Research Progress in Mechanical and Manufacturing Engineering Vol. 4 No. 1 (2023) 487-494
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RPMME

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/rpmme
e-ISSN : 2773-4765

Modelling The Deformation Behaviour of Recycled Aluminium Alloys Reinforced with Alumina Oxide Undergoing Finite Strain Deformation

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DOI: https://doi.org/10.30880/rpmme.2023.04.01.056
Received 15 July 2022; Accepted 26 January 2023; Available online 1 June 2023

Abstract: Recycled aluminium alloys have shown major economic and environmental benefits. Even though numerous works have been implemented to improve the properties, including the inclusion of alumina oxide (Al_2O_3) as aluminium matrix composites (AMCs), there are very limited efforts to predict the deformation behaviour of such material numerically. This is important before appropriate applications can be further established. Therefore, this research project is conducted to predict the deformation behaviour of aluminium alloy AA6061 reinforced alumina oxide through numerical analysis and compare the results with experimental test data published by another researcher. The deformation behaviour of the recycled aluminium alloy reinforced alumina oxide is tested over a range of strain rate ($6x10^{-1}s^{-1}$, $6x10^{-2}s^{-1}$ and $6x10^{-3}s^{-1}$) via uniaxial tensile test. Referring to the experimental data, the flow stress model – MAT_098: Simplified Johnson-Cook model in LS-DYNA is chosen. The constants of the material model are defined by the characterisation of experimental data. Next, LS-DYNA software is used to perform finite element analysis of the uniaxial tensile test. The numerical results are validated against experimental data. There is a good match between the numerical results and the experimental results.

Keywords: Recycled Aluminium Alloy Reinforced Alumina Oxide (Al_2O_3), Uniaxial Tensile Test, Finite Element Analysis, Simplified Johnson-Cook Model, LS-DYNA

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1. Introduction

Aluminium alloys are extensively used in many applications and industries due to their excellent properties such as good corrosion resistance, low density and strength. Aluminium alloys ranging from packaging beverage cans to aviation applications such as packaging, food industry, building construction, defensive item, transportation, automotive and aerospace [1]. Since then, it has been widely used to replace wood, steel and other materials. Due to economic and environmental benefits, the form of recycling aluminium can be well replaced by the major resources [2]. There is also a shortage of supply due to the high demand for aluminium. The production of primary aluminium in September 2017 was 4.927 million tons [3]. Since the growing usage of aluminium alloy, recycled aluminium alloys have shown to provide major economic benefits. In order to strengthen the material, aluminium matrix composites (AMCs) are introduced. The development of reinforced materials produces AMCs. The systematic research on their first-level thermomechanical properties has been carried out for about 30 years [4]. A study by Anguraj et al. [5] showed that the reinforced aluminium alloy such as alumina oxide (Al_2O_3), titanium nitride (TIN), aluminium nitride (AIN), boron nitride (BN), titanium carbide (TiC), boron carbide (B_4C), silicon carbide (SiC), zirconium carbide (ZrC), carbon (C), graphite, steel and fly ash are added to the aluminium matrix to improve the composite material performance. AMCs enhance mechanical properties such as toughness, strength, hardness, lightweight and wear-resisting [6]. These properties are widely used and meet the requirements for the aviation and automotive industries. Recently, a research used alumina oxide (Al_2O_3) mixed with recycled aluminium alloy to improve the tensile properties of the recycled material [3]. Alumina oxide is a compound of aluminium and oxygen. Through material reinforcement, the production of composite materials can be used in this field. Recycled aluminium alloys reinforced with alumina oxide can enhance the tensile properties and deformation behaviour.

Nowadays, structural mechanics show a trend to find numerical solutions for more extensive and detailed tasks. Computational simulation can predict future results, improve information flow, improve operational efficiency and fully understand problems [7]. It is generally believed that computer simulation can replace expensive, critical situations and time-consuming laboratory experiments. Through simulation, the situation can be changed and the results can be investigated. Moreover, a few previous research related to the numerical analysis of aluminium alloys is reviewed. Based on the study carried out by Talebi-Ghadikolaee et al. [8], the finite element code Abaqus was used to create a finite element model to study the behaviour of AA6061-T6 aluminium alloy plate during U-shaped bending. When experimental data were compared to numerically projected fracture displacements, it is seen that numerical analysis can be predicted with reasonable accuracy [8]. According to Panov [9], the new material model was applied to the explicit finite element DYNA3D to describe the strain rate and temperature-dependent behaviour of aluminium alloy AA7010 during uniaxial tensile testing. Dog bone specimens have been used to determine the geometry of the specimens and bearing axial loads through simulation methods. Numerical analysis was in good agreement with experimental data [9]. As stated by Nawale et al. [4], the numerical calculation results of LS-DYNA can be improved by studying the mechanical characteristics of the aluminium alloys accurately, selecting the material model correctly, forming a uniform mesh and establishing an accurate contact surface control card between the specimen and the steel bar [4]. Based on Hoang et al. [10], a two-dimensional axisymmetric model was used to perform numerical analysis in LS-DYNA, the effects of several physical factors on the final failure of AA7278-T6 aluminium self-piercing rivets were discussed and experiments were carried out. In comparison to the experimental test, the numerical findings revealed that it was time-consuming [10]. Furthermore, Børvik et al. [11] investigated the perforation of an AA6005-T6 panel both experimentally and numerically. The explicit finite element algorithm LS-DYNA was used for numerical analysis. The experimental results are used to calibrate Johnson-Cook constitutive relations and the fracture criteria has been slightly changed. The numerical model is shown to be capable of accurately capturing the main physics in the experiment. The numerical value and the experimental result have a high level of agreement [11]. Based on few authors had studied, numerical analysis shows a great agreement between the numerical value and the experimental result. The methods of conducting the simulation are reviewed based on few past research papers. The types of software used for simulation and strain rate play a big role in the uniaxial tensile test. ABAQUS, LS-DYNA, and ANSYS are examples of numerical analysis software.

Several material models can be used to forecast how materials will behave under this condition, including the Johnson-Cook model, Voyiadjis and Abed model, Preston-Tonk-Wallace model, Zerilli and Armstrong model, Khan-Huang-Liang model and Gao and Zhang model [12]. It is a common choice for high-strain-rate applications. It has been widely employed by numerous researchers to anticipate the behaviour of materials [13]. As a result, the Johnson-Cook model is employed to get a precise constitutive model. Many tests establish the deformation behaviour of materials such as tensile test, bending test, compression test, Taylor impact test and others. In this research, the uniaxial tensile test is used to analyse the deformation behaviour of materials. The tensile test is the most crucial test method in destructive material testing [14]. A standard dog bone specimen is uniformly loaded in the longitudinal direction with relatively small increased stress and record the elongated data. Different strain rates are considered to model the deformation behaviour of recycled aluminium alloys AA6061 reinforced with alumina oxide under the uniaxial tensile test. Previous studies have shown that numerical analysis for recycled aluminium alloys AA6061 reinforced with alumina oxide has not been performed yet. However, the ability to predict the deformation behaviour of material has become a challenge to the designers and the user of metal structures. A thorough understanding of all the factors is required to simulate something. Otherwise, the simulations are difficult to create.

At present, most analysis is focused on experiment test. However, numerical analysis has great significance than experiment test. In this research project, an investigation of the deformation behaviour of recycled aluminium alloy AA6061 reinforced alumina oxide subjected to various strain rates ($6x10^{-1}s^{-1}$, $6x10^{-2}s^{-1}$ and $6x10^{-3}s^{-1}$) of the uniaxial tensile test are simulated using LS-DYNA software. In this study, the Simplified Johnson-Cook model with the least effort material constant is used. This research is based on the uniaxial tensile test experiment previously studied by Issek et al. [15]. The numerical results and experimental results are verified to show the finite element method and analysis capabilities used.

2. Numerical Analysis

2.1 Finite Element Model Development

In this research, the material chosen is the recycled aluminium alloy AA6061 reinforced with alumina oxide which is consistent with the reference previous study by Issek et al. [15]. Specimen geometry of the uniaxial tensile test is formed according to ASTM-E8 dog bone shape as shown in Figure 1.

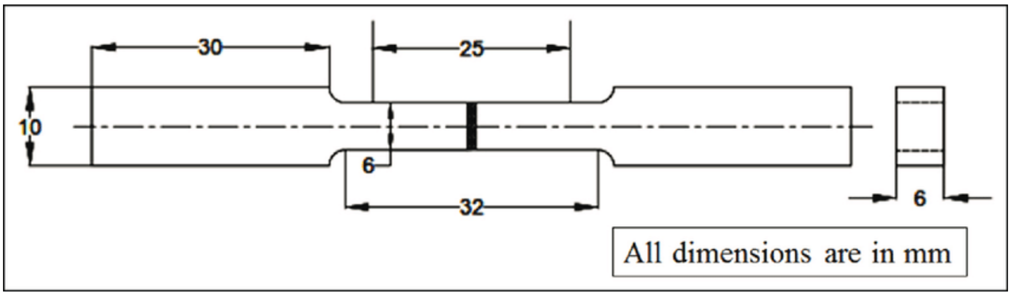


Figure 1: Standard Geometric of ASTM-E8 for Tensile Test's Specimen

Figure 2 illustrates the finite element model development process. First of all, the material geometry is developed with standard geometric of ASTM E8. Then, the material input constants are applied to the finite element model with the characterization of the Simplified Johnson-Cook model. Next, the finite element model is meshed using the 3D solid map method and quad source shell (square) shape with 0.5 mm of the element size. Subsequently, the boundary is set with a fixed constraint and force at the end of the model specimen. Lastly, the contact algorithm is set that used for problem analysis to get the stress and strain values.

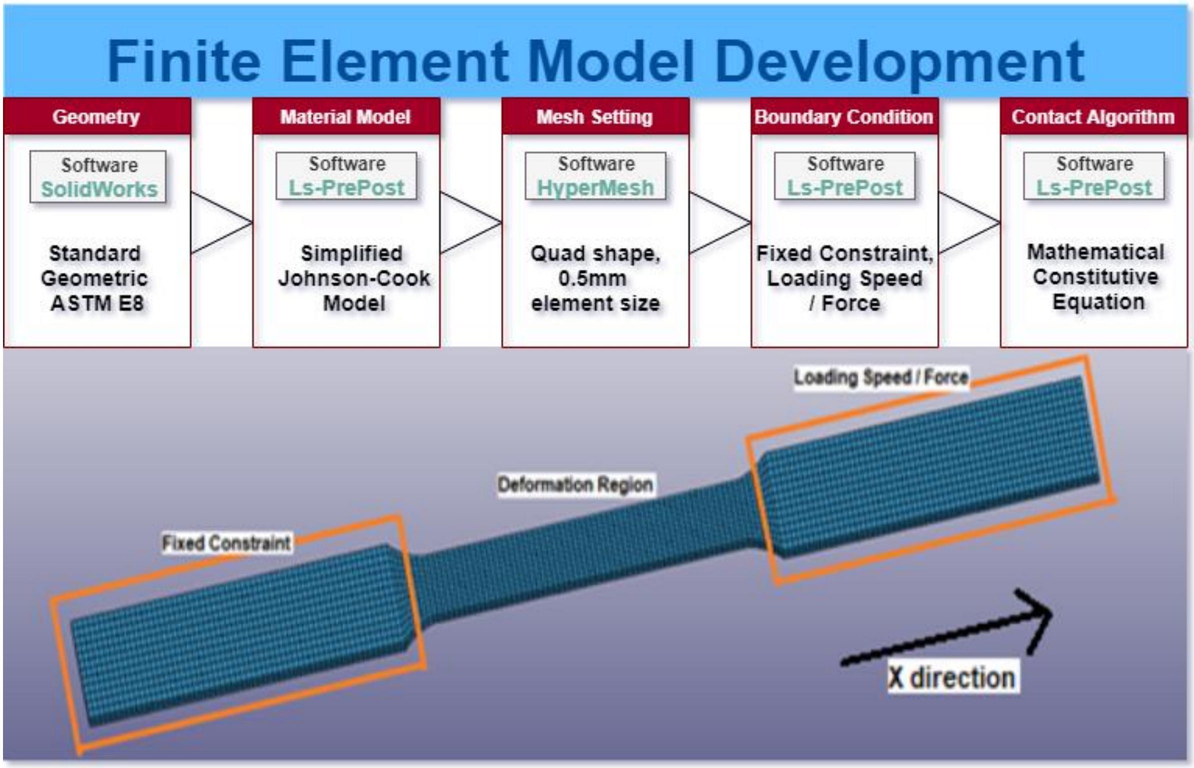


Figure 2: Flow of Model Development

Based on the reference uniaxial tensile test experiment, the strain rate used for the test is shown in Table 1. The recycled aluminium alloy AA6061 reinforced alumina oxide is tested at a quasi-static strain rate ($6\times10^{-3}s^{-1}$ to $6\times10^{-1}s^{-1}$).

Table 1: Test Matrix for Uniaxial Tensile Test [15]

	Strain Rate (s^{-1})	Crosshead Speed (mm/min)	Extensometer (Gauge length) (mm)
Ambient Temperature 28° C (ASTM E8)	6×10^{-3}	0.15	25
	6×10^{-2}	1.50	25
	6×10^{-1}	15.00	25

2.2 Simplified Johnson-Cook

Simplified Johnson-Cook is chosen as the constitutive model. The material constants for the chosen constitutive model are derived from uniaxial tensile test experiment raw data by Issek et al. [15] and utilised as input parameters for the finite element model.

The Simplified Johnson-Cook model is simplified from the original Johnson-Cook model, which discards the temperature dependence. The simplified Johnson-Cook model is a plastic model based on strain, strain rate and four constants that need to be fully defined. The flow stress model is expressed as:

$$\sigma_{eq} = \left[A + B\varepsilon_{pl}^{n}\right]\left[1 + C\ ln\dot{\varepsilon}^{*}\right] \qquad \boldsymbol{Eq}.1$$

Here, ε_{pl} represents the effective plastic strain and $\dot{\varepsilon}^{*} = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$ is the dimensionless strain rate for reference strain rate ($\dot{\varepsilon}_0$). A, B, n, and C denote the material input constants. A is the yield stress of the material under reference conditions, B is the strain hardening constant, n is the strain hardening exponent and C is the strain rate dependence coefficient.

In order to simplify the process of finding the constants, the reference strain rate factor is set to be the strain rate of one of the experiments. In the present study, the reference strain rate ($\varepsilon^{\cdot}{}_{0}$) is set as $6x10^{-3}s^{-1}$. To determine the material constants A, B and n, the strain rate dependence effect $[1 + Cln\dot{\varepsilon}^{*}]$ is assumed equal to be 1. Hence, when the stress rate is equal to the reference strain rate factor, Equation $\boldsymbol{Eq}.\mathbf{2}$ is simplified as:

$$\sigma_{eq}(\dot{\varepsilon} = \dot{\varepsilon}_0) = \left[A + B\varepsilon_{pl}^{n}\right]\left[1 + C\ ln\dot{\varepsilon}^{*}\right] = \left[A + B\varepsilon_{pl}^{n}\right] \qquad \boldsymbol{Eq}.2$$

Next, the solver function in Microsoft Excel is used in this study to compute the material constants. Using the value of true stress and effective plastic strain obtained from the experiments of which the strain rate is equal to the reference strain factor, the material constants of A, B and n are calculated.

After deriving A, B, and n, rearrange Equation $\boldsymbol{Eq}.\mathbf{1}$ to calculate the value of C that controls the effect of strain rate. For constant C, the experiment data of strain rate $6x10^{-2}s^{-1}$ and $6x10^{-1}s^{-1}$ experiments must be considered. The solver function in Microsoft Excel is then used to calculate the constant C.

The material constants A, B, n and C are calculated as shown in Table 2.

Table 2: Parameter Simplified Johnson-Cook model A, B, n and C

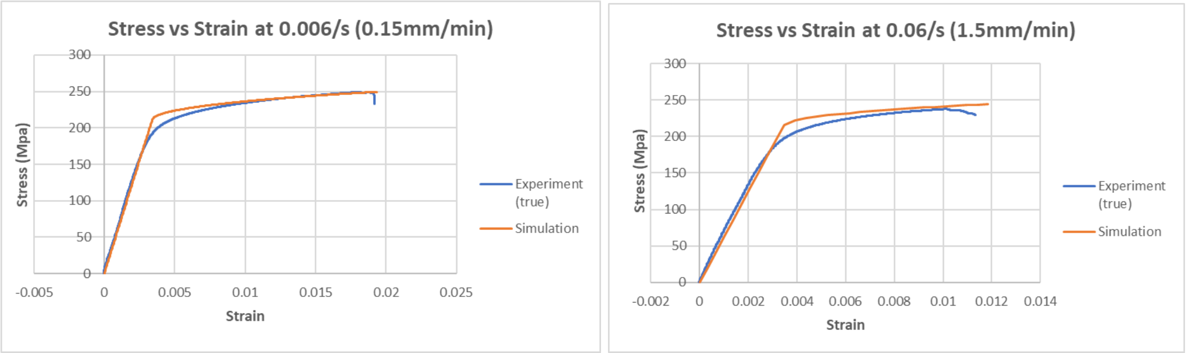
Yield Strength, A (MPa)	Strain Hardening, B	Strain Hardening Exponent, n	Strain Rate Constant, C
212.5223	363.7547	0.5155815	0.0098

2.3 Finite Element Analysis

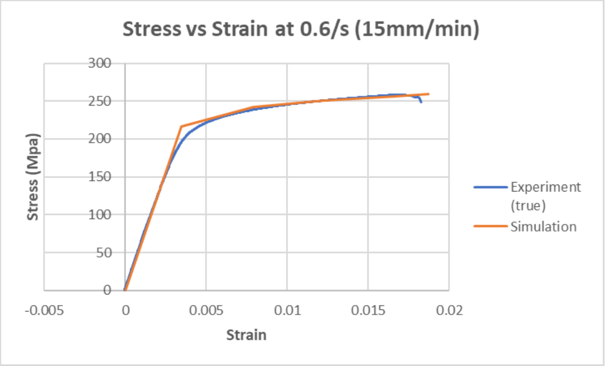
In this stage, the strain rates ($6x10^{-1}s^{-1}$, $6x10^{-2}s^{-1}$ and $6x10^{-3}s^{-1}$) are subjected to the finite element model and the result are revealed through LS-DYNA and Ls-Prepost software. The stress, strain and deformation results are obtained and tabulated. The results obtained are compared with the published experimental uniaxial tensile test to validate that the computer simulation able to capture the result.

3. Results and Discussion

Element analysis was performed using the MAT_098 material model: Simplified Johnson-Cook model in LS-DYNA. The test used dog bone specimen made of recycled aluminium alloy AA6061 reinforced alumina oxide with ASTM E8. The experimental tests were carried out with three strain rates $6x10^{-1}s^{-1}$, $6x10^{-2}s^{-1}$ and $6x10^{-3}s^{-1}$ respectively. Figure 3 below illustrates the comparison of the experimental stress-strain curves with the simulation stress-strain curves.



(a) Strain rate at 6x10^{-3}s^{-1} (b) Strain rate at 6x10^{-2}s^{-1}



(c) Strain rate at 6x10^{-1}s^{-1}

Figure 3: Flow Stress Results Comparison between Simulation and Experiment Data

From the simulation results as shown in Figure 3 above, it can be noticed that the adopted material model, Simplified Johnson-Cook is capable to predict the elastoplastic deformation behaviour of the recycled AA6061 reinforced alumina oxide correctly with the derived input parameters. The flow stress of the simulation results shows a good match compared to the experimental data. The elastic slope is nearly identical to the experimental data. Although there have some differences in the plastic region, it is still within the accepted differences. The comparison of the simulation data and the experimental data are summarized in Table 3.

Table 3: Simulation Result vs Experiment data of Uniaxial Tensile Test

Loading speed, (mm/min)	Strain rate, (1/s)	Data	Young's Modulus, E (GPa)	Yield Strength, σ (MPa)	Ultimate Tensile Strength, UTS (MPa)
0.15	$6x10^{-3}$	Experiment	61.78	221.82	234.80
		Simulation	62.182	225.2837	245.00
1.5	$6x10^{-2}$	Experiment	62.80	226.72	235.29
		Simulation	62.203	229.6312	245.1738
15	$6x10^{-1}$	Experiment	63.56	223.93	254.44
		Simulation	62.076	225.00	256.433

In term of elasticity, the simulation value of elastic modulus for each test are very close agreement against the experimental data. The differences are only about 0.402 – 1.484 (percentage error: 0.65% – 2.33%). Furthermore, at the yield point, the differences in the yield strength for simulation results and experimental data are about 1.07– 3.4637 (percentage error: 0.48% – 1.56%). Based on the ultimate tensile strength value, the differences between the simulation data and experimental data are within

1.993 – 10.2 (percentage error: 0.78% – 4.34%). However, the simulation results are still accepted since the percentage error for overall flow stress is not more than 5%.

In addition, the results have shown that the ultimate tensile strength is very sensitive to strain rate. When the strain rate increases from $6\times10^{-3}s^{-1}$ to $6\times10^{-1}s^{-1}$, the ultimate tensile strength tends to increase. The ultimate tensile strength showed an increasing trend with the increase of strain rate, which is similar to the experiment.

In short, the deformation behaviour of recycled aluminium alloy AA6061 reinforced alumina oxide at different strain rates has been examined. Also, the derived input parameters for the chosen material model are successfully validated. The capabilities of the material model MAT_098 – Simplified Johnson-Cook Model in predicting such recycled material is proved. A good agreement is shown in each of the tests compared to the experimental data.

4. Conclusion

As a conclusion, this research objective considers successfully achieved which to study the deformation behaviour of the recycled aluminium alloy AA6061 reinforced alumina oxide undergoing several strain rates ($6x10^{-1}s^{-1}$, $6x10^{-2}s^{-1}$ and $6x10^{-3}s^{-1}$) of the uniaxial tensile test via numerical analysis. Based on the experimental data by previous study, the input constants for the Simplified Johnson-Cook model are derived. The illustration obtained from the numerical work can be proof that the Simplified Johnson-Cook model capable to predict and reproduce the experimental test results. The numerical analysis results with implemented the Simplified Johnson-Cook material model can be clearly seen that the flow stress of simulation results is similar to experimental tests conducted beforehand. The percentage error for overall flow stress is not more than 5% that is still acceptable. Besides, the results have shown that the ultimate tensile strength is very sensitive to strain rate. When the strain rate increases from $6\times10^{-3}s^{-1}$ to $6\times10^{-1}s^{-1}$, the ultimate tensile strength tends to increase.

In this study, the results are beneficial to other researchers in the future. At the same time, various applications can be explored with such material without requiring much experimental efforts. By applying numerical analysis, it contributed to environmental protection and safety engineering that are not normally feasible under real-world or laboratory conditions. Due to climate change and awareness of environmental issues, recycling and sustainability issues had become the focus of attention. The recycling of aluminium alloy is a green technology that is beneficial to the economy and reduces pollution. The high demand for primary aluminium alloys has leaded to insufficient supply and the greenhouse effect. The form of recycled aluminium alloy can well replace the main resources that widely used in various industries.

Since the numerical analysis results show a lack of some percentage of error in comparison between the properties, further work is needed to develop great agreement results in both experimental test and numerical analysis. Further research includes predicting the deformation behaviour and the fracture modes to be more accurate, different material models such as the Zerilli-Armstrong (ZA), Steinberg-Cochran-Guinan-Lund (SCG), Mechanical Threshold Stress (MTS) and Preston-Tonks-Wallace (PTW) needed to be considered. This research work by implementing the Simplified Johnson-Cook model will result in a good indication and as an overview for more appropriate material models should be considered in future to help towards a better understanding of the uniaxial tensile test.

Acknowledgement

Authors wish to convey a sincere gratitude to the Ministry of Higher Education (MOHE) and Universiti Tun Hussein Onn Malaysia (UTHM) for providing the financial means during the preparation to complete this research under Fundamental Research Grant Scheme (FRGS) – FRGS/1/2020/TK02/UTHM/02/5, Vot K331, and UTHM Contract Research Grant – Vot H276, respectively.

References

[1] C. S. Ho and M. K. Mohd Nor, “Tensile behaviour and damage characteristic of recycled aluminium alloys AA6061 undergoing finite strain deformation,” *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, 2020, doi: 10.1177/0954406220950349.

[2] C. S. Ho *et al.*, “Characterization of anisotropic damage behaviour of recycled aluminium alloys AA6061 undergoing high velocity impact,” *Int. J. Integr. Eng.*, vol. 11, no. 1, pp. 247–256, 2019, doi: 10.30880/ijie.2019.11.01.025.

[3] A. Ahmad, M. A. Lajis, N. K. Yusuf, and A. Wagiman, “Hot press forging as the direct recycling technique of aluminium- A review,” *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 4, pp. 2258–2265, 2016.

[4] S. P. Nawale, R. T. Vyavahare, and A. S. Aradhye, “High Strain Rate Response of A356/Al2O3 Aluminum Alloy MMCs Using Ls-Dyna,” *Procedia Eng.*, vol. 173, pp. 1967–1974, 2017, doi: 10.1016/j.proeng.2017.02.457.

[5] M. Anguraj, M. Easwaramoorthi, S. Jerold, and S. Chelladurai, “Mechanical Properties And Wear Behaviour of Aluminium Matrix Composites – An Overview,” no. December, 2017.

[6] N. K. Bhoi, H. Singh, and S. Pratap, “Developments in the aluminum metal matrix composites reinforced by micro/nano particles – A review,” *J. Compos. Mater.*, vol. 54, no. 6, pp. 813–833, 2020, doi: 10.1177/0021998319865307.

[7] E. Malec, “The Benefits of Using Computer Simulation Models to Support Decision-Making,” *Comput. Simul.*, pp. 205–214, 2018.

[8] H. Talebi-Ghadikolaee, H. Moslemi Naeini, M. J. Mirnia, M. A. Mirzai, S. Alexandrov, and H. Gorji, “Experimental and numerical investigation of failure during bending of AA6061 aluminum alloy sheet using the modified Mohr-Coulomb fracture criterion,” *Int. J. Adv. Manuf. Technol.*, vol. 105, no. 12, pp. 5217–5237, 2019, doi: 10.1007/s00170-019-04549-6.

[9] V. Panov, “Modelling of Behaviour of Metals at High Strain Rates,” *Ph.D. Thesis*, p. 209, 2006.

[10] N. H. Hoang, O. S. Hopperstad, M. Langseth, and I. Westermann, “Failure of aluminium self-piercing rivets: An experimental and numerical study,” *Mater. Des.*, vol. 49, pp. 323–335, 2013, doi: 10.1016/j.matdes.2013.01.034.

[11] T. Børvik, A. H. Clausen, M. Eriksson, T. Berstad, O. Sture Hopperstad, and M. Langseth, “Experimental and numerical study on the perforation of AA6005-T6 panels,” *Int. J. Impact Eng.*, vol. 32, no. 1–4, pp. 35–64, 2005, doi: 10.1016/j.ijimpeng.2005.05.001.

[12] A. A. Dehkharghani, “Tuning Johnson-Cook Material Model Parameters for Impact of High Velocity , Micron Scale Aluminum Particles,” no. August, 2016.

[13] M. Murugesan and D. W. Jung, “Johnson cook material and failure model parameters estimation of AISI-1045 medium carbon steel for metal forming applications,” *Materials (Basel).*, vol. 12, no. 4, 2019, doi: 10.3390/ma12040609.

[14] T. Groeneveld and A. Elsea, “Mechanical Testing Methods,” *Hydrog. Embrittlement Test.*, pp. 11-11–9, 2009, doi: 10.1520/stp38925s.

[15] M. L. Issek, M. K. M. Nor, C. S. Ho, and M. A. Lajis, “MATERIALS CHARACTERISATION AND FRACTURE AA6061 REINFORCED WITH ALUMINA OXIDE,” 2020.