STRAIN RATE EFFECTS ON THE DEFORMATION BEHAVIOUR AND FRACTURE MODE OF RECYCLED ALUMINIUM ALLOYS REINFORCED ALUMINA OXIDE

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DEDICATION

For my beloved family, family in-law, my husband and my kids.

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"By the Name of Allah, Most Gracious, Most Merciful"

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ABSTRACT

In recent years, reinforcement with alumina oxide (Al_2O_3) has been considered to enhance the mechanical characteristics of recycled aluminium alloys. However, there is no established information on the deformation behaviour of such recycled material when subjected to various loading conditions, including damage progression. In addition, minimal efforts were conducted to develop numerical modeling to predict the deformation behaviour. Based on this motivation, a hybrid experimental-numerical approach is used in this research project. A hot press forging method is used to produce the specimen. The deformation behaviour, including damage progression of recycled AA6061 reinforced alumina oxide was investigated using the uniaxial tensile test at different strain rates (6×10^{-3} – 6×10^{-1} s^{-1}) and the Taylor cylinder impact test at impact velocity ranging from 190 m/s – 370 m/s. The recycled AA6061 reinforced alumina oxide exhibits a strain-rate dependence behaviour and ductile-brittle elastoplastic from the experimental work. The mechanical properties of the recycled AA6061 reinforced alumina oxide are degraded due to the behaviour of alumina oxide (brittle) and damage progression under loading deformation. The Taylor cylinder impact tests showed three fracture modes (mushrooming, tensile splitting, and petalling) with a critical impact velocity of 280 m/s and also exhibits plastic anisotropic behaviour and anti-deformation solid capability. The increasing impact velocity increases the severity of damage progression of the recycled AA6061 reinforced alumina oxide. Metallurgical analysis showed that micro-voids were initiated in the pre-test specimen, and damage evolved due to the nucleation, growth, and coalescence of micro-voids when loading was applied. The numerical approach was performed in the finite element analysis using LS-DYNA to predict the deformation behaviour of recycled AA6061 reinforced alumina oxide. The Simplified Johnson-Cook model was chosen and the input parameters characterize based on uniaxial tensile test data. The simulation result was then validated against both tests' experimental data and showed a satisfactory agreement.

ABSTRAK

Dalam tahun kebelakangan ini, penggunaan alumina oksida (Al_2O_3) telah dipertimbangkan untuk meningkatkan ciri-ciri mekanikal aloi aluminium kitar semula. Walau bagaimanapun, tidak ada maklumat yang tepat tentang tingkah laku ubah bentuk bahan tersebut apabila dikenakan kepada pelbagai keadaan pemuatan, termasuk perkembangan kerosakan. Selain itu, usaha yang minimum telah dijalankan dalam pemodelan berangka untuk meramalkan tingkah laku tersebut. Berdasarkan motivasi ini, pendekatan eksperimen-berangka hibrid digunakan dalam projek penyelidikan ini. Kaedah penempaan tekan panas digunakan untuk menghasilkan spesimen. Tingkah laku ubah bentuk, termasuk perkembangan kerosakan aloi AA6061 kitar semula diperkuatkan dengan alumina oksida telah dikaji menggunakan ujian regangan sepaksi pada kadar regangan yang berbeza (6×10^{-3} – 6×10^{-1} s^{-1}) dan ujian hentaman silinder Taylor pada kelajuan hentaman yang berbeza antara 190 m/s hingga 370 m/s. Bahan tersebut menunjukkan tingkah laku yang bergantung pada kadar regangan dan elastoplastik mulur-rapuh dari kerja eksperimen. Ciri-ciri mekanikal menjadi terdegradasi kerana tingkah laku alumina oksida (rapuh) dan perkembangan kerosakan apabila dikenakan kepada pelbagai keadaan beban. Ujian hentaman silinder Taylor menunjukkan tiga mod patah (cendawan, pemisahan tegangan, dan kelopak) dengan kelajuan hentaman kritikal 280 m/s, serta menunjukkan tingkah laku anisotropik plastik dan kebolehan pepejal anti-deformasi. Peningkatan kelajuan hentaman meningkatkan keparahan perkembangan kerosakan. Analisis metalurgi menunjukkan lompang mikro diinisiasi dalam spesimen pra-uji, dan kerosakan berkembang disebabkan oleh nukleasi, pertumbuhan, dan penyatuan lompang mikro apabila pemuatan dikenakan. Pendekatan berangka dijalankan dalam analisis unsur terhingga menggunakan LS-DYNA untuk meramalkan tingkah laku ubah bentuk. Model Johnson-Cook yang ringkas dipilih dan parameter input dicirikan berdasarkan data ujian regangan sepaksi. Keputusan simulasi kemudiannya disahkan berdasarkan data eksperimen kedua-dua ujian dan menunjukkan keputusan yang memuaskan.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Yield Stress Constant (JC Model)
AA	-	Aluminium Alloy
Al	-	Aluminium
ASTM	-	American Society for Testing and Materials
B	-	Strain Rate Hardening Constant (JC Model)
$B_{0,1}$	-	Constant based on Dislocation Mechanics Analysis (Z-A Model)
BCC	-	Body-Centred-Cubic (Z-A Model)
b	-	Burgers Vector (MTS Model)
b_1 , b_2	-	Fitting Constants (MTS Model)
C	-	Carbon
C_{ij}	-	Strain Rate Coefficient (JC Model)
D_d	-	Elastic Constants (MTS Model)
$\boldsymbol{D_1}$	-	Damage model parameter
$\boldsymbol{D_2}$	-	Damage model parameter
$\boldsymbol{D_3}$	-	Damage model parameter
$\boldsymbol{D_4}$	-	Damage model parameter
$\boldsymbol{D_5}$	-	Damage model parameter
D_0	-	Initial Diameter of Cylindrical Specimen
DOF	-	Degree of Freedom
d	-	Grain Size/ Diameter (MTS Model)
$d\varepsilon$	-	Strain Increment
E	-	Elastic Modulus
EDS	-	Energy Dispersive X-ray Spectroscopy
EOS	-	Equation of State
F	-	Load/ Force

FCC	-	Face-Centred-Cubic (Z-A Model)
Fe	-	Iron
FESEM	-	Field-Emission Scanning Electron Microscopy
GHG	-	Greenhouse Gas
$\Delta \boldsymbol{G_0}$	-	Total Normalized Activation Energy (MTS Model)
$\boldsymbol{g_0}$	-	Normalized Activation Energy (MTS Model)
$h_{ij\ (i,j=1...6)}$	-	Anisotropy Coefficient
$J_{2,3}$	-	Second and Third Invariant of Deviatoric Stresses
JC	-	Johnson-Cook
K	-	Stiffness Matrix
$K_{0,1}$	-	Constant based on Dislocation Mechanics Analysis (Z-A Model)
k_y	-	Unpinning Constant (MTS Model)
k	-	Boltzmann Constants (MTS Model)
L	-	Length
L_d	-	Deformed Length
L_f	-	Final Length
L_o	-	Initial Length of Cylindrical Specimen
Mg	-	Magnesium
MPP	-	Massively Parallel Processor
MTS	-	Mechanical Threshold Stress Strength Model
M	-	Taylor Orientation Factor (MTS Model)
m	-	Thermal Softening Coefficient (JC Model)
n	-	Strain Hardening Coefficient (JC Model)
O	-	Oxygen
OM	-	Optical Microscope
p, q	-	Empirical Constants (MTS Model)
$\dot{\boldsymbol{r}}$	-	Radius Evolution for Isotropic Hardening
S_{scl}	-	Scaling Factor (MTS Model)
SEM	-	Scanning Electron Microscope
Si	-	Silicon
SMP	-	Symmetric Multiprocessing Processor
T	-	Temperature

T^*	-	Homologous Temperature
T_{melt}	-	Melt Temperature
T_{ref}	-	Reference Temperature
UTS	-	Ultimate Tensile Strength
u	-	Nodal Deformation
V	-	Impact Velocity
v	-	Poisson Ratio
$Z\text{-}A$	-	Zerilli-Armstrong Strength Model
ρ	-	Density
α	-	Hardening Parameter
μ	-	Shear Modulus (MTS Model)
μ_0	-	Shear Modulus at 0 K (MTS Model)
ε	-	Strain
$\varepsilon_{engineering}$	-	Engineering Strain
ε_{pl}	-	Effective Plastic Strain
ε_{true}	-	True Strain
$\dot{\boldsymbol{\varepsilon}}$	-	Strain Rate
ε_0	-	Reference Strain Rate
ε^*	-	Dimensionless Strain Rate for Reference Strain Rate
$\boldsymbol{\varepsilon_f}$	-	Strain fracture
$\Delta\varepsilon_{pl}$	-	Equivalent Plastic Strain Increment
$\sigma_{engineering}$	-	Engineering Stress
σ_{eq}	-	Equivalent Stress
σ	-	Stress
$\boldsymbol{\sigma_{friction}}$	-	Friction Stress (MTS Model)
σ_G	-	thermal Flow Stress (Z-A Model)
σ_{true}	-	True Stress
σ_{yield}	-	Yield Strength/ Yield Stress
$\sigma*$	-	Triaxiality Stress/ Ratio of pressure
$\hat{\sigma}$	-	Flow Stress (MTS Model)
$\beta_{0,1}$	-	Constant based on Dislocation Mechanics Analysis (Z-A Model)

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Aluminium alloys are widely used in many engineering applications such as automotive, aerospace, defense, and others. It is the second-most widely used metal in the world after steel due to its outstanding mechanical properties (Oberle et al., 2019). In 2005, domestic consumption of sheets and plates in the United States only was 9.59 billion pounds. The increasing demand for aluminium-based components and further globalization of the aluminium industry has contributed significantly to higher aluminium consumption globally, including in Malaysia. According to the World Bureau of Metal Statistics, aluminium consumption in Malaysia amounted to approximately 759.6 thousand metric tons in 2019 and was a significant increase compared to 2010. However, it causes a production shortage of aluminium to meet the demands.

The production of aluminium involves the purification of bauxite, including the electrolysis process, which consumes electricity, perfluorocarbon (PFC), and CO_2 emissions. This process can cause environmental pollution due to chemical reactions (Cui et al., 2010). This is also an issue for the environment since the production of primary aluminium requires a high energy consumption of up to 186 MJ/kg (Gaustad et al., 2012). The environmental concerns require efforts to improve and develop alternative sustainable materials to avoid dependency on the primary form of aluminium made from bauxite ore (Gaustad et al., 2012).

This issue has attracted the attention of many researchers, designers, and users of aluminium and its alloys to establish replacement materials with identical mechanical properties and material response when subjected to various loading conditions. Fortunately, aluminium alloy shows good recyclability, and further can be continuously recycled compared to other common recyclable materials (Rahim et al., 2015). Secondary production of recycled aluminium alloy also saves energy by almost 95% compared to primary production (13.6 GJ/t) (Schlesinger, 2006). Hence, recycling aluminium alloy offers better economical and environmentally friendly as well as a potential option to solve a supply and demand issue of the product shortage.

Even though the mechanical properties of recycled aluminium alloy are generally good, as observed in (Rahimian et al., 2011; Warikh et al., 2014; Chan et al., 2015; Selmy et al., 2016; Tokarski et al., 2016; Ahmad et al., 2017; Yusuf et al., 2017), much efforts are still required to understand and establish the deformation behaviour of such materials before any specific applications can be identified. Recent efforts to include reinforcement materials to improve the material response can be regarded as one of the most efficient works to improve the mechanical properties to fits numerous applications. The manufacturing process of this composite can be described as a mixing process between the metal with ceramics or plastics as a reinforcement to create superior and unique properties. Aluminium matrix is usually reinforced with hard ceramic such as alumina oxide (Al_2O_3), boron carbide (B_4C), and silica carbide (SiC), which results in high specific modulus, strength, and thermal stability. The alumina oxide (Al_2O_3) can improve the mechanical properties of its composite materials compared to the primary non-reinforced alloy (Lajis et al., 2017).

However, it can be observed that a comprehensive characterization of reinforced recycled aluminium alloys considering damage progression at various loading conditions is not yet established. An adequate analysis of damage initiation is also missing. Lack of understanding can cause mistakes in the potential applications and design identification (Wan et al., 2017), hence, it is considered in this research work. In addition, good understanding of a complex elastoplastic behaviour allow for the development of appropriate numerical modeling. This numerical effort is still new to a recycling aluminium alloy field as very minimal works published in the literature. It is a challenging and interesting area to explore since the capability to establish a good prediction tool for any newly materials is essential (Mohd Nor et al., 2013). Therefore, it is also brought into attention in this research to ensure a numerical prediction of the reinforced recycled aluminium alloys response is possible.

1.2 Problem Statement

The increasing demand for aluminium-based components and further globalization of the aluminium industry has contributed significantly to higher aluminium consumption. As aforementioned, the high demand for aluminium has led to a production shortage of the primary aluminium which can harm the environment. Aluminium recyclable capability is a massive advantage to deal with this issue. However, the main challenges to provide an identical characteristics as shown by the primary form of aluminium alloy are still to be addressed. Numerous concerns are yet to be answered related to the damage behaviour of such recycled material. This issue which related to damage ‘agents’ can cause a material degradation is still unclear for reinforced recycled aluminium alloys. It must be examined closely since micro-cracks and micro-voids normally evolve when the materials are subjected to various loading condition (Tillová et al., 2012).

To date, several works have been conducted to identify an appropriate recycling process using alumina oxide as an reinforcement materials (Gupta et al., 2013; Ahmad et al., 2017; Yusuf et al., 2019). However, a complete characterization of the deformation behaviour within elastic and plastic regions related to damage initiation and progression, including fracture modes under various loading conditions, is not yet established. Whereas, the strain rate dependent is significant for applications involving impact and dynamic loading.

In addition, even though many computer codes of finite element models have been developed for metal structures and the primary aluminium alloys, there have been no real attempts to model the complexity of the deformation behaviour of the reinforced recycled aluminium alloy. Therefore, it can be generally agreed that the numerical prediction of the deformation behaviour of such material still require much efforts and data to help the establishment in the respective applications.

Based on this motivation, this research project is conducted to investigate and characterize the deformation behaviour and fracture mode of recycled aluminium alloys reinforced alumina oxide undergoing finite strain deformation. This research project adopted a hybrid experiment-numerical approach. An experimental work of a uniaxial tensile test and Taylor cylinder impact test were used to characterize the deformation behaviour, damage initiation and progression, including the fracture modes. Relevant material constants were then characterized as input parameters in the numerical analysis stage of this research. Eventually, the corresponding finite element models for each experimental test were developed and validated against the experimental data.

1.3 Objective

The objective of this research project is:

1. To characterize the deformation behaviour and damage progression of the recycled aluminium alloy AA6061 reinforced alumina oxide undergoing finite strain deformation.
2. To examine the anisotropic characteristics, damage progression, including fracture mode of the recycled aluminium alloy AA6061 reinforced alumina oxide subjected to high-velocity impact.
3. To predict numerically deformation behaviour of recycled aluminium alloy reinforced alumina oxide.

1.4 Scopes of Research

The scopes of this research project are:

1. The material under consideration was aluminium alloy AA6061.
2. A direct recycling technique via hot press forging is adopted to produce the recycled reinforced alumina oxide specimen using the optimum setting (Lajis et al., 2017) defined in the literature.
3. A uniaxial tensile test investigated the characterisation of deformation behaviour and damage progression from quasi-static to intermediated strain rate.
4. A Taylor cylinder impact test was performed to investigate the anisotropic properties and damage progression, including fracture modes of the recycled reinforced specimen at a higher strain rate.

5. After the characterisation deformation behaviour of the material under consideration, the appropriate numerical analysis method was developed.
6. Both experiments were modelled using LS-DYNA finite element code to perform the numerical analysis.
7. The Simplified Johnson-Cook model was chosen and characterised using uniaxial tensile test data.
8. The Johnson-Cook damage parameters of primary AA6061 are adopted to predict the anisotropic deformation behaviour and fracture mode at high velocity impact.
9. The numerical modelled was validated against the experimental data.

1.5 Potential Contribution to Knowledge

This research project investigates the strain rate effects on deformation behaviour, damage progression, and fracture mode of recycled aluminium alloys reinforced alumina oxide via experimental and numerical analysis. The achievement of the experimental analysis can help better understand the material's behaviour undergoing finite strain deformation, including damage progression. This information is vital in identifying an appropriate application for recycled aluminium alloy reinforced alumina oxide in real life.

On the other hand, the numerical approach requires input parameters for the material model to predict the deformation behaviour of recycled reinforced material. This numerical part is new to the recycling aluminium alloy field. The achievement of this goal would contribute to a better prediction approach, specifically for recycled aluminium alloy reinforced alumina oxide. This information is also a guideline for other researchers to enhance further finite element analysis in any simulation tool to analyse such material in more comprehensive applications.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a comprehensive literature review related to this research work. The chapter starts with a general overview of topics related to recycled aluminium alloy, including recycling methods and aluminium matrix composite (reinforced recycled aluminium alloy). Next, this chapter discusses the aluminium matrix composite deformation behaviour subjected to various loading conditions and including damage characterisation of recycled aluminium alloy. This is followed by presenting finite element approaches to predict such materials' deformation behaviour. Finally, relevant strength models for strain-rate-dependent predictions are presented at the end of this chapter.

2.2 Recycled Aluminium Alloy

Solid waste in Malaysia is a hot topic due to the expeditious local population and high daily consumption (Hassan et al., 2001; Yusof et al., 2013). Therefore, many researchers are focused and exploring recycling and sustainable issues to reduce waste, improve environmental problems, and find the recycling materials that have potential in various applications.

The growth in usage of aluminium alloy was particularly rapid every year in various industrial sectors due to its excellent properties. However, the production of aluminium, including bauxite mining, requires high energy consumption that can affect the environment. To meet the demands while preserving the environment, secondary production by recycling aluminium is vital (Rahim et al., 2015). The

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