CHARACTERISATION OF DEFORMATION BEHAVIOUR AND DAMAGE PROGRESSION OF RECYCLED ALUMINIUM ALLOY AA6061

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For my beloved family

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ABSTRACT

Recycling aluminium has shown many benefits to the environment and economics. However, there is a challenge for such recycled material to achieve the same application as shown by the primary form material due to material degradation. The deformation behaviour and the damage progression of the recycled aluminium alloy are lacking in the literature and the development of an appropriate numerical analysis of such recycled material is also missing without these information. It is very important to understand the behaviour of the recycled aluminium under various deformation condition before any application is applied. The numerical analysis data is also important for the ease of future application simulation work. Based on this motivation, a hybrid experimental-numerical approach is used in this research project. The recycled aluminium alloy AA6061 is produced using hot press forging recycling approach. The recycled AA6061 is tested at different strain rates ($\times 10^{-3}$ – $\times 10^{-4}$ s^{-1}) and temperatures (100 – 300 °C) using Uniaxial tensile test and different impact velocity (170 – 370 m/s) via Taylor cylinder impact test to characterise the deformation behaviour, anisotropic behaviour, and damage behaviour of the recycled AA6061. From the experimental work, the recycled AA6061 exhibits a strain-rate dependence behaviour, mild-ductile-elastoplastic, and anisotropic behaviour. The mechanical properties of the recycled AA6061 are degraded due to the damage progression under loading deformation. Besides, three different fracture modes: mushrooming, tensile splitting, and petalling, are observed in the Taylor Cylinder Impact test and the critical impact velocity is found to be lower than 230 m/s. Subsequently, to model a numerical analysis for the prediction of the deformation behaviour of recycled AA6061, finite element analysis using LS-DYNA is performed. Referring to the experimental findings, the material model MAT_098 of Simplified Johnson-Cook model, are adopted and the input parameters are characterised. The simulation results are then validated against the experimental data. A satisfactory agreement is shown by the simulation results as compared to the experimental data in each test.

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ABSTRAK

Kitar semula aluminium telah menunjukkan banyak faedah kepada alam sekitar dan ekonomi. Walau bagaimanapun, terdapat cabaran bagi bahan kitar semula ini untuk mencapai aplikasi yang sama seperti yang ditunjukkan oleh bahan bentuk primer disebabkan degradasi bahan. Tingkah laku ubah bentuk dan kemajuan kerosakkan aloi aluminium kitar semula masih kurang dalam literatur dan pengembangan analisis berangka yang sesuai bagi bahan kitar semular tersebut juga hilang tanpa maklumat tersebut. Memahami tingkah laku aluminium kitar semula di bawah pelbagai keadaan ubah bentuk adalah amat penting sebelum sesuatu aplikasi digunakan. Data analisis berangka juga penting untuk kemudahan kerja simulasi aplikasi pada masa depan. Berdasarkan motivasi ini, pendekatan eksperimen-numerik digunakan dalam projek penyelidikan ini. Aloi aluminium AA6061 kitar semula dihasilkan menggunakan pendektan penekanan tekan panas. AA6061 kitar semula diuji pada kadar regangan yang berbeza ($\times10^{-3}$ – $\times10^{-4}$ s^{-1}) dan suhu (100 – 300 °C) melalui ujian tegangan Uniaxial, dan halaju tenaman yang berbeza melalui ujian hentaman silinder Taylor untuk mencirikan tingkahlaku ubah bentuk, anisotropik, dan kerosakan AA6061 kitar semula. Dari hasil kerja eksperimen, AA6061 kitar semula menunjukkan tingkah laku ketergantungan pada tahap ketegangan, daktil-elastoplastik, dan anisotropik. Sifat mekanik AA6061 kitar semula mengalami penurunan disebabkan oleh kemajuan kerosakan di bawah ubah bentuk pemuatan. Selain itu, tiga mod patah: cendawan, perpecahan tegangan dan petalling, ditunjukkan dalam ujian hentaman silinder Taylor dan halaju hentaman kritikal didapati di bawah 230 m/s. Selepas itu, analisis unsur terhingga menggunakan LS-DYNA dilakukan untuk meramalkan sifat ubah bentuk AA6061 kitar semula. Merujuk kepada penemuan eksperimen, model bahan MAT_098 Simplified Johnson-Cook model, digunakan dan parameter input telah dicirikan. Hasil simulasi kemudian disahkan terhadap data eksperimen. Hasil yang memuaskan dalam simulasi dibandingkan dengan data eksperimen dalam setiap tetapan ujian.

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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	-	Strain Rate Coefficient (JC Model)
C_{ij}	-	Elastic Constants (MTS Model)
D_d	-	Distance of Major Profile of Deformed Impact Specimen
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)
F, G, H, L, M, N	-	Anisotropic Coefficients (Hill's 1948)
Fe	-	Iron
GHG	-	Greenhouse Gas
GNT	-	Gurson, Needleman and Tvegaard Strength Model

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ΔG_0	-	Total Normalized Activation Energy (MTS Model)
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_0	-	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)
$R, P, Q_{xy}, Q_{yz}, Q_{zx}$	-	Lankford's Coefficients (Hill's 1948)
$\dot{r}$	-	Radius Evolution for Isotropic Hardening
S	-	Deviatoric Stress
S_{scl}	-	Scaling Factor (MTS Model)
SEM	-	Scanning Electron Microscope
Si	-	Silicon
SMP	-	Symmetric Multiprocessing Processor
T	-	Temperature
T^*	-	Homologous Temperature

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T_{melt}	-	Melt Temperature
T_{ref}	-	Reference Temperature
UTS	-	Ultimate Tensile Strength
u	-	Nodal Deformation
V	-	Impact Velocity
v	-	Poisson Ratio
Z-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
$\dot{\varepsilon}$	-	Strain Rate
$\dot{\varepsilon}_0$	-	Reference Strain Rate
$\dot{\varepsilon}^*$	-	Dimensionless Strain Rate for Reference Strain Rate
$\Delta\varepsilon_{pl}$	-	Equivalent Plastic Strain Increment
$\psi(\sigma)$	-	Plastic Potential Function
σ	-	Stress
$\sigma_{engineering}$	-	Engineering Stress
σ_{eq}	-	Equivalent Stress
$\sigma_{friction}$	-	Friction Stress (MTS Model)
σ_G	-	Athermal Flow Stress (Z-A Model)
σ_{true}	-	True Stress
σ_{yield}	-	Yield Strength/ Yield Stress
σ^*	-	Triaxiality Stress
$\hat{\sigma}$	-	Flow Stress (MTS Model)
Φ	-	Yield Criterion

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$\beta_{0,1}$ - Constant based on Dislocation Mechanics Analysis (Z-A Model)

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CHAPTER 1

INTRODUCTION

This chapter discusses the introduction of this research. The chapter starts by briefly presenting a background of aluminium alloy and then highlights the importance to explore its recycled form. Subsequently, the problem statement is discussed before the objectives and scopes of this research project are outlined. Finally, the structure of this thesis is presented.

1.1 Background of Study

Aluminium alloy has been recognised as one of the best materials for various applications in automotive, aerospace and military structures due to its excellent mechanical properties, such as good corrosion resistance, high specific modulus, low density and excellent formability, machinability and surface finish, including superiority in fatigue cryogenic (Cui & Roven, 2010). The increasing demand for aluminium-based components and further globalisation of the aluminium industry have contributed significantly to higher consumption of aluminium alloy. The growing consumption is expected to continue based on the economic growth in China, India, Russia and Brazil, including 60% growth in the Asia region.

The high demand for aluminium has led to a production shortage. This is an issue for the environment, since the production of primary aluminium requires a high energy consumption of up to 186 MJ/kg (Gaustad, Olivetti, & Kirchain, 2012). Specifically, the process for the production of aluminium alloy involves bauxite ore mining, molten salt electrolyte and alumina purification, which may lead to environmental pollution (Cui & Roven, 2010).

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Luckily, aluminium alloy exhibits recyclability potential. As emphasised by Rahim, Lajis, & Ariffin (2015), aluminium alloy is the only material that can be fully and continuously recycled. This is a better option to support the increasing demand for aluminium and is also significant from an ecological standpoint (Rahim et al., 2015). The re-melting of recycled aluminium saves almost 95% of the energy required to manufacture pure aluminium from bauxite ore (Ahmad, Lajis, Yusuf, et al., 2017; Ho et al., 2019; Kume et al., 2009). Instead of consuming more than five tonnes of bauxite to produce one tonne of primary aluminium metal, the recycling of aluminium can reduce more than 95% of greenhouse gas (GHG) emissions compared with the primary processes (Boin & Bertram, 2005). Due to numerous advantages towards environmental safety, low energy consumption and the closed-loop recycling of industrial waste, many manufacturers and users of metal structures are trying to explore and establish the application of recycled aluminium alloy.

One of the main challenges for recycled aluminium alloy is to provide the same characteristics as the primary form. Even though many aluminium solid-state recycling methods have been studied and introduced to define the optimum setting of the recycling process, it is generally agreed that there are still numerous concerns yet to be answered related to the damage behaviour of such recycled material. This topic is significant specifically for the chips-based recycled process but still has not been addressed so far in this particular field.

Furthermore, it is impossible to ignore the realm of the damage aspect. The lack of knowledge and understanding can impose a limitation on potential applications and failures of a proposed design (Wan et al., 2017). Therefore, it is utterly vital to understand the elastoplastic deformation behaviour related to damage in such recycled material undergoing finite strain deformation. A good understanding of the complex elastoplastic response also allows for the identification of the appropriate numerical modelling. The development of reliable prediction simulation tools can support the introduction of this material in real engineering applications. Yet, there has been no attempt to develop a detailed numerical analysis of recycled aluminium alloy. The technological demands placed upon this recycled material has increased the need for a better prediction of its deformation behaviour under different loading conditions.

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1.2 Problem Statement

Damage is the apparent defect due to the degradation of a material's mechanical properties. Damage "agents", such as micro-cracks and micro-voids, can be easily spotted and they evolve during the application of loading, leading to rupture and total failure (Tillová, Chalupová, & Hurtalová, 2012). The deformation of ductile fracture involving damage can be observed in numerous metals and alloys, even in their primary solid form (Voyiadjis & Kattan, 2005). Moreover, the adopted manufacturing processes to produce recycled materials may cause the onset of cracks in the materials (Castagne, Habraken, & Cescotto, 2003).

Looking at the importance and advantages of aluminium alloy, it is extremely crucial to consider the recycled form as an alternative to replace the primary resources. Even though there has been significant progress in the optimisation of recycling process for the recycled aluminium alloy, the material deformation behaviour of the recycled aluminium alloy undergoing finite strain deformation is still an open and exciting area of study to be explored. There are still various concerns yet to be solved concerning the complexity of damage initiation and damage evolution in recycled aluminium alloy exhibiting natural anisotropic behaviour in elastic and plastic regions. The characterisation can be established in the material undergoing finite strain deformation at various strain rates and temperatures. These issues are essential to be answered before potential applications in engineering structures can be identified.

Furthermore, an appropriate finite element model and parameters allow the behaviour simulation of a prototype or design under given condition to reduce the need for physical prototypes. The significance of the finite element analysis also provides a platform for future simulation of complex model. While many computer codes are available for metal structures and many researchers typically use finite element models for primary aluminium alloy, there have been no attempts to model frameworks specifically for recycled aluminium alloy.

Based on this motivation, a hybrid experiment-numerical approach was adopted in this research project. Deformation behaviour and damage progression of recycled aluminium alloy were characterised via experiment work. Furthermore, the input parameters for numerical analysis were evaluated from experiment data to predict the deformation behaviour of recycled aluminium alloy. Validation of simulation data was performed by comparing with a series of experiment data.

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1.3 Objectives of Research

The objectives of this research are:

i. To characterise the deformation behaviour of recycled aluminium alloy AA6061 undergoing finite strain deformation.
ii. To examine the damage progression and anisotropic characteristics, including fracture modes, of recycled aluminium alloy subjected to high-velocity impact.
iii. To model a numerical analysis and evaluate the material constants for the prediction of the deformation behaviour of recycled aluminium alloy.

1.4 Scope of Research

The scope of this research project is as follows:

i. The material under consideration was commercial aluminium alloy AA6061, which is widely adopted in automotive applications.
ii. A direct recycling technique—solid-state recycling method via hot press forging—was adopted to produce the recycled specimen.
iii. The optimum process setting of the adopted direct recycling technique was referred from the optimum setting defined in the literature.
iv. The characterisation of deformation behaviour was investigated at different strain rates and temperatures using uniaxial tensile test.
v. Uniaxial tensile test was also adopted to analyse damage progression.
vi. Taylor cylinder impact test was conducted to examine damage progression and anisotropic characteristic, including fracture modes, of recycled aluminium alloy subjected to high-velocity impact.
vii. An appropriate numerical analysis method was defined after the deformation behaviour of the recycled aluminium alloy under consideration was successfully analysed and concluded.
viii. Numerical analysis was only performed for uniaxial tensile test in this work.
ix. The input parameters of the chosen constitutive model for the recycled material were characterised based on experiment data of the uniaxial tensile test obtained in this work.

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