

Despite good castability of some Mg alloys such as AZ91D and AM60B, it is not always possible or economically viable to cast complex magnesium parts. Joining of different types of magnesium alloys or dissimilar materials is essential to enable the economic manufacturing of complex parts and structures. Among various joining methods, we focus on welding or more specific, Friction Stir Welding (FSW). Mechanical fastening or adhesive joining is not the subject of this paper. The principal technical challenge to the wide-spreading use of magnesium alloys in structural applications is to produce economical and reliable high quality joining which provides continuity of structural integrity between components in a fabricated structure. Loss of strength and any hindrance to the smooth flow of stresses across a joint are to be minimized.

The paper includes a short description of the key features involved in the joining of magnesium alloy, AM60B using the Friction Stir Welding techniques. Since FSW provides solid-state joining rather than fusion welding, more attention was paid to failure mode of welded pieces near joined area or so-called thermo-mechanical affected zone under tension and voids formed during friction stir welding. In addition, the effect of FSW processing parameters on the mechanical properties of AM60B will be presented.

EXPERIMENTAL PROCEDURE

FSW Process

Friction stir welding (FSW) is a relatively new solid state joining method [1] that is now well established for the production of very high quality welds of aluminum alloys. The process is accomplished by using a rotating, non-consumable tool that is translated along the length of a joint as illustrated schematically in Figure 1. It relies on the rotating welding head to produce heating and deformation that create a solid-state bond. This process requires no supplemental energy input, nor melting of bulk materials. In principal, FSW can be used to join many types of similar and dissimilar material combinations provided that tool/head can be developed to operate compatibly in the hot working temperature range of the workpieces.

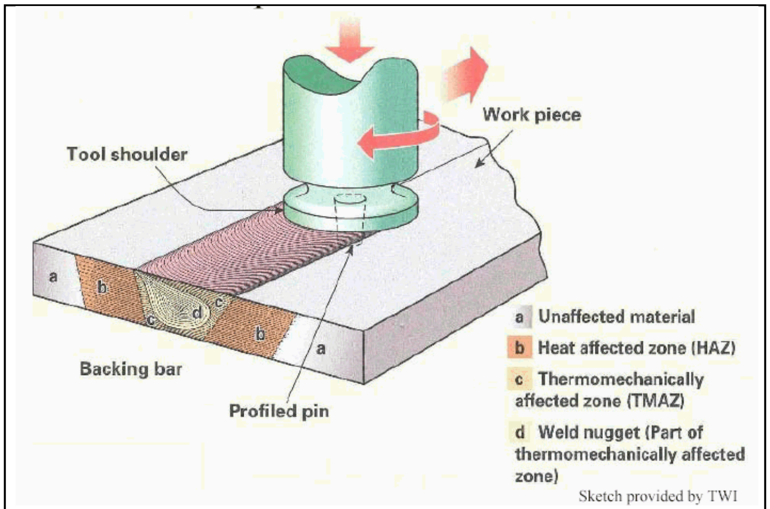

Figure 1. Schematic of friction stir welding.

Because melting is avoided, FSW also has potential for bonding many materials that are difficult or impossible to weld by more conventional methods, including alloys that are susceptible to solidification cracking, high-strength steels, metal-matrix composites, and other advanced alloys. For many conventionally welded aluminum alloys the fusion zones are typically weaker than the base metal. However, FSW offers a significant quality advantage that it is possible to make welds where the strength of the fusion zone is identical to that of the base metal alloy. Additionally, because the energy input used for FSW is relatively low (no melting occurs), the heat-affected or thermomechanically affected zones (TMAZ) and residual stresses associated with the welds are relatively small. Minimizing the weld heat-affected zones reduces concerns about property gradients across the weld joints. Lower residual stresses mean that distortion associated with FSW is not as large a concern as for conventional welding.

Friction stir welding of magnesium has not been studied as extensively as aluminum, but some have been reported [2,3,4,5]. Nagasawa, et al [2,5] FSW'ed 6-mm AZ31 plates with a rotational speed of 1750 rpm and a transfer speed of 88 mm/min, and found out that the mechanical strength of the weld was comparable to the base material but with only half of the ductility. The highest measured temperature was 460^{o}C, showing a true solid state process. Park, et al.[3] also studied the FSW on 6-mm AZ31 plates at 1220 rpm and 90 mm/min, which showed a much lower yield strength, and elongation, and a slightly lower ultimate tensile strength of the weld from transverse tensile test compared with the base material. With a micro-texture analysis, they concluded that a heterogeneously distributed (0002) basal plane contributed to the changes in the mechanical properties.

Nakata, et al.[4] studied the optimal processing conditions for FSW of 2-mm AZ91D thixomolded sheet. An increase of 38~50% of the tensile strength in the weld could be obtained over base material with rotational speed between 1240 to 1750 rpm and a transfer speed of 50 mm/min. They contributed the increase of strength to the fine recrystallized structure of 2~5 μm grain sizes.

<u>Experiment and Test Conditions</u>

Friction stir welding was conducted on a custom-built machine, made by MTS, at Oak Ridge National Laboratory, shown in Figure 2. The machine is capable to offer simultaneous force-controlled (or displacement controlled) operation of three independent axes with adjustable adaptable pin tool for on-the-fly mode switching between fixed, adjustable and self-reacting welding mode. It also handles computer controlled operations and key process parameter monitoring with the capability of making non-linear, variable thickness, and double curvature weld. The machine welding speed, for aluminum application, is up to 2000 mm/min while weld thickness varies from 1 to 40 mm. For this case, the friction stir welding tool was made of H13 tool steel where the shoulder diameter is of 0.75” and a threaded pin of 0.25” in diameter. The length of the pin was 0.185”, slightly shorter than the thickness of the magnesium casting plates to be joined.

Figure 2 Friction stir welding machine at Oak Ridge National Laboratory.

Two process speed conditions were used for this study: rotating speed of 375 and 450 rpm, respectively with transfer speed at 152.4 mm/min. These process conditions didn't involve any optimization work which will be addressed in a separate paper.

The magnesium casting plates of AM60B were produced by 700 Ton cold chamber casting process at Spartan LMP. The casting plate size each before welding was 127 x 25.4 x 6 mm and two plates were FSW butt joined along its long dimensions to form a specimen as shown in Figure 3. For sake of automotive applications, these casting plates joined with as-cast surface conditions. In other words, there is no sample cleaning or polishing before FSW. During the FSW, there is no shrouding gas applied at all.

Figure 3. Specimen geometry after FSW two casting plates.

RESULTS

A series of welding tests confirm the reproducibility of the FSW welds. Constant quality was achieved over the entire length of the weld as shown in Figure 3. There is little spatter adhering to the surface; consequently, final surface finishing is necessary. Certainly the spatter can be minimized once the specimens experience optimized welding conditions with the combinations of rotational speed, moving speed, and casting geometry and properties, etc.

The macroscopic photo in Figure 4 shows a transverse section of the weld joint where the pore forming tendency is macroscopically detectable regardless the welding speed. One of the contributors is the higher gas content in the base metal which is usually experienced in high pressure die casting process. However, in this case, there is no appreciable impairment of the mechanical properties due to the distribution and size of the pores. As contrary, the weld sometime exhibits slightly increase of the mechanical properties due to the re-distributing post-casting metal in the welding pool. This conclusion is confirmed by the tensile tests described in the followings.

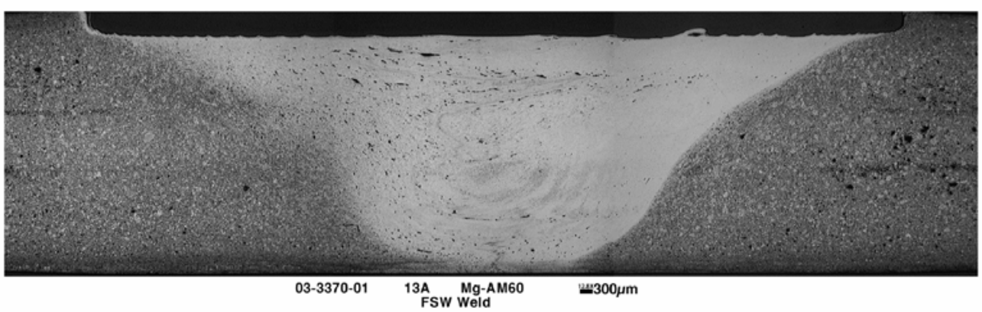

Figure 4. Transverse section of two FSW casting plates of AM60B.

For determining the strength of the welded joint, the test samples, according to ASTM B557 specifications, were taken from the middle of the specimen as shown in Figure 5. Two groups of FSW butt-jointed specimens were fabricated, namely M1 and M2 longitudinal, respectively. While both groups carry the same tool transfer speed at 152.4 mm/min, the group M1 is associated with a tool head rotational speed of 375 rpm and the group M2 links to a higher rotating speed of 450 rpm.

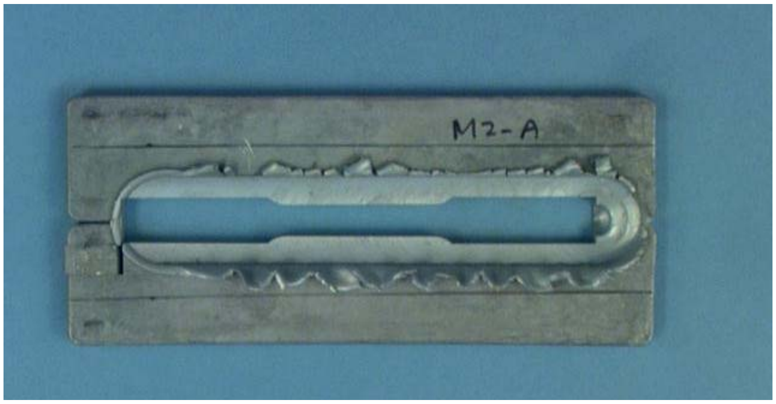

Figure 5 Longitudinal tensile sample per ASTM B557 subsize specimen

The tensile strength of the base metal is thereby compared with the strength values for the welds from the same batch shown in Figure 6 while the ductility values are presented in Figure 7.

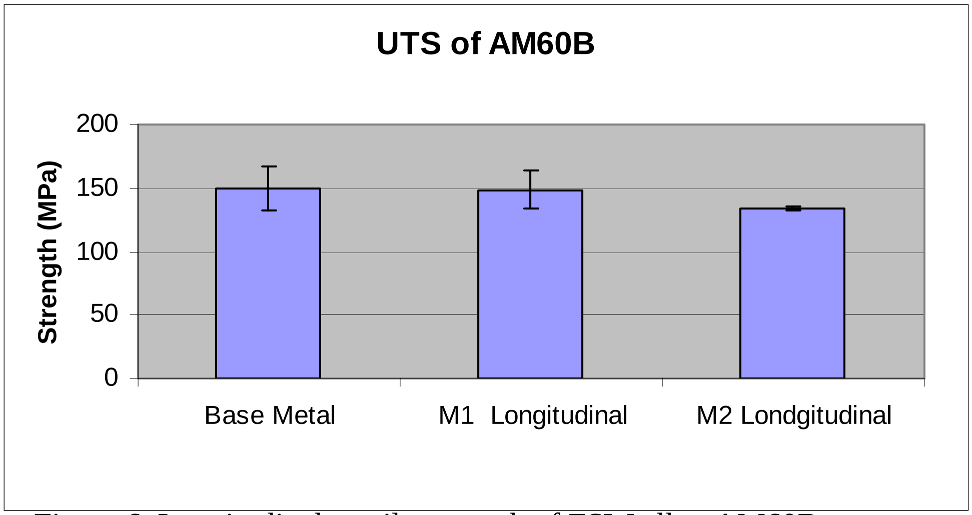

Figure 6 Longitudinal tensile strength of FSW alloy AM60B

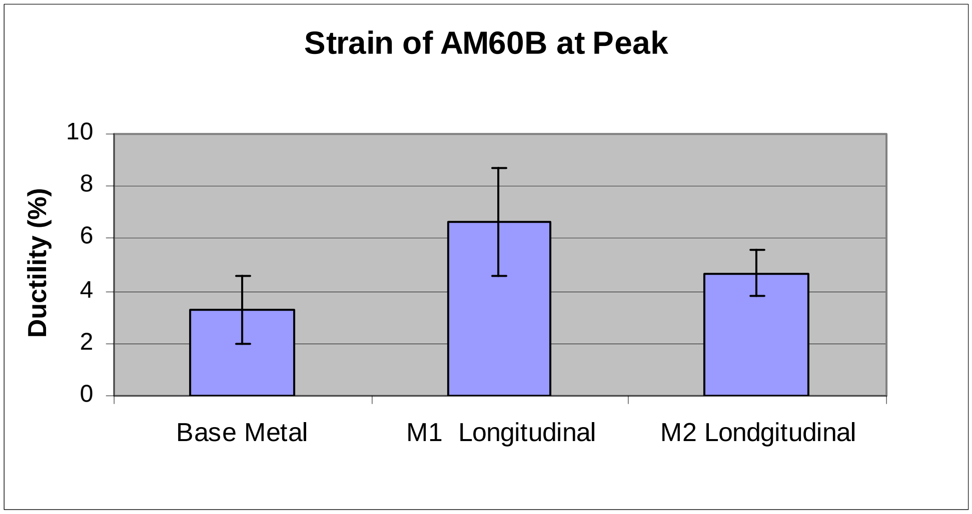

Figure 7 Longitudinal ductility of FSW alloy AM60B

CONCLUSIONS

A brief investigation has been carried out on the friction stir welding of magnesium alloy, AM60B. High pressure die casting samples have been butt-jointed at different rotational speeds and their mechanical properties of strength and strain were presented. In this study, FSW offers a quality advantage that leads the welds strength and ductility either identical or better than that of the base metal alloy. For automotive applications with FSW techniques, particularly for the 2005 Ford GT, however, further investigations must be conducted to meet the design and performance requirements of light-weight metal construction. In addition, it's important to apply the system engineering approaches to develop a cost-effective automated welding process for automotive production.

ACKNOWLEDGEMENTS

The authors would like to take this opportunity to thank Oak Ridge National Laboratory for sample preparations and acknowledge the generous support from the management in Manufacturing & Processes Dept, Ford Research & Advanced Engineering, Ford Motor Company. This research was in part sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of FreedomCAR and Vehicle Technologies, as part of the High Strength Weight Reduction Materials Program, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

REFERENCES

1. W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith, C.J. Dawes, "Friction welding", US Patent 5460317 A, The Welding Institute, Issued Oct. 24, 1995.
2. T. Nagasawa, M. Otsuka, T. Yokota, T. Ueki, "Structure and Mechanical Properties of Friction Stir Weld Joints of Magnesium Alloy AZ31", in "Magnesium Technology 2000", pp. 383-387, TMS, Warrendale, PA, 2000.
3. S.H. C. Park, Y.S. Sato, H. Kokawa, "Texture Effects on Tensile Properties in Friction Stir Weld of a Magnesium Alloy AZ31", Proceedings of 4th International Friction Stir Welding Symposium, Park City, Utah, May 14-16, 2003.
4. K. Nakata, S. Inoki, Y. Nagano, T. Hashimoto, S. Johgan, M. Ushio, "Friction Stir Welding of AZ91D Thixomolded Sheet", Proceedings of 3rd International Friction Stir Welding Symposium, Kobe, Japan, September 27-28, 2001.
5. Nagasawa, M. Otsuka, "Structure and Mechanical Properties of Friction Stir Weld joints of Magnesium Alloy AZ31", master thesis, Shibaura Institute of Technology, Tokyo, Japan, 2000.