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Master's Thesis

Comparison of Joint strength and Temperature distribution Characteristics in Dissimilar Al6061-T6/SS400 FSW welds and TIG assisted hybrid FSW welds

Graduate School of Chosun University

Department of Mechanical Engineering

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마찰교반용접(FSW)과 하이브리드(TIG-FSW)를 이용한 이종재료 알루미늄 합금/연강의 접합특성과 온도분포 비교

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전계성의 석사학위논문을 인준함

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CONTENTS

Chapter 3. Experimental Method of TIG Assisted Hybrid FSW Welding Process

Chapter 4. Mechanical and metallurgical Characteristics in FSW and TIG Assisted Hybrid FSW welds

List of Tables

List of Figures

ABSTRACT

마찰교반용접(FSW)과 하이브리드(TIG-FSW)를 이용한 이종재료 알루미늄 합금/연강의 접합특성과 온도분포 비교

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최근 효과적인 수송기계 분야의 강도 확보 및 경량화에 대한 요구가 부각됨에 따라 알루미늄합금과 같은 경량소재 사용이 시도되고 있다. 대부분 구조재료를 실 제품에 적용할 경우, 두 가지 이상의 재료가 사용되기 때문에 이 재료들 간의 접합이 필수적이라 할 수 있으며 물리적 특성 차이가 상이한 재료의 접합일 경우 기존의 용융 용접법 으로는 접합이 매우 어렵거나 불가능한 실정이므로 이에 대한 대책이 요구되어 지고 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 신뢰성을 높이 고자 하였다.

실험방법은 3mm 두께의 이종재료 Al6061-T6와 SS400 판재에 툴의 삽입위치(9:1,7:3)를 변수로 하여 접합을 실시하였으며, TIG와 FSW의 접합인자 즉, TIG 출력, 회전속도, 이송속도, TIG 조사 위치, TIG torch 각도 등을 선행 연구 되었던 조건을 바탕으로 고정 변수로 두고 접합부의 특성을 고찰하였다. 용접 실험 후 각 조건별 특징을 알아보기 위하여 접합부의 기계적 특성평가 및 금속학적 특성을 파악하고 Thermo-couple을 이용한 온도구배 실험을 통하여 FSW와 TIG-FSW Hybrid 용접의 접합부 온도분포 특성을 비교 확인 하였다.

Chapter 1

INTRODUCTION

There are many kinds of approach to meet the demands where consider the environmental problem and the resource exhaustion. Therefore, The highest performance and concurrent weight and cost reduction became more important in transportation industries such as automobile, aircraft, vessel and railway vehicle. So many researchers are focusing on lightweight structures which are economical and environmentally. Therefore, manufactures are developing the lighter materials with a higher mechanical properties by various methods like design and processing by alloy.

Steel joints are used in structure where high strength are desirable. Riveting and bimetallic strip joining techniques for steel joint increases manufacturing cost and require more work time.

To solve this problem, Friction stir welding process is a novel solid state joining process that was invented in 1991. FSW can avoid many problems associated with conventional fusion welding methods, there by producing defect free welds with excellent properties, even in some materials with poor weldability.

Due to its many advantages, FSW attracts a great deal of attention in the industrial fields, and is successfully applied to the joining of various aluminum alloy, magnesium and copper alloys. In recent years, FSW of materials such as steels and aluminum alloys has become a research carefully.

Dissimilar material combinatons 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 intermetalic reduces 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. Thus, to overcome this problem for joining dissimilar joint, TIG preheating can be implemented. Hence, this work intends to establish the possibility of joining Al6061-T6 and SS400 joints by TIG hybrid FSW welds. For this, weldability, thermal characteristics, mechanical characteristics and metallurgical characteristics and using Thermo-couple of dissimilar joints are studied. Successfully obtaining the process of dissimilar metal joining by TIG hybrid FSW welding of the experimental data influence the industrial and national competitiveness.

Chapter 2

Characteristics of FSW and TIG welding methods

2 . 1 Principle and characteristics of FSW

2.1.1 Principle of FSW

Friction stir welding (FSW) was developed at the TWI in 1991 as a solid-state joining process and was initially applied to lightweight metals. The concept is remarkably simple. A nonconsumable rotating tool with a designed probe and shoulder is inserted into the edges of sheets or plates to be joined. Fig. 2.2 shows schematic drawing of Friction Stir Welding process. Most definitions are self-explanatory, but advancing side and retreating side definitions require a brief explanation. Advancing side and retreating side orientations require knowledge of the tool rotation and travel direction. In Fig. 2.1 the FSW tool rotates in the counterclockwise direction and travels into the page. The advancing side in on the right, where the tool rotation direction is the same as the tool travel direction , and the tool retreating side is on the left, where the tool rotation direction is opposite the tool travel direction.

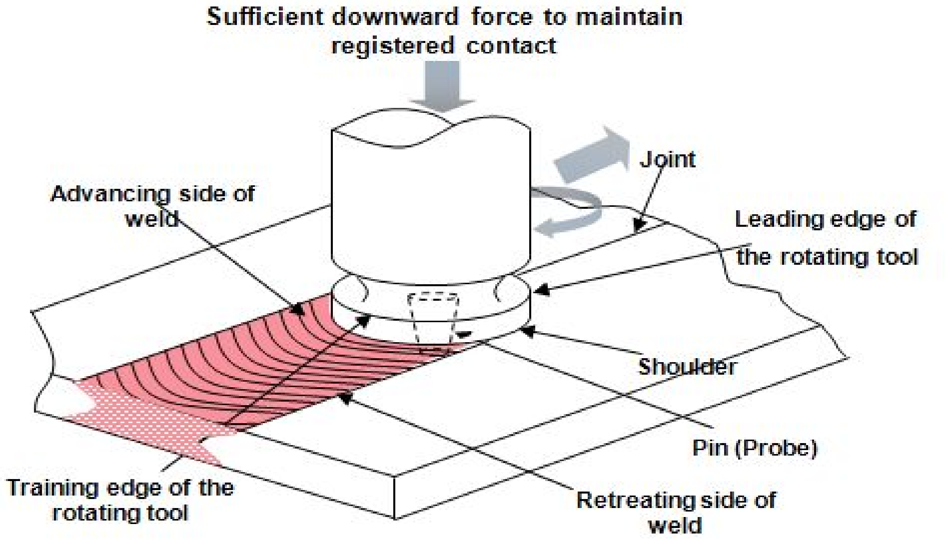
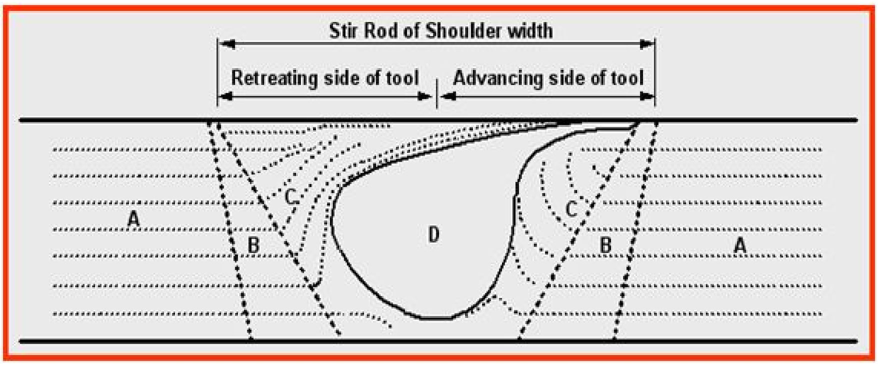


Fig. 2.1 Schematic of friction stir welding



A: BM (Base Metal)

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

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

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

Fig. 2.2 Microstructural regions in FSW welds

2.1.2 Characteristics of FSW

1) Advantage 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 consumable -conventional steel tools can weld over 1000m of aluminum and no filler or gas shied is required for aluminum.
- Easily automated on simple milling machines- lower operation costs 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, fewer welding passes are required.

2 . 2 Principle and characteristics of TIG

2.2.1 Principle of TIG

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 proper 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.

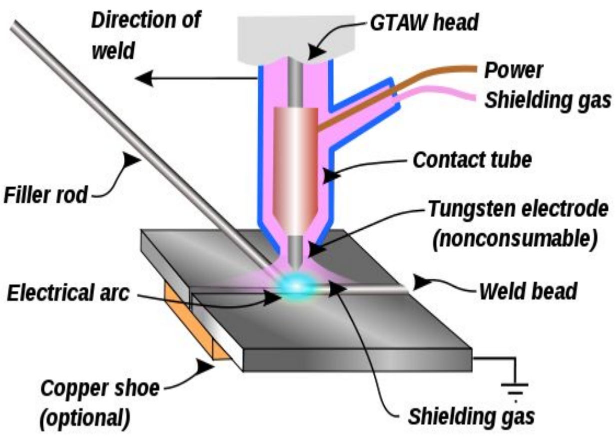


Fig. 2.3 Schematic of TIG welding

2.2.2 Characteristics of TIG

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.

2 . 3 Characteristics of aluminum alloy

2.3.1 Classification of aluminum alloys

Aluminium alloys are alloys in which aluminium (Al) 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 (4.0-13%) 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.

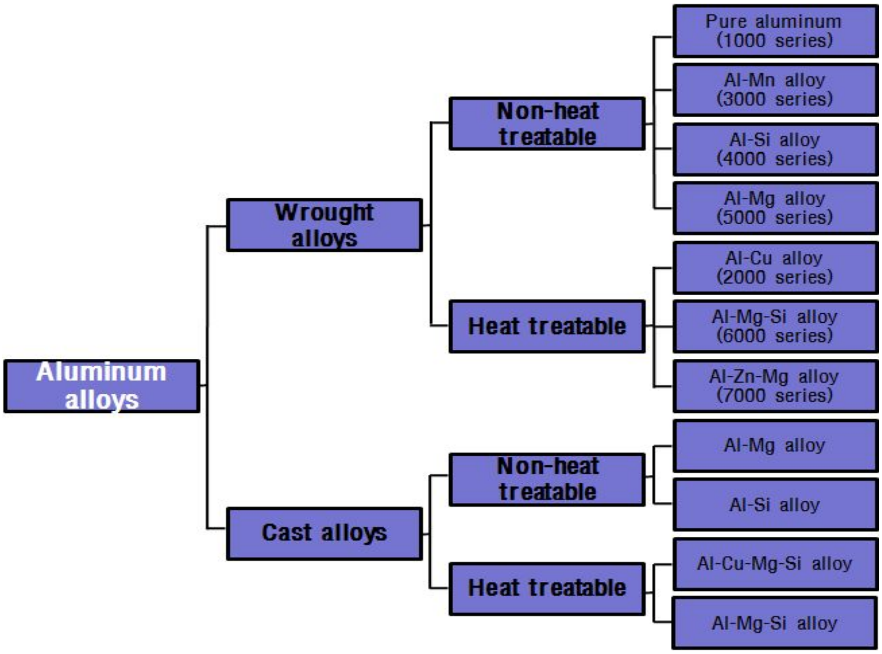


Fig. 2.4 Classification of Aluminum alloys

Table 2.1 Physical properties for aluminium alloys

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-T6

Alloy 6061 is one of the most widely used alloys in the 6000 series. This standard structural alloy, one of the most versatile of the heat treatable alloys, is popular for medium to high strength requirements and has good toughness characteristics. Because It has good mechanical properties and exhibits good weldability. Also, it has excellent corrosion resistance to atmospheric conditions and good corrosion resistance to sea water. So 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) Aluminum nasal cavity (unit weight party decision burglar) because of size, precision instrument Is used plentifully with the structural material of building etc.

2) The aluminum the formation is possible in the form which is various the deformation processing to be easy.

3) The aluminum to be fine from in air and to form the oxidation skim which is stabilized, the skim Prevents the side food. The aluminum alloy which has both a corrosion resistance and the burglar various use Is used.

4) Aluminum as defiant body. Electrical conductivity is a motion about 60% degree, but specific gravity About 3 minutes selfish because of 1 will compare on east of identical weight and the possibility which will lead the electric current of 2 times.

5) The heat conduction ratio of the aluminum opens at about 3 times of

season with the metal which delivers well, air conditioning System, engine part, various heat exchanger and solid color, even beverage can etc. this quality Is applied.

6) The aluminum with the visa adult, does not undergo the influence of the magnetic field. This feature aluminum Justice is a different quality and is light, the corrosion resistance, becomes strong point and the union of etc. the processing characteristic is good, Is applied in the product which is various.

7) The aluminum only will be the metal where the appearance is beautiful knows even with that oneself, the anode oxidation skim According to inflicting a control (Alumite) etc. various surface preparation technique, sees to be beautiful Will come, also, surface, or lightly, a method effect will improve.

8) When using the aluminum in the material of vacuum system, the gas room from metal oneself Compares in the material where the ratio which will dance decease vacuum arrival efficiency is different very and is superior very.

9) Aluminum liquid nitrogen (- 196℃) under pole low temperature of liquid oxygen (- 183℃) There is not brittle fracture and has the strong point where the tenacity is excellent.

10) When the aluminum compares the different metal and, oxidizing, to be difficult, in order for the fusion point to be low, Melts the aluminum product where the use ends and simply, there is will be able to remake.

2 . 4 Characteristics of carbon steel

2.4.1 Classification of carbon steel

The steel divides in the metal element with the resources which is most abundant, according to oil content of the carbon.

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.

From the iron mill the iron ore with the limestone and the coke puts in together in blast furnace inside and heats melts and makes at high temperature. To the pig iron the silicon (Si) and Mangan (Mn), is other than the carbon (C) (P), Hwang (S) etc. to be included, according to oil content of the carbon the nature of steel changes on a large scale.

The carbon other than season the impurity of the different element almost the railroad which is pure is not, the carbon below 0.02% contains in season. The quality of material about juniority is used with the iron core material of experiment, the electric motor, the generator and the transformer. With the metal where the carbon of some contains in season, according to oil content of the carbon the divides.

The railroad where the oil content of the carbon is more the carbon-steel far, with after words keeps a same feature. Bends, or, there is not a nature which extends almost and a possibility of making the product with rolling there is not. Weakly in shock, breakableness to beat there is not a possibility of making the product.

Chapter 3

Experimental Method of TIG Assisted Hybrid FSW Welding Process

3 . 1 Equipment and materials

3.1.1 TIG assisted hybrid FSW welding equipment and experimental setup

FSW system together with 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.

TIG welding torch to preheat the titanium alloy material was attached adjacent to the FSW tool shoulder, inclined at 45 degrees. The electrode tip of TIG is placed at a distance of about 20mm from the FSW tool probe. When the TIG torch is placed near to the tool probe, ie, less than 20mm, the current affects the tool surface and thus the desired preheating is not achieved.

Fig. 3.1 shows the FSW equipment. Fig. 3.2 shows the experimental Setup for TIG hybrid FSW process.

Items		Range
Type		Gentry type
Welding speed	X-axis	0.5~10mm/sec
	Y-axis	0.5~10mm/sec
	Z-axis	0.5~10mm/sec
	R-axis	1~20rpm
Rotation		300~3000rpm
Load Capacity		Max. 3000kgf

Fig. 3.1 FSW equipment

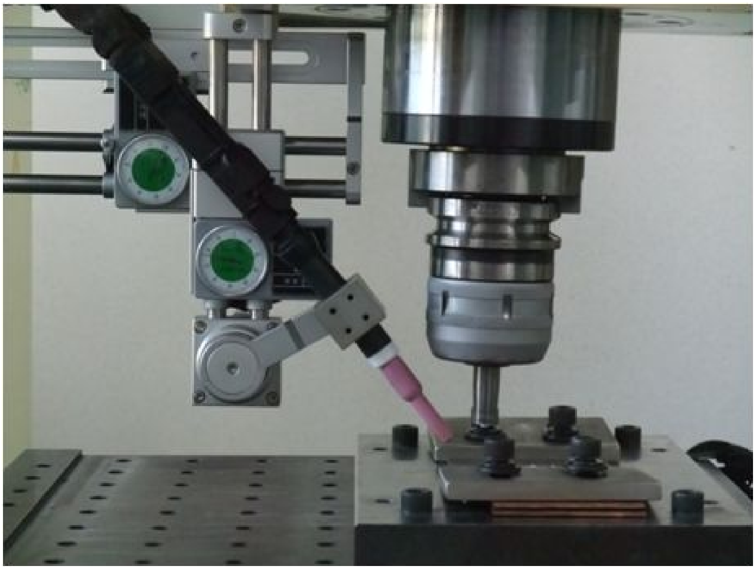


Fig. 3.2 Setup for TIG assisted hybrid FSW welding process

3.1.2 Characteristics of objective materials

The chemical compositions and mechanical properties of the materials for Al6061-T6 abd SS400 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 shows the configuration of the weld specimen.

Table 3.1 Chemical composition and mechanical properties of material used

Material	Chemical composition (Wt%)								
Al6061-T6	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
	0.70	0.64	0.28	0.08	0.37	0.19	0.01	0.05	0.05

Material	C	Si	Mn	P	S
SS400	0.1438	0.009	0.664	0.012	0.0039

Material	Mechanical properties		
	Y.S(MPa)	T.S(MPa)	Elongation(%)
Al6061-T6	300	330	13
SS400	312	450	37

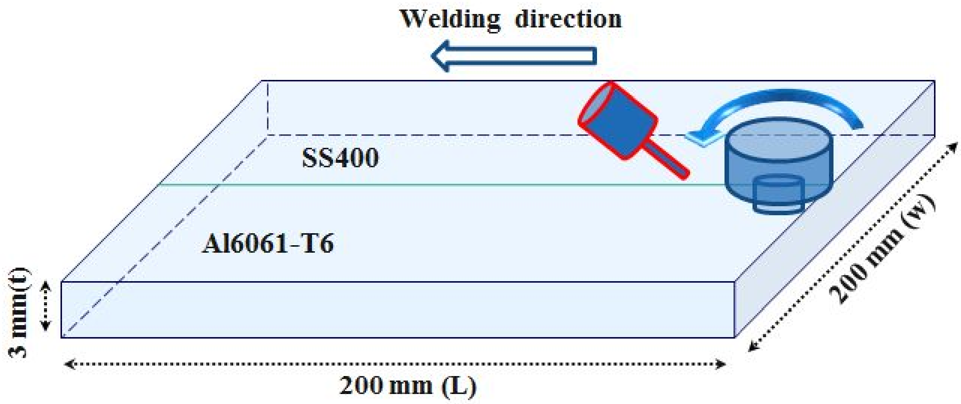


Fig. 3.3 Configuration of welded specimen

3 . 2 Details on FSW tool

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 rod specifications of FSW tool

(a) Tungsten carbide rod specifications

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

- Material : Tungsten carbide (Co:12%)
- Shoulder type : concave shoulder 3°
  (plastic flow and mixture agitation promotion of material)
- Pin type : Smooth frustum

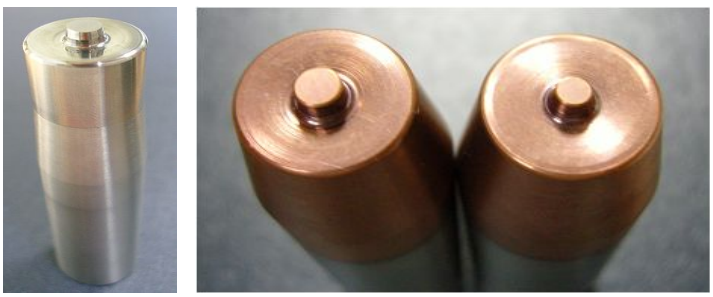


Fig. 3.4 FSW Tool shape

3 . 3 TIG assisted hybrid FSW welding method

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 3.4. 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.

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. 3.6 shows the Schematic of TIG hybrid FSW welding process. Welding condition for TIG hybrid FSW welding process is given in Table 3.4. Fig. 3.6 Fig. 3.7 shows the position of materials, TIG electrode and plunging of tool for TIG hybrid FSW.

Table 3.3 TIG Welding condition

No.	Welding speed (mm/s)	TIG current (A)	TIG pulse current (A)	Shielding gas-Ar (ℓ/min)	Tungsten electrode (mm)	Torch angle (˚)	Bead appearance	Cross section
1	1.0	60	50	7	Φ2.4	60		
2	1.0	70	60	7	Φ2.4	60		
3	1.0	80	70	7	Φ2.4	60		
4	1.0	85	75	7	Φ2.4	60		
5	1.0	90	80	7	Φ2.4	60		
6	1.0	100	90	7	Φ2.4	60		

Table 3.4 Hybrid FSW welding condition

Welding condition		Values
TIG	Current(A)	60 ~ 80
	Shielding gas(L/min)	Ar 7 ~ 10
	CTWD(mm)	s = 5
	Torch angle	60°
FSW	Rotation speed(RPM)	300 ~ 700
	Welding speed(mm/s)	0.4 ~ 1.2
	Shoulder dia.(mm)	Ø18
	Pin dia.(mm)	Ø6.5
	Room temperature	20°
	Tilt angle	2 ~ 3°
TIG-FSW Distance = 16 ~ 20mm		
Leading condition = TIG leading		
Dia. of electrode = 2.4mm		

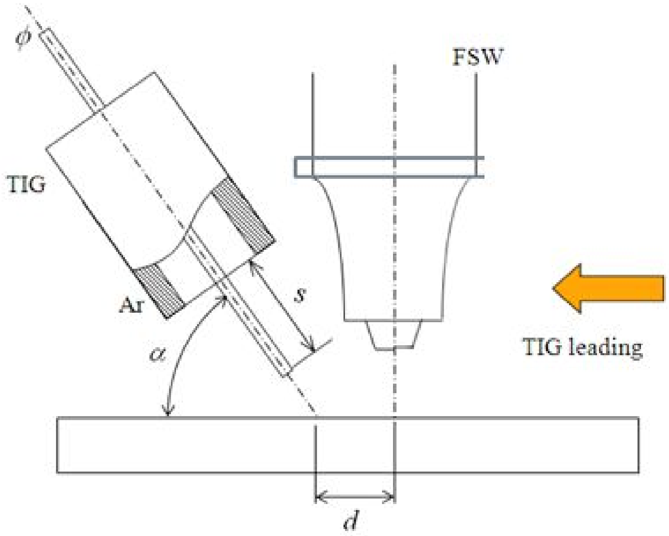


Fig. 3.5 Schematic of TIG assisted FSW welding process

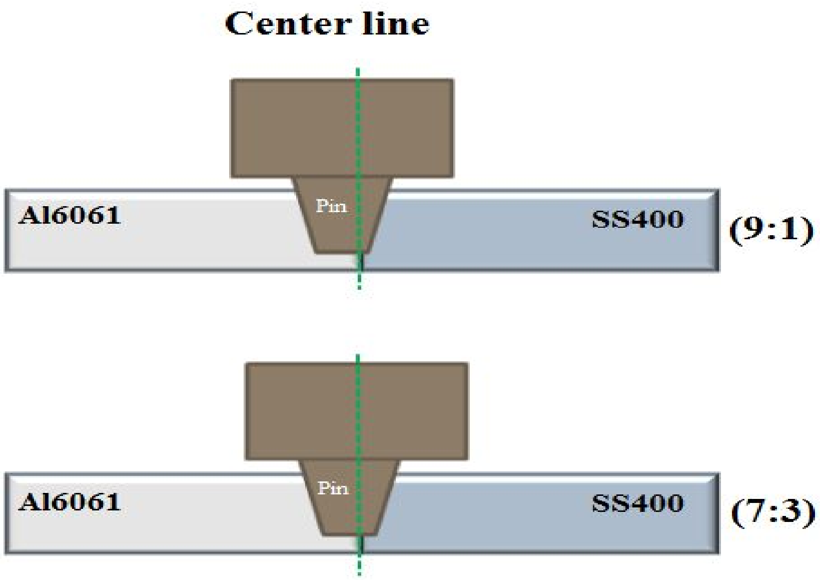


Fig. 3.6 Tool plunge position for TIG assisted FSW welding process

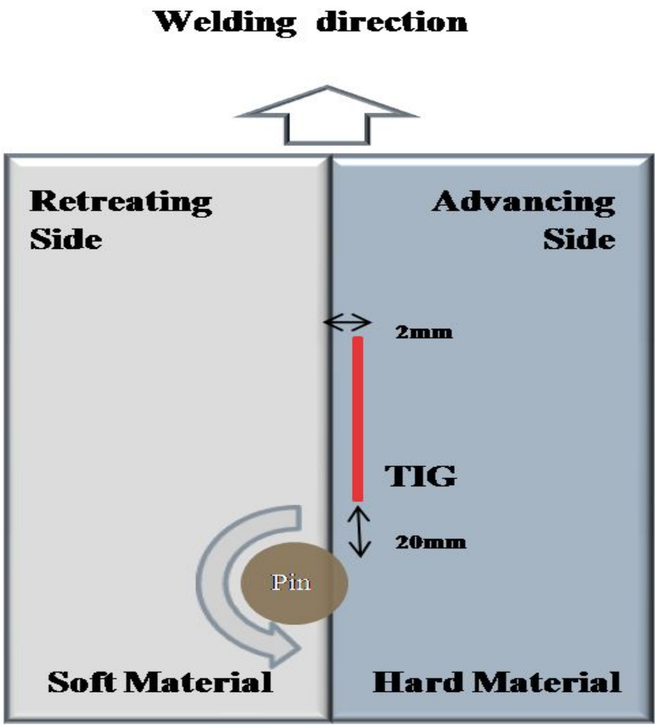
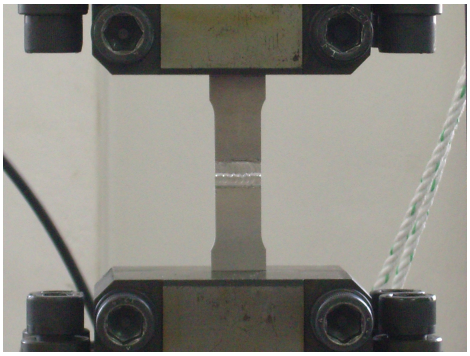


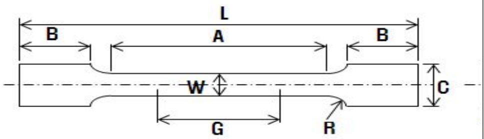
Fig. 3.7 Welding configuration for TIG assisted hybrid FSW process

3 . 4 Mechanical and metallurgical characteristic

3.4.1 Tensile test

Tensile test was carried out with Dongil-Simaz Universal Testing Machine (EHF-EG200KN-40L) using WINSERVO program. Fig. 3.8 shows the EHF-EG200KN-40L and tensile testing set up. The specimens are fabricated in accordance with the Korean standards (KS0801-13-B). The specimen dimensions are given in Tensile test was done with Load speed 0.033mm/sec and stress-strain curve was obtained.





G-Gage length : 60mm
W-Width : 12.5mm
T-Thickness : 3mm
R-Radius of fillet : 20mm
L-Overall length : 170mm
B-Length of grip section : 40mm
C-Width of grip section : 25mm

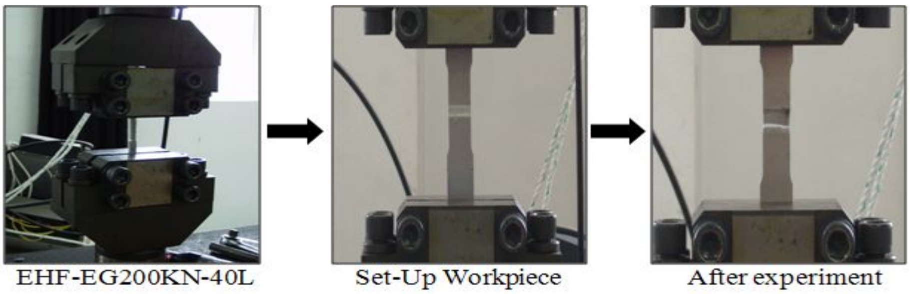


Fig. 3.8 Dimension of tensile test specimen

3.4.2 Hardness test

The hardness test of welded specimen was measured using AKASHI HM-112 vickers hardness tester as shown in Fig. 3.9 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. 3.9 shows hardness measurement points of welded specimen. Hardness profiles were measured along the transverse cross section of welded specimen at the center 1.5mm, bottom 2.5mm and top 0.5mm of the weld zone

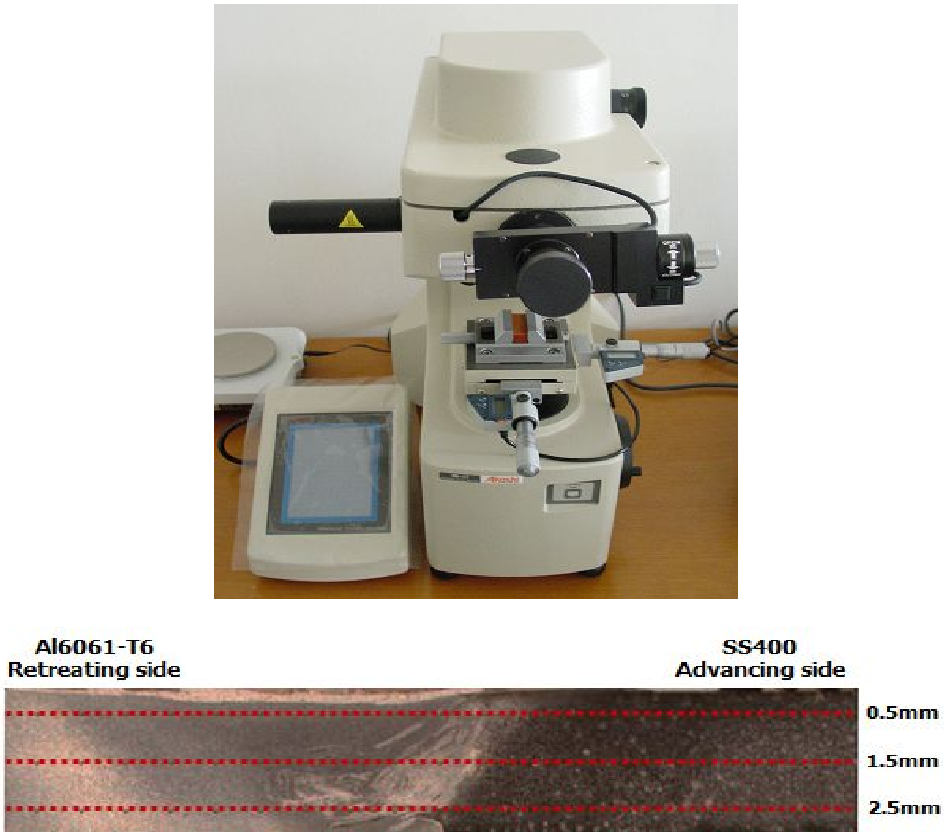


Fig. 3.9 Vickers hardness test machine and specimen

3.4.3 Microstructure analysis

The cross section of FSW welded specimen was cut perpendicular to the welding direction. It was polished with 1 and 3μm diamond suspension. Alumina powder was used as the final polishing solution, and then was chemically etched to observe the microstructure of the joint. Microstructure of the prepared specimen were investigated by OLYMPUS optical microscope as shown in Fig. 3.10

Fig. 3.10 Optical microscope equipment

3.4.4 Temperature measurement

When joining dissimilar materials, temperature gradient test was conducted to determine the temperature distribution near the junction temperature gradient test was conducted to In horizontal direction oblique line processed the hall in the Book of Psalms, after fixing K Type Wire in the hall, Thermo-couple and a for experiment used 5 minutes executed. TIG welding machines which uses with auxiliary heat source the laughter flow which wants is which degree temperature what kind of minute organization from the junction quality which is good and isothermal be visible, in order to observe executed. Fig. 3.11 is to show the equipment which is used in Temperature test specimen by Thermo-couple.

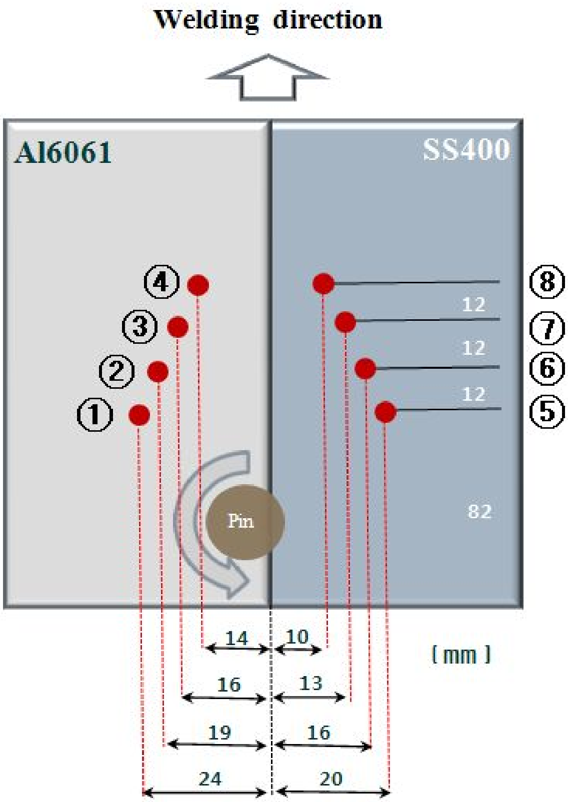


Fig. 3.11 Temperature measurement points in welds by thermo−couple

Chapter 4

Mechanical and metallurgical Characteristics in FSW and TIG Assisted Hybrid FSW welds

4 . 1 Bead profile of FSW and hybrid welds

4.1.1 TIG welds

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 preheating parameters and bead profiles

(a) Preheating parameters

No.	Material	Input point	Welding speed(mm/s)	TIG current(A)	TIG pulse current(A)	Shield gas-Ar (ℓ/min)	Wire (mm)	Torch angle (˚)
1	Al-SS400	center	1.0	80	70	7	Φ2.4 red	60
2	Al-Al	center	1.0	80	70	7	Φ2.4 red	60
3	SS400-SS400	center	1.0	80	70	7	Φ2.4 red	60

(b) Bead profile of preheating

<table>
<tr><th>No.</th><th>Material</th><th>Input point</th><th>Bead appearance</th></tr>
<tr><td>1</td><td>Al-SS400</td><td>center</td><td>
</td></tr>
<tr><td>2</td><td>Al-Al</td><td>center</td><td>
</td></tr>
<tr><td>3</td><td>SS400-SS400</td><td>center</td><td>
</td></tr>
</table>

4.1.2 FSW welds

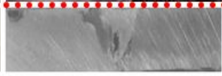
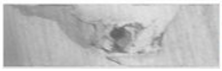
From many trials of experiment carried out on dissimilar joints by FSW, Tool Point only Plunge and with variable examined. best 3 trials was taken in to account and is tabulated as given in Table 4.2(a). Welding parameters of the best 2 trials are shown in Table 4.2(b). Rotation speed of the tool, tool 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. and several preliminary experiments are conducted to determine the appropriate offset of the probe to the butt line. Over 400rpm, from the cross section, 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 experiment sand macro images, tool rotation 400rpm at tool travel speed 1.2mm/s was found good and considered to carry out TIG assisted hybrid FSW welding process 400rpm more heat was generated due to friction at the tool-work piece interface and thus higher amount of SS400 inclusions were found in the Al6061-T6 stir zone.

Table 4.2 Bead profiles of FSW welds

(a) Welding parameters

No.	Material	Tool plunge point (Al/SS400)	Rotating speed (rpm)	Travel speed (mm/sec)	Rotation direction
1	Al-SS400	9:1	400	1.2	ccw
2	Al-SS400	7:3	400	1.2	ccw

(b) Bead surface appearance and cross section of dissimilar joint

rpm	Tool plunge point (Al/SS400)	Travel speed (mm/sec)	Top bead surface	Cross section	Fractured specimens	T.S (MPa)
400	9:1	1.2				315.6
	7:3	1.2				148.3
	7:3	1.2				30.8

4.1.3 TIG assisted Hybrid FSW welds

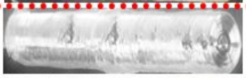
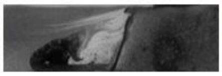
Table 4.3 (a) and (b) shows the TIG hybrid FSW parameters and obtained bead appearance for dissimilar joints of Al6061-T6 and SS400 butt joints. For TIG hybrid FSW process, the best welding parameters obtained from the FSW experiments and TIG preheating BOP test conditions were considered respectively. 3 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, Tool Plunge Point 9:1 excellent bead appearance was obtained and no weld defects was found in the cross section appearance. Above 300rpm tool rotation speed with TIG preheating, more heat was generated due to friction at the tool-work piece interface and thus higher amount of SS400 inclusions were found in the Al6061-T6 stir zone.

Table 4.3 Bead profiles of TIG assisted hybrid FSW welds

(a) Welding parameters

No.	Material	Tool plunge point (Al/SS400)	Rotating speed (rpm)	Travel speed (mm/sec)	Rotation direction	TIG current (A)	TIG pulsed current(A)	Shield gas (ℓ/min)	Torch angle (˚)	FSW-TIG distance (mm)
1	Al-SS400	9:1	300	1.0	ccw	80	70	7	60	20
2	Al-SS400	7:3	300	1.0	ccw	80	70	7	60	20

(b) Bead surface appearance and cross section of dissimilar joint

rpm	Tool plunge point (Al/SS400)	Travel speed (mm/sec)	Top bead surface	Cross section	Fractured specimens	T.S (MPa)
300	9:1	1.0				344.1
	7:3	1.0				153.1
	7:3	1.0				77.8

4.2 Mechanical properties of FSW and hybrid FSW welds

4.2.1 Tensile strength of FSW welds

Tensile test of dissimilar welded joint by FSW was carried out as per Korean standard. The tensile test results reveals that fracture occurs at the dissimilar joining interface as shown Table 4.4. From stress-strain curve, it is evident that the fracture pattern is brittle fracture mode as shown in Fig. 4.1 Maximum tensile strength is obtained for the weld joint made at tool rotation of 400rpm and travel speed of 1.2mm/s and tool plunge point of 9:1

Table 4.4 FSW welded specimen fractured after tensile test

Tool Rotation Speed (rpm)	Tool plunge point (Al/SS400)	Travel speed (mm/sec)	Bead surface	Fractured specimens	T.S (MPa)
400	9:1	1.2			315.6
	7:3	1.2			148.3
	7:3	1.2			30.8

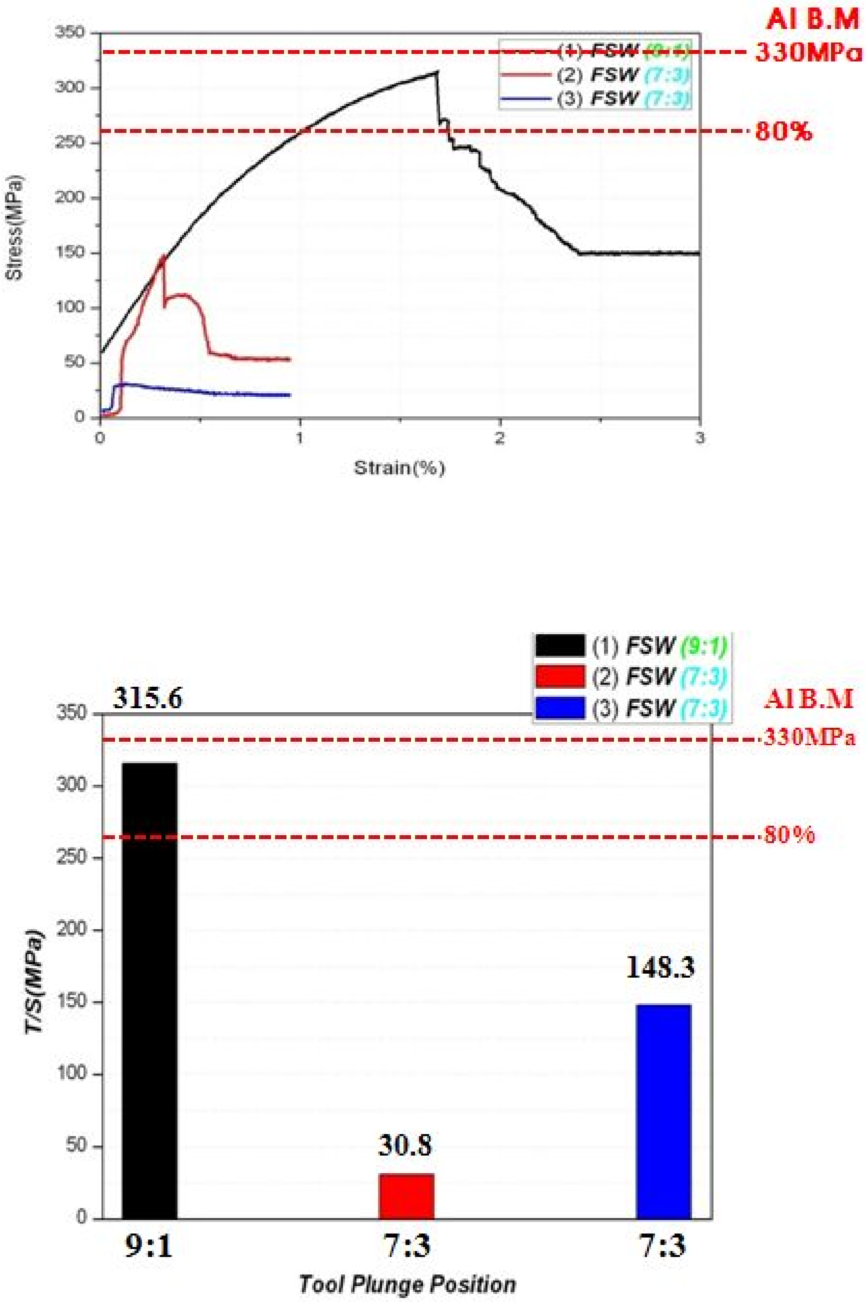


Fig. 4.1 Tensile strength of FSW welded specimen

4.2.2 Tensile strength of hybrid FSW welds

Table 4.5. shows the cross sections and fractured specimens of dissimilar joint by TIG hybrid FSW welding. As observed from the tensile test results, the fracture occurred at the joining interface in welded specimens at 300rpm tool rotation speed and tool plunge point of 9:1 and 7:3. The tensile strength of dissimilar joint by TIG hybrid FSW welding was found 80~90% by that of Al6061-T6 base metal. The maximum tensile strength obtained was 344.1MPa (Al6061-T6 base metal tensile strength 330MPa) over than that of base metal at tool rotation speed of 300rpm, travel speed 1.0mm/s and TIG current 80A. The stress-strain curve Fig. 4.2 shows that the specimen is fractured in a fracture pattern with little cleavage facet fracture When tool insertion points are the 7:3 particles dispersed from steel is in the aluminum increases.

Table 4.5 TIG assisted hybrid FSW welded specimen fractured after tensile test

Tool rotation Speed (rpm)	Tool plunge point (Al/SS400)	Travel speed (mm/sec)	Bead surface	Fractured specimens	T.S (MPa)
300	9:1	1.0			344.1
	7:3	1.0			153.1
	7:3	1.0			77.8

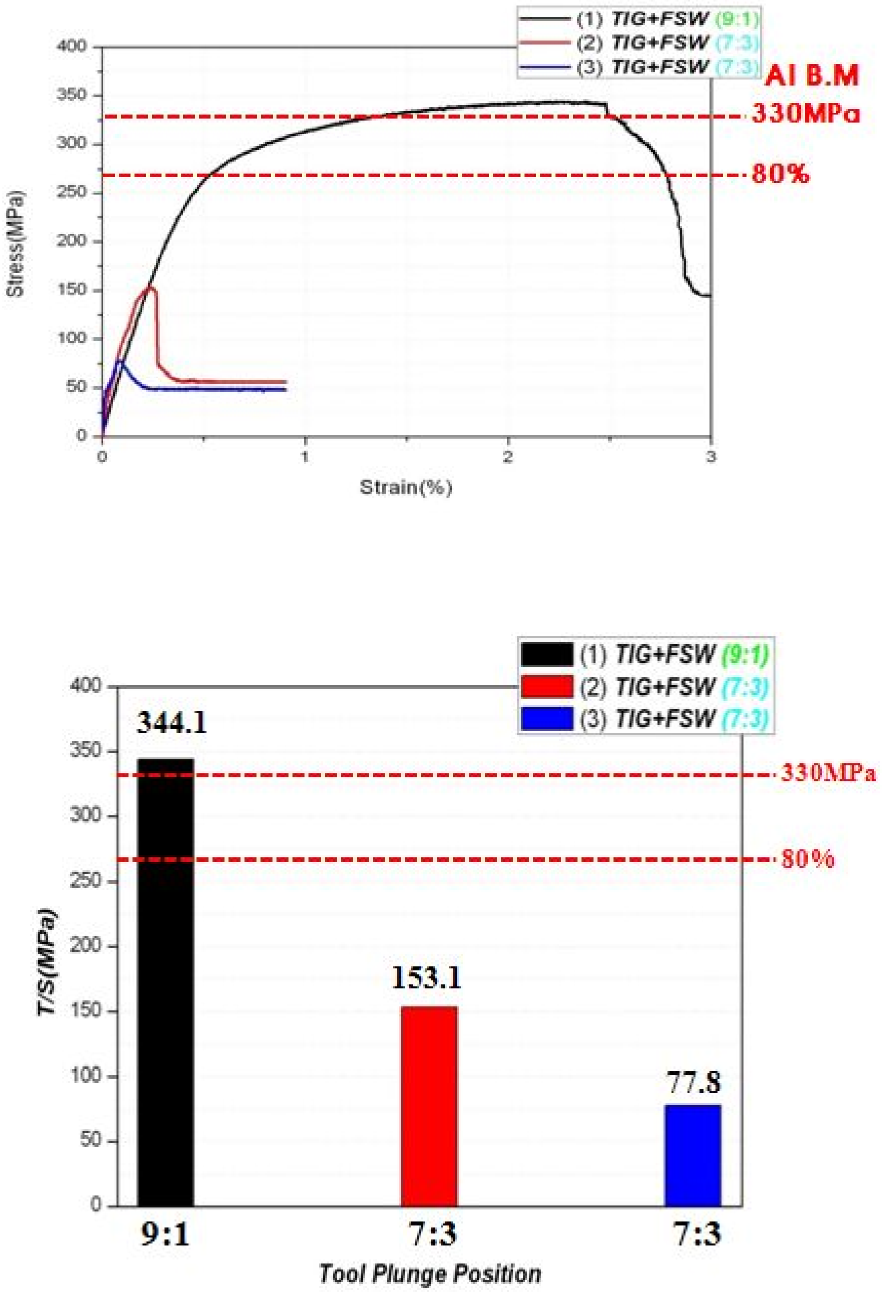
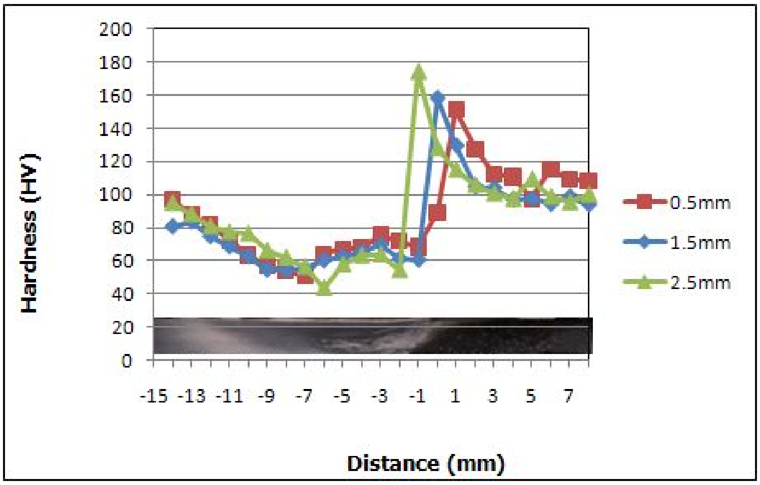


Fig. 4.2 Tensile strength of hybrid FSW welded specimen

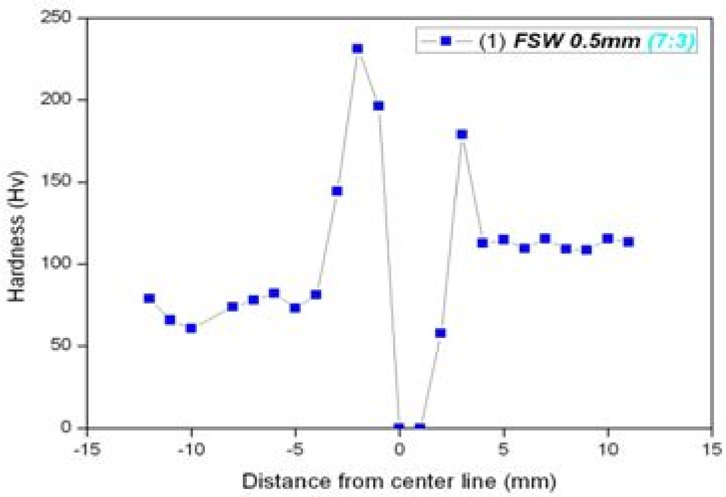
4 . 3 Hardness test results in FSW and hybrid FSW welds

The hardness distributions of dissimilar joints by TIG hybrid FSW welding is shown in Fig.4.3. A drop in hardness from base metal hardness is evident in the welding zone for Al6061-T6. Precipitation hardening alloys such as the Al6061-T6 show a loss of hardness in the HAZ, with some recovery in the nugget because a lower hardness due to the absence of strengthening precipitates at heat affected zone(HAZ) and the dissolved precipitates do re-precipitate or recrystallize subsequently at higher temperatures in the nugget zone. The hardness of Al6061-T6 at the thermo-mechanically affected zone(TMAZ) and stir zone(SZ) is more than HAZ because of the mechanical effect of plastic flow during weld formation.

On SS400, the hardness value at weld zone is more than that of base metal due to work hardening effect by TIG preheating and frictional heating. The base metal hardness of Al6061-T6 and SS400 are respectively. The hardness values HAZ, TMAZ and SZ of Al6061-T6 are respectively. The hardness of the weld nugget shows variable values because of the presence of the fine or coarse dispersed stainless steel particles in the weld nugget. When comparing hardness results(Fig. 4.3 and 4.4) of hybrid FSW welding with FSW at each 9:1 and 7:3 position higher hardness values are found in hybrid FSW welding 9:1 tool plunge position of This is because plastic flow is increased by TIG preheating causing finer recrystallized grains at the TMAZ and SZ.

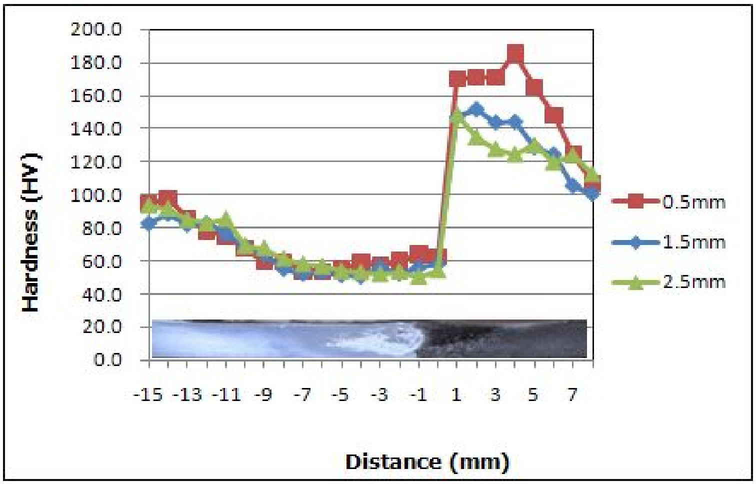


(a) 9:1

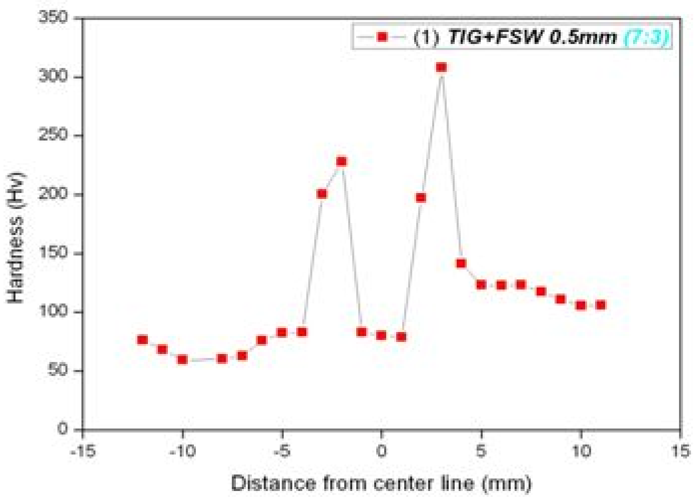


(b) 7:3

Fig. 4.3 Hardness distribution of FSW welds in different tool plunge position



(a) 9:1



(b) 7:3

Fig. 4.4 Hardness distribution of hybrid FSW welds in different tool plunge position

4 . 4 Temperature distribution measurement

The result of an Thermo-couple test for temperature distribution Table 4.6.~4.7. FSW conditions 400rpm, 1.2mm/s and TIG hybrid FSW welding 300rpm, from 1.0mm/s conditions Thermo-couple measurement resultant hybrid FSW welds from Steel sides top 345℃ were measured from highest 306.6℃ aluminium alloy side. From case Steel side of independence FSW the top 226.5℃ was measured from highest 298.7℃ aluminium alloy side. hybrid FSW welds are higher FSW welding was measured and the laughter flow which is caused by with increase of the case more temperature which with this result will use TIG welding machines with auxiliary heat effect according to the fact that gets the welding department which hybrid FSW welds which sees is better. Also from TIG hybrid FSW welds temperature of Steel sides the aluminium alloy appearing more highly the heat conduction ratio the aluminium alloy Steel in order to be better the heat conduction ratio which sees with TIG heat effect is caused by and the more temperature which increases stays to Steel sides and induces the laughter flow which is smooth. There is to reasoning being caused by welding characteristic evaluation and more comes to become feed with the fact that will be the possibility of getting the result which recovers. temperature measurement to do the before and a measurement following and is to show the set up.

Table 4.6 Temperature distribution in FSW welds

Hole position		Tool plunge point (Al/SS400)	Temp. (℃)	
			Start	Max.
Al	1	9:1	18.2	189.8
Al	2	9:1	17.7	234.7
Al	3	9:1	18.1	267.7
Al	4	9:1	17.9	298.7
STEEL	5	9:1	17.9	124.9
STEEL	6	9:1	17.7	153.3
STEEL	7	9:1	17.4	183.4
STEEL	8	9:1	17.9	226.5

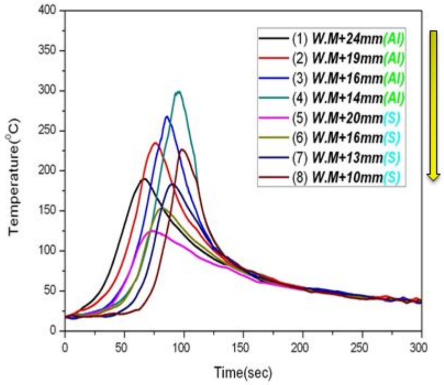
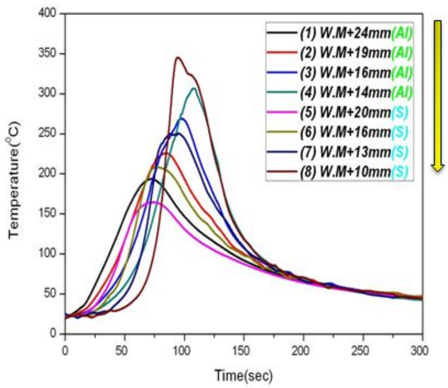


Table 4.7 Temperature distribution in TIG assisted hybrid FSW welds

Hole position		Tool plunge point (Al/SS400)	Temp. (℃)	
			Start	Max.
Al	1	9:1	22.8	193.7
Al	2	9:1	22.7	225.8
Al	3	9:1	22.8	269
Al	4	9:1	22.7	306.6
STEEL	5	9:1	22.9	164.7
STEEL	6	9:1	19.8	208.7
STEEL	7	9:1	24.4	250.5
STEEL	8	9:1	19.8	345



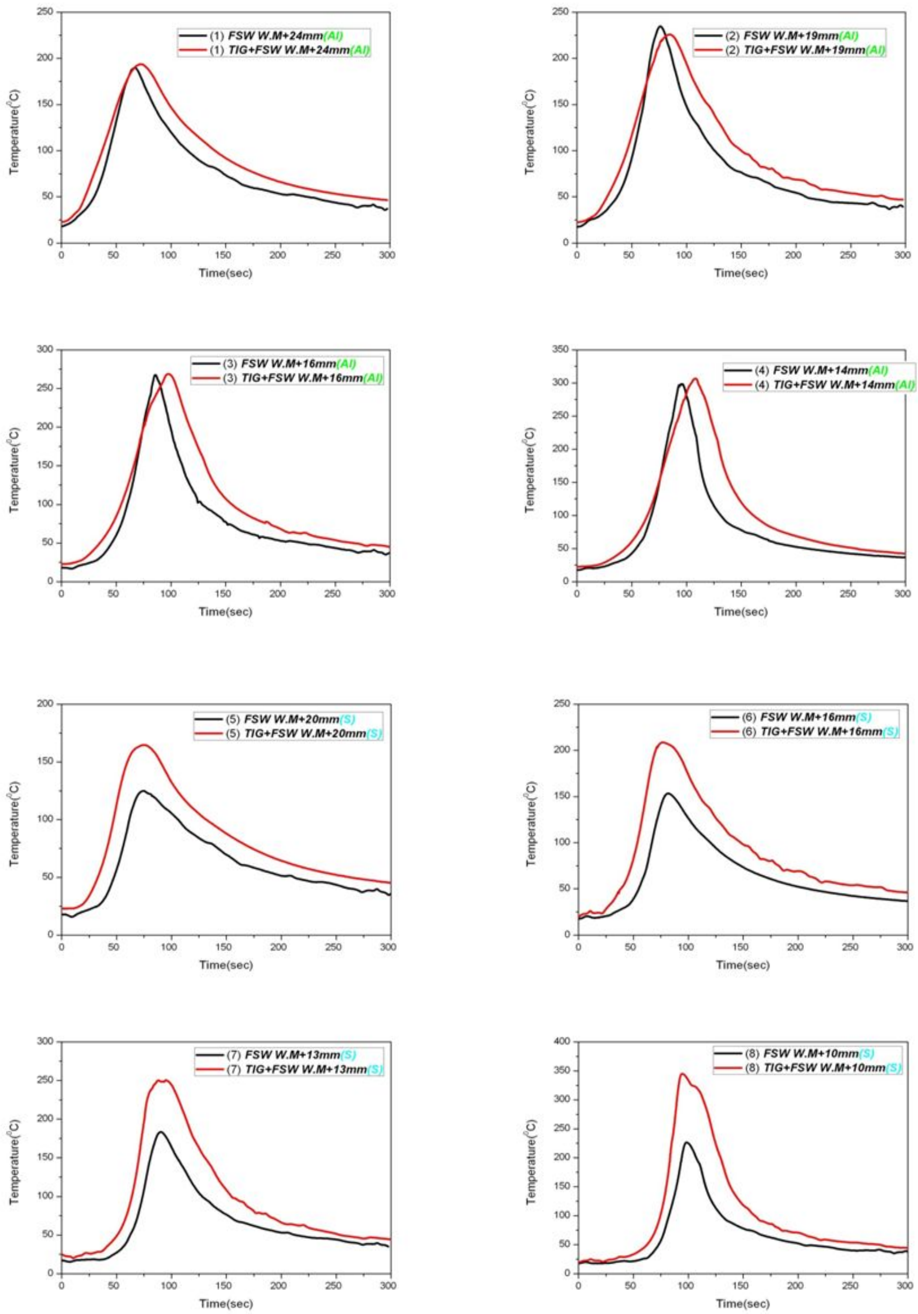


Fig. 4.5 Comparison of temperature distribution in FSW and TIG assisted hybrid FSW welds

4 . 5 Microstructure analysis

4.5.1 Microstructure of FSW welds

Microstructure of FSW welds is shown in Fig. 4.6 The base metal (point 'a') and HAZ (point 'b') exhibits almost similar microstructure. Grain size little bigger in HAZ than base metal. The TMAZ (point 'c') is characterized by a highly deformed structure. The base metal elongated grains were deformed in an upward flowing pattern around the nugget zone. The Al6061-T6 alloy in the weld nugget consists 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 probe 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.

4.5.2 Microstructure of hybrid FSW welds

Microstructure of hybrid FSW welds joints are shown in Fig. 4.7 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 hybrid FSW welds microstructure. At nugget zone, coarse grain size is appeared in hybrid FSW welds when compared to FSW because of more plastic flow due to TIG preheating effect.

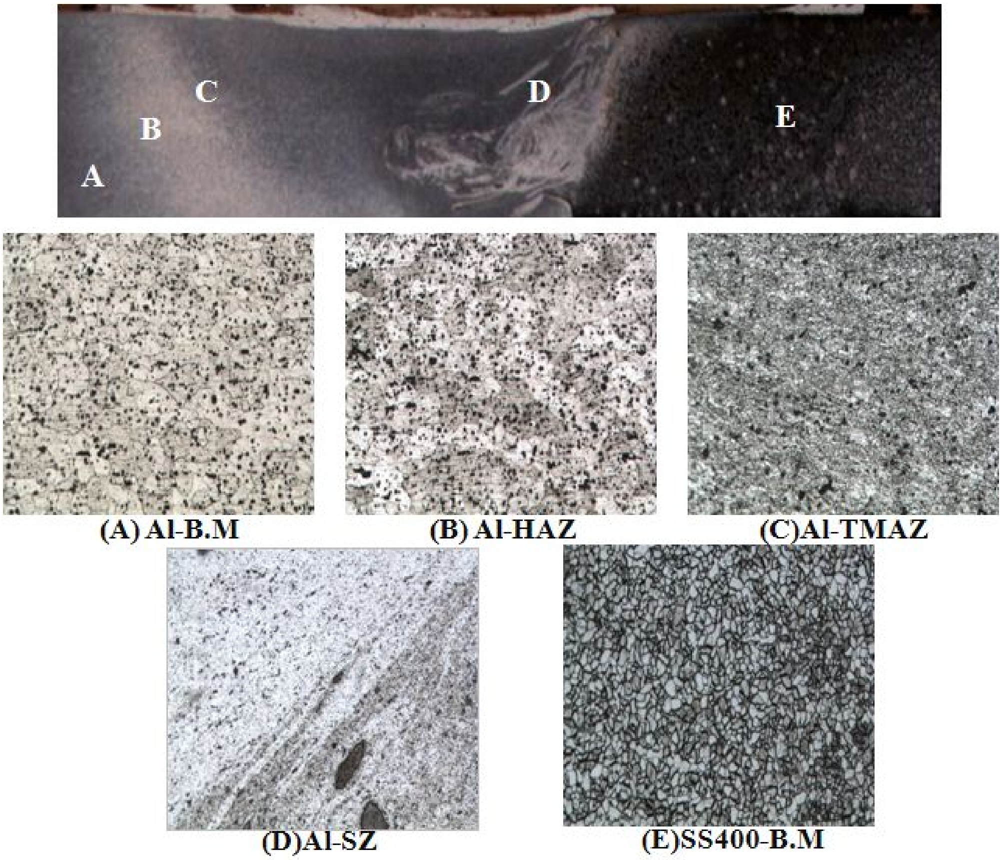


Fig. 4.6 Microstructure of FSW welds

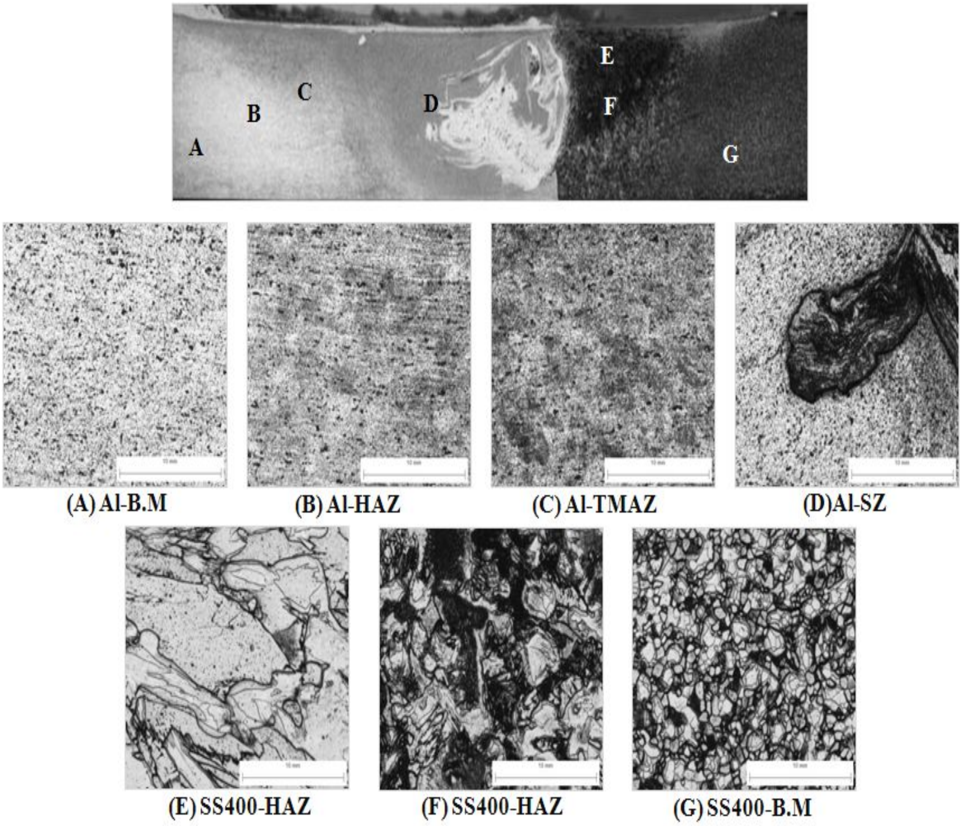


Fig. 4.7 Microstructure of hybrid FSW welds

Chapter 5

CONCLUSION

TIG assisted hybrid FSW welding was successfully carried out to join dissimilar materials (Al6061-T6 and SS400). In order to investigate the weldability of dissimilar materials Hybrid FSW welded joints, mechanical test(tensile test, hardness test, Thermo-couple test) and microstructral analysis have been carried out. Moreover, a comparative study has been carried out between Hybrid FSW welded joints and FSW welded joints. From this study conclusions are made as follows :

1) Because of the maximum plunge 9:1 force area, the heat generation in FSW of dissimilar joints was maximum at Al6061-T6 side which lead to brittle fracture of the weld joints. Hence, TIG hybrid FSW welding process helps to balance the heat generation at both Al6061-T6 and SS400 which increased the tensile strength of the dissimilar materials welded joints.
2) At a tool rotation speed of 300rpm with welding speed 1.0mm/sec, good tensile strength was obtained by TIG hybrid FSW welding. But comparing with FSW, overall welding experimental results of hybrid FSW welding is evident that good weldability can be made between rotation speed 300~400rpm and welding speed 1.0~1.2mm/s.
3) To achieve a good weld joint between Al6061-T6 and SS400, the tool plunge position 9:1 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.

4) The tensile strength of FSW dissimilar materials welded joints is found to be lower than that of TIG hybrid FSW welding at optimum welding conditions. The maximum tensile strength obtained was 344.1MPa for hybrid FSW welding respectively.

5) Thermo-couple measurement resultant TIG hybrid FSW welding compared in independence FSW and the high temperature was measured. When use TIG, is caused by with increase of the case temperature which welding machines with auxiliary heat source is mixed well and according to the FSW the condition whose TIG hybrid FSW welding which sees are better are thought with the fact that gets. Also, from the case welding department vicinity of hybrid welding steel temperatures more highly the aluminium the other difficulty thing the heat conduction ratio sees and with because good the aluminium steel is thought.

6) The hardness values were found different in the weld nugget of dissimilar materials welded joints 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 titanium at advancing side of welded joints. The hardness at the weld nugget across Al6061-T6 bond line are not seriously affected by presence of SS400 deposits.

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저작물 이용 허락서

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논문제목	한글 :마찰교반용접(FSW)과 하이브리드(TIG-FSW)를 이용한 이종재료 알루미늄 합금/연강의 접합특성과 온도분포 비교 영어 :Comparison of Joint strength and Temperature distribution Characteristics in Dissimilar Al6061-T6/SS400 FSW welds and TIG assisted hybrid FSW welds				

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( )

2012 년 2 월

저작자: 전 계 성 (인)

조선대학교 총장 귀하