UNIVERSITI PUTRA MALAYSIA

MECHANICAL CHARACTERIZATION OF AA6061-T6 ALUMINUM ALLOY FRICTION STIR AND TUNGSTEN ARC WELDED WITH AND WITHOUT POST-WELD HEAT TREATMENT

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By

FIROUZ FADAEIFARD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

December 2016

TO

My parents
My wife
My children
My brothers and sisters
My nieces and nephews

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

MECHANICAL CHARACTERIZATION OF AA6061-T6 ALUMINUM ALLOY FRICTION STIR AND TUNGSTEN ARC WELDED WITH AND WITHOUT POST-WELD HEAT TREATMENT

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Chairman: Associate Prof. Khamirul Amin Matori, PhD
Faculty : Institute of Advanced Technology

Friction stir welding (FSW) process is a solid-state method in which is accepted as a favorable joining method for aluminum alloys and other engineering materials. The joining of metal plates in FSW is done at below their melting point temperature and based on a thermo-mechanical action used by a non-consumable welding tool onto metal plates. Despite the fast development in solid state welding, fusing welding such as Tungsten Inert Gas welding (TIG) is still vastly applied for thick joint design. Furthermore, solid state joining such as FSW is not applicable for positions such as overhead, horizontal and vertical. On the other hand, aluminum alloys have been increasingly applied in different industries, therefore, several research works on the manufacturing processes of these alloys have been developed over the time such as joining (welding) processes. The 6061-T6 aluminum alloy is an Al-Mg-Si precipitation hardening alloy from the 6XXX series which is often employed because it presents relatively good mechanical properties in relation to its light weight. Since the microstructure of 6061-T6 aluminium alloy and chemistry as well as dimension and distribution of the intermetallic particles in the matrix of aluminium alloy may be changed owing to heat generated and severe plastic deformation during the welding process. Accordingly, mechanical properties of weldments can be changed after welding as opposed to the base metal. However, the vast part of these changing can be recovered by doing post weld heat treatment (PWHT).

Butt joints of 6061-T6 aluminum alloy were produced by FSW, and the influence of process parameters on their welds quality of weldments in terms of welding defects, microstructure, hardness distribution, and tensile properties by applying the shoulder angle and welding speed in the range of 0-10° and 63-110 mm/min, respectively, have been investigated using NDT, optical microscopy, scanning electron microscopy (SEM) equipped with energy dispersive x-ray (EDX) facilities, XRD, Electron backscatter diffraction (EBSD) and mechanical test such as microhardness test and the tensile test on the welded joints, as the first and second objective. The welding results obtained shown that among all the welding conditions, two welding parameters which is 10°– 89 mm/min and 10°-110 mm/min showed the highest tensile properties (184 MPa for UTS) and higher hardness. Consequently, one of them selected to perform post weld heat treatment (PWHT). In additional to above mentioned characterization, nanoindentation

test was done to find local mechanical and nanomechanical properties in as-weld and PWHT of selected sample (as stated in third objective). The majority of properties were closed to the base metal condition by performing PWHT.

The TIG welding process was performed on 60061-T6 aluminum alloy using ER5356 filler. All above mentioned characterization was performed to find mechanical and nanomechanical properties in as-weld and PWHT conditions. PWHT led to microstructural recovery of the Heat Affected Zone (HAZ) in addition to the appearance of β-phase (Al_3Mg_2) in the grain boundaries of weld zone. The ultimate tensile stress was improved to 204 MPa, even though the improvement in FSW sample (after PWHT) was better with almost 300 MPa.

Final comparison between the effect of these two process on mechanical, metallurgical and nanomechanical properties of 6061-T6 aluminum alloy as well as the effect of PWHT in the properties studied shows better mechanical, metallurgical and metallurgical properties.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENCIRIAN MEKANIKAL BAGI AA6061-T6 ALUMINIUM ALOI KIMPALAN KACAU GESERAN DAN TUNGSTEN ARKA DENGAN DAN TANPA RAWATAN HABA SELEPAS KIMPALAN

Oleh

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Proses kimpalan kacau geseran (FSW) adalah satu kaedah keadaan pepejal yang diterima sebagai satu kaedah yang baik untuk kaedah penyambungan bagi aluminium aloi dan bahan-bahan kejuruteraan yang lain. Penyambungan plat logam menggunakan FSW dilakukan di bawah suhu takat lebur dan berdasarkan tindakan mekanikal-haba yang dihasilkan oleh alat kimpalan ke atas plat logam. Walaupun pembangunan yang pesat dalam kimpalan keadaan pepejal, kimpalan leburan seperti kimpalan Tungsten Gas Lengai (TIG) masih banyak digunakan bagi penyambungan bereka-bentuk tebal. Tambahan pula, penyambungan keadaan pepejal seperti FSW tidak boleh digunakan untuk kedudukan seperti hujung, mendatar dan menegak. Sebaliknya, aluminium aloi semakin digunakan dalam industri yang berbeza, oleh itu, beberapa kerja penyelidikan mengenai proses pembuatan aloi ini telah dibangunkan dari masa ke masa seperti proses penyambungan (pengimpalan). Aluminium aloi 6061-T6 adalah aloi pemendakan pengerasan bagi Al-Mg-Si dari siri 6XXX yang sering digunakan, kerana ia mempunyai sifat-sifat mekanik yang baik jika dibandingkan dengan beratnya yang ringan. Disebabkan mikrostruktur 6061-T6 aluminium aloi dan sifat kimianya, serta dimensi dan pengagihan zarah antara-logam dalam matriks aluminium aloi boleh diubah kerana haba yang dihasilkan dan ubah bentuk plastik yang besar semasa proses kimpalan berlaku. Oleh itu, sifat-sifat mekanikal hasil kimpalan boleh diubah selepas kimpalan dibandingkan dengan logam asal. Walau bagaimanapun, sebahagian besar perubahan ini boleh diperolehi semula dengan melakukan rawatan haba selepas kimpalan (PWHT).

Penyambungan bahagian hujung 6061-T6 aluminium aloi telah dihasilkan menggunakan FSW, dan pengaruh proses parameter kepada kualiti kimpalan bagi hasil kimpalan dari segi kecacatan kimpalan, mikrostruktur, taburan kekerasan, dan sifat-sifat tegangan terhadap sudut bahu dan kelajuan kimpalan masing-masing dalam julat 0-10° dan 63-110 mm/min telah dikaji dengan menggunakan NDT, mikroskop optik, imbasan mikroskop elektron (SEM) yang dilengkapi dengan kemudahan tenaga serakan x-ray (EDX), XRD, pembelauan pancaran balik elektron (EBSD) dan ujian mekanikal seperti ujian kekerasan-mikro dan ujian tegangan pada sambungan kimpalan, seperti yang dinyatakan dalam objektif pertama dan kedua. Hasil kimpalan yang diperolehi menunjukkan bahawa di antara semua keadaan kimpalan, dua parameter kimpalan iaitu

10°-89 mm/min dan 10°-110 mm/min menunjukkan sifat tegangan yang paling tinggi (184 MPa untuk UTS) serta kekerasan yang lebih tinggi. Oleh itu, salah satu parameter telah dipilih untuk dilakukan proses rawatan haba selepas kimpalan (PWHT). Tambahan kepada pencirian yang dinyatakan di atas, ujian nano-indentasi telah dilakukan untuk mencari sifat-sifat mekanik dan nano-mekanikal setempat dalam sampel kimpalan dan PWHT yang dipilih (seperti yang dinyatakan di objektif ketiga). Majoriti ciri-ciri yang diperolehi adalah hampir kepada keadaan logam asal selepas PWHT dilakukan.

Proses kimpalan TIG telah dilakukan ke atas aluminium aloi 60061-T6 dengan menggunakan pengisi ER5356. Semua pencirian yang disebut di atas telah dilakukan untuk mencari sifat-sifat mekanik dan nano-mekanikal dalam kimpalan dan keadaan PWHT. PWHT menunjukkan kepada pemulihan mikrostruktur di zon yang terjejas haba (HAZ) sebagai tambahan kepada kemunculan β-fasa (Al_3Mg_2) di sempadan butiran bagi zon kimpalan. Tegasan tegangan muktamad telah meningkat kepada 204 MPa, walaupun peningkatan di dalam sampel FSW (selepas PWHT) lebih baik dengan hampir 300 MPa. Perbandingan akhir kesan di antara kedua-dua proses pada sifat-sifat mekanik, pelogaman dan nano-mekanikal 6061-T6 aluminium aloi serta kesan PWHT dalam sifat-sifat yang dikaji menunjukkan sifat mekanikal, pelogaman dan nono-mekanikal lebih baik.

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I certify that an Examination Committee met on 4 December 2016 to conduct the final examination of Firouz Fadaeifard on his thesis entitled "Mechanical Characterization of A6061-T6 Aluminum Alloy Friction Stir and Tungsten Arc Welded with and without Post-Weld Heat Treatment" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U. (A) 106] 15 march 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

FSW	Friction stir welding
OM	Optical Microscope
SEM	Scanning Electron Microscope
AFM	Atomic Force Microscopy
EDX	Electron Depressive X-ray
BM	Base Metal (Parent Alloy)
PWHT	Post Weld Heat Treatment
HAZ	Heat Affected Zone
TMAZ	Thermo Mechanical Affected Zone
NZ	Weld Nugget Zone
AS	Advancing side of WNZ
RS	Retreating side of WNZ
SZ	Stir zone
HI	Heat Index
UTS	Ultimate tensile strength MPa
$\omega(\Omega)$	Rotation Speed (rpm)
υ	Welding Speed (mm/min)
α	Shoulder Angle
TWI	The Welding Institute

CHAPTER 1

INTRODUCTION

1.1 Background

Aluminium has been existed and developed Since 115 years ago. American Charles Martin Hall, and a Frenchman Paul Heroult, independently, has developed a process allowing the economical production of aluminium by electrolysis from a fused salt bath in 1900st [1]. All favorable mechanical properties, acceptable corrosion resistance, light weight, appropriate weld-ability, and increased toughness make it more applicable. In recent years, aluminum alloys have become more popular in science and engineering fields according to its unique properties. Nowadays, Aluminum alloys have been increasingly applied in different industries; therefore, several research works in aluminum manufacturing have been developed like the joining processes. Welding, as a fabrication or maintenance process in aluminum alloys has been seen more in the researches of materials and metallurgy [1-5].

In modern industry, there are many different welding methods to join metals, ranging from the conventional oxyacetylene torch welding to laser welding. All types of welding can be divided in two common categories as fusion welding and solid state welding [6-8].

Heat is used in fusion welding processes with or without application of filler metal to unite two metals in molten state. Auxiliary materials such as shielding gas and flux may be used to make or ease the process possibility. Surface preparation is also required. Metal Inert Gas welding (MIG) and Tungsten Inert Gas welding (TIG) are two examples of the process [9-11]. The solid state welding, on the other hand, is the process where joining is produced at temperatures well below the melting temperature of base metal without any need for the filler material. Some examples of solid state welding are friction, explosion, hot pressure, ultrasonic and friction stir welding (FSW). The process has three important parameters: time, temperature and pressure. The last two, depending on the process, can be used individually or in combination to produce the joint [4-6].

1.2 Problem statement

Melting and solidification can cause several defects such as porosity and cracking, and, have negative effects on mechanical properties in both base and weld metal cited as an example of fusion welding disadvantages. However, FSW may possibly present extra potential for aluminum alloys since it can be performed without any toxic fumes, and without some welding defects that related to solidification. It means, since the base metal does not reach the melting point, defects like porosity normally coming from melting are not seen in this process. Moreover, base metals retain a majority of their original properties in addition to the fact that the heat affected zone (HAZ) is very small in comparison with fusion welding techniques [12-14].

Despite the fast development in solid state welding, fusing welding such as TIG is unavoidable for thick joint design. Although recent progress in robotic FSW, it is not easily applicable for some welding positions such as overhead, horizontal and vertical. Furthermore, there are limitations in using of FSW for different joint design. However TIG welding is used for all welding position as well as all welding joint designs. The site application of TIG welding is another benefit of this process compare to FSW [4, 6].

The FSW process includes complex interactions among the process parameters, alloy properties, and tool geometry affecting the final mechanical properties and quality of the weld [12]. The investigations and new researches on the role of process parameters such as shoulder geometry and welding speed on the microstructural development, defect formation, precipitations' role, mechanical properties and quality would be in demand. The proper choice of welding procedure and process parameters will lead to enhancement the mechanical and metallurgical properties [13]. Furthermore, there is no research in the effect of shoulder angle in mechanical properties of friction stir welded joint in heat treatable aluminum alloys.

On the other hand, there are many researches has been done in TIG welding as the most common fusion welding of heat treatable aluminum alloys by using 4-series aluminum alloys (such as ER4043) [6-8]. However, there is a few works by using ER5356 as a filler metal. Even there is no work to investigate precipitation and microstructure by using electron backscatter diffraction (EBSD) and nanoindentation for TIG welded joint.

Among Aluminum alloys, AA6061-T6 as an important heat treatable alloy, and widely used in many industries such as automotive, aerospace and shipbuilding due to good weld-ability, good corrosion resistance and appropriate mechanical properties [1-3, 5-8]. This material has seen in many applications for production such as Boeing's Delta II and Delta IV Expendable Launch Vehicle, Lockheed Martin's external tank for the space shuttle transportation system, and primary structures of ultra-lightweight jets like the Eclipse 500.

This widespread application of AA6061 in industries needs to be technically and scientifically supported by metallurgical and mechanical comparison between FSW and TIG processes. There are some works to evaluate and compare TIG and FSW in aluminum alloys [15, 16]. On the other hand, the local characterization as an effective evaluation, by using indentation and nanoindentation, has recently used in weldments [17]. The nanoindentation analysis can be applied for extract metallurgical and mechanical properties such as elastic modulus and hardness indentation [18]. However, this characterization has not applied yet to compare TIG and FSW in AA6061.

Post weld heat treatment (PWHT) has used to recover mechanical properties after welding. There are many attempts to investigate FSW joint by performing PWHT [19-

22] however, there is lack of knowledge about this comparison and evaluation after PWHT on as-weld samples of these 2 methods (TIG and FSW) and their related joints.

1.3 Objectives

The overall goal of this study is the new attempt to compare mechanical and metallurgical properties of AA6061-T6 TIG and FSW welded joints. The effect of PWHT on these properties are investigated for both welding process as well. It is expected that the goal of this research is to be achieved through the following objectives:

1. To characterize the mechanical and metallurgical properties of friction stir welded joints in different parameters.
2. To find the mechanical and metallurgical properties of selected sample among FSW weldments in as-weld and PWHT conditions.
3. To study the mechanical and metallurgical properties of TIG welded joints in as-weld and PWHT conditions.
4. To compare the metallurgical and mechanical properties of TIG and FSW welded joints.

1.4 Research Scope and Significance

Since there are different methods of welding, and each method includes different parameters, techniques, materials, thickness limitation and post processing. These varieties can consequence a complicated problem. Some scopes have been considered to execute this research.

1. This research is done for TIG welding and FSW.
2. The joint design is butt joint.
3. It is limited to welding 9.6 mm thick AA6061-T6 aluminum alloys for both welding process.
4. The shielding gas in TIG welding is Argon.
5. The variables of FSW are limited to welding speed (less than 110 mm/min) and shoulder angle (0º to 10º).
6. The post weld heat treatment is T6 that has done in less than 5 days after welding.

It needs to be said that the investigation and comparison of these two processes in mechanical characterization are limited to tensile test, microhardness and nanoindentation. Whereas the metallurgical properties are studied by using XRD, optical microscopy, SEM, FESEM and EBSD.

1.5 Thesis Layout

This thesis is organized into 5 chapters. Brief descriptions of the contents of each chapter are given as follows:

1. Chapter 1 includes a brief background, problem statements, objectives, limitations and scopes of this research.
2. Chapter 2 presents a literature review; including aluminum alloys, friction stir welding, TIG welding and indentation.
3. Chapter 3 describes the materials and research methodology used in the study including research design, experimental work, pin and shoulder, characterization method and mathematical formula of nanoindentation..
4. The results and data of FSW, PWHT of FSW sample, TIG and PWHT of TIG weldment are presented in chapter 4.
5. Chapter 5 concludes the findings of FSW and TIG, comparison and recommendation of possible future works.

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