[UCI]I804:24011-200000240090

August 2010

Master's Thesis

A Study on the Weldability of Dissimilar Butt joint (Al6061 / SS400) by TIG Assisted Friction Stir Welding

Graduate School of Chosun University

Department of Naval Architecture and Ocean Engineering

Jung-Mi Kim

A Study on the Weldability of Dissimilar Butt joint (Al6061 / SS400) by TIG Assisted Friction Stir Welding

TIG-FSW Hybrid 용접기술을 이용한 이종재료
Al6061 Alloy - SS400 용접부의 용접성에 관한 연구

August 2010

Graduate School of Chosun University

Department of Naval Architecture and Ocean Engineering

Jung-Mi Kim

A Study on the Weldability of Dissimilar Butt joint (Al6061 / SS400) by TIG Assisted Friction Stir Welding

Advisor : Professor Hee-Seon Bang

A Thesis submitted for the degree of
Master of Engineering

April 2010

Graduate School of Chosun University

Department of Naval Architecture and Ocean Engineering

Jung-Mi Kim

金正美의 碩士學位論文을 認准함

委員長 朝鮮大學校 敎授　房　漢　瑞　印

委　員 朝鮮大學校 敎授　尹　德　榮　印

委　員 朝鮮大學校 敎授　房　熙　善　印

2010年 5月

朝鮮大學校 大學院

CONTENTS

List of Tables

List of Figures

ABSTRACT

TIG-FSW Hybrid 용접기술을 이용한 이종재료 Al6061 Alloy - SS400 용접부의 용접성에 관한 연구

Kim, Jung-Mi
Advisor : Prof. Bang, Hee-Seon, Ph.D.
Department of Naval Architecture and Ocean Engineering,
Graduate School of Chosun University

차량, 항공기, 선박 같은 수송기기 산업에서는 환경문제와 함께 국제유가 상승으로 인한 경량화에 대한 요구가 부각 되면서 알루미늄 합금 같은 비철 금속의 경량소재 사용이 시도 되고 있다. 경량합금 중에서도 알루미늄 합금은 경량으로 비강도가 우수하며 여러 분야에서 폭넓게 사용되고 있으나, 알루미늄 합금을 용융 용접하여 구조물을 제작하는 경우, 용접 열에 의한 변형 및 기공, 균열 등의 결함이 발생하기 쉬우며 접합부의 강도저하가 비교적 쉽게 발생하여 이에 대한 대책이 요구되고 있다. 또한 대부분 구조재료를 실제품에 적용할 경우, 두 가지 이상의 재료가 사용되기 때문에 이 재료들 간의 접합이 필수적이라 할 수 있는데, 물리적 특성 차이가 상이한 재료의 접합일 경우 용융 용접법으로는 접합이 매우 어렵거나 불가능한 실정이므로 이에 대한 대책이 요구되어 지고 있다.

마찰교반접합(Friction Stir Welding : FSW)은 신개념의 용접법으로 1991년 영국 TWI(The Welding Institute)에서 처음으로 개발된 고상접합법의 하나로 용접에 의한 변형이 적고 비소모성 접합방법일 뿐만 아니라 용접결함, 흄, 소음 및 유해광선의 발생이 없이 고품질의 접합부를 얻을 수 있는 방법으로 각광 받고 있다.

따라서, 본 연구에서는 물리적 특성 차이가 상이한 이종재료의 접합 시 문제를 해결할 수 있는 새로운 기술로 FSW의 기술적 특징을 이용하였으며, TIG의 열원을 이용하여 소성유동을 높여 건전한 접합부의 구현 및 접합부의 신

뢰성을 높이 고자 하였다.

실험방법은 3mm 두께의 이종재료 Al6061-T6와 SS400 판재를 툴의 회전속도 및 이송속도를 변수로 하여 접합을 실시하였으며, TIG와 FSW의 접합인자 즉, TIG 출력, 회전속도, 이송속도, TIG 조사 위치, TIG torch 각도 등을 고려하여 접합부의 특성을 고찰하였다. 용접 실험 후 각 조건별 특징을 알아보기 위하여 접합부의 기계적 특성평가 및 미세조직 분석을 실시하였다.

Chapter 1

INTRODUCTION

1.1 Backgroung & Purpose

Considering the environmental pollution and the resource exhaustion, it is very important factor to improve the fuel efficiency in the transportation industries such as automobile, vessel, railway carriage and aircraft. Therefore, materials manufacturers are developing the lighter materials with a higher mechanical property by various methods such as alloy design, processing and heat treatment.

The nonferrous materials having a relatively low density and high mechanical property have been gradually applied in the limited part of automobile, vessel, railway carriage and aircraft. Those of metallic materials with higher mechanical properties and lower density are nonferrous materials.

Practical structures are becoming more complicated every year, so it is difficult to manufacture them from only one material to satisfy the environmental and service requirements. Such structures should be manufactured from a combination of materials. Dissimilar material combinations are very important in engineering design where a transition in physical and mechanical properties in necessary. It is necessary, therefore, to establish a bonding technique that could easily join dissimilar materials.

Generally, fusion welding process can not be applied to the welding of dissimilar materials because there are serious metallurgical problems in the fused zone of dissimilar materials combination, such as the formation of brittle intermetallic compounds. Although the formation of certain amount of intermetallic reaction product is necessary to obtain better joint strength, an excess of the intermetallic ruduces the joint strength to below practically usable value. For this reason, attempts have been made to join dissimilar materials by solid-state diffusion bonding and friction welding. As a result, intermetallic compounds are also formed and grow at the interface during the process. Friction Stir Welding has represented a reasonable joint strength due to minimizing of the formation of intermetallic compound, while this technique is only applicable in rotating part.

Thus, this research found that aluminum, which has high strength to weight and Structural steel (SS400), can be joined by FSW and TIG Welding. After above Hybrid Welding, we will search the characteristics of joining by measuring the microstructure and mechanical strength at interface. Consequently, the purpose of the research is to investigate the possibility of application of FSW and TIG Welding in the field of vessels, automobile, aircraft and the parts of transportation machinery.

Chapter 2

THEORETICAL BACKGROUND

2.1 Principles and characteristics of FSW

2.1.1 Principles of FSW

Friction Stir Welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint (Fig.2-1). The tool serves two primary functions : (1) heating of workpiece, and (2) movement of material to workpiece and plastic deformation of workpiece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. As a result of this process a joint is produced in "solid state".

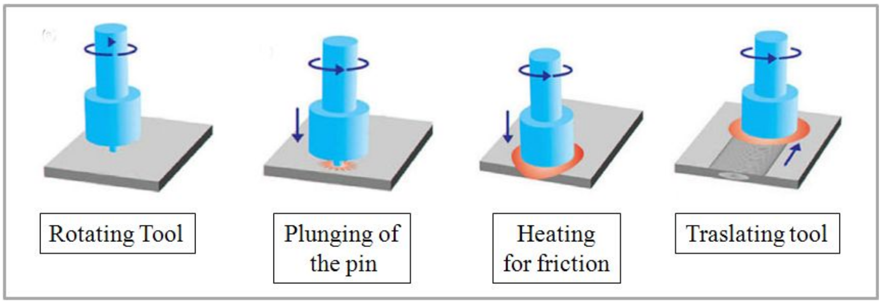


Fig. 2.1 Schematic of Friction Stir Welding

Fig.2-2 shows the general classification of FSW zone with microstrucutral characteristics and FSW zone can be devided by four zones.

A: BM (Base Metal)

B: HAZ (Heat Affected Zone : affected by heat generated during FSW)

C: TMAZ (Thermo mechanically Affected Zone; contains material that interacts indirectly with the tool, plastically deformed withpartial recrystallization)

D: SZ (Stir Zone or Weld Nugget: contains material that interacts directly with the tool, dynamically recrystallized)

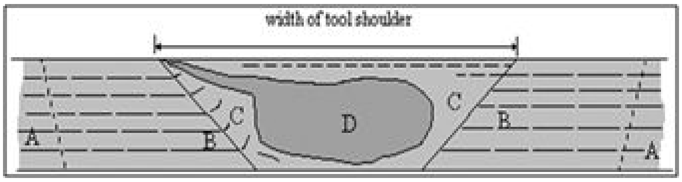


Fig. 2.2 Schematic of general FSW zone and each nomenclature

2.1.2 Process Definitions of FSW

1) Advancing side : The tool advancing side is the side of the tool where the local direction of the tool surface due to tool of rotation and the direction of traverse are in the same direction.
2) Backing plate : The backing plate, this is the fixture that the weld rests on. The weld is formed between the backing plate and the tool.
3) Plunge depth : The plunge depth is the maximum depth that the pin penetrates into the material. As the tool is tilted at an angle this is usually in the trailing edge of the tool.
4) Retreating side : The tool retreating side is the side of the tool where the local direction of the tool surface due to tool of rotation and the direction of traverse are in the opposite direction.

5) Rotation speed : The tool rotation speed is the rate of angular rotations per minute (rpm) of the tool around its axis.
6) Tool pin : part of the welding tool which rotates; it is normally shaped as a truncated cone. The pin extends from the shoulder and enters the joint line.
7) Tool shoulder : Part of the welding tool, which rotates and is normally disk shaped. The shoulder forms the weld cap.
8) Traveler speed : The welding speed is the speed(mm/s) of the tool traverse through the weld joint-line.

2.1.3 Characteristics of FSW

1) Advantages of Friction stir welding
  - Good mechanical properties in the as welded condition Improved safety due to the absence of toxic fumes or the spatter of molten material.
  - No consumables - conventional steel tools[clarification needed can weld over 1000m of aluminium and no filler or gas shield is required for aluminium.
  - Easily automated on simple milling machines - lower setup coSS400 and less training.
  - Can operate in all positions (horizontal, vertical, etc), as there is no weld pool.
  - Generally good weld appearance and minimal thickness under/over-matching, thus reducing the need for expensive machining after welding.
  - Low environmental impact.

2) Disadvantages of Friction stir welding
  - Exit hole left when tool is withdrawn.
  - Large down forces required with heavy-duty clamping necessary to

hold the plates together.

- Less flexible than manual and arc processes (difficulties with thickness variations and non-linear welds).
- Often slower traverse rate than some fusion welding techniques although this may be offset if fewer welding passes are required.

2.2 Principles and characteristics of GTAW

2.2.1 Principles of GTAW

Gas Tungsten Arc Welding (GTAW) is frequently referred to as TIG welding. TIG welding is a commonly used high quality welding process (Fig. 2.3). TIG welding has become a popular choice of welding processes when high quality, precision welding is required. In TIG welding an arc is formed between a nonconsumable tungsten electrode and the metal being welded. Gas is fed through the torch to shield the electrode and molten weld pool. If filler wire is used, it is added to the weld pool separately. In the TIG process the arc is formed between a pointed tungsten electrode and the workpiece in an inert atmosphere of argon or helium. The small intense arc provided by the pointed electrode is ideal for high quality and precision welding. Because the electrode is not consumed during welding, the welder does not have to balance the heat input from the arc as the metal is deposited from the melting electrode. When filler metal is required, it must be added separately to the weldpool.

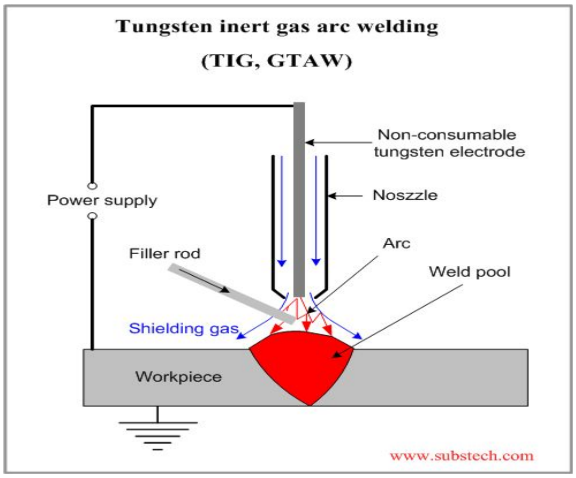


Fig. 2.3 Schematic of GTAWelding

2.2.2 Characteristics of GTAW

1) Advantages of TIG Welding

- Precise control of welding variables (heat).
- Welds can be made with or without filler metal.
- Weld composition is close to that of the parent metal.
- High quality weld structure.
- Slag removal is not required (no slag).
- Thermal distortions of work pieces are minimal due to concentration of heat in small zone.

2) Disadvantages of TIG Welding

- Excessive electrode consumption.
- Arc wandering.
- Oxidized weld deposit.
- Difficult arc starting.
- Low welding rate.
- Relatively expensive.
- Requres high level of operators skill.

3) Shielding Gases

- Argon.
- Argon/Helium.
- Oxidized weld deposit.

2.3 Type and characteristics of aluminum alloy

2.3.1 Type of aluminum alloys

Aluminium alloys are alloys in which aluminium is the predominant metal. Typical alloying elements are copper, zinc, manganese, silicon, and magnesium. There are two principal classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable(Fig. 2.4).

Cast aluminium alloys yield cost effective products of low melting point, although they generally have lower tensile strengths than wrought alloys. The most important cast aluminium alloy system is Al-Si, where the high levels of silicon (4-13%) contribute effective good casting characteristics.

Wrought alloys are divided into two classes-nonheat treatable and heat treatable. In the nonheat-treatable class, strain hardening (cold-working) is the only means of increasing the tensile strength. Heat-treatable alloys may be hardened by heat treatment, by cold-working, or by the application of both processes.

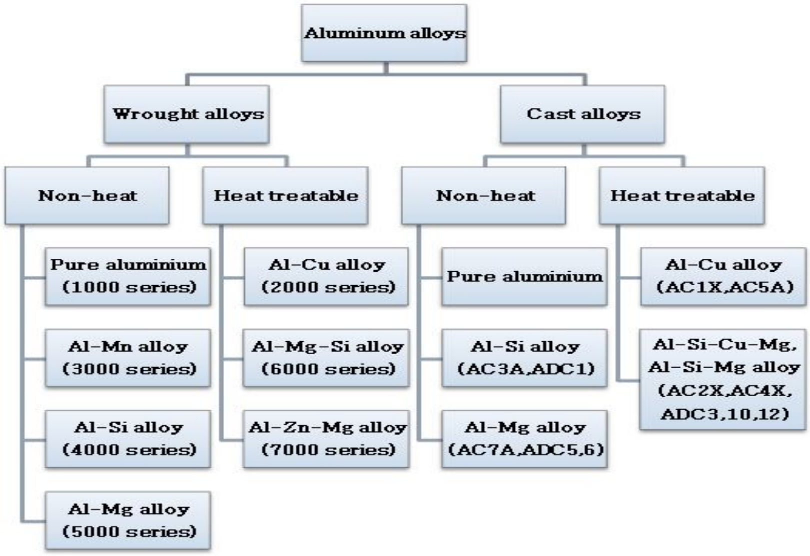


Fig. 2.4 Division of Aluminum

Table 2.1 Typical properties for aluminium

Property	Value
Atomic Number	13
Atomic Weight (g/mol)	26.98
Valency	3
Crystal Structure	Face centred cubic
Melting Point (°C)	660.2
Boiling Point (°C)	2480
Mean Specific Heat (0-100°C) (cal/g.°C)	0.219
Thermal Conductivity (0-100°C) (cal/cms. °C)	0.57
Co-Efficient of Linear Expansion (0-100°C) ($x10^{-6}$/°C)	23.5
Electrical Resistivity at 20°C (μΩcm)	2.69
Density (g/cm^3)	2.6898
Modulus of Elasticity (GPa)	68.3
Poisson's Ratio	0.34

2.3.2 Characteristics of aluminum alloy 6061

Al 6061 is a precipitation hardening aluminum alloy, containing magnesium and silicon as its major alloying elements. It has good mechanical properties and exhibits good weldability. It is one of the most common alloys of aluminum for general purpose use.
It is commonly available in pre-tempered grades such as, 6061-O (solutionized), 6061-T6 (solutionized and artificially aged), 6061-T651 (solutionized, stress-relieved stretched and artificially aged).

1) Mechanical properties

The mechanical properties of 6061 depend greatly on the temper, or heat treatment, of the material.

6061-O : Annealed 6061 (6061-O temper) has maximum tensile strength no more than 18,000 psi (125 MPa), and maximum yield strength no more than 8,000 psi (55 MPa). The material has elongation (stretch before ultimate failure) of 25-30 %.

6061-T4 : T4 temper 6061 has an ultimate tensile strength of at least 30,000 psi (207 MPa) and yield strength of at least 16,000 psi (110 MPa). It has elongation of 16%.

6061-T6 : T6 temper 6061 has an ultimate tensile strength of at least 42,000 psi (290 MPa) and yield strength of at least 35,000 psi (241 MPa). In thicknesses of 0.250 inch (6.35 mm) or less, it has elongation of 8% or more; in thicker sections, it has elongation of 10%. T651 temper has similar mechanical properties.

2) Application

- 6061 is widely used for construction of aircraft structures, such as wings and fuselages, more commonly in homebuild aircraft than commercial or military aircraft.
- 6061 is used for yacht construction, including small utility boats.
- 6061 is commonly used in the construction of bicycle frames and components.
- 6061 is also used in automotive parts, such as wheel spacers.
- 6061 is also used in the manufacture of aluminum cans for the packaging of foodstuffs and beverages.

2.4 Type and characteristics of Carbon Steel

2.4.1 Types of Carbon steel

Carbon steel is a metal alloy, a combination of two elements, iron and carbon, where other elements are present in quantities too small to affect the properties. The only other alloying elements allowed in plain-carbon steel are: manganese (1.65% max), silicon (0.60% max), and copper (0.60% max). Steel with a low carbon content has the same properties as iron, soft but easily formed. As carbon content rises the metal becomes harder and stronger but less ductile and more difficult to weld. Higher carbon content lowers steel's melting point and its temperature resistance in general.

Typical compositions of carbon are:

Mild (low carbon) steel: approximately 0.05% to 0.26% carbon content with up to 0.4% manganese content. Less strong but cheap and easy to shape; surface hardness can be increased through carburizing.

Medium carbon steel: approximately 0.29% to 0.54% carbon content with

0.60 to 1.65% manganese content. Balances ductility and strength and has good wear resistance; used for large parts, forging and automotive components.

High carbon steel: approximiately 0.55% to 0.95% carbon content with 0.30 to 0.90% manganese content. Very strong, used for springs and high-strength wires.

Very high carbon steel: approximately 0.96% to 2.1% carbon content, specially processed to produce specific atomic and molecular microstructures.

2.4.2 Characteristics of Structural Steel

SS400 is very cheap, excelling in weldability, and they can be subjected to various heat treatments. Since many machine tools are designed to cut mild steel material, it is very rare to encounter problems while machining.

1) Characteristics of SS400

- Guaranteed mechanical properties (strength, elongation, impact tenacity, etc.)
- Guaranteed process performance.
- Fine welding property.
- Fit for simply machined welded or riveted structures.

2) Application of SS400

- Building structure, bridge, ships, railway vehicles, pipeline machines and other structure units

Chapter 3

EXPERIMENT METHOD OF TIG-FSW PROCESS

3.1 Experimental work for TIG-FSW

3.1.1 TIG-FSW equipment and experimental setup

WINXEN FSW system together with DAIHEN Inverter ELECON 500P TIG welding machine is used in this welding experiment. FSW Tool system combined with TIG torch was arranged in order to conduct the welding experiment in X, Y and Z directions. Heat treated STD 11 plate was replaced with mild steel backing plate in order to prevent the backing plate wear.

Fig. 3.1 shows the FSW and TIG equipment.

ITEMS		RANGE
TYPE		GANTRY TYPE
Welding Speed	X-axis	0.5~10 mm/sec
	Y-axis	0.5~10 mm/sec
	Z-axis	0.5~10 mm/sec
	R-axis	1~20 RPM
Rotation		300~3000 RPM
LOAD Capacity		Max. 3000Kgf

ITEMS	RANGE
Rated Output Curent	AEP-500
Input Voltage Range	200V
Rated Input Voltage	AC20~500A /DC5~500A
Welding torch	AW-12

Fig. 3.1 FSW and TIG Welding equipment details

TIG welding torch to preheat the SS400 material was attached adjacent to the FSW tool shoulder, inclined at 60 degrees. The electrode tip of TIG is placed at a distance of about 20mm from the FSW tool shoulder. When the TIG torch is placed near to the tool shoulder, ie, less than

20mm, the current affects the tool surface and thus the desired preheating is not achieved.

Fig. 3.2 shows the experimental setup for FSW and TIG assisted FSW.

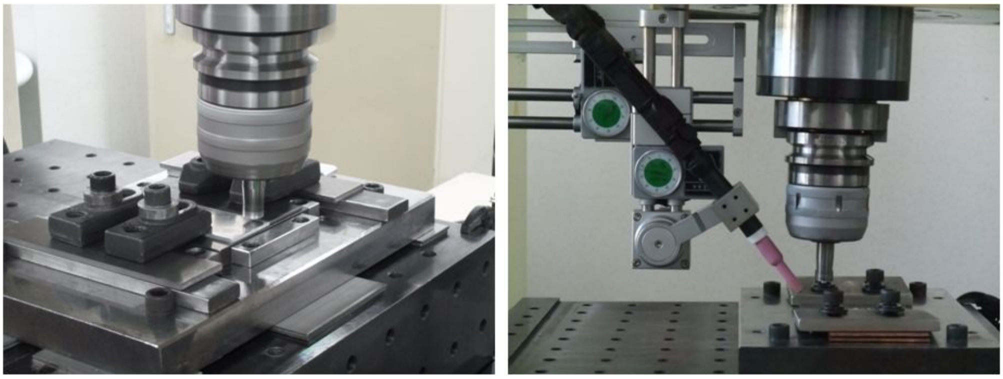


Fig. 3.2 Setup for FSW and TIG assisted FSW process

3.1.2 Details of objective materials

The chemical compositions and mechanical properties of the materials used in the experiment are given at Table 3.1.

Specimens of size 200mm(L) × 100mm(W) × 3mm(T) were made and the edge preparation at the contact side of the specimens is done by milling process. The welding surface was wiped with Methyl Alcohol to remove the grease before welding process. Fig 3.3 were shown a plot plan of specimen. Fig. 3.3 shows the configuration of the weld specimen.

Table 3.1 Chemical composition and mechanical property

Material	Chemical composition (wt%)								
Al 6061 -T6	Al	Fe	Si	Cr	Mg	Ti	Cu	Mn	Zn
	98	0.7	0.4-0.8	0.04-0.35	0.1	0.03	0.15-0.4	0.15	0.25
	Mechanical properties								
	Yield stress (MPa)	Elongation (%)	Tensile stress (MPa)	Heat conduction coff.	Density (g/cc)	Melting Point			
	300	12	330	0.4	2.7	650			
Material	Chemical composition (wt%)								
SS400	C	Si	Mn	P	S	Ni	Cr	Mo	기타
	0.16	0.32	1.63	0.008	0.013	0.03	0.04	-	-
	Mechanical properties								
	Yield stress (MPa)	Elongation (%)	Tensile stress (MPa)	Heat conduction coff.	Density (g/cc)	Melting Point			
	330	37	450	0.012	7.85	1473			

	L	B	t
Al6061-T6	200	100	3
SS400	200	100	3

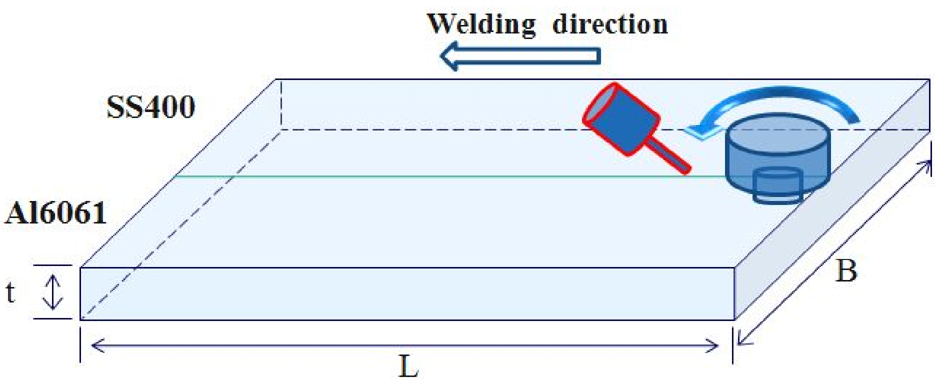


Fig. 3.3 Configuration of weld specimen

3.2 Description of tool material

The tool material is made of 12% Co tungsten carbide (WF20) to prevent the tool wear due to frictional contact with SS400 plate while conducting FSW process.

Table 3.2 shows the detail of tungsten carbide rod specifications.

Tool pin shape is of smooth frustum type and shoulder is designed to obtain the proper mixing at the stir zone with good plastic flow of the material. The shoulder is made concave with 3° clearance to act as an escape volume for the material displaced by the probe during the plunge action. The dimensions of shoulder and probe to cause substantial improvements in productivity and quality is shown in Fig 3.4.

Table 3.2 Tungsten carbide specifications

Co(±0.5%)	Grade	WC(±0.5%)	Grain Size(μm)	Density (g/cc)	Hardness (HV30)
12%	WF20	88%	0.6	14.15	1670

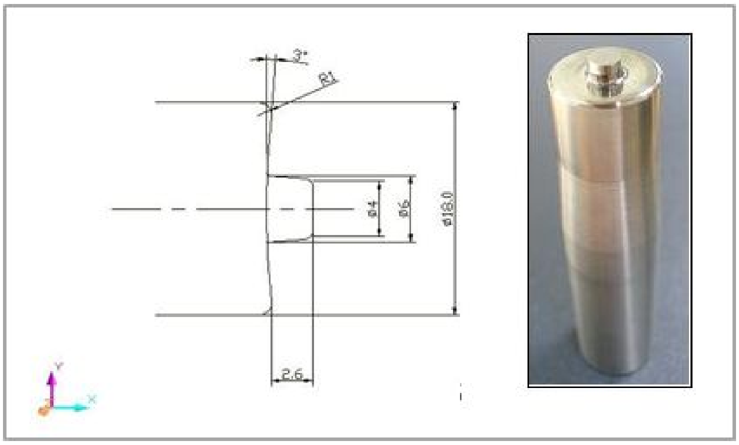


Fig. 3.4 Tool dimensions and shape

3.3 TIG assisted Friction stir welding condition

To ensure a successful and efficient welding cycle of dissimilar welding by TIG assisted FSW, the important parameters to be considered are tool rotating speed, tool travel speed, tool rotating direction and tool plunge position. The parameters to be considered for TIG heat source to obtain the desired preheating are current, shielding gas torch angle and FSW tool - TIG torch spacing.

The TIG preheating conditions was obtained by conducting BOP SS400 on SS400 plate and is given in Table 3.3.

From the previous researches on FSW of dissimilar materials, it is relevant that it is impossible to join dissimilar plates with tool position at the welding center line. This is due to the difference in hardness and mechanical properties of the materials.

Moreover, when tool was placed at the centre weld line, more heat is generated with high frictional force on SS400 side producing tool wear. Therefore, the plunge position was kept such that the probe outer face is at a distance 1-1.5mm away from the weld centre line to SS400 side and remaining part of the tool plunges at Al6061-T6 side.

The actual welding process was carried out with tool rotating direction counter clock wise (ccw) placing SS400 in the advancing side and Al6061-T6 in the retreating side. The TIG electrode was placed at 2mm away from weld center line to SS400 side and 20mm from the shoulder face. Fig. 3.5 shows the Schematic of TIG assisted FSWelding process. Welding condition for TIG assisted FSWelding process is given in Table 3.4. Fig. 3.6 shows the position of materials, TIG electrode and plunging of tool for TIG-FSW.

Table 3.3 TIG Welding condition

No.	Welding Speed(mm/s)	TIG Current(A)	TIG pulsed Current(A)	Shield Gas (Ar-ℓ/min)	Wire	Torch Angle (°)	Surface bead appearance	Cross section (Macro)
1	1.0	60	50	7	Φ2.4mm,red	60		
2	1.0	70	60	7	Φ2.4mm,red	60		
3	1.0	80	70	7	Φ2.4mm,red	60		
4	1.0	85	75	7	Φ2.4mm,red	60		
5	1.0	90	80	7	Φ2.4mm,red	60		
6	1.0	100	90	7	Φ2.4mm,red	60		

Table 3.4 TIG-FSWelding condition

Welding condition		Values
TIG	Current(A)	80~70
	Shielding gas(L/min)	Ar 7
	CTWD(mm)	s = 2
	Torch angle	60°
FSW	Rotation speed(RPM)	300~500
	Welding speed(mm/s)	0.8~2.0
	Shoulder dia.(mm)	Ø18
	Pin dia.(mm)	Ø6.0
	Room temperature	20°
	Tilt angle	2 ~ 3°
TIG-FSW Distance = 20mm		
Leading condition = TIG leading		
Dia. of electrode = 2.4mm		

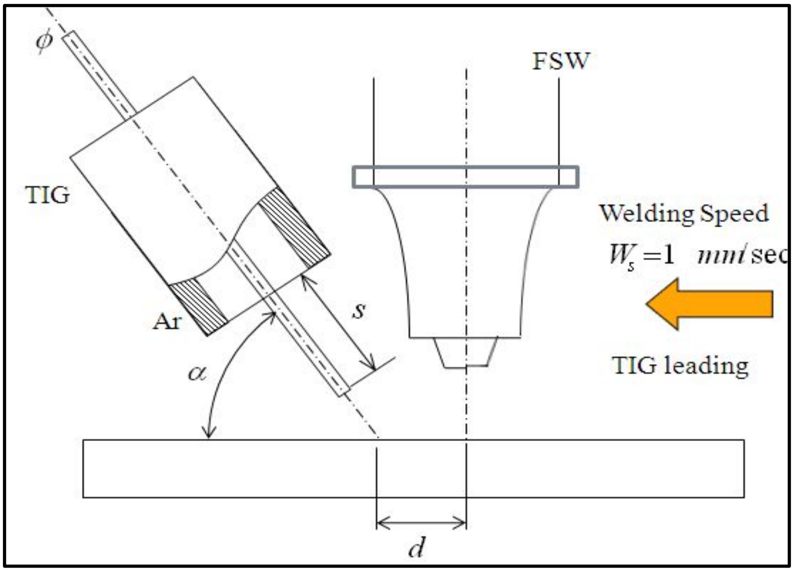


Fig. 3.5 Schematic of TIG assisted FSWelding process

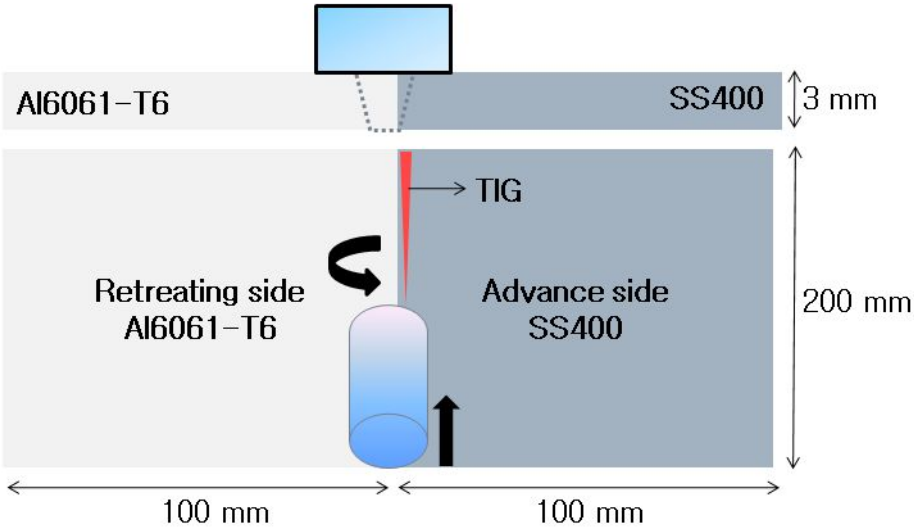


Fig. 3.6 Welding configuration for TIG-FSW

3.4 Experiment method

3.4.1 Tensile test

Tensile test was carried out with Dongil-Simaz Universal Testing Machine (EHF-EG200KN-40L) using WINSERVO program.
The specimens are fabricated in accordance with the national standards (KS0801-13-B). Tensile test was done with Load speed 0.033mm/sec Stress-Strain curve was obtained.
Fig. 3.7 shows the tensile testing setup and dimensions of the test specimen.

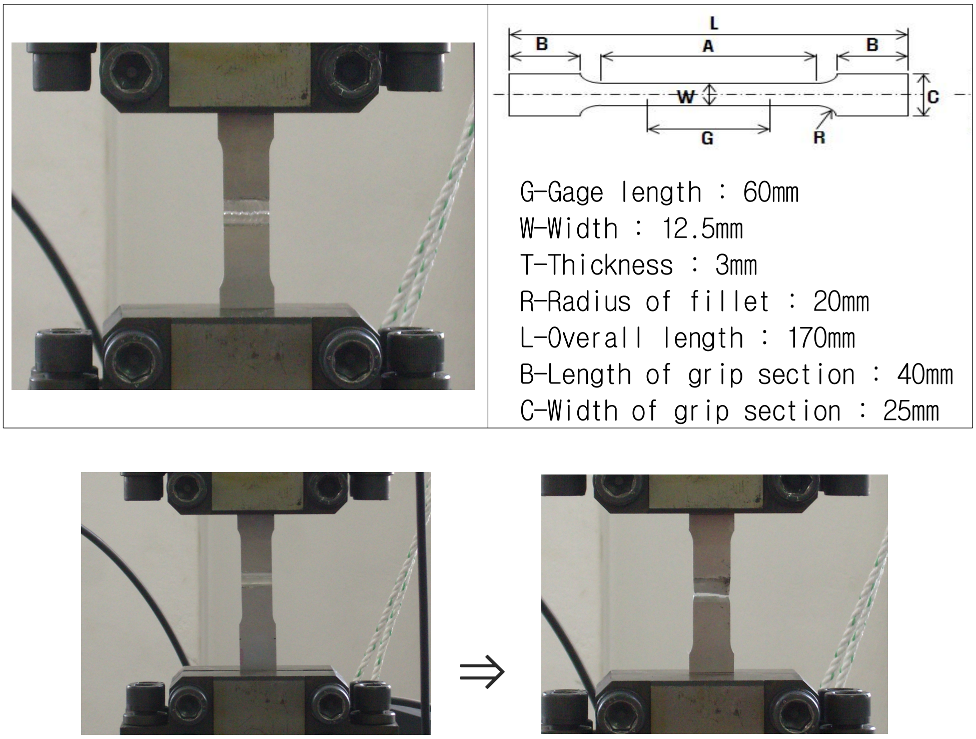


Fig. 3.7 Tensile test specimen dimensions

3.4.2 Hardness test

The hardness of a weld specimen was measured using Akashi HM-112 Vickers Hardness tester. The indenter employed in the Vickers test was a square-based pyramid whose opposite sides meet at the apex at an angle of 136° with load 500g applied for 10 sec.
Fig. 3.8 shows the Vickers hardness tester and test specimen. The hardness test was carried out on the welded specimen at points 0.5mm, 1.5mm, 2.5mm below top surface at three different positions at 1.0mm distance apart.

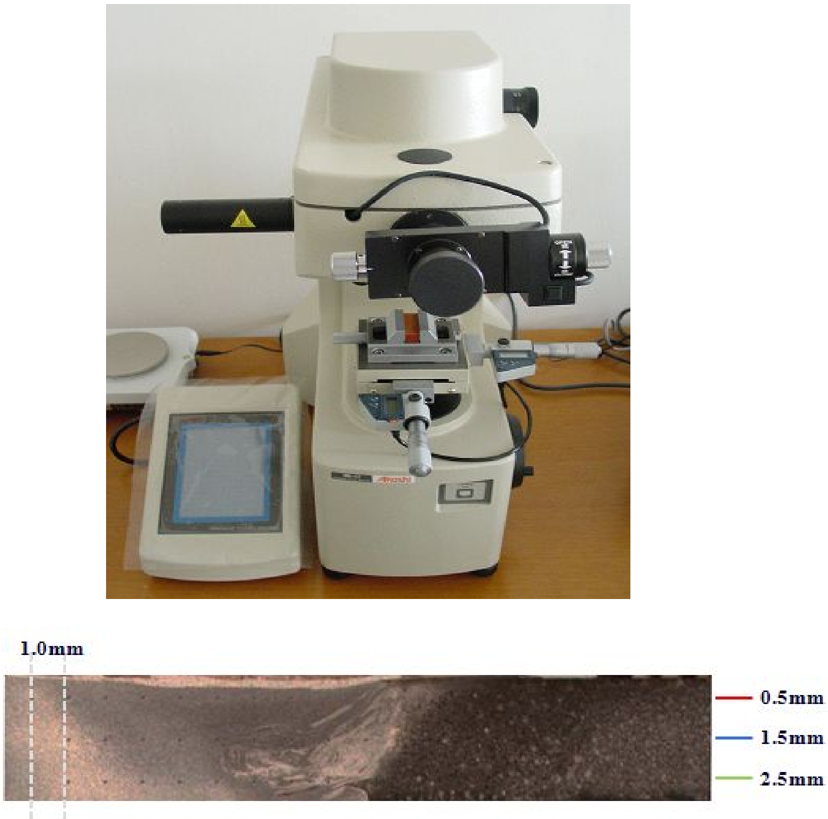


Fig. 3.8 Vickers hardness test machine and specimen

3.4.3 Micro structure analyses

The cross section TIG assisted FSW specimen was cut and polished to observe the micro structure of the dissimilar joint. Proper etching of Al6061-T6 was done using the mixture of 1.5㎖ Nitric acid, 3㎖ Hydro chloric acid, 3㎖ Hydro fluoric acid and 100㎖ distilled water. SS400 was properly etched using 5㎖ Nitric acid and 95㎖ Methanol.

The prepared specimen was mounted on OLYMPUS optical microscope to observe the micro structure as shown in Fig. 3.9.

Fig. 3.9 Optical microscope

Chapter 4

EXPERIMENTAL INVESTIGATION & RESULTS

4.1 Welding condition and bead shape

4.1.1 Experiment by TIG welding

Table 4.1(a) shows the TIG welding parameters used for this experiments. The material properties of Al6061-T6 and SS400 are different and the melting point of SS400 is two times higher than Al6061-T6 and therefore during welding, melting of Al6061-T6 occurs prior to SS400. Thus it was considered that it makes impossible to join similar and dissimilar weld with TIG welding process. The bead shapes obtained for dissimilar weld with TIG is given in Table 4.1(b).

Table 4.1 TIG welding parameters and obtained bead shapes

(a) Welding parameters

No.	Material	Input point	Traver Speed(mm/s)	TIG Current(A)	TIG pulsed Current(A)	Shield Gas (Ar-ℓ/min)	Wire	Torch Angle(°)
1	Al-SS400	center	1.0	80	70	7	Φ2.4mm, red	60
2	Al-Al	center	1.0	80	70	7	Φ2.4mm, red	60
3	SS400-SS400	center	1.0	80	70	7	Φ2.4mm, red	60

(b) Weld bead of dissimilar joint

No.	Material	Input point	Surface bead appearance	Remark
1	Al-SS400	center		BAD
2	Al-Al	center		BAD
3	SS400-SS400	center		BAD

4.1.2 Experiment by Friction stir welding

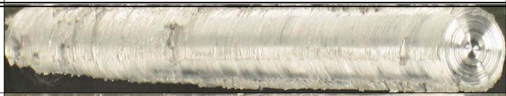
From many trials of experiment carried out on dissimilar joint by FSW, best 16 number of trials was taken in to account and is tabulated as given in Table 4.2(a). The bead shapes of the best 16 trials are shown in table 4.2(b). Rotation speed of the tool, tool travel speed and tool rotating direction were varied to obtain better results. Initial trials were done for obtaining better surface beads with proper exit holes. Over 600RPM, from the macro images, it was observed that the presence of SS400 deposits are more in the aluminium stir zone which can seriously affect the mechanical characteristics of weld joint. From the FSW experiments and macro images, tool rotation at 400 RPM at tool travel speed 0.6~1.2mm/s was found good and considered to carry out TIG assisted FSW experiments. Between 300 ~ 600RPM more heat was generated due to friction at the tool-workpiece interface and thus higher amount of SS400 inclusions were found in the Al6061-T6 stir zone.

Table 4.2 FSW parameters and obtained bead shapes

(a) Welding parameters

No.	Material	Adv. side	Tool plunge point	Rotating Speed (rpm)	Travel Speed (mm/s)	Rotation Direction
1	Al−SS400	SS400	9:1	300	0.6	ccw
2	Al−SS400	SS400	9:1	300	0.8	ccw
3	Al−SS400	SS400	9:1	300	1.0	ccw
4	Al−SS400	SS400	9:1	300	1.2	ccw
5	Al−SS400	SS400	9:1	400	0.6	ccw
6	Al−SS400	SS400	9:1	400	0.8	ccw
7	Al−SS400	SS400	9:1	400	1.0	ccw
8	Al−SS400	SS400	9:1	400	1.2	ccw
9	Al−SS400	SS400	9:1	500	0.6	ccw
10	Al−SS400	SS400	9:1	500	0.8	ccw
11	Al−SS400	SS400	9:1	500	1.0	ccw
12	Al−SS400	SS400	9:1	500	1.2	ccw
13	Al−SS400	SS400	9:1	600	0.6	ccw
14	Al−SS400	SS400	9:1	600	0.8	ccw
15	Al−SS400	SS400	9:1	600	1.0	ccw
16	Al−SS400	SS400	9:1	600	1.2	ccw

(b) Weld beads and macro images of dissimilar joint

RPM	Travel speed	Bead appearance	Macro image
300	0.6		
	0.8		
	1.0		
	1.2		
400	0.6		
	0.8		
	1.0		
	1.2		
500	0.6		
	0.8		
	1.0		
	1.2		
600	0.6		–
	0.8		–
	1.0		–
	1.2		–

4.1.3 Experiment by TIG Assisted Friction stir welding

Table 4.3 (a) and (b) shows the TIG assisted FSW parameters and obtained bead shapes for dissimilar joint of Al6061-T6 and SS400 butt joint. For TIG-FSW process, the best welding parameters obtained from the FSW experiments and TIG preheating BOP test conditions were considered respectively. 21 trials was carried out by varying different welding parameters to achieve the optimum welding condition. At, tool rotation speed 300RPM, TIG current of 80(A) and shield gas flow rate of 7ℓ/min, excellent bead shape was obtained and no weld defects was found in the cross sectional macro image. Above 500RPM tool rotation speed with TIG preheating, more heat was generated due to friction at the tool-workpiece interface and thus higher amount of SS400 inclusions were found in the Al6061-T6 stir zone.

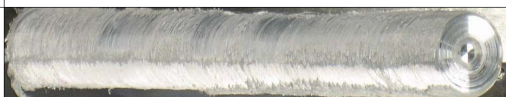
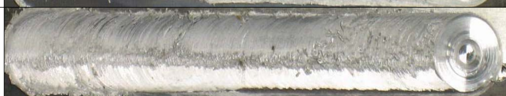
Table 4.3 TIG Assisted FSW parameters and obtained bead shapes

(a) Welding parameters

No.	Material	Tool plunge point	Rotating Speed	Travel Speed	Rotation Direction	TIG Current (A)	TIG pulsed Current (A)	Shield Gas (L/min)	Torch Angle
1	Al-SS400	9:1	300	0.8	ccw	80	70	7	60
2	Al-SS400	9:1	300	1.0	ccw	80	70	7	60
3	Al-SS400	9:1	300	1.2	ccw	80	70	7	60
4	Al-SS400	9:1	300	1.4	ccw	80	70	7	60
5	Al-SS400	9:1	300	1.6	ccw	80	70	7	60
6	Al-SS400	9:1	300	1.8	ccw	80	70	7	60
7	Al-SS400	9:1	300	2.0	ccw	80	70	7	60
8	Al-SS400	9:1	400	0.8	ccw	80	70	7	60
9	Al-SS400	9:1	400	1.0	ccw	80	70	7	60
10	Al-SS400	9:1	400	1.2	ccw	80	70	7	60
11	Al-SS400	9:1	400	1.4	ccw	80	70	7	60
12	Al-SS400	9:1	400	1.6	ccw	80	70	7	60
13	Al-SS400	9:1	400	1.8	ccw	80	70	7	60
14	Al-SS400	9:1	400	2.0	ccw	80	70	7	60

No.	Material	Tool plunge point	Rotating Speed	Travel Speed	Rotation Direction	TIG Current (A)	TIG pulsed Current (A)	Shield Gas (L/min)	Torch Angle
15	Al-SS400	9:1	500	0.8	ccw	80	70	7	60
16	Al-SS400	9:1	500	1.0	ccw	80	70	7	60
17	Al-SS400	9:1	500	1.2	ccw	80	70	7	60
18	Al-SS400	9:1	500	1.4	ccw	80	70	7	60
19	Al-SS400	9:1	500	1.6	ccw	80	70	7	60
20	Al-SS400	9:1	500	1.8	ccw	80	70	7	60
21	Al-SS400	9:1	500	2.0	ccw	80	70	7	60

(b) Weld beads and macro images of dissimilar joint

RPM	Travel speed	Appearance	Macro image
300	0.8		
	1.0		
	1.2		
	1.4		
	1.6		
	1.8		
	2.0		

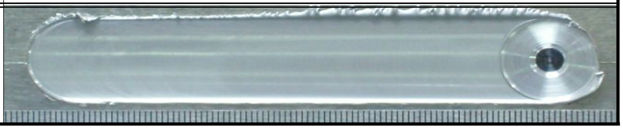
RPM	Travel speed	Appearance	Macro image
400	0.8		
	1.0		
	1.2		
	1.4		
	1.6		
	1.8		
	2.0		
500	0.8		
	1.0		
	1.2		
	1.4		
	1.6		
	1.8		
	2.0		

4.2 Tensile test results

4.2.1 Tensile test of similar joint (Al6061-T6)

Tensile test of similar joint of Al6061-T6 was carried out to understand the tensile strength of FSW joint made at 400RPM and 1mm/sec tool travel speed (Table 4.4). Testing was carried out as per korean standards. This result was used as a reference for the testing of TIG-FSW dissimilar joint. The tensile test results were shown in Fig4.1. The tensile strength of the FSW weld joint was obtained as 245MPa which is 74% of the tensile strength of base metal (330MPa).

Table 4.4 Bead appearance of similar joint specimen considered for tensile test

RPM	Travel speed(mm/s)	Appearance
400	1	

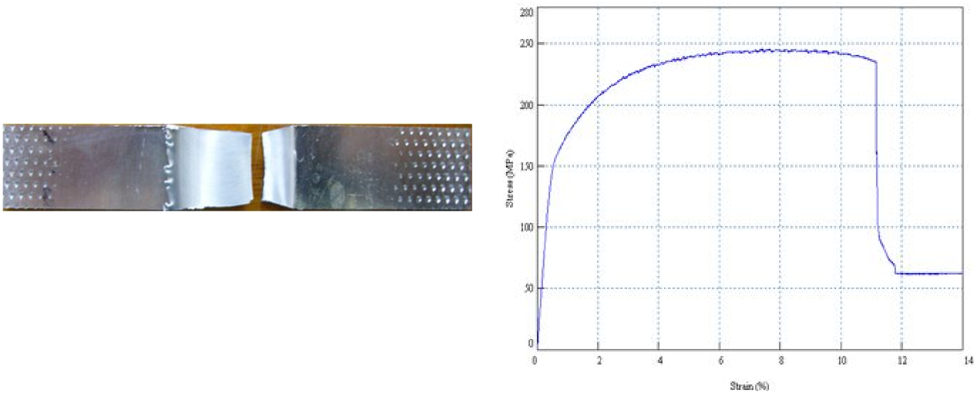


Fig. 4.1 Tested specimen and Stress-Strain curve

4.2.2 Tensile test of FSW dissimilar joint

Testing of tensile strength of dissimilar weld joint by FSW was carried out as per korean standards. The tensile test results reveals that fracture occurs at the dissimilar joining interface (Table 4.5). The fracture was occurred at the Al6061-T6 stir zone where SS400 inclusions are more.

From stress-strain curve it is evident that the specimen is subjected to brittle fracture (Table 4.6). Good tensile strength is obtained for the weld joint made at tool rotation 400RPM and travel speed 1.2mm/s.

The tensile test results are given in Fig. 4.2. The tensile strength ranges from 33.5% to 95.4%, that of base metal. Maximum tensile strength value is found 315.6Mpa, which is 95.4% of base metal (330Mpa).

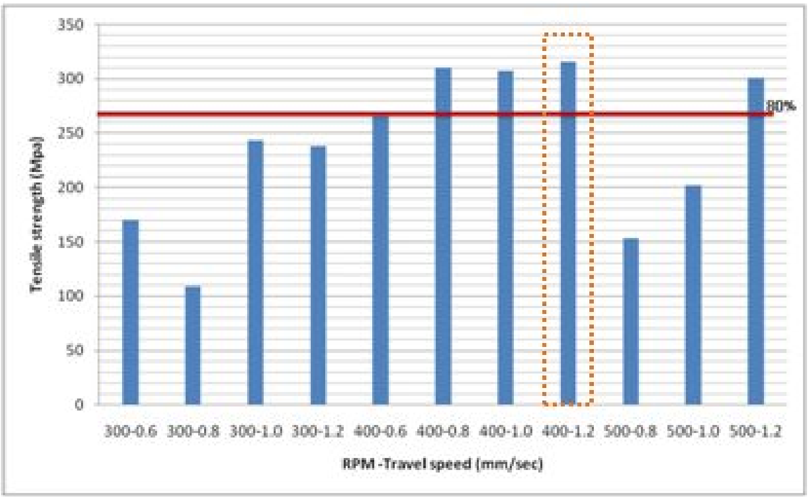


Fig. 4.2 Tensile test result (FSW)

Table 4.5 Cross sections and fractured specimens of dissimilar joint by FSW

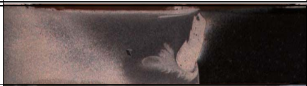
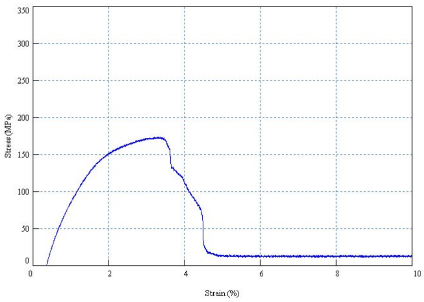
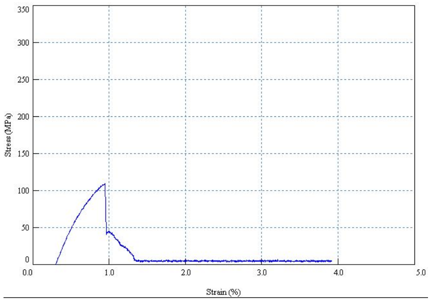
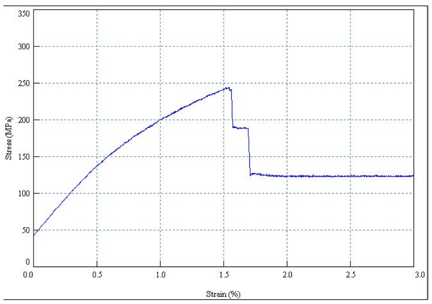
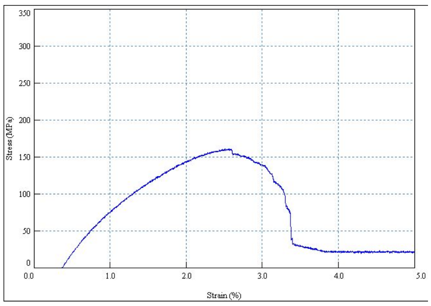
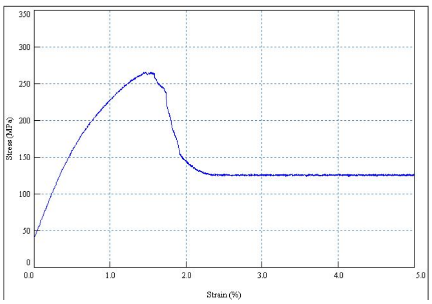
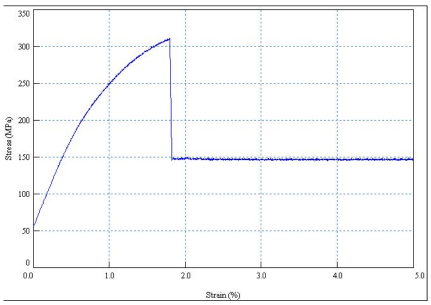
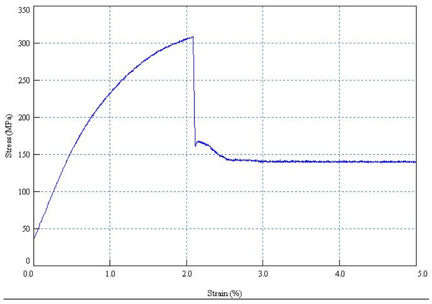
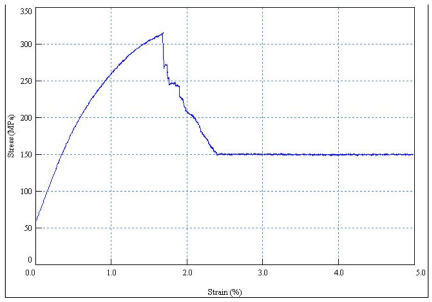
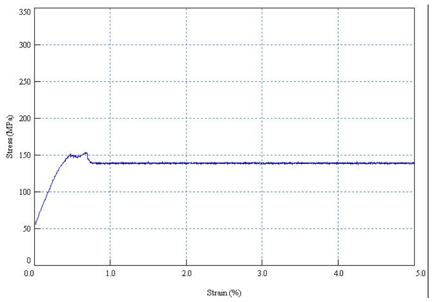
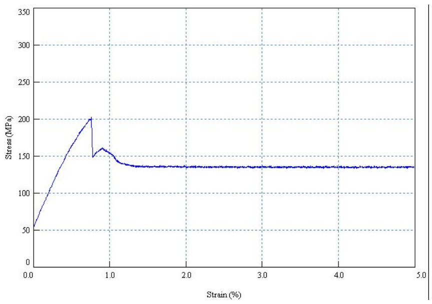
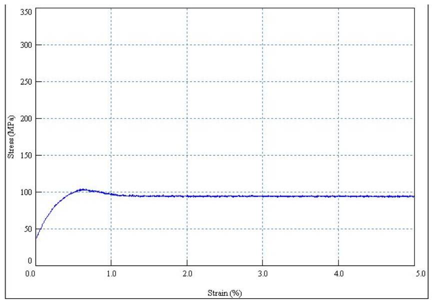
RPM	Travel speed	Macro image	Fractured specimens	T.S(MPa)
300	0.6			170.0
	0.8			108.9
	1.0			243.6
	1.2			238.1
400	0.6			265.3
	0.8			310.6
	1.0			307.8
	1.2			315.6
500	0.6		–	BAD
	0.8			153.3
	1.0			201.9
	1.2			301.1
600	0.6	–	–	BAD
	0.8	–	–	BAD
	1.0	–	–	BAD
	1.2	–	–	BAD

Table 4.6 Stress-strain curve for dissimilar weld joint by FSW

RPM	Travel speed(mm/s)	
	0.6	0.8
300		
	1.0	1.2
		
	0.6	0.8
400		

<table>
<tr><td rowspan="2">RPM</td><td colspan="2">Travel speed(mm/s)</td></tr>
<tr><td>1.0</td><td>1.2</td></tr>
<tr><td>400</td><td>
</td><td>
</td></tr>
<tr><td rowspan="4">500</td><td>0.6</td><td>0.8</td></tr>
<tr><td>–</td><td>
</td></tr>
<tr><td>1.0</td><td>1.2</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

4.2.3 Tensile test of TIG assisted FSW dissimilar joint

Table 4.7 shows the cross sections and fractured specimens of dissimilar joint by TIG assisted FSW. As observed from the tensile test results, the fracture occurred at the joining interface in specimens welded at 300 to 500RPM tool rotation speed. The tensile strength of dissimilar joint by TIG-FSW was found 50.0% to 104.2% than that of Al6061-T6 base metal(330Mpa). The good tensile strength obtained was 344.1MPa (Al6061-T6 base metal tensile strength 310MPa) i.e, about 104.2% than that of base metal at tool rotation speed 300RPM, travel speed 1.0mm/s and TIG current 80A. The stress-strain curve (Table 4.8) shows that the specimen is fractured in a brittle manner with little plastic deformation. The tensile test results are given in Fig. 4.3.

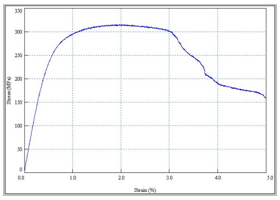
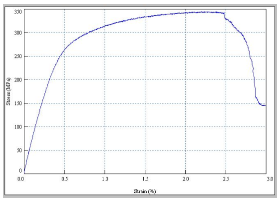
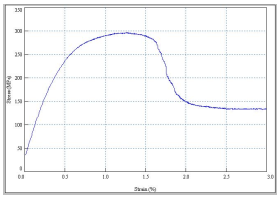
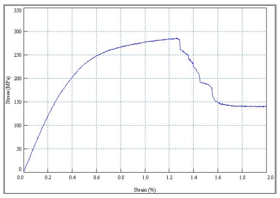
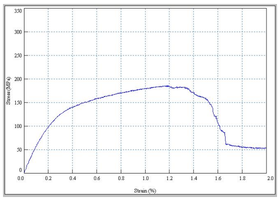
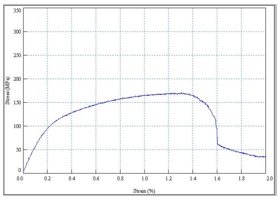
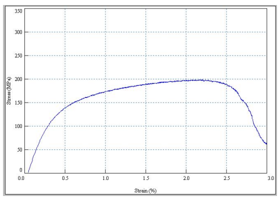
Fig. 4.3 Tensile test result (TIG assisted FSW)

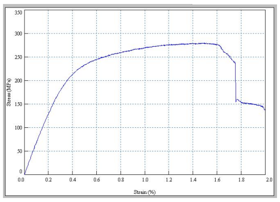
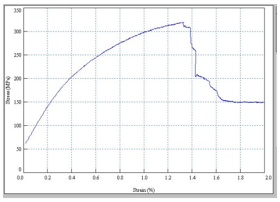
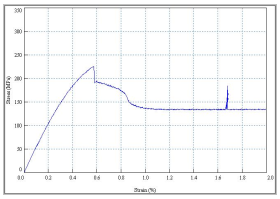
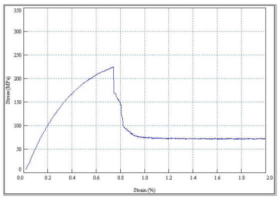
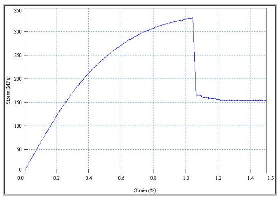
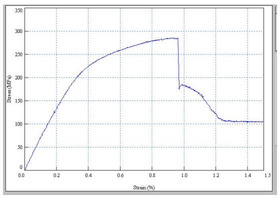
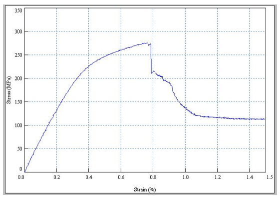
Table 4.7 Cross sections and fractured specimens of dissimilar joint by TIG assisted FSW

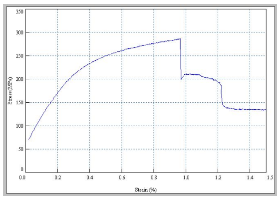
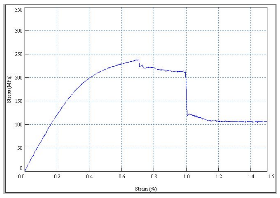
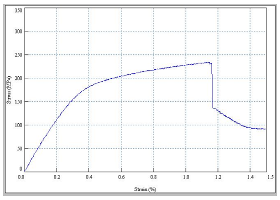
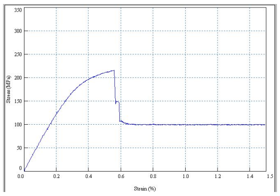
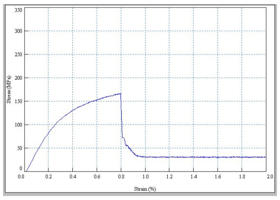
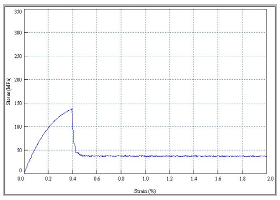
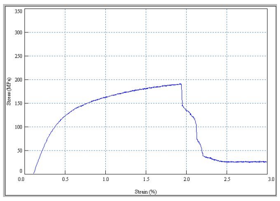
RPM	Travel speed	Macro	Fractured specimens	T.S(MPa)
300	0.8			313.8
	1.0			344.1
	1.2			295.6
	1.4			284.4
	1.6			182.8
	1.8			168.9
	2.0			221.1
400	0.8			286.1
	1.0			232.8
	1.2			315.3
	1.4			247.0
	1.6			329.2
	1.8			285.0
	2.0			275.3

RPM	Travel speed	Macro	Fractured specimens	T.S(MPa)
500	0.8			285.8
	1.0			283.3
	1.2			231.9
	1.4			215.6
	1.6			166.1
	1.8			138.1
	2.0			188.1

Table 4.8 Stress-strain curve for dissimilar weld joint by TIG assisted FSW

RPM	Travel speed(mm/s)		
	0.8	1.0	1.2
300			
	1.4	1.6	1.8
			
	2.0	–	–
		–	–

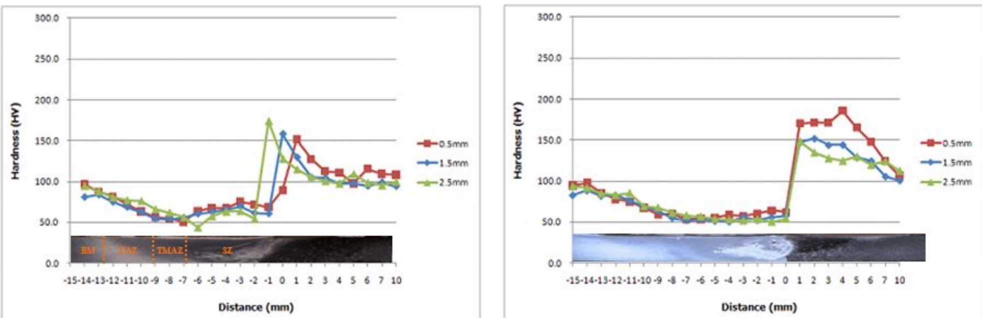
RPM	Travel speed(mm/s)		
	0.8	1.0	1.2
400			
	1.4	1.6	1.8
			
	2.0	–	–
		–	–

<table>
<tr><th rowspan="2">RPM</th><th colspan="3">Travel speed(mm/s)</th></tr>
<tr><th>0.8</th><th>1.0</th><th>1.2</th></tr>
<tr><td rowspan="6">500</td><td></td><td></td><td></td></tr>
<tr><td>1.4</td><td>1.6</td><td>1.8</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>2.0</td><td>–</td><td>–</td></tr>
<tr><td></td><td>–</td><td>–</td></tr>
</table>

4.3 Hardness test results

The hardness distributions of dissimilar joint by TIG and TIG-FSW is shown in Fig.4.4. The hardness at the TMAZ and HAZ is approximately 50% of the base metal before welding and is a characteristic of dynamic recrystallization that appears to provide a mechanism for solid state welding. Though frictional heating is greater near the top surface where maximum temperatures occurs, there is no much difference in hardness values at top and bottom of the stir zone (b.TIG assisted FSW). The difference in values at base metal, TMAZ and HAZ indicates that softening of material occurred due to plastic flow.

The hardness value at the weld bond line side sharply decreased towards the weld nugget from the level of the thermo-mechanically affected zone in the SS400 at advancing side of weld. The hardness of the weld nugget shows variable values because of the presence of the fine or coarse dispersed SS400 particles in the weld nugget.



welding condition : 400RPM, 1.2mm/s

welding condition : 300RPM, 1.0mm/s, TIG current 80A

(a. FSW only)

(b. TIG assisted FSW)

Fig. 4.4 Hardness distribution of dissimilar

4.4 Microstructure analyses of dissimilar joint

4.4.1 Microstructure of FSW dissimilar joint

Microstructure of FSW dissimilar joint is shown in Fig. 4.5. The base Al6061-T6 alloy contains elongated grains in the rolling direction. The Al6061-T6 alloy in the weld nugget consist of fine, equiaxed, recrystallized grains. The fine recrystallized grains in the stirred zone are attributed to the generation of high deformation and temperature during FSW.

The weld nugget exhibits a mixture of Al6061-T6 alloy and SS400 particles pulled away by forge of tool pin from the SS400 surface. Therefore the weld nugget has a composite structure of SS400 particles reinforced Al6061-T6 alloy. SS400 particles inclusions were more in the Al6061-T6 weld nugget and have an irregular shape and inhomogeneous distribution within the weld nugget.

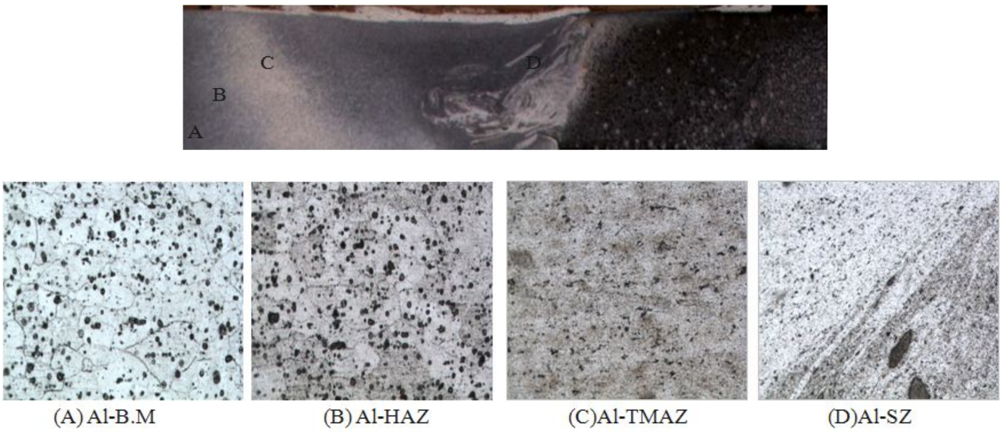


Fig. 4.5 Microstructural (FSW only)

4.5.2 Microstructure of TIG assisted FSW dissimilar joint

Microstructure of FSW dissimilar joint is shown in Fig. 4.6. From the microstructure image of Al6061-T6 base metal, it is clear that the base metal have the same microstructure with homogeneous grain distribution as in FSW. Compared to FSW process, only finer particles of SS400 inclusions were found in TIG-FSW microstructure. Due to preheating effect at SS400 plate the grain size is increased at HAZ.

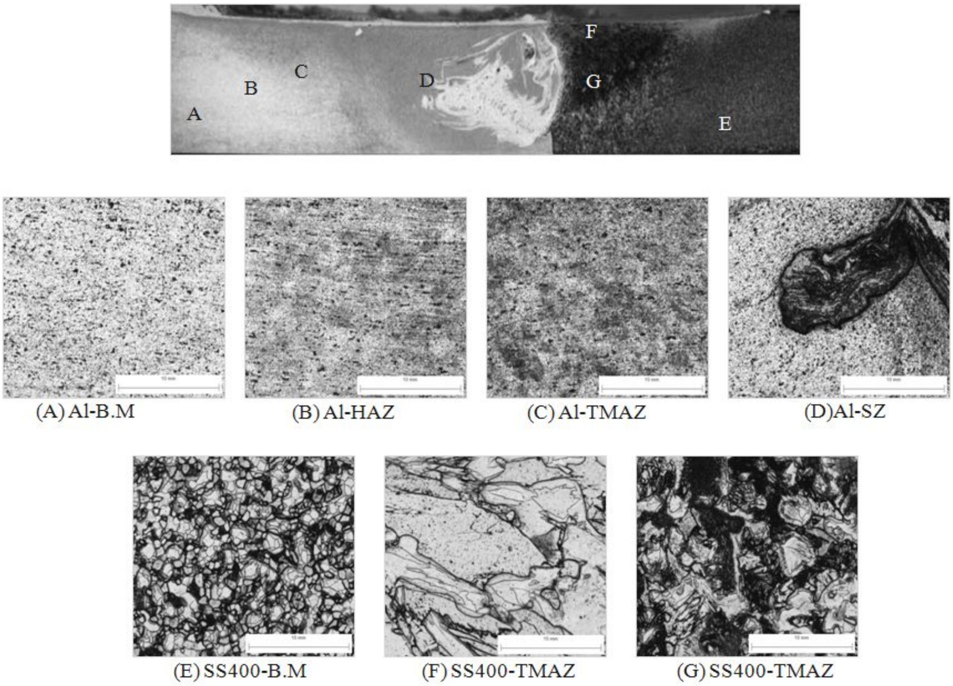


Fig. 4.6 Microstructural (TIG assisted FSW)

4.4.3 Microstructure analyses by using SEM and EDS

The weld nugget exhibits a mixture of Al 6061-T6 alloy and SS400 particles pulled away by forge of tool pin from the SS400 surface. Therefore the weld nugget has a composite structure of SS400 particles reinforced Al 6061-T6 alloy. Fig. 4.7 shows SEM of the cross section of the TIG assisted friction stir welded dissimilar Al6061-T6 alloy to SS400. SS400 particles on Al 6061- T6 alloy were found in the weld nugget. point C shows the SS400 microstructure of weld joint. However, re-crystallization of Al6061-T6 might have occurred in the weld zone with grain size very much smaller than SS400.

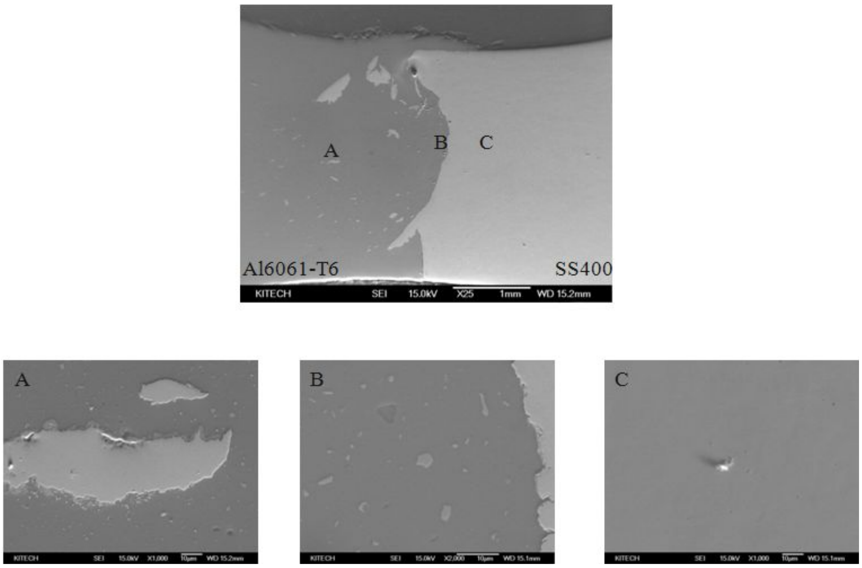
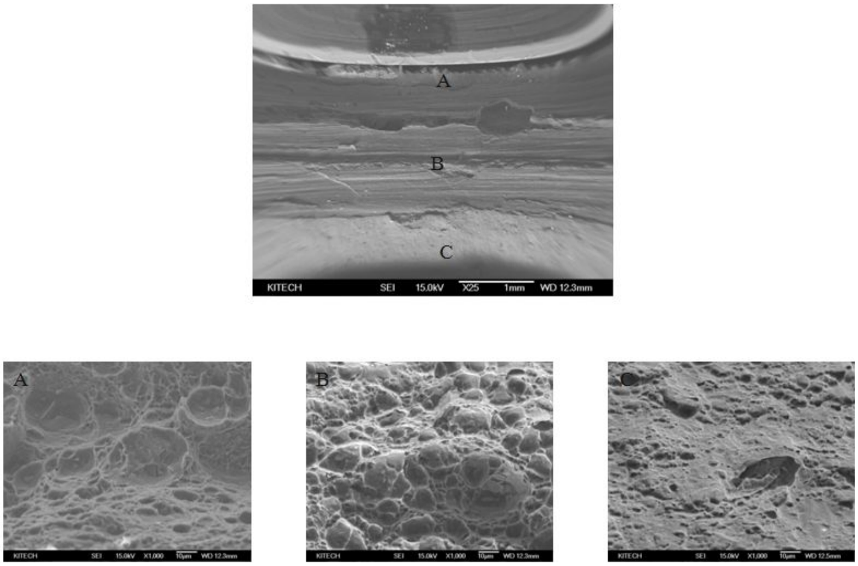
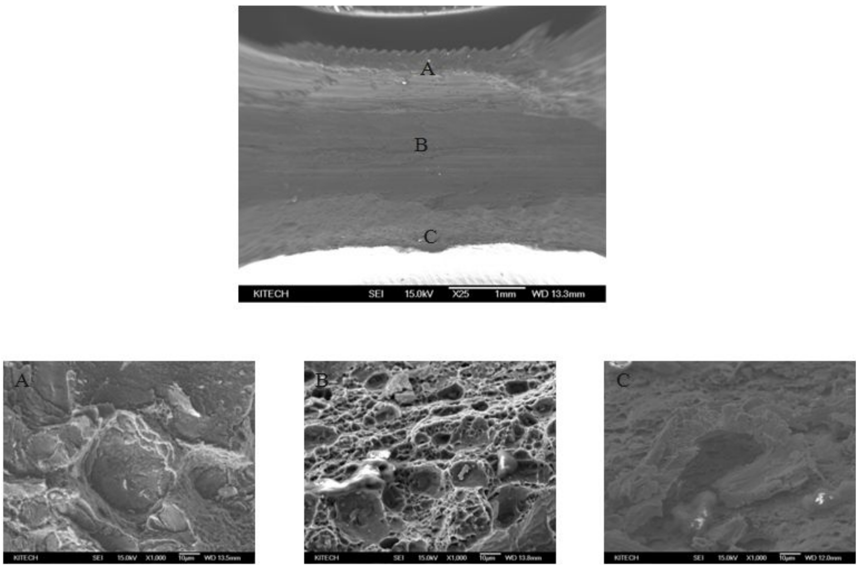


Fig. 4.7 SEM micrograph of dissimilar weld

From Fig. 4.8 (a) and (b), it is found that the ductile fracture occurred at weld nugget towards Al6061-T6 direction. The tool pin height is limited by work piece thickness and will not penetrate the workpiece. Therefore the crack is found originated at a depth where the tool pin interacts with the workpiece. Ductile fracture with dimple pattern is observed on the specimen fracture surface, when fractured with tensile load applied at transverse direction. At cleavage face of the grain boundary the brittle fracture is found at area where plastic deformation has not occurred.



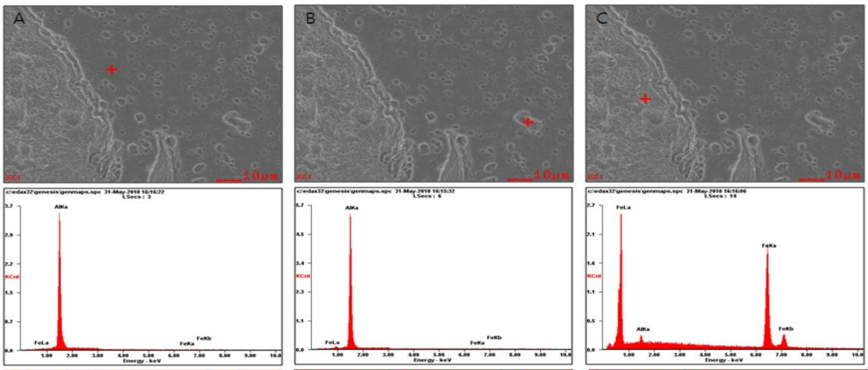
(a) Direction of Al6061-T6



(b) Direction of SS400

Fig. 4.8 SEM of dissimilar weld tensile fracture surface

From the EDS image of weld nugget zone along Al6061-T6 side, Fig. 4.9(a), at point A,the chemical compound of Al6061-T6 is same as that of base metal, at point B the chemical compound of Al6061-T6 is same as that of base metal and at point C chemical compounds of SS400 is found more with Al6061-T6 compounds. Along SS400 side, Fig 4.9(b), only SS400 chemical compounds were found at point A, B and C. The region where the diffusion of the Al6061-T6 does not reached can be judged from the image.

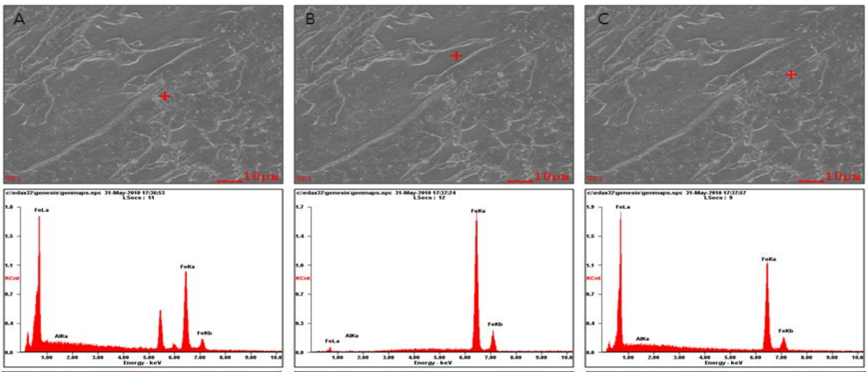


Element	Wt%	At%
AlK	98.85	99.44
FeK	01.15	00.56
Matrix	Correction	ZAF

Element	Wt%	At%
AlK	98.73	99.38
FeK	01.27	00.62
Matrix	Correction	ZAF

Element	Wt%	At%
AlK	01.56	03.17
FeK	98.44	96.83
Matrix	Correction	ZAF

(a) Chemical compounds of Al6061-T6 weld



Element	Wt%	At%
AlK	00.41	00.84
FeK	99.59	99.16
Matrix	Correction	ZAF

Element	Wt%	At%
AlK	00.13	00.26
FeK	99.87	99.74
Matrix	Correction	ZAF

Element	Wt%	At%
AlK	00.27	00.56
FeK	99.73	99.44
Matrix	Correction	ZAF

(b) Chemical compounds of SS400304 weld

Fig. 4.9 EDS analysis of dissimilar weld

Chapter 5

CONCLUSION

A new welding technique, TIG-FSW, was successfully applied to the joining of Al6061-T6 alloy and SS400. The Tensile strength, hardness distribution and microstructure of friction stir welded dissimilar Al6061-T6 alloy and SS400 joints have been studied in the present work.

1. To achieve a good weld joint between Al6061-T6 and SS400304, the tool plunge position was adjusted towards Al6061-T6 side to soften Al material and tool was made to rotate in counter clock wise direction. Al6061-T6 was placed in the retreating side and SS400 in the advancing side for conducting this welding experiment process. This is because the soften material flows in the direction of tool rotation and therefore the soften Al material flow was found to be good when Al was placed in the retreating side.
2. In FSW of dissimilar joint, because of the maximum plunge force area, the heat generation was maximum at Al6061-T6 side which lead to brittle fracture of the weld joint. Hence, TIG-FSW process helps to balance the heat generation at both Al6061-T6 and SS400 which increased the tensile strength of the dissimilar weld join. The tensile strength of dissimilar joint by FSW was found 33.0% to 95.4% that of Al6061-T6 base metal where as tensile strength was 53.3% to 104.2% when joined with TIG-FSW.
3. The best welding joint was obtained at tool rotation speed 300RPM, travel speed 1.0mm/s and TIG current 80A. The tensile strength was obtained as 344.1MPa (Al6061-T6 base metal tensile strength 330MPa) i.e, about 104.2% than that of base metal.
4. The hardness values were found different in the weld nugget of dissimilar joint depending upon the material properties. The hardness value at the retreating side sharply decreased towards the

weld nugget from the level of TMAZ in the SS400 at advancing side of weld. The hardness at the weld nugget across Al6061-T6 bond line are not seriously affected by presence of SS400 deposits.

5. SEM of the cross section of the TIG assisted friction stir welded dissimilar Al6061-T6 alloy to SS400. SS400 particles on Al 6061-T6 alloy were found in the weld nugget. SS400 micro structure of weld joint. However, re-crystallization of Al6061-T6 might have occurred in the weld zone with grain size very much smaller than SS400.

Finally, it is concluded that TIG assisted FSW process can be applied to dissimilar Al6061-T6 and SS400 successively in industrial applications.

REFERENCES

[1] G.H. Jeon, A Study on Weldability of TIG Assisted Friction Stir Dissimilar Welding of Al6061 Alloy and STS Sheet, 2010

[2] Y.J.Chao, and X.Qi: Heat transfer and thermo-mechanical analysis of Friction Stir joining of Al6061-T6 plates, 1st International Symposium on Friction Stir Welding, (1999).

[3] A.Askari, S.Silling, B.London, and M.Mahoney: Modelling and Analysis of Friction Stir Welding Processes, Friction stir welding and Processing, TMS publication,(2001) p.43.

[4] A.William, Using Gleeble flow stress data to establish optimum FSW processing parameter in Aluminium Alloys, Advanced material processing centre, (2002).

[5] H.S. Bang. "Study on The Mechanical Behaviour of Welded part in thick Plate - Three-dimensional Thermal Elasto-Plastic Analysis Baseon Finite Element Method." Journal of the Korean Welding Society, Vol.10, No.4, pp.37~43, December 1992.

[6] Rajesh S.R., "Development of mathematical model for Thermo - mechanical behavior of Friction Stir Welding an introduction Soldering by using FEM/BEM", 2007

[7] W.B. Lee, S.B. Jung, Gehard Biallas, Martin Schmuecker. "Joint properties and Interface Analysis of Friction Stir Welded Dissimilar Materials between Austenite Stainless Steel and 6013 Al Alloy" Journal of the Korean Welding Society, Vo.23, No.5, pp.469 ~476, October 2005.

[8] H. Kokawa, S.H.C. Park, Y.S. Sato, K. Okamoto, S. Hirano, M. Inagaki : Microstructures in Friction Stir Welded 304 Austenitic Stainless Steel, Welding in the World, 49(3/4), 2005, pp.34-40

[9] T.J. Lienert, W.L. Steelwag, Jr., B.B Grimmett, and R.W. Warke : Friction Stir Welding Studies on Mild Steel, Welding Journal,82(1),

2003, pp.1S-9S
[10] AWS, WELDING HANDBOOK, Vol.1, Eighth Edition, 1987.
[11] AWS, WELDING HANDBOOK, Vol.2, Eighth Edition, 1991.
[12] W.M. Thomas, P.L.Threadgill, and E.D. Nicholas : Feasible of Friction Stir Welding Steel, Science and Technology of Welding and Joining, 4(6), 1999, pp. 365-372
[13] L.E.Murr, et al.: Solid-state flow association with the friction stirwelding of dissmilar metals, Fluid flow phenomena in metals processing (1999), 31-40
[14] Huseyin Uzun, Claudio Dalle Donne, Alberto Argagnotto, Tommaso Ghidini, Carla Gambaro.:Friction stir welding of dissimilar Al 6013-T4 To X5CrNi18-10 stainless steel, Materials and Design 26 (2005) 41-.46
[15] Z. Sun, R. Karppi, "The application of electron beam welding for the joining of dissimilar metals: an overview", Journal of materials processing technology 59 (1996) 257-267
[16] H.S. Bang, G.Y. Han, "The plane-deformation thermal elasto -plastic analysis during welding of plate", The society of naval architects of korea p33~40, Apr.1994
[17] S. Katayama, et al.: Proc.5th Int.Conf.on TRENDS IN WELDING RESEARCH, Georgia, June (1998), pp.467-472.
[18] WELDING HANDBOOK, Eighth Edition, Volume 3, MATERIALS AND APPLICATION PART 1, pp.100~110, AMERICAN WELDING SOCIETY.
[19] E. G. WEST, THE WELDING OF NON-FERROUS METALS, CHAPMAN & HALL LTD,1951, pp.129~254.
[20] Hidekazu Murakawa and Jianxun Zhang, "FEM Simulation of welding process (Report I)", Trans. JWRI, Vol. 27, No. 1, pp.75~82, 1998.
[21] W.B. Lee, "MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELDING ALLUMINUM AND MAGNESIUM ALLOYS, 2006

Acknowledgments

First and foremost, I would like to express my sincere gratitude to my advisor Prof. Han-Sur Bang for having provided me an opportunity to do Master course under is guidance. I will be forever grateful for his constant encouragement and timely advice during my Master course.

Special thanks to Prof. Hee-Seon Bang, who has given me continuous support at various aspects, especially to carry out experiments and resolving technical problems. This gives me great opportunity to express my gratitude to Prof. Duck-Young Yoon, Prof. Kwi-Joo Lee, Prof. Je-Woong Park, and Prof. Young-Seob Kwon being a constant source of source and support.

Also, I extent my thanks to all my colleagues, especially Geun-Hong Jeon, Kye-Sung Jeon, Hyun-Jong Song and M.S.Bijoy in Department of Naval Architecture and Ocean Engineering for there help and support to over come my difficulties throughout my work.

Finally, I express my sincere thanks to my beloved parents and brother. I am forever in debt to them for what they have done for me.

저작물 이용 허락서

학 과	선박해양공학과	학 번	20087577	과 정	석사
성 명	한글: 김정미 한문 : 金正美 영문 : Kim, Jung-Mi				
주 소	광주광역시 북구 문흥동 928-10				
연락처	E-MAIL : kkjung0612@hanmail.net				
논문제목	한글 : TIG-FSW Hybrid 용접기술을 이용한 이종재료 Al6061 Alloy - SS400 용접부의 용접성에 관한 연구. 영어 : A Study on the Weldability of Dissimilar Butt joint (Al6061 / SS400) by TIG Assisted Friction Stir Welding				

본인이 저작한 위의 저작물에 대하여 다음과 같은 조건아래 조선대학교가 저작물을 이용할 수 있도록 허락하고 동의합니다.

- 다 음 -

1. 저작물의 DB구축 및 인터넷을 포함한 정보통신망에의 공개를 위한 저작물의 복제, 기억장치에의 저장, 전송 등을 허락함
2. 위의 목적을 위하여 필요한 범위 내에서의 편집・형식상의 변경을 허락함. 다만, 저작물의 내용변경은 금지함.
3. 배포・전송된 저작물의 영리적 목적을 위한 복제, 저장, 전송 등은 금지함.
4. 저작물에 대한 이용기간은 5년으로 하고, 기간종료 3개월 이내에 별도의 의사 표시가 없을 경우에는 저작물의 이용기간을 계속 연장함.
5. 해당 저작물의 저작권을 타인에게 양도하거나 또는 출판을 허락을 하였을 경우에는 1개월 이내에 대학에 이를 통보함.
6. 조선대학교는 저작물의 이용허락 이후 해당 저작물로 인하여 발생하는 타인에 의한 권리 침해에 대하여 일체의 법적 책임을 지지 않음
7. 소속대학의 협정기관에 저작물의 제공 및 인터넷 등 정보통신망을 이용한 저작물의 전송・출력을 허락함.

동의여부 : 동의(O) 반대( )

2010 년 6 월

저작자: 김 정 미 (서명 또는 인)

조선대학교 총장 귀하