UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

THE OPTIMIZATION OF T6 HEAT TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF THIXOFORMED LM4 ALUMINIUM ALLOY

Mohd Azizul Hikmi bin Safian

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MOHD AZIZUL HIKMI BIN SAFIAN

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DECLARATION

I declare that this thesis entitled "The Effect of T6 Heat Treatment on Microstructure and Mechanical Properties of Thixoformed LM4 Aluminium Alloy" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.

Signature : …………………………….

Name : …………………………….

Date : …………………………….

DEDICATION

To my beloved parents,

Hj Safian bin Hj Kasim

Hjh Faidzah binti Mohd Noor

My precious siblings

Lectures and friends

ABSTRACT

Thixoforming process is an attractive process that produces near net shape product with complex geometry. This process also produces lightweight parts that would reduce fuel consumption while maintaining their good mechanical properties. In this work, LM4 (light metal) aluminium alloys is used due to its low density among metals, high specific energy, good specific strength, high wear and high corrosion resistance. Thixoforming consists of three main processes that are thixotropic feedstock production, reheating and forming. The feedstock material for thixoforming was produced through cooling slope casting under argon gas atmosphere. Thixotropic feedstock is cast using cooling slope (CS) casting technique by pouring at 660 °C at 45 ° tilt angle with 400 mm slope length. The grains size and the shape factor is identified using the Image-J software. Differential scanning calorimetry (DSC) test is used to determine the heat flow and liquid fraction profile of LM4 aluminium alloy before thixoforming. The feedstock is then reheated in the induction furnace and heated up to their semisolid temperature at 580 °C (50 % of liquid content) followed by forming process by using vertical hydraulic press. After the thixoforming process, T6 heat treatment is conducted towards the thixoformed LM4 aluminium alloy with various combination of solution treatment (ST) and ageing temperature and time. The solution treatment is conducted at 510 °C to 530 °C for 30 min, 60 min and 120 min respectively followed by quenching and ageing at 160 °C to 180 °C for 2 hours, 4 hours and 6 hours respectively. Microstructure and phase formation were analysed using an optical microscope, scanning electron microscopy and X-ray diffraction while mechanical properties, coefficient of friction (CoF) and corrosion rate (CR) were obtained from hardness and tensile tests, wear test and corrosion test respectively. The result indicates that the solution treatment at 530 °C for 30 min, quenching in water and followed by ageing at 180 °C for 2 hours resulted in increased of the mechanical properties, wear resistance and corrosion resistance. The tensile strength, surface hardness, coefficient of friction and corrosion resistance of the thixoformed heat treated alloys is increased up to 252.387 MPa, 98.9 HV, 0.4259, 0.0102 mmpy respectively as compared to the thixoformed sample 184.526 MPa, 88.9 HV, 0.4321 and 0.0165 mmpy respectively. The microstructures of the T6 heat treated samples showed a spheroidization of eutectic silicon and the intermetallic phase Al_2Cu, β-Al_5FeSi and $Al_5Cu_2Mg_8Si_6$ were distributed homogenously in the sample. Based on the analysis, the new T6 heat treatment schedule with the solution treatment of 30 minutes showed a significant effect to increase the mechanical properties of the thixoformed alloys.

ABSTRAK

Proses pembentukkan-tikso adalah proses yang menarik yang menghasilkan produk hampir siap dengan bentuk geometri yang kompleks. Proses ini juga menghasilkan komponen yang ringan yang mampu mengurangkan penggunaan bahan bakar disamping mengekalkan sifat mekanikal yang baik. Dalam kerja ini, aloi aluminium LM4 (light metal) digunakan kerana ketumpatannya yang rendah antara logam, tenaga khusus yang tinggi, kekuatan khusus yang baik, kadar rintangan kehausan dan kakisan yang tinggi. Proses pembentukkan-tikso terdiri daripada tiga proses utama iaitu pembuatan bahan suapan tiksotropi, pemanasan semula dan pembentukan. Bahan suapan untuk pembentukkan-tikso dihasilkan melalui tuangan penyejukan beracuan dibawah pengaruh gas argon. Tuangan penyejukan beracuan (CS) pada 660 ° C pada 45 ° sudut kecondongan dengan panjang cerun 400 mm digunakan untuk menghasilkan bahan suapan tiksotropi. Saiz ira dan faktor bentuk dikenalpasti dengan menggunakan perisian Image-J. Sebelum pembentukan-tikso, ujian kalorimetri pengimbasan berbeza (DSC) digunakan untuk mengenal pasti aliran haba dan pecahan cecair aloi aluminium LM4. Kemudian, , bahan suapan dipanaskan semula diantara gegelung induksi sehingga suhu semisolid 580 ° C (50% kandungan cecair) diikuti dengan proses pembentukan dengan menggunakan tekanan hidraulik secara menegak ke dalam acuan. Selepas proses pembentukkan-tikso, rawatan haba T6 dijalankan terhadap aloi aluminium pembentukan-tikso LM4 dengan pelbagai kombinasi suhu dan masa perawatan larutan (ST) dan penuaan. Perawatan larutan dijalankan masing-masing pada suhu 510 ℃ hingga 530 °C untuk 30 minit, 60 minit dan 120 minit diikuti dengan lindap-kejut dan penuaan pada suhu 160 ℃ hingga 180 °C untuk 2 jam, 4 jam dan 6 jam. Pembentukan mikrostruktur dan fasa dianalisis menggunakan mikroskop optik, mikroskop elektron pengimbasan dan belauan sinar-x manakala sifat mekanik, pekali geseran (CoF) dan kadar kakisan (CR) diperoleh daripada ujian kekerasan dan tegangan, ujian kehausan dan ujian kakisan. Keputusan menunjukkan bahawa perawatan larutan pada suhu 530 °C untuk 30 minit, proses lindap-kejut di dalam air diikuti dengan penuaan pada 180 °C untuk 2 jam menyebabkan peningkatan sifat mekanik, rintagan kehausan dan rintangan kakisan. Kekuatan tegangan, kekerasan permukaan, kadar kakisan dan kadar rintangan karat bagi aloi pembentukan-tikso yang menjalani rawatan haba masing-masing meningkat sehingga 252.387 MPa, 98.9HV, 0.4259, 0.0102 mmpy berbanding dengan sampel pembentukkan-tikso iaitu 184.526 MPa, 88.9 HV, 0.4321 dan 0.0165 mmpy. Mikrostruktur rawatan haba T6 menunjukkan fasa pensferaan silikon eutektik dan fasa antara logam Al_2Cu, β-Al_5FeSi dan $Al_5Cu_2Mg_8Si_6$ teragih secara seragam di dalam sampel. Berdasarkan analisis, rawatan haba T6 yang baharu dengan 30 minit rawatan larutan menunjukkan kesan yang ketara dalam meningkatkan sifat mekanik aloi pembentukan-tikso.

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LIST OF ABBREVIATIONS

Al	-	Aluminium
Al-Si	-	Aluminium-Silicon
Al-Si-Cu	-	Aluminium-Silicon-Copper
ANOVA	-	Analysis of variance
BSE	-	Backscattered electron
CCD	-	Central Composite Design
CNC	-	Computer numerical control
CO_2	-	Carbon dioxide
CoF	-	Coefficient of friction
CR	-	Corrosion rate
CS	-	Cooling slope
Cu	-	Copper
Df	-	Degrees of freedom
DOE	-	Design of experiment
DSC	-	Diffrential scanning calorimetry
EDM	-	Electro-deposition machine
EEV	-	Energy efficient vehicle
El	-	Elongation
EMF	-	Electromagnetic field
Fe	-	Iron

GP	-	Guiner-Preston
ITT	-	International Telephone and Telegraph
LM	-	Light Metal
MHD	-	Magneto hydrodynamic
MS	-	Mechanical stirring
OM	-	Optical microscope
PoD	-	Pin-on-Disc
RAP	-	Recrystallization and partial remelting
RSM	-	Response surface methodology
SE	-	Secondary electron
SEM	-	Scanning electron microscope
SDR	-	Silicon density ratio
SF	-	Shape factor
Si	-	Silicon
SIMA	-	Stress-induced melt-activation
SSM	-	Semisolid metal
ST	-	Solution treatment
T_{Thixo}	-	Thixoforming temperature
T_{ST}	-	Solution treatment temperature
UTM	-	Universal Testing Machine
XRD	-	X-ray diffraction
YS	-	Yeild strength

LIST OF PUBLICATIONS

Journal

1. **Safian, M.A.H**., Salleh, M.S., Hussein, N.I.S., Sulaiman, M.A. and Yahaya, S.H., 2017. Production of LM4 Feedstock for Thixoforming by using Cooling Slope Casting. Journal of Advanced Manufacturing Technology (JAMT), 11(1), pp.77-90.
2. Salleh, M.S., **Safian, M.A.H**., Kamal, M.R.M., Marjom, Z., Yahaya, S.H., Mohamad, E. and Jamli, M.R., 2017. Effect of Thixoforming on the Microstructure and Mechanical Properties of Al-6% Si-3% Cu Alloy. Jurnal Teknologi, 79(5-2), pp.21-25.

CHAPTER 1

INTRODUCTION

This chapter is an introduction to the background of study, which focuses on the effect of T6 heat treatment on microstructure and mechanical properties of thixoformed light metal 4 (LM4) aluminium alloy. Research background, problem statement, objectives, scope and significance of the research are discuss in this chapter.

1.1 Research Background

In line with the vision 2020, Malaysia automotive industry aims to become the energy efficient vehicle (EEV) hub in terms of carbon emission level (CO_2/km) and fuel consumption (L/km). Over the past decade, automotive industry faced serious quality and weight issues in manufacturing critical parts. Therefore, semisolid metal (SSM) processing is used in automotive part manufacturing that meet a set of specifications in terms of lightweight parts that would reduce fuel consumption while maintaining their good mechanical properties (Hirsch et al., 2013 and Hirt et al., 1997). SSM processing also known as thixoforming allowed a near net shape processing with complex geometry.

Thixoforming process consists of thixotropic feedstock production, reheating at semi solid temperature and forming the feedstock into a mould (Salleh et al., 2014). In thixoforming, special method needed to produce thixotropic feedstock. Thixotropic behavior is a fine and evenly distributed globular solid phase in liquid matrix that will reduce their viscosity by increasing the shear (Jung et al., 2000). Therefore, complex geometries could be form at relatively low forming force. Feedstock can be produced either by solid or liquid state routes. However, cooling slope (CS) casting has been reported as the simplest technique while increasing the nucleation of grain growth and globularization of the α-alloy. CS casting ensures the primary dendrite arms breaking while the melt sliding down through the CS and fills the mould completely.

In order to improve the mechanical properties of as-thixoformed LM4 aluminium (Al) alloy, T6 heat treatment is performed. T6 heat treatment principle consists of solution treatment (ST), quenching and ageing. The ST is purposely to dissolve the Cu-containing particles at a high temperature close to the eutectic temperature. Previous studies have reported that ST is important to homogenize α-Al, reduce Si particle and affect the precipitation of alloying elements in ageing process (Zhang et al., 2002). In quenching, rapid cooling from solution treatment temperature, T_{ST} to $T_{ambient}$ would suppress the precipitation. Lastly, ageing ensures the uniform distribution of small precipitates that increase the alloy strength.

In this study, CS casting process was carried out in order to obtain thixotropic feedstock for the LM4 Al alloy. After producing feedstock via CS casting, the produced feedstock were inductively heat to semisolid temperature and formed by using the hydraulic press in the thixoforming machine. After that, T6 heat treatment is conducted to the thixoformed sample to identify the microstructure transformation, mechanical behavior and the wear and corrosion rate. Response Surface Methodology (RSM) in Design of experiment (DOE) software is used to generate the experiments matrix with several combinations of ST and ageing temperature and time.

This work has introduced a novel thixotropic feedstock production, reheating and thixoforming process with new combination parameter of T6 heat treatment that can produce LM4 Al alloy with high mechanical properties specifically higher tensile strength. In addition, primary alloy and silicon particles with fine and compact morphology of LM4 Al alloy ensure the mechanism seems to work during this novel process. Furthermore, varying the ideal temperature between ST and ageing process in T6 heat treatment also increase the product properties.

1.2 Problem Statement

T6 heat treatment consist of solid solution treatment, quenching and ageing is used to increase the alloy properties of semisolid metal processing. Nowadays, the suitable T6 heat treatment procedure is selected by referring to ASTM B917 for casting Al alloy. Therefore, there is very strong needs to investigate a suitable T6 heat treatment particularly for semisolid Al alloy. The standard T6 heat treatment for casting LM4 Al alloy solution treatment is 6 hours to 16 hours at 510 °C to 520 °C and ageing for 6 hours to 18 hours at 150 °C according to the ASTM B917.

During thixoforming, billet must undergo the re-heating process approximately around 570 °C for 5 minutes before forming operation takes place (Menargues et al., 2015). The temperature that involved has change the morphology of the Al structure. A new T6 heat treatment schedule for SSM processing to achieve the same mechanical properties as conventional casting alloys is needed. To achieve high and homogenous concentration of alloying elements, high solution treatment (ST) temperature closed to the eutectic temperature is needed. However, the combination of high temperature with short time is important to avoid localized melting on the Cu-containing while producing spheroidal microstructure in semisolid billet. The strength of Al alloys is expected to increase due to the solubility of solute obtained after the ST. Therefore, ST time can be reduced significantly due to low porosity and void content in the semisolid billet.

Furthermore, it is also important to identify new ageing process parameter to improve upon the mechanical properties offered by the existing cast and wrought alloys. Ageing is important in obtaining uniform distribution of small globular precipitates that significantly increase the alloy strength. To take full advantage of the benefits offered by thixofoming process, ageing at high temperature with short time significantly increase the precipitates formation and promote the diffusions mechanism, hence increase the alloy hardness.

Hence, by using the advantage of thixoforming processing, the T6 heat treatment schedule could be reduced, therefore, the production cost could be reduced significantly and thus reduce component cost. Moreover, the mechanical properties also increases make it more favorable in industrial application especially automotive industry.

1.3 Research Objectives

This study embarks on the following objectives:

1. To identify the optimum cooling slope casting parameter for thixotropic feedstock.
2. To identify the optimum solid solution and ageing temperature of T6 heat treatment for semisolid cast aluminium alloy.
3. To investigate the effect of varying temperature of T6 heat treatment on microstructure, morphology, and mechanical properties of thixoformed aluminium alloys.

1.4 Scope of Research

The nondendritic microstructure feedstock is prepared through the CS casting technique. Later, the solidified feedstock is used in the thixoforming process. After that, the T6 heat treatment is carried out at different solution and ageing temperatures using electric furnace with a temperature control of ± 2 °C. Solution treatments are performed at 510 °C to 530 °C for times varying from 30 min, 60 min and 120 min. After the solution treatment,