Friction Stir Welding: Dissimilar Aluminium Alloys

Noor Zaman Khan
Arshad Noor Siddiquee
Zahid Akhtar Khan

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Preface

Friction stir welding (FSW) is indeed a solid state welding process that has enabled joining materials that are otherwise difficult to be welded by other fabrication processes. It is relatively a young material-joining technique, which was invented in 1991 and it has proudly celebrated its silver jubilee. The authors are associated and involved in this process since last several years and have been conducting extensive experimental and analytical investigations in this area. Many industries including automotive, shipbuilding, rail, aerospace, etc. are adopting FSW commercially, which has led to an ever-increasing involvement of FSW researchers and engineers in successful implementation of this novel fabrication process. For research or experimental work in any field, background knowledge of that field is essential for achieving success and therefore, there is a need for a basic understanding of the FSW process with some experimental examples that serve as the starting platform for senior students, scholars, and investigators and it has primarily motivated us to shape our FSW experimental works and their findings in the form of this treatise. FSW area is very wide and it is difficult to cover its various aspects in a single text. Therefore, only some important aspects of FSW have been covered in this treatise. This text intends to provide valuable information and data related to FSW of dissimilar aluminum alloys. Academicians, researchers, practicing welding engineers, metallurgists, and fabrication industries should benefit from the material presented in this work.

Chapter 1 presents an introduction to the subject, which includes demand of aluminum alloys in industries, joining of aluminum alloys, joining of dissimilar aluminum alloys, FSW of aluminum alloys, and FSW of dissimilar aluminum alloys. It also describes the importance and benefits of the current research work.

Chapter 2 describes the working principle of FSW process and historical background of the process with its advantages, disadvantages, and applications. It also discusses the tool design, FSW process parameters, machine for FSW, work fixture for holding workpiece during welding, and response measurement for defining weld quality.

Chapter 3 presents a study on friction stir welding of aluminum alloys, which explores problems related to the welding of aluminum alloys, and FSW of 2xxx, 5xxx, 6xxx, and 7xxx series aluminum alloys.

Chapter 4 provides the description on FSW of dissimilar aluminum alloys and it covers various issues related to dissimilar materials welding and major challenges in the friction stir welding of these dissimilar materials. It also focuses on dissimilar FSW of 5xxx–6xxx, 2xxx–7xxx, and 6xxx–7xxx series aluminum alloys.

Chapter 5 describes the methodology used for performing experimental study on FSW of dissimilar aluminum alloys (5083 and 6063), which includes experimental setup, machine used, and welding tool design. It explains the phenomenon of defect formation during FSW of dissimilar aluminum alloys and summarizes joining of dissimilar aluminum alloy using FSW.

Noor Zaman Khan
Arshad Noor Siddiquee
Zahid A. Khan

Authors

Noor Zaman Khan is a full time UGC sponsored BSR doctoral fellow in the Department of Mechanical Engineering at Jamia Millia Islamia (A Central University), New Delhi, India. His PhD in the area of friction stir welding/processing is in advanced stage of completion. He earned his master's degree in production and industrial engineering in 2013 from Jamia Millia Islamia and bachelor's degree in mechanical engineering in 2011 from Jawaharlal Nehru Technological University, Hyderabad. His major research interest includes materials structure–property correlation, welding engineering, nonconventional machining, machining, and optimization of design and process parameters using design of experiments. He has published more than 10 articles in reputed journals and conference proceedings so far.

Arshad Noor Siddiquee is professor in the Department of Mechanical Engineering at Jamia Millia Islamia (A Central University), New Delhi, India. He earned PhD and MTech from IIT Delhi. He has supervised several MTech dissertations and currently he is supervising 10 doctoral research scholars. His major research interest includes materials structure property correlation, materials processing, welding engineering, machining and optimization of design and process parameters. He has published more than 90 articles in reputed journals and conference proceedings. He has also coauthored four books related to engineering and one monograph as well.

Zahid A. Khan is professor in the Department of Mechanical Engineering at Jamia Millia Islamia (A Central University), New Delhi, India. He earned his PhD in 2001 from Jamia Millia Islamia, New Delhi, India. His major research interest includes optimization of design and manufacturing processes parameters, ANN and fuzzy modeling, environmental ergonomics, etc. He has supervised five doctoral research scholars and many MTech dissertations so far and currently he is supervising five doctoral theses. He has published more than 100 articles in reputed journals and conference proceedings so far. He has also coauthored four books related to engineering and two monographs as well.

CHAPTER 1

Introduction

1.1 INTRODUCTION

Welding is a joining process that fabricates various parts or components so as to produce products of complex shapes and geometry, which are otherwise too difficult to produce through other manufacturing processes. In order to produce efficient, compact complex products that can fulfill their functional and esthetic requirements, it is necessary to use a suitable fabrication process to assemble together several smaller components possessing exotic properties. Welding is a common option to join such components. Joining of dissimilar material often poses serious challenges to such an extent that joining is sometimes not possible at all. This problem is mainly because of difference in mechanical, physical, chemical, and metallurgical properties of the materials being joined. Difference in melting point, thermal expansion coefficient, thermal conductivity, etc. may cause failure at the weldments even during welding. Welding constitutes an essential manufacturing process that enables the production of a wide range of products being used in automotive, shipbuilding, aerospace, and several other industrial sectors. However, welding processes are extremely complex and multidimensional in terms of materials, process, and workmen skill, which make the fabrication of desired quality joint extremely difficult.

Joining of dissimilar materials with desirable overall quality is a challenging research field and welding of dissimilar materials has always been a matter of concern for engineers and scientists worldwide. There has been an ever-increasing demand for products possessing properties such as light weight, high strength, good corrosion resistance, etc. In order to fabricate a single structure, comprising several components often of different materials that exhibit various desirable properties, it is essential to join dissimilar materials together. Thus, welding of different grades of aluminum alloys having desirable mechanical and thermal properties owing to their high specific strength, thermal conductivity, and corrosion resistance are in great demand. Property–microstructure relationship in aluminum alloys is presented in Table 1.1. Several examples are found where aluminum alloys of different grades are joined together so as to provide desirable properties to the structure. For example, joining of 5xxx aluminum alloy (used for hull) with 6xxx aluminum alloy (used for secondary structural component) in a ship; similarly joining of 2xxx (a material for lower wing) and 7xxx series aluminum alloy (used to make upper wing) in aircraft (Figure 1.1), etc.

Economical and technical advantages of joining dissimilar materials have enabled its use in various industrial applications. Joining dissimilar materials by FSW has emerged as a new research topic. FSW has not only

TABLE 1.1 Property–Microstructure Relationship in Aluminum Alloys

Property	**Microstructural Feature**	**Function of Feature(s)**
Strength	Uniform dispersion of small, hard particles, fine grain size	Inhibit dislocation motion
Ductility and toughness	No large particles, clean grain boundaries, fine structure, no shearable particles	Encourage plasticity, inhibit void formation and growth, work harden
Fatigue crack initiation resistance	No shearable particles, fine grain size, no surface defects	Prevent strain localization and slip steps on surface, prevent stress concentration
Fatigue crack propagation resistance	Shearable particles, no anodic phases or hydrogen traps, large grain size	Encourage crack closure, branching, deflection, and slip reversibility
Pitting	No anodic phases	Prevent preferential dissolution of second-phase particles
Stress corrosion cracking, hydrogen embrittlement (HE)	No anodic phases, or interconnected hydrogen traps, hard particles	Prevent crack propagation due to anodic dissolution of HE, homogenize slip
Creep	Thermally stable particles on grain boundaries, large grain size	Inhibit grain boundary sliding

Source: Reprinted from *Progress in Aerospace Sciences*, 32, E.A. Starke, J.T. Staley, Application of modern aluminum alloys to aircraft, 131–172, 1996, with permission from Elsevier.

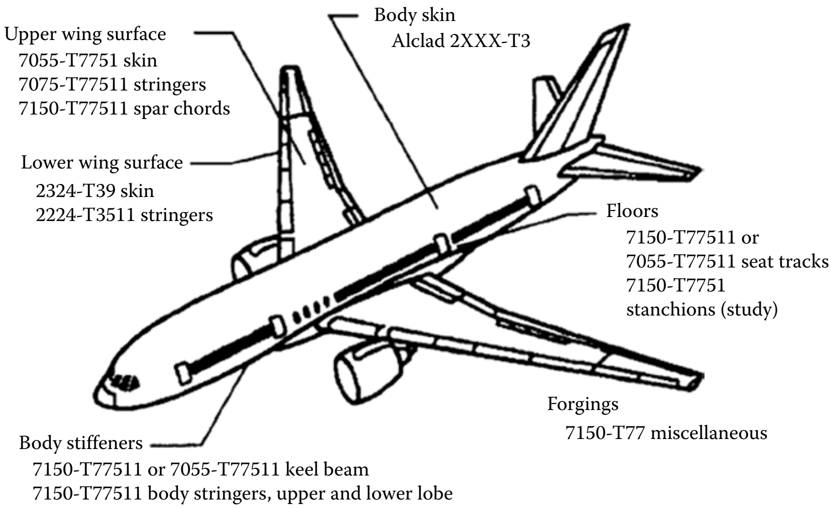

FIGURE 1.1 Application of different grades of aluminum alloys in Boeing 777. (Reprinted from *Progress in Aerospace Sciences*, 32, E.A. Starke, J.T. Staley. Application of modern aluminum alloys to aircraft, Copyright 1996, with permission from Elsevier.)

been found to produce near-defect-free joints with sound postwelding mechanical properties while joining various similar and dissimilar aluminum alloys but has also been able to effectively join a few previously difficult-to-weld aluminum alloys such as 2xxx and 7xxx series. However, to obtain acceptable quality welds important FSW process parameters need to be established for efficient joining of dissimilar aluminum alloys by preventing brittle intermetallic formation and imperfections in the joints to promote adequate flow of material and to mitigate deterioration in mechanical properties and surface morphology. Efficient and effective joining of dissimilar materials require adequate flow of material around the tool pin and proper mixing of material at stir zone (SZ) during welding for which the strategies pertaining to the joint design, tool design, and tool offset from the faying surface of base materials (BMs) need to be addressed as they play a critical role in the success of FSW of dissimilar alloys.

1.2 DEMAND OF ALUMINUM ALLOYS IN INDUSTRIES

Aluminum alloys possess various desirable properties such as good corrosion resistance, high strength-to-weight ratio, better fatigue strength that enable them to be used in different structural parts and other components for aerospace, marine, shipbuilding, and rail transport industries. The use of aluminum is expected to continue to increase worldwide, particularly in the transportation and manufacturing sectors. Aluminum alloys, being light in weight, have been the primary structural material for military and commercial aircraft for almost 80 years owing to their well-known mechanical behavior, strength-to-weight ratio, and mature manufacturing processes; and will remain so with the development of new-generation high-strength aluminum alloys. Use of light-weight material (aluminum alloys) in transportation sector reduces vehicle mass, which in turn minimizes fuel consumption and harmful emissions. Reduction in weight of the various modes of transportation reduces fuel consumption, which lessens frequent filling of fuel tanks. Use of light-weight material with high strength-to-weight ratio in making structures has a great impact on reduction in the cost that occur due to fuel consumption, frequent repair and maintenance, etc. Airframe manufacturers and material producers focus on the development of new aluminum alloys having good mechanical, metallurgical properties to meet customer requirements. Good mechanical properties and corrosion resistance of the materials may increase the life of the component and reduce repair costs.

Aluminum alloys are widely used by various industries in the fabrication of parts and components. More specifically 5xxx and 6xxx aluminum alloys have applications in shipbuilding, automobile, and aerospace, whereas 2xxx and 7xxx aluminum alloys have wide applications in aircraft components such as wings, tanks, fuselage, stringers, etc. as shown in Figure 1.1. Application of different aluminum alloys is listed in Table 1.2.

Reducing the weight of vehicles without compromising on the safety passengers are the two major challenges faced by automobile industries. Vehicle weight affects its performance, which is generally measured in terms of acceleration, top speed, and fuel consumption. Aluminum alloy is a light material with a high specific strength owing to which its use in the manufacturing of cars has tremendously increased. The use of aluminum alloy in space frame reduces the body weight of Audi A8 by 40% (Figure 1.2) (Miller et al., 2000).

Currently, all aluminum vehicles are also being produced on a commercial scale. Aluminum alloy sheets are widely used in inner and outer body panels of cars, which significantly reduce weight of vehicle. The sustained growth of industrial use of aluminum alloys depends to a great extent on the availability of a suitable joining process. Increasing use of aluminum in automobiles often requires dissimilar joining of steel with aluminum

TABLE 1.2 Specific Uses of Various Aluminum Alloys

Aluminum Alloys	Major Alloying Element	Typical Composition (wt.%)	Typical Properties and Application
1000 series	Unalloyed aluminum	>99 Al	Good electrical conductor, low strength: cooking foil, power transmission, utensils
2000 series	Copper	Al + 4–6 Cu + Mg	Strong heat-treatable alloy: aircraft external tanks, lower wings, fuselage
3000 series	Manganese	Al + Mn	Medium strength, excellent corrosion resistance, ductile: beverage cans, roofing, cooking pans, automotive radiators
5000 series	Magnesium	Al + 3 Mg	Strong work hardening alloy: pressure vessel, ship hulls, inner automotive body panel, boilers, storage tanks
6000 series	Magnesium + silicon	Al + Mg + Si	Moderate strength heat-treatable alloy: pipelines, bridges, external automotive body panel, structural members
7000 series	Zinc	Al + 6 Zn + 2 Mg + 1.5 Cu	Strong heat-treatable alloy: aircraft upper wings, fuselage
Al–Li alloys	Lithium	Al + 3 Li	Good strength to weight and low density: aircraft spar and skins

alloys, and employment of efficient joining techniques becomes highly crucial as these BMs have large differences in their physical, thermal, and chemical properties (Barnes and Pashby, 2000). A typical combination of strain hardenable Al–Mg (5xxx) alloys and the medium strength age hardenable Al–Mg–Si (6xxx) alloys is extensively used in automotive industry by car manufacturers. The 6xxx series alloys (e.g., AA6061) are exclusively used in external body panels and the 5xxx series alloys (AA5052) are used in inner body panels. But the biggest challenge with aluminum alloys is the problems associated with solidification during welding by conventional methods. Efficient welding process is required to weld the aluminum alloys so as to meet their heavy demand raised by user industries.

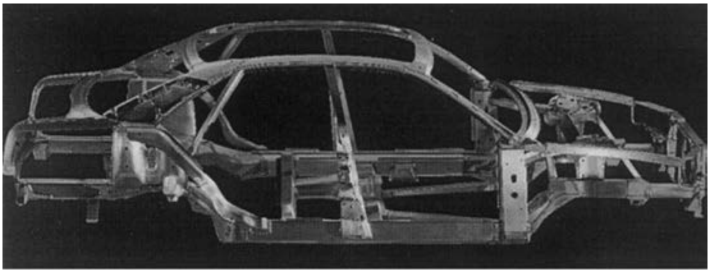

FIGURE 1.2 Aluminum space frame of Audi A8. (Reprinted from *Materials Science and Engineering A*, 280, W.S. Miller et al. Recent development in aluminum alloys for the automotive industry, 37–49, Copyright 2003, with permission from Elsevier.)

1.3 JOINING OF ALUMINUM ALLOYS

Despite several desirable mechanical properties possessed by aluminum alloys, they have not been able to completely replace other materials required by various industries. The major constraint that restricts the use of aluminum alloys is attributed to their joining process. Thus, novel joining techniques are required to efficiently weld them in order to fulfill the demand of user industries. Traditionally, mechanical fastening such as riveting, screwing, and occasionally arc welding had been used in fabrication of various parts for aircrafts and ships. However, mechanical fastening suffers from limitations such as it needs additional operations to maintain fit-up (i.e., creating holes and clamping, etc.), joints are prone to corrosion, and it is relatively difficult to make internal joints. Also, it acts as a crack initiation region in corrosive environment, which significantly reduces the joint strength (Barnes and Pashby, 2000).

Welding of aluminum alloys by fusion welding processes is difficult as compared to steel. Aluminum welding requires high heat input because of its high thermal conductivity and proper shielding gas due to high affinity to oxygen. Generally, aluminum alloys have melting point in the range of 570°C–650°C. Temperature requirement is high for achieving high heat input, which causes increase in the area of heat-affected zone (HAZ) that significantly deteriorates the quality of the welded joint. Also during welding of age hardenable aluminum alloys (2xxx, 6xxx, 7xxx) high heat input results in precipitate dissolution, which in turn degrades the mechanical properties. During welding of strain hardenable aluminum alloys (5xxx), high heat input results in loss of cold work, which in turn leads to reduction in mechanical properties. Moreover, relatively higher temperature