UNIVERSITI PUTRA MALAYSIA

CORROSION BEHAVIOUR OF FRICTION STIR WELDED LAP JOINTS OF 6061-T6 ALUMINUM ALLOY

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By

FARHAD GHARAVI

Thesis Submitted to the School of Graduate Studies,
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Dedicated to ***my father****, and* ***my mother*** for their encouragement throughout my study career. The completion of this work would not have been possible without their support.

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

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FARHAD GHARAVI

October 2014

Chairman: Khamirul Amin Matori, PhD

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Friction stir welding (FSW) process is an emerging "green" solid-state method in which is accepted as a favourable joining method for aluminium alloys and other engineering materials. The joining of metal plates 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. However, the microstructure of aluminium alloy and chemistry as well as dimension and distribution of the intermetallic particles in the matrix of aluminium alloy may be modified owing to heat generated and severe plastic deformation during the welding process. Accordingly, mechanical and corrosion properties of weldments can be changed after welding as opposed to the parent alloy. In this work, lap-welded joints of 6061-T6 aluminium 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 as well as effective plate thickness (EPT) by applying the rotation speed and welding speed in the range of 900-1200 rpm and 20-60 mm/min, respectively, have been investigated using visual inspection, CT-scan, optical microscopy, scanning electron microscopy (SEM) equipped with energy dispersive x-ray (EDX) facilities, and mechanical test such as microhardness test and lap shear tensile test on the lap-welded joints, as the first and second objectives.

The welding results obtained showed that among all the welding conditions, two welding conditions including 1000 rpm–60 mm/min and 900 rpm-40 mm/min were acceptable and desirable weldments with the highest mechanical properties. Thus, corrosion behaviour of acceptable welded lap joints, which was marked as FSLW 1 with 1000 rpm–60 mm/min and FSLW 2 with 900 rpm-40 mm/min welding conditions, has been evaluated as the third objective by potentiodynamic polarization (Tafel and cyclic polarization) and Intergranular corrosion (IGC) tests as well as ex-situ SEM and atomic force microscopy (AFM) examinations.

The IGC test results showed that Intergranular corrosion resistance of heat effect zone (HAZ) was poor compared to weld nugget zone (WNZ) in FSLW 1 and FSLW 2 samples. Tafel polarization test revealed that the corrosion resistance of parent alloy (PA) was higher than the weld regions in FSLW 1 and FSLW 2 samples. The PA, WNZ, and HAZ represented similar corrosion potential values after heat treatment (T6). Cyclic polarization test results for both FSLW 1 and FSLW 2 samples were good agreement with the previous results from the Tafel polarization test. Corrosion behaviour of different positions (top and bottom) of weld nugget zone revealed that the corrosion resistance of the top nugget zone was higher than that of bottom and parent alloy in both FSLW 1 and FSLW 2 samples. Finally, from these results, it is found that the welding process has a major effect on corrosion resistance of weld regions, which is attributed to the breaking down and dissolution of intermetallic particles.

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

TINGKAH LAKU KAKISAN BAGI KIMPALAN GESERAN KACAU PANGKUAN SENDI BAGI 6061-T6 ALOI ALUMINUM

Oleh

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Kimpalan kacau geseran (FSW) adalah suatu proses baru yang ‘hijau’ bagi keadaan pepejal yang sedang diterokai dan diterima sebagai satu kaedah yang baik untuk menyambung aloi aluminium dan bahan-bahan kejuruteraan yang lain. Penyambungan plat-plat logam dilakukan di bawah suhu takat lebur dan berdasarkan kepada tindakan termo-mekanikal yang digunakan oleh alat kimpalan tidak haus ke atas plat-plat logam. Sendi pangkuan aloi aluminium 6061-T6 adalah dihasilkan oleh FSW, dan proses parameter yang mempengaruhi kualiti kimpalan ke atas kimpalan telah disiasat dari segi kecacatan kimpalan, mikrostruktur, taburan kekerasan, dan ketegangan serta tebal plat yang berkesan (EPT) dengan menggunakan kelajuan putaran dan kelajuan kimpalan masing-masing dalam lingkungan 900-1200 rpm dan 20-60 mm/min. Keputusan kimpalan yang diperolehi menunjukkan antara semua syarat kimpalan, dua syarat kimpalan termasuk yang mengunakan kelajuan 1000 rpm-60 mm/min dan 900 rpm-40 mm/min adalah boleh diterima dan mempunyai sifat-sifat mekanikal tertinggi. Oleh itu, syarat kakisan yang diterima untuk kimpalan sendi pangkuan yang ditandai sebagai FSLW 1 dengan 1000 rpm-60 mm/min dan FSLW 2 dengan 900 rpm-40 mm/min, yang telah dinilai sebagai objektif kedua oleh polarisasi “potentiodynamic” (Tafel dan polarisasi kitaran) dan kakisan antara butiran (IGC) serta ex-situ FE-SEM. Keputusan ujian menunjukkan bahawa ketahanan kakisan antara butiran (IGC) dengan kesan haba zon (HAZ) adalah lebih rendah berbanding dengan zon nugget kimpal (WNZ) dalam sampel FSLW 1 dan FSLW 2.

Ujian polarisasi Tafel mendedahkan bahawa rintangan kakisan aloi asal (PA) adalah lebih tinggi daripada kawasan kimpalan dalam FSLW 1 dan FSLW 2. PA, WNZ, dan HAZ diwakili oleh nilai potensi hakisan sama selepas rawatan haba (T6). Keputusan ujian polarisasi kitaran untuk kedua-dua FSLW 1 dan FSLW 2 adalah menghampiri dengan keputusan sebelumnya dari ujian polarisasi Tafel. Tingkah laku kakisan untuk kedudukan yang berbeza (atas dan bawah) dari zon kimpalan nugget mendedahkan bahawa rintangan kakisan zon nugget atas adalah lebih tinggi daripada

bahagian bawah dan aloi bagi kedua-dua aloi FSLW 1 dan FSLW 2. Akhirnya, dari keputusan ini, didapati bahawa proses kimpalan mempunyai kesan yang besar ke atas rintangan kakisan kawasan kimpalan, yang boleh dikaitkan dengan pemecahan dan pembubaran zarah antara logam.

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I certify that a Thesis Examination Committee has met on 14 October 2014 to conduct the final examination of Farhad Gharavi on his thesis entitled "Corrosion Behaviour of Friction Stir Welded Lap Joints of 6061-T6 Aluminium Alloy" 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

AA6061	Aluminium Alloy
FSW	Friction stir welding
OM	Optical Microscope
SEM	Scanning Electron Microscope
AFM	Atomic Force Microscopy
EDX	Electron Depressive X-ray
PA	Parent Alloy
HAZ	Heat Affected Zone
TMAZ	Thermo Mechanical Affected Zone
WNZ	Weld Nugget Zone
AS	Advancing side of WNZ
RS	Retreating side of WNZ
SZ	Stir zone
HI	Heat Index
$\omega(\Omega)$	Rotation Speed (rpm)
υ	Welding Speed (mm/min)
TWI	The Welding Institute
OCP	Open circuit potential
E_{corr}	Corrosion potential
Icorr	Corrosion current (A/cm^2)
I_{pass}	Passivation current density
Epass	Passive potential
E_{pit}	Pitting Potential
E_{prot}	Protection Potential
E_{rp}	Repassivation Potential
E_{ptp}	Pitting Protection Potential
IGC	Intergranular Corrosion
NAMLT	Nitric acid metal loss test
SCC	Stress Corrosion Cracking
wt%	Weight percent
g/l	Gram per litter
mm	Millimetre

μm	Micrometre
A/cm^2	Amber per centimetre square
SCE	Saturated calomel electrode
h	Hour
HV	Vickers Hardness
Kg	Kilogram
kV	Kilo volt
LSM	Laser surface melting
mV	Millivolt

CHAPTER 1

INTRODUCTION

Aluminum and aluminum alloys are widely used in various industries including structural, transportation, shipbuilding, and aerospace. The main reasons for using this material are the result of its favorable mechanical properties, acceptable corrosion resistance, light weight, appropriate weldability, and increased toughness. Recently, aluminum alloys have become very attractive materials for scientists and engineers, and they have been studied extensively due to their beneficial properties [1]. AlMgSi alloys, often referred to as the 6XXX series, are wrought; The strength-to-weight ratio offered by AA6XXX alloys and their enhanced mechanical properties have become crucial criteria for their use in the transport, aerospace, and automotive industry, as well as for architectural and marine applications. The main application is as extruded products and approximately half of all extruded profiles produced worldwide are AlMgSi alloys [2]. AA 6061 (Al-Mg-Si alloy), examined in this study, is a precipitation hardening aluminium 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 aluminium for general purpose use. Applications include construction of aircraft structures, such as wings and fuselages, ship structures, marine frames, pipeline, storage tank, automotive parts, such as wheel spacers. Many aluminium docks and gangways are constructed with 6061-T6 extrusions, and welded into place. Although this kind of aluminium alloy is tried to join by conventional fusion welding processes, but it is difficult to make a joining due to creation of solidification cracking, liquation cracking and micro porosity formation in the fusion zone. Accordingly, Friction Stir Welding (FSW) has increasingly been applied particularly in situations where these defects need to be avoided.

The Welding Institute (TWI) of Cambridge, UK developed Friction Stir Welding (FSW) in 1991 as an emerging green solid state joining process, friction stir welding is used to join Al alloys of all compositions such as alloys essentially considered unweldable [3]. In this process, joining metal plates is done based on a thermo-mechanical action used by a non-consumable welding tool onto metal plates [3]. The material being joined is never melted at any point during the process, which avoids some of the defects seen in fusion welds. Because of this, FSW is seen as one of the most important welding developments in over a decade [4]. FSW process was invented as a replacement method to fusion joining processes for aluminium alloys and other engineering materials. With use of this process, the porosity and hot cracking defects, often generated with fusion welding, are largely eliminated with resulting improved mechanical and corrosion properties.

As a part of the fabrication process, welding is one of the most important manufacturing technologies used in the aluminum alloy industry. Accordingly, the welding of aluminum and its alloys has always represented a great challenge for designers and technologists. As a matter of fact, the main problem associated with this kind of joint process can arise from the focus on heat-treatable alloys because heat, generated by the welding process, is responsible for the decay of mechanical properties by causing phase transformations and inducing softening of the alloy [1,2,4]. It has been shown that minor differences in the composition and microstructure of the weldment can create an electrochemical potential difference between various regions of welded joints and, thus, generates localized galvanic corrosion. It has been demonstrated that the conventional fusion welding process would cause less resistance to corrosion as a result of having many defects on the edges such as high porosity, cracks, residual stress, incorrectly selected filler, and an incorrect design. Elimination of these defects by using friction-stir welding (FSW), which is a solid-state process, substantially increases an alloy’s corrosion resistance [4].

1.1 problem statement

The research presented in this thesis involves a specific weld joint called a lap joint. This weld configuration can be suitable for many industries where the butt configuration is not practical or required. This type of weld joint poses unique challenges not present in other friction stir weld joints. In fact, aerospace structures such as airplane panels, wing frames and floor decks which are regularly supported with stringers, they are usually joined to the outer skins with lap-welded joints [4]. Moreover, many parts in automotive industry such as automotive engine frames, wheel rims, and car back supports are certainly involved with lap-welded joints [4]. Although, butt joint has been considered by many researchers in order to study for it, meanwhile study of friction stir lap welding (FSLW) has received considerably less attention. The corrosion behaviour of the FSW in different aluminium alloy has been examined by a number of researchers. In this case, the most investigation of corrosion behaviour is performed on butt joints and lap configuration joints are rarely considered.

Most AA6XXX alloys are generally considered to have good corrosion resistance compared to other series of aluminium alloy. However, some treatments or processes such as thermo mechanical treatment or alloying have an effect on the localized corrosion alloys. Accordingly, the treatments or processes can lead to create a pitting corrosion and intergranular corrosion (IGC) in the alloys [1-4,7]. In fact, FSW is a thermo mechanical treatment, which combines frictional heating and stirring motion to soften and mix the interface between two metal plates to produce fully consolidated welds [2-4]. Although the heat input in the FSW process is relatively low and the time at temperature is short compared to fusion welding, various grain structures and grains recrystallization phenomena dynamically occurring during the FSW process, 6XXX series of stir welded Al alloy, have different mechanical properties and various corrosion susceptibility in each area of the jointed zone [3-9,12]. The effect of welding parameters on the corrosion resistance in AlMgSi alloys, despite its industrial importance, has not received considerable attention and is not fully understood.

1.2 Research Objectives

Actually, this comprehensive study is the first report attempting to quantify the corrosion evaluation of FSLW in AA6061-T6 aluminium alloy according to welding parameters and process sensitivity. The goals of the present study is to evaluate the influence of FSW parameters mainly ω and ν on the microstructure and mechanical properties of AA6061-T6 and then corrosion behaviors of desirable AA 6061-T6 welded lap joints. In this study, parametric studies were performed involving a lap type of weld including process parameters such as rotation speed (ω, rpm) and welding speed (ν, mm/min). Different rotation speeds and welding speeds were determined according to predefine welding process parameters. Overlap shear tensile testing and micro- hardness measurement was conducted for evaluating the effect of the FSW process on the mechanical properties of weldments. Metallography examinations of weldments structure (i.e. macro and micro) was performed for investigating the influence of the FSW process on the microstructure of AA6061-T6 aluminum alloy. According to ASTM standards, corrosion behaviors of desirable AA 6061-T6 welded lap joints was examined by using various corrosion test methods including immersion test (i.e. intergranular corrosion test, ASTM G110) and potentiodynamic polarization tests (i.e. Tafel plots and pitting scans, ASTM G59 &G61). Optical microscopy (OM), atomic force microscopy (AFM), and field emission scanning electron microscopy (FE-SEM) equipped with dispersive energy X-ray (EDX) analysis were utilized for characterizing the weldment microstructures.

The summery of research objectives are listed as following:

1- To Prepare the AA6061-T6 weldments by friction stir welding process.

This step is including:

1.1 Selection of main welding variable parameters (welding speed and rotation speed)
1.2 Joint design (lap joint)
1.3 Pin designing
1.4 Lap joint fabrication
1.5 Welding performance by use of CNC machine according to welding procedure (different welding and rotation speeds)
1.6 Soundness inspection of lap welded joints by visual inspection and CT-scan

2- To evaluate the sound lap welded joint for selecting the desirable joints.

2.1 Metallography examinations of weldments structure (macro and micro)
2.2 Mechanical properties tests such as micro-hardness test and overlap shear testing

3- To study the corrosion behaviors of desirable AA 6061-T6 welded lap joints by using corrosion test methods such as:

3.1 Immersion test (Intergranular Corrosion (IGC)) (ASTM G110)
3.2 Potentiodynamic polarization tests
3.2.1 Tafel Polarization Method (ASTM G59)
3.2.2 Cyclic Polarization (Pitting Scans) (ASTM G61)

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