MICROSTRUCTURE AND RESIDUAL STRESS FORMATION
IN AN AA6040 TO AZ31B FRICTION STIR WELD

R.S. Coelho\textsuperscript{1,2}, A. Kostka\textsuperscript{2}, H. Pinto\textsuperscript{2}, A. Rothkirch\textsuperscript{3}, J. Dos Santos\textsuperscript{4} and A.R. Pyzalla\textsuperscript{1,2}

\textsuperscript{1}Now at Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, D-14109, Berlin, Germany
\textsuperscript{2}Max-Planck-Institut für Eisenforschung GmbH, D-40237, Düsseldorf, Germany
\textsuperscript{3}HASYLAB at DESY, D-22607, Hamburg, Germany
\textsuperscript{4}GKSS Forschungszentrum Geesthacht GmbH, D-21502, Geesthacht, Germany

ABSTRACT

The microstructure and residual stresses of an AA6040 Al to AZ31B Mg friction stir weld are studied using scanning electron microscopy and X-ray diffraction. The complex material flow promoted by the friction stir welding process results in a fine grained structure in the stir zone of both materials due to dynamic/recovery recrystallization. The interface between the materials is characterized by the presence of intermetallic phases which likely consist of Al\textsubscript{12}Mg\textsubscript{17} and Al\textsubscript{3}Mg\textsubscript{2}. The residual stress distribution has the typical “M-like” profile common in friction stir welding processes.

INTRODUCTION

Lightweight construction increasingly incorporates hybrid systems, which require the development of adequate joining techniques associated with low heat input. In most dissimilar alloy systems, conventional fusion welding promotes the liquation of low melting point constituents, thus compromising the performance of the joined component due to the formation of brittle intermetallic phases.

Based on extreme plastic deformation in the solid state, friction stir welding (FSW) has rapidly become an important process for joining dissimilar alloys. Developed at The Welding Institute (TWI) of UK in 1991 [1], FSW has many advantages compared to fusion welding techniques, such as defect-free welds, low distortion, and good mechanical properties [2-4]. In FSW a rotating cylindrical tool promotes complex mechanical mixing of the base materials (BM) and involves dynamic recrystallization (DRX) in the stir zone (SZ) [5,6]. The process is now well established, particularly for materials difficult to join by fusion techniques, such as Al alloys.

Mg and its alloys, the lightest available construction metals, are attractive as replacement for Al alloys and, in combination with them, for specific structural applications [7-9]. Diverse studies have recently reported the potential of joining Al alloys to Mg alloys by means of FSW [10-13]. However, the formation of brittle intermetallic phases and residual stresses invariably cause inferior mechanical properties of dissimilar joints. The microstructure and residual stresses (RS) in dissimilar FSW of Al to Mg alloys thus deserve particular attention to allow for optimizing the process parameters as well as controlling microstructure and the resulting properties of the joints.

Therefore, the present study aims at elucidating the mechanisms of microstructure and residual stress formation in the SZ and thermomechanically affected zone (TMAZ) of dissimilar FSW of Al to Mg alloys. The microstructure investigations involve scanning electron microscopy (SEM) equipped with electron backscattered diffraction (EBSD). Synchrotron X-ray diffraction was applied to characterize the distribution of intermetallics and RS within the welded area.
This document was presented at the Denver X-ray Conference (DXC) on Applications of X-ray Analysis.

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EXPERIMENT

Materials and welding procedure

The FSW was applied to join dissimilar 2 mm thick plates of AA6040 Al alloy to AZ31B Mg alloy (size: 300 mm x 100 mm x 2 mm) at GKSS Research Center Geesthacht, Germany. The welding setup is presented in Figure 1 with the AZ31B Mg alloy taking place on the advancing side of the process. The main FSW parameters were: rotation speed 1400 rpm; travel speed 225 mm/min; down force 5.5 kN and tool tilt 2.5°. A welding tool consisting of a 13 mm diameter shoulder and a 5 mm cylindrical threaded pin was selected for this study, and the joint was manufactured using a Tricept TR805 robot equipped with a vacuum clamping (the clamping forces are indicated by black arrows in Figure 1).

Figure 1. Sketch of the FSW butt-joint configuration applied to join AA6040 Al alloy to AZ31B Mg alloy.

Microstructure analyses

Microstructure and local texture investigations were conducted using scanning electron microscopy (SEM) in combination with electron back scattered diffraction (EBSD), Zeiss Neon 40 field emission gun SEM equipped with the Hikari EDAX/TSL EBSD and a Jeol Jsm-6490 Tungsten filament SEM equipped with the Pegasus EDAX/TSL EBSD. The specimens for SEM characterization were sectioned, ground, polished, and cleaned using 5% Nital solution. For the EBSD experiments different metallographic procedures were applied to obtain a good diffraction pattern quality of the AA6040 Al alloy. Additionally, the specimens were electropolished.

Complementary microstructure analysis using X-ray diffraction

Additional microstructure characterization was conducted applying synchrotron X-ray diffraction at the experimental station G3 / HASYLAB / DESY in Hamburg, Germany. The analysis was made with the MAterial X-ray IMaging (MAXIM) camera [14], a charge couple device (CCD) detector for spatially resolved measurements using a wavelength of ~1.79 Å (energy ~6.9 keV). The incident beam direction was chosen parallel to the joint to obtain best spatial resolution in a direction perpendicular to the joint direction. The camera instrument applies an array of parallel collimator tubes in front of its CCD (1024*1024 pixel, 13x13 μm² pixel size) to suppress crossfire of radiation diffracted from different locations of the specimen [15]. Single diffraction images were taken at a fixed sample inclination $\omega = 10^\circ$ for different diffraction peaks of Mg and Al. Moreover, a $2\theta$ scan at $\omega = 10^\circ$ was taken within a range from 41.5° to 42.7°. The single images taken at different diffraction peaks were resampled to account for projection and each image of the $2\theta$ scan was averaged parallel to the joint direction, i.e. the image stack was reduced to 2 dimensions (position perpendicular joint, 2$\theta$) to improve statistics.
Residual stress analysis

Residual stress (RS) investigations were also conducted at the experimental station G3, using a scintillation detector behind a radial divergence limiting collimator. The $\sin^2 \Psi$ technique [16] was applied to the measurements on the top and bottom side of the dissimilar butt-joint welded specimen. The measurements were carried out with a radiation energy of 6.9 keV, beam size of 1.5 mm x 1.5 mm, $\sin^2 \Psi$ range of 0-0.8, step size 0.2 in $\sin^2 \Psi$, using the Mg(112) and Al(311) reflection.

RESULTS AND DISCUSSIONS

Microstructure

SEM investigations of the cross-section (Figure 2) show the absence of defects (macro-pores and cracks) in the welded area. In contrast to the lower part of the joint cross-section, the examination reveals a heavy plastic deformation at the upper part. The substantial deformation heating and pressure promoted by the shoulder movement during the welding process confines the materials within the weld region, causing differences in flow stress along the sample thickness which endorses the appearance of a plastic deformation gradient.

![Cross-section SEM micrograph of the friction stir welding zone. AZ31B Mg alloy placed on the advancing side and AA6040 Al alloy on the retreating side of the weld.](image)

A close view from the interface area shown in Figure 2 is given in Figure 3a, complemented by energy dispersive X-ray data (EDX) (Figure 3b and 3c). Obtained results show the mixing of both materials and presence of the chemical gradient on the interface resulting from mechanical bonding/interdiffusion of the components (arrows).

![A close view of the cross-sectional upper part area selected in Figure 2 (a) and the EDX analysis of both element distributions (green for Al alloy (b) and red for Mg alloy (c)).](image)

Figure 4 shows the inverse pole figure maps of the areas indicated in Figure 2. The quantitative microstructure analyses focused on the BM and the welded regions: heat affected zone (HAZ), TMAZ, and SZ.
**AA6040 Al alloy side:** Figure 4a shows the transition of BM to the TMAZ. The BM shows occasional large grains (average grain size of about 50 µm ± 20 µm), and the location of the interface between the BM and the HAZ is not evident. The deformed grains shown in the upper part of Figure 4a represent the TMAZ. Figure 4b shows the transition TMAZ (average grain size of about 2 µm ± 0.5 µm) to the SZ (average grain size of about 0.5 µm ± 0.2 µm) where a gradient of grain sizes occurs. Due to the strong plastic deformation in the vicinity of the pin in the TMAZ, various stages of subgrain development can be observed. A change in texture is also observed crossing the BM towards the TMAZ, which is connected with the heavy plastic deformation and occurrence of DRX [17-21].

**AZ31B Mg alloy side:** Figure 4c shows the SZ which is characterized by the presence of bands with different crystallographic orientations due to the heavy plastic deformation and DRX. The average grain size is approx. 4 µm ± 1 µm.

![Figure 4. The EBSD analysis of the AA6040 Al alloy showing the transition BM-TMAZ-SZ (a and b) and the AZ31B Mg alloy SZ (c).](image)

**Phase composition**

A high resolution analysis of the joint interface reveals evidences of two intermetallic phases (Figure 5a). The results also show that these intermetallics appear to grow towards the AA6040 Al alloy side which is in agreement with the analysis presented in Figure 3. Additionally, EDX analyses presented in Figure 5b show the concentration of the Mg and Al across the interface of both materials. Early investigations have demonstrated that the intermetallic compounds Al$_{12}$Mg$_{17}$ and Al$_3$Mg$_2$ form during diffusion bonding [22,23] according to the binary Mg-Al phase diagram [24].
Figure 5. Cross-section SEM micrograph of the friction stir welding interface area (a). Plot (b) gives the concentrations of Al and Mg across the interface, obtained from EDX analyses.

The spatial phase distribution within the welded area was assessed by X-ray diffraction on top of the joint. Single diffraction images were taken at a fixed sample inclination $\omega = 10^\circ$ for the Mg(100), Mg(101), and Al(111) reflections, see Figure 6a, 6b, and 6c, respectively. The analysis using methods known from remote sensing [25,26] allows the visualization of the BMs by deducing the location of the welded area. Additionally, it provides a basis for comparison with the microscopic investigations. The results show coarse grains in both of the alloys’ BM at a distance of several millimeters relative to the welded area (upper and lower parts of Figure 6b and 6c). Closer to the welded interface smaller structures are visible. A similar structure was observed in the microscopic investigations (see section Microstructure) and is mentioned in [27] as well. The lower intensity observed in Figure 6a compared with Figure 6b can be correlated with the indication of texture evolution as was also observed by microscopic investigations (see Figure 4c). Figure 6d shows the combined image of the different reflections in the RGB (Red, Green and Blue) scale in order to facilitate the visualization of the phase constituents.

The diffracted intensity measured on the welded area of $2\theta$ ranging from 41.5° to 42.7° is given as contour plot as well as in 3D in Figure 7. This $2\theta$ range covered the Mg(101) reflection and the strongest diffraction lines of the intermetallics. The analysis shows that three regions can be recognized in Figure 7a: AZ31B Mg alloy BM on the upper part, AA6040 Al alloy BM on the lower part and the transition zone in between. The Mg(101) reflection of the BM shows an increasing intensity with increasing $2\theta$. The AA6040 Al alloy BM shows no diffraction peak in the region scanned. In comparison to the AZ31B Mg alloy BM, it shows less diffuse scattering. In addition, the investigations reveal an area between ~5 mm and ~7 mm, which corresponds to the Al/Mg interface. In contrast to both BMs, it shows diffraction beginning at $2\theta \sim 42^\circ$, indicating the occurrence of one or more additional phases inside the weld: Al$_{12}$Mg$_{17}$ and Al$_3$Mg$_2$ (arrows Figure 7a and 7b). This confirms the qualitative evidence provided by EDX analysis (Figure 5).
Residual stresses

The RS investigations do not reveal significant differences in the longitudinal stresses of top and bottom of the joint (Figure 8). The transversal stresses, on the other hand, evolve a depth gradient characterized by tensile stresses on top and compression at the bottom which suggest the existence of a temperature gradient throughout the thickness of the welded area. This is in agreement with the microstructure inspections which reveal a non-equal partitioning of Al and Mg between the top and bottom sides (Figure 2).

In longitudinal direction (welding direction) (Figure 8a), the top side shows the typical “M-like” profile of FSW processes [2], however, slightly displaced to the AA6040Al alloy side. Since the aluminium alloy is located at the retreating side, this displacement can be attributed either to differences in thermal expansion or to the different forces which act in the advancing and retreating sides. The main heat input during FSW is assumed to be caused by the friction between the tool shoulder and the sample surface. Thus, the heat generation is no longer concentrated within a narrow line as during fusion welding, but rather spread throughout a broad region having the width of the tool shoulder diameter. The strongest temperature gradients are not expected to be in the center of the weld, but at the edges of the shoulder. This area is characterized by the highest tangential speeds of the tool and thus, also by the highest heat production rates. Therefore, the last regions to cool down are those at a distance from the weld center directly under the tool shoulder’s edge. Hence, the RS distribution after FSW can be seen as a superposition of two single-peaked profiles as observed after fusion welding with each
tensile RS maximum lying at one of the edges of the tool shoulder. As a result, two tensile stress maxima appear asymmetrically (dissimilar joint) displaced with respect to the weld centerline. The large variances observed analyzing the AA6040 Al alloy side can be correlated with the coarse grain structure presented in this alloy, which influenced the full width half maximum (FWHM) of the diffracted reflection peaks. Nevertheless, the maximum RS values correspond to less than one third of the yield strength of each analyzed materials.

Figure 8. Residual stress distribution throughout the weld centerline determined by Synchrotron radiation: top (a and c) and bottom side analysis (b and d).

CONCLUSIONS

The microstructure and residual stress distribution of a FSW of AA6040 Al to AZ31B Mg alloy were characterized. The study reveals:
- the absence of macro-cracks after welding process.
- a complex microstructure formation with evidence of dynamic/recovery recrystallization process in the SZ characterized by a fine grained structure.
- a strong gradient of grain size crossing the BM-TMAZ-SZ of the AA6040 Al alloy within various stages of subgrain development in TMAZ.
- evidences of \( \text{Al}_{12}\text{Mg}_{17} \) and \( \text{Al}_3\text{Mg}_2 \) intermetallic phase formation. These phases were observed at the interface between both materials and seem to grow into AA6040 Al alloy side.
- residual stresses of low magnitude and the typical “M-like” profile common for the FSW process slightly displaced to the AA6040Al alloy side.
ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Helmholtz Association of German Research Centers for its financial support by means of the virtual institute “Photon and Neutron Research on Advanced Engineering Materials” (VI-PNAM). HASYLAB at DESY is acknowledged for beam-time at instrument G3 at Doris, in particular Dr. T. Wroblewski. R.S.C. thanks to the Program Alßan – a European Union program of high level scholarship for Latina America – for its financial support (scholarship No. E04D046587BR).

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