JOINING OF ADVANCED MATERIALS

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Summary

Weldability has always played an important role in determining wider utilization of any material and component-manufacturing route. The newly developed materials generally require novel joining techniques. There has been a great advancement in alloy development over the last two decades concerning welding. Recent advancements in laser technology have made it possible for a range of materials to be welded. Solid state friction stir welding, developed at the beginning of 1990s, can be used successfully to weld Al-alloys, particularly higher strength precipitation strengthened grades, which are very difficult to weld using conventional fusion welding processes. Furthermore, new weldable materials grades have recently been developed, that is, low C, N, S, and P containing weldable steel grades for the offshore and pipeline industry. These newly developed supermartensitic stainless steels are cheaper than duplex or super duplex steels and much easier to weld owing to their very low C, N, and S contents.

Producing sound joints economically has always been considered a milestone in a research and development scheme for a new material. However, the microstructure–mechanical properties relationships for bonded or welded joints should be understood fully for widespread application of new materials. The three joining processes—diffusion bonding, friction stir welding, and laser beam welding—are considered in this literature review, since these processes are capable of joining a wide range of materials of interest in many industrial applications, and offer remarkable advantages over conventional fusion welding processes. Coverage includes friction stir welding of Al-alloys, joining of Mg-alloys, and supermartensitic stainless steels. The purpose of the review is to outline progress made in this area and to make suggestions for future work.

1. Introduction

Joining is a generic term, covering numerous processes such as welding, brazing, soldering, adhesive bonding, diffusion bonding, and mechanical fastening. One or more of these processes are used in the manufacturing of even simple products (for example, kitchen knives in which wooden handles are attached to the blade with metal fasteners). The role of joining is more important in the production of more complex objects such as automobiles or aircrafts, consisting of numerous components made of different materials that are assembled by a joining processes.

Joining processes may be classified according to the use of filler materials in the joint, the extent to which external heating and/or pressure are utilized, and the state of the materials being joined. Solid state joining processes do not utilize filler materials. The joint is developed through external pressure and heat source, supplied externally such as in diffusion bonding, or developed internally such as through friction in friction welding. Liquid-state processes, such as oxyfuel, arc, and resistance welding, involve fusion: that is, partial melting of the materials to be joined. These processes require application of heat, such as in oxyfuel and arc welding, and/or pressure, such as in resistance welding. The source of heat may be chemical, electrical, or optical (such as lasers). Recent trends and developments in the joining of materials are discussed in this publication.

Recent developments in laser technology and friction stir welding allow significant reductions in weight of structural components by the ability to produce well-designed joints avoiding overlapping. This results in a reduction in fuel consumption in both the transport and aerospace industries. Friction stir welding has proved quite reliable to produce sound butt joints in Al-alloys that are difficult to fusion weld. This solid state joining process (as well as diffusion bonding) can be used successfully in the joining of difficult-to-fuse weld materials, because of the fact that these processes do not significantly alter the microstructure in the joint area. As a consequence, joints can be achieved with better mechanical properties than those produced by fusion processes. Diffusion bonding also offers the possibility of producing sound bonds between dissimilar materials.

Various aspects of the similar and dissimilar joints of advanced materials made by laser welding, diffusion bonding, and friction stir welding or other conventional joining technologies still require a vast amount of research and development, supported by the knowledge gained over many years of work on conventional materials. It is obvious that a better understanding of the microstructure-mechanical properties relationships of the bonded or welded joints will feed back to the materials development and optimization activities in both conventional and new materials areas.

Current metallic materials of interest for joining studies include:

- Titanium aluminide intermetallics
- Nickel aluminide intermetallic alloys
- Iron aluminide intermetallic alloys
- Oxide dispersion strengthened (ods) alloys
- Metal matrix composites (mmcs)
- Nickel based superalloys
- Al-alloys including al-li alloys
- Mg-alloys
- Supermartensitic stainless steel.

Most of these alloys are mainly used in the aerospace industry. Although the use of welding in the aerospace industry is rather limited compared to other major industries, it has gradually increased over the last decade as a result of the development of welding methods (laser beam welding, friction stir welding, and so on) which have a less detrimental effect on local material properties and shape (minimum distortion) than more conventional arc welding. Friction stir welding is now being considered as a potential candidate for joining difficult-to-weld lightweight alloys, such as Al- and Mg-alloys. Mg-alloys are currently attracting a great deal of interest for applications in the transport industry because of their low weight. And some of these materials listed above, such as corrosion resistant supermartensitic stainless steels, have recently been developed for structural applications in the oil and gas industries. The characterization of the strength-mismatched joints (that is the presence of higher or lower strength levels in the weld zone than in the base material) produced in these steels is also of current interest. This review discusses the recent developments in friction stir welding of Al-alloys, joining of Mg-alloys, and supermartensitic stainless steels, and as a result provides newly available information.

2. Friction Stir Welding of Aluminum Alloys

2.1. Introduction

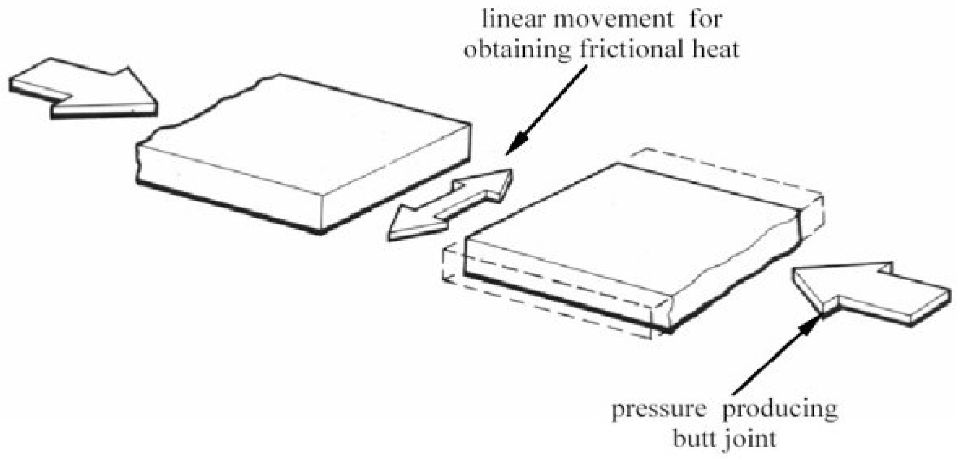

Figure 1. Schematic illustration of linear friction welding (LFW). Source: Nicholas D. (1991) *TWI Bulletin* **6**(32), 124–127.

Friction welding as a solid state joining process has been considered as a potential candidate for joining a range of “difficult to weld” materials because of its inherent advantages, such as short welding time, minimal surface preparation, and ease of automation. The use of rotary friction welding was however limited to solid or tubular cylindrical sections because of the nature of energy delivery in this joining process. The linear friction welding process for non-cylindrical sections has been developed and used for some limited applications (see Figure 1). Recently, the use of friction welding has been greatly extended by a novel process variant, namely friction stir welding (FSW), which can join primarily lightweight plate materials, mostly in butt-joint configurations. This process was developed and patented at the Welding Institute (TWI), UK in 1991.

The high strain rate/high temperature deformation cycle applied during joining alters the metallurgical and mechanical properties of material immediately at and adjacent to the bondline in rotary and linear friction welding, and within the weld zone in friction stir welding. This leads to diverse metallurgical effects, such as:

- The formation of fine dynamically recrystallized equiaxed grains at the bondline, occurring in all metal/metal joints, compared with the larger elongated grains of the joints produced by gas metal arc welding (GMAW).
- Softened zone formation (strength undermatched area) as a result of solution, overaging, and reprecipitation when age-strengthened base materials are welded.
- The formation of new and sometimes brittle microstructural phases, for instance, the formation of strain-induced martensite in dissimilar joints involving austenitic stainless steel.
- Intermetallic formation in dissimilar metal joints.
- Particle fragmentation (cracking) when Al-based and Mg-based composite materials are welded; particle agglomeration in Fe-based superalloy MA 956 friction joints.

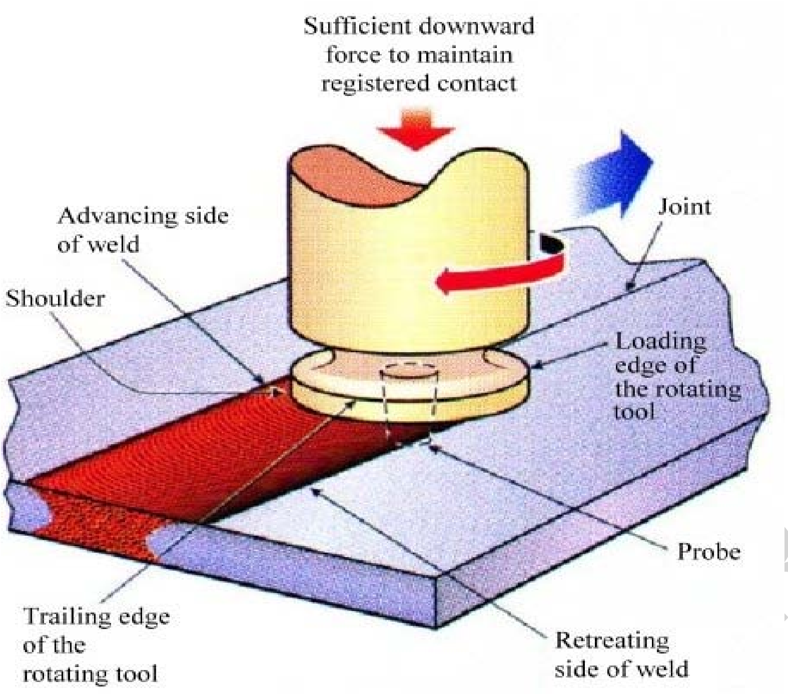

Figure 2. Schematic illustration of friction stir welding (FSW). Source: Thomas W.M. et al. (1991). *Friction Stir Butt Welding*, International Patent Appl. no. PCT/GB92/0220 and GB Patent Appl. no. 9125978.8, Dec. 1991, US Patent no. 5 460 317.

The FSW process is one of the most interesting joining techniques to have emerged over recent years, and offers great potential for applications in several major industries including aerospace, automotive, shipbuilding, and the military. It is shown schematically in Figure 2. The parts to be joined are placed on a backing plate and clamped using a powerful fixture. A non-consumable cylindrical tool, consisting of a unique auger-type pin with a cylindrical shoulder, is rotated, plunged and traversed along a square butt weld joint using conventional milling equipment and backside supports. The material around the pin tool is frictionally heated, plasticized, and extruded/forged from the leading to the trailing face of the pin, where the stirred material consolidates and cools under hydrostatic pressure conditions. Friction stir welding offers easy production operations, elimination of filler wire and shielding gas, development of a fine microstructure, and no loss of alloying elements, resulting in improved mechanical properties, and minimal weld defect formation (for example, absence of cracking or porosity), often coupled with reduced distortion and residual stresses compared with conventional fusion welding processes. Needless to say, to achieve such joint qualities, a suitable process window should be developed for a given material and plate thickness. It is claimed that aluminum alloys in the thickness range of 1.2 to 75 mm have been joined by this process using one and double-sided welding methods.

2.2. Welding Metallurgy of Friction Stir Welding

A typical microstructure of the transverse cross-section of the asymmetric weld nugget produced in FSW is shown in Figure 3. The unique feature is the formation of a series of concentric rings, commonly referred to as onion rings, annual rings, or ring structure. The cross-section of the weld consists of three distinct regions: a dynamically recrystallized zone, a thermo-mechanically affected zone (TMAZ) immediately adjacent to the nugget, and a thermally affected zone farther away from the nugget, similar to heat affected zone (HAZ) in fusion welds. The dynamically recrystallized zone is thought to be caused by dynamic recovery.

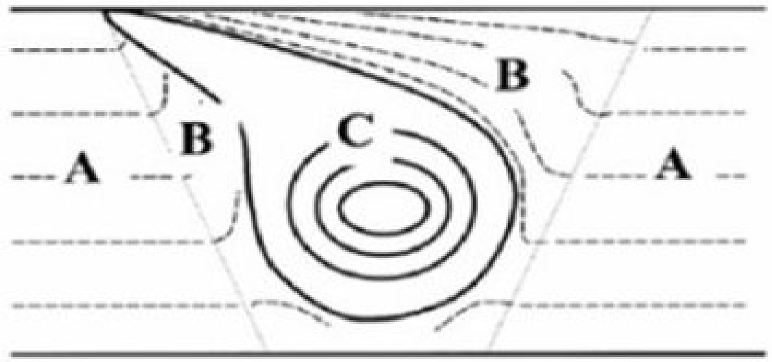

Figure 3. Schematic showing the cross-section of a typical weld nugget produced by FSW. A: heat affected zone (HAZ), B: thermomechanically affected zone (TMAZ), and C: dynamically recrystallized zone (DRZ). Source: Dong P. et al., *Proceedings of the First International Symposium on Friction Stir Welding*, June 14–16 1999, Thousand Oaks, California.

Friction stir welds for a given pin tool geometry is governed by three basic parameters: pin tool rotation speed, pin tool speed, and pin tool depth. Rotation and travel speeds are both readily controllable and do not vary significantly during welding for most welds made with a fixed pin tool geometry. The depth of the pin tool, however, is a critical parameter and difficult to control. It has been shown experimentally that the tip of the pin tool must remain within ~0.508 mm of the backing surface to produce a full penetration weld. The distance from the tip of the pin tool to the back surface of the workpiece is known as the “penetration ligament.” Hence surface preparation is more critical in friction stir welding than in radial or linear friction welding processes. Material thickness variations must be kept to a minimum to maintain a consistent penetration ligament during joining. The pin tool size must also be kept as small as possible to reduce shrinkage because of low heat input and small weld nugget size.

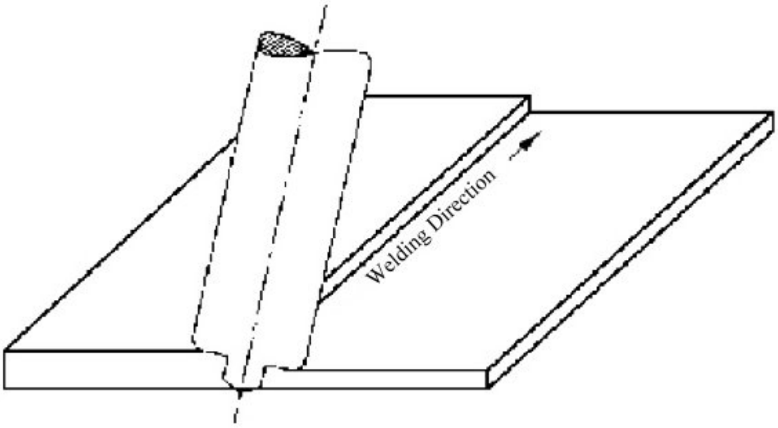

Figure 4. Schematic showing FSW of tailor blanks with dissimilar sheet thickness using a tilted tool. Source: Kalle S. and Mistry A. (1999). *Proceedings of the First International Symposium -n Friction Stir Welding*, June 14–16 1999, Thousand Oaks, California.

The application of FSW has recently been extended to tapered thickness welding and circumferential welding without the problem of keyhole left from the withdrawal of the pin by the development of automated retractable pin tools (RPT). Promising results were reported in tapered FSW of Al–Li alloy 2195. However, the results are limited and further work should be conducted to optimize RPT parameters. The application of FSW in the welding of tailored blanks in the automotive industry is also recently attracting a great deal of interest. It has been suggested that a smoother thickness change than is obtainable with laser welding could be achieved if a tilted FSW tool was plunged into the stepped side of the joint as shown in Figure 4. (Further information on the developments of the FSW process can be found in the *Proceedings of the First International Symposium on Friction Stir Welding and GKSS-TWI Workshop* given in the bibliography.)

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Biographical Sketches

Professor Dr. Gürel Çam received his B.Sc. degree in Metallurgy from İstanbul Technical University in Turkey, and his Ph.D. degree in Materials Science from Imperial College, University of London in 1990. Between 1990 and 1994, he worked as Assistant Professor in the Department of Mechanical Engineering, University of Gaziantep, Turkey. From 1994 to 1999, he worked on a number of fundamental and industrial research projects, including Brite-Euram and Ma-Tech Projects, at GKSS Research Center, Geestacht, Germany. He has over 50 published works in the fields of materials science, welding metallurgy, and fracture behavior of weldments. He is currently Professor of Joining Technologies in the Department of Mechanical Engineering, Mustafa Kemal University, Hatay, Turkey.

Dr. Mustafa Koçak, after graduating in Mechanical Engineering from the Middle East Technical University (METÜ), Turkey, in 1979 with a B.Sc., obtained his Ph.D. in Engineering from the University of Bath, UK, in 1982. He was a Research Fellow at the Department of Metallurgy, University of Liverpool, UK, from 1982 to 1984.

Since October 1984 he has been working on a number of basic and industrial research projects in the fields of joining technologies and assessment of welded and bonded joints at the GKSS Research Center. He is currently head of the "Umsetzung und Nutzung (WUN)" Department at the Institute for Materials Research, GKSS Research Center.

Dr. Koçak has authored about 130 publications in the field of joining and assessment of welds, and has addressed and chaired numerous sessions in international material and welding conferences including past ESIS, ASM, and annual ASME/OMAE conferences. He has co-edited numerous volumes of OMAE conference proceedings. He chaired the WELDING-90 International Conference, October 1990 in Germany and co-chaired two International Conferences MIS-MATCH '93 and MIS-MATCH'96 in May 1993 and April 1996 respectively, in Germany. Dr. Koçak co-chaired two European Symposiums on "Assessment of Power Beam Welds – ASPOW", February 4–5 1999, GKSS Research Center Geesthacht, Germany, and on "Structural Integrity Assessment Procedure – SINTAP", November 23–24 1999, GKSS Research Center Geesthacht, Germany, organized with British Steel, UK.

Dr. Koçak has co-coordinated the European Commission BRITE EURAM Project “Assessment of Quality of Power Beam Weld Joints – ASPOW”, 1099-Contract BRPR-CT95-0021, completed in 1999. He currently coordinates the EU-GROWTH project JOTSUP – Development of Advance Joining Technologies for 12%Cr Supermartensitic Steel Line Pipes, 2000–2003, which has a budget of €5.4 million and 13 partners.

Dr. Koçak is currently on the editorial board of the journal *Science and Technology of Welding and Joining*, a publication of the Institute of Materials, UK. He is past chairman of the International Institute of Welding (IIW) Sub Commission X-F “Weld Mis-match Effect” and currently chairs the International Institute of Welding (IIW) Commission X: “Structural Performance of Welded Joints – Fracture Avoidance.”