

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**INVESTIGATION OF SIMILAR AND
DISSIMILAR FRICTION STIR WELDED METAL
MATRIX COMPOSITES UNDER VARIABLE
LOADING**

by
Nahit ÖZTOPRAK

December, 2018
İZMİR

INVESTIGATION OF SIMILAR AND DISSIMILAR FRICTION STIR WELDED METAL MATRIX COMPOSITES UNDER VARIABLE LOADING

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Doctor of
Philosophy in Mechanical Engineering, Mechanics Program**

**by
Nahit ÖZTOPRAK**

**December, 2018
İZMİR**

Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**INVESTIGATION OF SIMILAR AND DISSIMILAR FRICTION STIR WELDED METAL MATRIX COMPOSITES UNDER VARIABLE LOADING**” completed by **NAHİT ÖZTOPRAK** under supervision of **PROF. DR. EMİNE ÇINAR YENİ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.



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ACKNOWLEDGEMENTS

I would first like to express my deepest gratitude to my supervisors Prof. Dr. Çınar Emine YENİ and Prof. Dr. Binnur Gören KIRAL for their excellent guidance, consistent support, encouragement and advices through the thesis. They always helped me in overcoming the difficulties encountered. It is my pleasure to have an opportunity work with them. I would also like to acknowledge Prof. Dr. Gökdeniz NEŞER for the useful discussions on the periodical meetings of this research. Special thanks are also due to Assoc. Prof. Dr. Derya EREN AKYOL for her support.

I thank especially to Hüseyin Tarık SERİNDAG (İskenderun Technical University) for his support and help about performing preliminary studies. I would thank to my colleagues at Dokuz Eylül University; in particular Akar DOĞAN and Gökçe Mehmet GENÇER for their encouragement and support. The incredible support of Gökhan ÖZDAMAR (EGE MATA) during the fatigue tests is also highly acknowledged. I wish to express my sincere thanks to Oylum ÇOLPANKAN for her technical assistance in the course of SEM analyses and contribution to this study.

Lastly and most importantly, I wish to express my cordial appreciation to my parents for their enormous love, understanding, patience and support and my older brother who have supported me throughout my education life. Without them, I would not be in a situation of writing a PhD thesis. Their endless love and perseverance gave me forces to make this study.

I am also grateful everyone who directly and indirectly supported me in the completion of this thesis.

This thesis was financially supported by Dokuz Eylül University Department of Scientific Research Projects under the project BAP-2016.KB.FEN.021.

Nahit ÖZTOPRAK

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ABSTRACT

Recently, increasing requirements to reduce weight in various modern industries have attracted an explicit interest in engineering applications of lightweight structural materials. Accordingly, metal matrix composites (MMCs) have acquired wide popularity due to their remarkable features. Sound joining of these materials has gained importance for applications in engineering structures and components. When compared with conventional joining methods, friction stir welding (FSW) seems to be an outstanding candidate due to its unique properties as a solid-state welding technique.

Few researches have been performed on the dissimilar friction stir butt joints of MMC-monolithic aluminum alloy so far and there is little information related to the effects of FSW process on the mechanical properties of both similar and dissimilar MMC welds. The present thesis investigates the weldability of particulate-reinforced MMCs between each other and also with different materials. As a result, similar and dissimilar sound joints without weld defects are achieved. Thereafter, microstructure, mechanical properties and fatigue response of the similar and dissimilar joints are investigated. In general, it has been seen that the mechanical properties of the similar and dissimilar joints are comparable with those of the base materials. It is the first time that the study on the fatigue behavior of MMC-aluminum alloy joint was conducted.

Keywords: Friction stir welding, metal matrix composites, dissimilar joints, fatigue, mechanical properties

DEĞİŞKEN YÜKLEME ALTINDA SÜRTÜNME KARIŞTIRMA KAYNAKLI BENZER VE FARKLI METAL MATRİKS KOMPOZİTLERİN İNCELENMESİ

ÖZ

Son zamanlarda, çeşitli modern endüstrilerde ağırlığı azaltmak için artan gereksinimler, hafif yapısal malzemelerin mühendislik uygulamalarına açık bir ilgi çekmiştir. Buna bağlı olarak, metal matris kompozitler (MMK) dikkat çekici özellikleri nedeniyle geniş popülerlik elde etmiştir. Bu malzemelerin emniyetli birleştirilmesi mühendislik yapılarındaki ve bileşenlerindeki uygulamalar için önem kazanmıştır. Diğer geleneksel birleştirme yöntemleriyle karşılaştırıldığında, bir katı hal kaynak tekniği olarak kendine özgü özellikleri sebebiyle sürtünme karıştırma kaynağı (SKK) mükemmel bir aday gibi görünmektedir.

Bu zamana dek MMK ve monolitik alüminyum alaşımının benzer olmayan sürtünme karıştırma alın bağlantısı üzerine az sayıda araştırma yapılmıştır ve SKK işleminin benzer ve benzer olmayan MMK kaynakların mekanik özellikleri üzerindeki etkileri ile ilgili çok az bilgi vardır. Bu tez parçacık takviyeli MMK'lerin birbirleri ve farklı materyaller ile kaynaklanabilirliğini araştırmaktadır. Sonuç olarak, kaynak hataları olmayan benzer ve farklı güvenilir bağlantılar elde edilmiştir. Sonrasında, benzer ve benzer olmayan bu bağlantıların içyapı, mekanik özellikler ve yorulma cevabı incelenmiştir. Genel olarak, benzer ve farklı bağlantıların mekanik özelliklerinin ana malzemelerinkiler ile karşılaştırılabilir olduğu görülmüştür. MMK-alüminyum alaşımı bağlantısının yorulma davranışı üzerine yapılan ilk çalışmadır.

Anahtar kelimeler: Sürtünme karıştırma kaynağı, metal matris kompozitler, benzer olmayan bağlantılar, yorulma, mekanik özellikler

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

The increasing demand in respect of weight reduction to enhance fuel economy, reduce exhaust gas emissions and to obtain higher operation efficiency have led to the use of light-weight materials in many engineering applications (Khodabakhshi, Simchi, Kokabi & Gerlich, 2016; Michael Rajan, Dinaharan, Ramabalan & Akinlabi, 2016; Mohammadnezhad et al., 2015). Accordingly, aluminum matrix composites (AMCs) have been drawing more attention of especially automotive, aerospace and defense industries due to their high strength to weight ratio, high thermal stability, excellent wear resistance, lower thermal expansion and advanced mechanical properties at elevated temperatures by comparison with corresponding monolithic alloys (Babu et al., 2016; Ceschini, Boromei, Minak, Morri & Tarterini, 2007a). Furthermore, particle-reinforced metal matrix composites are of an explicit interest owing to their low cost, manufacturing convenience, outstanding deformability and quasi-isotropic mechanical properties (Hussain, R. Hashemi, H. Hashemi & Al-Ghamdi, 2016; Ni, Chen, Xiao, Wang & Ma, 2013; Pirondi & Collini, 2009). Therefore, these materials are increasingly gaining favor in various industries such as automotive, aerospace, marine, railway, electronics and sporting goods (Pirondi, Collini & Fersini, 2008).

Growing usage of AMCs in many engineering applications has come to a point that the joining of these materials is a challenging problem to research extensively. The feasible welding processes of AMCs are generally conventional fusion welding and solid-state welding. However, fusion welding methods can demonstrate various undesired effects such as voids, cracks, solidification shrinkage, chemical reactions between matrix material and the reinforcement, precipitation distortion in the joint and so forth (Herbert, Shettigar, Nigalye & Rao, 2016). These problems commonly influence the mechanical properties of the joints negatively (Minak, Ceschini, Boromei & Ponte, 2010). Besides that, welding of AMCs and monolithic alloys in an

attempt to provide enhanced mechanical performance, obtaining cost-effective and superior assemblies is a critical secondary process in the manufacturing of most structures when these materials are practically used as the structural components. For this reason, sufficient joining of dissimilar materials is attractive in many engineering applications and can be acceptable so as to improve mechanical properties by use of AMCs only at determined locations in an engineering structure where necessary (Guo, Gougeon & Chen, 2012; Sharifitabar & Nami, 2011). On the other hand, joining of these materials through traditional fusion welding processes may result in undesirable effects due to the similar reasons such as chemical reactions between reinforcement-matrix materials, insufficient mixing of base and filler materials, dissolution of particle reinforcement, undesirable phases in the matrix material and presence of several inclusions (Feng, Xiao & Ma, 2008; Lee et al., 2006; Prater, Strauss, Cook, Gibson & Cox, 2013; D. Wang, Xiao, Q.Z. Wang & Ma, 2013). Therefore, friction stir welding (FSW) is considered as a promising solid-state joining method to resolve these unfavorable problems.

FSW is a rapidly emerging solid-state welding method that was developed in 1991 by The Welding Institute of United Kingdom (UK) especially for joining of high-strength aluminum alloys (Thomas et al., 1991). Afterwards, the method has been used in the welding of several high-strength metallic materials such as magnesium, copper, titanium, steel and metal-matrix composites that are difficult to weld by traditional fusion welding methods (Cam, 2011). The joining in FSW is generated by frictional heating between a nonconsumable tool having a stirring pin and the workpieces to be welded. As a result of the heating, plastic flow in the material achieves the welding throughout the weld line. The recrystallized finer scale grains or precipitates formed in this process result in the evolution of microstructure of the weld region. The features such as the process temperature being below the melting temperature of the workpieces, providing a homogeneous dispersion of the reinforcement by the rotating action of the tool, shortening the processing time, no need for cover gas or admixture material brings this method forward considering other welding methods (Avettand-Fènoël & Simar, 2016; Mishra & Ma, 2005; Salih, Ou, Sun & McCartney, 2015).

Fatigue is one of the most critical concerns for any welded structural materials subjected to dynamic loading in many engineering applications, even though FSWed joints provide several superior properties compared to those of fusion welds (Das, Chakraborty & Pal, 2014; Xu, Liu, Chen & Luan, 2014; Yan, Liu & Fang, 2016; Zhou et al., 2016). Therefore, fatigue performance of FSWed joints necessitates to be elucidated in detail. Generally, welding parameters and post-weld variables such as residual stresses and weld surface quality have significant effects on the fatigue strength of FSWed joints (He et al., 2016; Sharma, Dwivedi & Kumar, 2014). In addition, decline in stress concentration of the welded joints assures sufficient fatigue properties (Polezhayeva et al., 2015). To date, with respect to the researches on the fatigue properties of AMCs, several works have been devoted on the fatigue behavior of only oxide-ceramic particle (Al_2O_3) reinforced AMCs (Cavaliere, Rossi, Di Sante & Moretti, 2008; Ceschini, Boromei, Minak, Morri & Tarterini, 2007b; Pirondi, Collini & Fersini, 2008). As a matter of fact, there is no study related to the influence of tool rotation speeds on the fatigue response of FSWed AA6061+SiCp composite. In addition, there is little information related to the fatigue response of dissimilar FSWed joints between the AMC and monolithic aluminum alloy. To this end, this study focuses on the microstructures, mechanical properties and fatigue fracture behaviors of similar and dissimilar friction stir butt-welded AA6061/SiCp composite joints.

Within this thesis, a study on the microstructure and mechanical properties of the dissimilar joint was carried out in an attempt to understand the effects of post-weld heat treatment (PWHT) on microstructural evolution, microhardness, tensile and three-point bending properties of the dissimilar FSWed joint between AA6061/SiCp composite and AA6061-O, at first. Second of all, a well-rounded research on the microstructural evolution, hardness behavior, tensile properties, impact toughness and failure response under transverse impact of the dissimilar joint between AA6061-T6 and AA6061/SiC/20p composite was experimentally achieved. Thereafter, fatigue properties of the friction stir butt welded AA6061/SiC/20p composites were investigated at varying tool rotation speeds. The stress-based approach was studied on the analyses against fatigue failures of the similar joints.

Fractured surfaces of the joints were scrutinized to identify the characteristic features of fatigue failure. The tensile strengths, percentage of elongations of the similar joints were measured through the transverse tensile tests and joint performances of the joints were also calculated as part of the study. In addition, Vickers hardness profiles were determined throughout the mid-thickness of the welded joints. Finally, fatigue response of the dissimilar FSWed joint between AA6061/SiC/20p composite and 6061-T6 aluminum alloy was studied, in detail. Furthermore, fracture surfaces of the fatigue test specimens were investigated. Mechanical strength of the weld under monotonic tensile loading was also determined within the research.

1.2 About the Theme of Thesis

This work comprises of a certain part of the ‘Investigation of the Behaviors of Friction Stir Welded Composites under Dynamic Loads’ project. This project was supported by Dokuz Eylul University, Department of Scientific Research Projects under the Project id of 2016.KB.FEN.021 and investigated the weld properties of similar and dissimilar FSWed joints. In the thesis, the study of weldability of particulate-reinforced MMCs between each other and also with different materials, and investigation of the effect of FSW method on the microstructure characteristics, mechanical properties and fatigue behaviors of these joints are aimed by means of the foregoing project.

Background information on the thesis subject is presented in Chapter 2. Metal-matrix composites are investigated with regards to their classification, constituents, applications, fabrication techniques and welding methods. This chapter also gives a general overview of FSW from the point of operation principle, microstructural zones, probable weld defects, process parameters, application areas, advantages and drawbacks. Lastly, the topics of S-N curves, fatigue failure mechanism, fatigue in MMCs and fatigue design in welds are briefly discussed in the chapter.

Literature survey of the study is detailed in Chapter 3. There are various researches in the literature about the weld characterization, tool wear or parameter

optimization of FSWed both similar and dissimilar joints. However, determining the fatigue performance of similar and dissimilar FSWed AMCs is the lacking in literature and there were few studies related to this subject. In the view of such information, Chapter 4 includes the problem statement, scope of the study and objectives. This chapter also reviews the methods applied within the thesis.

Preliminary studies performed as part of the thesis are given in Chapter 5. Similar FSW of 6061-O aluminum alloys (AA6061-O) and dissimilar FSW of AA6061-O and AA7075-O are presented in terms of microhardness and tensile properties, especially.

Chapter 6, Chapter 7 and Chapter 8 are dedicated to the published three articles on dissimilar FSW of AA6061+SiCp/AA6061-O, dissimilar FSW of AA6061-T6/AA6061+SiCp and similar FSW of AA6061/SiC/20p-T1, respectively. Apart from these, results and discussion of the effects of FSW on the mechanical properties in terms of monotonic tensile, microhardness and fatigue behavior of dissimilar FSWed AA6061+SiCp/AA6061-T6 joint is also presented in Chapter 9.

Finally, suggestions for further works in addition to the findings and observations of this thesis are indicated in Chapter 10. This chapter also includes the summary of conclusions.

1.3 List of Publications

Three journal papers were published within the thesis as well as conference papers. The list of publications that is ordered according to the publishing dates is presented below:

- i. Oztoprak, Yeni & Kiral. (2017). Determination of the influences of various tool rotation speeds on the tensile properties of friction stir welded AA6061/SiCp composite. 3rd International Conference on Mechanics of Composites (MECHCOMP3). Bologna, Italy. 4 -7 July 2017.

- ii. Oztoprak, Yeni & Kiral. (2017). Impact behavior of nugget zone in dissimilar friction stir welded AA6061-T6 and AA6061/SiCp composite. 6th Rostocker International Conference: Thermophysical Properties for Technical Thermodynamics (THERMAM2017). Rostock, Germany. 17 -18 July 2017.
- iii. Oztoprak, Yeni & Kiral. (2018). Effects of post-weld heat treatment on the microstructural evolution and mechanical properties of dissimilar friction stir welded AA6061+SiCp/AA6061-O joint. Latin American Journal of Solids and Structures.
- iv. Oztoprak, Yeni & Kiral. (2018). Fatigue and monotonic tensile behaviors of friction stir welded AA6061/SiC/20p-T1 composite joints at various tool rotation speeds. Materials Research Express.
- v. Oztoprak, Yeni & Kiral. (2018). Dissimilar friction stir butt welding of AA6061-T6 and AA6061/SiCp composite: microstructural characteristics, impact toughness, hardness, strength under transverse impact. Transactions of the Indian Institute of Metals.

CHAPTER TWO

BACKGROUND

2.1 Introduction

The primal components of all natural and artifactitious structures comprise of materials. Both the evolution of available material features and the development on the variety of structural materials are in a close relationship with the technological advancements. Herewith, requirement on the enhancement of structural efficiency is at the ground of the emergence of new materials. Besides, in order to improve advanced structures and technology, new occasions are also provided by the new materials themselves (Vasiliev & Morozov, 2007).

Among the structural materials such as metallic materials, composites, polymers and ceramics, composites are gaining favour progressively. Herein, composite materials can loosely be defined as the combination of two or more constituent materials on a macroscopic scale to obtain a new material system with better material properties compared to the conventional materials. In this way, the engineering properties such as stiffness, mechanical strength, fatigue behavior, thermal features, corrosion and wear resistance can be enhanced through the development of a composite material. Typically, a reinforcement material and a base material (matrix) form a human-made composite material (Reddy, 2004).

Composite materials have found widespread applications throughout history. In other words, there are many areas of usage for both natural and artifactitious composites in old times. Nevertheless, it is not known when composites were firstly used. Even so, the relative impact of some structural materials in the chronological alteration is demonstrated in Figure 2.1. Based upon the figure, it was found that the importance of composite materials has been increasing since about the 1960s and it is estimated that the relative importance of composite materials will continue to grow. Accordingly, considering the fact that composite materials have expeditiously

progressed, new combinations of composite systems and emerging materials are expected to be continuously developed (Staab, 1999).

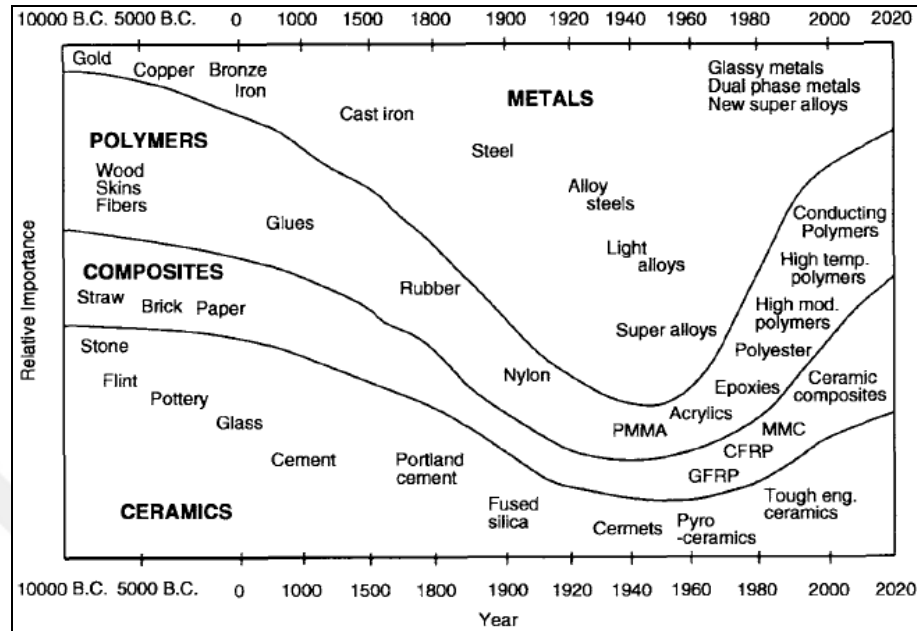


Figure 2.1 Relative importance of the structural materials historically (Staab, 1999)

As stated previously, a composite is generally made from two different phases: the discontinuous phase is called the reinforcement and the continuous phase is called the matrix material. The features, geometric properties and intensity of the constituents play a crucial role on the physical and mechanical properties of composites. In the design of a composite system, numerous factors such as the constituents' types, concentration of each constituent, boundary and loading conditions affect the composite structure and consequently mechanical performance of the created system (Staab, 1999).

When the classifications and types of composite materials are analyzed, composites are generally categorized by the structure of reinforcement material such as the fiber, particulate, flake, filled and laminar. Also, the advanced composites can usually be classified according to the matrix material. Polymer Matrix Composites (PMCs), Metal Matrix Composites (MMCs), Ceramic Matrix Composites (CMCs), Carbon-Carbon (CC) and Hybrid composites are the main types of composite

materials. Classifications and important types of composite materials are shown in Figure 2.2 and Figure 2.3, respectively (Vinson & Sierakowski, 2002).

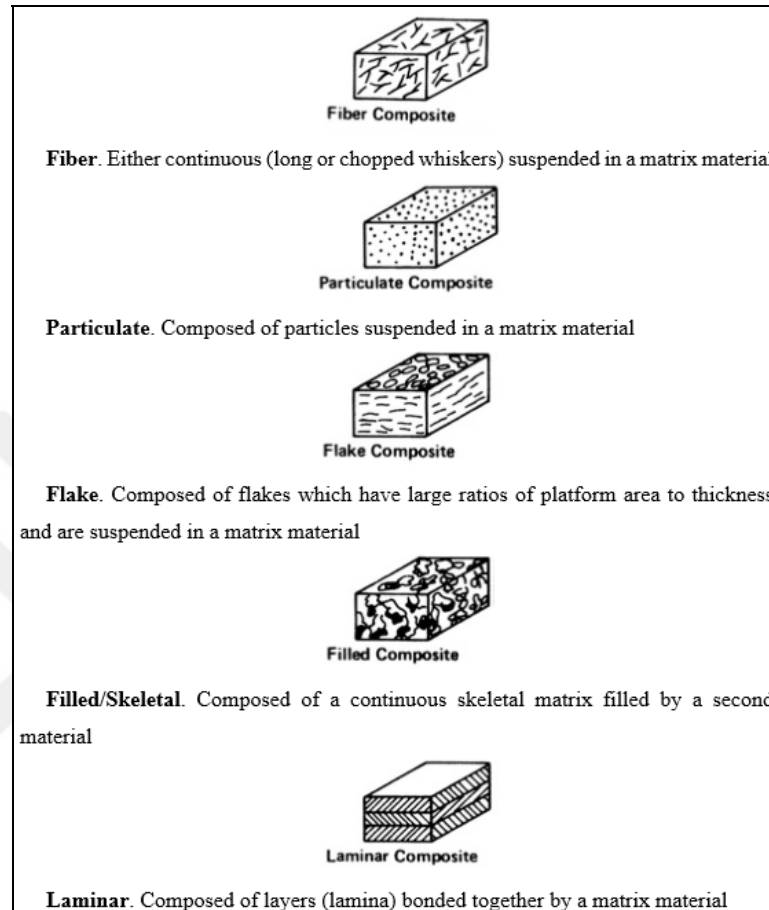


Figure 2.2 Schematics of composite material classifications (Vinson & Sierakowski, 2002)

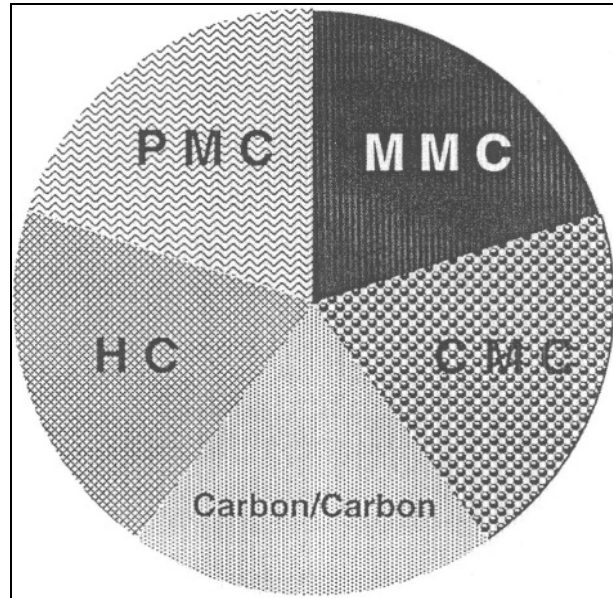


Figure 2.3 Pie chart of the principal composite materials (Vinson & Sierakowski, 2002)

2.2 Definition of MMCs

Metal matrix composites (MMCs) means that the composites have a metal matrix such as aluminum alloys, magnesium alloys or titanium alloys, as the name states. Metallic materials are principally reinforced in an attempt to enhance or reduce their physical or mechanical properties as needed in the design. To set an example, it is explicit that the strength of metallic materials can be improved while some thermal and electrical features of the materials can be decreased with the reinforcement of silicon carbide (SiC) fibers (Kaw, 2006).

MMCs are generally utilized for providing some significant advantages over conventional monolithic metals. These main advantages comprise of higher specific strength, elastic modulus, superior mechanical properties at elevated temperatures and lower thermal expansion features. Besides that, MMCs have received considerable attention owing to their outstanding utilities such as preferable fatigue and wear resistances, higher elastic behaviors, prominent thermal and electrical conductivities, moisture nonsusceptibility and higher operating temperatures over PMCs. On the other hand, MMCs have some drawbacks such as the properties of

high density and high processing temperature by comparison with PMCs (Kaw, 2006).

As noted earlier, aluminum, magnesium, copper and titanium can be enumerated as the most common matrix materials used in MMCs. When these alloys are evaluated, aluminum alloys, which can be utilized at and above the temperature of 300 °C, usually used with silicium carbide coated boron reinforcements. Among these alloys, AA6061 has an important place with the properties of high strength, resistance to corrosion and high toughness compared to other materials such as AA2024 and pure aluminum (1100). Considering magnesium alloys, it is known that the graphite reinforcements are generally used in conjunction with these alloys. Besides that, borsic fibres commonly constitute of titanium matrix that has an operating temperature of about 800 °C. Lastly, when the feature of high thermal conductivities are considered, copper matrix composites come into prominence. With the addition of graphite reinforcements, the drawbacks of monolithic copper such as high density and inadequate application temperature can be enhanced. Beside this, copper matrix composites with outstanding thermal conductivity and tensile behavior are also presented by the addition of niobium particles. Herein, it should be noted that the reinforcements should have compatible thermal features with the binder material so as to achieve sound metal matrix composites (Akovali & Uyanik, 2001).

2.3 Classification of MMCs

MMCs can consist of various configurations with regard to the types of reinforcing member and formation process. In this context, the general four categories of MMCs are (Mallick, 2008):

- I. Fiber-reinforced MMCs including continuous, discontinuous or whisker reinforcements.
- II. Particle-reinforced MMCs including particles or platelets that have sizes in between 0.5 and 100 μm . In this case, higher volume fractions can be obtained with the particulate addition compared to whiskers-reinforced composites.

III. Dispersion-strengthened MMCs including smaller particles, that are about $<0.1\text{ }\mu\text{m}$ in diameter, by comparison with particle-reinforced MMCs.

IV. The latter are in-situ MMCs, as the name indicates, implies the in situ formation of dispersed phase in the eutectic alloys.

Within fiber reinforced-MMCs, long carbon and boron fiber-reinforced composites have not found widespread usage area owing to the challenge in the fabrication of composite based on the chemical reactions between the reinforcement and matrix material, even though there have been long-term researches on these continuous fiber-reinforced composites. Accordingly, reduction on the mechanical properties of the composites becomes unavoidable as a result of the problem. Therefore, in order to remove or decline the problem about chemical reaction, surface treatments on fibers have been introduced. However, this brings another problem on the fiber cost in addition to the high cost of the MMC fabrication by the supplement of long carbon or boron fibers. Because of this, whiskers and particles of silicium carbide (SiC_w and SiC_p) have increasingly been under consideration in recent years. Figure 2.4 exhibits the tensile features of common SiC_w and SiC_p reinforced aluminum matrix composites. When SiC reinforcement generally analyzed, it is known that SiC have outstanding properties from the point of resistance to chemical reactions at the working temperatures used. Besides, compared to the continuous fibers such as carbon and boron, they are quite advantageous in terms of being more affordable. Moreover, the efficient integration into the metallic binders through the prominent production methods of MMCs is another important merit of these reinforcements (Mallick, 2008).

Material (Alloy/SiC _w or p/ vol. frac.-temper)	Orientation	UTS, MPa (ksi)	YS, MPa (ksi)	Elongation, %	Modulus, GPa (Msi)
2009/SiC _w /15%-T8 (Sheet)	L	634 (91.9)	483 (70)	6.4	106 (15.37)
	T	552 (80)	400 (58)	8.4	98 (14.21)
2009/SiC _p /20%-T8 (Sheet)	L	593 (86)	462 (67)	5.2	109 (15.8)
	T	572 (82.9)	421 (61)	5.3	109 (15.8)
6013/SiC _p /15%-T6 (Extrusion)	L	517 (75)	434 (62.9)	6.3	101 (14.64)
6013/SiC _p /20%-T6 (Extrusion)	L	538 (78)	448 (65)	5.6	110 (15.95)
6013/SiC _p /25%-T6 (Extrusion)	L	565 (81.9)	469 (68)	4.3	121 (17.54)
6013/SiC _w /15%-T6 (Extrusion)	L	655 (95)	469 (68)	3.2	119 (17.25)
6090/SiC _p /25%-T6 (Extrusion)	A	483 (70)	393 (57)	5.5	117 (17)
6090/SiC _p /40%-T6 (Extrusion)	A	538 (78)	427 (61.9)	2.0	138 (20)
7475/SiC _p /25%-T6 (Extrusion)	A	655 (95)	593 (86)	2.5	117 (17)

Notes: L, longitudinal; T, transverse; A, average.

Figure 2.4 The typical tensile features of some SiC_w and SiC_p reinforced aluminum matrix sheets and extrusions (Mallick, 2008)

In this subchapter, commonly accepted configurations of the particulate metal matrix composites are handled based upon the scope of the thesis. Accordingly, particle reinforced composites with metallic matrix can also be divided into two common configurations (Jones, 1999):

- I. Metallic particles in metallic matrix composites
- II. Nonmetallic particles in metallic matrix composites

Within these combinations, it is infeasible that the dissolving of a metallic particle in a metal matrix. In order to enhance the processability of copper and steel, lead particles are utilized in general. Besides, tungsten, molybdenum, chromium particles, which have inherently brittle features at room temperature, can be incorporated into a metallic matrix with a ductile manner. Hereby, a MMC with ductile characteristic is obtained. At this point, liquid sintering process commonly used to obtain more ductile particles by virtue of the penetration of the binder around the reinforcing particles (Jones, 1999).

In the second combination, cermets, which are obtained by the addition of nonmetallic particles into a metal matrix, can be divided into two main categories as oxide-based and carbide-based cermets. Considering those of oxide-based, these cermets are usually used in the practices of tool making and applications of elevated temperature that require abrasion resistance. In other respects, there are various fields of application for the carbide-based cements that comprise of carbides of titanium, tungsten and chromium as the reinforcement particles. For instance, it is known that tungsten carbide (WC) reinforced cobalt matrix composite is used in several machine components such as valves and wiring moulds that necessitate enhanced hardness. In addition, turbine parts as an application of elevated temperatures are prominent machine elements that can be manufactured from titanium carbide-reinforced nickel or cobalt matrix composites. Moreover, chromium carbide-reinforced cobalt matrix composites are used in valves because their outstanding properties of high erosion and corrosion resistance. In addition to all these, both oxide-based and carbide-based particles have the fields of application on some parts of nuclear reactors (Jones, 1999).

2.4 Constituents of Particle-reinforced MMCs

Particle reinforced metal-matrix composites have received substantial attention in many engineering applications of aerospace and industry owing to their physical and mechanical properties. Herein, coherency of the composite constituents play a crucial role on the improved material properties obtained. Making the composite suitable to require particular demands is only possible by addition of specific reinforcing particles and modifying the volume fraction of them in the metallic matrix. Therefore, reinforcement selection has an importance in an effort to avoid high cost, undesirable physical and mechanical properties and drawbacks in the manufacture of the composite (Smith, 2001).

2.4.1 Common Reinforcements for Particle-reinforced MMCs

As stated previously, particle reinforced MMCs are of an explicit interest in many engineering fields that necessitate improved fatigue feature, enhanced abrasion resistance or superior material strength. Besides that, the composites may be intended in order to accommodate more than one prominent feature. Here listed are the common reinforcements generally used in a particle reinforced MMC to provide these outstanding properties. Also, Table 2.1 summarizes the typical properties of these commonly used reinforcements.

Table 2.1 Physical and mechanical properties of commonly used ceramic particulate reinforcements (Smith, 2001)

Ceramic	Density, g/cm ³	Elastic modulus		Knoop hardness	Compressive strength		Thermal conductivity		Coefficient of thermal expansion		Specific thermal conductivity, W · m ² /kg · K
		GPa	10 ⁶ psi		MPa	ksi	W/m · K	Btu · ft/h · ft ² · °F	10 ⁻⁶ /K	10 ⁻⁶ /°F	
SiC	3.21	430	62.4	2480	2800	406.1	132	76.6	3.4	6.1	41.1
B ₄ C	2.52	450	65.3	2800	3000	435.1	29	16.8	5.0	9.0	11.5
Al ₂ O ₃	3.92	350	50.8	2000	2500	362.6	32.6	18.9	6.8	12.2	8.3
TiC	4.93	345	50.0	2150	2500	362.6	20.5	11.9	7.4	13.3	4.2

Considering the aforementioned reinforcements in turn, it is known that SiC reinforced MMCs have more widespread usage areas compared to other reinforcements. The addition of SiC in a metallic matrix provides several advantages to the composite such as enhanced material properties in terms of strength, stiffness, thermal conductivity, abrasion and fatigue resistance and diminished thermal expansion. In addition, the properties such as the density being relatively low and being cost-efficient bring this reinforcement forward by comparison with the others. Herein, it is worthwhile to mention that the size and shape of reinforcement significantly affect the behavior of composite. To exemplify, the utilization from fine particles is an important factor to obtain enhanced fatigue behavior. In order to provide uniform dispersion of particles, equalizing the sizes of reinforcements and metallic matrix also play a crucial role. The influences of reinforcement particle size on the substantial properties of a composite are demonstrated in Figure 2.5 (Smith, 2001).

		Yield strength	Ultimate strength	Modulus	Ductility	Fatigue strength	Crack initiation resistance	Formability
Reinforcement particle size and effects	Fine	↑	↑	↑	↓	↑	↑	↓
	Coarse	↓	↓	↓	↑	↓	↓	↑

Figure 2.5 Summary of the influence of alteration in particle size on composite properties (Smith, 2001)

When boron carbide is investigated, it is clear that this reinforcement is especially used for composite systems that require low chemical reaction with the metallic matrix and low density. Besides, boron carbide has an outstanding facility to neutron absorption. Therefore, B₄C is being evaluated for the applications of nuclear confinement. Furthermore, weldability and castability of B₄C-reinforced MMCs make this reinforcement attractive in many engineering applications owing to its nonreactive feature in the matrix. In opposition to those of SiC and B₄C, aluminum oxide (Al₂O₃) reinforced MMCs present lower mechanical properties with regards to the strength, stiffness and fracture toughness. Nevertheless, this reinforcement finds wide applications especially in the fabrication of cast MMCs due to its nominal nonreactive feature and affordable charge. Unlike the aforesaid three reinforcements, titanium carbide (TiC) is primarily used for elevated-temperature applications, merely. Based upon its attractive feature of stability at elevated temperatures, TiC is commonly utilized for nickel and titanium alloys-based MMCs without any chemical reaction with metallic matrix. However, the downsides of this reinforcement can be enumerated as high price and high density features. Thus, these limitations highlight the importance of advisable employment of TiC particles only at elevated-temperature applications (Smith, 2001).

2.4.2 Metallic Matrices for Particle-reinforced MMCs

The characteristics of matrix material, reinforcement and interface between binder materials and reinforcements play a significant role on the features of MMCs.

Therefore, in order to obtain MMCs with the property of high strength to weight ratio in many engineering applications such as automotive, space and aerospace, researches on the metallic matrices of especially aluminum and titanium alloys are increasingly gaining favour. Herein, the requirements for the designed composite systems such as strength, operating temperature and cost determine the needed metallic matrix material. For moderate and elevated-temperature applications, titanium alloys are known as the outstanding candidate. On the other hand, aluminum alloys find wide application due to their prominent lower density and lower cost compared to titanium alloys. In addition to all these, other important parameters such as fatigue behavior, toughness and ductility are nonignorable factors in the selection of the metallic matrix (Pandey, 2001).

2.4.2.1 Aluminum Alloys

Commonly used aluminum alloys in the manufacturing of MMCs can be divided into three classes: wrought commercial aluminum alloys, high temperature aluminum alloys and, lighter and high-modulus alloys. When these aluminum alloys are scrutinized carefully, it is known that the wrought heat treatable aluminum alloys such as 6xxx (Al-Mg-Si), 2xxx (Al-Cu-Mg) and 7xxx (Al-Zn-Mg-Cu) series have well-rounded areas of usage compared to the other aluminum classes. To obtain enhanced mechanical properties thank to precipitation hardening, heat treatment is applied to these alloys. They have found wide applications especially in the aerospace and other engineering applications due to their broad array of ductility and strength features. Considering the fact that 6xxx series alloys have outstanding fracture toughness and ductility, these heat treatable alloys have received remarkable attention amongst other two series for the fabrication of MMCs, even though some mechanical properties of these alloys such as strength are lower by comparison with Al-Cu-Mg (2xxx) and Al-Zn-Mg-Cu (7xxx) series. The typical tensile properties and chemical compositions of generally used classes of heat treatable aluminum alloys can be seen in Table 2.2. Based on their properties of high ductility, corrosion resistance and good weldability, these alloys are commonly utilized for medium-strength engineering applications. Among Al-Mg-Si alloys, 6061 aluminum alloys

(AA6061) with the balanced amounts of Mg and Si are known as one of the most familiar heat treatable alloys. In order to enhance the corrosion resistance characteristic of AA6061, usually 0.2%Cr is supplemented to this alloy. Besides that, this also includes titanium in an effort to designate recrystallization process. By the way, it is worthwhile to mention that titanium, chromium, zirconium and manganese are commonly utilized for grain-refining process in the aluminum alloys (Pandey, 2001). In light of these explanations, it should be noted once again that the feature of metallic matrix has a significant role on the mechanical properties of a particle reinforced MMC.

Table 2.2 Chemical compositions and tensile features of some heat treatable aluminum alloys (Pandey, 2001)

Alloy	Composition	Temper	Yield strength in 0.2%		Ultimate tensile strength		Elongation, %	Fracture toughness (K_{Ic})	
			MPa	ksi	MPa	ksi		MPa $\sqrt{m}$	ksi $\sqrt{in.}$
6061	Al-1Mg-0.6Si- 0.25Cu-0.19Cr-0.1Ti- 0.7Fe	T6	275	39.9	310	45.0	12	27	25
6063	Al-0.7Mg-0.4Si- 0.1Cu-0.1Cr-0.1Ti- 0.35Fe	T6	215	31.2	240	34.8	12	...	...
2014	Al-4.5Cu-0.5Mg- 0.26Mn-0.7Fe-0.8Si	T6	410	59.5	480	69.6	13	31	28
2024	Al-4.3Cu-1.5Mg- 0.6Mn-0.5Fe-0.5Si	T8	450	65.3	480	69.6	6	26	24
2124	Al-3.9Cu-1.5Mg- 0.6Mn-0.3Fe-0.2Si	T8	440	63.8	490	71.1	8	32	29
2618	Al-2.3Cu-1.6Mg-1Ni- 1.1Fe-0.15Fe-0.15Si	T61	330	47.9	435	63.1	10	...	...
2219	Al-6.3Cu-0.02Mg- 0.3Mn-0.3Fe-0.2Si- 0.1Zr	T87	315	45.7	475	68.9	10	36	33
7075	Al-5.6Zn-2.5Mg- 1.6Cu-0.23Cr-0.2Ti	T73	430	62.4	500	72.5	13	32	29
7050	Al-6Zn-2.3Mg-2.3Cu- 0.11Zr-0.15Fe-0.12Si	T7	510	74.0	550	79.8	11	33	30
7090 ^(a)	Al-8Zn-2.5Mg- 0.95Cu-1.45Co- 0.15Fe-0.12Si	T7	580	84.1	620	89.9	9	26	24
7091 ^(a)	Al-6.5Zn-2.5Mg- 1.45Cu-0.4Co- 0.15Fe-0.12Si	T7	545	79.0	590	85.6	11	46	42
CW67 ^(a)	Al-9Zn-2.5Mg-1.5Cu- 0.14Zr-0.1Ni	T7	580	84.1	614	89.1	12	43	39

^(a) Alloys fabricated through powder metallurgy process

2.4.2.2 Titanium Alloys

As noted earlier, titanium alloys are very attractive with outstanding physical and mechanical properties for the elevated-temperature engineering applications such as stationary gas turbines, aircraft and automotive engines (Lapin et al., 2017). Besides that, titanium alloys find wide applications for MMCs owing to their superior strength and high temperature features by comparison with aluminum alloys (Pandey, 2001). Regarding commonly used titanium alloys utilized for MMC applications, the moderately alloyed alpha family (such as commercially pure Ti and Ti-5Al-2.5Sn), the intermediate alpha-beta alloys (such as Ti-6Al-4V), the metastable beta class (such as Ti-10V-2Fe-3Al and Ti-15V-3Cr-3Sn-3Al), and the stable beta alloy class (such as Ti-30Mo) can be enumerated as the generally used four fundamental classes (Smith & Froes, 1984). Among titanium alloys, Ti-6Al-4V has been commonly used for the structural applications in aircraft, aerospace and sporting goods due to their outstanding properties of high strength to weight ratio, good corrosion resistance and mechanical strength at elevated temperatures (Anandajothi, Ramanathan, Ananthi & Narayanasamy, 2017; Zi-Run et al., 2017). Herein, discontinuously reinforced titanium-matrix composites possess a considerable potential in the engineering applications of automotive and aerospace industries owing to their capability at elevated temperatures, prominent corrosion resistance and high strength (Chen et al., 2017). Considering particle reinforcements that are compatible with titanium matrix, TiC has attracted researchers due to its chemical stability, high strength and elastic modulus, high hardness and similar physical properties such as density and thermal expansion coefficient with titanium alloys (He, Chang, Wu & Zhang, 2017; Zhang, Song, Wei, Yang & Dai, 2017).

2.4.2.3 Magnesium Alloys

The attracting characteristics of magnesium (Mg) alloys such as low density, good sound absorption, high damping and specific heat capacity make them outstanding candidates for MMCs as a metallic matrix (Kucuk, Elfarah, Islak & Özorak, 2017). Besides that, magnesium alloys are widely used in the automotive, aerospace and

electronic industries considering these properties (Braszczyńska-Malik & Kamieniak, 2017). Herein, Mg alloys have attracted remarkable interest owing to their lower density by comparison with other structural materials, especially. These alloys are accepted as the lightest structural materials due to their density features that are about two-thirds of aluminum and one-fifth of steel (Singh & Bala, 2017). On the other hand, Mg alloys present some drawbacks such as lower corrosion and creep resistance, and poor strength at high-temperature applications (Bhadouria, Kumar, Thakur, Dixit & Arora, 2017). In order to overcome these drawbacks and enhance the properties of Mg alloys, ceramic particles (carbides, nitrides and oxides), metallic and nonmetallic particles, fibers, whiskers and hybrid reinforcements can be incorporated in a Mg-alloyed matrix. At this juncture, due to the superior features such as more isotropic mechanical properties, ease of fabrication and cost-effectiveness by comparison with other configurations, particle reinforced Mg-matrix composites have commonly experienced wide applications (Zeng et al., 2017). In addition to particle-reinforced composites, carbon fiber-reinforced Mg-matrix composites have attracted significant interest in many engineering applications of automotive, aerospace and military industries particularly due to their high specific strength (Qi et al., 2017). Among Mg alloys as a lightweight metallic matrix, AZ91D is the most common alloy owing to its good mechanical strength, resistance to corrosion and castability (Anbuechziyan, Mohan, Sathianarayanan & Muthuramalingam, 2017). In addition, the major reinforcements utilized for Mg matrix composites are generally SiC, TiC, B₄C, Al₂O₃, Y₂O₃ and carbon nanotubes (Braszczyńska-Malik & Przełozynska, 2017; Nelson, Agne, Anasori, Yang & Barsoum, 2017; Turan, Akgul, Turen & Ahlatci, 2017; Zhang et al., 2017).

2.4.3 Aluminum-based MMCs

Among all particle-reinforced MMCs, aluminum matrix composites (AMCs) are one of the irreplaceable materials for many engineering applications in modern industry owing to their enhanced mechanical and physical properties such as high strength, stiffness and quasi-isotropic properties. There are several effective reinforcements used in AMCs such as SiC, Al₂O₃, TiC, TiB₂, WO₃, and so on (Dan

et al., 2017; Y. Zhao, Ma, Chen, X. Zhao & Liu, 2017). Considering these common reinforcements, SiC-reinforced AMCs have come into prominence due to their outstanding elastic modulus, dimensional stability, lower thermal expansion coefficient and enhanced wear resistance by comparison with monolithic alloys as well as their relatively cost-effectiveness (Huang, Zhang, Xiao & Ma, 2017). On the other hand, incorporation of SiC reinforcements can create unfavorable brittle phases, which retrogress interfacial bonding in a MMC, due to their possible reaction with alloying elements and aluminum alloy itself. By contrast, TiB₂ has proven to be a promising candidate for AMCs owing to its feature of fully wettability by aluminum matrix (X. Liu, Y. Liu, Huang, Han, & Wang, 2017).

In addition to all these reinforcements, silicon nitride (Si₃N₄), graphite and others have been finding suitability in particular applications. To give an example, it is known that the graphite reinforced AMCs, which have superior resistance to abrasion and anti-friction feature, have been utilized especially for tribological application areas. Regarding SiC reinforcements once again, it is also worth to mention that the increment in the reinforcement volume fraction enhances tensile strength, yield strength and modulus of elasticity and declines the failure elongation, ductility and fracture toughness. Besides that, the increment in reinforcement volume fraction has a significant effect on the decrease of thermal expansion coefficient, thermal and electrical conductivities. The effects of reinforcement on certain physical and mechanical properties depending upon reinforcement volume percent are demonstrated in Figure 2.6 (Campbell, 2010).

Taking into account the common applications of AMCs, a standard notation system was created by the Aluminum Association. Thereafter, the American National Standards Institute has approved this designation system. According to ANSI 35.5-1992, for instance, 7075/Al₂O₃/10p describes aluminum alloy 7075 reinforced with 10 volume percent of alumina (Al₂O₃) particles. Another example, 2124/SiC/25w identifies AA2124 reinforced with 25 volume percent of SiC whiskers (Campbell, 2010). Herein, it should be noted that the rebuilt form of ANSI 35.5 was developed in 2013 as ANSI H35.5-2013 Metal Matrix Composite. As to their

manufacturing methods, solid-base and liquid-base techniques were performed to fabricate AMCs. However, main limitations to the utilization of solid-base and liquid-base procedures are poor bonding strength between reinforcement/matrix material and incomplete wettability of reinforcement in matrix melts and unfavorable interfacial phase formation (Esmaily, Habibolahzade & Tajally, 2017).

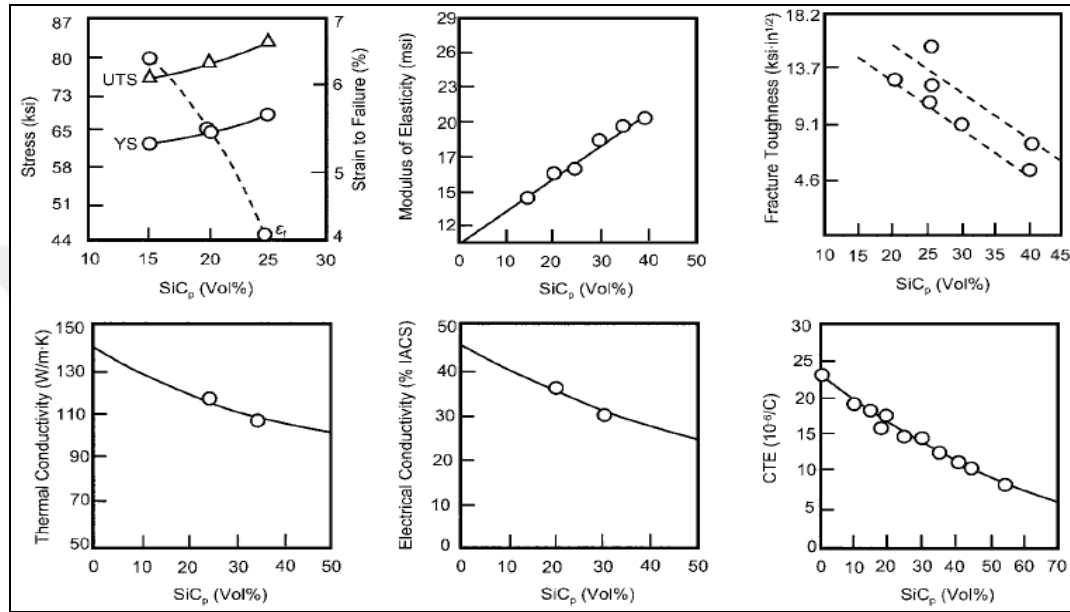


Figure 2.6 Physical and mechanical properties of SiC_p -reinforced AMCs as a function of reinforcement volume fractions (Campbell, 2010)

2.5 Familiar Applications of MMCs

Common applications for MMCs are put in an appearance in various industries such as aerospace, automotive and electronics. In addition, these materials also find potential applications in commercial and industrial products (Hunt, 2007).

2.5.1 Aerospace

Considering the fact that the engineering applications in aircraft industry necessitate superior mechanical properties such as strength, fracture toughness, fatigue and corrosion resistance in conjunction with cost-effectiveness, only AMCs have received a great deal of attention for aircraft structure. AA6092/ SiC /17.5p

sheets were utilized in the ventral fins and fuel access door covers of Lockheed F-16 aircraft instead of monolithic aluminum alloys. The photograph of U.S. Air Force F-16 with the notification of composite ventral fin is presented in Figure 2.7. Thus, service life of these components improves through the increased specific stiffness. Besides that, in order to provide the reduction in weight and fabrication cost, SiC reinforced AA2009 replaced a titanium part in the Eurocopter rotor sleeve. Moreover, SiC-reinforced AMC is used as a substitute for carbon fiber-reinforced polymeric tube that is used as floor support strut in Airbus aircraft. Regarding space structures, continuous fiber-reinforced AMCs find wide applications in the space shuttle and antenna boom. There are many other aerospace applications of MMCs. For example, replacement of monolithic aluminum rack by the AA6061/SiC/25p composite, which assures 30% of reduction in weight, has been reported. Furthermore, AA6061/SiC/40p has been drawing attention in various aerospace applications such as optical system gimbal and inertial guidance unit (Hunt, 2007).



Figure 2.7 The F-16 jet fighter contains ventral fins and fuel access door covers made from the AMC. The composite ventral fin is displayed by the red arrow (Hunt & Herling, 2004)

In the case of aeroengine applications, static and variable vanes at the ground of the compressor and bypass structure of the fan are the potential practices of AMCs. At this point, it is worthwhile to note that these potential applications have approximately 150 °C of service temperature. Therefore, AMCs are significant candidates as a substitute for unreinforced aluminum and titanium alloys where high mechanical strength to weight ratio is a substantial criterion apart from elevated-temperature applications. Nevertheless, the higher cost of AMCs compared to both

aluminum and titanium alloys limits these materials to find wider applications in many engineering structures. Within potential applications of AMCs in aeroengines, the titanium guide vanes of Trent engine titanium, which necessitate high stiffness, good fatigue features and high corrosion and erosion resistance, are replaced with AMCs. In this way, reduction in weight of 15% and cost reduction of 50% are provided, roughly. Figure 2.8 shows the assembly of aluminum-matrix-composite fan outlet guide vanes (Hooker and Doorbar, 2004).



Figure 2.8 AMC application in guide vane assembly of the Trent engine (Hooker and Doorbar, 2004)

2.5.2 Automotive

In order to meet the requirements of fuel economy, reduced gas emissions and safetied of a vehicle in conjunction with cost-effectiveness, automotive industry has been driving considerable attention toward lightweight materials. Herein, AMCs provide several advantages in engine applications and other structural components particularly with their high strength to weight ratio. Among AMCs, especially SiC and Al_2O_3 reinforced particulate composites have received broad acceptance in the fabrication of engine blocks, pistons, brake rotors, connecting rods, drive shafts and other structural engineering parts. Familiar applications of some MMCs are summarized in Table 2.3. Considering engine blocks and pistons, enhanced engine efficiency is provided by the application of AMCs. Besides that, improved cylinder pressures can also be achieved by using AMCs. Toyota has been using short Al_2O_3

fiber-reinforced MMC as a piston material in its diesel engine since 1985. Regarding brake rotors, Al/SiC_p composites find wide applications in many manufacturers such as General Motors EV-1, Chrysler and Lotus Elise. These composite brake rotors permit reduction in the weight in the order of 50% and provide decline in the abrasive wear rate by comparison with cast iron (Prasad & Asthana, 2004).

Table 2.3 Showed applications of selected cast AMCs in the automotive industry (Prasad & Asthana, 2004)

Manufacturer	Component and composite
Duralcan, Martin Marietta, Lanxide	Pistons, Al/SiC _p
Duralcan, Lanxide	Brake rotors, calipers, liners, Al/SiC _p
GKN, Duralcan	Propeller shaft, Al/SiC _p
Nissan	Connecting rod, Al/SiC _w
Dow Chemical	Sprockets, pulleys, covers, Mg/SiC _p
Toyota	Piston rings, Al/Al ₂ O ₃ (saffil) & Al/Boria _w
Dupont, Chrysler	Connecting rods, Al/Al ₂ O ₃
Hitachi	Current collectors, Cu/graphite
Associated Engineering, Inc.	Cylinders, pistons, Al/graphite
Martin Marietta	Pistons, connecting rods, Al/TiC _p
Zollner	Pistons, Al/fiberfrax
Honda	Engine blocks, Al/Al ₂ O ₃ – C _f
Lotus Elise, Volkswagon	Brake rotors, Al/SiC _p
Chrysler	Brake rotors, Al/SiC _p
GM	Rear brake drum for EV-1, drive-shaft, engine cradle, Al/SiC _p
MC-21, Dia-Compe, Manitou	Bicycle fork brace and disk brake rotors, Al/SiC _p
3M	Missile fins, aircraft electrical access door, Al/Nextel _f
Knorr-Bremse; Kobenhavn	Brake disc on ICE bogies, SiC/Al
Alcoa Innometalx	Multichip electronic module, Al/SiC _p
Lanxide	PCB Heat sinks, Al/SiC _p
Ceracast	Electronic packages, Al/graphite foam
Textron Specialty Materials	PCB heat sinks, Al/B

Cylinder liners, connecting rods and suspension components are also prominent possible applications of AMCs for automakers. When aluminum engine blocks are analyzed, these machine elements generally comprise of cast iron cylinder liners owing to the low wear resistance of aluminum alloys. Therefore, Honda and Porsche have been practising on MMC cylinder liners that have enhanced wear characteristics and superior cooling efficiency ratios by comparison with cast iron cylinder liners. Regarding connecting rods and suspension components such as wheel hubs or control arms, aluminum matrix nano-composites may be outstanding candidates for the replacement of steel and titanium connecting rods or cast iron suspension components. In addition to all these, MMCs are ideal candidates for the applications

of crankshaft journals, accessories, chassis, battery and so forth in an automobile (Macke, Schultz & Rohatgi, 2012). Figure 2.9 shows the Al/graphite composite bearing used in a connecting rod.



Figure 2.9 A bearing manufactured from cast Al/graphite composite (Rohatgi, 1991)

2.5.3 Electronic Packaging and Thermal Management

In addition to the previously mentioned familiar practices, MMCs are also continuously finding their application in the fields of electronic packaging and thermal management. Herein, SiC-reinforced AMCs, carbon fiber-reinforced aluminum and copper composites have been attractive materials among other configurations. Considering the cost-effectiveness of SiC particle-reinforced AMCs, these composites with favorable features of thermal conductivity rise to prominence by using SiC particles with high purity. Besides, these composites have significant advantages based on their affordable manufacturing processes, which provide near-net-shape results, compared to conventional materials. Al/SiCp composite microwave carrier and package are exhibited in Figure 2.10. Having a lightweight feature and higher thermal conductivities compared to corresponding materials make these composites ideal candidates for these applications. Powder metallurgy is commonly used for the fabrication of these components. Besides that, Al/SiC

packages have also been manufactured through investment casting. Furthermore, diamond and aluminum nitride (AlN) particles have been taken into consideration based upon experimental researches (Zweben, 1992).

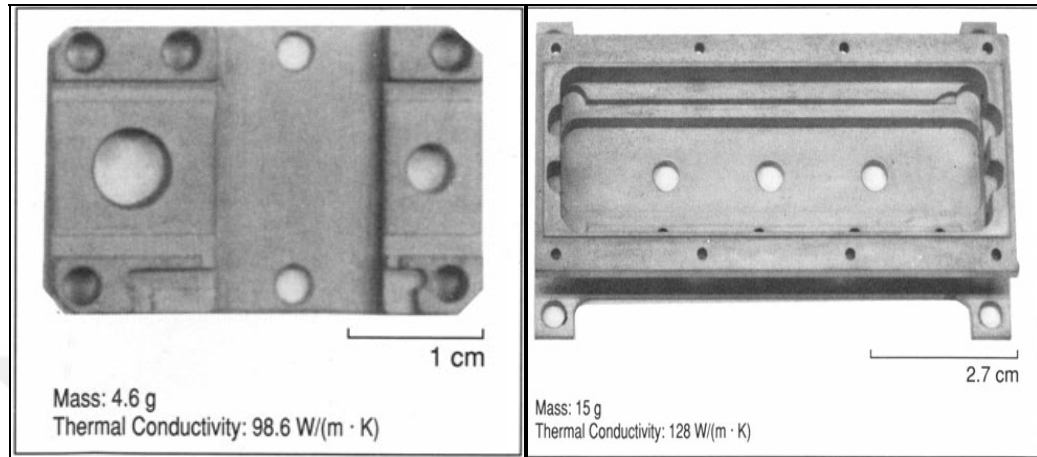


Figure 2.10 Al/SiCp composite of (a) microwave carrier (b) microwave package (Zweben, 1992)

The increasing demand for thermal management of materials in electronic components such as microelectronics and semiconductors has led to the use of MMCs owing to their superior thermal conductivity that has important effects on the dissipation of heat and ultra-low thermal stresses. Taking their superior properties of thermal conductivity into consideration, SiC/metal, carbon/metal and diamond/metal composites are prominent configurations. Besides that, AMCs are more attractive than other matrix materials where high strength to mass ratio is required, primarily (Qu, Zhang, Wu & Ren, 2011). Examples of the selected near-net-shape MMCs are seen in Figure 2.11.

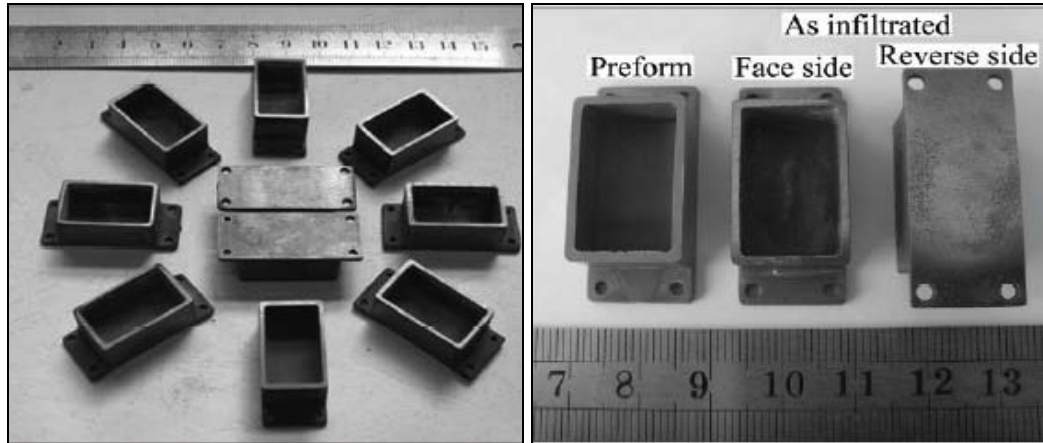


Figure 2.11 Metal-matrix preforms fabricated by (a) Infiltrated Al/SiCp and (b) Infiltrated Cu/SiCp (Qu, Zhang, Wu & Ren, 2011)

Recently, carbon nanotubes (CNTs) are also considered as an outstanding candidate as a reinforcement in copper for the contemporary applications of electronic packaging. Electrodeposition of CNTs-reinforced copper is one of the known practices. Figure 2.12 demonstrates the aforesaid composite as a thin foil application (Aryasomayajula & Wolter, 2013).



Figure 2.12 Thin foil made from copper-CNT composite (Aryasomayajula & Wolter, 2013)

2.5.4 Potential Applications in Commercial and Industrial Products

The characteristic properties of MMCs have also given these materials opportunity in the widespread applications from bicycle to nuclear reactors. Considering bicycle industry, frames, handlebars and seat posts are familiar applications of MMCs. At this point, it is worth noting that the industry demands good durability and stiffness features from the structural materials. For the sake of example, one company has used Al_2O_3 -reinforced 6061 aluminum alloy for the bicycle frame. Another example is B_4C -reinforced AMCs that are promising candidate for nuclear shielding applications such as storage casks. Besides all these, AA6061/SiC/20p was also utilized for the mast of racing vessels generally made from unreinforced aluminum (Hunt, 2007).

2.6 Manufacturing of MMCs

In this subchapter, the fabrication techniques of MMCs are concisely elucidated. There are many techniques for the manufacturing of MMCs. These processes can be divided into various categories such as liquid-state techniques, solid-state techniques, deposition techniques and in-situ processes. In liquid processing techniques, the composite takes shape as a result of the solidification of molten metallic matrix in which reinforcements are incorporated. Wetting between the reinforcement and the molten metal is the main consideration within the process so as to obtain a high mechanical performance. Herein, coating of the dispersed phase reinforcements plays an important role on the enhancement of interfacial bonding. Stir casting and infiltration processes are commonly used methods among liquid-state fabrication. Regarding solid-state fabrication of MMCs, bonding of metallic matrix and dispersed phase owing to the reciprocal diffusion between them is at the ground of the formation of a MMC. The common methods of solid-state fabrication of MMCs can be enumerated as diffusion bonding and powder metallurgy (Kandpal, Kumar & Singh, 2014). Considering all of these processes, the cost of method is the main attention in the fabrication of MMCs (Jha, Dvivedi, Rajesha S & Srivastava, 2014).

2.6.1 Stir Casting

In this method, MMC is fabricated by mixing the particulate reinforcement with a molten metallic matrix. Afterwards, the process set-up allows the constituents to solidify. High-energy mixing is utilized for the dispersion of the particulates without subsidence of the reinforcements. Density, particle sizes and potential chemical reactions are the main concerns within the process. By way of the process, composites with volume fractions between 10% and 40% can be obtained. Also, the process is attractive for productions that require cost effectiveness and large-sized components. Furthermore, it is known that this process is commonly used for the fabrication of particle-reinforced AMCs (Miracle, 2005). Figure 2.13 illustrates the schematic representation of stir casting.

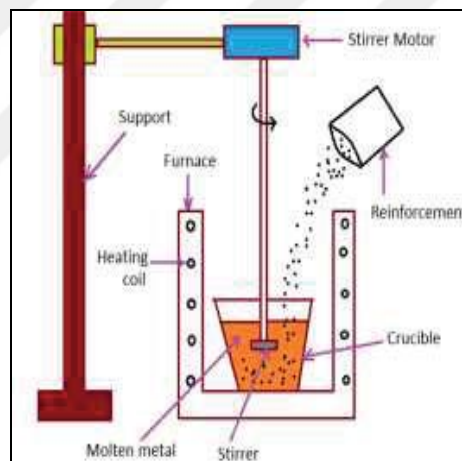


Figure 2.13 Schematic illustration of stir casting method (Hynes, Kumar, Tharmaraj & Velu, 2016)

2.6.2 Liquid Metal Infiltration

A second method of making a MMC is the infiltration of a preform by a liquid metallic matrix. The process is generally achieved by an external pressure applied to the liquid metal (Figure 2.14). Squeeze casting is known as a process in which a piston is utilized for the external pressure. It is important to note that this pressure is frequently necessary in an attempt to provide wetting between the reinforcements and the liquid matrix. In the process, a metallic matrix such as aluminum alloy,

which relatively has low fusion temperature, is mostly chosen. Nonetheless, manufacturing composites with a low filler volume fraction is a demanding consideration owing to the challenge in making preforms with low filler volume fraction (Chung, 2010).

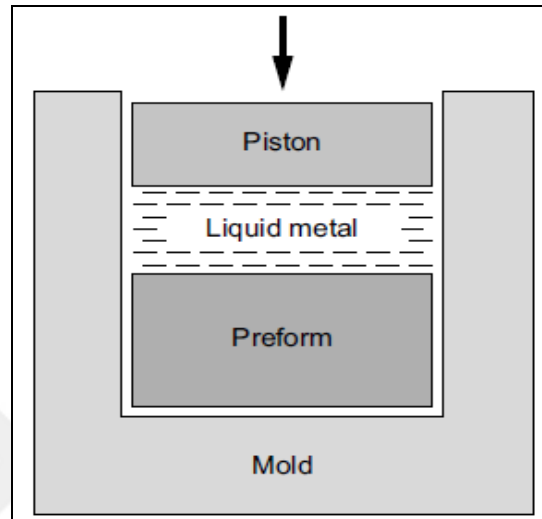


Figure 2.14 Schematic representation of process in liquid metal infiltration (Chung, 2010)

2.6.3 Diffusion Bonding

As a solid-state fabrication method, diffusion bonding involves the stacking of a metallic matrix and dispersed phase in a particular sequence and then pressing the constituents at an elevated temperature. In contrast with complicated shape components, composite plates and tubes might be manufactured through this process (Anish, Singh & Sivapragash, 2012).

2.6.4 Powder Metallurgy

Mixing the powders of metallic matrix and reinforcing particle is one of the most familiar processes for the fabrication of MMCs. In the technique, cold isostatic compaction, canning, vacuum degassing and consolidation process, which take place at an elevated temperature such as extrusion or hot-pressing, are generally utilized subsequent to blending. The powder processing technique for a particle-reinforced

MMC is demonstrated in Figure 2.15. Considering the MMCs produced by powder metallurgy (PM), the composites slightly include oxide particles that may have substantial effect on the matrix, especially in the course of heat-treatment (Bujari & Kurahatti, 2016).

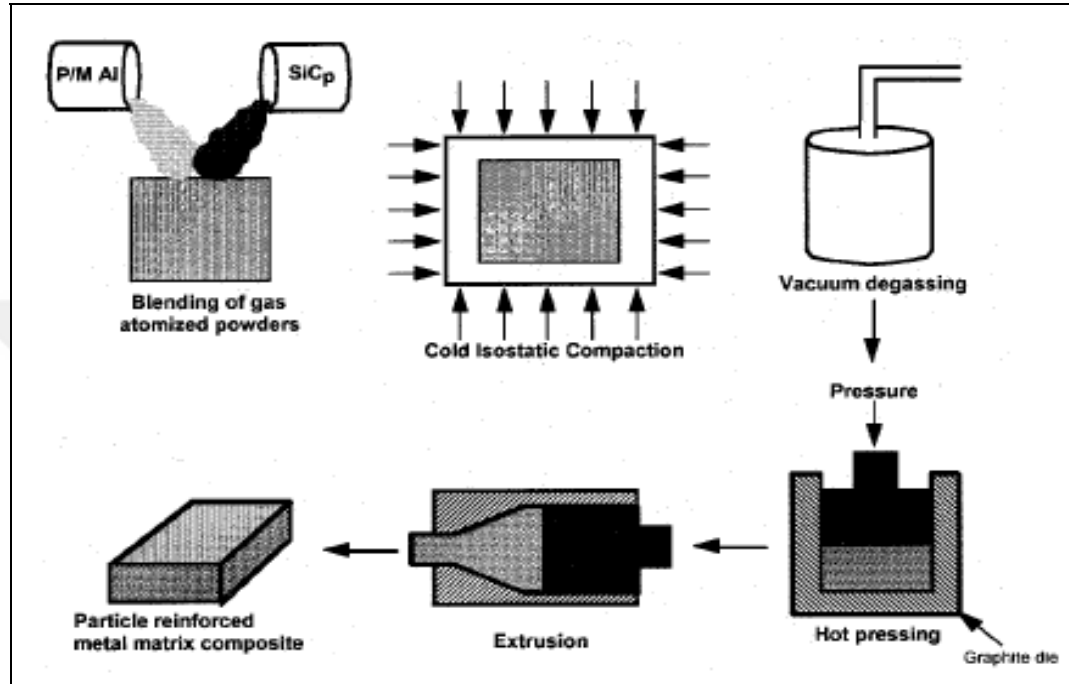


Figure 2.15 Powder metallurgy production (Bujari & Kurahatti, 2016)

Taking into account all of these techniques, PM technique has been an outstanding candidate for the fabrication of MMCs, even though the liquid-state methods have attracted great attention owing to their cost-effectiveness, especially. Herein, the downsides of the liquid metal processes such as possible chemical reactions at the interfaces and nonuniform dispersion of reinforcements impede these techniques to find widespread applications. In addition to all these, further researches on other promising manufacturing techniques required to be performed in an effort to improve their application areas in the future (Bains, Sidhu & Payal, 2016). Table 2.4 shows the fabrication techniques of MMCs with regards to the main properties of some selected examples.

Table 2.4 Summary of MMC manufacturing categories (Bains, Sidhu & Payal, 2016)

Composite type/process	Examples (reinforcement/matrix)	Main features
Solid-state processing	$\text{Al}_2\text{O}_3/\text{SiO}_2$ BeO particulate in Cu or Ag	Modest strength improvement - Good electrical conductivity
a. Insitu forming - internal oxidation		
b. Powder forming - sintered aluminum powder	Al_2O_3 particulate/Al matrix	Moderate strength and stiffness to around 300°C - Low density
- long or short fibers or particulate incorporated by powder metallurgy	$\text{Al}_2\text{O}_3/\text{SiC}$ in Al alloy matrices	Good stiffness/strength to modest particulate incorporated temperatures - Low density - Low thermal expansion
Mechanical alloying	oxide particles in super alloy matrix	- High performance alloy - High strength at high temperature
c. Diffusion bonding - long fibers in intermetallics	SiC fibers in Ti_3Al etc.	Some problems over oxidation at high temperature
Liquid-state processing	SiC or Al_2O_3 /light alloy matrices	Modest improvements in properties
a. Molten metal mix processing		
b. Infiltration of preforms	SiC whisker, Al_2O_3 fibers/Al alloys C/Al and Mg alloys SiC/Ti alloys B/Al alloys	-Good stiffness and strength to 200°C -Low density -Low thermal conductivity
c. Dispersion	various ceramic dispersoids into the melt	Some problems in controlling the microstructure
Semisolid processing	Si in Al	-Modest strength -Good wear characteristics
d. Spraying	particulate/short or long fibers in alloy matrices, for example, SiC or Al_2O_3 /in Al alloy	-Good stiffness and strength -Low density -Low thermal expansion coefficient
e. In situ processing	TiB_2 particulate/Al alloy	Good strength ductility and toughness - Fatigue resistant
Other techniques	Carbon nanotubes (CNTs) reinforced copper	-No clustering of molecules
Molecular level mixing	(Cu) matrix nanocomposites	-Uniform dispersion
a. CIP+HIP	TiC_p particulate/Al alloy	-Formation of oxidation Constraint of high temperature use -Microstructure modification
c. Sputtering method	titanium aluminide alloy, Ti-Al-Nb, on short-length SiC fibers	- Clean environment with excellent impurity control - Good repeatability/reproducibility - Homogeneity of the deposited matrix

2.7 General Welding Methods for AMCs

As noted earlier, particle-reinforced AMCs are promising structural materials especially in the automotive and aerospace industries owing to their high strength to weight ratio, superior wear resistance and low thermal expansion coefficient (Li, Wang, Xiao & Ma, 2018; Wang, Xiao, Ni & Ma, 2014). On the other hand, drawbacks in the joining of MMCs limit the application areas of these materials (Fernández, Ibáñez, Cioffi, Verdera & González-Doncel, 2017).

In order to obtain complicated or massive structures from AMCs, joining becomes unavoidable (Pal, 2005). Herein, welding, mechanical fastening, brazing and adhesive bonding are utilized for the joining of MMCs that can be used in high-temperature applications. Within these methods, welding plays a crucial role due to its advantages over other techniques. In a welding process of similar or dissimilar materials, minimizing heating of the metallic matrix, reducing exposure of the reinforcements to high temperatures and minimizing forces applied to the composite structure are particularly desired. Therefore, non-fusion welding processes, resistance-welding processes and high-energy density beam processes can be enumerated as the preferred methods with regards to the frequency of occurrence. Considering non-fusion and resistance welding, melting of the matrix almost is not observed during the process. In addition, the characteristic features of these methods apart from diffusion welding such as having quick heating rate, having short times at peak temperatures and fast cooling subsequent to welding impede possible unfavorable consequences. At this juncture, there are various limitations in the joining of MMCs through diffusion welding, resistance welding, laser beam welding or electron beam welding. As to capacitor-discharge bonding, it is known that there have been outstanding joints for SiC-reinforced AMCs (Messler, 2004). On the other hand, when many types of fusion processes considered, results in terms of weld performance usually indicate that there are unfavorable influences of the processes. For instance, fusion-welding processes of SiC or Al₂O₃ reinforced MMCs may result in decomposition of these reinforcements in molten matrix in an attempt to create undesired phases (Storjohann et al., 2005). Furthermore, it is widely known that the probable defects like presence of cracks, porosity, solidification shrinkage, distortion, oxide inclusions, brittle intermetallic compounds or inadequate penetration depth are other significant outcomes in the processes (Govindan, Raghuvaran & Pandian, 2017; Mata, Pérez, Medina, Vázquez & Arizmendi, 2016; Peddavarapu, Raghuraman, Bharathi, Sunil & Manikanta, 2017). Consequently, the aforementioned problems related to fusion-welding processes can be removed through solid-state welding methods such as friction stir welding (FSW), particularly (Deepandurai & Parameshwaran, 2016; Jamalian et al., 2016).

2.8 FSW

FSW has been so far the only outstanding solid-state process that can be applied to either similar or dissimilar MMCs due to its prominent process features such as the operating temperature being below the melting temperature of the workpieces, especially. Therefore, as a solid-state welding process, FSW technique may remove or minimize the undesired effects of fusion welding methods (Bist, Saini & Sharma, 2016).

As stated within the introduction part of this thesis, FSW that was invented at The Welding Institute of UK in 1991 especially for aluminum alloys has been continuing to progress. Many sheets and plates of aluminum alloys can be welded through this technique without using filler material or cover gas during the process. The process provides an opportunity in the sound joining of materials with various thicknesses between 0.5 and 65 mm. Furthermore, FSW provides these joints without any known weld defects. Regarding the possible workpieces, FSW has been drawing more attention on a wide range of materials recently, even though the process was initially developed for nonferrous alloys such as 2xxx and 7xxx series aluminum alloys that were traditionally known as nonweldable materials (Esab, 2016).

As part of this theoretical background, working principle, microstructural zones, process parameters, applications and lastly the advantages and drawbacks of FSW process are summarily elucidated.

2.8.1 Working Principle of FSW Process

A rotating nonconsumable tool, workpieces of similar or dissimilar material configurations, backing plate and clamping apparatus are parts of a FSW process, in general. Considering these constituents, the rotational welding tool consists of a shoulder and a pin that are specifically designed and manufactured. At this point, it is worthwhile to mention that the height of the probe should be specially designed pursuant to the thickness of the workpieces. Usually, the configurations of butt or lap

joints are arranged for the workpieces to be joined. Moreover, thick plates with several configurations can be welded out of preliminary preparation. In the process, backing plate and clamping apparatus also play a significant role on the quality of welds (Khairuddin, Abdullah, Hussain & Almanar, 2012).

The process generally consists of four stages namely the plunging, dwelling, welding and retract phases. In a nutshell, firstly, pin of the nonconsumable tool is dipped into the adjacent surfaces of the workpieces through the instrument of axial load subsequent to clamping of the workpieces influentially on a backup plate that is commonly fixed to a FSW adapted machine. This stage ensures that the workpieces plasticize by virtue of the increased temperature and proceeds till the contact of tool shoulder with the surfaces of workpieces is provided. At the time, the introduced shoulder contact considerably increases the temperature with dwell for a length of time. Herewith, the strength of the workpiece material is decreased and the generated heat also induces the material to become more plastic. Accordingly, translocation of thin softened material layers is provided by way of the surfaces of pin and shoulder. Herein, plastic dissipation heat generation substitutes for the friction heat generation within limits. Material deformation and displacement of the workpieces are also maintained through these plastic deformation mechanisms and mechanical frictional work. After then, the welding phase commences when the hot working temperature of the workpieces that facilitates to stir and replace the material is provided. At this juncture, the rotating tool is traversed along the weld line at a predetermined weld speed. During this welding phase, flow of the plasticized soft material is provided from the leading edge to the trailing edge of the rotation tool. The forged plasticized workpiece material in the trailing side then inherently cools and consequently causes the formation of the weld nugget. Within the scope of the welding stage, it should be noted that the process cyclically generates recurrent heat generation. This situation continuously develops within the stage from beginning to the end. In addition, welding parameters such as tool rotational speed and welding speed have a strong influence on this cyclic transient heat generation process. Lastly, the process comes to the conclusion through retracting stage following the welding phase. In this stage of FSW process, the process tool is taken out from the end of workpiece materials.

Exit phase usually creates a cylindrical pinhole in the weld zone, intrinsically (Khairuddin, Abdullah, Hussain & Almanar, 2012). Figure 2.16 demonstrates the basic principle and schematic drawing of friction stir butt-welding process. In a FSW process, actually, asymmetric joint is obtained based on the influence of tool rotation direction. The directions of tool rotation and welding have different effects on each side of the weld. By the way, one side is called as the advancing side in which case the direction of tool rotation is parallel to the traverse direction. In other respects, other side is named as the retreating side in which the direction of tool rotation has opposite sense compared to the traverse direction. Furthermore, it is important to note that the tool design, welding equipments, tool rotation speed and welding speed take an important place on the weld quality obtained by a FSW process (Simar et al., 2012).

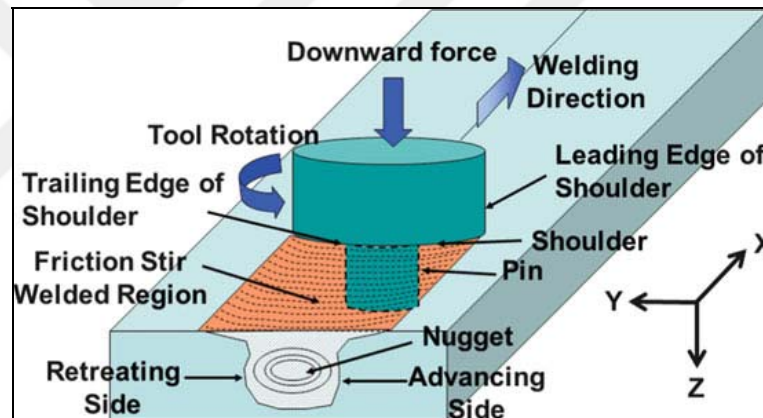


Figure 2.16 Schematic illustration of FSW process in a butt joint configuration (Mishra, De & Kumar, 2014)

Regarding material flow and joining mechanism in a FSW process, generated material flow is one of the most crucial considerations on the weld quality of the process. As noted earlier, FSW joint results from the transportation of soft workpiece material from leading edge to the trailing edge and the material flow around the pin takes place by way of the retreating side, to a large extent. Moreover, it is known that most of the flow takes place close to the top surface of the workpieces. In addition to these, a dissymmetrical stir zone is commonly observed owing to the tensed soft material near the top surface. Herein, it is needed to notice that the features of

material flow play a significant role in determining the appropriate process parameters including the rotating tool design. Besides that, in any case, quite complicated plasticizing material flow is obtained based upon the workpieces, FSW parameters and tool design (He, Gu & Ball, 2014).

When the formation of a FSW joint and the whole movement of soft workpiece material are to be exhaustively investigated, it is commonly observed that there are three different tendencies as to material flow in the mechanism of joining. Rotational motion of the tool, rotation of the pin and lastly, consisted relative motion between the rotating tool and the workpieces can be enumerated as the main factors on the overall movement of the workpiece material in a FSW joining. By comparison with the flow in traditional fusion welding methods, it is known that there are disparities based upon the dissimilar FSW of materials. Contrary to homogeneous weld pool in a conventional fusion weld, weld metallography in the FSWed joint may generally exhibit nonuniform concentration (Nandan, DebRoy & Bhadeshia, 2008).

Taking into account the 3D plastic flow during a FSW process, it has been realized that the viscosity of plasticized material exhibits different trends at different elevations of the process. At the upper elevations close to the tool shoulder, it is explicit that there is a significant increase in the wake of a decline with the increasing distance from the tool axis. On the other hand, the computed viscosity values demonstrate an increase by means of the increasing distance from the tool axis at the lower elevations. Figure 2.17 depicts the contours of spatial variation of viscosity and velocity at different horizontal planes during the process. Regarding the stream traces at the same elevations, recirculation of the material around the tool pin is another finding in the case of no slip at the interface between the tool and the workpiece. In addition, motion of the rotating shoulder substantially affects the areas of these nearly circular, closed streamlines, at higher elevations. Moreover, material transform constitutively takes place around the tool pin in the retreating side (Nandan, Goy, Lienert & DebRoy, 2006). Streamlines on the different horizontal planes at three different elevations are exhibited in Figure 2.18.

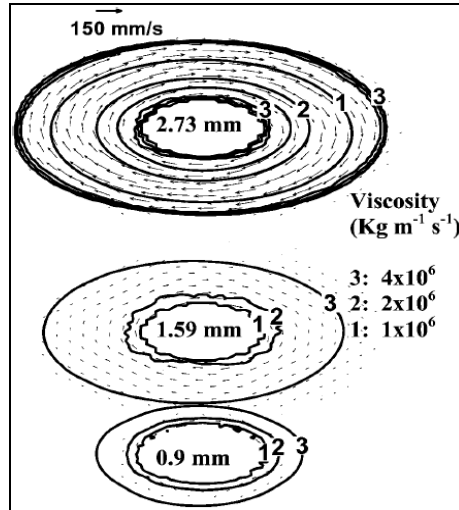


Figure 2.17 Viscosity contours and velocity vectors at horizontal planes: (a) 0.35 mm, (b) 1.59 mm and (c) 2.28 mm below the top surface in the FSW of 304 stainless steel plate of thickness 3.18 mm (Nandan, Goy, Lienert & DebRoy, 2006)

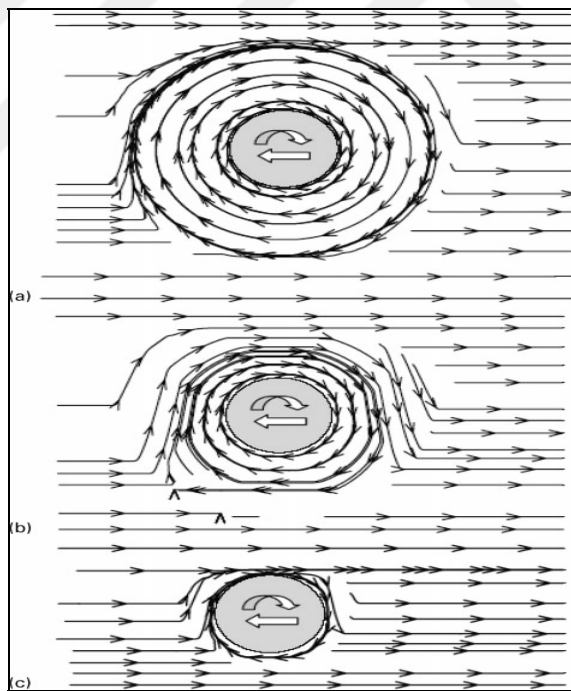


Figure 2.18 Streamlines on different horizontal planes at three different elevations (a) 0.35 mm, (b) 1.59 mm and (c) 2.28 mm below the top surface in the FSW of 304 stainless steel plate of thickness 3.18 mm (Nandan, Goy, Lienert & DebRoy, 2006)

2.8.2 Microstructural Zones of FSW Joints

Within the scope of a FSW process, there are several thermomechanical processes that are in interaction with each other. Plasticized material flow, dynamic recrystallization, heating and cooling rates and consequently mechanical performance of the joint are generally influenced through these interactions. Regarding the microstructure, a typical FSW weld consists of four separate microstructural zones, namely the stirred (nugget) zone (SZ), the thermomechanically affected zone (TMAZ), the heat-affected zone (HAZ) and base metal (BM) (Nandan, DebRoy & Bhadeshia, 2008). Figure 2.19 shows an example of typical microstructural regions in a FSWed joint.

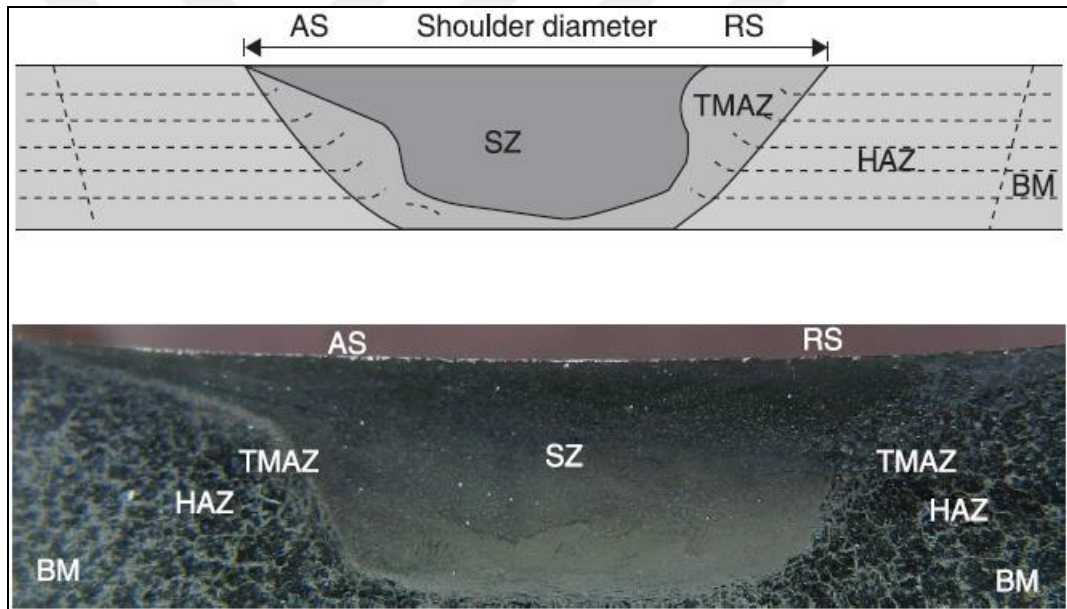


Figure 2.19 (a) A typical welding zones in FSWed joint, (b) a macrograph exhibiting various microstructural regions (Reese, 2016)

2.8.2.1 Stirred (nugget) Zone

This region, generally defined as the weld nugget or dynamically recrystallized zone (DXZ), commonly comprises of finer recrystallized grains owing to the intrinsically consisted frictional heating and plastic flow. As a result of the process,

onion ring structures are usually reported within the SZ. Low dislocation density is another prevalent characteristic feature for the dynamic recrystallized grains. Considering the shape of the nugget zone, basin-shaped nugget and elliptical nugget can be enumerated as the two primary types. At this juncture, it should not be forgotten that there are numerous possible shapes of SZ based on the properties of the workpiece, tool design and welding parameters. Besides that, diameter and design of the pin have also significant effect on the shape of the SZ. Examining the grain sizes within the SZ, finer and equiaxed-recrystallized grains mainly compose this region. Sizes of these grains generally vary with workpiece material, process conditions and parameters. It is known that the plastic deformation and temperature of thermal cycle during the process play a seminal role on the grain size. For the sake of example, reduction in the recrystallized grain size with increased plastic deformation or grain growth by way of the increase in peak temperature of the thermal cycle are well accepted occurrences in consequence of the process. Moreover, the grain size generally demonstrates variation throughout the weld nugget mainly due to the temperature alteration within the weld zone. It is interesting to note that the grain sizes decrease as their location move away from the weld-centerline. On the other part, grain growth is usually observed within regions close to the top of the weld zone. Furthermore, thickness of the workpieces have substantial influence on the grain size variation within the weld nugget. Regarding the recrystallization processes in aluminum alloys, continuous dynamic recrystallization (CDRX), discontinuous dynamic recrystallization (DDRX) and geometric dynamic recrystallization (GDRX) mechanisms are thought to be the conceivable factors. As a matter of fact, DDRX is considered as the effectual mechanism by reason of the presence of finer recrystallized grains within the SZ compared to the subgrain size of the BM. Precipitate dissolution and coarsening is another subject that needs to be considered subsequent to FSW. Based on workpiece material and thermal cycle during the process, coarsening, dissolution or reprecipitation of these strengthening materials can be observed (Mishra & Ma, 2005). Figure 2.20 demonstrates a typical overview of probable microstructural changes within different welding zones.

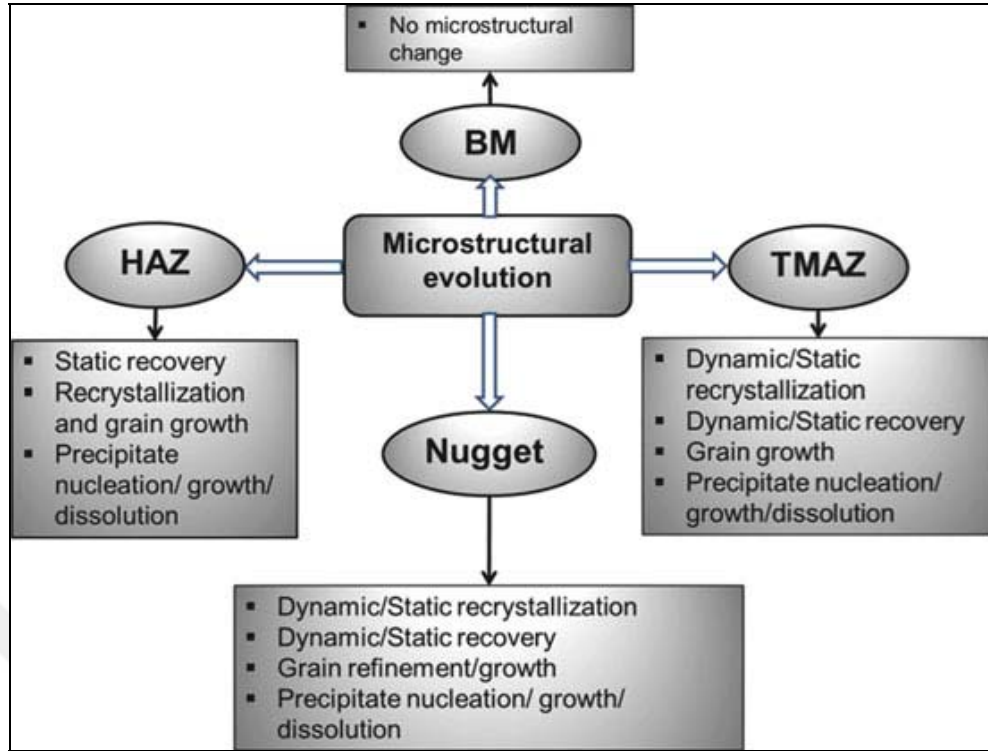


Figure 2.20 An overview of microstructural evolution within different welding zones (Mishra, De & Kumar, 2014)

2.8.2.2 Thermomechanically Affected Zone

As indicated in Figure 2.21, there is a transition region, which exposes both generated heat and plastic deformation following the FSW process, between the BM and the SZ when microstructural evolution in FSW is considered. Highly deformed grain structure is one of the most characteristic features of this region. Initial grains of BM are deformed within TMAZ by way of the material flowing pattern. Dissolution of strengthening precipitates may be observed in this zone, even though the dynamic recrystallization process is thought to be impossible in the wake of the process within TMAZ (Mishra & Ma, 2005). On the other hand, it is widely accepted that the recrystallization mechanisms generally proceed at the boundary between TMAZ and SZ. Regarding the grain sizes within TMAZ, observations generally indicate that the grain structure of this zone is quite larger by comparison with the grain size of SZ (Tiwari, Shukla & Chandra, 2013).

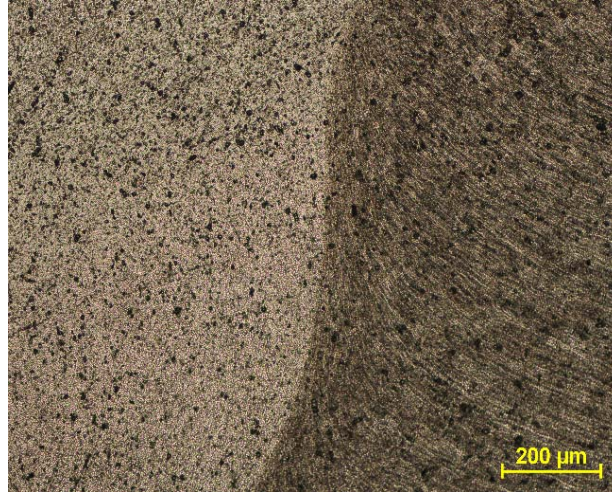


Figure 2.21 Example of a transition region in FSWed 6061Al (Personal archive, 2017)

2.8.2.3 Heat-affected Zone

Considering all traditional fusion welding processes as well as FSW, the heat-affected zone (HAZ) is commonly observed within weld regions. This region experiences only a thermal cycle without plastic deformation. Generated heat during the FSW process might still play an important role in the microstructural evolution of this zone, even though HAZ has lower potential temperatures by comparison with TMAZ (Tutum, 2009). Therefore, the distinctness in mechanical features in consequence of the microstructural modifications can be distinguished within this region (Perovic et al., 2012).

Regarding the grain structure within HAZ, the grains in this zone are affected only by the generated heat of the process. Thus, it is not possible to observe the deformed grains based upon the mechanical influence of the process. However, overaging of the precipitates that result in a decrease in mechanical features of the FSWed joint is widely seen in HAZ. Another important issue related to this zone is the difficulty in determining the position of HAZ within the weld region. Herein, this zone is generally associated with the region with minimum hardness values in the weld. This is usually possible, but not always (Biro, Chenelle & Lados, 2012).

2.8.2.4 Base Material

As indicated in the term, this region is not affected by the results of FSW process such as the plastic flow or the generated heat. Similar to HAZ, it is especially difficult to define the bulk material boundary that is not influenced by the process. At this point, hardness measurements can be used to determine the span between the center of SZ and the base material (Biro, Chenelle & Lados, 2012).

2.8.3 Common Weld Defects within the FSW process

There are various factors within FSW such as the process parameters, properties of workpieces and tool design that may have significant and sophisticated influences on the defect formation. Some prominent defects that commonly occur pertaining to the material flow or geometrical issues can be seen in Figure 2.22 (Arbegast, 2008).

Erratic tool motion, generation of high heat input and inadequate load levels within the process results in the formation of surface flaws, excess flash and kissing bond type defects (Cam & Mistikoglu, 2014). Besides that, a void in a weld zone is another common defect type in FSWed joints. Presence of such voids is thought to be due to the material flow irregularities in the SZ owing to the inappropriate selection of the process parameters, notably. For example, it is known that the high traverse speed in the process may cause the presence of aforesaid voids in the vicinity of weld surface or on the margin of weld nugget at the advancing side especially. Moreover, formation of wormhole defects is also more likely to develop at increased weld speeds (Kah, Rajan, Martikainen & Suoranta, 2015).

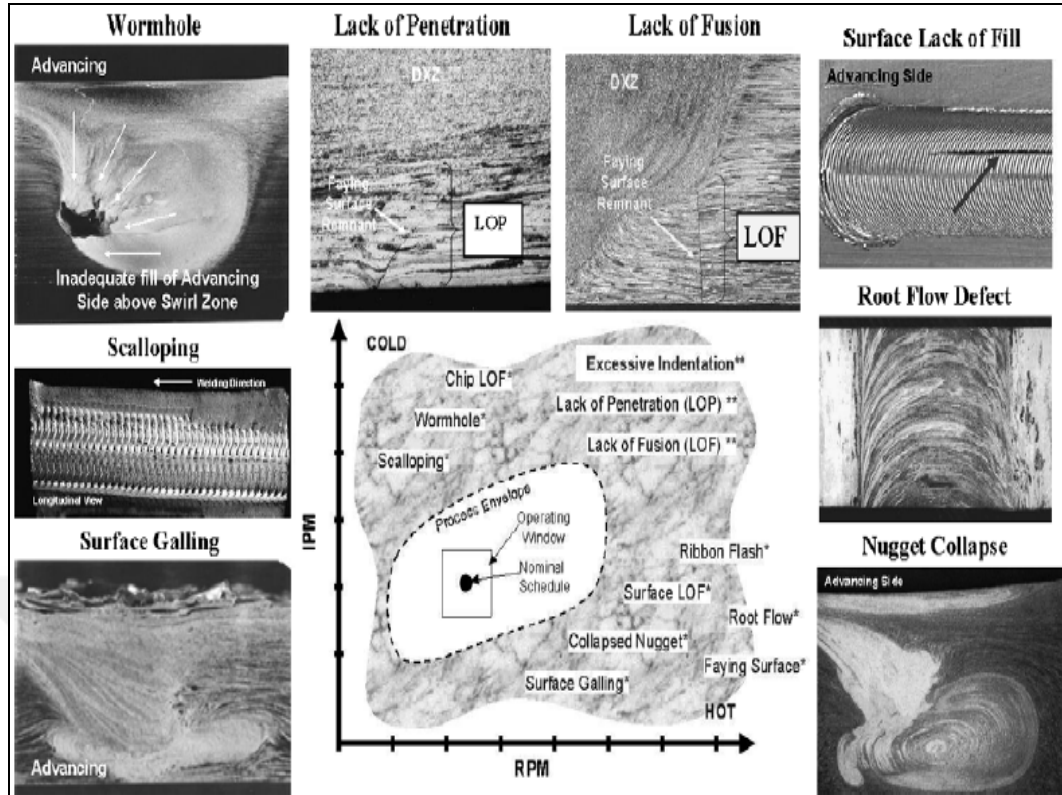


Figure 2.22 Possible welding flaws in a FSWed joint (Arbega, 2008)

2.8.4 FSW Parameters

In order to arrange a FSW process, tool design, tool rotational speed, welding speed, tilt angle of the tool and the axial pressure on the tool (the downward force) can be considered as the main process variables (D.M. Neto & P. Neto, 2013). It is largely accepted that these parameters play a significant role in determining the temperature distribution, force in the welding direction and torque. At this juncture, it is important to point out that the peak temperature considerably increases as the tool rotational speed and the downward force rises. Besides that, friction coefficient, design of the tool, tilt angle, applied axial pressure and shear stress which take place at the interface between the tool and the workpiece are other variables that substantially determine the torque (Cam, 2011). The main process variables are concisely reported within this subchapter.

2.8.4.1 Tool Design

In a FSW process, the nonconsumable tool plays an important function in the heating of workpieces, ensuring the plasticized material flow and maintaining the softened workpiece material underneath the shoulder. As it has been mentioned earlier, the softened material moves from the front to the back of the pin with the effects of rotation and travelling motion of the FSW tool. Herein, it is worthwhile to mention that the material flow around the pin is generally quite complicated based on the design features of the tool. The FSW tools can be classified into three types as the fixed, adjustable and self-reacting tools. Figure 2.23 shows the FSW tool types that are commonly used in the process. When these tools are considered, the tool in which the shoulder and probe are together in a single piece is called as the fixed probe tool. In other respects, the adjustable tool design corresponds to two independent parts made up of separate shoulder and tool probe. In this way, the pin length can be adjusted during the process. Additionally, this design allows to the replacement of the probe when it is damaged or eroded. Lastly, the bobbin type tool, which comprises of top shoulder, pin and bottom shoulder, is designed for the multithreading of pin in various FSW processes with several joint thicknesses (Zhang, Cao, Larose & Wanjara, 2012).

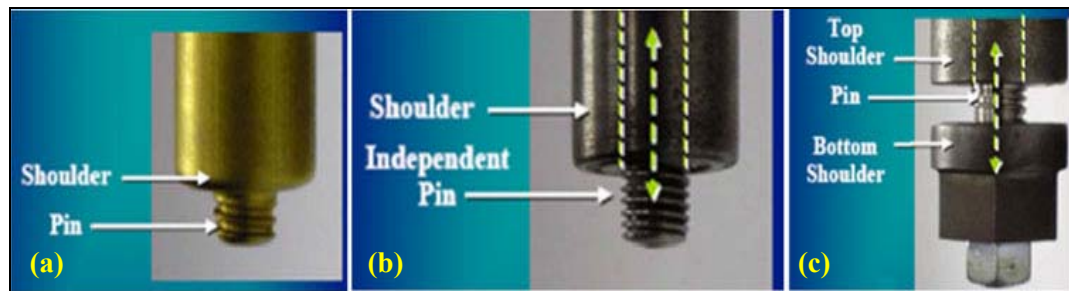


Figure 2.23 Commonly used FSW tool types: (a) fixed (b) adjustable (c) bobbin (Zhang, Cao, Larose & Wanjara, 2012)

Regarding the shoulder and probe types, Figures 2.24 and 2.25 exhibit the shapes and features of the tool shoulder and probes, respectively. In general, the outer surfaces of the shoulder are cylindrical, and sometimes the conical surface may be

used. As seen in Figure 2.24, the flat, concave and convex profiles are typically utilized for the shoulder end surfaces. Moreover, in order to provide sound welds, the end surfaces can be shaped in various end styles such as the scrolls, concentric circles, grooves and so forth. Among these shoulder end styles, scrolls are known to be the most commonly used end style. As for the probe shapes, flat or domed end shapes are general utilized for the probes. The flat design is known as the most largely used form. As revealed in the figure, the outer surfaces of the probe are mostly cylindrical, yet the tapered form might be used. Herein, it should be noted that the cylindrical probes are particularly used for the workpieces whose thicknesses are less than 12 mm. In addition to these, the probe outer and end surfaces can have different features as seen in Figure 2.25 (Zhang, Cao, Larose & Wanjara, 2012).

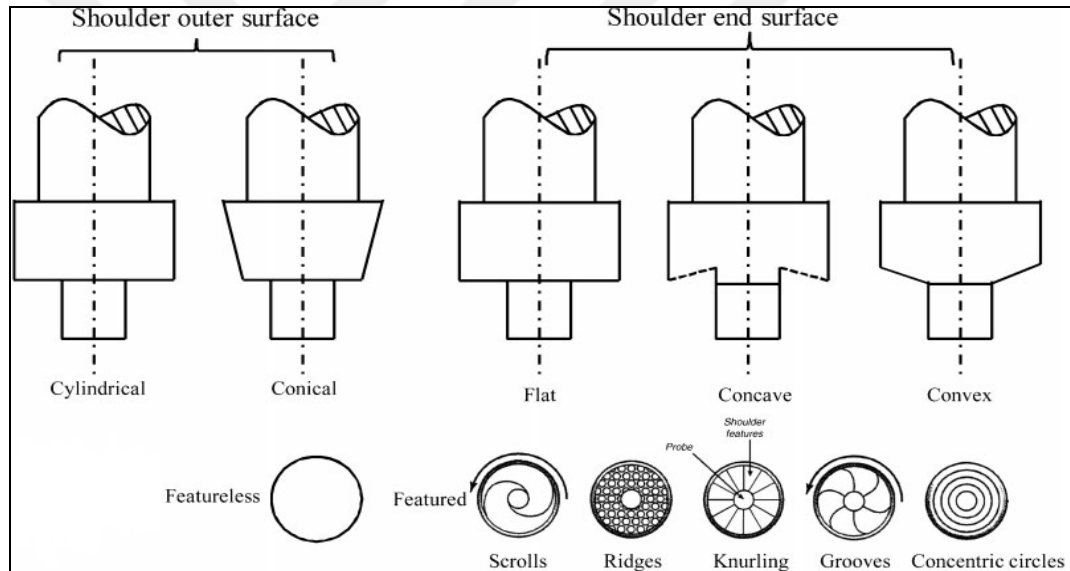


Figure 2.24 Commonly used shoulder shapes and features (Zhang, Cao, Larose & Wanjara, 2012)

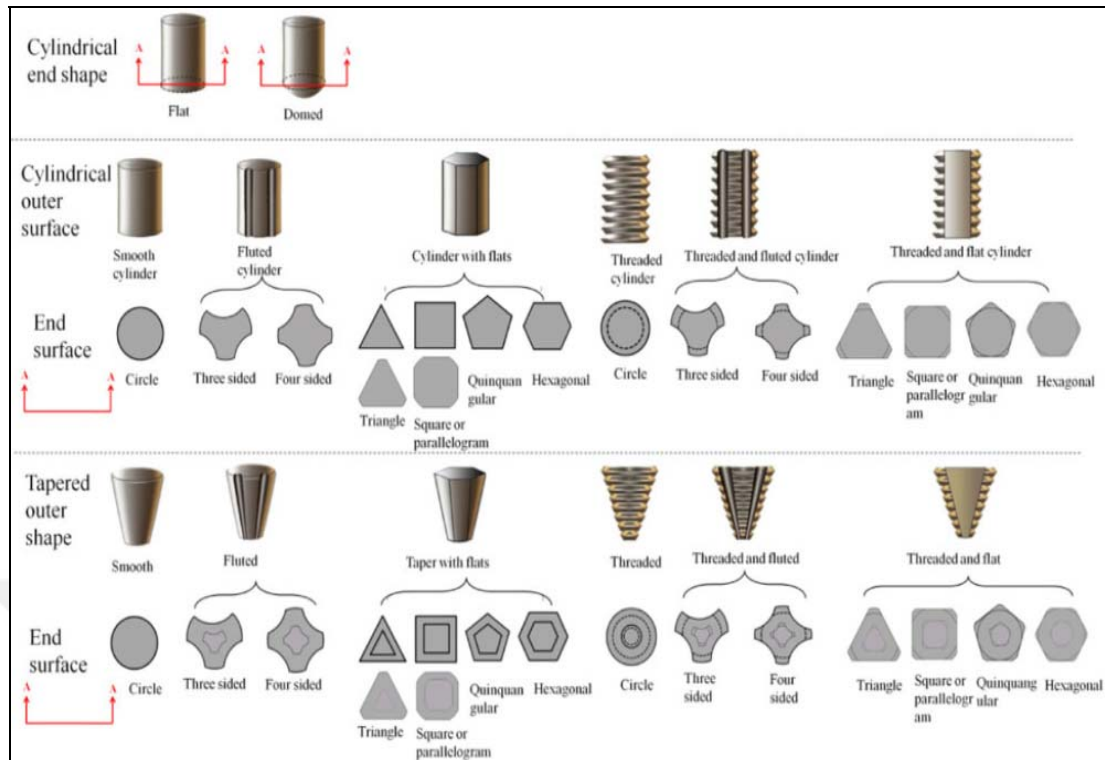


Figure 2.25 Commonly used pin shapes and their typical features (Zhang, Cao, Larose & Wanjara, 2012)

Another important point in the tool design is the material selection of FSW tools. Tool-steel, polycrystalline cubic boron nitride (pcBN) tools and tungsten (W) based nonconsumable FSW tools are commonly used for the process. Considering the steel tools, this material has been used for the joining of aluminum alloys, magnesium alloys and AMCs, predominantly. In addition, joining of dissimilar workpieces in both lap and butt joint designs may also be performed by use of the steel tools. Table 2.5 shows some selected tool designs used for FSW of various MMCs. Regarding the pcBN tools, this tool material is an outstanding candidate for the relatively hard materials such as the titanium alloys and some steels due to its superior features of high thermal stability, sufficient strength and hardness at elevated temperatures. Furthermore, the material provides smooth weld appearance owing to its low friction coefficient. Nevertheless, high cost in the fabrication impedes the widespread utilization of pcBN tools. As concerns the W-based tools, these tools expeditiously erode away in welding of hard materials and have inadequate toughness, even though the tools have good features at elevated temperatures. In addition to all these, studies

on the applications of tungsten carbide (WC) based and silicon nitride (Si_3N_4) tools for the FSW have also been practiced (Rai, De, Bhadeshia & DebRoy, 2011).

Table 2.5 Tool designs and welding parameters utilized for FSW of various MMCs (Rai, De, Bhadeshia & DebRoy, 2011)

Workpiece material	Tool material	Tool shape and size	Operating parameters	Remarks	Reference
6061-T6 Al + 20% Al_2O_3 , 5 and 6 mm thick	AISI oil hardened Tool steel (62 HRC)	SD: 19 mm; PS: SCT; PD: 6.3 mm	500–2000 rev min^{-1} ; 60–540 mm min^{-1} ; 1° tilt	No wear after some distance (150–300 mm) depending on process parameters	9, 10
Al 359+ 20%SiC, 4 mm	AISI oil hardened tool steel (62 HRC)	SD: 19 mm; PS: SCT; PD: 6.3 mm; PL: 3–6 mm	500–1000 rev min^{-1} ; 360 and 660 mm min^{-1}		11
Al 359+ 20 vol.-%SiC, 4 mm	AISI oil hardened steel	SD: 19 mm diameter; PD: 6.3 mm	1000 rev min^{-1} ; 60–540 mm min^{-1}		26
Al–10 wt.-%TiB ₂ , 6 mm	High C high Cr steel (60–62 HRC)	SD: 16 mm; PS: SSq, TSq, SOct, TOct, SHex, THex,	2000 rev min^{-1} ; 30 mm min^{-1}	Joint efficiencies: 78.9–99.5%	84
Al–15 wt.-%Mg ₂ Si, 6 mm	H13 steel	SD: 18 mm; PS: TCT; PL: 5–7 mm	710–1400 rev min^{-1} ; 125 mm min^{-1}	Joint efficiencies: 80–98%	14
AA 6061–(3–7)%TiC, 6 mm	High C, high Cr steel	PS: SSq, TSq, SHex, THex, TOct	30–135 mm min^{-1}	Joint efficiencies: 72–114%	139

*SD: shoulder diameter; PL: pin length; PD: pin diameter; PS: pin shape; SCT: straight circular threaded; TCT: tapered circular threaded; SSq: square; TSq: tapered square; SHex: hexagonal; THex: tapered hexagonal; TOct: tapered octagonal. Joint efficiency is the ratio of the tensile strength of the joint to that of the base metal.

2.8.4.2 Rotational Speed, Welding Speed, Tilt Angle and Plunge Force

The variables subject to the foregoing subhead are called as the machine related FSW parameters. When the influences of these variables are briefly described, it is known that the tool rotational speed has a significant effect on the microstructural evolution and mechanical properties of the FSWed joints. The amount of heat rises during the process as the rotation speed increases. At this juncture, it is important to point out that there is an optimum rotational speed to obtain good mechanical properties subsequent to the process. Following a specific rotational speed, obtained excessive heat may result in turbulent flow of the plasticized material in the stir zone. Hereat, joint strength might decline in consequence of the probable micro-voids. In other respects, it is also known that a lower rotational speed may compose insufficient plastic deformation and poor mechanical features. By the way, it is noteworthy that the tool rotation speed has a greater effect on the tensile strength as

compared with other variables. Regarding the traverse speed, there is an optimum range for this parameter similar to the rotational speed. As a lower welding speed allows to the formation of fine-grained texture, it may also results in the reduction of tensile strength due to the ill-conditioned material consolidation. When the effects of the tilt angle are considered, tilt angle within the FSW process exhibits important influences on the generated heat and material flow, particularly. In the case of tilt angle being less than 1.5° or greater than 4.5° , some weld defects may occur as a result of the process (Verma, Gupta & Misra, 2016). Tilt angles used in a FSW process are demonstrated in Figure 2.26. Lastly, it must be mentioned that the axial force plays an important role in the plunge depth and heat generation during the process. In general, sufficient axial forces are required so as to obtain sound joining for the materials with a high melting temperature (Ji, Zuo & Wang, 2016). Therefore, axial force control is necessary in order to fabricate defect-free welds with favorable quality (Zhao, Bi & Wang, 2016).

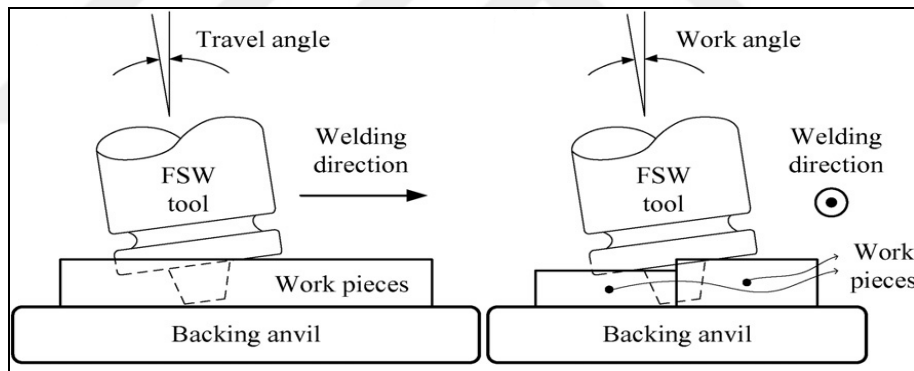


Figure 2.26 Schematic representation of the tilt angles used in a FSW process (Mendes, Neto, Loureiro & Moreira, 2016)

2.8.4.3 Joint Design

It is widely accepted that the FSW process is a mature technology for simple connections such as the butt joints and overlap joints. Nonetheless, it is important that the process can be applied to different joint configurations in order to have wider application areas. In other words, new connections are necessary to draw advantage from the merits of the method. Herein, T-joints, box sections or rebated joints can be

enumerated as the promising examples. Furthermore, T-joints have received noteworthy attention among other geometries owing to the large number of possible application areas (Penalva, Otaegi, Pujana & Rivero, 2009). Figure 2.27 demonstrates some typical joint configurations for FSW.

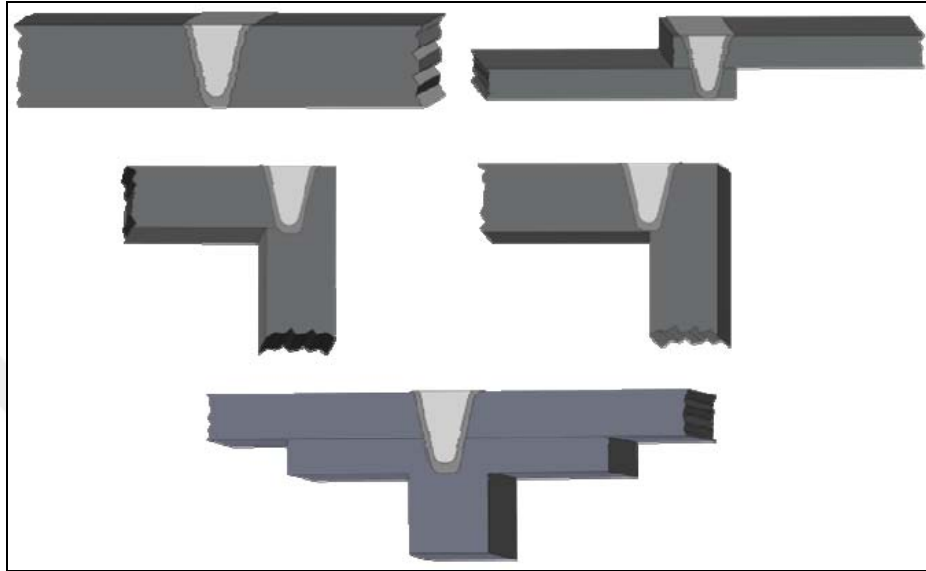


Figure 2.27 Joint geometries for FSW (Gabor & Santos, 2013)

2.8.5 Applications of FSW

FSW is increasingly gaining favor in many engineering applications of especially aircraft, marine and space industries (Rajamanickam & Balusamy, 2008). Within the commercial applications of FSW, butt-welds comes to the forefront when compared to other configurations such as the friction stir spot welds (FSSWs) and lap-welded joints. In this subchapter, some selected application areas of FSW are reported. In other respects, it is important to note that the contemporary examples are continually added to the industrial applications of the process (Threadgill, Leonard, Shercliff & Withers, 2009).

2.8.5.1 Aerospace

A few applications of FSW that have been utilized by aerospace industry are shown below (Threadgill, Leonard, Shercliff & Withers, 2009):

- Fuel tanks of Delta II and Delta IV rockets
- Fuel tank of the Space Shuttle
- Airframe of the Eclipse 500 business jet

2.8.5.2 Automotive

Regarding the applications of FSW in the automotive industry, some of the examples are listed below (Threadgill, Leonard, Shercliff & Withers, 2009):

- Crash boxes
- Seat parts
- Suspension components
- Wheel rims
- For Rear doors and bonnets as FSSW

2.8.5.3 Shipbuilding and Marine

The following applications can be enumerated as the possible engineering applications of FSW in the shipbuilding and marine industries (FSW, Industrial Applications, n.d.):

- Bulkhead, deck or floor panels
- Promenade decks and body of the ships
- Derricks and masts
- Platforms for helicopters
- Marine structures
- Cooling plants

2.8.5.4 Railway

Considering high-speed trains with extrusions of aluminum alloys, the following applications can be listed as the suitable engineering applications of FSW in the railway industry (FSW, Industrial Applications, n.d.):

- Railway wagons and tankers
- Body of containers
- Railway rolling stocks

2.8.5.5 Land Transport

In addition to the commercial usage of FSW in automobiles, the following applications can be enumerated as the possible engineering applications of FSW in land transportation (FSW, Industrial Applications, n.d.):

- Truck bodies
- Buses and caravans
- Means of transport for airfield
- Vehicles with armour plating
- Travelling cranes

In addition to all these applications of FSW, the process was considered as a promising candidate by Apple Co. for the sound joining of case components of 2012 Apple iMac. Furthermore, the process has been used by TWI so as to manufacture a propellant tank to be used at the European Space Agency. Also, FSW is planned to be used in copper storage tanks of Finnish and Swedish nuclear waste plants (Friction stir welding - joining the future of industry, n.d.).

2.8.6 Advantages and Drawbacks

In metal joining process, it is thought that the FSW, which is considered as a green technology based upon its well-rounded, environment-friendly and energy efficient features, is one of the most important developments recently discovered. This solid-state process has many advantages over traditional joining processes (Dialami, Chiumenti, Cervera & Saracibar, 2017). Some of the virtues of the process are listed below (Singh, 2012):

- Weld is performed in the solid-state without melting the workpieces
- Provides promising mechanical performance in as-welded condition
- Enables the joining of dissimilar materials
- No filler or shielding gas is necessary especially for the FSW of aluminum alloys
- The process can be easily applied on a milling machine, which reduces the setup costs
- The absence of welding pool increases the operational capability
- Reduces the secondary process costs subsequent to the welding due to successful weld surface and thickness conformity obtained
- Adverse effects on environment are very low
- Ensures safer working conditions particularly owing to the absence of toxic gases.
- Avoids possible thermal distortion
- Facilitates the assembly process in aircraft parts especially by removing the applications of rivet

By comparison with traditional fusion welding processes, FSWed joints with superior microstructural characteristics also demonstrate outstanding fatigue, flexural, creep and tensile features (Ma, Feng, Chen & Shen, 2017). On the other hand, the process has some limitations (Friction Stir Welding - Working Principle, Advantages, Disadvantages with Application, n.d. ; Singh, 2012):

- Unfilled exit hole is formed at the end of the process when the nonconsumable tool is removed
- Requires quite heavy clamping devices
- At preliminary stage, requires high investment cost for a FSW machine
- Requires influential axial forces to hold tool pin within the workpieces
- Generally, the process is slower in comparison to other welding processes
- Incapable of applications requiring metal recovery and deposition

2.9 Fatigue in Materials

Fatigue is a technical phenomenon that may eventuate in a crack or complete failure of structures, machine components or vehicles owing to the repeated fluctuating loadings. These cyclic loadings can produce damage in a component even if the stresses are below the ultimate strength of the materials. When it is thought that the main cause of material damage is fatigue, prevention of fatigue failure is one of the most significant concerns in an engineering design. At the present time, stress-based approach, strain-based approach and fracture mechanics approach can be enumerated as the widely accepted approaches in order to design and analyze a component for fatigue damages. As to the strain-based and fracture mechanics approach, these methodologies mainly include the detailed evaluation of localized stress and crack propagation mechanisms, respectively (Dowling, 1993). Within this subchapter, the stress-life approach is discussed.

Considering many engineering applications, it is explicit that materials are subjected to constant amplitude loading between maximum and minimum stress levels. Figure 2.28 illustrates some cyclic stressing with constant amplitude.

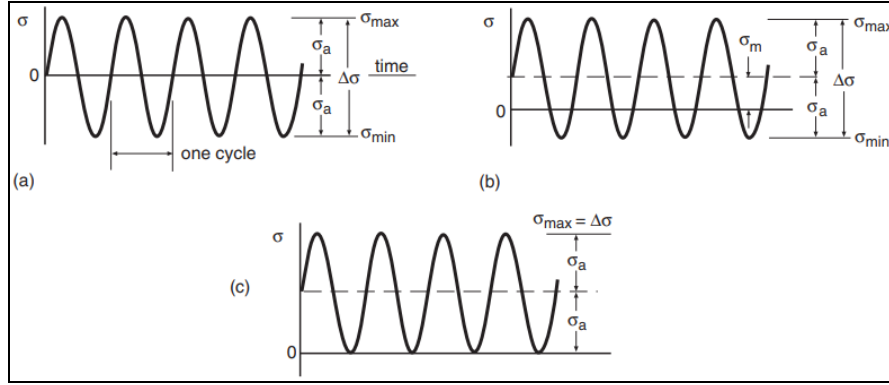


Figure 2.28 Designation of constant amplitude stressing: (a) completely reversed cyclic stressing, (b) with a nonzero mean stress and (c) with a zero minimum stress (Dowling, 1993)

Herein, the stress range is described by Equation (2.1).

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \quad (2.1)$$

The mean stress is described by Equation (2.2).

$$\sigma_m = (\sigma_{\max} + \sigma_{\min}) / 2 \quad (2.2)$$

The alternating stress is described by Equation (2.3).

$$\sigma_a = (\Delta\sigma) / 2 = (\sigma_{\max} - \sigma_{\min}) / 2 \quad (2.3)$$

The stress ratio is described by Equation (2.4).

$$R = \sigma_{\min} / \sigma_{\max} \quad (2.4)$$

The amplitude ratio is described by Equation (2.5).

$$A = \sigma_a / \sigma_m \quad (2.5)$$

2.9.1 Stress versus Fatigue Life (S-N) Curves

It is widely accepted that the modern fatigue experiments are based on the studies that were performed by A. Wöhler (1867) on iron and steel samples in German railroad system. Wöhler deduced that the applied stress amplitude in the cyclic loading substantially influences the fatigue response of a material. Figure 2.29 exhibits a typical plot of the stress amplitude vs. number of cycles to fatigue failure. This plot is referred as Wöhler's diagram or S-N curve. At this juncture, it should be mentioned that the mean stress value is zero for the given curve. Regarding the regions in the figure, REGION I indicates that the material is exposed to a stress close to or exceeding the yield strength. Fatigue life of the material within this region is manipulated through plastic strain. It should also be noted that this region till $N=10^4$ cycles to failure is commonly named as the low-cycle fatigue region. On the other hand, REGION II is widely called as the high-cycle fatigue and continues up to about 10^6 cycles. Material within this region is dominated elastically and exposed to a stress below the yield strength. Beyond these cycles to failure, unlimited life for ferrous alloys and titanium commences (REGION III). As it is noticeable from Figure 2.30, there are two different behaviors in ferrous alloys and titanium with a severe knee and in nonferrous alloys with lasting attitude. As it is seen from the curve for ferrous alloys and titanium, there is a fatigue limit (endurance limit) of the component. This limit indicates the maximum stress limit that can be theoretically applied to a material for an infinite life. In some materials such as aluminum, stainless steel or copper, number of cycles to fatigue failure can slightly continue to grow beyond $N=10^6$ cycles as the stress amplitude declines. Fatigue limits in these materials should be specified at obtained cycles to failure (Milella, 2013).

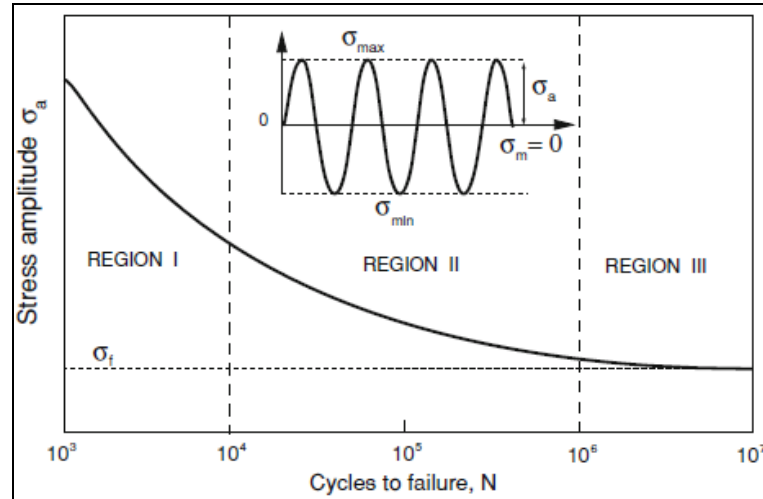


Figure 2.29 A typical S-N curve exhibiting three different regions to investigate fatigue response of a material (Milella, 2013)

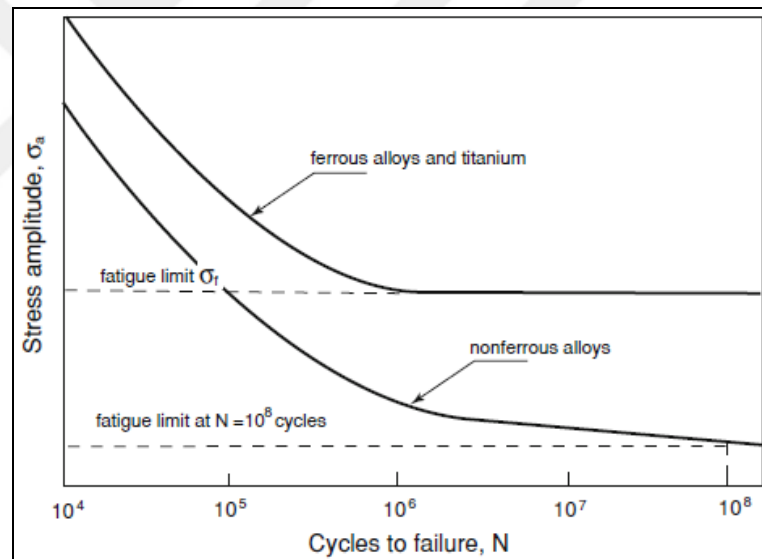


Figure 2.30 Common two types of S-N curves (Milella, 2013)

Together with not being a general rule, minimum 7 and maximum 14 samples can be used in order to obtain S-N curves. Herein, test parameters and appropriate number of samples are important factors for determining the number of samples to be used. In addition, it is also common knowledge that the stress range selection in the tests considerably depends on experiment (Little & Jebe, 1975). In other respects,

there are researches in the literature investigating the approaches to plot an S-N curve using a small number of samples (Strzelecki & Sempruch, 2016).

2.9.2 Fatigue Failure Mechanism

When a material is exposed to repeated cyclic loadings, progressive, indigenous and permanent microstructural changes are observed through fatigue. Besides, the loading stresses will be commonly below the material's tensile strength. These changes eventuate in occurrence of cracks and their following development to a size that results in final failure subsequent to enough number of load fluctuations. Broadly speaking, the fatigue damage mechanism consists of three phases: crack initiation, crack propagation and final failure. The concurrent activity of cyclic stressing, tensile stress and consisted plastic strain lead to the fatigue damage. It is important to point out that the compressive loading might generate localized tensile stresses, even though compressive loads will not lead to fatigue (Boardman, 1990).

Figure 2.31 shows the different phases of fatigue life. Cyclic slip, which states dislocation motions, contributes to crack initiation and crack growth. Cracks initiate at the internal or external free surfaces due to the lower restriction on cyclic slip. Besides that, there are several inducements for crack initiation at the material surface such as the inhomogeneous stress distribution and surface roughness. After crack nucleation, the microcrack brings about a stress concentration at the tip so long as the size of the crack is in the order of a few grains. As the crack grows in the material within some neighboring grains, adjacent grains contribute to restriction increment on slip displacements. Thereby, it becomes increasingly hard to accommodate the slip displacements by a single slip system only. Thereafter, it starts occurring on slip planes within different directions. An example of the schematic of microcrack cross-section is demonstrated in Figure 2.32. Providing that a crack starts growing by passing through a substantial amount of grains, the crack front needs to maintain congruent. In other words, the crack cannot grow in each grain at any propagation rate and in a haphazard direction. Resistance of crack growth of the material is at the ground of crack growth rate (Schijve, 2009).

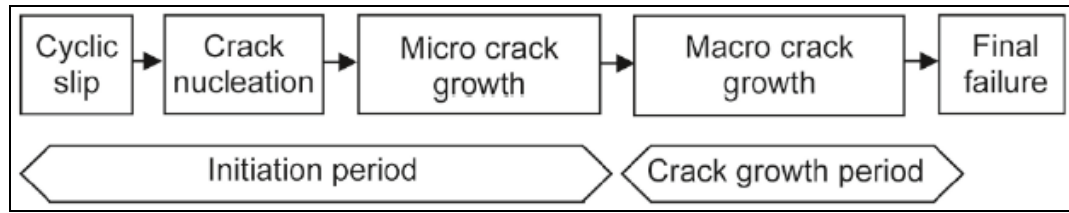


Figure 2.31 Stages of fatigue damage process (Schijve, 2009)

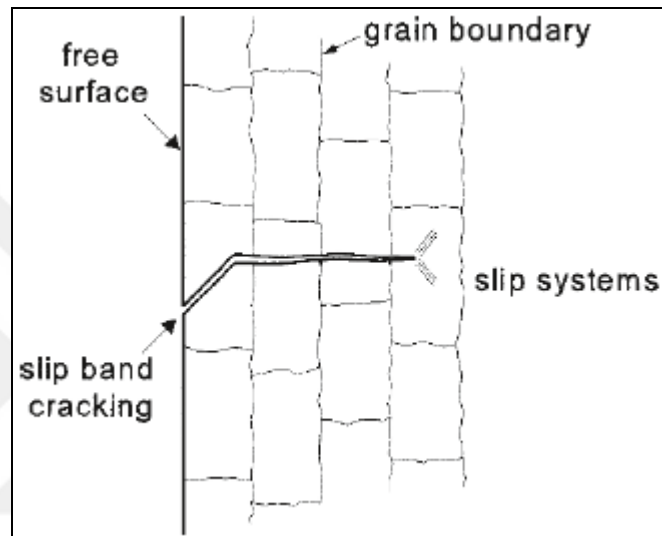


Figure 2.32 Schematic representation of microcrack cross-section (Schijve, 2009)

2.9.3 Fatigue in MMCs

As emphasized earlier in the thesis, particle-reinforced MMCs stand out due to their especially high specific modulus and strength. Therefore, these materials have been drawing more attention in many engineering applications such as the automotive and aerospace in which MMCs will be subjected to repeated fluctuating loads (Ma et al., 2015). Among MMCs, it is well-known that SiC-reinforced aluminum matrix composites (Al/SiCp) is becoming increasingly attractive in various structural applications owing to their superior features (Pan et al., 2017).

Interfacial debonding between reinforcing particle and matrix material, particle rupture and matrix cracking are common failure modes of MMCs based on fatigue.

However, it should be noted that the probable anisotropic features of reinforcements might make it difficult to evaluate the fatigue failure mechanisms within composites. Particle fracture rate under fluctuating loading is significantly affected by specific matrix material properties, particle volume fraction and size. Fatigue response of Al/SiCp composites such as crack growth rate or endurance limits is dramatically influenced by reinforcing particles. Considering the fatigue crack propagation, there is a close relationship between particle fracture and maximum stress intensity as the fatigue crack size increases (Pramanik & Basak, 2018). By the way, it should be noted that the fabrication process also play an important role on the fatigue behavior of MMCs (Divagar, Vigneshwar & Selvamani, 2016). Processing induced defects or inclusions have a negative effect on the fatigue resistance of MMCs (Li et al., 2017).

In a way, it could be said that the disconformity between thermal expansion coefficients of particle reinforcing and matrix material generates the residual thermal stresses. These thermal stresses affect the mechanical and physical features of MMCs and are considered as the inducements of plastic deformation within the matrix, which cause crack initiation and propagation or rupture of material (Tevatia & Srivastava, 2017).

2.9.4 Fatigue Design in Welds

In order to prevent premature failure of components during their operating time, fatigue design is a quite critical phenomenon within an engineering design. It is also common knowledge that the welding as an assembly process is the most outstanding solution to obtain a sound mechanical joining. Considering the fact that welding has such a significant place in the engineering applications, extensive work has been devoted on the fatigue analyses of welded joints. Hereby, a great variety of approaches for fatigue assessment has been available so as to estimate fatigue damage of welded joints (Susmel, 2014). To date, several standard design codes have been introduced to fatigue design and analysis of welded joints (Aluminum Association, 2015; BSI, 1992; CEN, 2007; CSA, 2014; Hobbacher, 2016).

Recommendations for Fatigue Design of Welded Joints and Components by The International Institute of Welding (IIW) is only presented within this subchapter.

Pertaining to the approaches for fatigue assessment, S-N curves based upon constant amplitude cyclic loading are at the forefront. In other respects, Palmgren-Miner rule is widely considered for variable amplitude loading. Herein, nominal stress, notch strain, structural hot spot stress, effective notch stress, notch stress intensity factor and crack propagation approach can be enumerated as the common techniques. There are also various considerations on fatigue assessment of welded joints. Plate thickness effect, multiaxial stresses, welding misalignments and residual stresses are well-known factors on fatigue design. Lastly, enhancement of weld quality, lowering the stress concentration and post-weld treatments such as grinding, shot peening and so forth provide fatigue strength improvement for welded joints (Fricke, 2015).

2.9.4.1 Fatigue Design Curves by IIW

These recommendations provide determinate knowledge on the design and analysis of welded joints against fatigue failure under fluctuating loading. Nominal stress range is at the ground of fatigue assessment of welded joints. The influences of stress concentrations, residual stresses, weld imperfections and post weld treatments are included within the fatigue design curves. S-N curve for each structural detail is characterized by fatigue strength of detail at 2×10^6 cycles that are termed as fatigue class (FAT) (Hobbacher, 2016). For the sake of example, transverse butt-welds welded from one side without backing bar of aluminum is identified as FAT 28 and this fatigue resistance curve gives a stress range of 28 MPa. Figure 2.33 shows the fatigue strength S-N curves for some structural details of aluminum welds. As it is noticeable from the figure, the slope of each curve except FAT 71 is $m=3$. In addition to this, constant amplitude fatigue limit (CAFL) is also characterized by fatigue strength of each detail at 10^7 cycles. This is also termed as knee point as seen in the figure. Another noteworthy point is that the fatigue strength modifications are

possible for each FAT class with respect to wall thickness, stress ratio and post weld processes (Hobbacher, 2016).

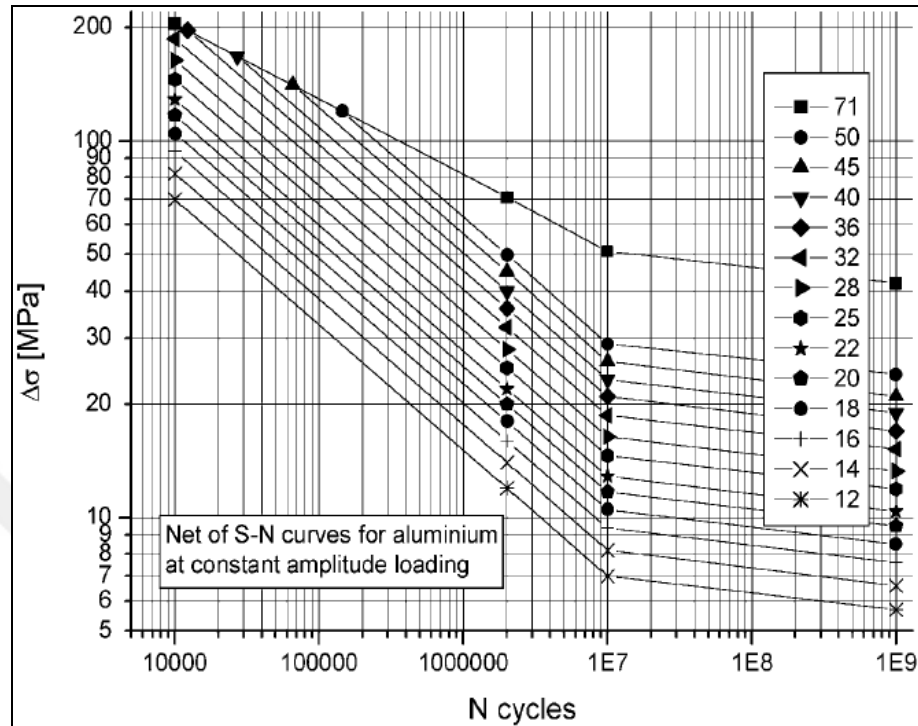


Figure 2.33 Fatigue strength S-N curves for aluminum (Hobbacher, 2016)

CHAPTER THREE

LITERATURE SURVEY

3.1 Introduction

Owing to their high specific strength to weight ratio, enhanced mechanical properties, superior wear resistance and lower thermal expansion by comparison with corresponding alloys, metal matrix composites have been increasingly used in several engineering applications (Ceschini, Boromei, Minak, Morri & Tarterini, 2007a). On the other hand, the drawback in the joining of these materials to themselves or other outstanding engineering materials impedes them from having more widespread usage (Prater, 2011). Herein, FSW process is gaining favor due to its benefits such as good mechanical performance, scarcity of general fusion weld defects and low residual stress and distortion (Periyasamy, Mohan, Balasubramanian, Rajakumar & Venugopal, 2013). Accordingly, comprehensive studies have been performed on the application of FSW of MMCs in the literature. This chapter covers a pithy review of the literature from the point of characterization of the FSWed metal-matrix composite joints, tool wear in the FSW of MMCs and optimization of the FSW parameters to obtain good mechanical behavior.

3.2 Characterization of Similar and Dissimilar FSWed AMCs with Various Particle Reinforcements

To date, considerable work has been devoted on the application of FSW of similar and dissimilar AMCs. However, these researches have been particularly carried out on the microstructural investigation and mechanical analyses of the FSWed joints. Taking into account all of these works, only a few data are available on the dissimilar FSWed joints. In other respects, these studies are only related to dissimilar FSW of AMCs and monolithic aluminum alloys without fatigue behaviors of the FSWed joints.

Marzoli, Strombeck, Dos Santos, Gambaro & Volpone (2006) studied the thermal and microstructural stability of the aluminum matrix composite (AA6061/Al₂O₃/20p) after FSW and reported that a higher heat input is necessary at the beginning of the weld in order to obtain requisite plasticity. Microstructure and mechanical properties of the joint were also evaluated. Consequently, defect-free and high strength welds were achieved through the selected parameters. Figure 3.1 demonstrates the welding parameter matrix.

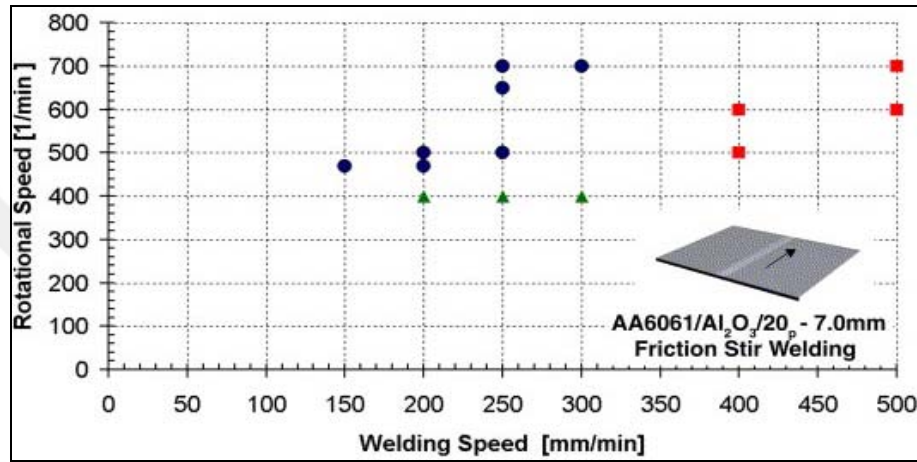


Figure 3.1 Parameter matrix: ▲, Imperfect welds; ●, defect-free welds; ■, leading limit of the FSW process (Marzoli, Strombeck, Dos Santos, Gambaro & Volpone, 2006)

The sufficiency of FSW on the joining of dissimilar materials is one of the most important merits of this promising technology. Sharifitabar & Nami (2011) investigated the microstructure evolution and hardness behavior of the FSWed joints between 2024-T4 aluminum alloy and Al/Mg₂Si MMC. They also presented the effect of one and two passes throughout the weld line on these parameters. The welding parameters such as the tool rotational speed, tool travel speed and shoulder penetration depth were determined by considering weld results of the similar materials. In addition to these, positioning of the workpieces markedly affects the microstructure evolution and mechanical properties of the joint. To utilize from the harder material (2024 AA) on the advancing side caused the formation of macro interface properly. Therefore, the softer material (Al/Mg₂Si) was placed in the retreating side through the first pass. According to the results, broken and rearranged

eutectic Mg_2Si particles were obtained in the stir zone and eutectic phase of the aluminum alloy was observed due to the high heat input that caused eutectic melting in the weld zone. Finally, the hardness profiles of the joint were also introduced after one and two weld pass. Figure 3.2 shows the variation of hardness across the joint in one and two weld passes.

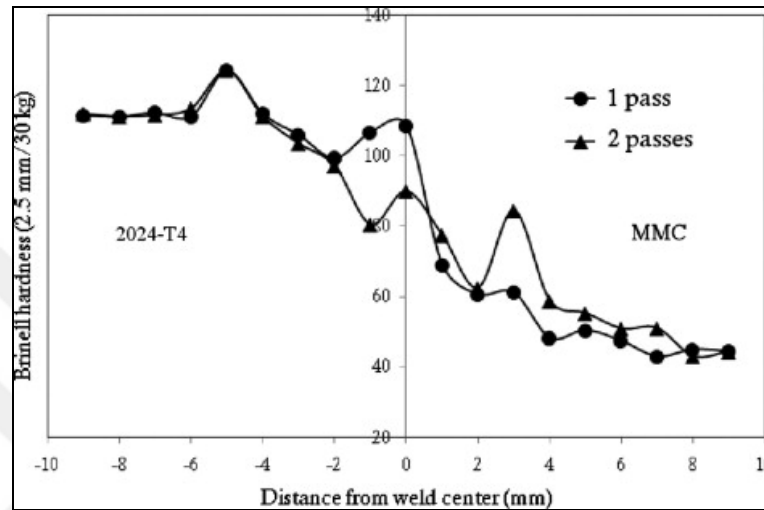


Figure 3.2 Hardness profiles across the dissimilar joints (Sharifitabar & Nami, 2011)

Feng, Xiao & Ma (2008) studied the effect of post-weld heat treatment (PWHT) on the microstructure evolution and mechanical properties of FSWed AA2009/SiCp composite. The microstructural evolution was investigated through OM, SEM and TEM. Figure 3.3 exhibits the microstructure of the joint under different circumstances. Tensile properties of the joints including tensile strength and percentage of elongation were also reported in the study. The hardness profiles across the mid-thickness of the welded joints were determined in order to evaluate the hardening effect of the processes. Their results demonstrated that the FSW can be applied to join the AA2009/SiCp composite and then FSW joints can be subjected to a strengthening heat treatment. The results indicated that the PWHT has no significant effect on the microstructure evolution, whilst the process resulted in a joint performance along transverse directions of %95. In addition, it should be pointed out in the present study that although the T4-treatment did not change the

hardness values across the weld zones, the hardness profile showed a significant increase in the NZ of as-extruded composite subsequent to FSW.

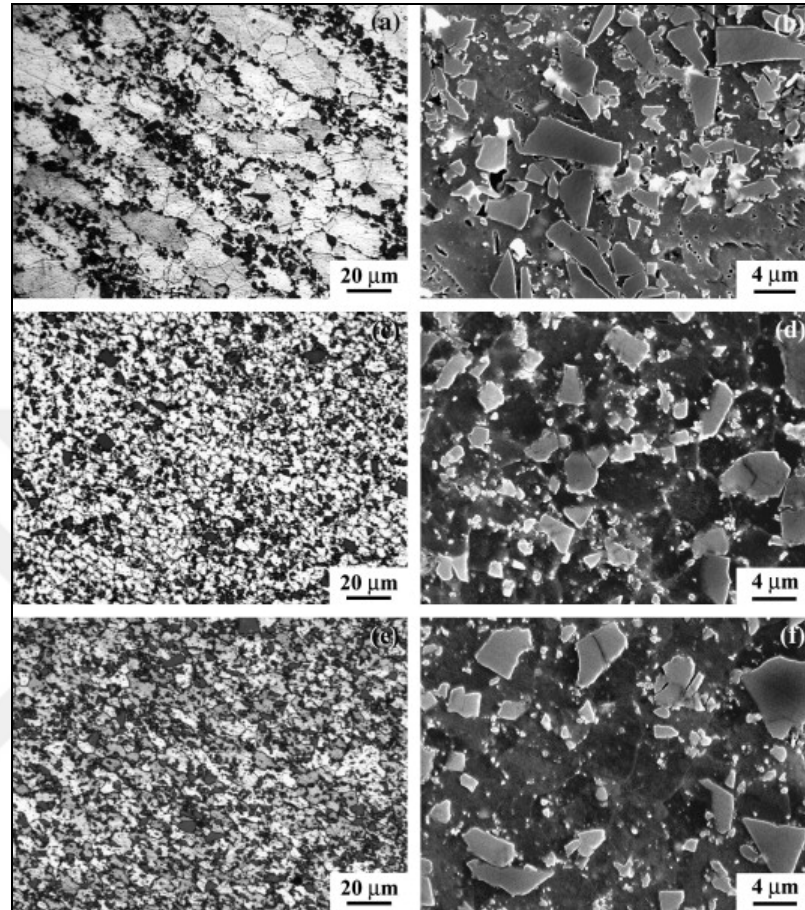


Figure 3.3 OM and SEM images of AA2009/SiCp composites: (a) and (b) base metal, (c) and (d) nugget zone under as-FSW condition, (e) and (f) nugget zone under T4-treatment condition (Feng, Xiao & Ma, 2008)

Kalaiselvan, Dinaharan & Murugan (2014) evaluated the effect of FSW on the microstructure and other mechanical properties of AA6061/B₄C cast composite. They performed various trial runs to determine the optimal welding parameters that produce defect-free welds. OM and SEM were used to characterize the microstructure evolution in the weld region and finer grains were observed in the weld zone due to the dynamic recrystallization during the FSW. They also noted that the bigger B₄C particles in the stir zone were broken and fragmented subsequent to the process. In addition, the fracture surfaces of the composite before and after FSW

were investigated in detail and they recorded that the surface of FSWed composite was flat and the failure mode was brittle in opposition to the base material. The fracture surfaces of AA6061/B₄C composite before and after the process are demonstrated in Figure 3.4.

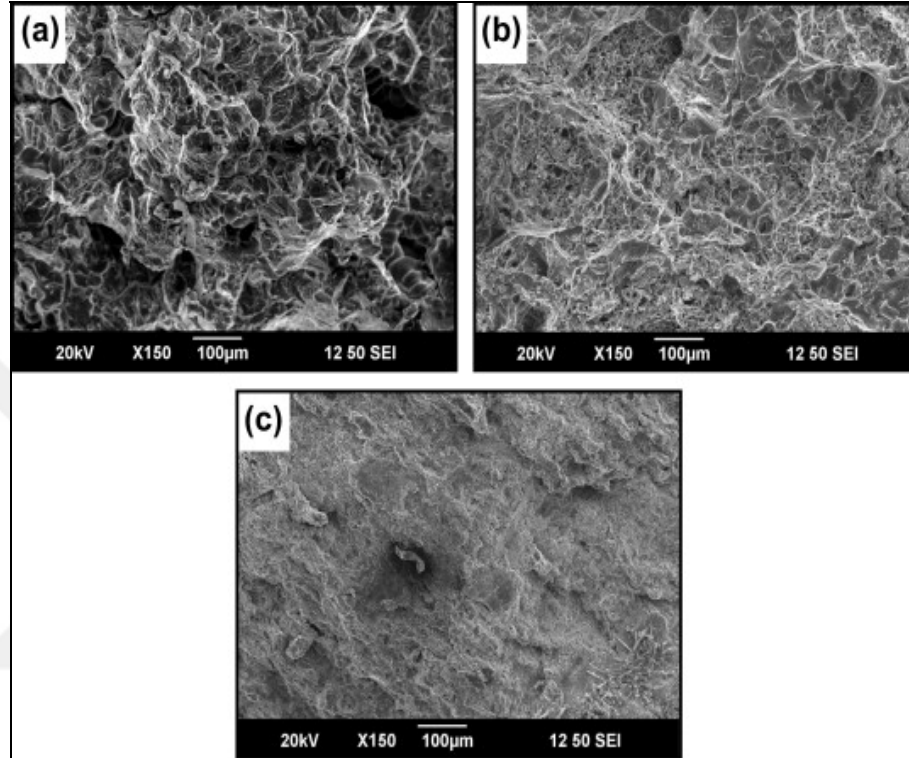


Figure 3.4 SEM images showing micrographs of the fracture surfaces in (a) cast AA6061, (b) cast and (c) welded AA6061/B₄C composite (Kalaiselvan, Dinaharan & Murugan, 2014)

Dissimilar FSW between different materials such as AA1100-B₄C and AA6063 was also evaluated (Guo, Gougeon & Chen, 2012). Microstructure and mechanical properties of the joints were investigated similar to the aforementioned researches. Main welding parameters and tensile results of the FSWed joints are presented in Table 3.1 and Table 3.2, respectively. In addition to this, the effect of the use of convenient tool offset was investigated in terms of the wear property. The results showed that the proper offset on the AA6063 side introduced less wear. Microstructural characterizations of the joints were also presented by way of the different instruments such as OM, SEM, EDS and EBDS. The EBSD results demonstrated that the microstructure evolution finished with the dynamic

recrystallization of the subgrains. The microhardness profiles across the welds were also obtained. It is worthy of note that the hardness of the nugget of the AA6063 side exhibited a dramatic decrease. However, the hardness of the nugget on the MMC side displayed a reasonable increase.

Table 3.1 Welding parameters of the dissimilar joints (Guo, Gougeon & Chen, 2012)

Code	Advancing side material	Rotation speed (rpm)	Welding speed (mm min ⁻¹)	Offset (mm)	Tilt angle (°)
DF1	6063 alloy	2000	100	0	3
DF2	6063 alloy	2000	200	0	3
DF3	6063 alloy	2000	100	0.8	3
DF4	Al-B ₄ C MMCs	2000	100	0	3

Table 3.2 Tensile test results comparison of the dissimilar FSWed joints (Guo, Gougeon & Chen, 2012)

Conditions	UTS (MPa)	YS (MPa)	Elongation (%)	Joint efficiency (UTS)	Failure location (MMC side)
Base MMC	126 ± 2	61 ± 1	13 ± 3	-	-
DF1	127 ± 1	81 ± 4	9 ± 1	100%	Base
DF2	128 ± 1	81 ± 2	10 ± 1	100%	Base/TMAZ
DF3	126 ± 1	79 ± 1	8 ± 1	100%	Base
DF4	127 ± 1	80 ± 2	8 ± 1	100%	Base/TMAZ

There are various kinds of reinforcements used in AMCs. Typical reinforcements include silicon carbide (SiC), aluminum oxide (Al₂O₃), boron, carbon and titanium carbide (TiC). However, the new kinds of reinforcements such as B₄C, TiB₂ or ZrB₂ have found widespread application areas due to their superior properties. Dinaharan & Murugan, (2012a) carried out the FSW of AA6061/ZrB₂ composites and investigated the effect of FSW on the microstructure, mechanical and wear properties of the joints. They reported the homogeneous distribution of ZrB₂ particles in the weld zone. They also obtained the microhardness profiles and tensile properties of the joints. They recorded a significant increase of microhardness in the weld zone owing to the dynamic recrystallization of the grains. In their study, increasing tensile strength was achieved as the weight percentage of ZrB₂ particles was increased, as expected. Finally, they evaluated the sliding wear behavior of the joints and reported that the welded composites had higher wear resistance by comparison with the parent

composite. Figure 3.5 shows the wear rate of as-cast and FSWed AA6061/ZrB₂ composites.

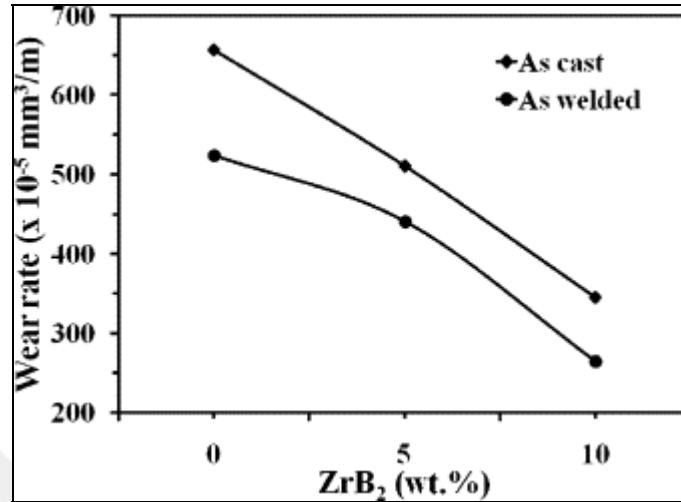


Figure 3.5 Sliding wear rate comparison of as-cast and FSWed composites (Dinaharan & Murugan, 2012a)

The weldability of thick plates of 2124Al/25vol%SiC_p composite through FSW was sought by the researchers (Cioffi et al., 2013). Besides, the effects of tool rotation speeds on the microstructural features and mechanical properties were also evaluated in the study. In the wake of the study, in order to obtain sound joints of the aforementioned composite materials, it was reported that suitable tool rotation speeds should be between 550-800 rpm/min. Moreover, the hardness profile of the weld region at 800 rpm/min was stated and it was determined that the hardness results in the stir zone were close to that of the base material within the research. As a result of the performed mechanical tests, percentage elongation values in the tensile tests were found fairly lower compared to the parent material while high performances were obtained in the tensile strength of the joints. Furthermore, compressive tests were conducted on the welds so as to evaluate the compressive features of the joints as part of the study. Table 3.3 exhibits the summary of mechanical test results.

Table 3.3 Tensile and compressive test results of the welds (Cioffi et al., 2013)

	Mechanical properties			
	Sample	σ_{02} (Mpa)	σ_{max} (Mpa)	e_{max} (%)
Tensile	300	421.4	543.9	1.9
	550	406.6	552.4	2.6
	800	435.4	442.8	0.3
	BM	657.3	741.9	5.3
	300 + T6	438.2	438.2	0.2
	550 + T6	478.8	642.1	2.9
	800 + T6	-	254.8	0.1
Compressive	300	503.9	769.8	17.1
	550	516.9	832.9	18.0
	800	550.0	840.6	15.7
	BM	600.2	846.2	15.9

Lastly, Khodabakhshi, Yazdabadi, Kokabi & Simchi (2013) studied the microstructure characterization, mechanical properties and fracture behavior of the FSWed (P/M) Al-2 vol% Al₂O₃ nanocomposite welds. In addition, influence of the FSW parameters on the welding quality was also investigated. Within this research, FSWed wrought AA1050 was utilized for the comparison. The trend for the tensile properties of FSWed monolithic alloy and nanocomposite depending on the FSW parameters are shown in Figure 3.6. Based upon the findings in this study, it was reported that the joining of the powder metallurgy processed nanocomposite was only applicable in the case of enhanced material flow at high heat inputs during the process. In addition, grain refinement mechanism in the different weld zones was found. Moreover, microhardness enhancement was determined for some regions such as fine-grained zone (FGZ) and melted-zone (MZ). Furthermore, brittle fracture mode was observed for P/M material.

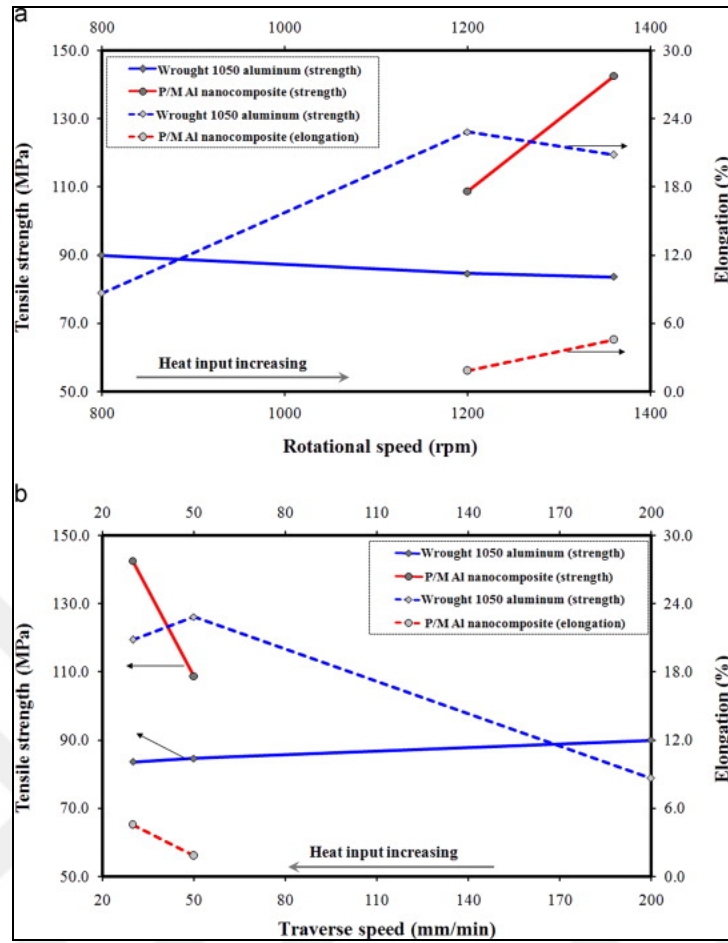


Figure 3.6 Comparison of the FSWed different welds as a function of (a) rotational speed and (b) transverse speed (Khodabakhshi, Yazdabadi, Kokabi & Simchi, 2013)

3.3 Tool Wear in the FSW of MMCs

In a successful welding process, a FSW tool is explicitly one of the most important constituents. Herein, design and material selection have a profound effect on the nonconsumable tool performance, success of the joining and manufacturing cost. On the other hand, short-lived FSW tools due to the tool wear especially restrict the wider application of the process on hard engineering materials (Rai, De, Bhadeshia & DebRoy, 2011). A FSW tool generally consists of a flat or conical shoulder and a tapered or conical pin that may include various features such as flats or threads. Besides that, these features and design of the tool can influence the formation of weld defects (Simar & Fènoël, 2017). This subchapter details some

prominent studies on the tool wear characterization and the optimization for weld parameters and nonconsumable tool.

Prado, Murr, Soto & McClure (2003) observed the tool wear and the rate of wear of FSWed AA6061-T6/Al₂O₃/20p composite in the course of the process. In the study, four different welding speeds were used in conjunction with a constant tool rotation speed. With the performed experiments, it was aimed to determine the self-optimized shape of the tool with sound welds out of any extra tool wear. Figure 3.7 shows the illustration of the pin phases with the wear. As a result of the self-optimization period, a slightly-inclined frusto-conical shaped tool view was roughly observed. However, it should be noted that the shape of the tool showed an alteration with the increasing welding speed. In addition to all these, sound welds were achieved for both the unworn and worn tools. Nevertheless, effects of the tool wear on microstructure evolution and mechanical behavior in terms of the tensile strength were not examined within the work.

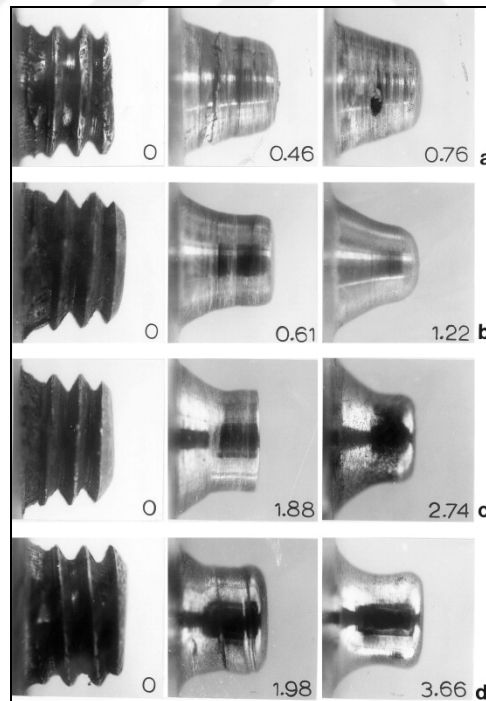


Figure 3.7 Tool pin phases showing tool wear features for constant tool rotation speed of 1000 rpm and different welding speeds (a) T=1 mm/s; (b) T=3 mm/s; (c) T=6 mm/s; (d) T=9 mm/s (Prado, Murr, Soto & McClure, 2003)

The threaded tool wear in the FSW of Al359/SiCp composite was also studied to obtain a self-optimized shape of the process tool (Shindo, Rivera & Murr, 2002). According to the results, it was observed that the rate of tool wear declines with increasing weld speed and terminates above the specific weld speed such as 11 mm/s. In addition, the homogeneous dispersion of the SiC particles was notably observed in the weld zones. Moreover, harder weld zone compared to that of parent material was reported within the study. Mid-thickness hardness distributions of the welds in relation to beginning and end of FSW are illustrated in Figure 3.8.

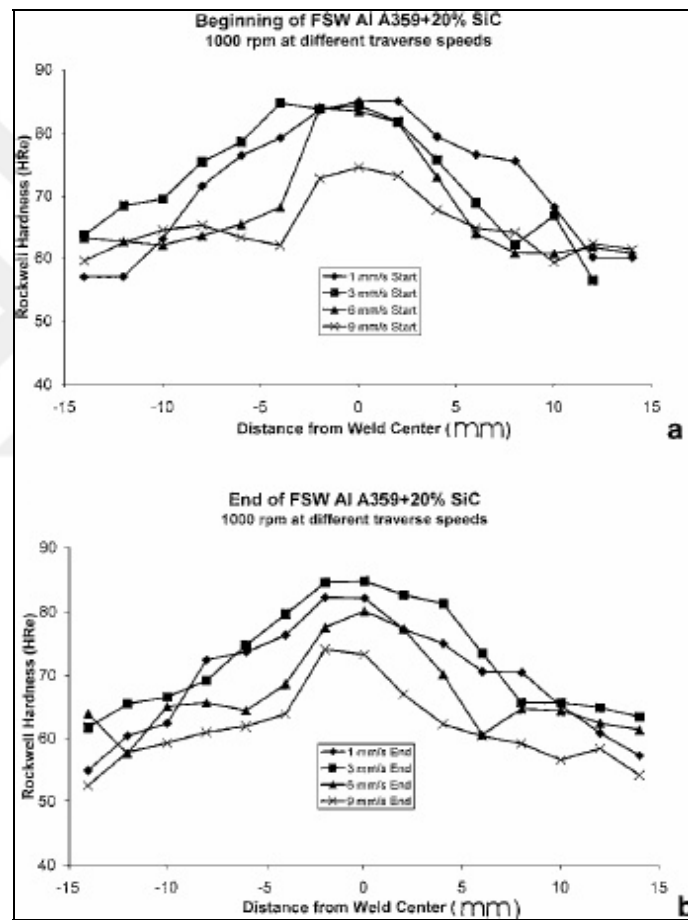


Figure 3.8 Comparison of mid-thickness hardness distribution of the welds in relation to beginning and end of FSW (Shindo, Rivera & Murr, 2002)

In additional to work by Shindo et al. (2002), the influences of tool rotation speed on the optimization of tool shape and rate of tool wear were also evaluated for the FSWed Al359+20% SiC composite in the present study (Fernandez and Murr, 2004).

Besides that, the effects of welding speed to optimize the tool rotation speed were investigated. Moreover, characterization of the microstructure for the parent material and weld zone of the joint was carried out through OM and TEM within the research. Considering the results, it can be inferred that the wear of threaded steel tool increased at low welding speeds and high tool rotation speeds. Afterwards, self-optimized shape of the tool with no tool wear was obtained. In addition, more homogeneous microstructure and undamaged particles were observed in the microstructural investigations subsequent to the welds fabricated by self-optimized tool. Figure 3.9 demonstrates the schematic representation of the self-optimized tool evolution.

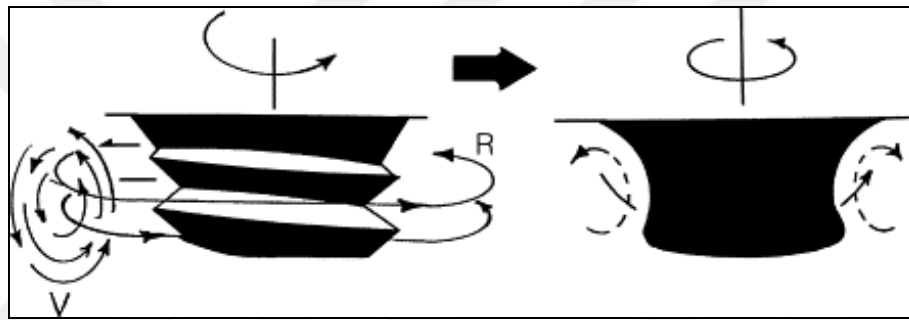


Figure 3.9 Regime of flow related to the formation of self-optimized tool shape (Fernandez and Murr, 2004)

The applicability of in-process sensing with regards to the wear amount of the tool was investigated in the FSW of AA359/SiC/20p composite. In this way, an exhaustive survey was aimed so as to observe and control the tool wear rate in the course of FSW by the researchers (Prater et al., 2015). Accordingly, long weld distances were provided in order to evaluate the relationship between the tool wear and in-process signals. From the results, it is noticed that the torque imposed by the process tool was associated with the radial wear amount of the pin. This finding provides in-process measuring of tool wear through the signals of process. Herewith, evaluation of torque by way of in-process measurements can ensure the replacement of the tool at the right time. At this juncture, it is worthwhile to mention that the link between the tool wear and torque was special to welding parameters, material of

workpieces and tool design. The comparison of a threaded tool utilized for the FSW of a trial joint can be seen in Figure 3.10.

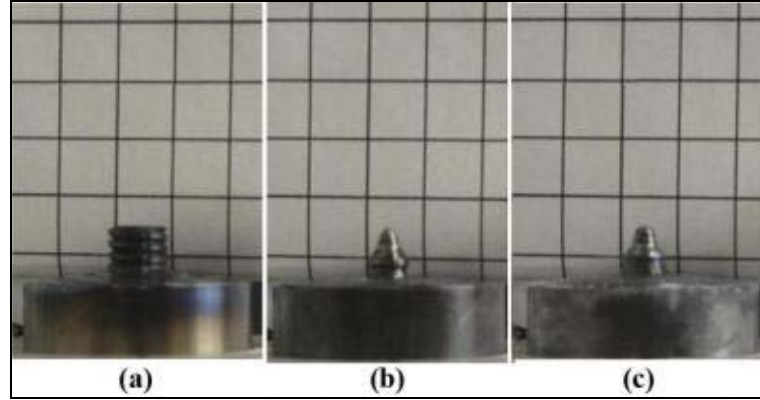


Figure 3.10 The threaded tool consisting of a spherical, convex shoulder: (a) pre-production, (b) subsequent to a 9-ft-long FSW at 1400 rpm/9 ipm, (c) subsequent to a 9-ft-long FSW at 1400 rpm/9 ipm through torque control (Prater et al., 2015)

3.4 Role of Process Parameters on the Mechanical Properties of FSWed MMCs

The effects of FSW parameters such as welding speed, axial force, tool pin profile and tool rotational speed on the tensile behavior of FSWed AA6061/TiCp composite joints were studied by the researchers (Gopalakrishnan & Murugan, 2011). Therefore, a mathematical model was developed to predict the tensile strength of the joints. Based on their results, it is found that the tool pin profile and welding speed play a crucial role on the tensile properties of the joints. Using a tapered square tool with a proper welding speed provided a maximum joint performance in terms of the tensile strength. However, microstructure evolution and detailed mechanical properties of the joints were not evaluated in the present study. Figure 3.11 shows the selected profiles for the tool probes.

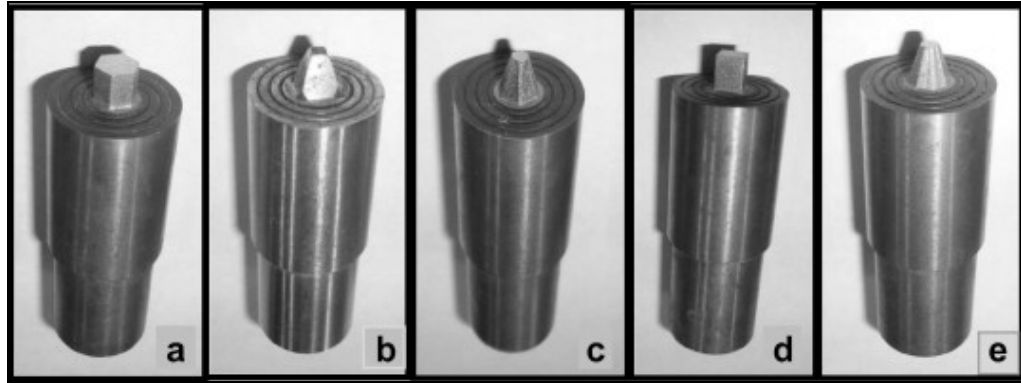


Figure 3.11 Pin profiles used in the process: (a) hexagon, (b) taper square, (c) taper hexagon, (d) square, and (e) taper octagon (Gopalakrishnan & Murugan, 2011)

In a similar way, Dinaharan & Murugan (2012b) used a mathematical model in an attempt to optimize the FSW parameters of AA6061/ZrB₂ in-situ composite. The four factors such as tool rotation speed, welding speed, axial force and weight percentage of ZrB₂ particles were evaluated. Their results indicated that the parameters independently had substantial effect on the tensile strength of the joints. The optimized parameters were determined as 1155 rev.min⁻¹ of tool rotation speed, 48.8 mm.min⁻¹ of welding speed, 5.9 kN of axial force and 10 wt% of ZrB₂. The soundness of the developed mathematical model is exhibited in Figure 3.12.

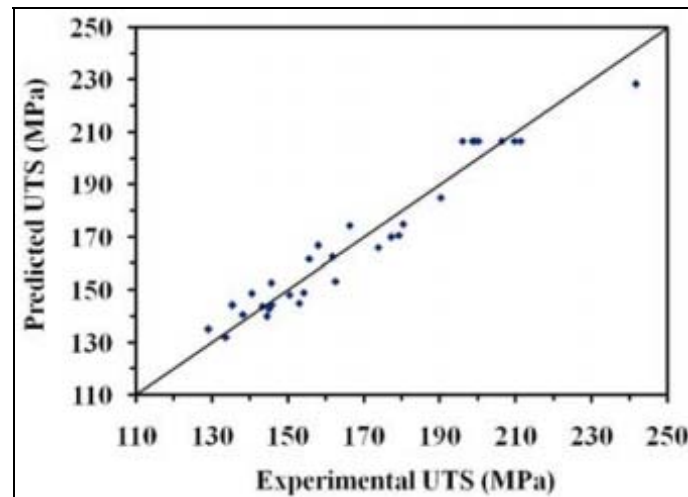


Figure 3.12 Scatter diagram showing the validity of the model (Dinaharan & Murugan, 2012b)

The influences of FSW parameters such as tool rotation speed (N), welding speed (S), applied axial force (F) and volume fraction of the reinforcement (R) on the mechanical properties in terms of the tensile strength and joint efficiency and also on the microstructure of AA6061-B₄C composite joints were investigated within the research (Kalaiselvan & Murugan, 2013). Accordingly, in order to evaluate the impact of the process parameters and to anticipate the ultimate tensile strength of the FSWed joints, the researchers developed a mathematical model. In the study, the experimental design matrix comprising a four-factor (process parameters) and their five levels were utilized for the implementation of FSW experiments. Thereafter, the accuracy of the developed mathematical model was inspected through the analysis of variance method. When the results are analyzed, the paramount tensile strength was observed for the joint FSWed by use of a tool rotation speed of 1000 rpm, a welding speed of 1.3 mm/s, an axial force of 10 kN and the particle reinforcement of 12%. The ranges and levels of process parameters and the developed design matrix with the tensile test results are presented in Table 3.4 and Table 3.5, respectively.

Table 3.4 The ranges and levels of the welding parameters (Kalaiselvan & Murugan, 2013)

Process parameter	Notation	Level				
		-2	-1	0	1	2
Rotational speed/(r·min ⁻¹)	N	800	900	1000	1100	1200
Welding speed/(mm·s ⁻¹)	S	0.3	0.8	1.3	1.8	2.3
Axial force/kN	F	6	8	10	12	14
Reinforcement/%	R	4	6	8	10	12

Table 3.5 The experimental design matrix with tensile results (Kalaiselvan & Murugan, 2013)

Trial run	Design matrix				Estimated UTS/MPa	Joint efficiency/%
	<i>N</i>	<i>S</i>	<i>F</i>	<i>R</i>		
1	-1	-1	-1	-1	146.2	76.54
2	+1	-1	-1	-1	137.1	71.78
3	-1	+1	-1	-1	131.5	68.85
4	+1	+1	-1	-1	139.3	72.93
5	-1	-1	+1	-1	148.8	77.91
6	+1	-1	+1	-1	142.2	74.45
7	-1	+1	+1	-1	150.5	78.80
8	+1	+1	+1	-1	141.3	73.98
9	-1	-1	-1	+1	163.9	79.56
10	+1	-1	-1	+1	154.2	74.85
11	-1	+1	-1	+1	165.7	80.44
12	+1	+1	-1	+1	159.3	77.33
13	-1	-1	+1	+1	142.9	69.37
14	+1	-1	+1	+1	151.4	73.50
15	-1	+1	+1	+1	158.2	76.80
16	+1	+1	+1	+1	149.3	72.48
17	-2	0	0	0	124.7	62.66
18	+2	0	0	0	131.5	66.08
19	0	-2	0	0	121.1	60.85
20	0	+2	0	0	136.2	68.44
21	0	0	-2	0	128.8	64.72
22	0	0	+2	0	138.3	69.50
23	0	0	0	-2	175.5	94.86
24	0	0	0	+2	200.1	93.06
25	0	0	0	0	188.5	94.72
26	0	0	0	0	181.7	91.31
27	0	0	0	0	179.8	90.35
28	0	0	0	0	185.4	93.17
29	0	0	0	0	183.2	92.06
30	0	0	0	0	186.5	93.72
31	0	0	0	0	185.1	93.02

The welding quality of FSW process is substantially comprised of welding parameters such as tool rotational speed, welding speed and tilt angle of the process. From this viewpoint, Bozkurt, Kentli, Uzun & Salman (2012) investigated the mechanical properties of AA2124/SiC/25p composite joints under various tool rotational speeds (355 rpm-1400 rpm). In addition, effects of the process parameters on the tensile behavior of the FSWed joints were also presented as part of the research. Decision tree technique was used to anticipate the tensile properties of the joints. As per the obtained results, it was reported that the weld efficiency declines with the increasing welding speed in the case of constant tool rotational speed. Besides that, the applicability of decision tree so as to predict mechanical properties was ascertained through the results with sufficient precision, within the study. Figure 3.13 demonstrates the impacts of the process parameters to ascertain the predicted values.

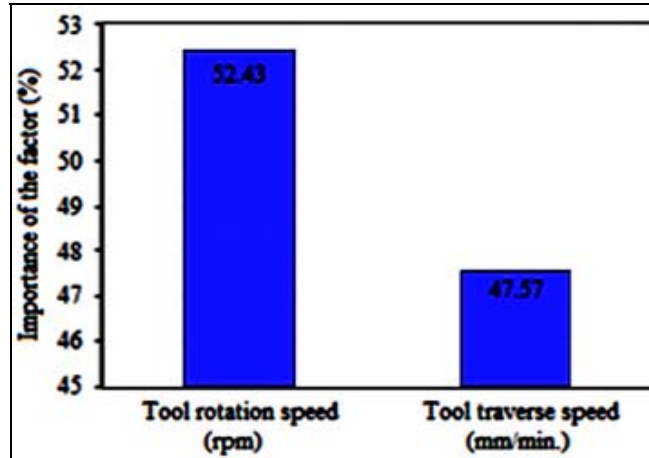


Figure 3.13 Impacts of the process factors (Bozkurt, Kentli, Uzun & Salman, 2012)

3.5 The Contemporary Prominent Practices of FSW

In order to fabricate metal matrix composites so as to enhance the surface feature in terms of wear resistance and tribological properties of monolithic alloys, reinforcement particles and their homogeneous dispersion are needed on the raw metallic surface. By taking into consideration the aforementioned requirement, friction stir processing (FSP) is developed based upon the working principles of FSW process (Ebrahimzad, Ghasempar & Balali, 2017; Narimani, Lotfi & Sadeghian, 2016).

Chen et al., (2015) performed several quantitative microstructural characterizations in order to evaluate the effects of nanoparticles on the microstructure evolution of AA6063/TiB₂/8p composite after FSP. Dislocation distribution and dislocation density of the FSPed aluminum-matrix composite and FSPed monolithic alloy were compared through the synchrotron X-ray analysis. The obtained XRD patterns are exhibited in Figure 3.14. The analysis results showed that the dislocation density of the composite is higher than that of the base material subsequent to FSP. The results also confirmed that the dislocation distribution was more homogeneous in the FSPed composite by comparison with the base material. In addition, it was reported that the microhardness values in the NZ of the composite have exhibited a significant increase in regard to the base material. In their study, it

was also verified that the appropriate heat treatment such as T6 heat treatment could be utilized to enhance the mechanical properties of the joint.

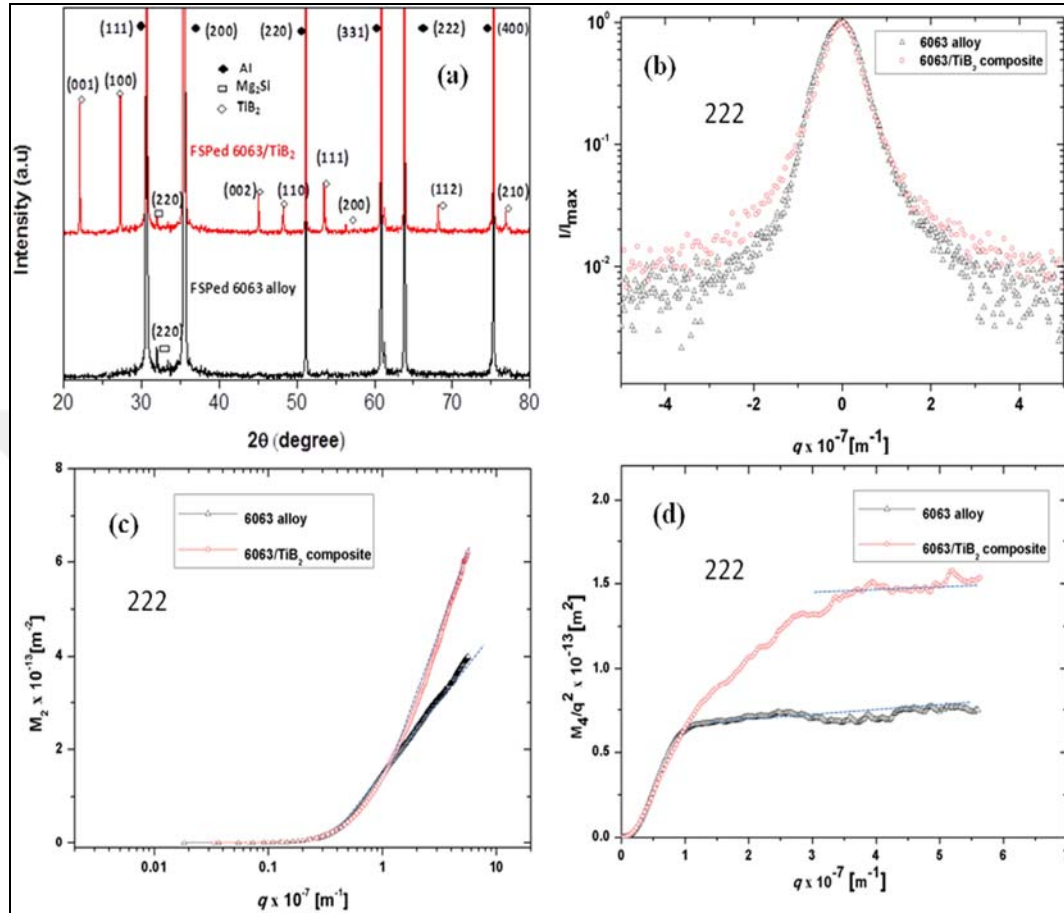


Figure 3.14 (a) Synchrotron XRD patterns of the FSPed AA6063 and FSPed AA6063/TiB₂, (b) magnified broadened peaks of 222 reflections of both specimens, (c) variance and (d) forth-order moment of 222 peaks demonstrated in (b) (Chen et al., 2015)

Dissimilar FSW was performed between the aluminum alloys 6082-T6 and 5083-H111 by using SiC nanoparticles (Pantelis et al., 2016). In the study, different number of FSP passes was conducted to determine the effect of welding parameters on the microstructure evolution of weld nugget (WN). The results showed that the increasing number of weld passes provides a more uniform dispersion of SiC nanoparticles. The banded structure including different areas richer and poorer in SiC nanoparticles was also observed. The microhardness profile of the optimum joint that resulted in absence of defects and agglomeration was determined. From their results,

it can be inferred that the addition of SiC nanoparticles can significantly improve the hardness property of WN. In addition, nanomechanical properties of the weld zone were measured by nanoindentation tests to evaluate the effect of microstructure evolution on the mechanical properties of the materials. The test results demonstrated that the elastic modulus of the material was improved by the addition of SiC nanoparticles. Figure 3.15 shows the longitudinal distribution of plasticity percentage and elastic modulus with SiC reinforcement.

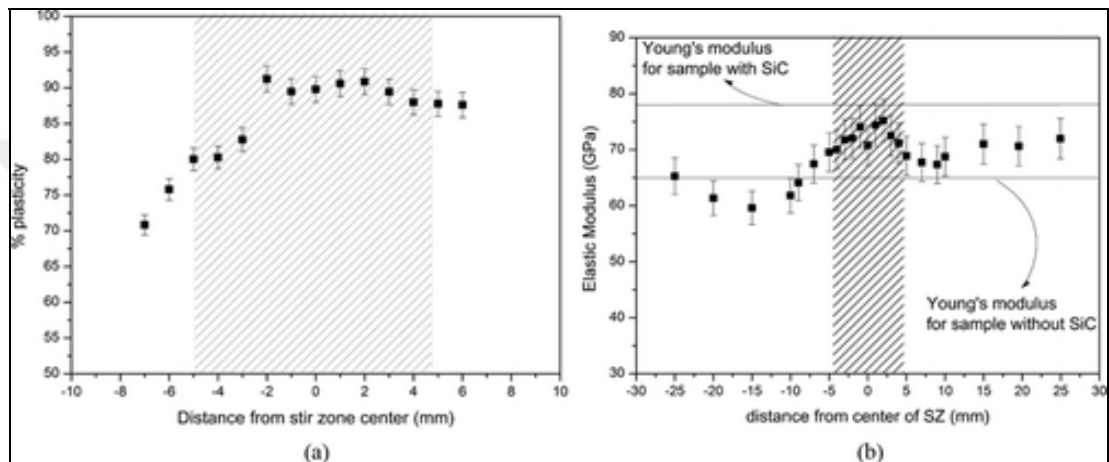


Figure 3.15 The longitudinal variance of (a) plasticity percentage, (b) Young's modulus with SiC addition (Pantelis et al., 2016)

In a similar way, Tabasi, Farahani, Givi, Farzami & Moharami (2016) used SiC nanoparticles in the nugget so as to obtain metal matrix composite in the stir zone of the joint. Within the work, 7075-T6 aluminum alloy and AZ31 magnesium alloy were utilized for the dissimilar FSW. In order to embed the reinforcement nanoparticles free from particle irregularity, a new embedded groove was presented in the study. Within the study, the admixture patterns of weld stir zones, texture in the FSWed joints, intermetallic phases in the stir zones, distribution of nanoparticles and tensile properties of FSWed samples were exhaustively elucidated. Besides, the influences of tool rotational speed and welding speed were also evaluated in an attempt to improve microstructure of the dissimilar joints. According to the results, it was reported that sufficient mixing of the dissimilar alloys was obtained through increasing tool rotation speed and decreasing welding speed. Particle dispersions in

the stir zone of various FSWed specimens were demonstrated in Figure 3.16. In addition to this, it was observed that the grain size in the stir zone decreases with the increasing tool rotation speed. Compared to the base materials, reduction in the ductility and tensile strength of the FSWed joint was determined owing to the evolution of hard intermetallic phases.

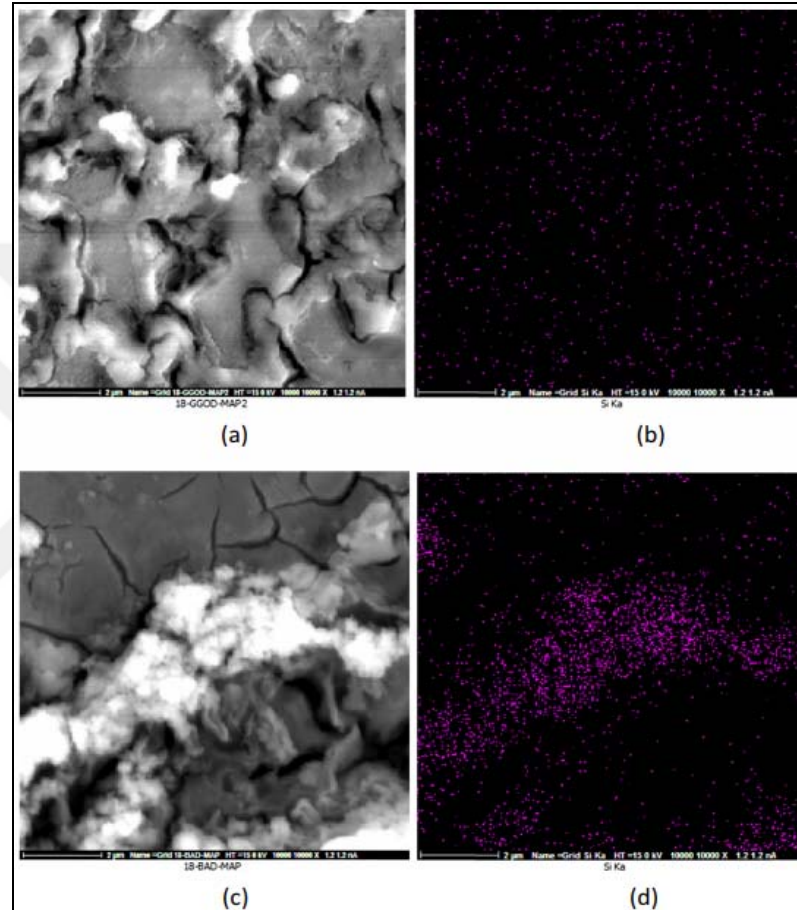


Figure 3.16 SEM images and particle dispersion maps of FSWed different samples: (a) and (b) RS=710 rpm, WS=22.4 mm/min, (c) and (d) RS=710 rpm, TS=35.5 mm/min (Tabasi, Farahani, Givi, Farzami & Moharami, 2016)

CHAPTER FOUR

SCOPE AND OBJECTIVES

Aluminum-based metal matrix composites (MMCs) are excellent candidates for light-weight engineering applications in various industries such as the automotive, aerospace and defense owing to their high strength to weight ratio, outstanding thermal conductivity, good wear and corrosion resistance (Ahn, Choi, Kim & Jung, 2012; Guo, Amira, Gougen & Chen, 2011). Therefore, particle-reinforced aluminum matrix composites having the wide areas of usage are consciously utilized within the thesis. However, the drawbacks in the joining of MMCs to themselves or to various engineering materials prevent their widespread usage. Accordingly, sufficient joining of these composites is increasingly demanded due to the common structural applications of the aforesaid materials.

In the light of abovementioned information, the major objective of this study is to investigate the microstructure, mechanical properties and fatigue response of similar and dissimilar FSWed MMCs. For this purpose, MMC plates with different thicknesses have been provided at first. Tools have been manufactured depending upon the similar and dissimilar workpieces as the strength of the material significantly affects the wear property. Then, workpieces have been prepared for the FSW process. After that, FSW has been performed by using high-powered FSW adapted milling machine. The aforementioned procedure was continued up to obtain sound welding. After providing a sufficient joining, metallographic observations of the welds were presented through the optical microscopy (OM) and scanning electron microscopy (SEM). Mechanical characterization of the joints was also introduced in terms of the tensile strength, microhardness, flexural strength and fracture toughness. Finally, behavior of the some selected similar and dissimilar joints under variable loading was studied within the thesis.

CHAPTER FIVE

PRELIMINARY WORKS

As stated previously, this chapter compendiously presents a part of the preparatory studies performed in an effort to evaluate the relationship between FSW parameters (tool rotation speed, welding speed, workpiece position and tool diameter) and mechanical properties of the FSWed aluminum alloy joints. Besides that, characterization of the similar and dissimilar joints was carried out before the investigation of similar and dissimilar FSWed MMC joints. Thus, FSW process of the AMCs was achieved more snugly.

Thirteen different FSWed joints were fabricated within the preparatory studies. However, a certain part of the obtained results is exhibited in the thesis. The joints are listed in Table 5.1. Joint-1 was performed between AA7075-O workpieces by a constant welding speed through three different rotational speeds. Joint-2 and Joint-3 were created between AA6061 materials by two diversified tools with the same welding parameters. Joint-4 was obtained by dissimilar FSW between AA6061-O and AA7075-O alloys in which case the 7075 aluminum alloy was placed on the advancing side. Finally, Joint-5 was obtained again by the FSW between the same alloys in which case the 7075 aluminum alloy was fixed on the retreating side. In these studies, temperature distribution around the weld line was also measured by means of the K-type thermocouples and a non-contact infrared thermometer. The process setup for the FSW is demonstrated in Figure 5.1 and the photos of the fabricated joints can also be seen in Figure 5.2. Later on, these plates were prepared for the microstructure characterization and mechanical behavior investigation. For that purpose, microstructure, hardness and tensile test samples were cut off from the workpieces as can be seen in Figure 5.3. Within this chapter, some of the prominent results will be included in terms of the similar AA6061-O joints and dissimilar joints between AA6061-O and AA7075-O.

Table 5.1 Welding Parameters of the fabricated joints

#Joints	#Material	#Rotational Speed (rev/min)	#Welding Speed (mm/min)	#Tool Diameter (mm)
Joint-1.1	AA7075-AA7075	1250	250	18
Joint-1.2	AA7075-AA7075	1500	250	18
Joint-1.3	AA7075-AA7075	1750	250	18
Joint-2.1	AA6061-AA6061	1250	150	18
Joint-2.2	AA6061-AA6061	1500	150	18
Joint-2.3	AA6061-AA6061	1750	150	18
Joint-3.1	AA6061-AA6061	1250	150	20
Joint-3.2	AA6061-AA6061	1500	150	20
Joint-3.3	AA6061-AA6061	1750	150	20
Joint-4.1	AA7075(AS)-AA6061(RS)	1100	100	18
Joint-4.2	AA7075(AS)-AA6061(RS)	1300	100	18
Joint-5.1	AA6061(AS)-AA7075(RS)	1100	100	18
Joint-5.2	AA6061(AS)-AA7075(RS)	1300	100	18

*AS=Advancing Side; RS=Retreating Side

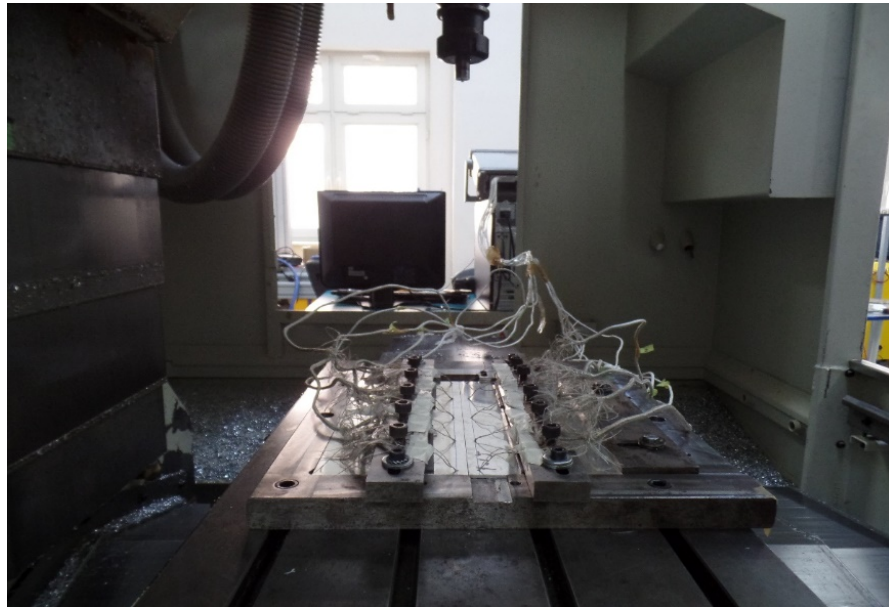


Figure 5.1 Process setup for the FSW (Personal archive, 2016)

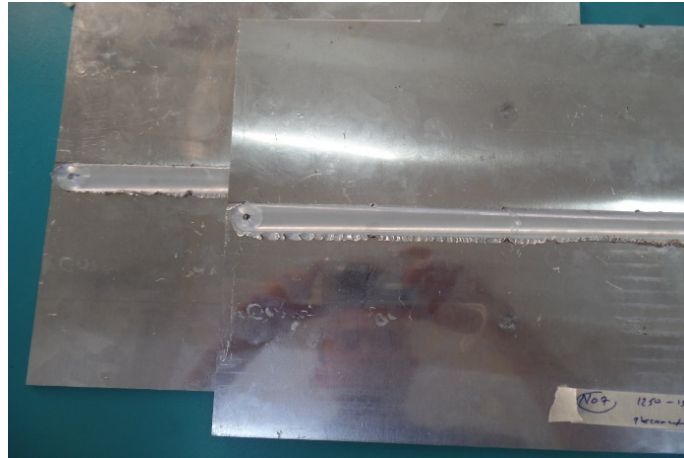


Figure 5.2 Photograph of the FSWed aluminum alloy plates (Personal archive, 2016)



Figure 5.3 Test coupons for the material characterization (Personal archive, 2016)

5.1 Similar FSW of AA6061-O

5.1.1 Materials and Experimental Procedure

3.2 mm thick plates of AA6061-O were friction stir butt-welded by a FSW adapted vertical CNC milling machine. The aluminum plates of size 300 x 130 x 3.2 mm³ were joined by FSW using one constant travel speed and three different rotational speeds. The parameters were chosen by taking into consideration the results of preliminary experimental studies. A hot work tool steel (H13) with a shoulder 18 mm in diameter and a cylindrical threaded pin 4 mm in diameter was used. The fabricated welding tool is shown in Figure 5.4. Before welding, the

surfaces of the plates were decontaminated from possible oxide films and inclusions by a steel file. Afterwards, the aluminum plates were FSWed along the extrusion direction (Oztoprak, Serindag, Yeni & Kiral, 2016a).



Figure 5.4 Fabricated welding tool used for FSW process (Personal archive, 2016)

5.1.2 Macrostructures of the Joints

Figure 5.5 exhibits the cross sections of the joints. Some weld defects were located in the stir zone (SZ) of Joint-2.2 though Joint-2.1 and Joint-2.3 did not exhibit any defects. The onion ring formation can also be seen in the nugget zone of Joint-2.1 and Joint-2.3. It is also worth pointing out that the diversified thermomechanical histories of the joints create different zones including nugget zone (NZ), thermomechanical affected zone (TMAZ) and heat affected zone (HAZ).



Figure 5.5 Macrostructures of the friction stir welded AA6061-O (Personal archive, 2016)

5.1.3 Microhardness

The Vickers hardness measurements were performed along the mid-thickness of the FSWed joints through an applied load of 100 g. The span between each measurement was 0.5 mm to obtain the hardness profile of the FSWed joints created using the tool with 18 mm shoulder diameter. Microhardness profiles of the joints can be seen in the Figures 5.6-5.8. The hardness of base material was in the range of 35-40 HV and the stir zone demonstrated the highest hardness for all joints. The maximum hardness was about 62.9 HV on the advancing side of the Joint-2.3. It follows from the microhardness distribution profile that the increasing tool rotational speed significantly affects the microhardness behavior of the joints. The obtained profiles can be attributed to the microstructural evolution of the material. The changes in the grain size and distribution due to the high temperature and plastic flow in different weld regions compose the given alteration. As indicated in Figure 5.7, there is a disordered variation in the hardness profile of the Joint-2.2 by comparison with other fabricated joints as the presence of the weld defect detected in the stir zone, such as porosity, considerably affects the mechanical behavior of the material. On the other hand, a hardness increase was observed from base material to stir zone for all joints including Joint-2.2. It is worth noting that this considerable increase in the joints can be attributed to the O-temper condition of the workpieces. As a result of frictional heating, an intensive plastic flow arises in the workpieces at an elevated temperature and this creates finer scale grains in the weld zone compared to the base material.

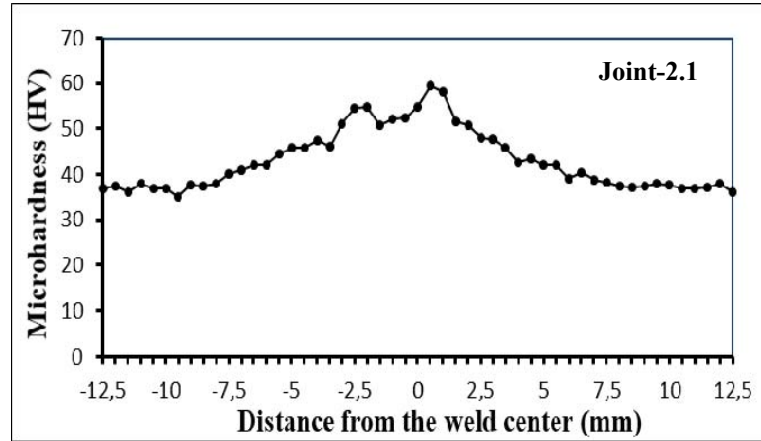


Figure 5.6 Microhardness profile on the cross-section of Joint-2.1

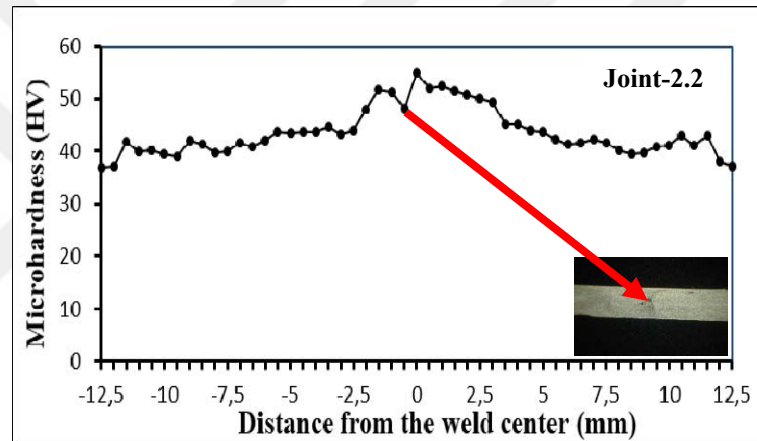


Figure 5.7 Microhardness profile on the cross-section of Joint-2.2

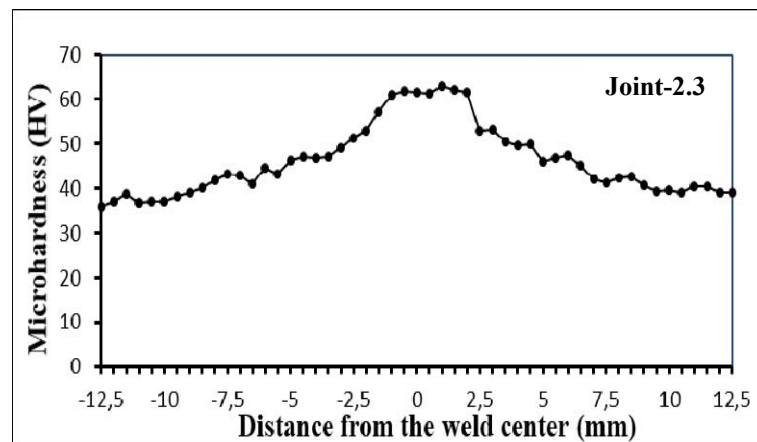


Figure 5.8 Microhardness profile on the cross-section of Joint-2.3

5.1.4 Tensile Properties

Transverse tensile properties of the FSWed joints are determined by tensile tests that are performed at room temperature at a constant speed of 1 mm/min. At least five tensile tests were carried out for three different joints. Figures 5.9-5.11 illustrate the engineering stress-elongation curves of the tensile test specimens. All FSWed joints of AA6061-O temper demonstrated a similar trend to that of the base material. Besides, the FSW resulted in a 97.7% performance of the strength in Joint-2.3 considering that the 6061 aluminum alloy has a tensile strength and elongation of 123 MPa and 28.2%, respectively (Ipekoglu, Erim, Kiral, & Cam, 2013). It is worth mentioning that this performance in the tensile strength can be associated with the microstructure evolution of the material after joining. Moreover, all test specimens including Joint-2.2 with some defects fractured on the retreating side of the weld in the base material. Failure positions of all joints are also located away from the weld region.

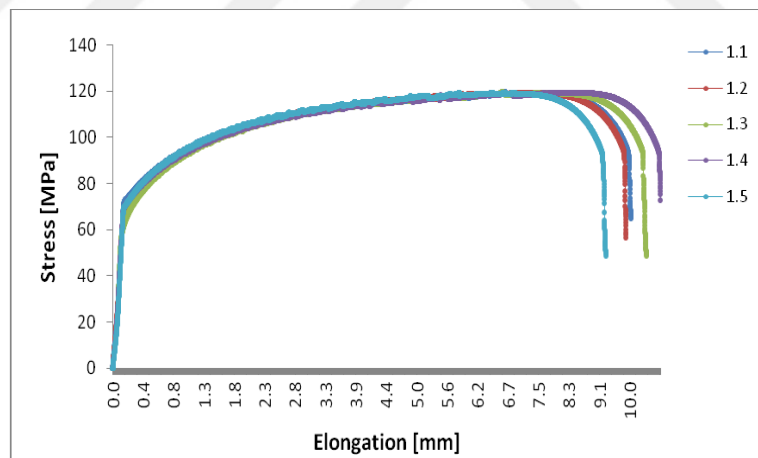


Figure 5.9 Tensile behaviour of Joint-2.1

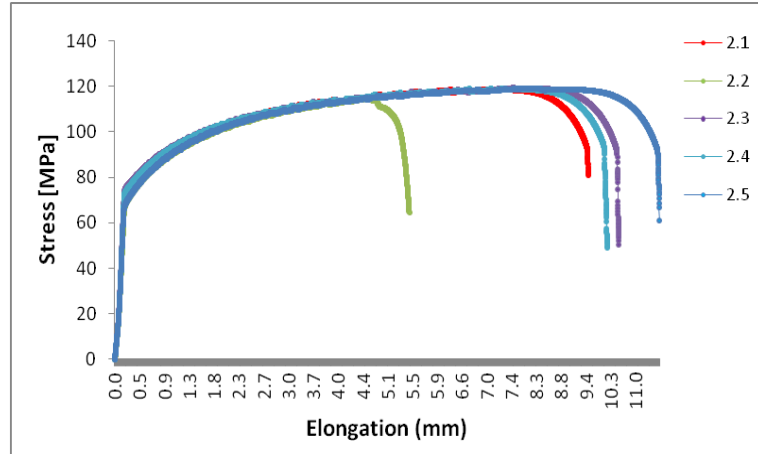


Figure 5.10 Tensile behaviour of Joint-2.2

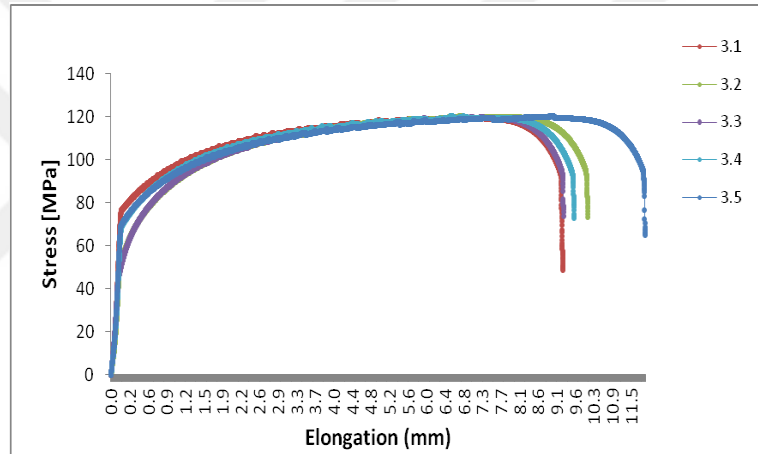


Figure 5.11 Tensile behaviour of Joint-2.3

The mechanical testing results including the tensile strength and failure elongation of the specimens are compared in Table 5.2. According to the results, it is seen that Joint-2.3 demonstrated a higher mean tensile strength value, i.e., 120,156 MPa, than that of other joints. On the other hand, ductility of the specimens is about two-thirds that of the base material. In brief, the tensile tests on AA6061-O temper confirm that the successful FSW process can provide good performance in tensile strength while reduces the elongation to failure as expected.

Table 5.2 Tensile test results

#Specimen		1	2	3	4	5	Average	Performance (%)
Base Material	Tensile Strength (MPa)	-	-	-	-	-	123	-
	Elongation (P_{ct})	-	-	-	-	-	28.2	-
Joint-2.1	Tensile Strength (MPa)	119.6	116.8	117.2	117.08	117.02	117.55	95.6
	Elongation (P_{ct})	20.8	20.6	21	21.2	19.2	20.56	72.9
Joint-2.2	Tensile Strength (MPa)	116.2	112.3	117.0	116.79	116.87	115.87	94.2
	Elongation (P_{ct})	19.8	13.2	22.2	20.9	24.2	20.06	71.1
Joint-2.3	Tensile Strength (MPa)	120.0	120.3	119.7	120.39	120.28	120.15	97.7
	Elongation (P_{ct})	20.9	21.2	19.6	20.4	24.4	21.3	75.5

5.1.5 Concluding Remarks

In the present work, the FSW of 3.2 mm thick AA6061-0 plates were carried out using a hot work steel (H13) tool. The achieved conclusions can be summarized as follows:

- (a) A hardness increase was observed from base material to stir zone for all joints.
- (b) A successful similar FSW process can provide outstanding performance in tensile strength as reducing the elongation to failure as expected.

5.2 Dissimilar FSW of AA6061-O and AA7075-O

5.2.1 Materials and Experimental Procedure

The dissimilar parent materials that were used in this research were 3.2 mm thick plates of AA7075-O and AA6061-O. General dimensions of the workpieces were 300 x 130 x 3.2 mm³. The aluminum alloy plates were joined by FSW using one constant travel speed and two different rotational speeds. Material positions in the

processes were also switched. The process parameters were chosen by taking into consideration the results of preliminary experimental studies. In a similar way, the rotating tool was manufactured from a hot work tool steel (H13) with a shoulder 18 mm in diameter consisting of a cylindrical threaded pin 4 mm in diameter (Oztoprak, Serindag, Yeni & Kiral, 2016b).

5.2.2 Tensile Properties

Tensile properties of the dissimilar FSWed joints are tested by transverse tensile tests that were performed at room temperature at a constant speed of 1 mm/min. Four tensile tests were carried out for each different joint. Figures 5.12-5.15 illustrate the engineering stress-strain curves of the tensile test specimens. All FSWed dissimilar joints approximately demonstrated trends similar to those of the parent materials. Besides, the FSW also resulted in 94.30%, 94.29%, 94.13% and 93.89% performance of the strength in Joint-4.1, Joint-4.2, Joint-5.1 and Joint-5.2, respectively. It is worth mentioning that these performances in the tensile strength can be attributed to selection of proper welding parameters. Moreover, all test specimens fractured through the weak side (AA6061-O) of the joints. Failure positions of all joints are also located away from the weld region (Figure 5.16).

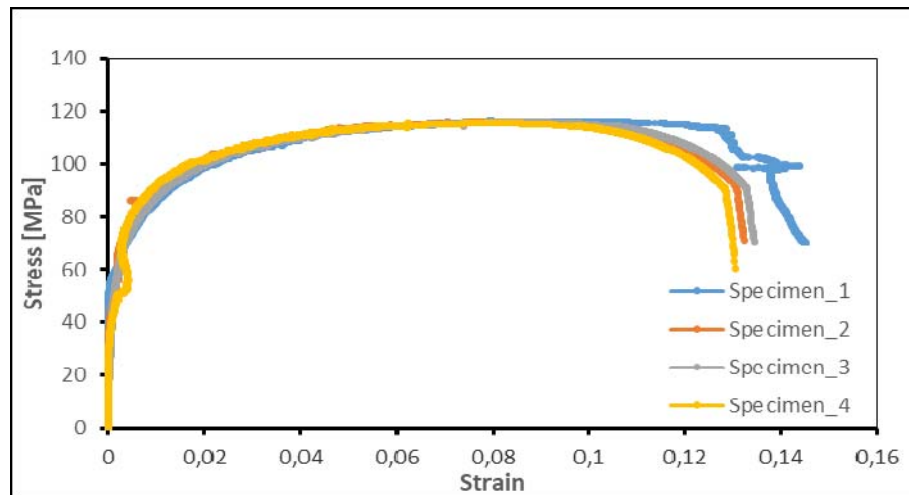


Figure 5.12 Tensile behavior of Joint-4.1

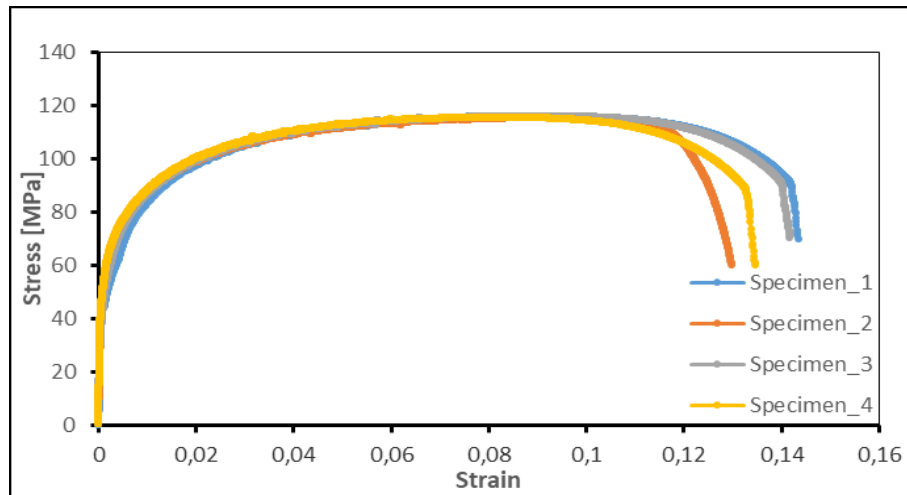


Figure 5.13 Tensile behavior of Joint-4.2

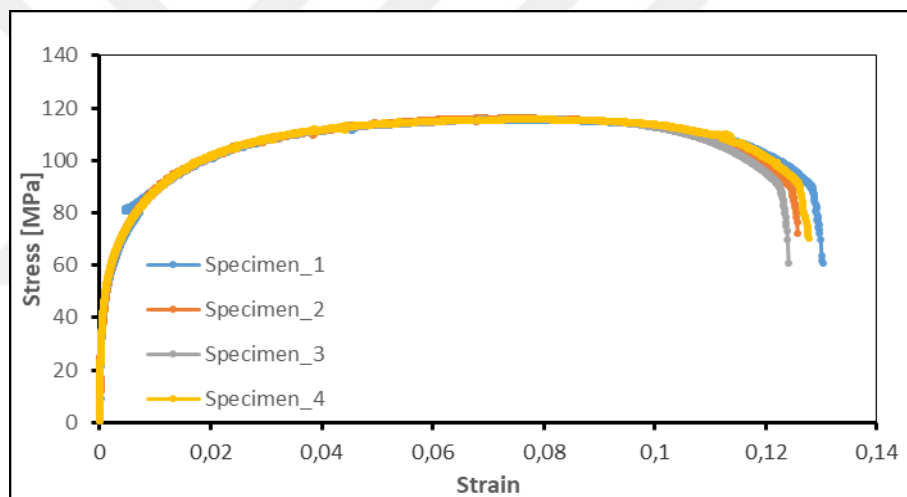


Figure 5.14 Tensile behavior of Joint-5.1

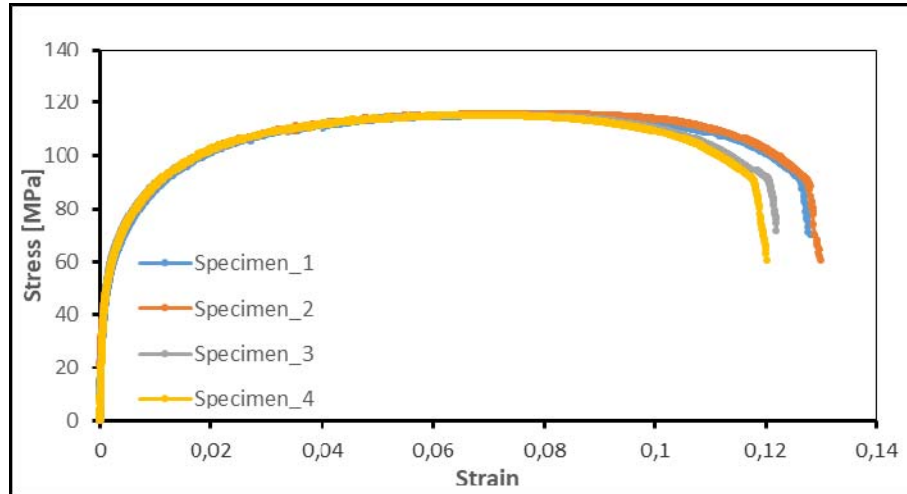


Figure 5.15 Tensile behavior of Joint-5.2



Figure 5.16 Failure positions of the tensile test specimens (Personal archive, 2016)

The mechanical testing results including the tensile strength and percentage of elongation (P_{ct}) of the specimens are compared in Table 5.3. Tensile properties of the 7075 aluminum alloy can also be found in the study by Ipekoglu, Erim, & Cam (2014). According to the results, it is explicit that Joint-4.1 demonstrated a higher mean tensile strength value, i.e., 115.99 MPa, than those of the other joints. On the other hand, ductility of the specimens is about one-half those of the base materials. It should be noted that the tensile test results demonstrated slight variation as the tool

rotational speed was increased. Similarly, it is needed to notice that the material position during process has no significant effect on the tensile properties of the dissimilar joints. All joints showed relatively the same percentage of elongation. Elongation of 15.2%, 14.75% and 13.8%, 13.9% were obtained for different material positions during the process. The highest percentage of elongation was obtained for Joint-4.1 (1100 rpm; 100 mm/min), having the weak material on the retreating side of the weld. In brief, transverse tensile tests on the dissimilar joints between AA6061-O and AA7075-O confirm that the successful FSW process can provide good mechanical performance in tensile strength while reduces the failure elongation.

Table 5.3 Tensile test results

#Specimen		1	2	3	4	Average	Performance (%)
Base Material (6061-O)	Tensile Strength (MPa)	-	-	-	-	123	-
	Elongation (P_{ct})	-	-	-	-	28.2	-
Base Material (7075-O)	Tensile Strength (MPa)	-	-	-	-	203.5	-
	Elongation (P_{ct})	-	-	-	-	18.9	-
Joint-4.1	Tensile Strength (MPa)	116.35	115.94	116.09	115.59	115.99	94.30
	Elongation (P_{ct})	18.0	14.3	14.4	14.1	15.2	53.90
Joint-4.2	Tensile Strength (MPa)	116.13	115.77	116.23	115.78	115.98	94.29
	Elongation (P_{ct})	15.7	14.2	15.2	13.9	14.75	52.3
Joint-5.1	Tensile Strength (MPa)	115.51	116.20	115.73	115.66	115.78	94.13
	Elongation (P_{ct})	14.3	13.2	13.7	14.0	13.8	48.94
Joint-5.2	Tensile Strength (MPa)	115.20	115.93	115.46	115.33	115.48	93.89
	Elongation (P_{ct})	14.6	14.1	13.5	13.2	13.9	49.11

5.2.3 Hardness

Hardness profiles of the dissimilar joints are presented in Figures 5.17-5.20. As seen from the figures, there is a hardness increase in the joint area of the dissimilar joints, generally. This hardness increase is thought to be due to the grain refinement and precipitation hardening of the particles taking place in the weld region. In addition, the hardness increase in the TMAZ at the AS is also significantly higher than that of the RS due to the higher strength of AA7075. Furthermore, it follows from the results that the tool rotational speed has a profound effect on the microhardness profiles of the dissimilar joints. The max. hardness is about 176 HV on the AS of Joint-4.1. The results can also be associated with the microstructural evolution of the material. On the other hand, a hardness loss was observed in the joint area of dissimilar joints. As seen in the figures, the minimum hardness in the joint area was determined to be about 55.1 HV for Joint-4.1 and 59.4 HV for Joint-4.2. It should be noted that the microstructure of the stir zone consists of consecutive layers of these two dissimilar alloys and is dominated by the alloy placed at the AS prior to joining. It is also noteworthy that the width of the weld regions are much narrower than those observed in the similar joints.

The hardness profiles of Joint-5.1 and 5.2 are also presented in the figures. According to the figures, there is a hardness increase in the joint area of the joints, similarly. The max. hardness is about 150 HV and 151 HV on the RS of Joint-5.1 and Joint-5.2, respectively. It can also be seen that width of the weld region is larger than those observed when the high strength alloy is placed at the AS prior to joining.

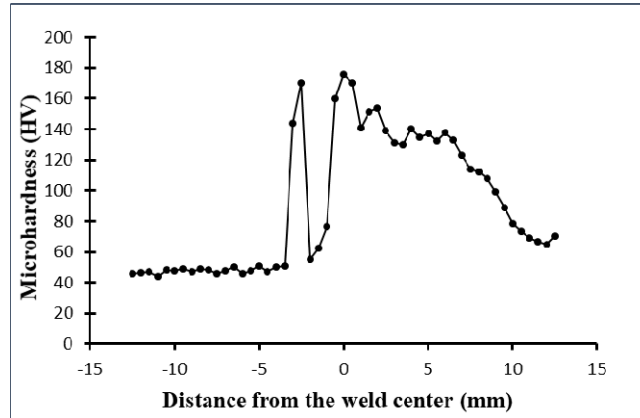


Figure 5.17 Microhardness profile on the cross-section of Joint-4.1

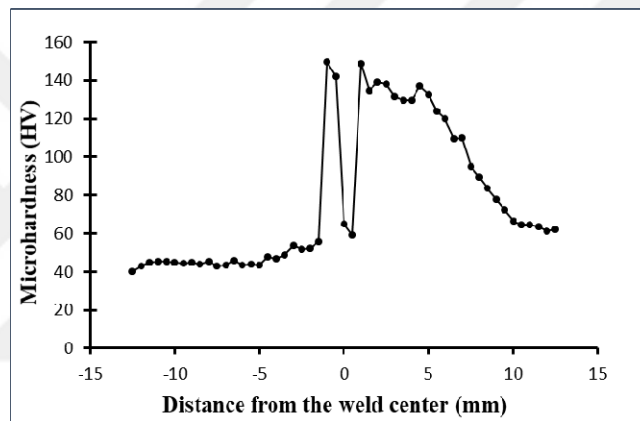


Figure 5.18 Microhardness profile on the cross-section of Joint-4.2

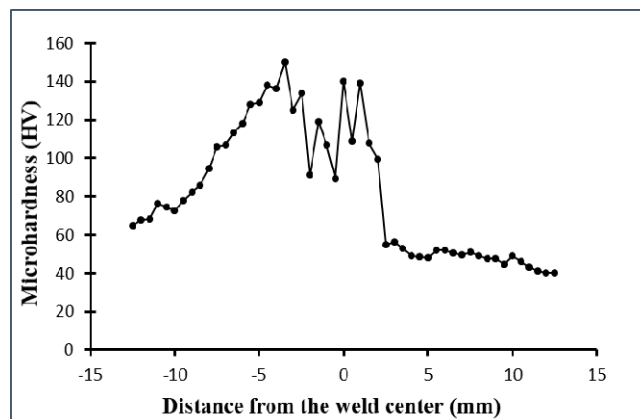


Figure 5.19 Microhardness profile on the cross-section of Joint-5.1

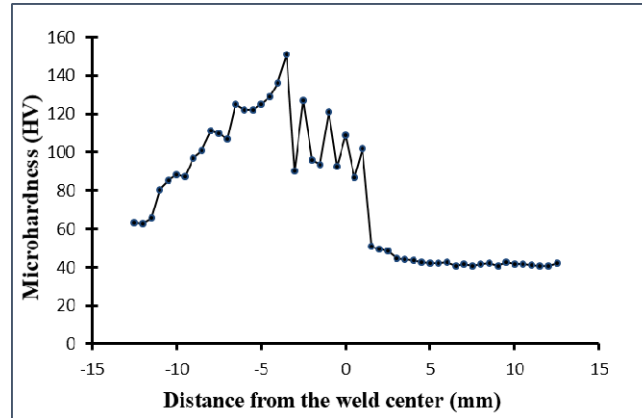


Figure 5.20 Microhardness profile on the cross-section of Joint-5.2

5.2.4 Concluding Remarks

In the present study, the FSW of 3.2 mm thick AA6061-0 and AA7075-O plates were carried out using a hot work steel (H13) tool. In addition, mechanical properties of the joints were evaluated. As a result, the following conclusions can be obtained:

- (a) Compared to other dissimilar joints, Joint-4.1 demonstrated a higher mean tensile strength value.
- (b) Ductility of the specimens is reported as about one-half those of the base materials.
- (c) A successful FSW process can provide good mechanical performance in tensile strength while reduces the elongation to failure as expected.
- (d) A hardness increase was observed from parent materials to stir zone for all dissimilar joints. However, complicated mixing of the workpieces was observed on the basis of microhardness distribution of the joints.

CHAPTER SIX

DISSIMILAR FSW OF AA6061+SiCp/AA6061-O

As part of the thesis, a well-rounded research on the microstructure evolution, microhardness, tensile and three-point bending properties of the FSWed AA6061+SiCp/AA6061-O joint was performed. Besides that, the influences of post-weld heat treatment (PWHT) on these aforementioned characteristic features was evaluated.

6.1 Materials and Method

In the present research, 3.4 mm-thick AA6061/SiC/20p composite and 3.2 mm-thick AA6061-O were used. The physical properties of as-received composite and the chemical composition of AA6061-O are presented in Table 6.1 and Table 6.2, respectively. After machining each workpiece into the dimensions of 300 mm x 120 mm, friction stir butt-welding process was applied to dissimilar materials with a tool rotational speed of 1250 rpm, welding speed of 125 mm/min and a tool indentation depth of 0.4 mm into upside of the workpieces. The tool tilt angle was set to 1° for the welding experiment. Single-pass welding procedure was introduced and AA6061/SiC/20p composite was located in the advancing side as the monolithic alloy was placed in the retreating side within the study. Figure 6.1 exhibits the clamping fixture and the general layout of welding process. Before the FSW process, workpieces were cleaned through a steel file in order to remove probable oxidation layers. It should also be noted that the tool was rotated in the clockwise direction. By the way, a noncontact infrared thermometer (Fluke 576 CF) was utilized to inspect the temperature distribution around the weld zone during the welding process. The rotating tool was made of AISI 4140 steel and then heat treated to achieve a hardness of 65 HRC. Diameter of the shoulder was 20 mm and length of the pin was 3.50 mm. Diameters of the pin root and pin tip are 6 mm and 5 mm, respectively. Dimensions of the fabricated tool are shown in Figure 6.2.

Table 6.1 Physical properties of AA6061/SiC/20p composite (Oztoprak, Yeni & Kiral, 2018a)

Density (g/cm ³)	Elastic Modulus (GPa)	Specific Stiffness (GPa/g/cm ³)	Poisson's Ratio	Solidus (°C)	Specific Heat Capacity (J/g/°C)
2.8	102	36	0.3	570	0.85

Table 6.2 Chemical composition of AA6061-O (wt.%) (Oztoprak, Yeni & Kiral, 2018a)

Material	Mg	Si	Fe	Cu	Cr	Zn	Mn	Ti
AA6061-O	1.1	0.68	0.6	0.3	0.19	0.14	0.09	0.03

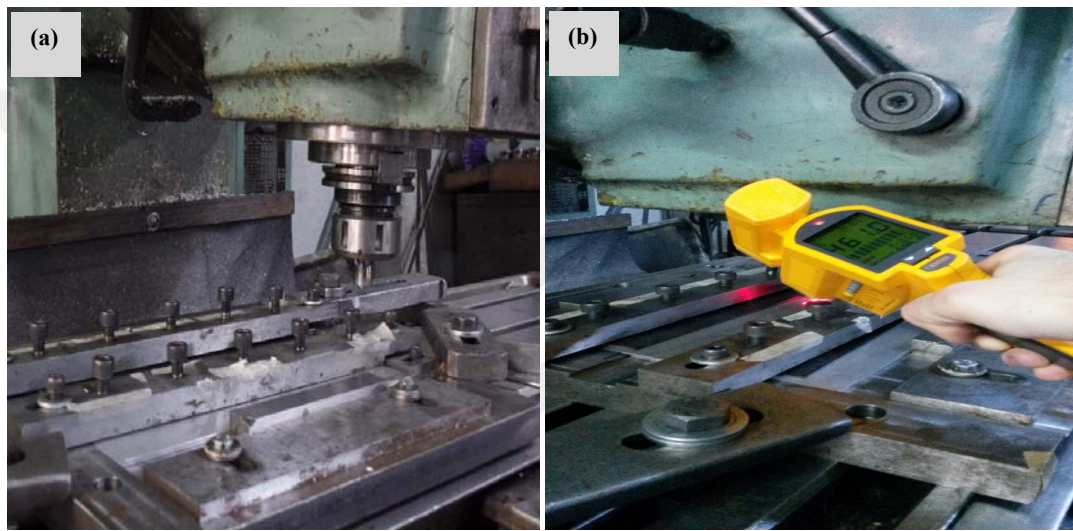


Figure 6.1 Photographs of (a) clamping device and (b) an example for FSW process (Personal archive, 2017)

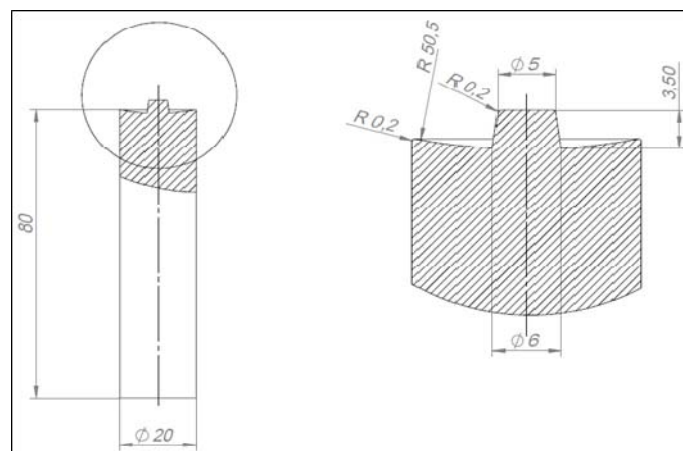


Figure 6.2 FSW tool dimensions used within the research (Oztoprak, Yeni & Kiral, 2018a)

After the welding, specimens were removed perpendicular to the welding line through water-jet for metallographic examination and mechanical tests. Figure 6.3 and Figure 6.4 demonstrate the sampling schematic for the weld characterization and the specimens used in the material characterization for each case, respectively. Transverse tensile properties of the FSWed joints are determined in terms of tensile strength, percentage of elongation at failure and also joint performance. Tensile test specimens were extracted according to ASTM: E8 and three specimens were tested for each condition (as-welded and post-weld heat treated). Dimensions of the tensile test specimens are shown in Figure 6.5. All tensile tests were performed on Shimadzu AG-X (100 kN) Universal Testing Machine at a constant speed of 1 mm/min at room temperature. Figure 6.6 exhibits the photograph in the course of a transverse tensile testing of the dissimilar joint.

The Vickers micro-hardness profiles of the joints were reported across the mid-thickness of the welds perpendicular to the welding direction of the plate. The hardness profiles for each condition were generated through a load of 100 gr with a dwell time of 10 s. The span between each indentation was also set to 0.5 mm during measurements. Besides that, three-point bending tests of the joints were performed according to the standard (EN ISO 5173). Root test of the specimens were carried out using the same tensile testing machine with a crosshead speed of 2 mm/min. The distance between each support was set to 50 mm. Unlike the transverse tensile tests, two flexural tests were carried out for each condition. The three-point bending test apparatus is depicted in Figure 6.7.

As to the microstructural examination, metallographic specimens were mounted in bakelite, sandpapered using different grades of abrasive paper (up to 2000xsandpapers) and subsequently polished with polycrystalline diamond paste (3 μm) and colloidal silica (1 μm). Thereafter, as-welded samples were etched using a reagent of Keller while the investigation was achieved on PWHTed sample using a HF+HNO₃ solution. Etching periods were 20 s and 120 s for as-welded and PWHTed samples, respectively. For PWHT process, FSWed sample was first solution heat treated at 530 °C for one hour, then quenched in a water of 42 °C and finally

artificially aged at 178 °C for eight hours. The stages of PWHT process are exhibited with a diagram in Figure 6.8.

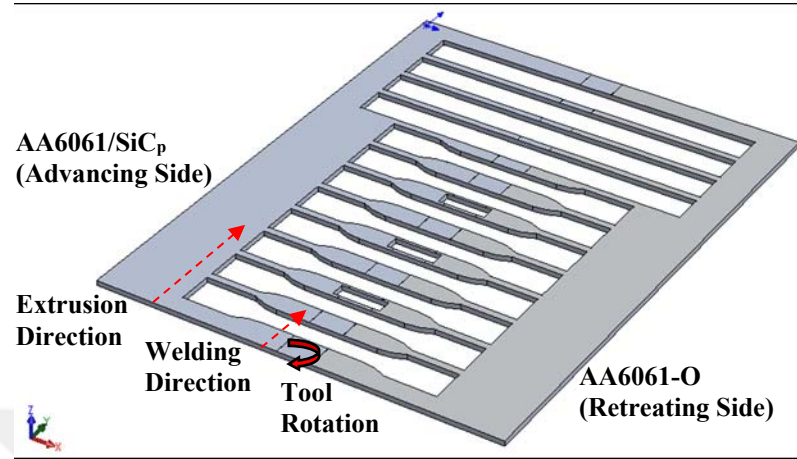


Figure 6.3 Sampling schematic of dissimilar FSWed joint (Oztoprak, Yeni & Kiral, 2018a)



Figure 6.4 Photograph of the samples for each condition (Personal archive, 2017)

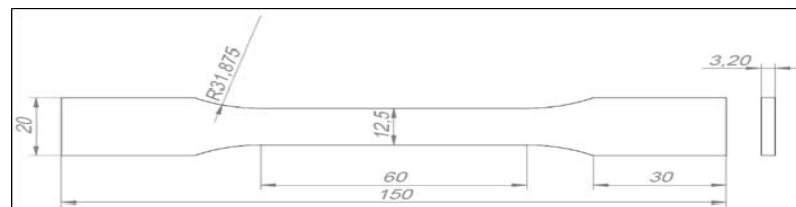


Figure 6.5 Dimensions of tensile test specimen (all dimensions are in mm) (Oztoprak, Yeni & Kiral, 2018a)



Figure 6.6 Test rig used in the research (Personal archive, 2017)



Figure 6.7 Bending test in progress (Personal archive, 2017)

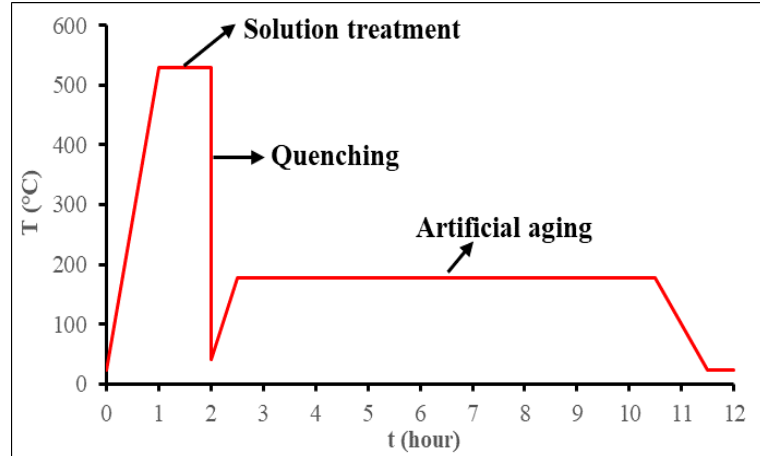


Figure 6.8 Diagram of the PWHT cycle (Oztoprak, Yeni & Kiral, 2018a)

6.2 Macrostructural and Microstructural Characterization

Pictures of the macrostructures of FSWed joint before and subsequent to FSW are shown in Figure 6.9. Major fusion welding defects such as the porosity or inclusion are not detected within the macrostructures. It is common knowledge that the varied thermo-mechanical histories during the FSW process generates four different zones on the cross-section of a FSW: stir zone (SZ), thermomechanically affected zone (TMAZ), heat-affected zone (HAZ) and base material (BM) and it is explicit that the mixture of the dissimilar materials is sufficiently provided according to the figure. In other respects, zone of transition is not visible in both macrographs. It is also needed to notice that the onion ring structure is evident in Figure 6.9(a).

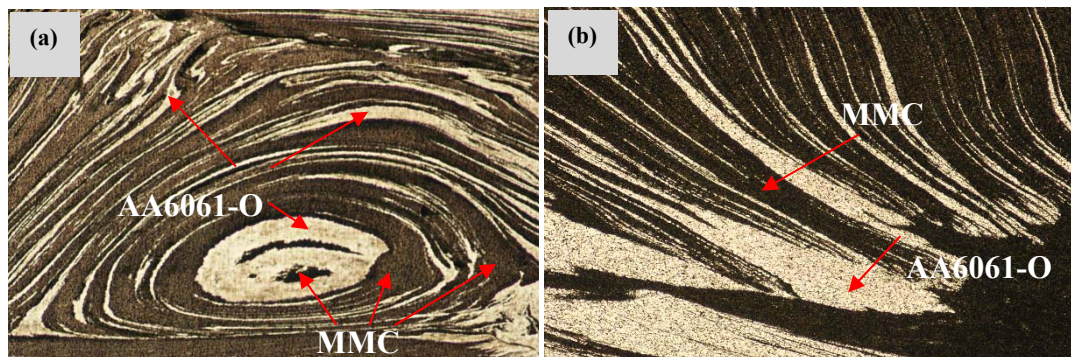


Figure 6.9 Optical macrographs of the dissimilar joint (a) as-welded (b) after PWHT (Oztoprak, Yeni & Kiral, 2018a)

Figure 6.10 presents the optical micrographs of the dissimilar joints in both as-welded and PWHTed conditions with regards to AA6061-O side. When the figure is carefully investigated, it is noteworthy that the PWHT process removes the dendritic microstructure of the base material. Besides that, PWHT results in the grain refinement for the base metal. A more homogeneous grain structure is reported after PWHT. Considering the microstructure within HAZ, PWHT leads to the elongated fibrous microstructure to coarsen. It is additionally discovered that the aspect ratio of the structure decreases following the PWHT. Deformed and elongated grain structures are also characteristic feature of the TMAZ. Moreover, the microstructure in the TMAZ consists of more equiaxed grains thanks to the PWHT. Lastly, dynamically recrystallized and finer scale grains in SZs take the place of initial elongated dendritic grains. Herein, it is important to point out that the grain size in the SZ does not show any significant change after PWHT. In addition to all these, precipitate formation with PWHT process is clear from the figure.

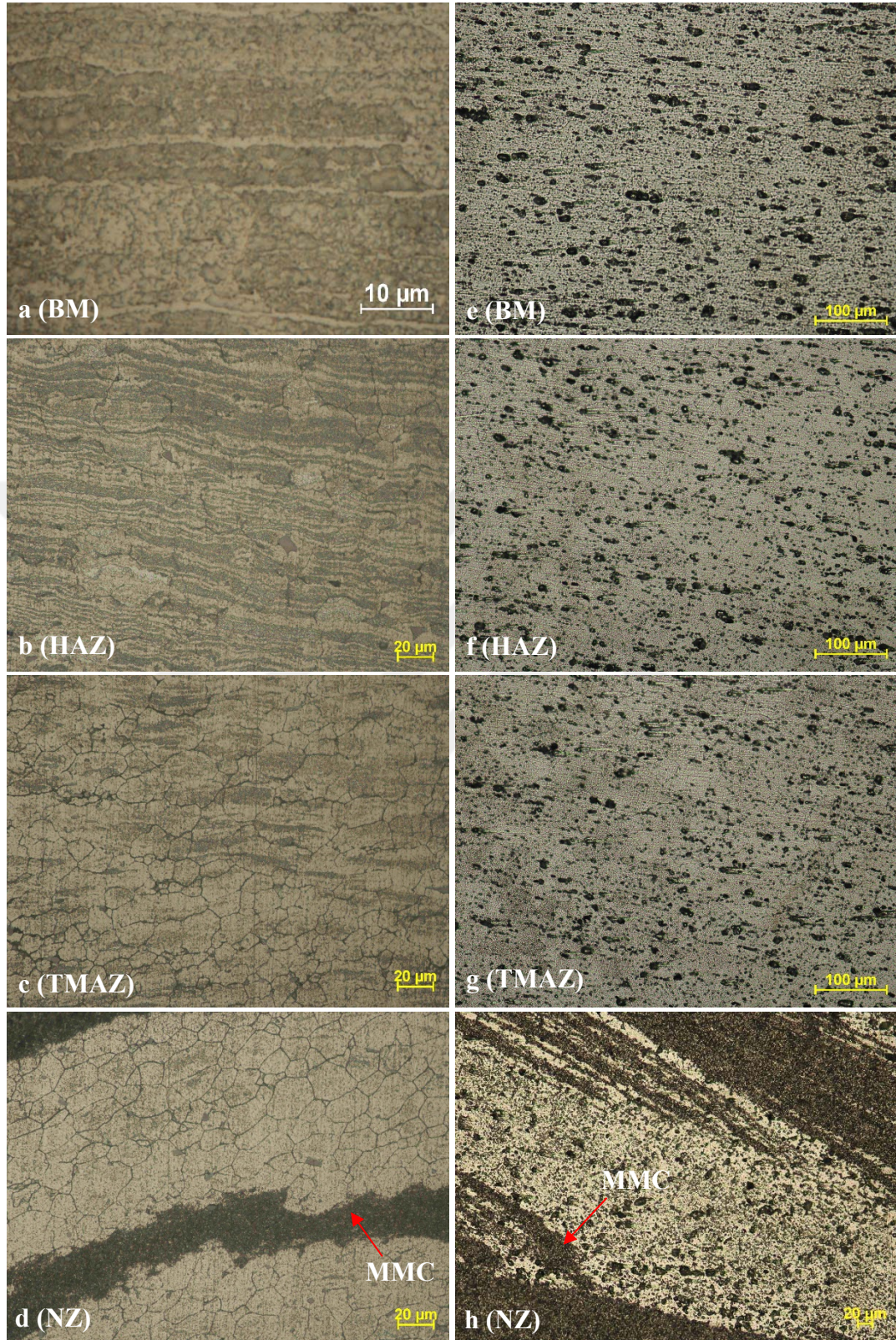


Figure 6.10 Microstructure of different zones: (a-d) as-welded (e-h) PWHTed specimens (Oztoprak, Yeni & Kiral, 2018a)

6.3 Particle Dispersion

It is well known that the phase analysis of dissimilar FSWed joints plays a significant role in determining the element distribution and possible compounds generated within SZ (Sahu, S. Pal & S.K. Pal, 2017). Figure 6.11 exhibits the energy dispersive x-ray (EDX) analysis at the MMC side in the joint. According to the figure, it can be seen that there are uniformly distributed SiC particles in the aluminum matrix. In addition to this, EDX mapping in the SZ of the dissimilar joint is also performed and Figure 6.12 shows the mapping elemental analysis on the SZ of as-welded specimen. From the figure, it is evident that there are particle rich regions within SZ, even though the reinforcing particles are dispersed all over the aluminum matrix. Regarding the dispersion of SiC particles within the weld zone, Figure 6.13 presents the particle distribution of FSWed joint before and following the PWHT. It is clear from the figure that the size of SiC particles in the BM varies between 0.7 μm and 2 μm . It is also noticed that these reinforcing particles differ from each other within the weld zone in terms of the shapes and sizes excluding HAZ. Accordingly, the TMAZ consists of fine and oriented SiC particles. On the other hand, fractured SiC particles within SZ draw the attention. In consequence of the abrasion by way of the FSW tool and owing to the attrition of reinforcing particles with each other are at the ground of explanation of this event (Sahraeinejad, Izadi, Haghshenas & Gerlich, 2015). Moreover, there are clustered particles in the NZ. As to the final shape of the particles in the NZ, a more spherical form is further observed by comparison with the other joint regions. Lastly, particle poor and particle rich regions are another characteristic feature of this zone. SEM images of the joint subsequent to PWHT are also presented in Figure 6.13(e-h). As it is noticeable from the micrographs, there is no difference in the particle size, shape and dispersion through the PWHT.

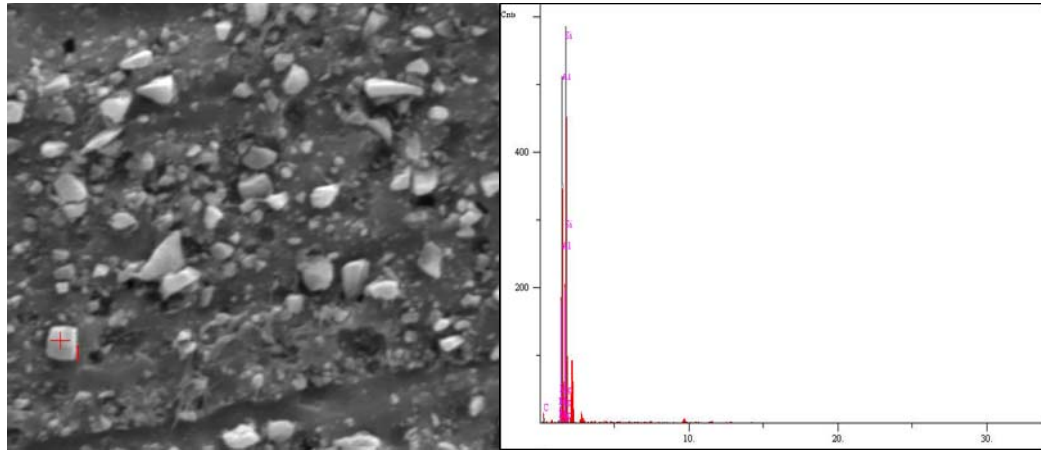


Figure 6.11 EDX elemental analysis at point '+' on AA6061/SiCp composite (Oztoprak, Yeni & Kiral, 2018a)

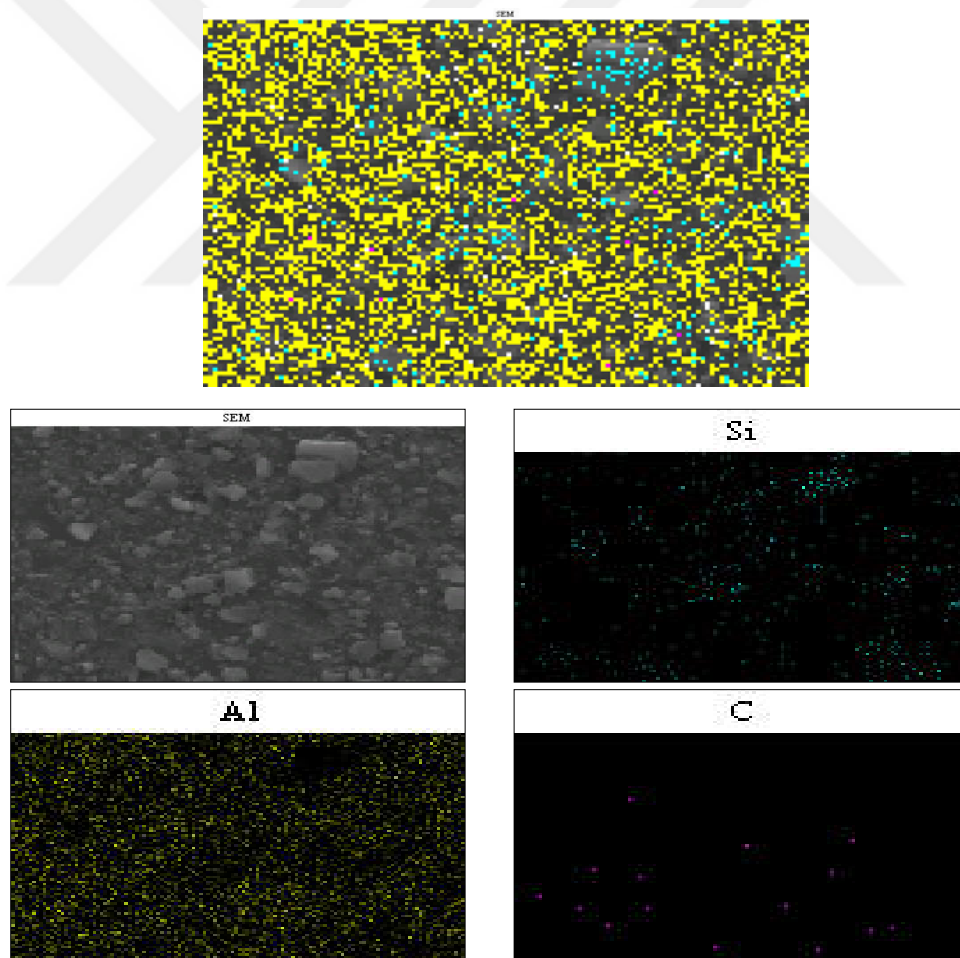


Figure 6.12 Element distribution mapping on the SZ of FSWed specimen in as-welded condition (Oztoprak, Yeni & Kiral, 2018a)

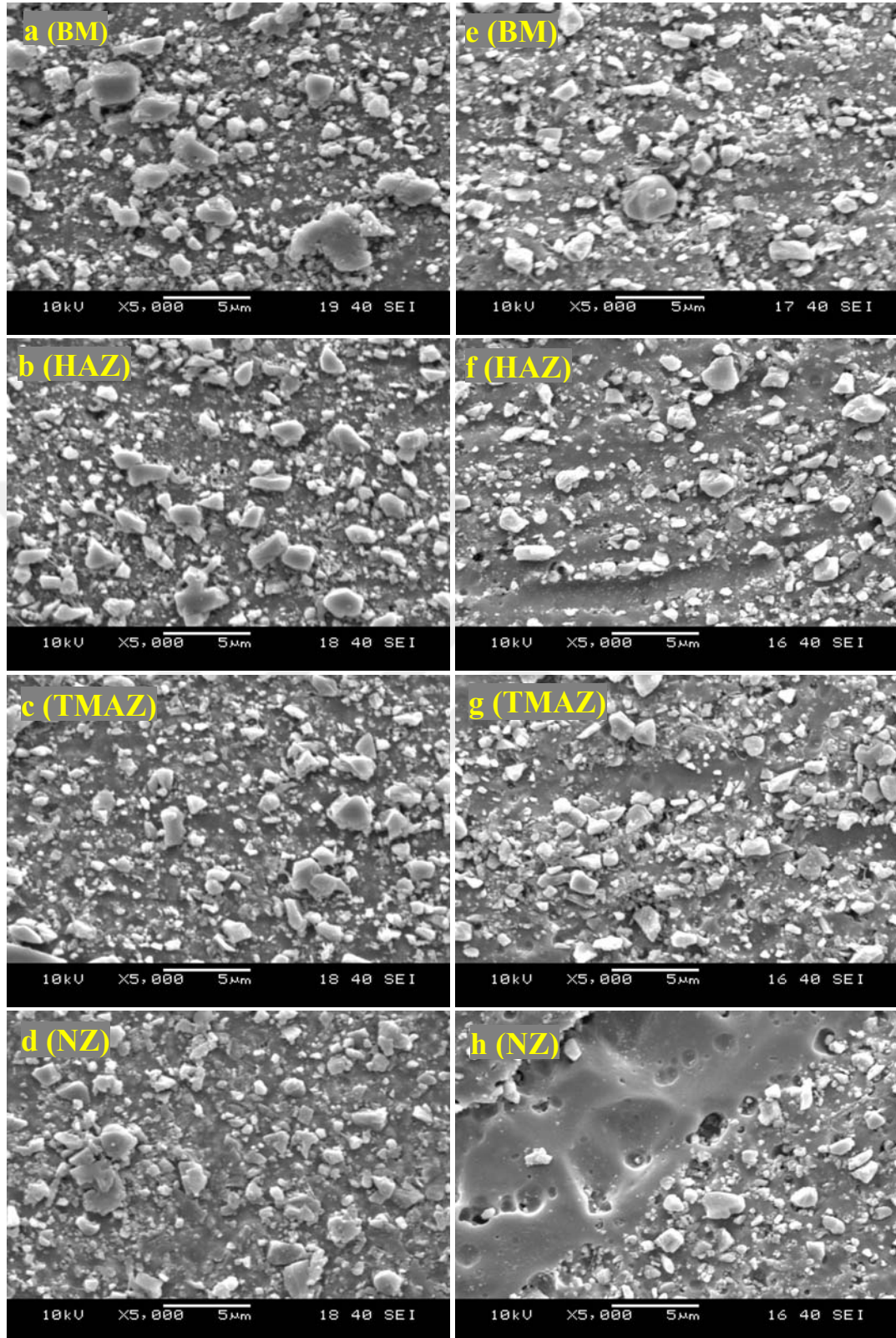


Figure 6.13 SEM images of (a-d) as-welded and (e-h) PWHTed specimens (Oztoprak, Yeni & Kiral, 2018a)

6.4 Microhardness Distributions of the Joint

The Vickers microhardness distribution of as-welded and PWHTed samples is depicted in Figure 6.14. The hardness profiles are measured along the mid-thickness of the joints in order to elucidate the hardening or softening influence of both welding and PWHT processes. Within the weld zone, it is worthwhile to mention that there is a blended interference of the dissimilar workpieces. In addition, the process results in a wide weld zone. This may be mainly attributed to the high tool plunge depth during the process. From the figure, it can be inferred that the parent materials for AA6061-O and AA6061/SiCp demonstrate Vickers hardness between the range of 40-44 HV and 144-158 HV, respectively. The microhardness values for the base materials exhibit an explicit increment after PWHT. The highest hardness values on the monolithic alloy and the composite are 52 HV and 203 HV, respectively. It can be seen that the Vickers hardnesses of stir zones are achieved to be higher than that of the monolithic alloy for both circumstances. This increment might be attributed to the microstructural evolution of the monolithic alloy with O-temper condition. It is found from the figure that the average Vickers microhardness within HAZ at the RS is slightly lower than the hardness within HAZ at the monolithic alloy side in as-welded condition. Besides, a complicated hardness profile in HAZ at the composite side is obtained after PWHT. On the other part, more homogenous hardness profile is reported within TMAZ at the RS after PWHT. These findings are also in tight agreement with the performed microstructural examinations.

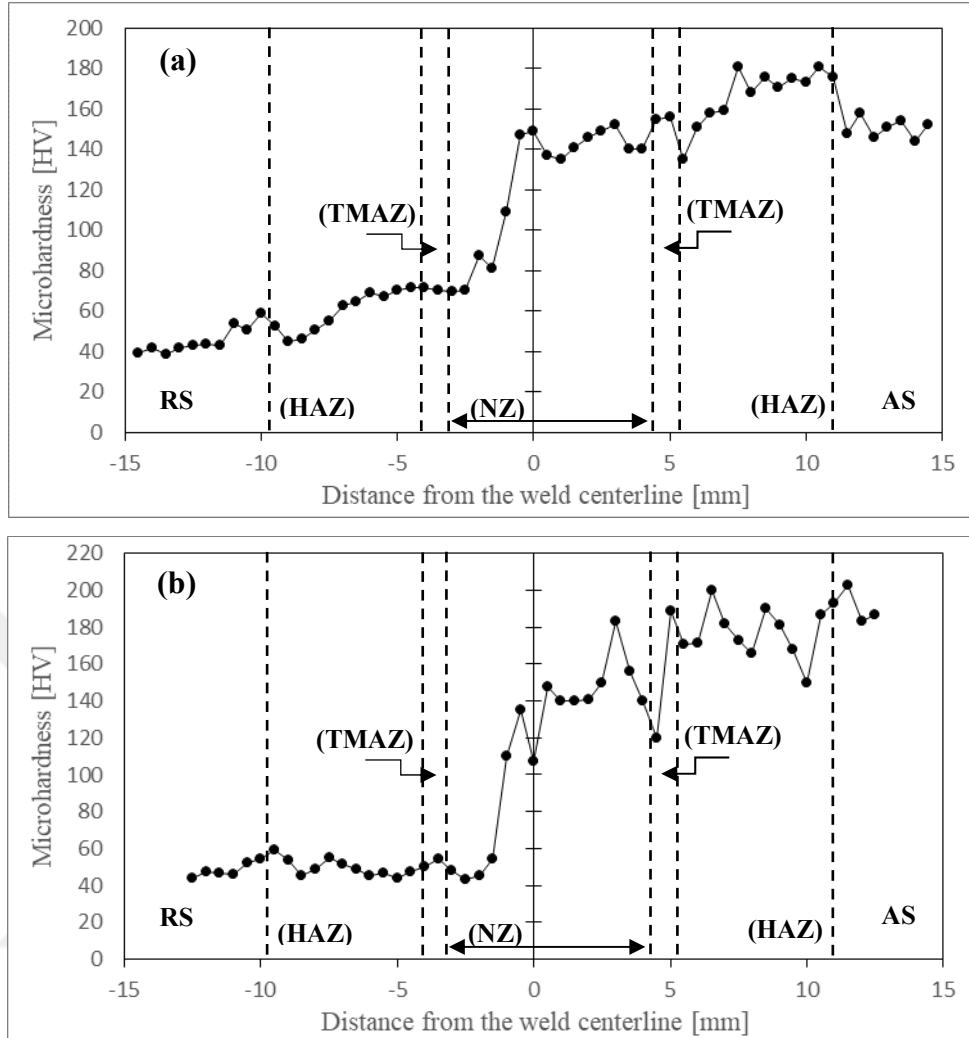


Figure 6.14 Microhardness variations within weld zone: (a) as-welded and (b) PWHTed condition (Oztoprak, Yeni & Kiral, 2018a)

6.5 Tensile Properties

The AA6061/SiCp composite shows a tensile strength and failure elongation (%) of 309.64 MPa and 5.62, respectively. The monolithic aluminum alloy also has a tensile strength and elongation of 116.5 MPa and 28.5%, respectively (Ipekoglu & Cam, 2014). Transverse tensile properties of the as-welded specimens are shown in Figure 6.15 with regards to the stress-elongation behavior. It has been realized from the figure that there is a similar attitude to that of the monolithic alloy for all test samples. Table 6.3 summarizes the tensile properties of FSWed specimens. Accordingly, the tests

show a maximum tensile strength of 120.74 MPa. Besides that, the transverse tensile test results correspond to a joint efficiency of 103.64%, 103.29% and 103.17% for the specimens, respectively. These results highlight the importance of the favorable selection of welding parameters so as to obtain sound joining with a high mechanical performance. In the current research, joint efficiency is reported as the division of the ultimate tensile strength (UTS) of the weld to that of AA6061-O. At this juncture, the as-welded joints fractured on the RS within the BM. The fracture locations of joints that are adequately away from the weld zones are shown in Figure 6.16. This result demonstrates the achievement on the FSW process. On the other hand, maximum failure elongation of the samples is 9.25% that indicates a joint efficiency of 32.46%.

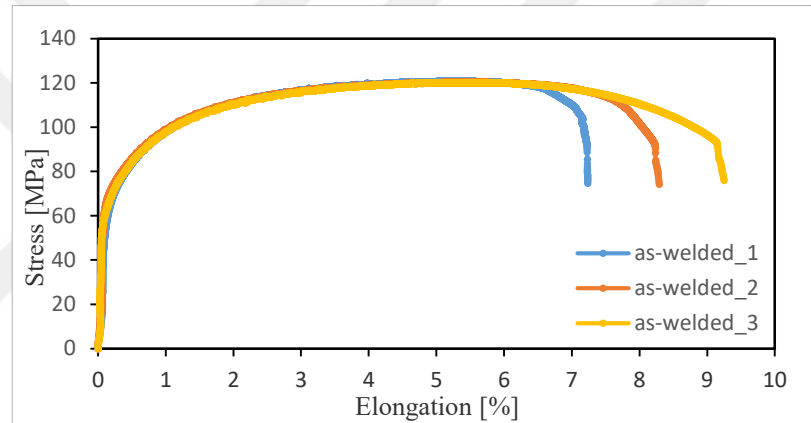


Figure 6.15 Transverse tensile properties of as-welded specimens (Oztoprak, Yeni & Kiral, 2018a)

Table 6.3 Tensile test results of as-welded specimens (Oztoprak, Yeni & Kiral, 2018a)

	Specimen_1	Specimen_2	Specimen_3
Tensile Strength [MPa]	120.74	120.33	120.19
Elongation (%)	7.24	8.29	9.25

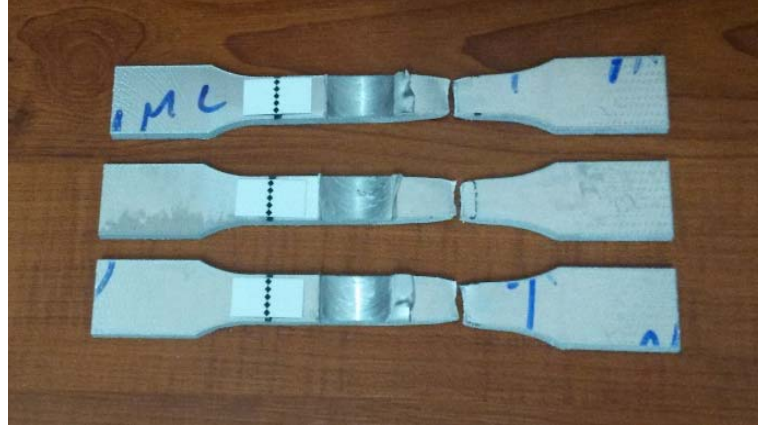


Figure 6.16 Rupture positions of test specimens (Oztoprak, Yeni & Kiral, 2018a)

The effects of PWHT and the comparison of tensile properties in terms of the tensile strength and failure elongation are shown in Figure 6.17. It is evident from the findings that the PWHT significantly enhance the strength of the dissimilar joint between the AA6061/SiCp and AA6061-O. On the other hand, reduction of failure elongation is noted. The dissimilar FSWed joints exhibit a maximum tensile strength and elongation (%) of 183.30 MPa and 4.37, respectively. These results explicitly indicate the increased tensile strength of 52.22% with PWHT. In other respects, the PWHT process leads to the reduction in the failure elongation. Percentage of elongation is decreased by 47.09% with PWHT. Considering the fracture locations of PWHTed samples, the specimens fractured within HAZ of the welds on the RS. Herein, it is important to point out the decline in the microhardness close to the boundary between HAZ and the BM at the ground of this event. Figure 6.18 shows the fracture locations of tensile samples of FSWed joint in PWHTed condition and the SEM image of the fracture surface. It is easily observed from the fractograph that there is a great number of dimples with several shapes on the surface that represents signs of ductile fracture.

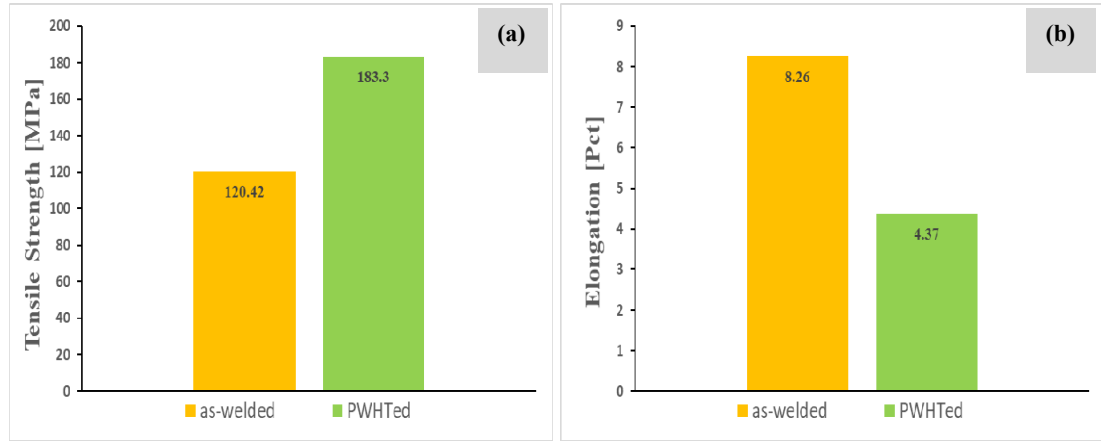


Figure 6.17 Tensile properties of the FSWed joints: (a) tensile strength (b) elongation [Pct] (Oztoprak, Yeni & Kiral, 2018a)

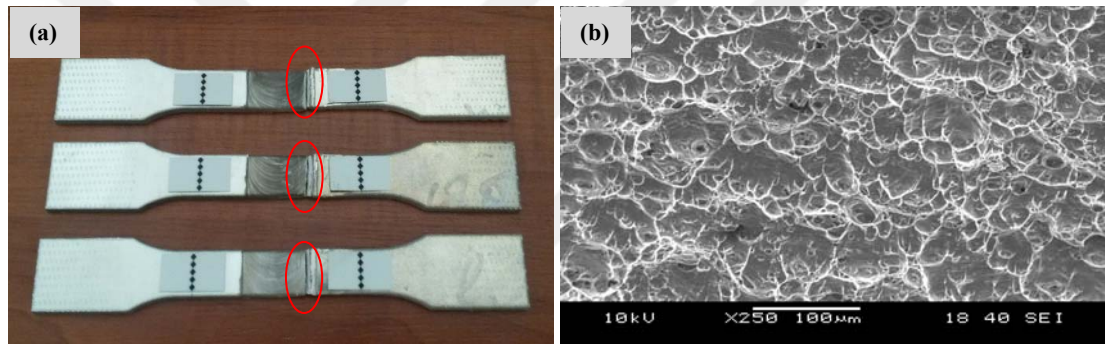


Figure 6.18 PWHTed specimens: (a) rupture positions (b) SEM image (Oztoprak, Yeni & Kiral, 2018a)

6.6 Three-point Bending Behavior

Three-point bending tests are conducted to evaluate the flexural properties of both as-welded and PWHTed samples. Accordingly, an investigation on the bending force vs. extension behavior and bending angle of the joints are performed. As a general rule, the specimens are tested up to the failure or until they take final bending forms. Within the research, no failure is noted for both conditions. As shown in Figure 6.19, a comparison is carried out between as-welded and PWHTed specimens. It is evident that the maximum bending force shows a slight increase after PWHT. The maximum forces achieved are 962.27 N and 1038.20 N, respectively. Furthermore, bending extension exhibits a considerable increment subsequent to PWHT. Bending extension

increases by 121.96% with the applied PWHT process. A maximum extension of 30.83 mm is noted for the PWHTed sample.

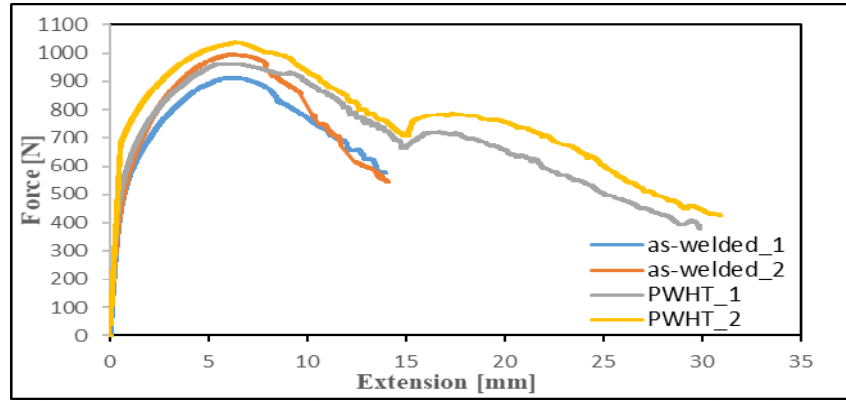


Figure 6.19 Bending force versus extension curves of the dissimilar joint before and after PWHT (Oztoprak, Yeni & Kiral, 2018a)

As regards to the bending angle analysis of the welds, the PWHT results in the increment of bending angle. This observation clearly demonstrates the enhanced bending resistance of the weld with the PWHT. Figure 6.20 illustrates the bending test specimens and the associated bending angles of the dissimilar joints. As it is evident, bending angle of the as-welded samples is approximately 90° and the specimens take an L-shape following the bending tests. On the other part, a U-shape is reported for the PWHTed samples.

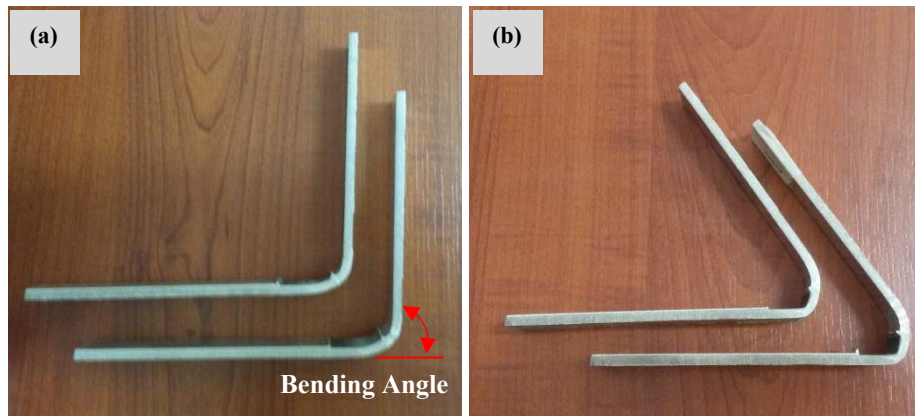


Figure 6.20 Three-point bending tested samples: (a) as-welded (b) PWHTed (Oztoprak, Yeni & Kiral, 2018a)

CHAPTER SEVEN

DISSIMILAR FSW OF AA6061-T6/AA6061+SiCp

To explore the impact response of a dissimilar joint, FSW was performed between AA6061-T6 and AA6061+SiCp composite. In addition to this, microstructure, microhardness profile and transverse tensile properties of the dissimilar joint were also scrutinized carefully. As a matter of fact, this research is motivated by the need for evaluating the mechanical properties of the welds that are exposed to several transverse impact energies.

7.1 Experimental

In this work, dissimilar friction stir butt-welding was carried out on 3.2 mm thick 6061-T6 aluminum alloy and AA6061/SiC/20p composite through a FSW adapted vertical milling machine. The workpieces of 300x120x3.2 mm³ were joined using a tool rotational speed of 1000 rpm, welding speed of 80 mm/min and a tilt angle of 1°. The penetration depth into the upper surfaces of the plates was adjusted as 0.2 mm during the process. Single-pass welding procedure was implemented and AA6061-T6 was placed at the advancing side (AS) to fabricate the dissimilar joint. The rotating welding tool was made of AISI 4140 steel with a shoulder diameter of 20 mm. The conical unthreaded pin 5 mm in diameter and 2.9 mm length was used to stir and flow the dissimilar materials through the welding line. As it has been mentioned earlier, surfaces of the workpieces were decontaminated from possible oxide films by a steel riffler and cleaned by acetone. Physical properties of the as-received composite and chemical composition of the monolithic aluminum alloy are given in Table 7.1 and Table 7.2, respectively.

Table 7.1 Physical properties of AA6061/SiCp (Oztoprak, Yeni & Kiral, 2018b)

Density (g/cm ³)	Elastic Modulus (GPa)	Specific Stiffness (GPa/g/cm ³)	Poisson's Ratio	Thermal Conductivity @ 25°C (W/m°K)	Solidus (°C)	Specific Heat Capacity (J/g°C)
2.8	103	36	0.3	150	570	0.85

Table 7.2 Chemical composition of AA6061-T6 (wt.%) (Oztoprak, Yeni & Kiral, 2018b)

Material	Mg	Si	Fe	Cu	Cr	Zn	Mn	Ti
AA6061-T6	0.9	0.65	0.54	0.25	0.19	0.05	0.11	0.07

The conventional metallographic methods are performed for the metallographic examination. Respectively, mounting, sanding, polishing and finally etching procedures were utilized. Metallographic specimens used in this study were ground using different grades of sandpaper, then polished with diamond paste (3 and 1 μm) and colloidal silica (1 μm), finally etched in a reagent composed of $\text{CH}_3\text{OH}+\text{HCl}+\text{HNO}_3+\text{HF}$ solution for 10 s. The samples were finally investigated on a Nikon Epiphot 200 inverted metallurgical microscope and the scanning electron microscope (SEM) of JEOL JSM-6060. Figure 7.1 exhibits the schematic illustration for sampling from the dissimilar joint.

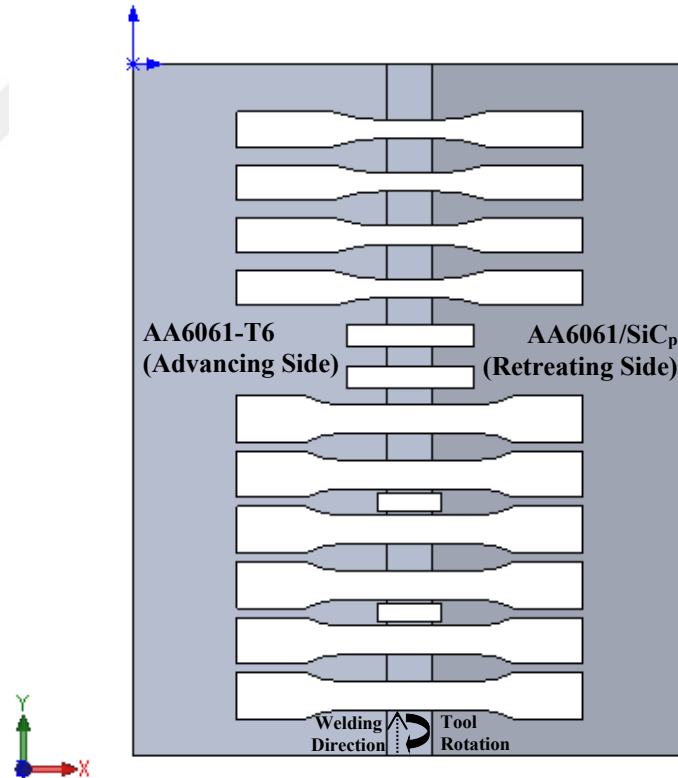


Figure 7.1 Schematic illustration of sample preparation (Oztoprak, Yeni & Kiral, 2018b)

Transverse tensile properties of the dissimilar FSWed joint are evaluated by tensile tests that are conducted at room temperature at a constant speed of 1 mm/min. Tensile tests were carried out in accordance with ASTM E8M using a Shimadzu AG-X (100 kN) Universal Testing Machine. The specimens were cut out perpendicular to the welding direction. Within the study, tensile properties of the dissimilar joint were obtained by calculating the four as-welded samples as two tensile tests were carried out for the damaged specimens subsequent to each low-velocity impact. Figure 7.2 demonstrates the schematic illustration of the dimensions of tensile test specimens. Besides, Vickers hardness measurements were performed across the mid-thickness of the FSWed joint through an applied load of 100 g. The span between each measurement and the dwell time in the course of the tests was 0.5 mm and 10 s, respectively.

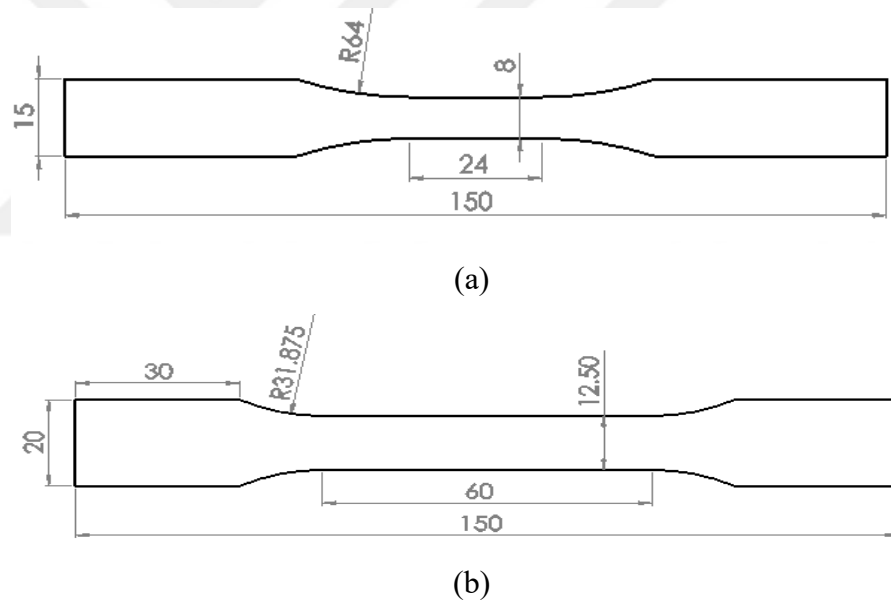


Figure 7.2 Dimensions of the tensile test specimens (a) as-welded (b) under transverse impact (Oztoprak, Yeni & Kiral, 2018b)

Charpy impact tests were also carried out for both the dissimilar joint and the parent materials. All V-notched Charpy samples with a dimension of 10 mm x 3.2 mm x 55 mm³ were prepared in accordance with ASTM E23-04. The impact toughness of the specimens were determined on a pendulum-type impact test device at ambient temperature conditions. Figure 7.3 shows the dimensions of the Charpy

V-notched impact test specimens. Lastly, fracture surfaces of the impact-tested specimens were observed with the SEM of JEOL JSM-6060.

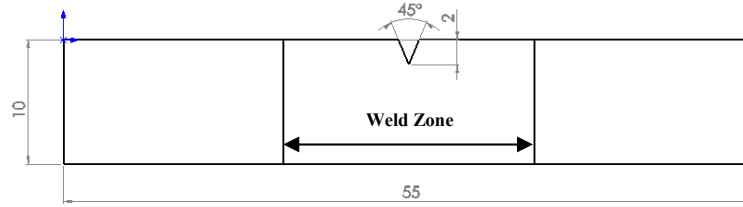


Figure 7.3 Schematic of Charpy impact test specimens (Oztoprak, Yeni & Kiral, 2018b)

Low velocity impact tests were conducted in a CEAST-Fractovis Plus drop-weight test machine at room temperature, shown in Figure 7.4 with the test fixture. The capacity of the load cell was 22 kN. Within the tests, the impact load was concentrated at the upper surface of the weld zone of the samples in the transverse direction with the impact energies of 2.5, 5 and 7.5 J through a hemispherical impactor nose of 12.7 mm diameter. Figure 7.5 represents the specimens subjected to various transverse impacts.

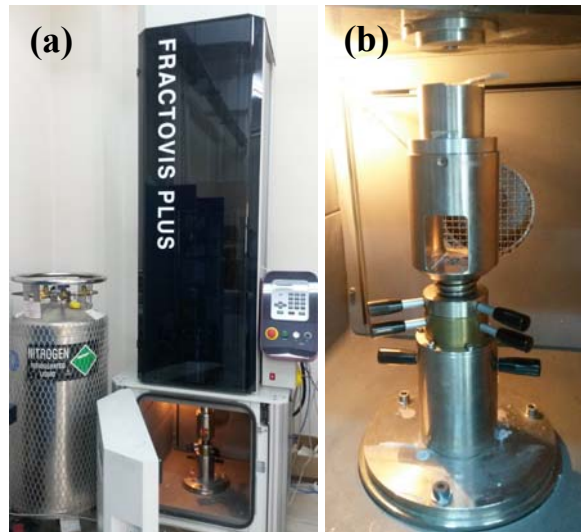


Figure 7.4 Drop-weight (a) impact test machine (b) test fixture (Oztoprak, Yeni & Kiral, 2018b)

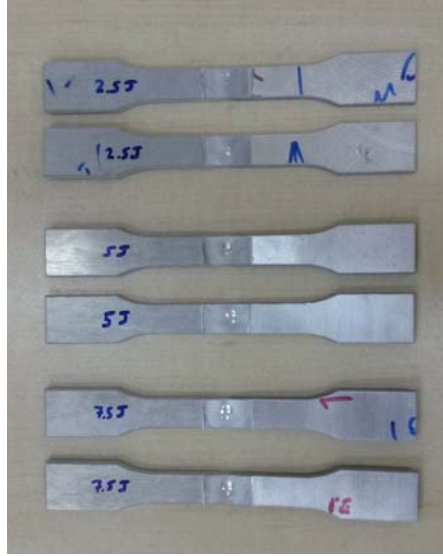


Figure 7.5 Photographs of the specimens impacted at 2.5, 5 and 7.5 J (Oztoprak, Yeni & Kiral, 2018b)

7.2 Microstructural Characterization

The grain structures of AA6061-T6 within the dissimilar FSWed joint are shown in Figure 7.6. Primarily, it is worthwhile to mention that defect-free weld was observed within the weld region. In addition, it is explicit that there are four distinguishable zones namely the BM, HAZ, TMAZ and NZ eventuated in the FSWed joint. When these regions are examined separately, the BM has elongated fibrous grains with an average grain size of about 45 μm . Besides that, fibrous elongated sub-structures are also observed within this region. Moreover, it has been found that the microstructure of HAZ still shows the elongated fibrous sub-structures along the direction of extrusion. Herein, it should be noted that the HAZ in a FSWed joint experiences only a thermal cycle that results in the grains to grow or remain unchanged. As to the TMAZ, equiaxed grain structure takes place in consequence of the apparent plastic deformation. This zone is characterized by the grains that have smaller sizes by comparison with those of both in the BM and HAZ. Average grain size of about 20 μm was observed within the region. Microstructure of the SZ is also characterized by fine and equiaxed grains owing to the severe plastic deformation and frictional heating. This is because of the dynamic recrystallization of the SZ. The average grain size within this zone was approximately 15 μm . Accordingly, it has

been reported that the amount of grain boundary increases through the FSW process. This finding also demonstrates the incremental dislocation density.

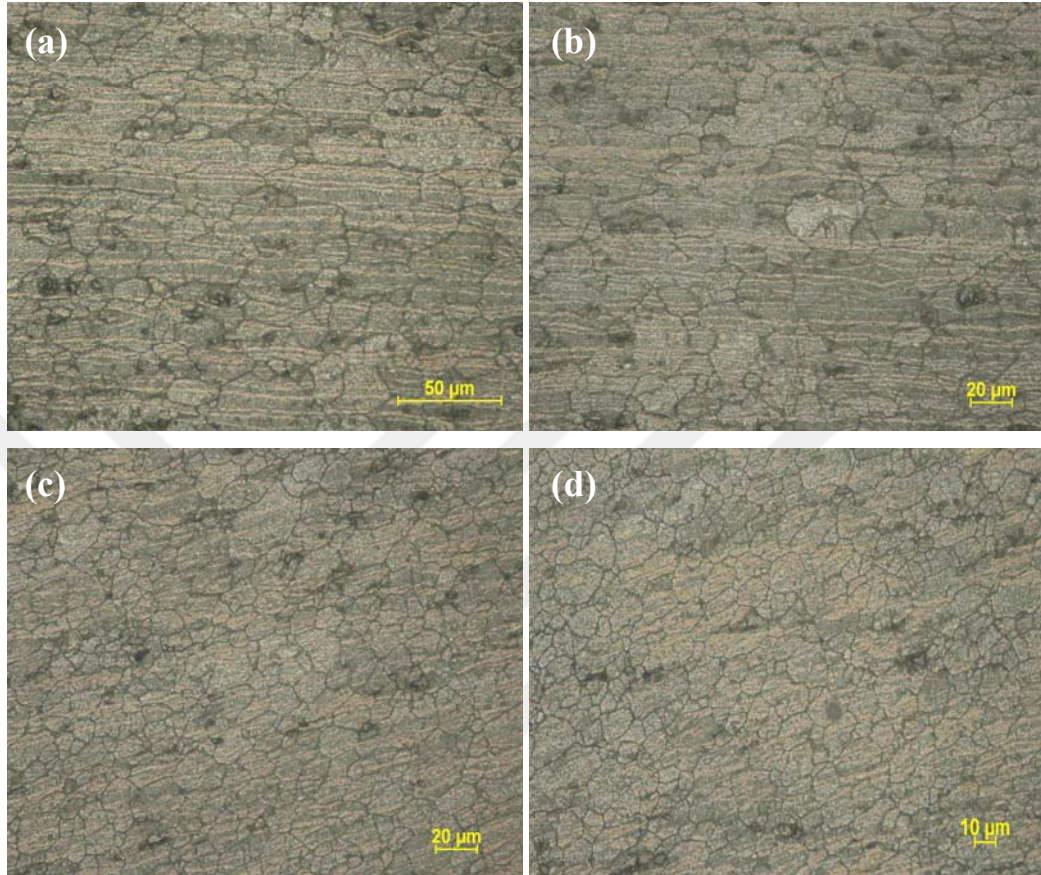


Figure 7.6 Optical microstructure of AA6061-T6 within the joint (a) BM (b) HAZ (c) TMAZ (d) NZ (Oztoprak, Yeni & Kiral, 2018b)

The scanning electron micrography of SiC particle dispersion within the weld zone is shown in Figure 7.7. At this juncture, it should be noted that the microstructural characterization of the MMC in the dissimilar joint by OM or SEM is a challenging problem to solve. After all, particle distribution within the dissimilar weld is comprehensively elucidated. In the figure, SiC particles seem as white while the matrix material seems as gray. The microstructural observations indicate that there is a haphazard distribution of the SiC particles in the BM. The HAZ is also characterized by the similar texture. In other respects, the TMAZ consists mostly of oriented SiC particles as a result of the shear deformation during the process. Finally,

agglomerated particles with several shapes and sizes are observed in the NZ. This diversity in the particle shapes can be related to the abrasion of the reinforcements with each other. Furthermore, energy dispersive x-ray (EDX) analysis of the SZ is also provided. The findings for the designated point (one of the dispersed particles) are shown in the Figure 7.8 below.

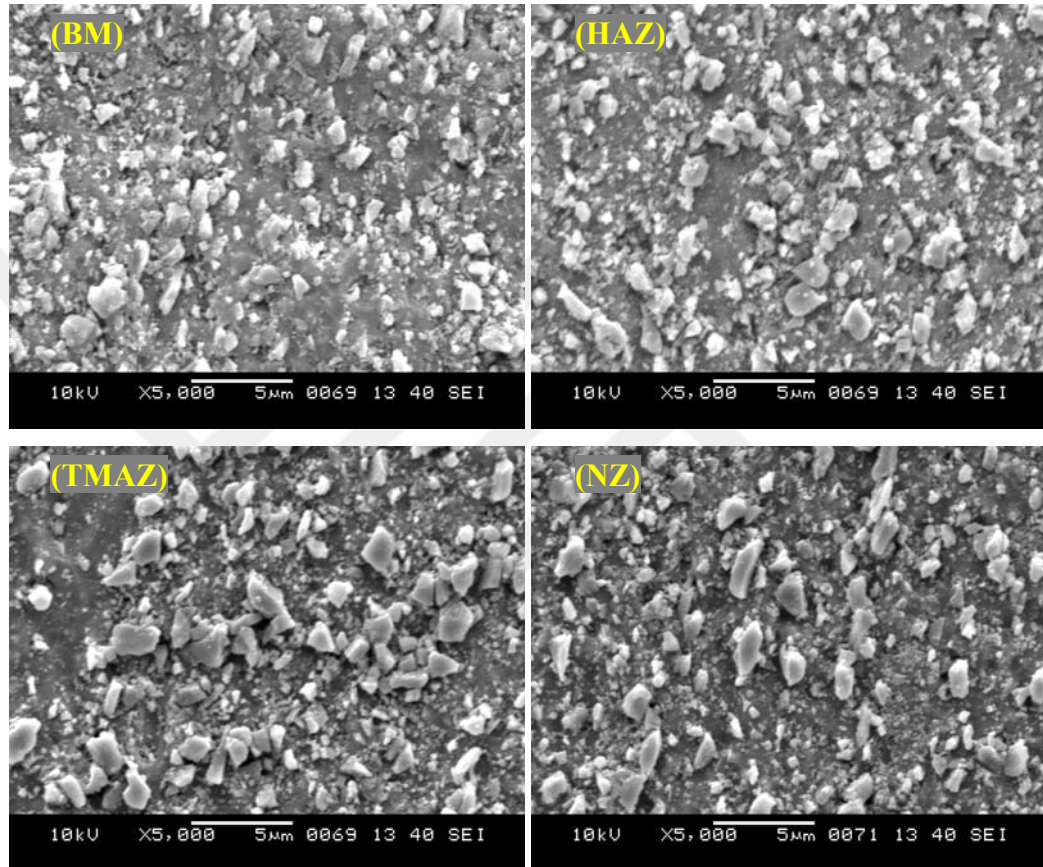


Figure 7.7 SEM micrographs of SiC distribution at different regions in the weld zone (Oztoprak, Yeni & Kiral, 2018b)

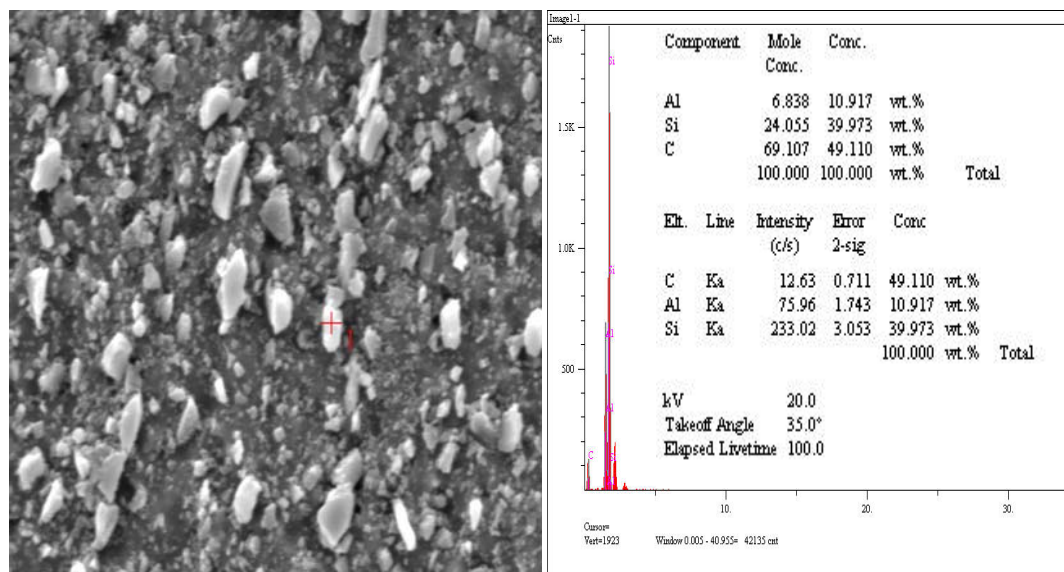


Figure 7.8 EDX elemental analysis on the dissimilar FSWed joint (Personal archive, 2018)

7.3 Vickers Microhardness Profile

In Figure 7.9, Vickers microhardness distribution profiles measured along the mid-thickness and also across the weld thickness of the joint are illustrated. Based on the hardness profiles, hardness of the base materials varies from 60 HV to 65 HV and 125 HV to 132 HV for AA6061-T6 and AA6061/SiC/20p composite, respectively. As it is observed, the microhardness values considerably increase within the TMAZ and NZ relative to the monolithic alloy at the AS. This finding coincides well with the grain structures of AA6061-T6. Besides that, the maximum hardness values in the TMAZ and NZ are reported as approximately 86.9 HV and 90.1 HV, respectively. As it is seen in the figure, minimum hardness values are observed within the HAZ at the monolithic alloy side. It is also interesting to see that the hardness distribution from TMAZ to NZ has a roughly uniform profile at the AS.

In other respects, microhardness distribution from BM to TMAZ at the composite side is almost steady without significant alterations. However, intense reduction is reported in microhardness of the NZ by comparison with the composite base material. Herein, it is clearly observed that the NZ mostly comprises of 6061-T6 aluminum alloy and thus the obtained findings are at the ground of the characteristic

of the monolithic alloy. Within the research, microhardness of the joint at the weld centerline along the thickness is also investigated by Vickers hardness testing. The results indicate that the top of the nugget over the mid-thickness has higher values, i.e., 137 HV and 122 HV. This may mainly be attributed to the existing reinforcing SiC particles within the measuring points. Consequently, the overall results show that a slight increase in the hardness within the NZ is observed after the process by comparison with the microhardness of the monolithic alloy. However, Vickers microhardness demonstrates a sudden drop of 57.5 HV adjacent to HAZ at the AS.

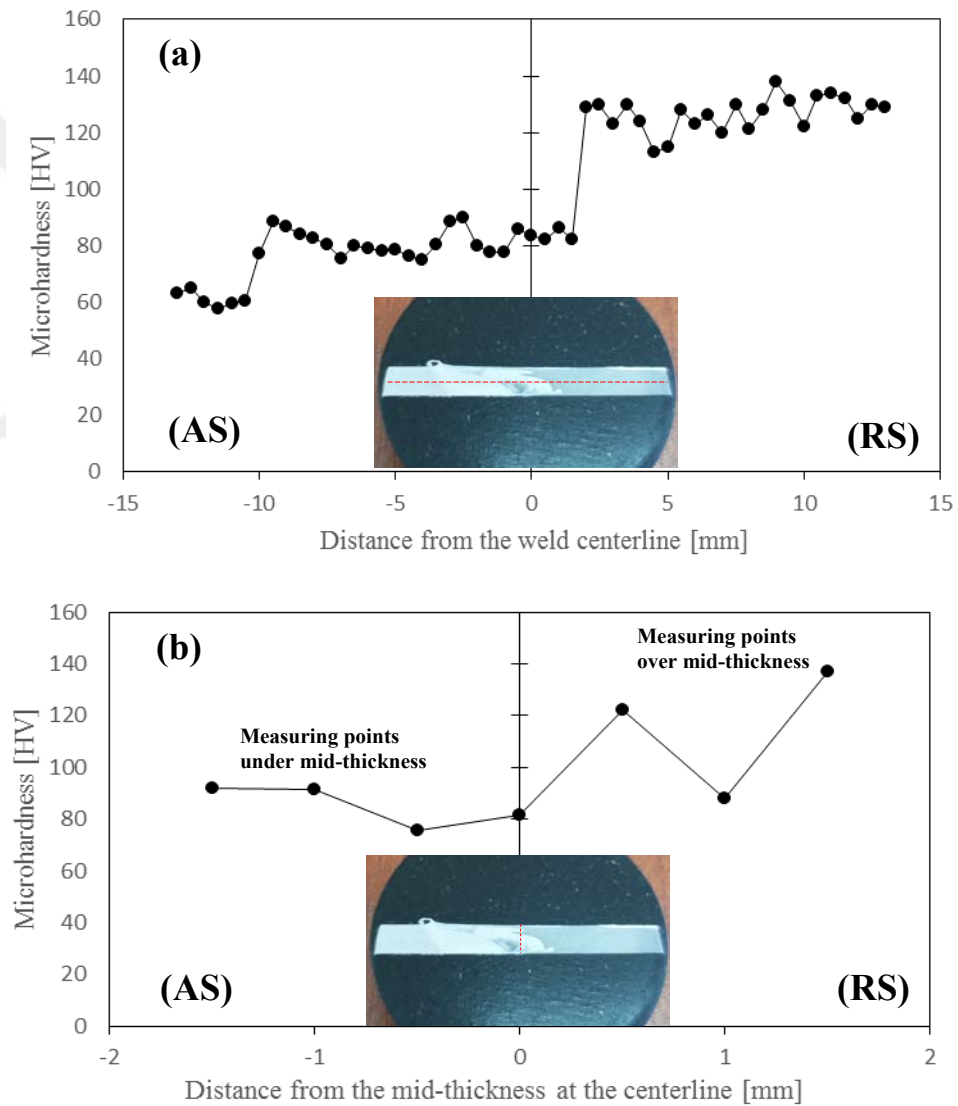


Figure 7.9 Microhardness distributions of the joint across (a) mid-thickness and (b) centerline (Oztoprak, Yeni & Kiral, 2018b)

7.4 Transverse Tensile Test Results

Tensile stress-strain curves of four specimens obtained by the dissimilar FSW are shown in Figure 7.10. Besides that, samples of the base materials are also tested to find out their ultimate tensile strength and failure elongation (Pct). As a result, ultimate tensile strength and failure elongation of the monolithic alloy reach the maximum values of 333.12 MPa and 5.05%, respectively. Similar tensile properties of the composite base material are in the order of 307.6 MPa and 5.60%, respectively. Transverse tensile test results of the dissimilar joint are given in Table 7.3. Calculated joint performances are also exhibited in the table. At this juncture, the joint performances are calculated by dividing the properties of the dissimilar joint to that of the composite base material. It is seen from this table that the joint efficiencies with regards to the tensile strength and percentage of elongation are about 67.62% and 83.57%, respectively. The findings also indicate a 208.01 MPa of mean tensile strength of the dissimilar joint. Moreover, Figure 7.11 shows the fracture locations of the welds. It is easily observed that all samples fractured at the advancing side (AA6061-T6) of the joint adjacent to the HAZ. Another noteworthy point is the wide HAZ in the joint owing to the high heat input during the FSW. Therefore, fracture in all samples takes place within the monolithic alloy side away from the weld nugget, even though the average tensile strength of the joint is lower than that of AA6061-T6.

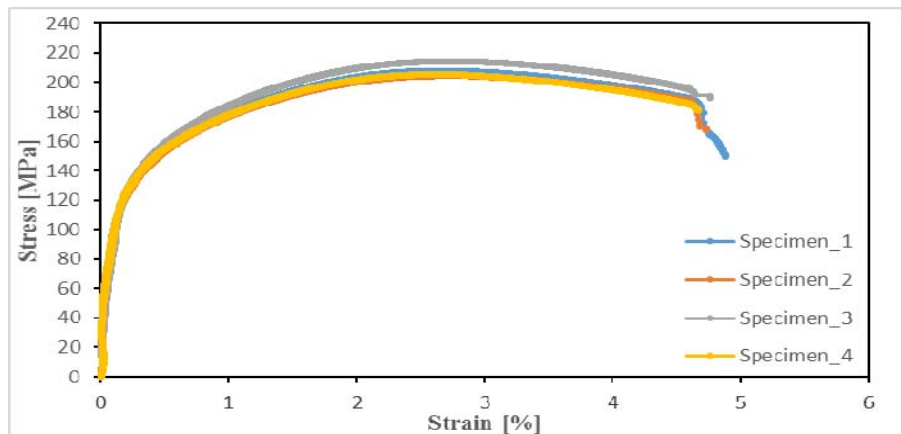


Figure 7.10 Stress-strain responses for the dissimilar FSWed specimens (Oztoprak, Yeni & Kiral, 2018b)

Table 7.3 Summary of the tensile test results of the samples (Oztoprak, Yeni & Kiral, 2018b)

Specimen		1	2	3	4	Average	Perf. ^a (%)
FSWed Joint	Tensile Strength (MPa)	207.84	204.46	214.40	205.35	208.01	67.62
	Elongation (P _{ct})	4.71	4.69	4.65	4.67	4.68	83.57

^aPerformance = (joint strength(or elongation)/strength(or elongation) of the composite) x 100.

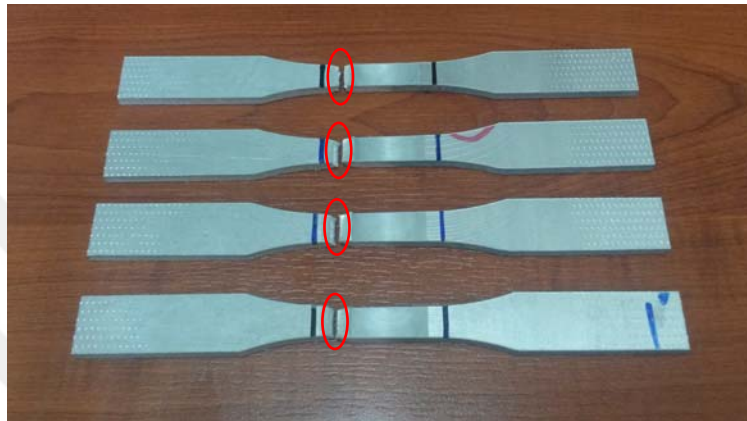


Figure 7.11 Fracture locations of the welds (Oztoprak, Yeni & Kiral, 2018b)

7.5 Charpy V-notch Impact Testing Results

In the study, Charpy impact tests are performed to evaluate the impact toughness of the dissimilar joint between AA6061-T6 and AA6061/SiCp composite. Samples of the joint before and following the tests are exhibited in Figure 7.12. Besides that, Charpy impact toughness of the parent materials are also evaluated and presented within the research to compare findings.

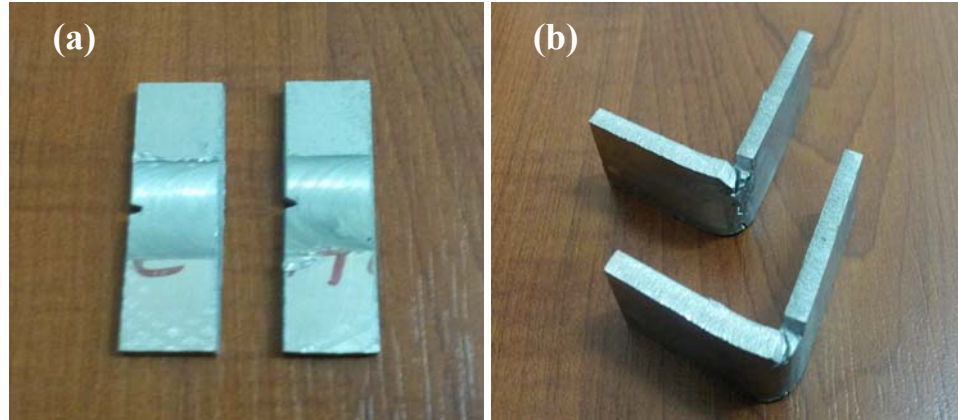


Figure 7.12 Photographs of the specimens used for Charpy impact testing (a) before and (b) subsequent to tests (Oztoprak, Yeni & Kiral, 2018b)

Summary of the Charpy impact test results are demonstrated in Figure 7.13. A total of six tests are carried out, two from each. According to the results, it is discovered that the dissimilar weld exhibits outstanding Charpy absorbed energy, especially compared to the composite base material. The findings clearly demonstrate that there is an increase of 15.4% and 318.4% in fracture toughness by comparison with AA6061-T6 and AA6061/SiCp composite, respectively. This can be attributed to the sound material mixing in the SZ that eliminates the embrittlement characteristic of the dissimilar weld. Herein, it should be noted that the particle volume fraction in the composite has a significant influence on the energy absorption feature of the joint.

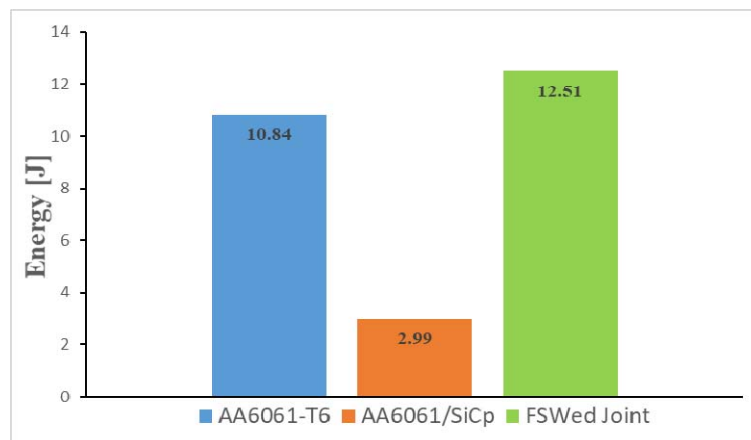


Figure 7.13 Comparison of the Charpy absorbed energies (Oztoprak, Yeni & Kiral, 2018b)

Photographs of the specimens after Charpy V-notch impact tests are presented in Figure 7.14. The findings indicate that only one of the composite specimens demonstrates a catastrophic failure. Other samples of the dissimilar joint and AA6061-T6 are not entirely damaged. These results are consistent with that obtained in the mean energy absorption values by Charpy V-notch impact tests. As it is noticeable from the picture, there is an L-shape in the samples of the dissimilar joint as other samples take a V-shape following the Charpy impact tests. In a way, when the absorbed energy in the test increases, bending angle of the specimens inversely are on the decline. The overall results explicitly show that the dissimilar FSWed joint exhibits the minimum bending angle while the maximum impact toughness is seen within these samples.

Finally, further study is carried out on the fracture morphology examination of the impact-tested specimens. SEM fractographs of the broken surfaces are shown in Figure 7.15. At this juncture, it is important to point out that there is no void formation in the fracture surfaces of the samples. Fracture surface of the AA6061/SiCp composite is observed with numerous fine dimples that confirms the ductile transgranular fracture. Besides, some regions within the fractograph demonstrate large and deep dimples. However, shallow and homogeneously distributed dimples compose the fracture surface of the monolithic alloy. These findings are also in tight agreement with the absorbed energies by Charpy V-notch impact tests. As to the fracture surface of the dissimilar joint, indications of both ductile and brittle fracture mode are observed. In the region comprising the particle-reinforced composite, the surface represent the quasi-cleavage fracture mode. On the other side, it can be inferred that the SiC-free zone has a characteristic of finer and shallower dimples compared to that of the monolithic alloy owing to the microstructural modification in the SZ by the FSW process.

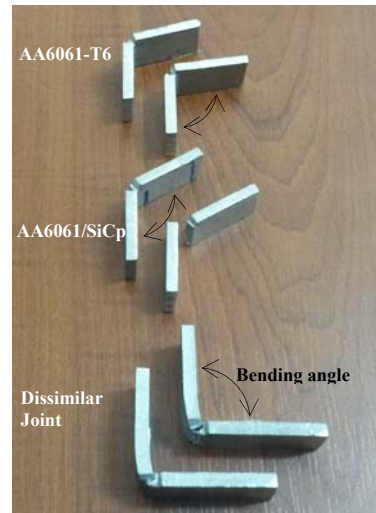


Figure 7.14 Charpy V-notched impact test specimens subsequent to the tests (Oztoprak, Yeni & Kiral, 2018b)

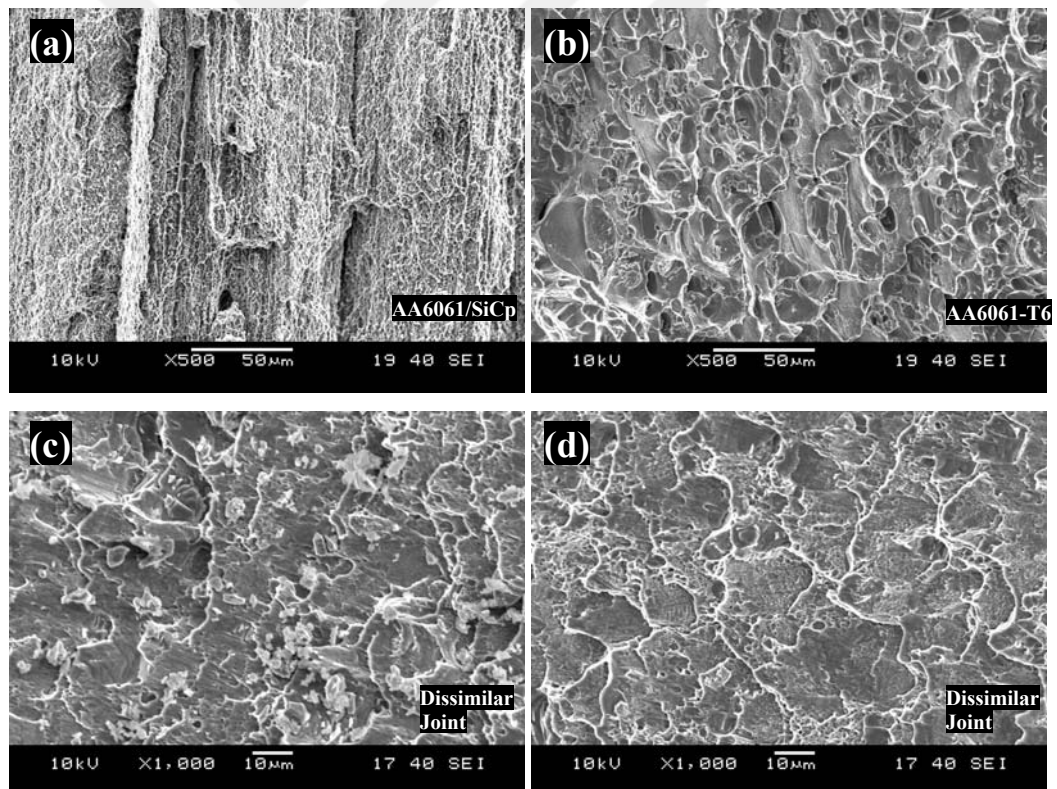


Figure 7.15 SEM images of the fracture surfaces (a) AA6061/SiCp (b) AA6061-T6 (c) Dissimilar joint with region comprising the MMC (d) Dissimilar joint with region comprising the monolithic alloy (Oztoprak, Yeni & Kiral, 2018b)

7.6 General Impact Response

In order to study the general impact response of the weld nugget, contact force-time, contact force-deflection and impact energy-time curves obtained through drop weight low-velocity impact tests at 2.5, 5 and 7.5 J are evaluated. First of all, it is important to note that neither perforation nor crack initiation was observed during the tests. Besides that, it was additionally discovered that the damaged area on the weld nugget expands while the impact energy is increased, as expected. Summary of the impact responses of the dissimilar weld at the various impact energy levels is depicted in Figure 7.16. Although two samples were tested at each energy level, only one sample was included in the results because the findings are very close to each other. According to the findings, the maximum contact force among the peak forces during the tests is reported as 7616.67 N at an energy level of 7.5 J even though there is no big difference in the impact time. Based upon the curves, it should also be noted that there is a decrement in the stiffness of the weld nugget at both 5 J and 7.5 J. As to the contact force-deflection responses of the weld, all curves compose a closed form that reflects the rebounding attitude. Loading and unloading cases during the tests also generate the ascending and descending sections. At this point, it is worthwhile to mention that the slope of the ascending section of the loadings represents bending stiffness of the samples. As it is noticeable from the curves, the samples show the characteristic of bending stiffness close to each other. On the other hand, distinctive deflection responses of the specimens at various impact energies are notable. Maximum deflection in the weld nugget is also observed as 0.99 mm at 7.5 J, which is higher than that of the samples of 2.5 and 5 J. From the comparison of energy-time curves, it can be found that the absorbed energy levels are 1.89, 4.05, and 6.25 J at 2.5, 5 and 7.5 J impact, respectively. These findings clearly indicate the variations between the absorbed energy within the material and the transverse impact energy applied. Absorbed kinetic energy is at the ground of this inequality.

In addition to all these, tensile properties of the dissimilar joint exposed to the various transverse impact energies are also investigated. Post-impact tensile test results of the welds are illustrated in Figure 7.17. According to the figure, similar

trend to those of the as-welded specimens is observed for all specimens. The mean ultimate tensile strengths of the samples are calculated as 213.48, 211.18 and 208.60 MPa at energy levels of 2.5, 5 and 7.5 J, respectively. As it is seen, tensile strength values decrease as the energy level is increased. In other respects, a decrease in the failure elongation of all specimens has been realized after the transverse impacts owing to the plastic deformation within the samples. Downward tendency in the elastic modulus of the specimens is another noteworthy point through the increasing impact energy levels. There are elastic modulus of 43.57, 36.03 and 29.89 GPa at 2.5, 5 and 7.5 J, respectively. Lastly, fracture locations of the welds are demonstrated in Figure 7.18. It is explicit that all specimens fractured on the advancing side adjacent to the HAZ. These results clearly indicate the good strength of the weld nugget subsequent to different transverse impact levels.

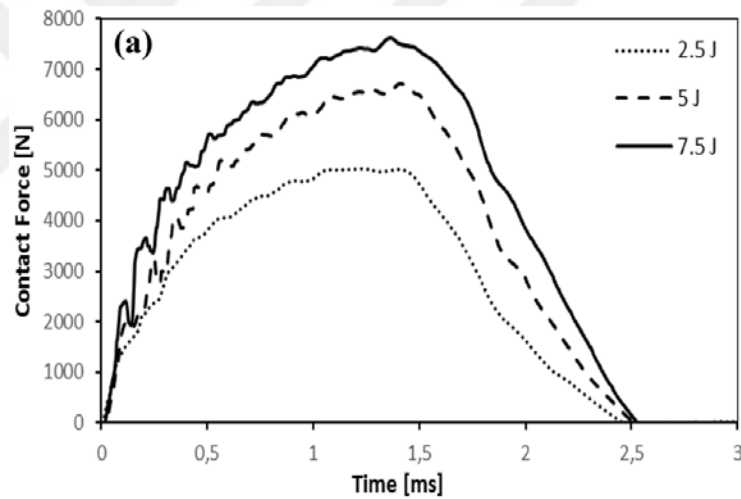


Figure 7.16 Comparison of the impact responses at various impact energy levels: (a) Contact force-time curves (b) Contact force-deflection curves (c) Energy-time curves (Oztoprak, Yeni & Kiral, 2018b)

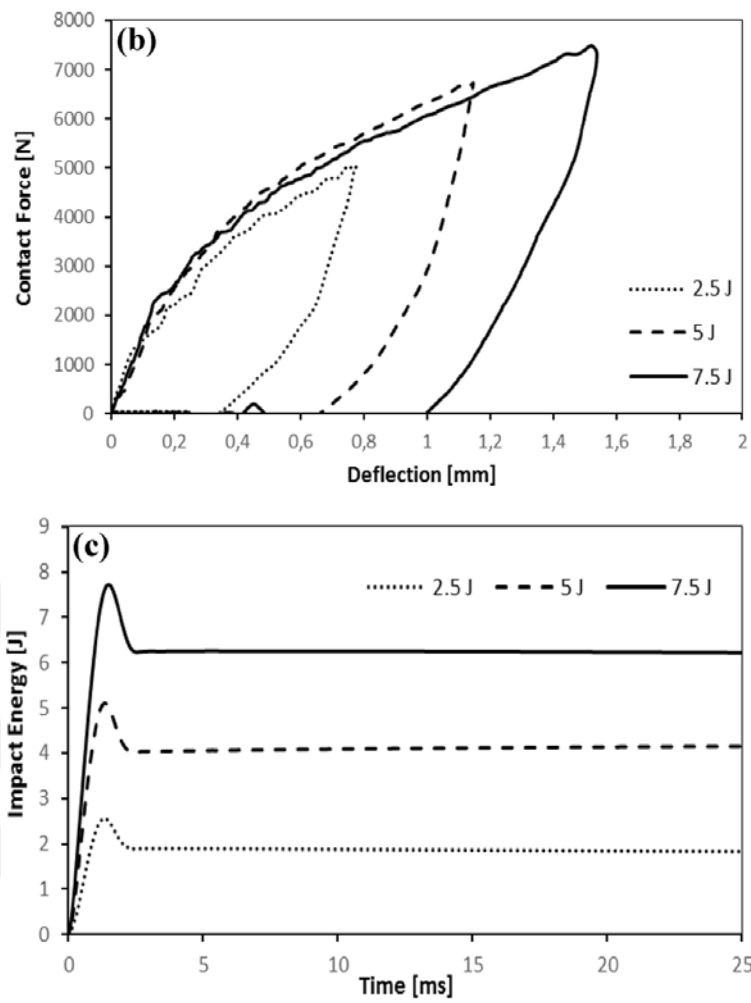


Figure 7.16 continues

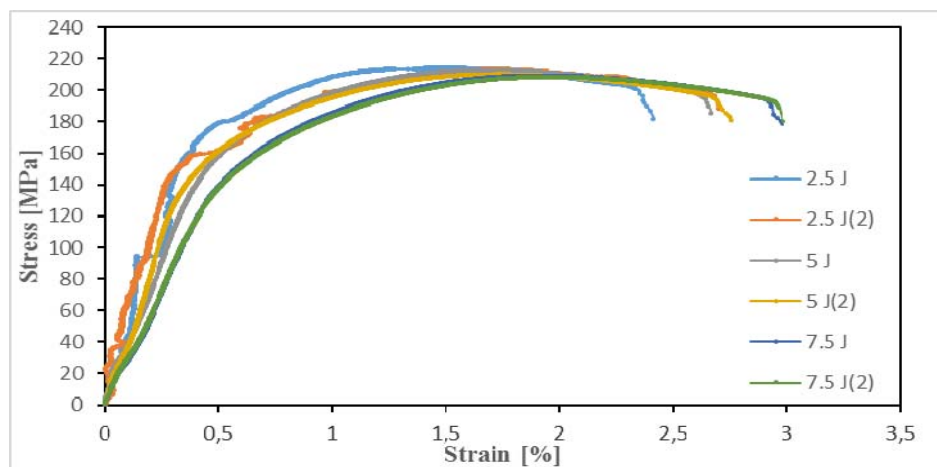


Figure 7.17 Stress-strain responses of the welds under various impact energies (Oztoprak, Yeni & Kiral, 2018b)



Figure 7.18 Fracture locations of the impact-tested specimens after tensile tests (Oztoprak, Yeni & Kiral, 2018b)

CHAPTER EIGHT

SIMILAR FSW OF AA6061/SiC/20p-T1

Influences of welding parameters on mechanical performance and fatigue life of the friction stir butt-welded AA6061/SiC/20p composites have been evaluated in this chapter. To this end, three different tool rotational speeds are utilized for the fabrication of FSWed joints with the other parameters remaining the same. Thereafter, transverse tensile properties, microhardness profiles, and finally fatigue and fracture behaviors of the similar joints have been investigated. Besides that, microstructural information of the joints has been scrutinized from the point of particle dispersion.

8.1 Experimental Work

The plates of AA6061/SiC/20p of 3.8 mm-thick in T1 condition are used as the base material for the present research. The physical properties of the workpiece can be found in Table 6.1 and Table 7.1. Within the study, the metal-matrix composites were friction stir butt welded using a vertical milling machine. Table 8.1 exhibits the process parameters of the AA6061/SiC/20p-T1 joints. The FSW tool made from AISI 4140 high strength steel had diameters of 20 mm for the shoulder with concave bow and 5 mm for the pin tip. Schematic diagram and the dimensions of the FSW tool are depicted in Figure 8.1. Figure 8.2 also shows the photograph of the FSW application.

Table 8.1 Welding parameters of the joints (Oztoprak, Yeni & Kiral, 2018c)

#Joint	#Material	#Rotational Speed [rev.min ⁻¹]	#Welding Speed [mm.min ⁻¹]	#Tool Diameter [mm]	#Tilt Angle [°]
1	AA6061/SiC/20p-AA6061/SiC/20p	1000	100	20	2
2	AA6061/SiC/20p-AA6061/SiC/20p	1250	100	20	2
3	AA6061/SiC/20p-AA6061/SiC/20p	1600	100	20	2

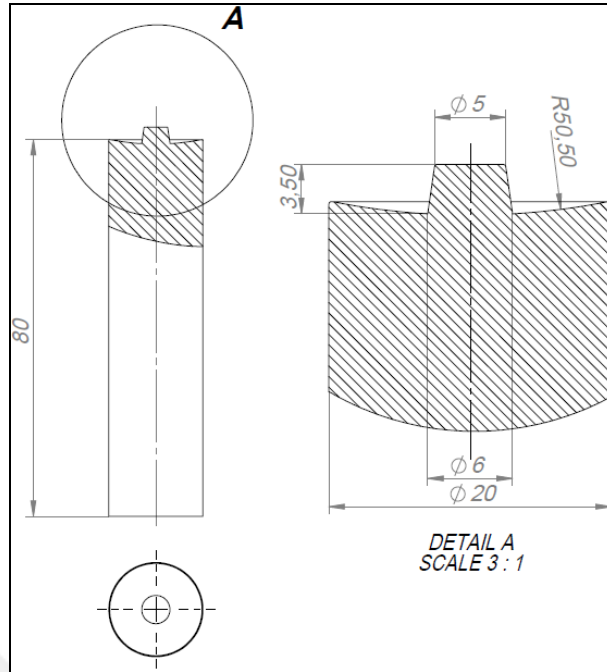


Figure 8.1 Dimensions of the FSW tool (Oztoprak, Yeni & Kiral, 2018c)



Figure 8.2 Similar FSW of AA6061/SiCp composites in progress (Oztoprak, Yeni & Kiral, 2018c)

As regards the mechanical and fatigue testing details, Figure 8.3 demonstrates the sampling schematic of the joints for the weld characterization. Similar to other

chapters, transverse tensile properties of the similar FSWed joints are reported with regards to tensile strength, percentage of elongation at rupture and also joint performance. Four specimens were tested as part of the research. Dimensions of the tensile test specimens are demonstrated in Figure 8.4. All tensile tests were performed on Shimadzu AG-X (100 kN) Universal Testing Machine at a constant speed of 1 mm/min at ambient temperature. Figure 8.5 also shows the photograph of transverse tensile test samples.

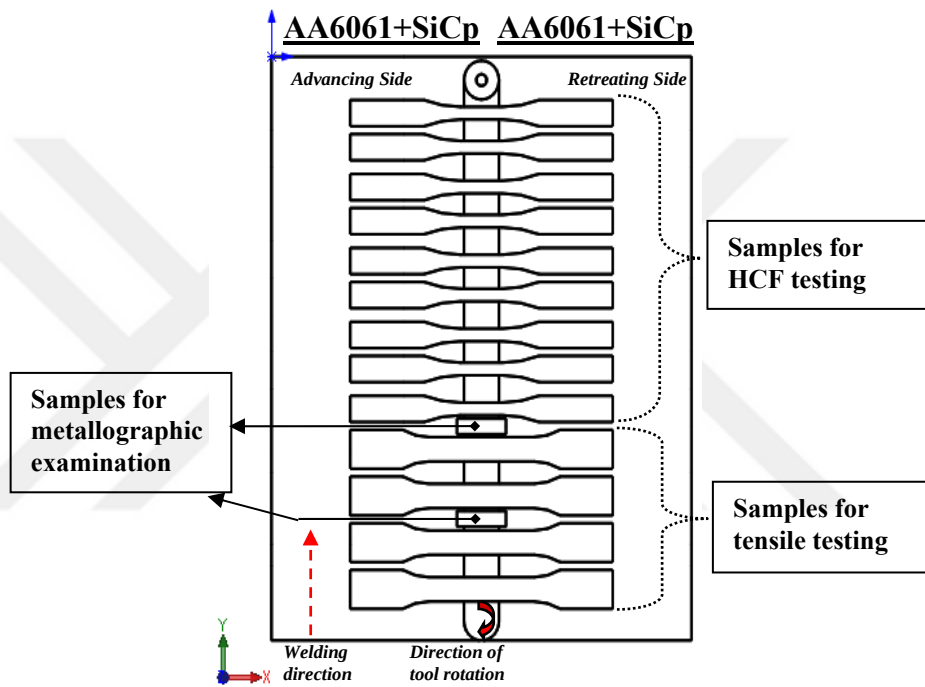


Figure 8.3 Sampling schematic of the joint (Oztoprak, Yeni & Kiral, 2018c)

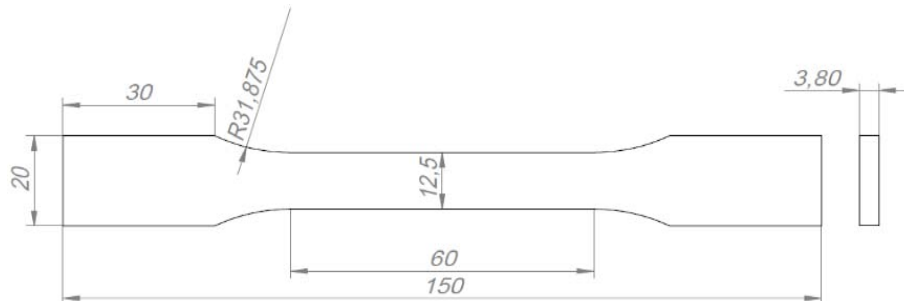


Figure 8.4 Principal dimensions of the transverse tensile test specimens (Oztoprak, Yeni & Kiral, 2018c)



Figure 8.5 Photo of the transverse tensile test specimens (Oztoprak, Yeni & Kiral, 2018c)

As for the Vickers microhardness measurements of the joints, distributions across the mid-thickness of the similar joints were obtained by Shimadzu HMV-2 E microhardness tester at a 100 g loading, 10 s dwell time and a span of 0.5 mm. It is noteworthy that the samples were emiered and polished in order to achieve infallible observations.

For the fatigue testing of the FSWed joints, the test coupons were tested according to ASTM E466 using a Shimadzu (EHF-EV200k2-040-0A) servo-hydraulic testing machine. Figure 8.6 and Figure 8.7 present the fatigue test machine and the test fixture, respectively. The fatigue tests were performed in air at ambient temperature in the stress-controlled situation at a frequency of 20 Hz and a stress ratio of $R=0.1$. In the tests, a sinusoidal wave function in the tension-tension mode was used. Within the research, the fatigue tests for the joints were automatically terminated when the samples had not ruptured up to 2×10^6 cycles. In addition, high-frequency stress-controlled fatigue tests of the base composite were also executed in the same test details of the similar joints. To that end, fatigue life assessment of the base material is carried out by way of six specimens. The range of maximum stress varied from 69.35 MPa to 173.37 MPa at the $R=0.1$. On the other part, the range of maximum stress varied from 85.42 MPa to 179.38 MPa, 80.87 MPa to 177.90 MPa and 76.93 MPa to 138.47 MPa for Joint-1, Joint-2 and Joint-3, respectively. Table 8.2 summarizes the details of fatigue testing for the base composite and FSWed joints. Dimensions and shape of the samples of fatigue tests are shown in Figure 8.8. Herein, it is important to note that the welds of fatigue test specimens are transverse to the loading direction.

It is also common knowledge that the fatigue behavior of a material is considerably affected by the surface finishing process of the samples (Uematsu, Kakiuchi, Mizutani, Ishida & Fukunaga, 2018). Therefore, all fatigue specimens were prepared using a water-jet. Besides that, all surfaces of the specimens were manually polished before the fatigue testing. Several grades of sandpaper (1200xsandpaper, 2000xsandpaper and 2500xsandpaper) were used in the processes. In addition to all these, fractographic examination of some failed samples was performed by scanning electron micrography in order to provide supplement observations on the fatigue response of both similar joints and base material.



Figure 8.6 Photo of the fatigue testing machine (Oztoprak, Yeni & Kiral, 2018c)



Figure 8.7 Photo of the fatigue test in progress (Oztoprak, Yeni & Kiral, 2018c)

Table 8.2 Parameters of the fatigue testing (Oztoprak, Yeni & Kiral, 2018c)

	% of Yield Strength (approx.)	Number of Specimens	Stress Range (MPa)	Max. Stress (MPa)	Min. Stress (MPa)	Mean Stress (MPa)	Alternating Stress (MPa)
BM	40	1	62.41	69.35	6.94	38.14	31.21
	50	1	78.02	86.69	8.67	47.68	39.01
	60	1	93.63	104.03	10.40	57.21	46.82
	70	1	109.22	121.36	12.14	66.75	54.61
	90	1	140.43	156.03	15.60	85.81	70.22
	100	1	156.03	173.37	17.34	95.35	78.02
Joint-1	% of Yield Strength (approx.)	Number of Specimens	Stress Range (MPa)	Max. Stress (MPa)	Min. Stress (MPa)	Mean Stress (MPa)	Alternating Stress (MPa)
	50	1	76.88	85.42	8.54	46.98	38.44
	60	1	92.25	102.50	10.25	56.37	46.12
	70	2	107.63	119.59	11.96	65.77	53.81
	80	1	123.01	136.67	13.66	75.16	61.50
	90	1	138.38	153.75	15.37	84.56	69.19
	100	2	153.76	170.84	17.08	93.96	76.88
Joint-2	% of Yield Strength (approx.)	Number of Specimens	Stress Range (MPa)	Max. Stress (MPa)	Min. Stress (MPa)	Mean Stress (MPa)	Alternating Stress (MPa)
	50	1	72.79	80.87	8.08	44.47	36.39
	60	1	87.34	97.04	9.70	53.37	43.67
	70	2	101.9	113.22	11.32	62.27	50.95
	80	1	116.45	129.39	12.94	71.16	58.22
	90	1	131.01	145.56	14.55	80.05	65.50
	100	1	145.56	161.73	16.17	88.95	72.78
	105	1	152.84	169.82	16.98	93.40	76.42
	110	1	160.11	177.90	17.79	97.84	80.06
Joint-3	% of Yield Strength (approx.)	Number of Specimens	Stress Range (MPa)	Max. Stress (MPa)	Min. Stress (MPa)	Mean Stress (MPa)	Alternating Stress (MPa)
	50	1	69.24	76.93	7.69	42.31	34.62
	60	1	83.08	92.31	9.23	50.77	41.54
	70	2	96.93	107.70	10.77	59.23	48.46
	80	2	110.78	123.08	12.30	67.69	55.39
	90	1	124.63	138.47	13.84	76.15	62.31

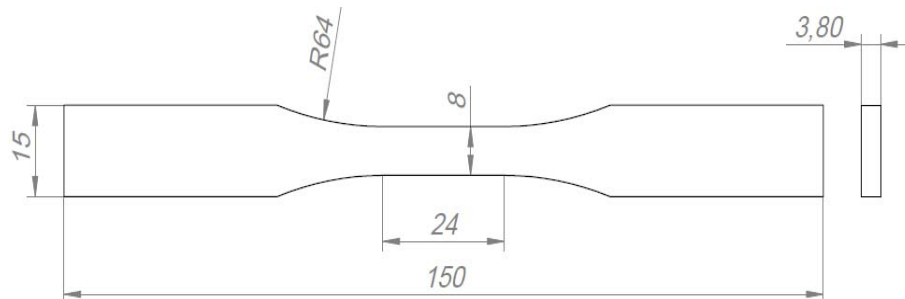


Figure 8.8 Fatigue test specimen configuration (all dimensions are in mm) (Oztoprak, Yeni & Kiral, 2018c)

8.2 Tensile Properties

Before the tensile tests of the FSWed joints, tensile properties of the base material were also reported within the research, once again. Figure 8.9 exhibits the stress versus elongation curves of the base composite. Accordingly, the parent material shows a mean tensile strength and elongation at failure (%) of 309.63 MPa and 5.61, respectively. Transverse tensile test results of the FSWed joints are also depicted in Figures 8.10-8.12. When the figures are examined, it is explicit that there is a similar trend to that of the metal-matrix composite for all joints in terms of the tensile behavior. In addition, the transverse tensile test results correspond to a joint efficiency of 97.29%, 92.43% and 88.66% for Joint-1, Joint-2 and Joint-3, respectively. In other words, joint efficiencies decline with the increment in the tool rotational speed. Same as before, joint efficiency is calculated as the ratio of the tensile strength of the weld to that of the base material. Herein, it is important to point out that the joints fractured within the weld zone, even though the process resulted in the relative high mechanical performances. This event may have a close connection with the reduction of area in the weld zone owing to the high tool penetration depth. Besides that, it should also be noted that optimum welding parameters are needed to obtain sufficient results after FSW. Figure 8.13 demonstrates the failure locations of similar joints.

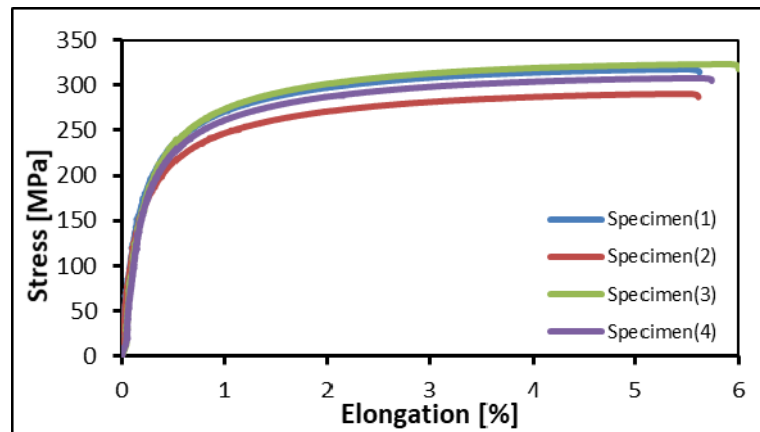


Figure 8.9 Stress vs. elongation behavior of the base composite (Oztoprak, Yeni & Kiral, 2018c)

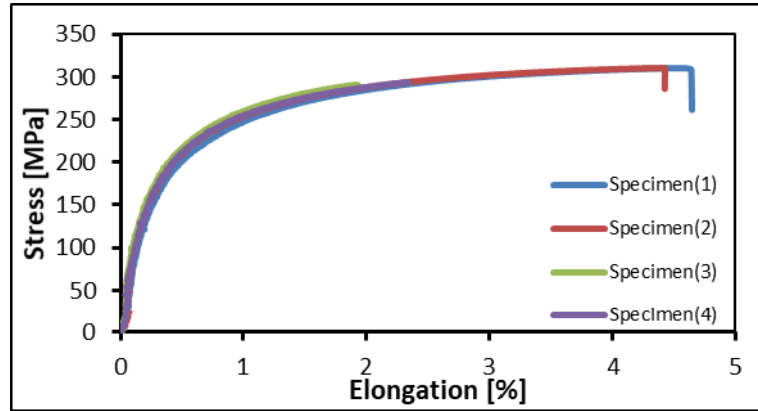


Figure 8.10 Stress vs. elongation behavior of Joint-1 (Oztoprak, Yeni & Kiral, 2018c)

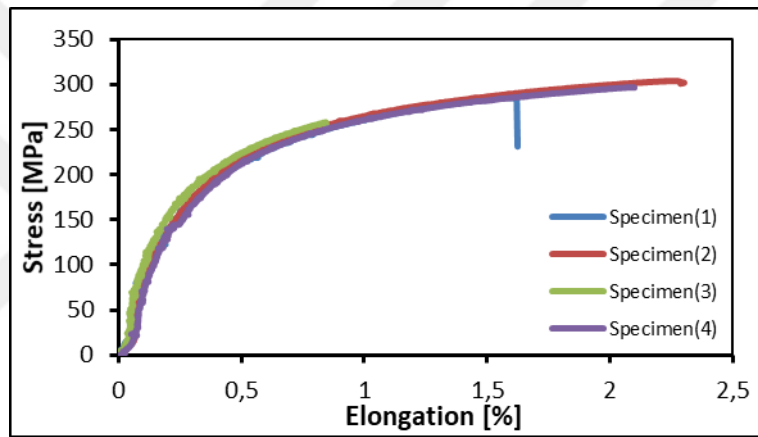


Figure 8.11 Stress vs. elongation behavior of Joint-2 (Oztoprak, Yeni & Kiral, 2018c)

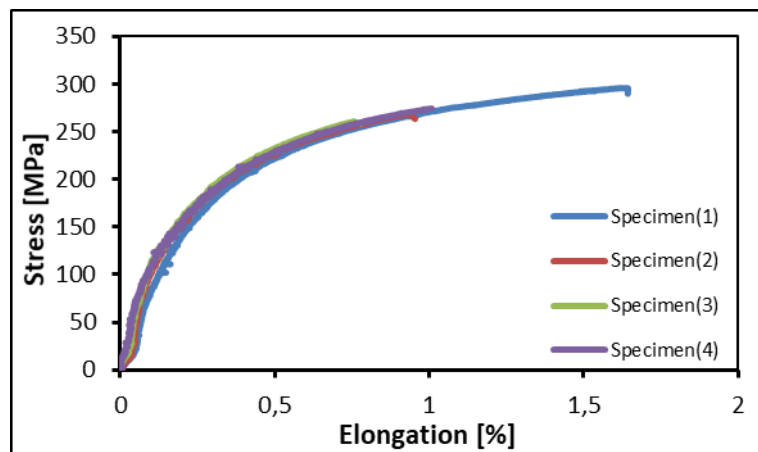


Figure 8.12 Stress vs. elongation behavior of Joint-3 (Oztoprak, Yeni & Kiral, 2018c)



Figure 8.13 Failure locations of the FSWed joints (Oztoprak, Yeni & Kiral, 2018c)

For better understanding, the transverse tensile test results for the base material and FSWed joints are compared in Table 8.3. The table summarizes the ultimate tensile strength and percentage of elongation (P_{ct}) values of all tensile test samples. As it is noticeable in the table, Joint-1 exhibits a higher mean tensile strength value of 301.23 MPa by comparison with other joints. As previously stated, it is seen that the mean tensile strength decreases as the tool rotational speed increases from 1000 rpm to 1600 rpm. Conversely, percentage of elongation at rupture decreases to one-half that of the base material subsequent to FSW. In addition, the mean failure elongation values decline with the increasing tool rotational speed. At this juncture, tool wear and fractured reinforcing particles play a significant role on the ductility of the FSWed joints. When all these findings are evaluated, it is noteworthy that the sound FSW of AA6061/SiC/20p composites can provide promising mechanical performance in tensile strength while reduces the percentage of elongation at failure.

Table 8.3 Summary of the transverse tensile test results (Oztoprak, Yeni & Kiral, 2018c)

#Specimen		1	2	3	4	Mean Value	Performance (%)
#Base Material (AA6061/SiCp)	Tensile Strength (MPa)	317.42	290.35	323.15	307.61	309.63	-
	Elongation (P _{ct})	5.50	5.47	5.88	5.60	5.61	-
#Joint-1	Tensile Strength (MPa)	309.95	310.92	290.85	293.18	301.23	97.29
	Elongation (P _{ct})	4.54	4.42	1.92	2.33	3.30	58.82
#Joint-2	Tensile Strength (MPa)	285.29	304.56	257.57	297.31	286.18	92.43
	Elongation (P _{ct})	1.58	2.26	0.84	2.09	1.69	30.12
#Joint-3	Tensile Strength (MPa)	295.30	268.36	260.51	273.84	274.50	88.66
	Elongation (P _{ct})	1.63	0.93	0.76	1.00	1.08	19.25

Performance = (joint strength(failure elongation)/strength(failure elongation) of parent material) x100

8.3 Microhardness Profiles of the Joints

In order to evaluate the probable alteration of microstructure within the weld zone and consequently the variety in mechanical properties, Vickers microhardness results are reported across the mid-thickness of FSWed joints based upon the distance from the weld centerline. Figures 8.14-8.16 show the typical Vickers hardness profiles of the similar FSWed joints. As it is demonstrated in the figures, the representative base metal hardness is in the range of 110-125 HV. This event may be attributed to the fact that the variation in the dispersion of reinforcing particles is in nanosize within the parent metal-matrix composite. Besides that, it is seen that all hardness profiles exhibit a similar behavior to that of the parent material. In other saying, a homogeneous microhardness map is roughly observed along the mid-thickness of the weld seam for all FSWed joints. As a matter of fact, microstructure evolution in the weld zone is at the ground of these hardness distributions obtained. On the other hand, the diversity of microhardness values is evident on the advancing side in both Joint-2 and Joint-3. These findings are also consistent with that obtained in the transverse tensile tests. It is easily observed that the mean Vickers value within SZ

declines with the increasing tool rotational speed from 1000 rpm to 1600 rpm. The maximum mean Vickers in the SZ of Joint-1 results in 119.77 HV.

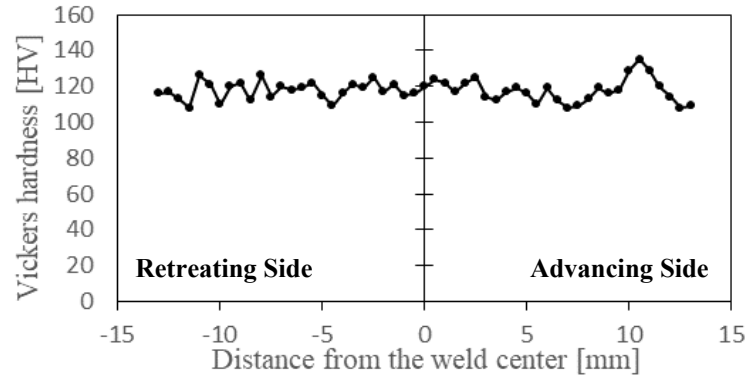


Figure 8.14 Microhardness in the cross-section of Joint-1 (Oztoprak, Yeni & Kiral, 2018c)

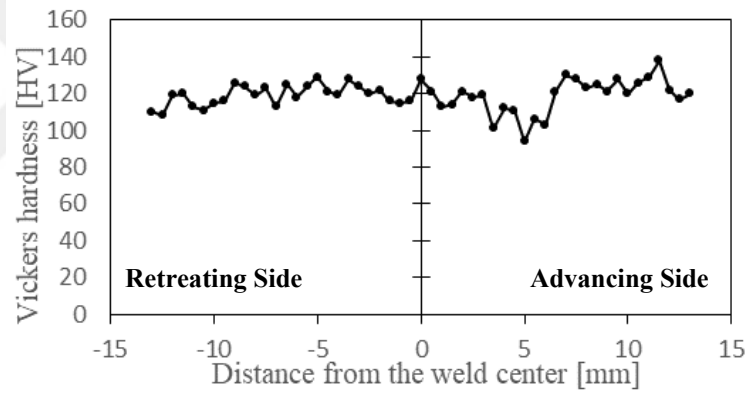


Figure 8.15 Microhardness in the cross-section of Joint-2 (Oztoprak, Yeni & Kiral, 2018c)

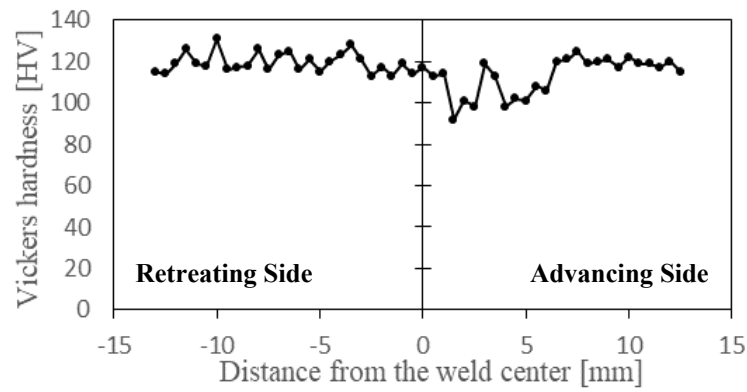


Figure 8.16 Microhardness in the cross-section of Joint-3 (Oztoprak, Yeni & Kiral, 2018c)

8.4 Fatigue Properties

Within the thesis, the fatigue behavior of FSWed AA6061/SiC/20p-T1 joints at various tool rotational speeds is analyzed. Besides, S-N curve of the base composite is also represented in order to make a comparison. Figure 8.17 reveals the S-N curves of both the base material and similar welds from the fatigue testing performed at ambient temperature. As it is evident, the maximum stress in cyclic loading versus corresponding fatigue life to failure expresses the fatigue data obtained. The fatigue tests were carried out in tensile-tensile loading, as previously stated. It should be noted that these curves are widely used to determine the fatigue strength of a component under cyclic loading. Herein, 2×10^6 cycles without failure of the specimen is referred as the reference fatigue life and therefore, the tests were discontinued when the number of fatigue cycles exceeds 2×10^6 . In other words, fatigue strength of the specimens is determined in this way. The samples that achieve the designated 2×10^6 cycles without fracture is demonstrated through black arrows within the graphics.

As can be seen in the figure, the fatigue lifetime continuously decreases in each case with the increasing maximum stress applied. The highest fatigue strength by comparison with other joints is noted for Joint-2 as 113.22 MPa. Besides, a fatigue limit of 102.5 MPa and 92.31 MPa is easily observed for Joint-1 and Joint-3, respectively. As for the base material, a fatigue strength of 121.36 MPa is reported. According to these findings, it is clear that the base composite presents a slightly higher fatigue limit than the FSWed joints. At this juncture, it is needed to notice that Joint-3 is more susceptible to fluctuating loadings compared to other welds. The lowest strength was achieved at 1600 rpm. This may mainly be associated with the relatively poor mechanical properties of the joint with regards to the microhardness map and tensile strength. In other respects, the highest fatigue strength among the similar FSWed joints was achieved at 1250 rpm (Joint-2). Herein, it is worthwhile to mention that the particle dispersion has a significant place in determining the fatigue behavior of MMCs. Therefore, stir zones of the joints are also scrutinized in terms of the particle dispersion (Figure 8.18). Accordingly, it was discovered that there is a

more homogeneous SiC dispersion within the SZ of Joint-2 as compared to that of other joints. Besides that, energy dispersive x-ray (EDX) analysis of the SZ is also provided. The findings for the designated point (one of the dispersed particles) are shown in the Figure 8.19 below. By extension, it can be noted that the relevant point only comprises the chemical composition of the particles and the aluminum matrix, as expected. It is seen that the concentration of other materials such as iron and nickel is quite small.

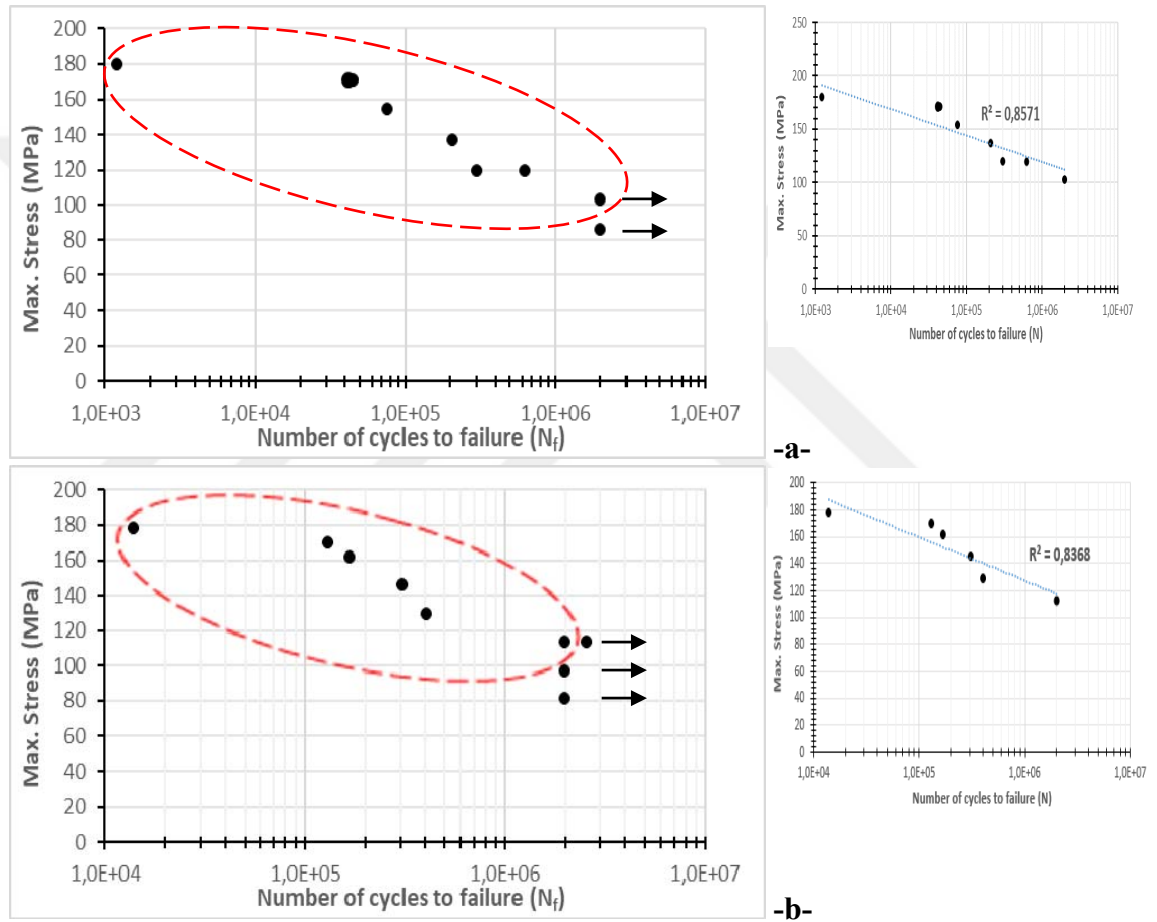


Figure 8.17 S-N data for the base composite as well as the FSWed joints: (a) Joint-1 (b) Joint-2 (c) Joint-3 (d) composite (Oztoprak, Yeni & Kiral, 2018c)

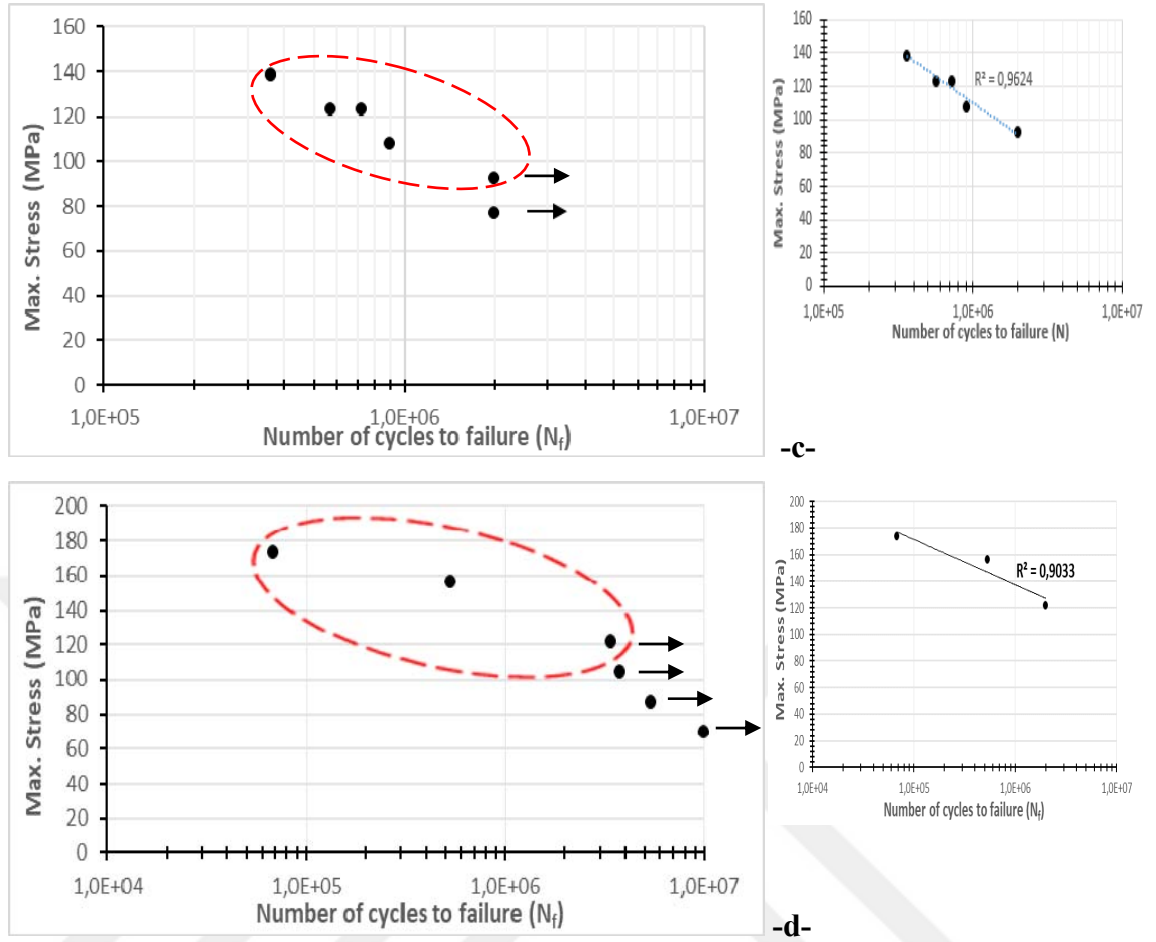


Figure 8.17 continues

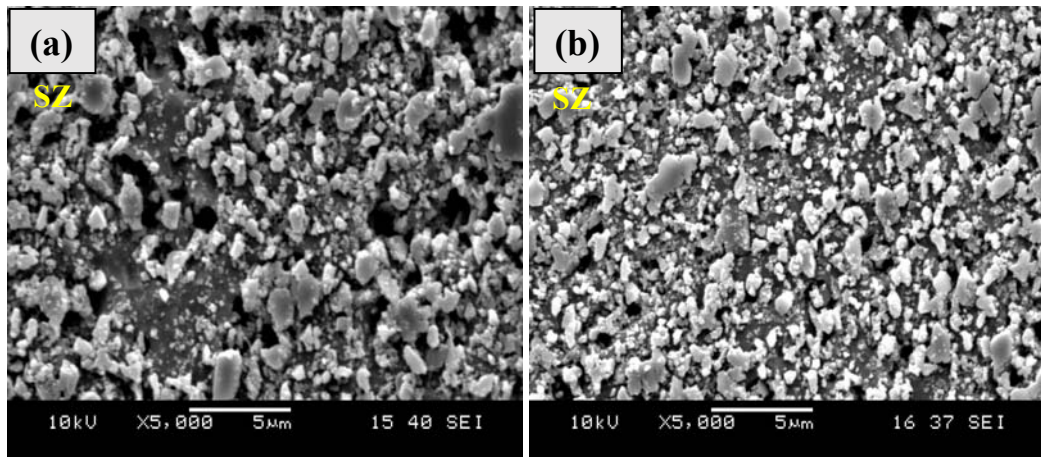


Figure 8.18 SEM images of (a) Joint-1 (b) Joint-2 (c) Joint-3 (Oztoprak, Yeni & Kiral, 2018c)

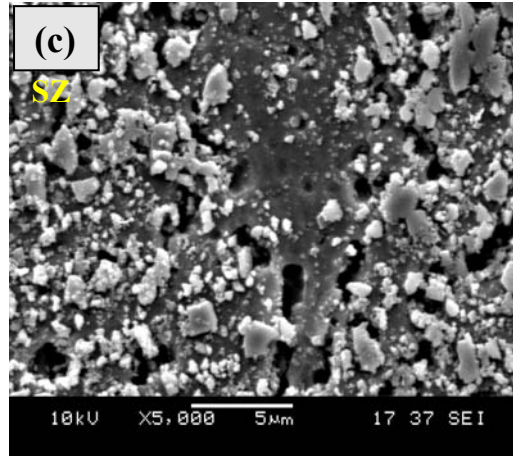


Figure 8.18 continues

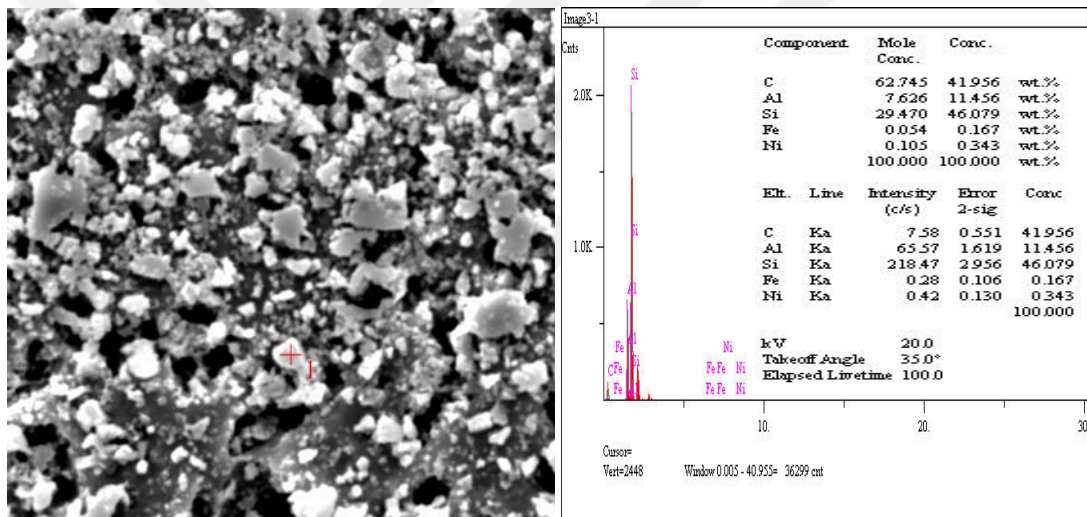


Figure 8.19 EDX elemental analysis on the SZ of AA6061/SiC/20p-T1 joint (Personal archive, 2018)

8.5 Fractography

To further evaluate the fatigue behavior of the BM and FSWed joints, the fractographs of some selected samples were investigated through SEM. SEM fractographs of the base composite, Joint-1, Joint-2 and Joint-3 are shown in Figures 8.20-8.26, respectively. It can be found from Figure 8.20 that the fracture surface of BM is almost flat with fine and shallow dimples. These indications show the ductile failure of BM. Besides that, the indicators of macroplastic deformation are

characteristic feature of the final fracture region. In other respects, a pronounced crack propagation zone could not be detected within the fractograph owing to the relatively low applied stress range.

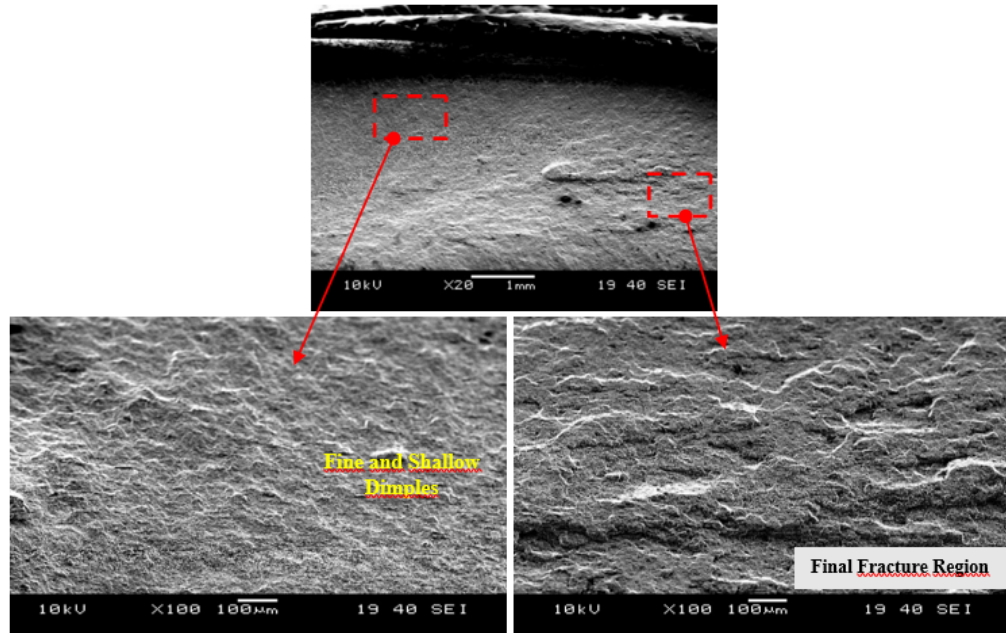


Figure 8.20 SEM images showing fracture surface of BM at a max. stress of 69.35 MPa / over 10^7 cycles (Oztoprak, Yeni & Kiral, 2018c)

As regards to the FSWed joints, all samples ruptured within the weld zones without presenting necking. A catastrophic failure is observed in the sample of Joint-1 at a maximum stress of 179.38 MPa owing to the coalescence and rapid growth of the voids (Figure 8.21). No fatigue crack propagation region is reported within the image.

As to the fractograph of second sample of Joint-1 at a max. stress of 119.59 MPa (Figure 8.22), the surface seems more flat by comparison with the sample having lower fatigue life. In addition, the fracture surface shows the crack nucleation side, radial steps and the final fracture region. On the other hand, growth bands that are visual signs of the fatigue phenomenon are not very apparent in the fractograph. As it is noticeable from the figure, crack initiation occurs at the top surface of the specimen. Moreover, the radial steps are another characteristic feature of the surface.

It is explicit from the figure that these observations depict the crack initiation zone and the direction of crack propagation. As for the final fracture region, the surface is characterized by the plastic flow of aluminum matrix.

Figure 8.23 demonstrates an SEM overview of the fracture surface of Joint-2 at a max. stress of 177.90 MPa. It is evident that there are various crack nucleation regions within the fractograph. In addition, formation of fatigue striations are observed. In this zone, fine and shallow dimples are noted. This region is also characterized by micro voids. On the other hand, it is needed to notice that there is a region with deeper and larger dimples in the surface. Relatively high plastic deformations occurring locally may be at the ground of this observation. As to the final fracture region, a great number of shallow dimples is noticed.

Fractographic study on the second sample of Joint-2 at a max. stress of 129.39 MPa shows two different zones unlike the first specimen (Figure 8.24). The surface can be characterized by an interfacial crack traversing throughout the specimen. In the crack propagation region, finer and more shallow dimples by comparison with other zones are reported. A larger crack propagation area is also noticed in the figure as compared with that of the first sample in the low-cycle fatigue region. Lastly, indications of both ductile and brittle failure modes are observed within the final fracture region.

SEM images belonging to Joint-3 are shown in Figure 8.25 and Figure 8.26 for the sample at a max. stress of 107.70 MPa and at a max. stress of 76.93 MPa, respectively. At first glance, some pores and numerous voids within both fractographs draw the attention. Herein, it should not be forgotten that these observations may cause crack initiation. As to Figure 8.25, striations that indicate the plastic flow of aluminum matrix are observed in the fracture surface. Besides, there are shallower dimples on the matrix material within the final fracture region. On the other part, a v-shaped hollowed morphology is observed for the second fractograph of Joint-3 (Figure 8.26). Quasi-cleavage fracture mode is the characteristic feature of the surface. Crack propagation zone is also not visible for this specimen.

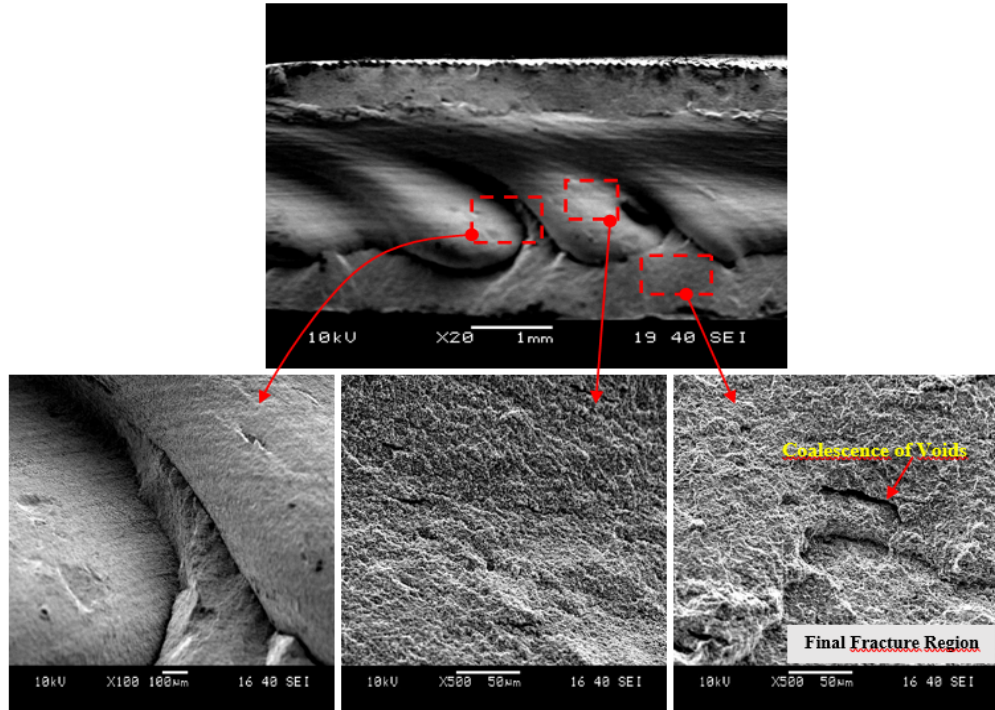


Figure 8.21 SEM images showing fracture surface of Joint-1 at a max. stress of 179.38 MPa / 1223 cycles (Oztoprak, Yeni & Kiral, 2018c)

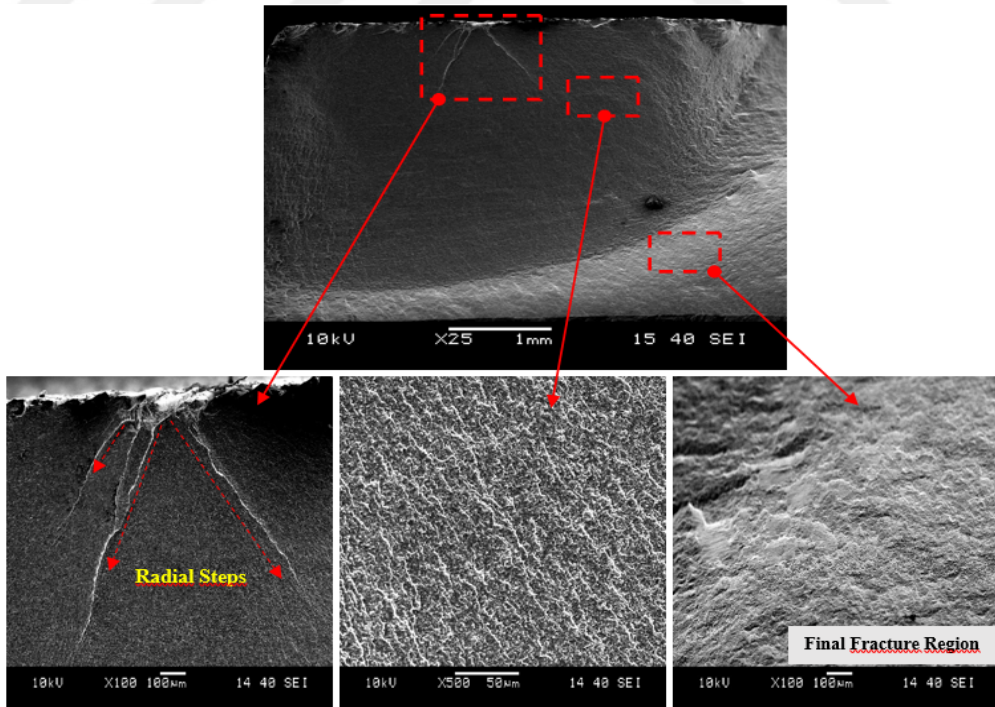


Figure 8.22 SEM images showing fracture surface of Joint-1 at a max. stress of 119.59 MPa / 627848 cycles (Oztoprak, Yeni & Kiral, 2018c)

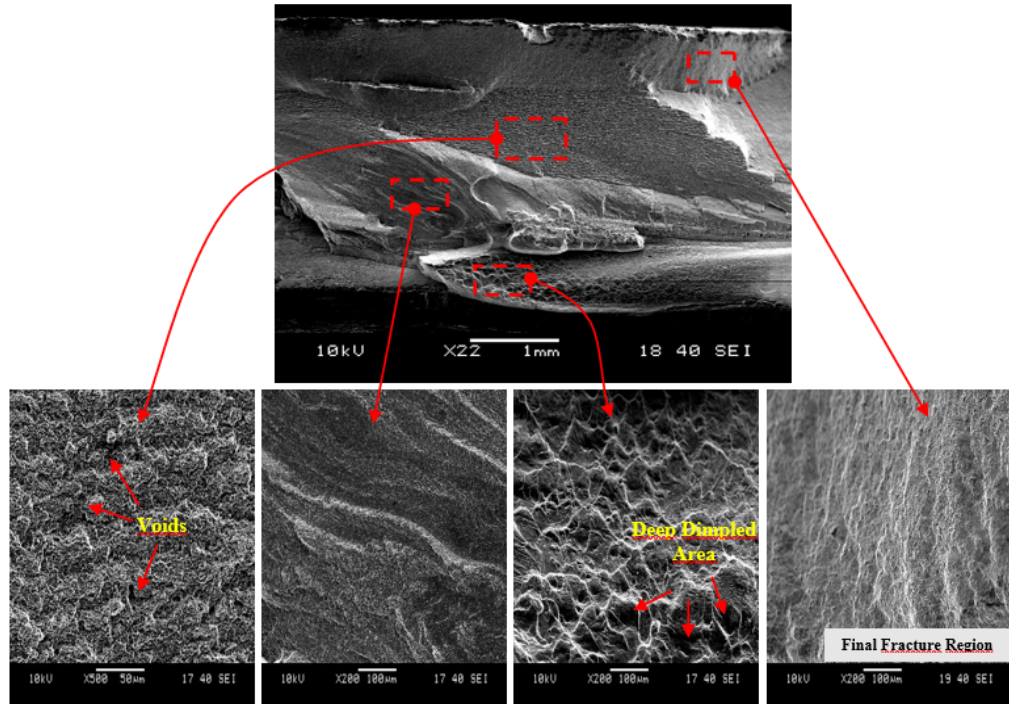


Figure 8.23 SEM images showing fracture surface of Joint-2 at a max. stress of 177.90 MPa / 13916 cycles (Oztoprak, Yeni & Kiral, 2018c)

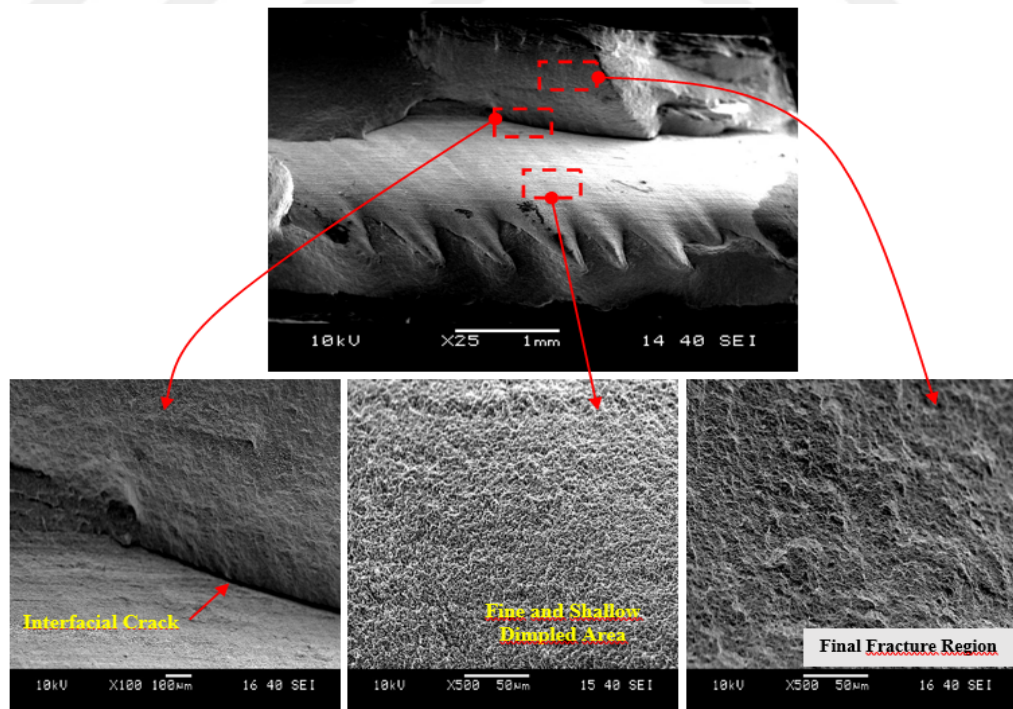


Figure 8.24 SEM images showing fracture surface of Joint-2 at a max. stress of 129.39 MPa / 403979 cycles (Oztoprak, Yeni & Kiral, 2018c)

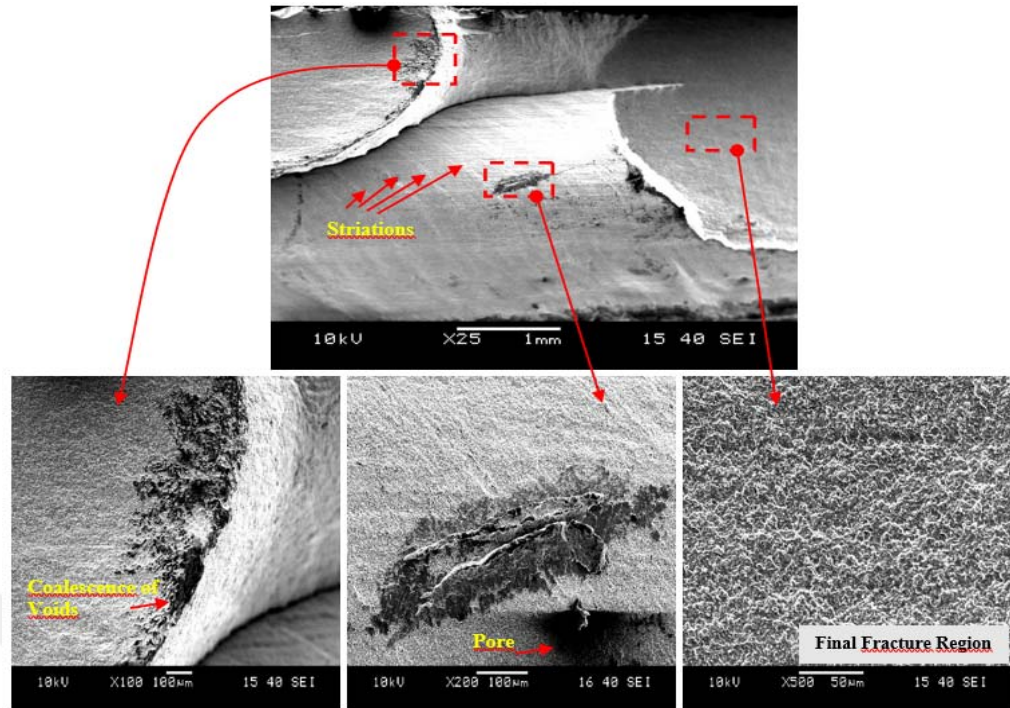


Figure 8.25 SEM images showing fracture surface of Joint-3 at a max. stress of 107.70 MPa / 271004 cycles (Oztoprak, Yeni & Kiral, 2018c)

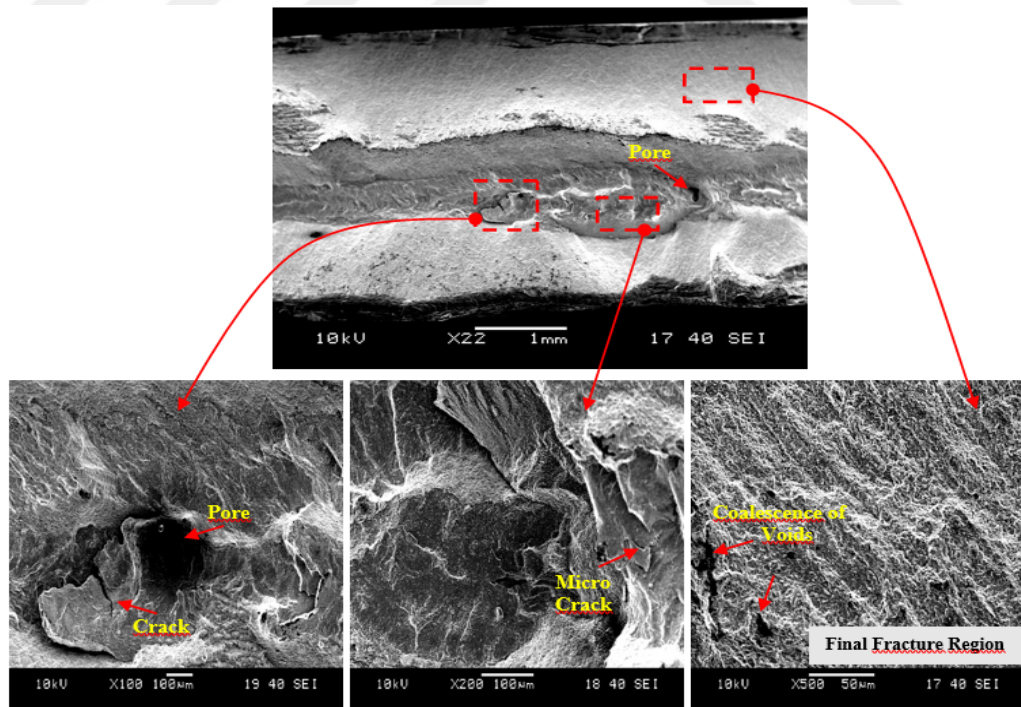


Figure 8.26 SEM images showing fracture surface of Joint-3 at a max. stress of 76.93 MPa / 2380664 cycles (Oztoprak, Yeni & Kiral, 2018c)

CHAPTER NINE

DISSIMILAR FSW OF AA6061+SiCp/AA6061-T6

Within the research, AA6061/SiC/20p composite was joined with AA6061-T6 through FSW in butt-weld configuration. The effects of the process on the mechanical and fatigue properties of the dissimilar FSWed joint were investigated in detail. Correspondingly, tensile properties and microhardness profile of the joint have been reported. Axial loading fatigue tests were performed by using the dissimilar welds. Moreover, fracture morphology examination of the welds was also carried out using a SEM.

9.1 Materials and Experimental Procedure

The workpieces used in this work for the FSW experiment were AA6061/SiC/20p-T1 composite and 6061-T6 aluminum alloy. The workpieces were in the form of plates 300 mm long, 130 mm wide, 3.4 mm and 3.2 mm thick for the composite and monolithic alloy, respectively. As well, AA6061+SiCp composite located in the advancing side. The physical properties of as-received composite can be found in Table 6.1 and Table 7.1 within this thesis. The chemical composition of AA6061-T6 is also given in Table 9.1. After the plates were decontaminated by a steel file, FSW process was executed with a tool rotational speed of 1000 rpm and welding speed of 80 mm/min. The tool tilt angle of 1° was utilized for the single-pass welding experiment. Just like in other aforesaid studies, the welding tool was rotated in the clockwise direction during the FSW. An AISI 4140 steel tool with a shoulder of 20 mm diameter was used. The tool has a shoulder with concave bow, diameters of the pin end and pin root are 5 mm and 6 mm, respectively.

Table 9.1 Nominal chemical composition of AA6061-T6 (wt.%)

Material	Mg	Si	Fe	Cu	Cr	Zn	Mn	Ti
AA6061-T6	0.9	0.65	0.54	0.25	0.19	0.05	0.11	0.07

After the accomplished FSW, the samples were removed perpendicular to the weld line by a water-jet for mechanical and fatigue tests. Figure 9.1 illustrates the sampling schematic for the joint characterization. All transverse tensile tests were carried out at room temperature at a constant crosshead speed of 1 mm/min using a Shimadzu AG-X (100 kN) Universal Testing Machine. As well, four samples were tested for the dissimilar joint. Vickers microhardness distribution was also noted across the mid-thickness of the weld. The measurements were performed by EMCOTEST Durascan 20 G5 at a 100 g loading, 10 s dwell time and a span of 0.5 mm. Figure 9.2 presents the photograph of the testing device. Lastly, the stress-controlled fatigue tests of the dissimilar FSWed joint were performed. The prepared samples are seen in Figure 9.3. A sinusoidal waveform was used with an oscillation frequency of 20 Hz and the stress ratio of $R=0.1$ in the cyclic fatigue tests. The fatigue tests were performed at ambient temperature. Herein, it should be mentioned that the tests were discontinued at 2×10^6 cycles. Furthermore, fractographic examination of the ruptured samples was also conducted as part of the study. Table 9.2 depicts the fatigue testing details.

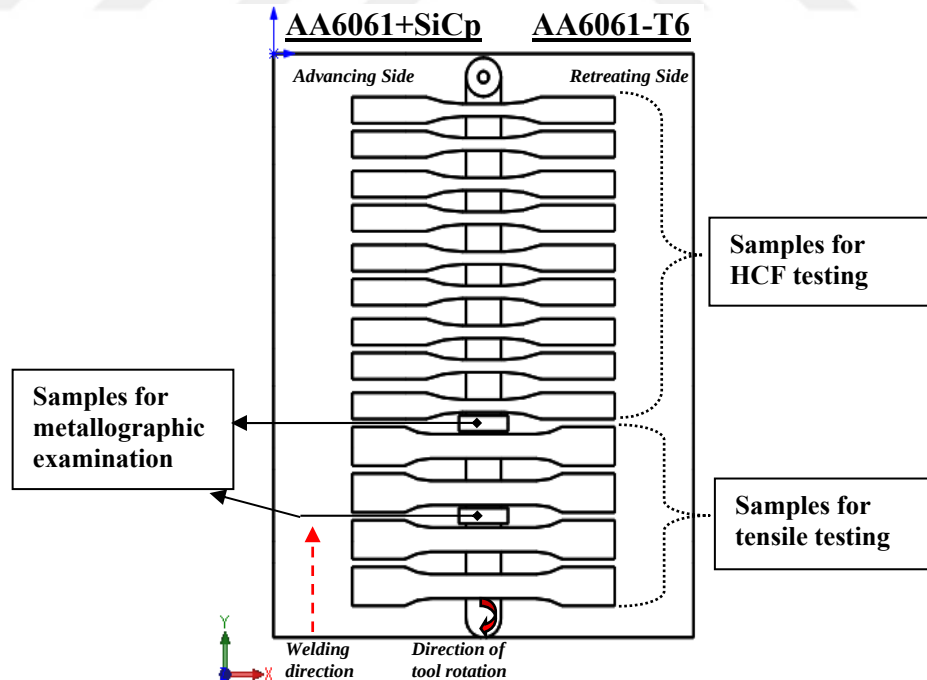


Figure 9.1 Sampling schematic of the joint

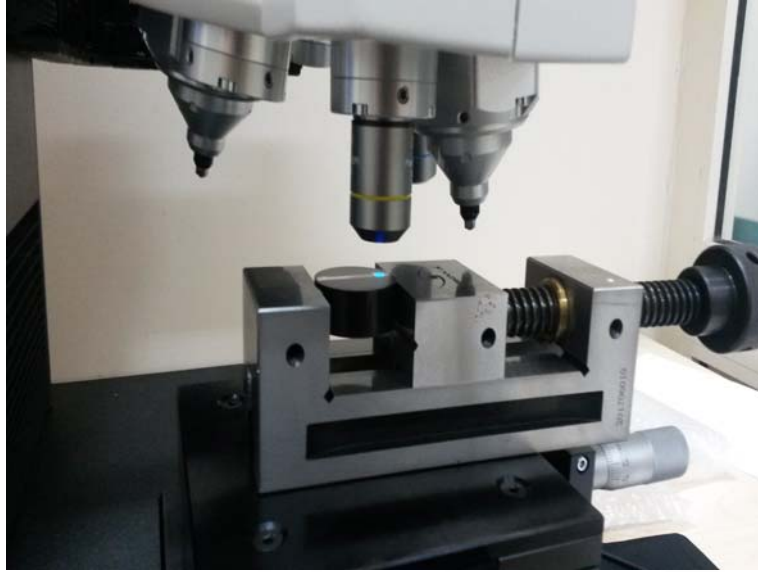


Figure 9.2 Photograph of the apparatus with the sample installed (Personal archive, 2018)

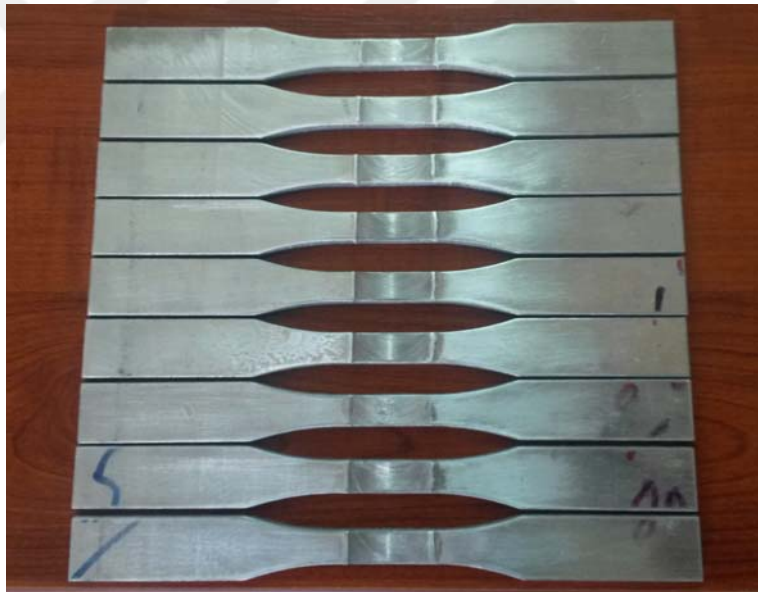


Figure 9.3 Photograph of the fatigue test specimens (Personal archive, 2018)

Table 9.2 Parameters used in fatigue testing

	% of Yield Strength (approx.)	Number of Specimens	Stress Range (MPa)	Max. Stress (MPa)	Min. Stress (MPa)	Mean Stress (MPa)	Alternating Stress (MPa)
Dissimilar FSWed Joint	60	1	64.86	72.06	7.2	39.63	32.43
	70	1	75.67	84.07	8.4	46.24	37.84
	80	1	86.48	96.08	9.6	52.84	43.24
	90	2	97.29	108.09	10.8	59.45	48.65
	100	1	108.10	120.10	12.0	66.05	54.05
	110	1	118.91	132.11	13.2	72.66	59.46
	120	1	129.72	144.12	14.4	79.26	64.86

9.2 Microhardness Profile

Figure 9.4 shows the Vickers microhardness distribution along the mid-thickness of the dissimilar FSWed joint. From the figure, it can be seen that the as-received composite exhibits the microhardness values in the range of 119-125 HV while the hardness of AA6061-T6 is about 65 HV. For the monolithic alloy side, an explicit rise in the hardness values has occurred from BM to SZ. Maximum hardness value in the SZ is also noted as 114 HV. On the other side, hardness values tend to decrease towards the SZ from BM within the composite side. When compared to the other dissimilar joint with as-received composite in the RS (Figure 7.9), a clear increase in the Vickers at the SZ is noticed. Besides that, no sudden hardness drop is observed along the weld zone. The findings indicate that there is a downward tendency in the microhardness values from AS to RS as an overall trend. The minimum hardness values are located within HAZ in the BM at the RS.

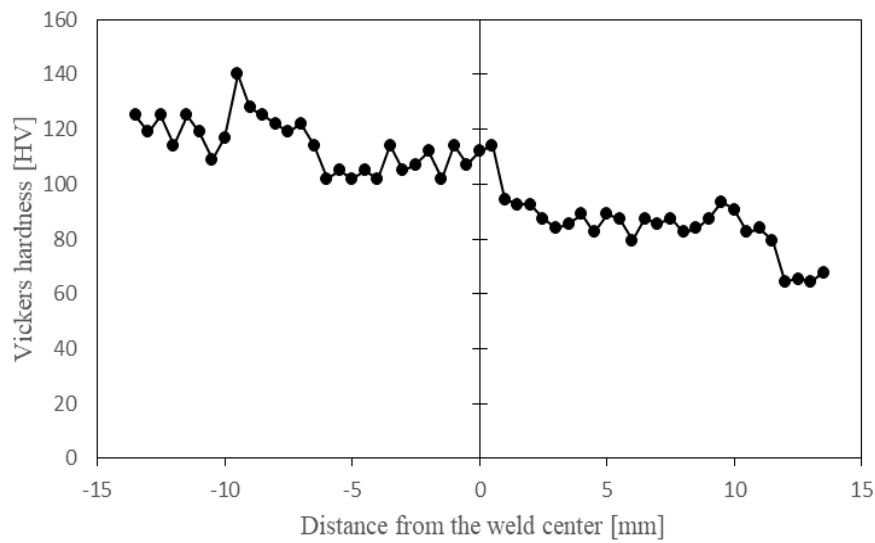


Figure 9.4 Microhardness distribution along the mid-thickness of the dissimilar joint

9.3 Transverse Tensile Properties

As stated previously, the ultimate tensile strength and the failure elongation of as-received composite were in the range of 305-310 MPa and 5.60-5.65%, respectively. Similar tensile properties of the 6061-T6 aluminum alloy were also noted as 333.12 MPa and 5.05%. The typical engineering stress-elongation curves of the dissimilar joint along transverse direction are demonstrated in Figure 9.5. Tensile testing results are also summarized in Table 9.3. According to the findings, the mean tensile strength and elongation (%) of the joint are 214.49 MPa and 2.58%, respectively. When the tensile properties of the weaker material (AA6061/SiC/20p-T1) are taken into account, a joint efficiency of 70% is obtained in terms of the tensile strength. Besides that, all samples except one ruptured on the RS within HAZ in the BM. Figure 9.6 presents the fracture locations of the specimens. It is clear in the figure that a specimen ruptures at the weld zone. At this juncture, it is interesting to see that the fracture surface for this specimen exhibits the indication of about 45° shear fracture.

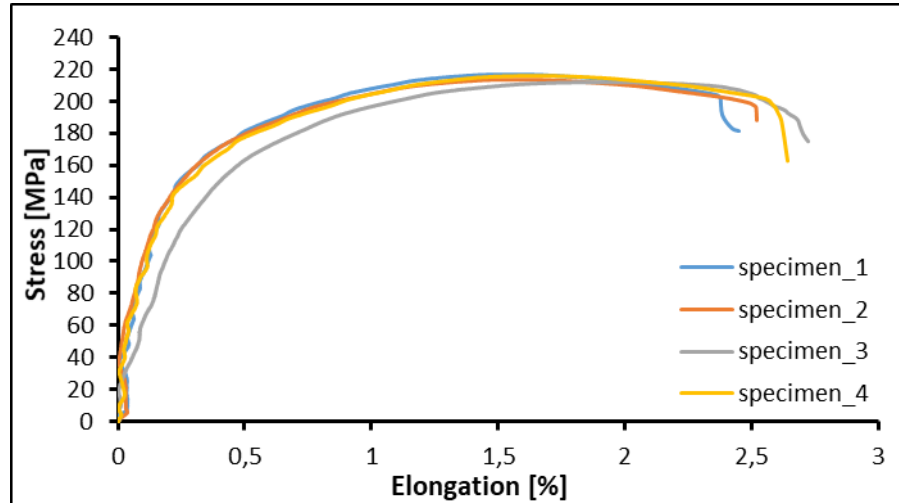


Figure 9.5 Tensile behavior of the FSWed AA6061+SiCp/AA6061-T6 joint

Table 9.3 Tensile test values of the dissimilar welds

	Specimen_1	Specimen_2	Specimen_3	Specimen_4
Tensile Strength [MPa]	216.53	213.69	212.07	215.66
Elongation (%)	2.45	2.52	2.72	2.64

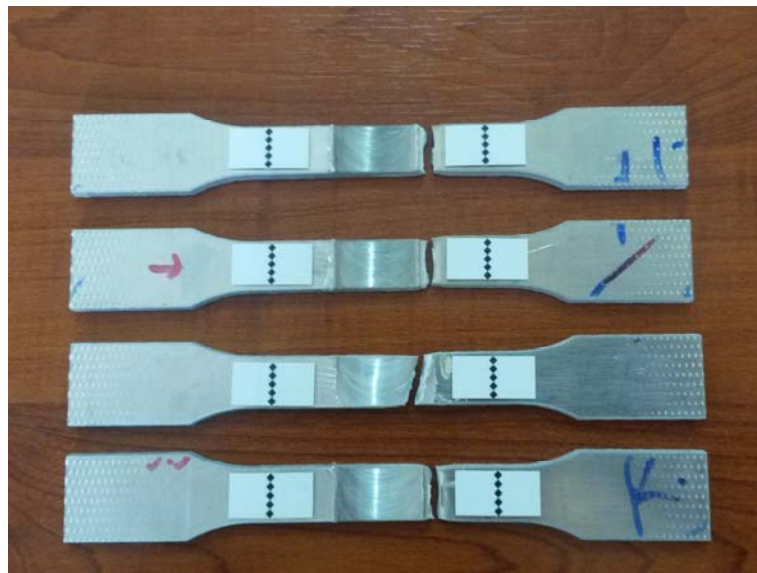


Figure 9.6 Fracture locations of tensile test specimens (Personal archive, 2018)

9.4 Fatigue Response and Fracture Surfaces

S-N curve of the FSWed dissimilar joint is revealed in Figure 9.7. Similarly, black arrows in the figure represent the undamaged specimens that exceeded the designated number of cycles. By the way, fatigue strength of the dissimilar joint at 2×10^6 cycles are utilized for comparison as in other cases. As it is noticeable from the figure, the welds have a fatigue strength of 96.08 MPa. This value coincides with 80% of the YS of the dissimilar joint. Accordingly, the dissimilar weld has a lower fatigue strength than that of the base composite. Fatigue strength of the dissimilar joint corresponds to %79.76 of the fatigue strength of AA6061/SiC/20p composite. In other respects, it should be noted that most of the welds fractured within HAZ at the RS.

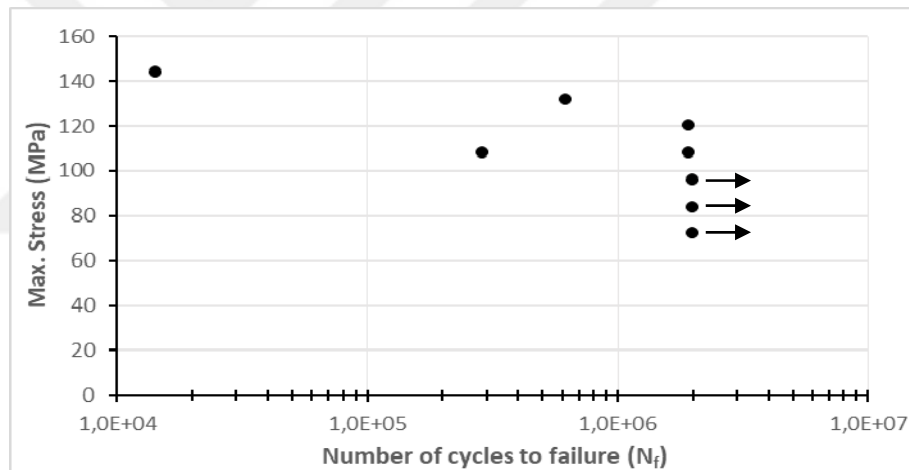


Figure 9.7 Maximum stress vs log fatigue life of the FSWed dissimilar joint

Within the thesis, fracture surfaces of some specimens were also examined through SEM following the final fatigue failure. Figures 9.8-9.10 exhibit the fracture morphologies of three specimens failed at high-cycle fatigue region. The fracture mainly occurred at the AA6061-T6 side subsequent to the fatigue tests. On the other side, only the sample at a max. stress of 144.12 MPa failed within the weld zone (Figure 9.10).

As to the fractographies, a partially flat fracture surface is reported for the sample that is ruptured following the 1933577 fatigue cycles. The fatigue striations are not very visible, but it is thought that the crack initiated from the surface of the specimen and propagated toward the center of the material. As seen from the figure, it is also evident that the final fracture region of the sample is substantially characterized by the microscopic voids with various shapes. Besides that, coalescence and growth of the voids draw the attention for the second fractograph (Figure 9.9). A nonhomogeneous void distribution is also observed in the final failure region. For the specimen failed at the weld zone (Figure 9.10), the fracture surface is covered with a different morphology and comprises a macro pore. As in the foregoing specimens of FSWed MMCs, it is not possible to precisely locate the crack nucleation and crack propagation regions. The fact remains that the micrograph also shows the plastic flow of the aluminum matrix within the final fracture zone. Unlike other samples, it is not possible to observe any shallower microvoids in the surface.

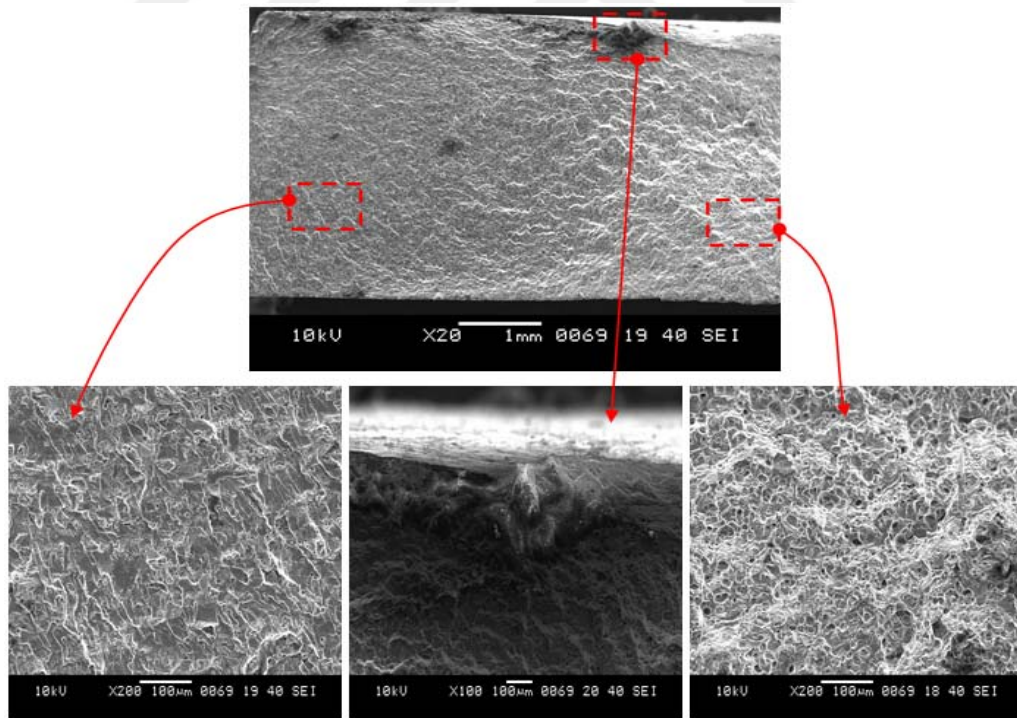


Figure 9.8 SEM images of the ruptured specimen of AA6061+SiCp/AA6061-T6 joint at a max. stress of 120.10 MPa / 1933577 cycles

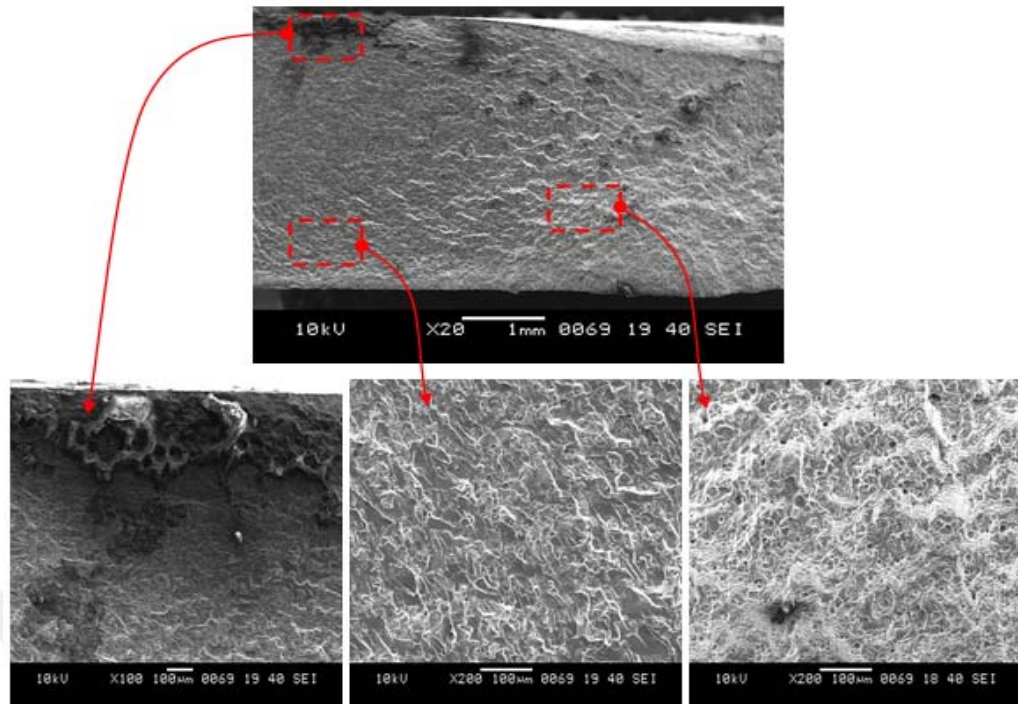


Figure 9.9 SEM images of the ruptured specimen of AA6061+SiCp/AA6061-T6 joint at a max. stress of 132.11 MPa / 621614 cycles

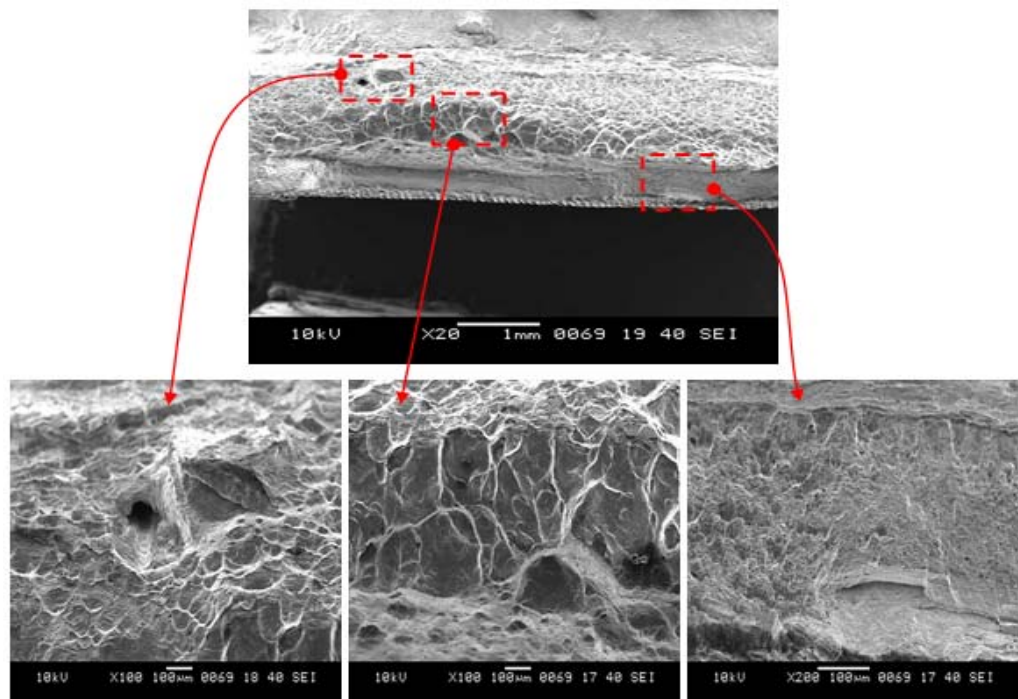


Figure 9.10 SEM images of the ruptured specimen of AA6061+SiCp/AA6061-T6 joint at a max. stress of 144.12 MPa / 14349 cycles

CHAPTER TEN

SUMMARY AND RECOMMENDATIONS

Nowadays, extensive researches have been devoted on FSW due to the outstanding process features of this rapidly emerging solid-state welding technology. However, in spite of the several studies carried out on the application of FSW of MMCs, there are only a few works that deal with their fatigue behaviors, and more particularly with their dissimilar welds. To this end, the research presented in this thesis focuses on the weldability of particulate-reinforced AMCs between each other and also with different materials. Investigation of fatigue responses of the similar and dissimilar joints makes this study significant for further understanding of the effects of FSW process.

In this thesis, dissimilar FSW of AA6061+SiCp/AA6061-O, dissimilar FSW of AA6061-T6/AA6061+SiCp, similar FSW of AA6061/SiC/20p-T1 and dissimilar FSW of AA6061+SiCp/AA6061-T6 are scrutinized and the effects of the process on these dissimilar and similar welds are reported.

10.1 Dissimilar FSWed AA6061+SiCp/AA6061-O Joint

The effects of PWHT on the microstructural evolution, microhardness, tensile and three-point bending properties of the dissimilar FSWed joint are studied and discussed, in detail. The major findings of this research can be summarized as follows:

- FSW produces dynamically recrystallized and finer scale grains in the NZ. However, PWHT has no remarkable effect on these grains. In other respects, PWHT process introduces more precipitate formation within the weld zone.
- Finer SiC particles are observed in the NZ subsequent to FSW. On the other hand, there is no significant difference with regards to the dispersion of SiC particles subsequent to PWHT.

- FSW results in the increase of microhardness values of SZ in both as-welded and PWHTed condition by comparison with that of the monolithic alloy. There is an explicit increase in the Vickers microhardness of the workpieces after PWHT.
- Transverse tensile testing results show that there is a maximum joint efficiency of 103.64% in terms of the tensile strength. However, failure elongation declines through FSW. The process produces a maximum joint efficiency of 32.46% in terms of the failure displacement.
- After PWHT, dissimilar FSWed joints exhibit a maximum tensile strength and failure elongation of 183.30 MPa and 4.37%, respectively. These findings clearly demonstrate an increase of 52.22% in the strength. However, PWHT results in the decline of ductility of the dissimilar joint.
- All tensile test specimens in as-welded condition fractures away from the weld regions at the RS. Failure takes place in the HAZ of welds at the RS for the samples in PWHTed condition.
- Findings from the three-point bending tests indicate that the bending angle increases subsequent to PWHT. In other words, the applied heat-treatment process provides a higher bending resistance. In addition, PWHT also produces a substantial increase in bending extension and bending modulus.
- The overall results from this research demonstrate the importance and positive influence of PWHT on several mechanical properties of the welds after FSW of the workpieces in annealed (O-treated) condition. In the case of welding of materials in O-temper condition, it should not be forgotten that the FSW process of age-hardenable aluminum alloys generally does not result in the decline of strength in the weld zone.

10.2 Dissimilar FSWed AA6061-T6/AA6061+SiCp Joint

A comprehensive study on the microstructural evolution, hardness behavior, tensile properties, impact toughness and failure response under transverse impact of the dissimilar AA6061-T6/AA6061+SiCp joint is conducted. The major findings of this research can be summarized as follows:

- FSW produces dynamically recrystallized and fine grain structure of AA6061-T6 in the NZ. Besides, it is clear that there are concentrated SiC particles within the NZ.
- Microhardness measurements show the minimum Vickers hardness values that are reported beside the HAZ in the base material of AA6061-T6. In other respects, the hardness profile indicates a slight enhancement in the hardness values within the NZ by comparison with that of the monolithic alloy.
- Transverse tensile testing results show that there are joint efficiencies of 67.61% and 83.57% in the tensile strength and percentage of elongation, respectively. In addition, all tensile test specimens fracture on the monolithic alloy side of the weld.
- FSW results in a remarkable energy absorption property in the dissimilar AA6061-T6/AA6061+SiCp joint. The process provides a significant enhancement of 318.4% in the impact energy at room temperature compared to that of the base composite.
- Fracture surfaces of both base materials and the dissimilar joint coincide well with the energy absorption characteristics of the Charpy test specimens. No weld defect formation is reported in the fracture surface of the dissimilar joint after the Charpy impact tests. The fracture surface can clearly be characterized by the indications of both ductile and brittle fracture modes.

- As a result of the drop weight low-velocity impact tests, neither perforation nor crack initiation is reported. Considering the general impact response of the weld nuggets, maximum contact force increases as the energy level is promoted from 2.5 J to 7.5 J. On the other hand, a slight decrease is reported in the tensile strength of the welds through the increment on the transverse impact energy level from 2.5 J to 7.5 J.

10.3 Similar FSWed AA6061/SiC/20p-T1 Joints

This research primarily aims to investigate the fatigue behaviors of the FSWed AA6061/SiC/20p-T1 joints at varying tool rotation speeds. The fractographic study is also performed. Besides, the effects of various tool rotation speeds on the mechanical properties such as the transverse tensile properties and the microhardness profiles are also determined. The major findings of this research can be summarized as follows:

- None of the conventional weld defects is observed after FSW at the given welding parameters. The most appropriate homogeneous distribution of SiC is reported in the SZ belonging to welds at a tool rotational speed of 1250 rpm, welding speed of 100 mm/min and tilt angle of 2°.
- The increment of tool rotation speed from 1000 rpm to 1600 rpm produces a decrease in the transverse tensile strength of the similar AA6061/SiC/20p-T1 joints. A maximum joint efficiency of 97.29% in the tensile strength is obtained for the welds at a tool rotational speed of 1000 rpm, welding speed of 100 mm/min and tilt angle of 2°. Failure elongation of the joints also decreases with the increment of tool rotation speed from 1000 rpm to 1600 rpm.
- The Vickers hardness of stir zones is measured approximately similar to that of the base material for all FSWed joints. In other words, FSW results in almost homogeneous hardness profiles throughout the joint area. The decrease of the

mean Vickers in the SZ at higher tool rotation speeds as 1250 rpm and 1600 rpm also attracts the attention.

- The maximum fatigue strength of 113.22 MPa that demonstrates a joint efficiency of 93.29% is achieved with FSW at a tool rotational speed of 1250 rpm. On the other hand, the welds at 1600 rpm are found to be more sensitive to cyclic loading than other welds.
- Fracture surface morphology of the FSWed joints in the HCF and LCF regions are significantly different from each other. Interfacial crack and mixed failure modes are reported for the specimens of the joint at 1250 rpm in the HCF and LCF region, respectively. However, the welds at 1600 rpm are characterized by the macro voids, pores and inclusions, which show a tight agreement with the findings of stress-controlled fatigue tests.

10.4 Dissimilar FSWed AA6061+SiCp/AA6061-T6 Joint

In this work, fatigue behavior, fracture surfaces and mechanical properties in terms of microhardness and transverse tensile properties of the dissimilar friction stir butt-welded AA6061+SiCp/AA6061-T6 joint are investigated, experimentally. The major findings of this research can be summarized as follows:

- Minimum hardness values are observed within the HAZ in the BM at the monolithic alloy side. There is an explicit increase in the Vickers at the SZ when compared to the other dissimilar joint with as-received composite in the RS.
- FSW results in a maximum joint efficiency of 70% in terms of the tensile strength. All tensile test specimens except one fractures on the RS within HAZ in the BM. Failure elongation of the joint also decreases following the FSW process. When compared to the other dissimilar joint with AA6061+SiCp in the RS at the same welding parameters, it has been reported

that using the as-received composite at AS slightly enhances the joint efficiency in terms of the transverse tensile strength.

- The process produces a fatigue strength of 96.08 MPa that exhibits a joint efficiency of %79.76. The fact remains that most of the dissimilar joints fractures within HAZ at the RS as with the tensile tests.
- A partially flat fracture surface is observed in the HCF region for the specimen that is fractured following the 1933577 fatigue cycles while the same sample seems to have no visible fatigue striations. In the sample with lower fatigue life, final failure region is characterized by nonhomogeneous void distribution. Another noteworthy point is the macro pore on the fracture surface of the sample with the lowest fatigue life.
- This study leads researchers to a better understanding of dissimilar FSW and is the first by reason of it investigates the fatigue behavior of dissimilar joint between the AMC and monolithic alloy.

10.5 Future Research and Recommendations

In the present study, similar and dissimilar welds are successfully obtained. Thereafter, microstructure, mechanical and fatigue properties of these joints are reported through various scientific experiments. The findings of this thesis demonstrate the weldability of AMCs with each other and with different materials, authentically. However, further investigation in the near future is required. Suggestions for future researches can be summarized as follows:

- Different tool geometry, material and weld configurations can be investigated. To prevent tool wear and to obtain smoother weld appearance, pcBN tools can be introduced.

- Further focus should be on dissimilar FSWed joints between MMCs with different particle volume fractions.
- For a better microstructural evolution, various cooling strategies can be performed during FSW process.
- Downward force measurements are recommended through a load cell during welding operations.
- Non-destructive examination of welds is recommended following the FSW in an effort to detect faults.
- Micrographs should be taken with Electron Backscatter Diffraction Analysis (EBSD) to characterize the grain structure, size and their distribution in the joint.
- It is recommended that temperature distribution should be measured through thermocouples mounted in the tool or workpieces in addition to the noncontact infrared thermometer.
- Further researches should include finite element (FE) model of the process between similar and dissimilar MMCs.
- Future research can be extended to friction stir spot welding (FSSW) of Al-alloys and MMCs in lap joining configuration.

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