FRICTION STIR WELDING OF CRYOROLLED Al 5083 ALLOY: OPTIMIZATION OF PROCESS PARAMETERS USING TAGUCHI TECHNIQUE

By

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Dissertation submitted in partial fulfillment

of the requirements for degree of Master of Science

(Materials Engineering)

JULY 2019

ACKNOWLEDGEMENT

In the name of Allah, the most Gracious, the Most Merciful. First and foremost, all praises to Allah, Who has given me time, patience and courage to finish the project and complete my thesis. Without His blessing, I would not be able to finish my study here.

Despite the fact that it is my name printed on the cover page, I know that none of these pages would existed without the help of some kind people. It is my pleasure to acknowledge all these people. First of all, I would like to thank School of Material and Mineral Resources, Universiti Sains Malaysia for providing comfortable facilities and continuous support. Next, I would like to offer my utmost gratitude to my supervisor Dr. Anasyida Binti Abu Seman @ Hj Ahmad who I considered as my second mom here at Universiti Sains Malaysia that have repeatedly consult me in completed this project. Thank your Dr. Anasyida. Then, I must extend my deepest gratitude to all the staffs and technician in School of Material and Mineral Resources, Universiti Sains Malaysia who has kindly help and guided me to do this research from the beginning until the end of the project especially Mr. Junaidi, Mr Norshahrizol, Mr. Farid, Mr. Shahrul Ami, Mr. Hasnol, Mr. Syafiq, Mr. Mokhtar, Mr. Azrul and Mr. Syahid. Not a day went by when I did not feel the love and support from my family, siblings and friends. To my father, Anuar Bin Jusoh thanks you for unrelenting belief in me. To my mother, Norazlina Binti Muhammad Ali thanks you for all the support. I am also indebted to every individual for their involvement directly or indirectly throughout this project. I really appreciate their relevant and constructive comment. Thank you for all kindness, friendship and moral support during my research study. I am forever grateful for all your welcomed distractions, kind words and continued awe and amazement that I would one day be a Master of Science (Materials Engineering) holder.

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LIST OF ABBREVIATIONS

FSW	Resistance Spot Welding
AA5083	Aluminium 5083 alloy
SPD	Severe Plastic Deformation
ARB	Accumulative Roll Bonding
CR	Cryorolling
ECAP	Equal Channel Angular Pressing
CGP	Constrained Groove Pressing
UFG	Ultrafine Grained
NZ	Nugget Zone
TMAZ	Thermo Mechanically Affected Zone
HAZ	Heat Affected Zone
BM	Base Metal Zone
FESEM	Field Emission Scanning Electron Microscope
EDX	Electron Dispersive X-ray
UTM	Universal Testing Machine
XRD	X-ray Diffraction
S/N	Signal to Noise
ASTM	American Society for Testing and Materials

DOE	Design of Experiment
OA	Orthogonal Array
SSQ	Sum of square of reciprocal
MSSQ	Mean of sum of square of reciprocal
ANOVA	Analysis of Variance
WE	Working Electrode
CE	Counter Electrode
RE	Reference Electrode
SCE	Saturated Calomel Electrode
SHE	Standard Hydrogen Electrode

LIST OF SYMBOLS

nm	Nanometer
GPa	Gigapascal
MPa	Megapascal
HV	*Vickers Hardness scale*
°C	Degree Celcius
g/cm3	Gram per Cubic Centimeter
kgf	Kilogram-Force
E_{corr}	Corrosion Potential
I_{corr}	Corrosion Current
mm/year	Milimeter per Year
wt. %	Weight Percentage
µm	Micrometer

KIMPALAN GESERAN TERADUK KRIOGELEKAN ALOI Al 5083: PENGOPTIMUMAN PARAMETER-PARAMETER PROSES MENGGUNAKAN TEKNIK TAGUCHI

Aloi aluminium mempunyai ira halus telah menarik dalam aplikasi struktur kerana sifat mekanikal yang sangat baik. Walau bagaimanapun, halangan terbesar untuk penyambungan aloi Al ira halus menggunakan kimpalan leburan adalah pembesaran saiz ira yang akan mengurangkan sifat mekanikal aloi Al berira halus. Kimpalan geseran teraduk merupakan satu teknik penyambungan yang dikehendaki kerana ia dapat mengekalkan mikrostruktur ira yang halus. Tujuan kajian ini adalah untuk mengkaji parameter proses kimpalan geseran teraduk aloi kriogelekan Al 5083. Sebelum proses kimpalan geseran teraduk, aloi Al 5083 telah di kriogelek sehingga 50 % pengurangan untuk menghasilkan struktur ira yang sangat halus. Daripada corak XRD, aloi Al 5083 yang telah di kriogelek mempunyai saiz kristalit yang lebih kecil (15.85 nm) berbanding dengan aloi Al 5083 yang asal (81.75 nm). Parameter kimpalan geseran teraduk yang dikaji adalah kelajuan putaran (600 rpm, 865 rpm and 1140 rpm) dan sudut condong (1.5˚, 2˚ and 3˚). Teknik Taguchi L9 tatasusunan ortogon telah diaplikasikan untuk menentukan proses parameter yang paling berpengaruh yang mana akan menghasilkan kekerasan yang tertinggi pada zon kimpalan (ZK) berbanding dengan zon terkesan haba (ZTH) dan logam asas (LA). Melalui cara reka bentuk parametrik Taguchi, proses parameter tahap optimum ditentukan dan efek bilangan pas telah dikaji. Pencirian termasuk kekerasan, kekuatan tegangan, kekuatan lenturan dan ujian kakisan. Kekerasan tertinggi pada zon kimpalan (224.21 HV) telah dicapai dalam eksperimen 5 dengan kelajuan putaran 865 rpm dan sudut condong 2˚. Kesan interaksi kelajuan putaran dan sudut condong menunjukkan kekerasan maksimum (63.2 HV, 61.7 HV) pada 865 rpm dan 3˚, kemudian menurun kepada (53.0 HV, 55.8 HV) pada 1140 rpm dan 1˚. Pengurangan pada kekerasan

pada 1140 rpm adalah disebabkan kelajuan putaran yang tinggi dan menyebabkan kadar penyejukan menjadi perlahan disebabkan zon kimpalan mencapai suhu yang lebih tinggi, menghasilkan ira yang lebih besar (220 μm) pada 1140 rpm dan ira yang lebih kecil (110 μm) pada 865 rpm. Tren yang sama juga dapat dilihat dalam kekuatan tegangan dan kekuatan lenturan untuk kesan interaksi pada kelajuan putaran dan sudut condong. Pada kelajuan 865 rpm, kekuatan tegangan dan kekuatan lenturan tertinggi (185.43 MPa, 208.26 MPa) telah diperolehi berbanding pada kelajuan 600 rpm dan 1140 rpm disebabkan haba yang mencukupi dalam memastikan aliran bahan yang lancar untuk menggalakkan penyambungan yang baik. Sementara itu, sudut condong 3˚ menunjukkan kekuatan terbaik untuk ketegangan dan kelenturan disebabkan daya tempaan yang tinggi yang menyebabkan ubah bentuk plastik yang tinggi dan ira yang lebih halus. Semua sampel menunjukkan sampel patah dalam keadaan mulur dan rapuh. Berdasarkan nilai nisbah S/N dan purata tertinggi untuk faktor A dan B, keadaan optimum kesuluruhan adalah A2 (865 rpm) dan B3 (3º). Kesan bilangan pas pada sampel optimum menunjukkan dua bilangan pas mempunyai kekerasan (75 HV), kekuatan ketegangan (282.54 MPa) dan kekuatan lenturan yang terbaik tetapi mempunyai kadar kakisan yang paling tinggi (1.816 x 10^{-2} mm/year).

FRICTION STIR WELDING OF CRYOROLLED Al 5083 ALLOY: OPTIMIZATION OF PROCESS PARAMETERS USING TAGUCHI TECHNIQUE

ABSTRACT

Ultrafine-grained (UFG) Al alloys have attracted great attention for structural applications because of their excellent mechanical properties. However, the major restriction in joining of UFG Al alloys using fusion welding is coarsening of UFG which deteriorates the mechanical properties of the UFG Al alloys. Friction stir welding (FSW) is found to be a desirable joining technique for UFG materials, since it retains the fine grained microstructure. This study was aimed to investigate the FSW process parameter of cryorolled Al 5083 alloy. Prior to FSW process, as received Al 5083 alloy was cryorolled up to 50% reduction to produce UFG structure. From the XRD pattern, the cryorolled Al 5083 alloy has a smaller crystallite size (15.85 nm) compared with as received (81.75 nm). The FSW welding parameters investigated are rotational speed (600 rpm, 865 rpm and 1140 rpm) and tilt angle (1.5˚, 2˚ and 3˚). Taguchi technique L9 orthogonal array was applied to determine the most influential processing parameter which will yield the highest hardness (nugget zone), tensile strength and flexural strength of FSW cryorolled Al 5083 alloy. Through the Taguchi parametric design way, the optimum levels of process parameters were determined and effect number of passes were studied. Characterization include hardness, tensile strenth, flexural strength and corrosion test. In microhardness study, all the experiments show the highest hardness at the nugget zone (NZ) compared to heat affected zone (HAZ) and base metal (BM). The highest hardness in NZ (224.21 HV) was achieved in experiment 5 with rotational speed of 865 rpm and tilt angle of 2˚. The interaction effect of rotational speed and tilt angle showed that the hardness maximum (63.2 HV, 61.7 HV) at 865 rpm and 3˚, then decreased to (53.0 HV, 55.8 HV) at 1140 rpm and 1˚. Decreasing in hardness at 1140 rpm is due to high rotational speed

and, cooling rate become slower as NZ reach higher temperature, thus produces coarser grain (220 μm) at 1140 rpm and smaller grain (110 μm) at 865 rpm. The same trends were observed in tensile and flexural strength for the interaction effect of rotational speed and tilt angle. At 865 rpm the highest tensile strength and flexural strength (185.43 MPa, 208.26 MPa) was obtained as compared to 600 rpm and 1140 rpm due to sufficient heat which ensure smooth material flow to promote good joining. While, the tilt angle of 3˚showed the best strength for tensile and flexural due to high forging force which caused high plastic deformation and finer grain. All the samples showed ductile and brittle mode of fracture. Based on the highest values of the S/N ratio and mean levels for the significant factors A and B, the overall optimum condition obtained were A2 (865 rpm) and B3 (3º). The effect of number of passes on optimized samples showed that two number of passes have the highest value of hardness (75 HV), tensile strength (282.54 MPa) and flexural strength (307.13 MPa) but the highest corrosion rate (1.816 x 10^{-2} mm/year).

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

Aluminum nowadays is used for numerous engineering applications and design application because of the high strength to weight ratio criteria. The unique properties of aluminum alloys such as ecological friendly, good weldability, high strength and good corrosion resistance made them a good candidate for replacing heavier alloy that currently used in industries such as automotive and structural (Krishna et al. 2015). One of the advantages of pure aluminum that make it being used in forming process is due to the fact that it has high ductility and good ratio of Young's modulus to mass density especially if the grain size is reduced significantly (Hamid et al. 2015). Nowadays, around 48% of aluminium alloy that used in research and industries are in the form of plates and sheets (Krishna et al. 2016). This type of alloy become increase in number as many researchers tend to improve their mechanical properties such as toughness and strength. This mechanical properties such as toughness and strength could be improved by altering the grain size of the material and make it more refined. By reducing the size of grain of bulk Al alloys to more refined grain could increase its mechanical properties.

With the ultrafine grained metals development are increasing rapidly, severe plastic deformation (SPD) techniques namely rolling have become important. The common SPD techniques used are equal channel angular pressing (ECAP), accumulative roll bonding technique (ARB), constrained groove pressing (CGP) and cryorolling (CR) were also considered as SPD techniques. The ARB and ECAP required a special processing equipment (in differential speed rolling), and limited size (Liu et al. 2014). In order to overcome this constraint (special processing equipment and limited size) rolling was done at cryogenic temperature where the low temperature is maintained by using liquid nitrogen (Yu et al., 2013). Cryorolling was identified as a viable route to produce a large scale product with ultrafine-grain size. During the cryorolling process, there is a phenomenon called suppression of dynamic recovery which increased the strength of the material. Dynamic recovery occur when dislocation is annihilated due to the ease of cross-slip or climb of dislocations. However, during cryorolling, dynamic recovery was suppressed (the mobile dislocations are restricted making the cross-slip or climb of dislocations become difficult). The higher number of dislocation generated and thick dislocation walls created as the dislocations present within the grain interiors (Hilditch et al., 2009). The dislocation walls further agglomerated into subgrain boundaries. A great amount of strain-induced boundaries (SIB) produced by formation and rearrangement of dislocations contribute to the sub-micron grains sized in UFG materials forming (Mishra et al. 2015). In addition, high formation of higher density dislocation was found in cryrolling compared with other severe plastic deformation techniques. This high density of dislocation will act as driving force that will produce sub-microcrystalline or ultrafine grained material. (Panigrahi et al, 2008).

The major restriction of UFG metals in industrial application is the reliability of welding process that could retain UFG structure without losing their nanoscale structure and its properties. A traditional welding process based on melting is not practical because this occurs at high temperature which destroys the UFG structure and results in larger grain size. This also will reduce the mechanical strength at the joining line of the workpieces. In this work, Friction Stir Welding (FSW) was chosen as an innovative bonding technique to weld aluminium alloy. FSW take place in solid state whereby the melting temperature of the material does not reach the melting point of the base metal, hence the metal does not completely melt (Gibson et al, 2014). FSW was invented back in 1991 and it is a versatile, ecological friendly and energy efficient. Compared to SPD, FSW also can be considered as one of plastic deformation process which altered the grains of the parent metal (PM) to fine grain structure. Moreover, excellent mechanical properties and fine grain structure of UFG Al alloys can be retained even after FSW. Up to now, many kinds of aluminium alloys from the commercial pure aluminium to highly alloyed 2xxx and 7xxx series was successfully joined by friction stir welding. In addition, compared to other welding technique, FSW have relatively lower temperature rise and therefore can be considered the best choice for joining and welding of UFG materials.

1.2 PROBLEM STATEMENT

Recently, joining UFG aluminium and its alloys using FSW is the subject of interest by many researchers. Plates with more refined structure could be obtained during accumulated roll bonding (ARB) (Sun et al. 2009; Topic et al. 2009) or constrained groove pressing (CGP) (Khorrami et al. 2012) were joined using FSW. Sun et al. (2009) reported that the hardness of the nugget zone of accumulative roll bonded (ARBed) aluminum 1050 sheets has been decreased due to the grain growth in this nugget zone. Topic et al. (2009) examined the hardness and microstructure of ARBed AA 1050 and AA 6016 aluminum sheets using FSW technique. It was confirmed that the fine grained microstructure can be maintained within the nugget after FSW. In addition, Khorrami et al. (2012) have investigated the CGPed commercial purity aluminum sheets welded using FSW at different welding conditions such as rotational and traverse speeds. For severely deformed specimen by CGP, a reduced in hardness was noticed at the nugget zone compared to that of base metal due to thermal instability resulted from high stored energy during CGP. Moreover, strength of CGPed samples reduce with increasing in rotational speed due to grain growth phenomenon. In addition, Sato et al. (2004) investigated the microstructure of stir zone and hardness of samples that is subjected to 6 cycles of ARB processes followed by FSW. It has been reported a slight reduction of hardness in the ARBed samples at the nugget zone occurs after the FSW process.

Parameters of the FSW process for UFG Al alloy are crucial to obtain quality and properties of joints. For example, shoulder diameter, tool travel, tool rotational speeds and tool tilt angle have been investigated by several researchers using conventional parametric design approach. This method is time consuming. Taguchi statistical design is one of the great tool to detect significant factor from various factors with less number of experiment. A number of work on optimization of FSW aluminium alloy have been reported in literatures (Bayazid et al. 2015; Koilraj et al. 2012; Shojaeefard et al. 2014; Panda et al. 2015; Ugrasen et al. 2018). However, it appears that the optimization of FSW process parameters of aluminium alloy processed by cryorolling using Taguchi method has not been reported yet. Considering the above facts, the Taguchi L9 method is adopted to analyze the effect of FSW process parameters (rotational speed, tilt angle) for optimum hardness (NZ), tensile strength and flexural strength of friction stir welded joints of Al 5083 alloy processed by cryorolling.

1.3 OBJECTIVES

The objectives of this research are as follow:

1. To determine the mechanical properties of cryorolled Al 5083 alloy joints with different combination of welding parameters.
2. To optimize the friction stir welding process parameters; rotational speed and tilt angle of cryorolled Al 5083 alloy using Taguchi technique.
3. To investigate the effect of number of passes on microstructure, mechanical properties and corrosion properties of cryorolled Al 5083 alloy.

1.4 SCOPE OF RESEARCH

In this study, the as received Al 5083 alloy with thickness 5 mm was cryorolled up to 50% reduction to produce ultrafine grained (UFG) Al 5083 alloy. The as received and cryorolled Al 5083 alloy were characterized for microstructure analysis and crystallite size. The cryorolled sample were fabricated by friction stir welding (FSW) using different process parameters such as tool rotational speed (600 rpm, 865 rpm and 1140 rpm) and tool tilt angle (1°, 2° and 3°) under constant travel speed. FSW joints was characterized using optical microscope to reveal the weld joint quality. Hardness of the joint also was determined using Vicker microhardness. Instron Universal testing machine was used to determine the tensile and flexural properties of FSW joints. Tensile tested sample then was observed using field scanning electron microscope (FESEM) to observe the fracture morphology. Then FSW process parameter was optimized using Taguchi technique. Next, effect of different number of pass on the optimize samples were evaluated and characterized by testing machine mentioned before. Lastly, corrosion resistance of the joint also was determined using potentiodynamic polarization test.