Friction stir welding of dissimilar alloys – a perspective

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Friction stir welding does not involve bulk melting of the components that are joined. This has inspired attempts to exploit it for joining materials which differ in properties, chemical composition or structure, and where fusion can lead to detrimental reactions. The purpose of this special issue of *Science and Technology of Welding and Joining* was to assess the status of friction stir welding of dissimilar alloys and to identify the opportunities and challenges for the future.

Keywords: Friction stir welding, Dissimilar alloys, FSW

Introduction

Friction stir welding (FSW) has now become an important process in the joining of aluminium alloys and other materials which are soft relative to the material used as the tool for stirring the metal.[1–9] Since there is no macroscopic melting involved, the controls needed in fusion welding to avoid phenomena such as solidification and liquation cracking, porosity, and loss of volatile solutes can be avoided. These recognised advantages of solid-state joining[1] have led to attempts to use FSW for a wide range of alloys. A recent compilation of papers[10–19] was devoted to the joining of steels by FSW, but as yet there do not appear to be cost-effective tools which would enable the process to compete against the well-established fusion welding processes. The search for robust tools continues, but one of the papers in the compilation revealed a method which rather cleverly by-passed the issue.[18] A joint was made between aluminium and steel with the ordinary tool avoiding all contact with the steel. This focused our attention on the large activity throughout the world on the exploitation of FSW in the joining of dissimilar alloys,[20–25] especially with respect to joints between iron and aluminium-based alloys. Such joints arise in many scenarios including automotive, aerospace, and ship-building industries, where fusion welding simply is not appropriate given the chemical and mechanical incompatibilities between the components to be joined. It may, in some of these circumstances, be possible to bear the cost of expensive tools if no other solutions are available.

The generic issues to be faced include, for example, the different deformation behaviours of the dissimilar materials, the possible formation of detrimental intermetallic compounds, and differences in physical properties such as thermal conductivity. These factors and others contribute to the asymmetry in both heat generation and material flow[26–28] during FSW. Indeed, it is necessary to choose which side of the joint should contain the advancing or retreating part of the weld. The application of FSW to dissimilar alloys clearly poses a unique set of challenges.

The FSW of relatively soft combinations of alloys (e.g., Al/Mg) is of particular interest in aerospace and automotive applications although hard combinations have not achieved commercial viability. Recently Murr[29] has reviewed the FSW of a wide variety of dissimilar alloys and demonstrated that it is possible, on a laboratory scale, to friction stir weld aluminium metal matrix composites and other difficult materials not amenable to fusion processes. In many of these cases there are no alternatives available to friction stir welding.

The primary difference between the FSW of similar and dissimilar alloys is the discontinuity in properties across the butting surfaces, which has a large influence on the patterns of material flow during stirring. A change in the direction of tool rotation, causing a switch in the advancing and retreating sides, leads to complex spikes in the microhardness values.[29] It is well known that much of the material flow occurs along the retreating side and this review[29] illustrates the importance of plasticised materials flow patterns and dynamic recrystallisation in the stirred regions of similar and dissimilar welds.

The papers[30–38] in this issue of *STWJ* critically examine the current status, problems and opportunities for the friction stir welding of dissimilar materials. They cover a wide range of alloy systems including dissimilar aluminium alloys[31,32,37,38] aluminium/magnesium,[36] and aluminium alloy/steel pairs.[33,34] The joint configurations range from butt[30–33,38] to lap[34–37] to T-joints.[38] There is a wealth of data on process development,[30,34,38] welding variable windows for sound FSW welds,[30,32,35,36] mechanical properties,[31–34,36–38] microstructural and compositional characterisations,[30,33,34] material flow,[32] residual stress,[30] the role of intermetallic compounds,[36] work hardening,[33] and failure modes.[33,35,37]

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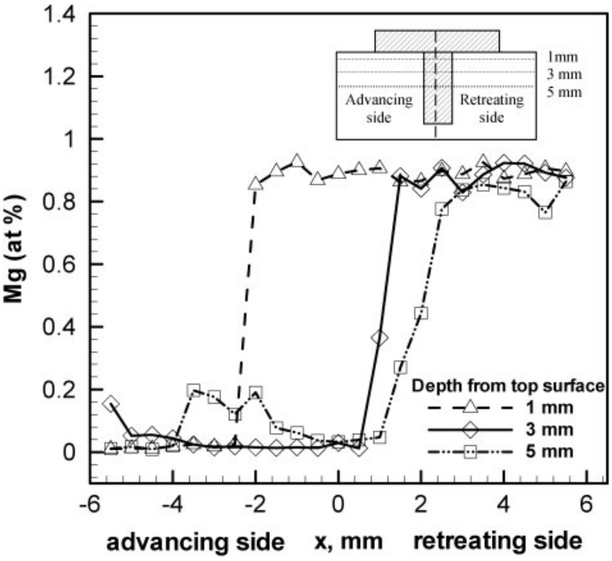
Contributions were invited from many authors based on their record of relevant publications using the commonly available electronic databases for scholarly journal publications. The papers that were received in a timely manner were peer reviewed in the usual manner. The editors thank all authors for their contributions and encourage further contributions or commentaries for the benefit of the welding community.

Papers in the special issue

Laboratory research on the FSW of dissimilar steels can provide significant scientific insight into the technology. Choi *et al.*[30] show that the placement of a stronger steel in the advancing side reduces the weld nugget size and increases the extent of martensite formation compared to placement in the retreating side. Since the temperatures are highest on the advancing side,[1,12,14] the location of a harder steel on the advancing side leads to higher temperatures and stress. The research[30] illustrates that the outcome of the FSW of dissimilar steels is significantly affected by the asymmetry in temperature and stress between the advancing and retreating sides. The extent of asymmetry depends on the properties of the two alloys and the welding parameters. Kumar and Kailash[31] showed that this asymmetry can be important even for dissimilar aluminium alloys that have much higher thermal conductivity than steels. They[31] compared the tensile strength and ductility of similar and dissimilar aluminium alloy FSW welds and showed that the position of the tool with respect to the original joint interface affects the strength and ductility of the joints. The optimal strength and ductility of the weld can be obtained only if the tool offset distance is optimised.

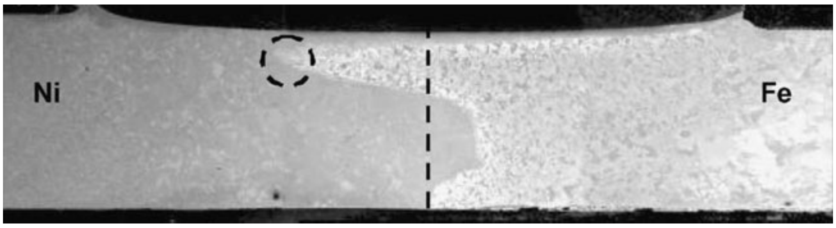
It is evident that an important aspect in the friction stir welding of dissimilar metals is the selection of the appropriate alloys for the advancing and the retreating sides to obtain optimum mixing and weld properties. The effects of placing aluminium alloys 5052 and 6061 on the advancing and retreating sides were evaluated by examining the concentration profiles of magnesium, yield strength along the and perpendicular to the FSW direction and the hardness profiles in a paper by Park *et al.*[32] They[32] found proper mixing when alloy 5052 was placed on the advancing side. In contrast, a thinner weld nugget and inadequate mixing occurred with 6061 on the advancing side.[32]

Karlsson *et al.*[24] showed that when joining copper with aluminium-5083, the weld contained isolated copper regions within the aluminium side of the nugget due to inefficient mixing. In a previous study, Nandan *et al.*[25] examined the concentration of magnesium during welding of AA 1200 (advancing side) and AA 6061 (retreating side). Their experimental data of the magnesium concentration in a transverse section at various depths from the top surface, across the weld centre-line are shown in Fig. 1. The interface between the two plates is identified by distance '0' in the x-axis. The results show that the concentration profile of magnesium depended on the distance from the shoulder. At 1 mm below the shoulder, the concentration of the magnesium was very close to that of the AA 6061 at the location of the original interface. At distances 3 and 5 mm below the shoulder, the concentrations of Mg were closer to that of AA1200 alloy at the location of the original interface. The alloy AA1200 was placed in the advancing side. The distribution of Mg is the result of asymmetric transport of the two plasticised alloys with most of the material flowing around the pin in the retreating side. A similar behaviour can also observed from Fig. 2 that shows iron and nickel regions in a transverse section perpendicular to the welding direction. Just below the shoulder, iron is present near the original interface. In contrast, further below the shoulder at about mid-thickness, the original interface region shows nickel which was placed in the advancing side. Thus, the distribution of Fe and Ni depends on both the distance from the shoulder and the original interface. In summary, both the experimental results of Nandan *et al.*[25] and Ayers *et al.*[39] clearly demonstrate that the transport of plasticised materials is fairly complex and the distribution of materials in the weld depends on the distances from the shoulder and the interface. In fusion welding, the alloying elements mix with the consumables on an atomic scale, driven by a strongly recirculating liquid metal flow in the weld pool. In contrast, during FSW, the results[24,25] demonstrate that the mechanical alloying does not lead to intimate mixing and true solid solutions do not form in bulk scale. One consequence is that welding variables need to be carefully controlled to avoid defect formation.



1 **Experimentally determined concentration profiles of magnesium at depths of 1, 3 and 5 mm from the top surface across the weld center-line for AA 1200 (advancing) and AA 6061 (retreating side) weld at 710 RPM and a weld velocity of 1·05 mms^{-1} (Ref 25)**

This is further emphasised by the work of Chen and Lin,[33] who examined the impact toughness of FWS welds between AA6061 aluminium alloy and SS400 low carbon structural steel. The need to optimise tool rotation speed, traverse speed, the extent of tool tilting and the tool pin diameter was clear. The high hardness in the weld region, exceeding that in the base materials, was attributed to work hardening. The failures in the optimised best welds occurred due to tough shear fracture whereas the other welds failed by a brittle cleavage fracture.[33]



2 A macrograph showing Fe and Ni regions in a transverse section to illustrate the complex transport of the two metals. The plates were 6·25 mm thick and Ni was placed in the advancing side. The vertical line shows the original interface and SEM/EDS map of the region within the circle showed considerable interdiffusion of Ni and Fe. Reprinted from Scripta Materialia, 53 by R. Ayer, H. W. Jin, R. R. Mueller, S. Ling and S. Ford, 'Interface structure in a Fe–Ni friction stir welded joint', 1383–1387, Copyright (2010), with permission from Elsevier (Ref 39).

Miles *et al.*[34] demonstrated a new approach to FSW of dissimilar alloys where a consumable bit was used to create a spot weld. The process has been demonstrated[34] for very soft and very hard alloys, like dual-phase (DP) 590 and DP 980 steels, and light alloys such as AA 5754. Like the conventional FSW process, the weld properties depend on the welding variables selected. The important variables include the design of the joining bit, its hardness, the nature of the alloys and the speeds and feed rates used. For the best welding conditions, the lap shear strength of the welds was better than that of self-piercing rivets and the FSW was capable of joining soft and very hard material combinations,[34] like AA 5754 and DP 980 steel.

Two papers[35,36] discuss the formation of eutectic during FSW. Chen and Nakata[35] investigated the effect of zinc coating on the weldability of low carbon steel with AZ31 Mg alloy. Their data[35] showed improved weldability of the alloy pair when the zinc coating was used. The failure loads were higher for the welds with zinc coated steel than those without the zinc. Based on microstructural and compositional studies, they[35] suggested that a low-melting eutectic phase forms at the interface during welding of the zinc coated steel. Expulsion of this low melting phase during welding leads to improved contact with fresh steel surface and enhanced diffusion between the magnesium alloy and steel leading to better welds.[35] Sato *et al.*[36] evaluated the lap shear strengths of FSW spot welds of AA5083 aluminium alloy and AZ31 magnesium alloy combination and examined the results with the help of microstructural characterisation of the weld region. Although intermetallic compounds are generally considered to be harmful, and Al_3Mg_2 was present in the welds in many cases, the lap shear strengths of the welds were adequate. Microstructural examination revealed that the Al_3Mg_2 intermetallic was sometimes embedded in a eutectic of α-Mg and $Al_{12}Mg_{17}$ and the welds had good lap shear strengths. Their research[36] illustrates the complexities of the FSW process and the need for detailed characterisation of welds prior to qualifying the welds for service.

In service performance of dissimilar metal FSW joints depends upon the loading conditions. The effects of loading conditions on the failure modes of dissimilar aluminium alloy FSW spot welds were examined by Tran and Pan.[37] They showed that the failure occurred at a much lower load during tensile loading than during shear loading.[37] Important experimental data on load carrying capacities and fatigue lives of these dissimilar aluminium alloy FSW welds are also presented in this work.[37]

Joint geometry is an important factor in the design of welds. Tavares *et al.*[38] compared the yield strength (YS), ultimate tensile strength (UTS), elongation and fatigue strength of FSW welds of dissimilar aluminium alloy butt joints and T joints. The yield and ultimate tensile strengths were similar for the two configurations whereas the elongation and fatigue strength were somewhat lower for the T-joints. Mechanical property characterisation is needed prior to commercial application of any weld configuration.

Concluding remarks

The literature on the FSW of dissimilar alloys including many recent papers[20–23,30–38] in *STWJ* provides a comprehensive picture of both the current status of the field and the opportunities and challenges for the future. Although friction stir welding has found many commercial applications in a relatively short time, most of the reported applications have been for the welding of both similar and dissimilar aluminium alloys. Expansion of the scope of its application to harder alloys will require the development of cost effective, wear resistant, reliable tools with adequate tool life, although there are a few ingenious configurations which avoid tool related issues.

Perhaps the most important need for the FSW of dissimilar alloys is for the joining of aluminium alloys with steels. Two papers[33,34] in this issue illustrate the factors involved in achieving this goal. A potential route to prevent rapid tool wear is to prevent any direct contact between the tool and the steel. Indeed, an interesting possibility explored in a paper[33] involves placement of a commonly used tool steel within the aluminium alloy a short distance away from the original aluminium alloy steel interface. However, the location of the tool must be carefully optimised and it is clear that sound welds are obtained in a very narrow window of welding variables. As we have noted before,[10] dealing with such a complexity involves a cost, and for every aluminium-steel combination, detailed exploratory work is necessary to determine the process window and joint configuration consistent with sound welds. Automation and control would be vital for achieving this goal because of the critical importance of the location of the tool pin with respect to the original interface between the two alloys.

An unusual application of FSW is in the joining of aluminium alloys with aluminium metal matrix composites.[29] This and other applications where traditional fusion welding process simply do not apply, provide a welcome opportunity to use FSW if the laboratory tests can be scaled up for practical uses which are cost effective.

In summary, significant progress has been made in understanding the problems and issues related to the friction stir welding of dissimilar materials. Much of the progress has been in better understanding of the physical processes of dissimilar alloy welding, and the structure and properties of various welds. However, cost effective and reliable welding of aluminium and other light weight alloys with harder alloys such as steels will require considerable further development. The need in the engineering industries for sophisticated materials tailored to accommodate demands for rigid, light weight structures may be powerful drivers for the further development of the friction stir welding of dissimilar materials.

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