FRICTION STIR WELDING AND PROCESSING BOOK SERIES

# Friction Stir Welding of Dissimilar Alloys and Materials

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The Boulevard, Langford Lane, Kidlington, Oxford OX51GB, UK
225 Wyman Street, Waltham, MA 02451, USA

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ISBN: 978-0-12-802418-8

**Library of Congress Cataloging-in-Publication Data**
A catalog record for this book is available from the Library of Congress

**British Library Cataloguing-in-Publication Data**
A catalogue record for this book is available from the British Library

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# Preface to This Volume of Friction Stir Welding and Processing Book Series

This is the fourth volume in the recently launched short book series on friction stir welding and processing. As highlighted in the preface of the first book, the intention of this book series is to serve engineers and researchers engaged in advanced and innovative manufacturing techniques. Friction stir welding was invented more than 20 years back as a solid state joining technique. In this period, friction stir welding has found a wide range of applications in joining of aluminum alloys. Although the fundamentals have not kept pace in all aspects, there is a tremendous wealth of information in the large volume of papers published in journals and proceedings. Recent publications of several books and review articles have furthered the dissemination of information.

This book is focused on joining of dissimilar alloys and materials, an area that is getting a lot of attention recently; and friction stir welding promises to be a breakthrough technique for this as well. The promise of friction stir welding for such joints lies in its ability to minimize the extent of intermetallic formation in dissimilar metals. The change in the flow behavior brings in additional challenges as well. There are early successful examples of implementation of dissimilar metal joining and hopefully this book will provide confidence to designers and engineers to consider friction stir welding for a wider range of dissimilar alloy and dissimilar metal joining. It will also serve as a resource for researchers dealing with various challenges in joining of dissimilar alloys and materials. As stated in the previous volume, this short book series on friction stir welding and processing will include books that advance both the science and technology.

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*February 16, 2015*

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# CHAPTER 1

# Introduction

Humans and materials have flocked together since the humans have roamed the earth. As a matter of fact, the influence of materials on human civilization has been so profound, our progress is sometimes described in terms of materials—stone age, copper age, bronze age, and iron age. Industrial revolution was a major turning point in the history of human civilization which propelled the development of new materials. New materials enabled building of stronger and cheaper artifacts used in a variety of situations such as ground, sea, and aerospace transportation-related applications. The twentieth century witnessed a phenomenal growth on the materials development front, and designers of engineering structure were presented with a monumental task of selecting an appropriate or a set of materials for a particular component. On the one hand the availability of a wide spectrum of materials allowed designers to be very creative with the design of any component, on the other it posed a new set of challenges in terms of integrating different types of materials in a single structure. Among many, the assembly of components made of materials widely differing in chemical, thermal, physical, and mechanical properties became a challenge. For the majority of dissimilar materials, mechanical fastening is an appropriate choice. But the demand on high-performance structures has shifted attention from mechanical joining such as riveting and bolting to welding. Although a great number of welding techniques have been developed so far to deal with different types of materials, the welding of dissimilar materials still remains a challenge.

## 1.1 EXAMPLES OF ENGINEERING SYSTEMS NEEDING DISSIMILAR JOINTS

The need for joining dissimilar materials often arises in industrial applications due to demand for a wide variety of materials to impart complex shape, different loading or performance conditions needed in different

Friction Stir Welding of Dissimilar Alloys and Materials. DOI: http://dx.doi.org/10.1016/B978-0-12-802418-8.00001-1
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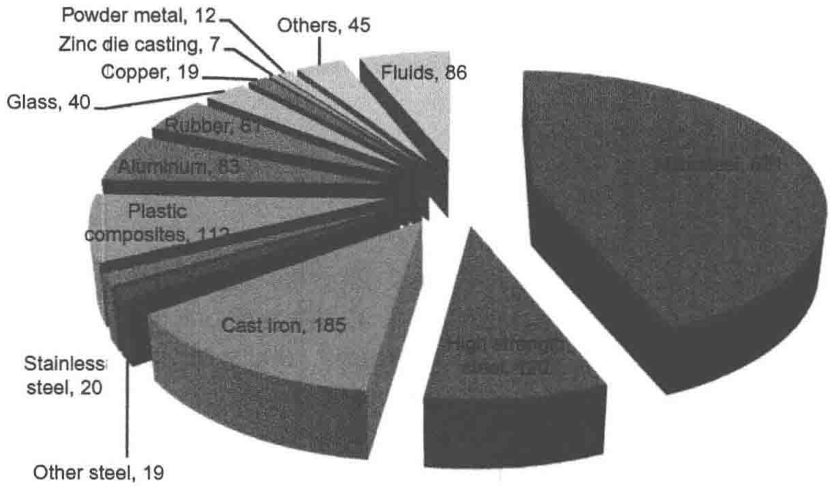


*Figure 1.1 Material distribution of total vehicle curb weight in kilogram (Mayyas et al., 2012).*

parts of the assembly such as high strength and corrosion resistance. Materials have been the backbone for industry, and advanced lightweight materials are essential especially for transportation industries to improve fuel economy while maintaining or improving safety and performance. Steels, owing to their attractive properties, recyclability, matured state of the art, and relatively low cost, have historically been the preferred choice for structural application in automotive industry. However, it is becoming clear that not a single material can fit all applications. The multi-material concept including a hybrid of light metals is now a trend for the automotive industry (Figure 1.1). With extra push toward the use of light materials, the fraction of light materials including polymer matrix composites is poised to increase in the near future. Traditional steel components can be replaced or partially replaced with lighter materials such as advanced high-strength steel, aluminum alloys and polymer.

One area where dissimilar material joint is essential in a structure is the fabrication of tailor-welded blank (Figure 1.2). A tailor-welded blank consists of joining sheets of different materials and/or the same material with different thicknesses, which is then submitted to a stamping process to form into the desired shape. Tailor-welded blanks are primarily used in the automotive industry and offer a significant potential on weight reduction for applications such as side frames, doors, pillars, and rails, because no reinforcement is required. The main

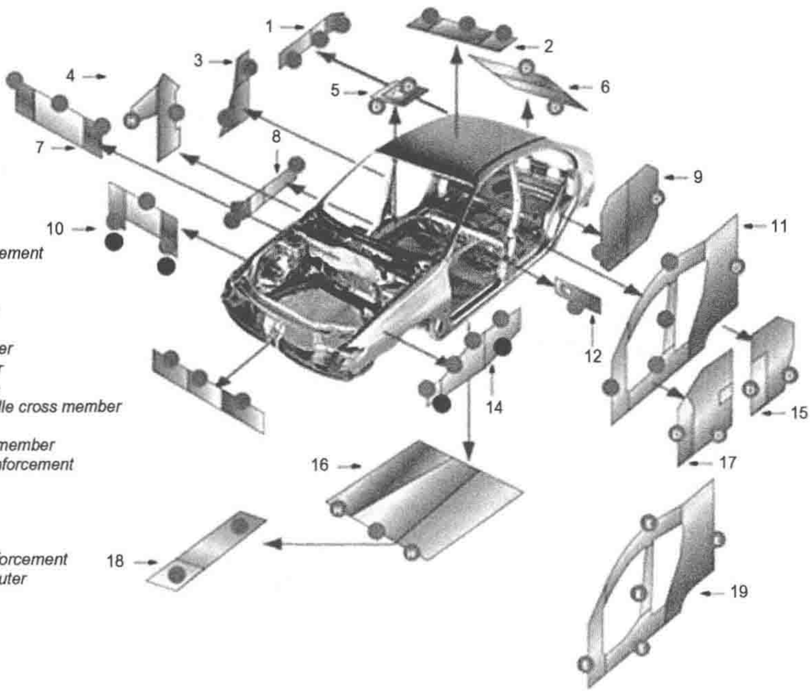


*Figure 1.2 Tailor-welded blanks for automotive application (http://automotive.arcelormittal.com/tailoredblanks/TB_products/Applications, last accessed on 01.12.15).*

advantage of a tailor-welded blank is that it allows the joining of multiple pieces to fabricate much larger components as well as proper distributions of weight and material properties in the final stamped part with a consequent reduction in weight and cost.

In addition to the body structure, there are also components and devices in an automobile consisting of dissimilar material joints, such as powertrain components. Figure 1.3 presents a turbocharger impeller for high-efficiency gas and diesel engines. The impeller is made of carbon steel and Inconel and welded by using electron beam. The dissimilar material assembly enables the lightweight design as well as superior performance.

Advanced materials, structures, and fabrication technologies are needed to enable the design and development of advanced future aircraft especially in airframe and propulsion systems. The high-performance materials such as titanium alloy and nickel-based superalloy, and adaptive materials such as piezoelectric ceramics, shape memory alloys, shape memory polymers, and carbon fibers, can only be

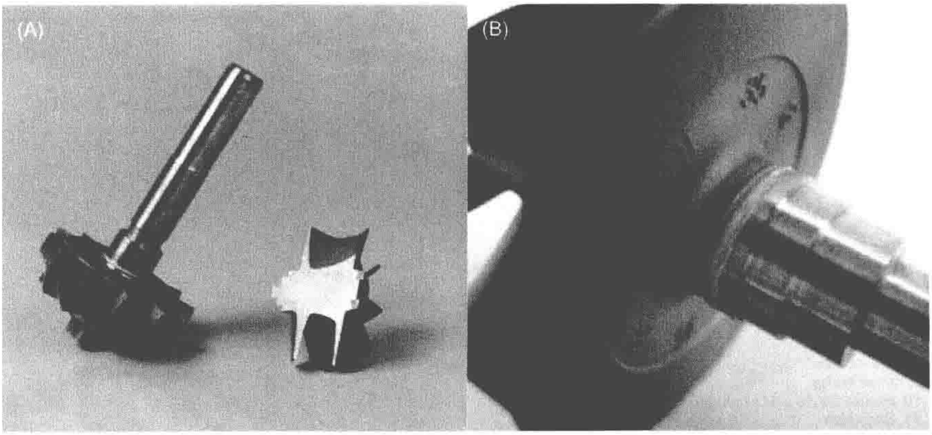


*Figure 1.3 (A) Turbocharger impeller made of carbon steel (shaft) and Inconel (impeller). (B) Magnified view of the weld between shaft and impeller (http://www.ptreb.com/industries/automotive/turbocharger_impeller_welding/, accessed on 30.11.14).*

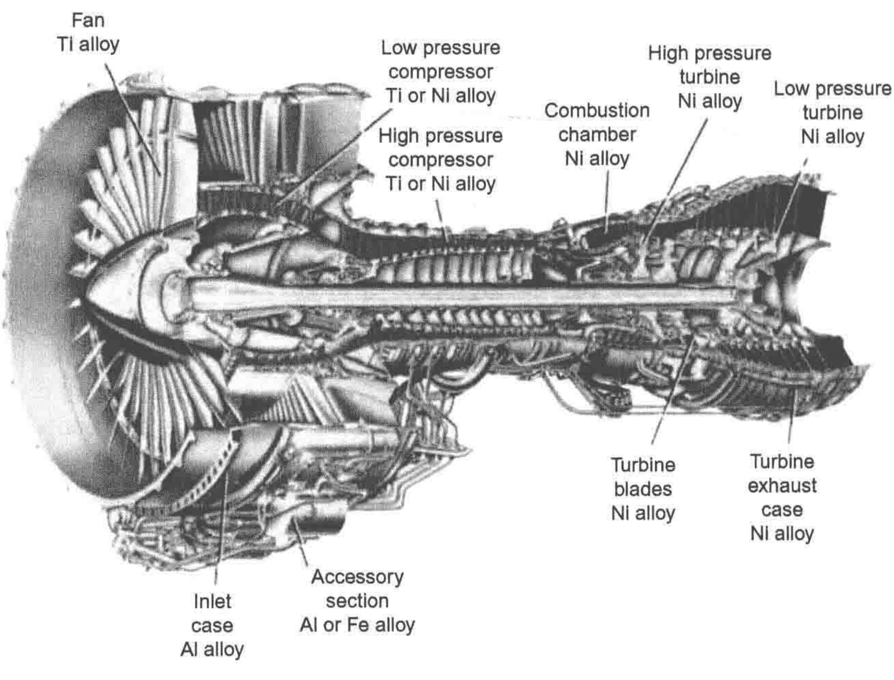


*Figure 1.4 Aircraft engine with multifunctional materials (Campbell, 2006).*

used where they are essential. To integrate these materials into airframe and/or aircraft engine structures, development of joining and integration technologies including metal to metal and metal to ceramic is critical (Figure 1.4).

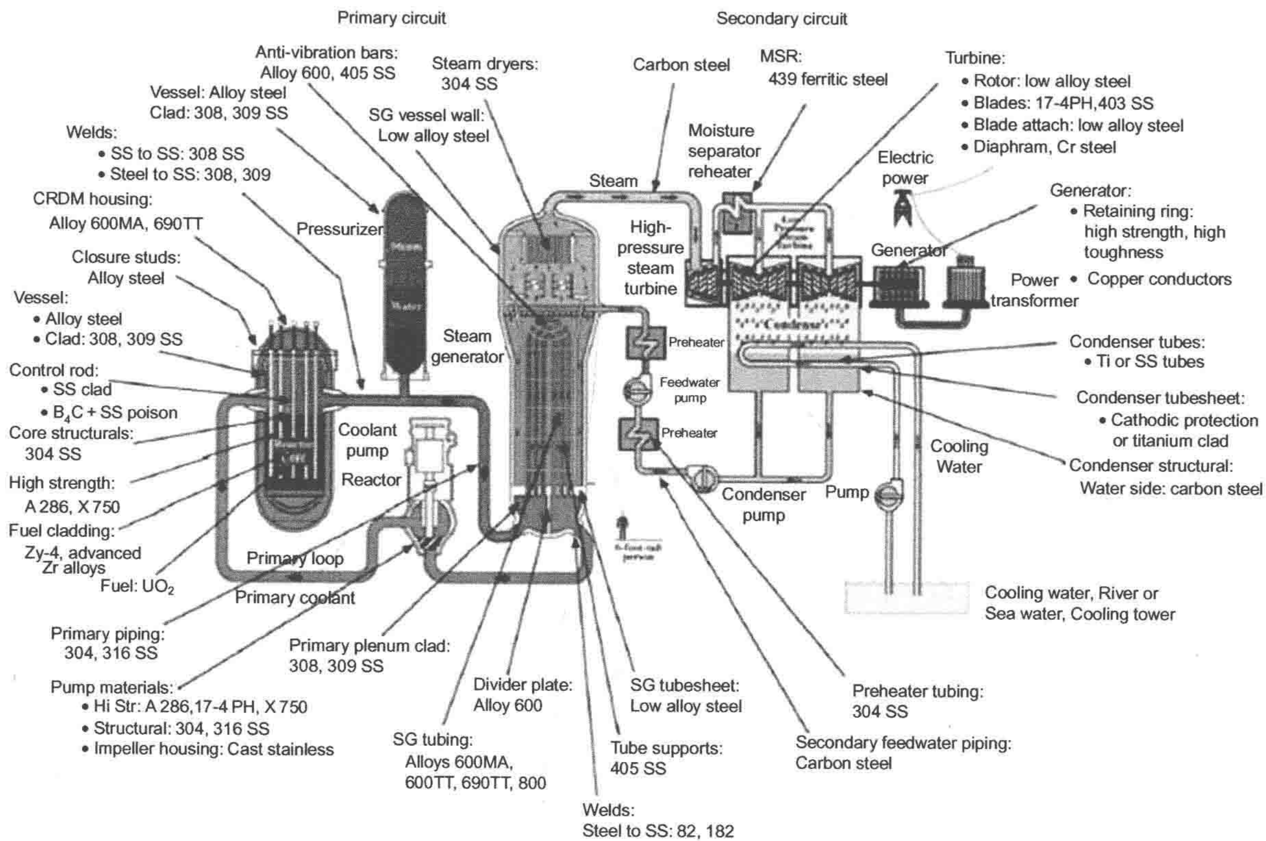


*Figure 1.5 A schematic diagram showing different parts of a pressurized light-water nuclear reactor and materials used in the construction (Zinkle and Was, 2013).*

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Figure 1.5 shows a schematic of pressurized light-water nuclear reactor showing the use of an array of different high-temperature materials in the primary and secondary circuits including the reactor. It is appreciated that materials with better performance would be needed in reactors being designed for longer lifetime and superior capability. Similar need is being felt in the development of ultra-supercritical steam boilers expected to operate at 760°C and 35 MPa. The current design allows boilers to operate at 620°C and 20 MPa (Sridhar et al., 2011). Again, to meet increased expectation from the materials will require not only development of materials with increased performance but also development and use of advanced integration technologies.

Above examples taken from various industries show that a wide range of materials are needed for successful performance of engineering structures. A large number of components made of different materials are integrated to give rise to the final structure. A number of engineering solutions are available to assemble subsystems and choice of which depends on a number of factors including availability, cost, and performance expected from the system.

## 1.2 CONVENTIONAL JOINING TECHNIQUES

Figure 1.6 shows a few commonly used joining techniques for similar and dissimilar materials. Among all the advantages of welding include cheaper and faster integration time, flexibility in design, weight savings, higher structural stiffness, high joint efficiency, air and water tightness, and no limit on the width which can be welded together. Conventionally both fusion welding and solid-state welding techniques have been used to join dissimilar materials. Solid-state welding techniques include friction stir welding (FSW), ultrasonic welding, explosion welding, and diffusion welding. Brazing and soldering also have been tried to create joints between dissimilar welds.

## 1.3 DISADVANTAGES OF CONVENTIONAL WELDING TECHNIQUES FOR DISSIMILAR MATERIALS

Although the majority of the issues encountered in the dissimilar metal welding using fusion welding techniques are present in solid-state welded joints, it is less severe in solid-state welds. Some of the

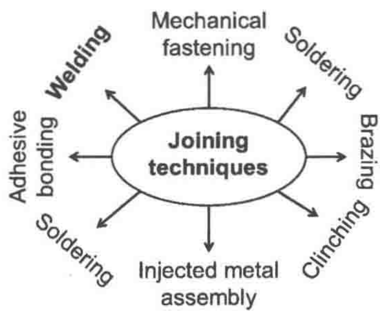


*Figure 1.6 Various techniques used to join similar and dissimilar materials.*

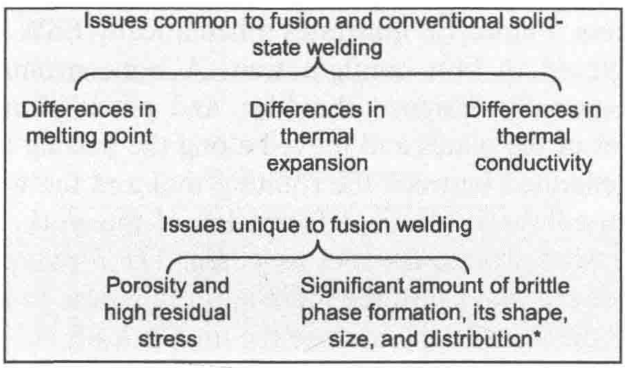


*Figure 1.7 A few issues commonly encountered in dissimilar metal welding using fusion and conventional fusion welding techniques (*actually formation of brittle intermetallic phase is also found in solid-state welding; however, it is less severe in solid-state welding than that in fusion welding).*

advantages of the solid-state weld over fusion welds with regard to similar welds still hold good during dissimilar material welding—for example, the absence of porosity and less distortion during solid-state welds. Due to high temperature during fusion welding compared to solid-state welding, most of the time the use of filler material results in a weld material where metallurgical characteristics, mechanical, and physical properties are totally different from individual materials used in dissimilar welds. Some of the issues faced during solid-state welding and fusion welding are depicted in Figure 1.7.

## 1.4 FRICTION STIR WELDING

Among all the solid-state welding techniques, FSW is a relatively new technique. FSW is a solid-state joining process invented in 1991 at The Welding Institute, UK (Thomas et al., 1995). It is a remarkably simple

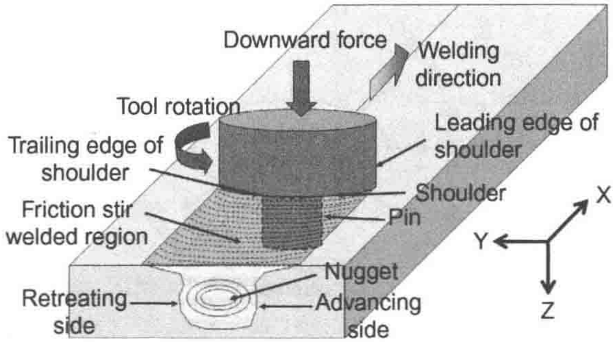


*Figure 1.8 A schematic drawing of FSW in a butt joint configuration (Mishra and Ma, 2005).*

welding process. Figure 1.8 illustrates schematically FSW processes for two plates placed in butt configuration. A nonconsumable rotating tool having specially designed shoulder, and pin is plunged into the abutting edges of the plates and moved along the parting line. The frictional heat generated between the rotating tool and the workpiece and the heat from adiabatic plastic deformation of the workpiece material cause the material around the tool to soften. The forward motion and the rotation of the tool cause the material in this state to move around the tool from the front to the back of the tool. It leads to a joint formation between the two plates. Different terminologies used in FSW are also labeled in the schematic shown in Figure 1.8. Most definitions are self-explanatory, but advancing side and retreating side definitions require a brief explanation. The side of the weld where the sense of tangential velocity of the rotating tool is parallel to the sense of the tool traverse is termed as advancing side, and if opposite, retreating side.

Note that, as the name suggests, the entire process of weld formation takes place below the melting point or solidus of the alloy. It leads to avoidance of most of the issues associated with fusion welding of materials. Additional key benefits of FSW as compared to fusion welding are summarized in Table 1.1.

Figure 1.9 illustrates various zones representing different microstructural states in the weldments as observed on the transverse cross-section of friction stir welds. The zone D represents dynamically recrystallized zone referred to as nugget. Thermo-mechanically affected zone (TMAZ), labeled here as region C, is the region of the weld which does not undergo complete recrystallization. Nugget and TMAZ regions experience plastic deformation at high temperature.

| Table 1.1 Key Benefits of FSW (Mishra and Ma, 2005) | | |
|---|---|---|
| **Metallurgical Benefits** | **Environmental Benefits** | **Energy Benefits** |
| • Solid-phase process<br>• Low distortion<br>• Good dimensional stability and repeatability<br>• No loss of alloying elements<br>• Excellent mechanical properties in the joint area<br>• Fine recrystallized microstructure<br>• Absence of solidification cracking<br>• Replace multiple parts joined by fasteners<br>• Weld all aluminum alloys<br>• Post-FSW formability | • No shielding gas required<br>• Minimal surface cleaning required<br>• Eliminate grinding wastes<br>• Eliminate solvents required for degreasing<br>• Consumable materials saving, such as rugs, filler wire, or any other gases<br>• No harmful emissions<br>• No radiant energy as in fusion welding; hence simple safety glasses enough | • Improved materials use (e.g., joining different thickness) allows reduction in weight<br>• Only 2.5% of the energy needed for a laser weld<br>• Decreased fuel consumption in lightweight aircraft, automotive, and ship applications |

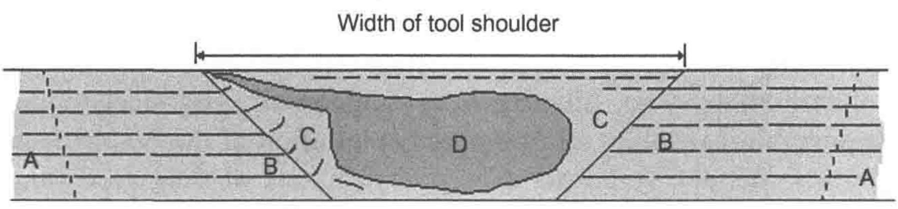


*Figure 1.9 A schematic of transverse cross-section showing different zones of a friction stir weld. A, BM; B, HAZ; C, TMAZ; and D, Nugget (Mishra and Mahoney, 2007).*

Heat-affected zone (HAZ) is the region of the weldments where only the influence of thermal excursion is present. Base material (BM) is the region which has the same set of properties as in as-received condition. The microstructural states of these zones are heavily dependent on FSW parameters.

The advent of FSW has completely revolutionized the field of welding. FSW is considered to be the most significant development in metal joining in decades. The high-strength aluminum alloys, such as 2XXX and 7XXX series aluminum alloys, are classified as "nonweldable" by fusion techniques. So, when the FSW was invented in 1991, it opened up new opportunities to weld high-strength aluminum alloys. Table 1.2 shows an example of strength levels achieved in initial studies of FSW of AA2024 and AA7075. Subsequently, other attributes of FSW, like defect-free welds, lower residual stresses, and lower distortion, led to numerous implementations using lower strength aluminum alloys.

Table 1.2 An Example of Results for AA2024Al and AA7075Al Alloys That Led to Excitement for Implementation of FSW (Mishra et al., 2014)

| Base Alloy and Temper | Parent Material | Gas-Shielded arc Welded Butt Joint | | FSW | |
|---|---|---|---|---|---|
| | Tensile Strength (MPa) | Tensile Strength (MPa) | % of Parent | Tensile Strength (MPa) | % of Parent |
| 2024-T3 | 485 | Nonweldable | – | 432 | 89 |
| 7075-T6 | 585 | Nonweldable | – | 468 | 80 |

## 1.5 APPLICATIONS OF FRICTION STIR WELDED DISSIMILAR MATERIALS

Joining of dissimilar materials is becoming increasingly important as engineers strive for reduced weight and improved performance from engineering structures. FSW has already been adopted extensively for joining aluminum alloys in automotive, rail, aircraft, aerospace, and shipbuilding industries. The combination of dissimilar materials, such as aluminum to steel, aluminum to magnesium, and steel to nickel base superalloy, enables an optimum exploitation of the best properties of both materials. A barrier placed in front of welding of dissimilar materials with quite different base metals is the formation of brittle intermetallic compounds, which diminishes the strength and integrity of a structure. Recent efforts on reducing such deleterious compounds by using FSW have led to the implementation and mass production of dissimilar materials structures for industrial applications.

The progress made in welding lightweight materials, such as aluminum and magnesium alloys, make the mass production of light transportation systems possible and hence a significant reduction in fuel consumption. FSW has been adopted by the automotive industry for more than a decade to join aluminum alloys. Recently, Honda Motor Corporation has implemented FSW to join dissimilar aluminum alloy and steel in an automobile front structural component in production vehicle Honda Accord. The front subframe which carries the engine and some suspension components, is made of die cast aluminum and press formed steel halves. FSW was applied to weld the aluminum to the steel in a lap configuration at various locations as indicated by short stitches. Honda claimed that the total body weight is reduced by 25% compared to the conventional steel subframe with reduced electricity consumption by approximately 50% (http://world.honda.com/news/2012/4120906Weld-Together-Steel-Aluminum/).

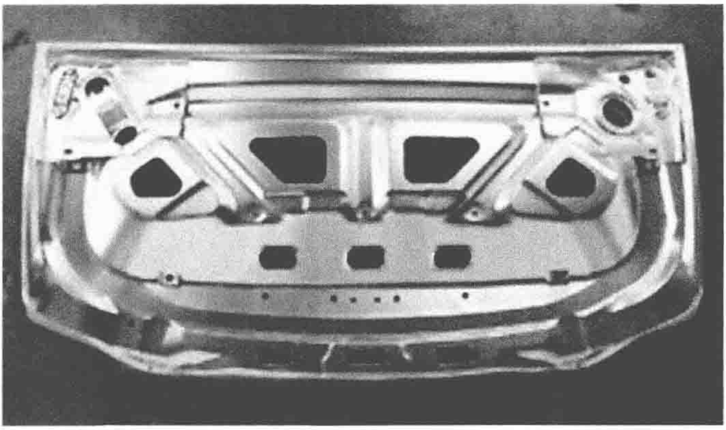

*Figure 1.10 FSW to join the aluminum deck lid to galvanized steel brackets by Mazda (Mishra and Mahoney, 2007).*

Mazda Motor Corporation has developed direct friction stir spot joining technology to weld aluminum alloy and steel, and applied it to join the trunk lid of the Mazda MX-5. Figure 1.10 shows Mazda's dissimilar friction stir welded deck lid with aluminum sheet to galvanized steel brackets. In addition to the prominent weight reduction, Mazda also claims that this technology improves the potential of coupling aluminum parts to steel in vehicle bodies and helps lower the costs of production.

Tailor blanks with various dissimilar materials combinations, such as different aluminum alloys, aluminum and magnesium alloys, aluminum and steel, have been researched via FSW for both automotive and aircraft applications. Figure 1.11 shows dissimilar tailor-welded blanks of 1 mm thick sheets of AA 5182 and AA 6016 aluminum alloys. The welded blanks were further formed by deep drawing cylindrical cups. Although the mechanical behaviors are different between two aluminum alloys, the weld line remained straight and aligned at the middle of the cups after deep drawing.

FSW of dissimilar metals has also been used in other sectors, such as the health industry. Figure 1.12 shows a vacuum-tight component in X-ray equipment of Siemens Medical Solutions. The component is fabricated by FSW domed aluminum sheets to flat stainless steel sheets, manufactured by Riftech GmbH in Greesthacht, Germany. A noticeable cost reduction by approximately 20% has been achieved due to significantly reduced defective welds by using FSW process.

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