© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Damage Characteristics of Recycled Aluminium Alloys AA6061 Undergoing Finite Strain Deformation of Tensile Loading

C. S. Ho[1], M. K. Mohd Nor[1*], M. A. Lajis[2], M. S. A. Samad[3]

[1]Faculty Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, 86400, MALAYSIA

[2]Sustainable Manufacturing and Recycling Technology, Advanced Manufacturing and Material Center (SMART-AMMC), Faculty Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, 86400, MALAYSIA

[3]Department of Computer Aided Engineering Vehicle Development and Engineering, Perusahaan Otomobil Nasional Sdn Bhd, Shah Alam, Selangor, 40150, MALAYSIA

*Corresponding Author

DOI: https://doi.org/10.30880/ijie.2022.14.04.001
Received 10 January 2020; Accepted 14 February 2022; Available online 20 June 2022

Abstract: Recycling aluminium alloys has excellent advantages to avoid bad environmental effects while providing significant economic benefits. Many efforts are demanded to identify the appropriate applications, especially in automotive and aerospace fields. It can be observed that various recycling methods have been adopted and examined. However, it is generally agreed that there is still a need for improved recycling methods to fulfil the needs of the required applications as shown by its primary resources. It is a massive challenge and an obvious drawback in such materials due to the degradation of material's properties related to damage, hence, must be critically analyzed before the potential applications can be identified. Based on this motivation, the present study establishes the effects of temperature and strain rate of hot-forged recycled aluminium alloys AA6061 via uniaxial tensile test implementations. The test is conducted at elevated temperatures of 100°C, 200°C and 300°C, at two different strain rates of 10^{-4} s^{-1} and 10^{-3} s^{-1}. The tensile behaviour and damage are analyzed in terms of stress-strain curves and microstructural analysis, respectively. The microstructure and fracture surface of such materials are observed using Scanning Electron Microscope (SEM) and Optical Microscope (OM). Generally, the flow stress of recycled AA6061 increases with increasing strain rate and decreases with increasing temperature. The quantity and size of the micro-voids observed is enhanced with the increases in strain rate. It is due to the growth and coalescence of the micro-voids. From the OM analysis, the gap between the grain boundaries become wider with the increases in temperature; thus, the strength of the material decreases.

Keywords: Recycled Aluminium Alloys, Uniaxial Tensile Test, Metallurgical Analysis

1. Introduction

Aluminium alloys are widely used in many industries and applications ranging from the packaging beverages cans to aeronautic application. It is due to the remarkable properties of aluminium alloys and has a combination of low density and high strength profile [1], [2]. The high demand usage of aluminium alloys had been shifting the attention on replacing primary resources with recycled aluminium alloys. Recently, many recycling approaches have been

*Corresponding author: khir@uthm.edu.my

implemented in recycling aluminium alloys able to give a promising result. However, there is still a need for improved recycling methods to explore the dynamic mechanical behaviour of such materials undergoing various strain rates and temperatures. It is vital since aluminium alloys are usually performed under high temperature, especially in automotive and aerospace application, and it may occur to collide with other objects at different impact velocities [3], [4]. Thus, it is essential to characterize the effects of strain rate and temperature on the mechanical behaviour of recycled AA6061 to assure consistency and reliability.

In practice, different applications govern the materials deformation behaviour within different strain rate regimes. It is generally divided into few categories with different mechanical dynamic loading test, as shown in Fig. 1. The range of strain rate between 10^{-6} – 10^{-5} s^{-1} is known as creep behaviour. It is typically inspected at elevated temperatures, and a creep type laws are adopted to define such behaviour. The range of strain rate from 10^{-4} to 10^{-1} s^{-1} is associated with the quasi-static stress-strain curve. It can be obtained via a tensile test and compression test at a constant strain rate. For an intermediate strain rate regime, it is in the range from 10^{0} to 10^{2}. The stress-strain behaviours may change, and specialized testing methods have to be adopted. Eventually, for a high strain rate response, which ranging higher than 10^{3} s^{-1}, the material deformation governs within the inertia, thermal and wave propagation effects. And its deals with shock wave propagation when the strain rate is higher than 10^{5} s^{-1} [5], [6]. In the present study, a uniaxial tensile test is used to test the material behaviours at a constant strain rate; hence, a quasi-static strain rate range is selected to obtain the stress-strain relations.

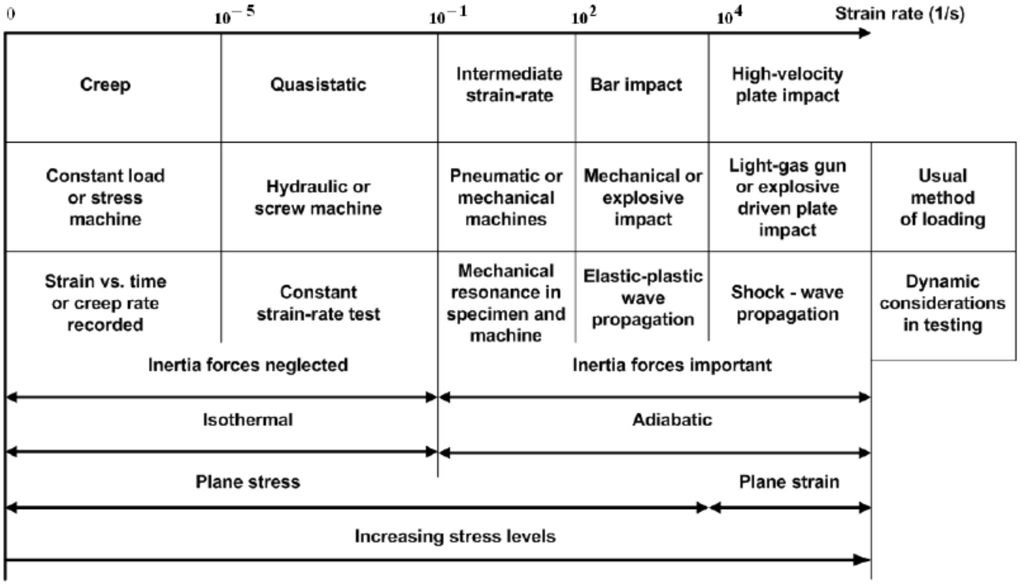


Fig. 1 - Classification of mechanical dynamic testing

Previously, many researchers studied the effects of loading speed and temperature on different material. For instance, Noradila et al. reported that Al-Zn magnesium alloys AZ31 is dependent on loading speed but not for AZ61 [3]. The effects of temperature and strain rates on the tensile behaviour of dual-phase steel DP800 also studied by Cao et al., in which the increasing of strain rate causing higher yield strength and ultimate tensile strength (UTS) value with the decreasing in temperature [7]. Further, Nor and Suhaimi had reported that the commercial aluminium alloys AA5083 and AA6061 are sensitive to the changes in temperature and strain rate [8]. Panov examined the mechanical behaviour of aluminium alloys AA7010 and AA2024 concluded that AA7010 shows strain rate and temperature-dependent response but AA2024 only dependent on temperature changes [5]. The tensile behaviour of AA7017 at various strain rate and temperatures is studied by Bobbili et al. [9]. The results revealed that the flow stress decreases with increasing temperature. The damage in the materials at a higher strain rate is worse compared to lower strain rates.

In the recent year, many researchers only focused on the optimization of the recycling process setting and addition of reinforced material into the recycled material to enhance its strength properties. For instance, Ahmad et al. determine the optimum extrusion temperature and ageing time for the heat treatment process in recycling aluminium via hot extrusion. Three different extrusion temperatures (450, 500 and 550 °C) and ageing time (240, 360 and 480 minutes), are used to determine the optimum hardness of the recycled product [10]. The results revealed that at the highest extrusion temperature able to enhance the chip bonding and maximum hardness for 240 minutes ageing time considered as the peak-aged [10]. Later, Ahmad et al. used the addition of aluminium oxide as a reinforced material embedded in the aluminium matrix to enhance the hardness properties [11].

Furthermore, in the study by Yusuf et al., recycled AA6061 via hot press forging recycling process under different operating temperature (430, 480 and 530 °C) and pressing time (60, 90 and 120 minutes), is conducted to obtain the optimum hot-pressed setting. A high tensile strength recycled product is produced, and the result is comparable to the theoretical AA6061-T4 temper [12]. As mentioned in previous, a material can collide with other objects at different loading condition in real-life. Even though the optimum settings are defined, and it is proved to enhance the strength of the recycled material, the study focused only provides few characteristic, such as ultimate tensile strength and elongation to failure, at ambient temperature. The data is still lacking on the detail of damage characteristics, such as the quantity and size of micro-cracks and micro-voids in the material, undergoing finite strain deformation at various temperature and strain rate conditions. It is utterly inadequate if the application in automotive and aerospace is admired.

Generally speaking, recycling aluminium alloys positively contributes to reduce pollution and to save energy as compared to *the* primary *aluminium* alloys production. Nowadays, lack of analysis and data related damage initiation and development, including fracture such material undergoing finite strain deformation have limited the identification of its potential applications in automotive and aerospace industries. It is impossible to establish the application without this primary data, the tensile tests of recycled AA6061, therefore, are conducted in this work under various temperatures and strain rates to scrutinize the tensile behaviour. Further, the corresponding fracture surfaces and microstructural analysis are performed using a Scanning Electron Microscope (SEM) machine to review the damage characteristics of such materials undergoing finite strain deformation.

2. Experimental Procedure

It is essential to understand the exact behaviour of a material undergoing finite strain deformation to probe the potential of the material in the advanced application. The most applicable experimental procedure for material characterization is the uniaxial tensile testing, as it is simple and cost-effective [8]. The experimental data obtained from these testing can lead to a better understanding of recycled aluminium alloys behaviour, and it is also useful to derive the related material's behaviours which might be provided for further investigation via relevant simulation model. In the present study, the experiment procedure is divided into two phases, as presented below.

2.1 Specimen Preparation

Fig. 2 shows the flow of the specimen preparation process. The AA6061 chips are produced using MAZAK vertical centre Nexus 410A-II CNC machine. Chips size with an average size of 5.2 mm × 1.097 mm × 0.091 mm can perform better in term of strength [11], [12]. The chips machining parameters are shown in Table 1. Acetone solution is used to clean the chips by using utilizing ultrasonic bath and then dried for about 30 minutes in the thermal oven at 60°C [13].

A hot press forging machine is used to form the chips into dog-bone shaped according to ASTM standard [14], [15]. The dimension of the specimen is shown in Fig. 3, where ASTM E21 is used for testing at elevated temperature. The hot press forging process is conducted at constant temperature and pressure at 530°C and 47 MPa (35.6 tonnes), respectively. The holding time for the hot pressing process is 120 minutes, including four times of pre-compacting cycle (2 minutes/cycles). Subsequently, the hot-forged specimen is quenched at a quench rate of 100°C/s and immediately put in a 175°C thermal oven for 120 minutes artificial ageing process. The specimen going through this complete heat-treated recycling process is denoted as T5-temper.

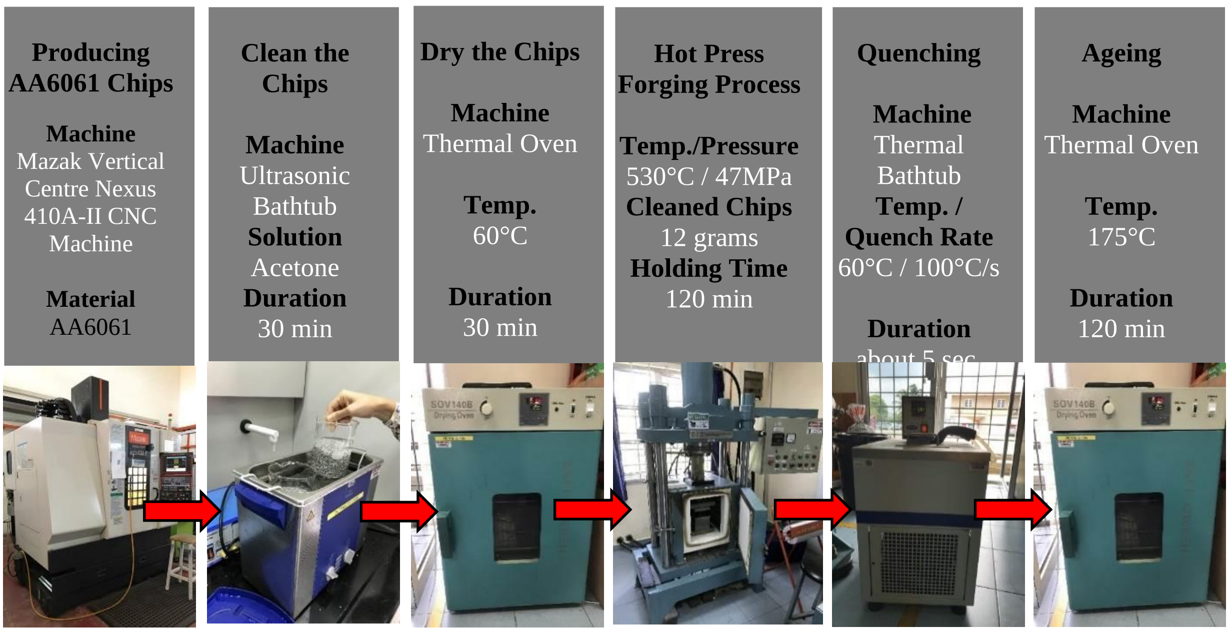


Fig. 2 - Flow of specimen preparation

Table 1 - Chips milling parameter

Parameter	Value
Cutting Speed, *v*	377 m/min
Diameter tool	10 mm
Feed, *f*	0.05 mm/tooth
Depth of Cut	1 mm

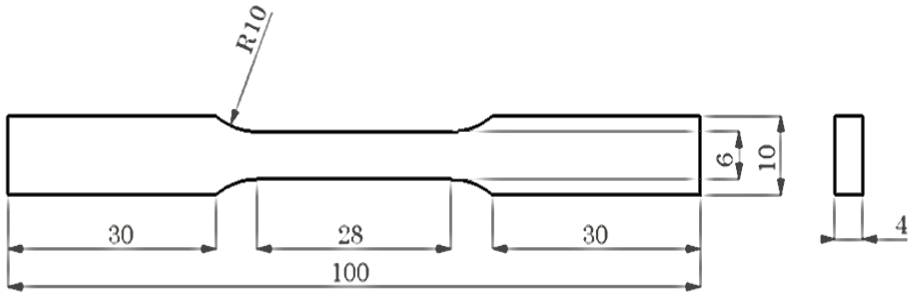


Fig. 3 - Standard geometric of ASTM E21

2.2 Experimental Implementation

The tensile tests are performed using a universal testing machine of Zwick Roell Z030. The experimental design is shown in Table 2. It can be seen that the specimens are tested at various temperatures of 100˚C, 200˚C and 300˚C using two testing speeds of 1.5 mm/min and 15 mm/min. The specimen is pre-heated for about 30 minutes at the test temperature before the tensile load is applied. The fracture surfaces of the tensile specimens are examined under SEM machine.

Table 2 - Test matrix

Temperature (˚C)	Loading Speed (mm/min)	Strain Rate (1/s)
100	1.5	5.8×10^{-4}
	15	5.8×10^{-3}
200	1.5	5.8×10^{-4}
	15	5.8×10^{-3}
300	1.5	5.8×10^{-4}
	15	5.8×10^{-3}

3. Results and Discussions

Fig. 4 shows a sample of the post-test specimen. It can be observed that the deformation occurs within the gauge length of the specimen. The fractured surface shows a quite sharp and rough cup and cone shear fracture without an obvious necking. This behaviour confirms ductility of the material due to an adequate plastic strain energy (plastic deformation) that driven by ductile fracture mechanism of voids initiation, growth and coalescent in the material.

3.1 Stress-Strain Curve Analysis

The experimental data is summarized into stress-strain curves as depicted in Fig 5. In general, it can be concluded that the recycled material sensitive to the changes of temperature and strain rate. The range of the ultimate tensile strength (UTS), yield strength and Elastic's modulus are mainly within 209 MPa – 224 MPa, 158 MPa – 188 MPa and 69 GPa – 70 GPa, respectively. As depicted in Fig 5(a) and 5(b), the flow stress is generally increasing as the strain rate increases. This behaviour is clearly observed at 300 °C; however, it is less pronounced at 100 °C and 200 °C. Bobbili et al. [9] reported that the flow stress decreases with the decreasing in strain rates for aluminium 7071 as low strain rate required a longer time to energy accumulation, which thus reduces the stress level. Besides, Latif et al. [16] reported that the flow stress of magnesium alloy AZ31 and AZ61 increased at increasing strain rates due to high dislocation density and the activation of critical resolved shear stress of non-basal slip systems for magnesium alloys. Ma'at et al.

[17] also reported that the flow stress of AA6061 increases with the strain rate increasing and temperature decreasing. This phenomenon is generally due to the effects of strain rate hardening.

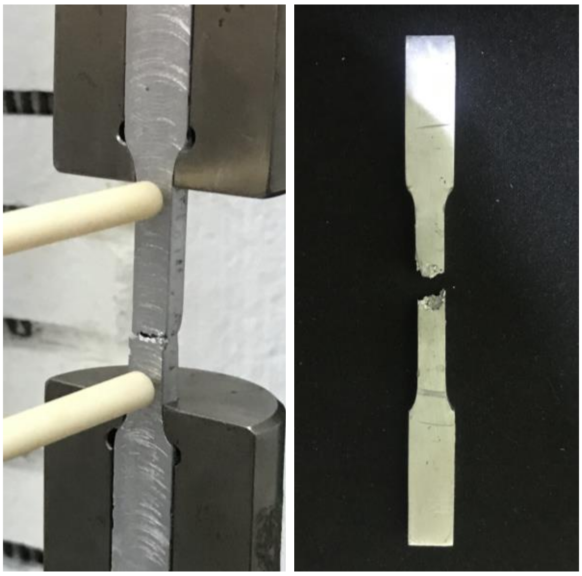
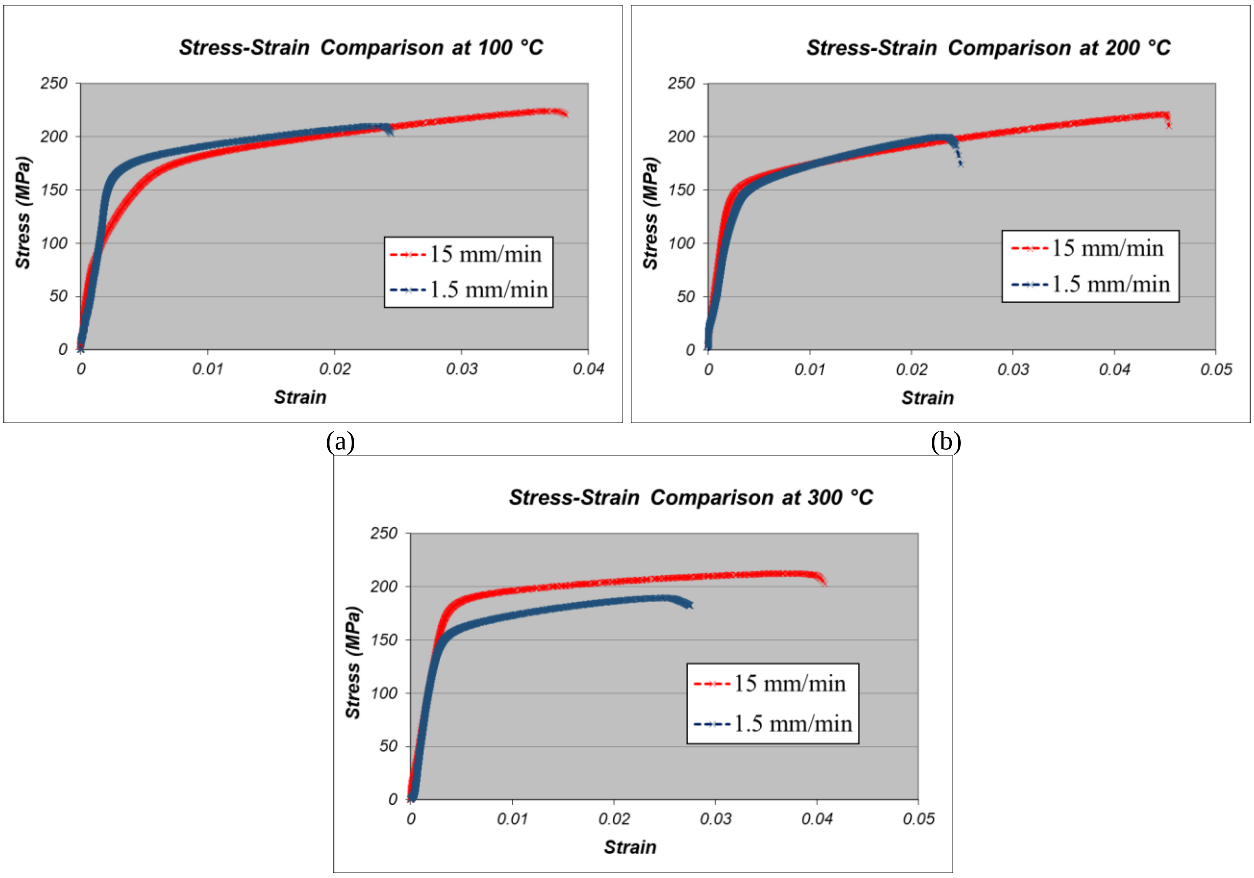


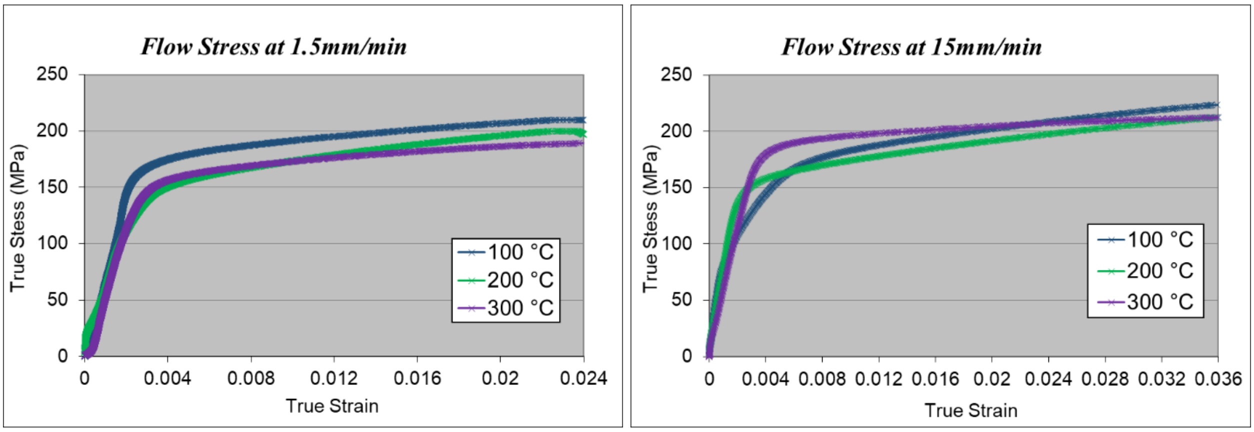
Fig. 4 - Sample of post-test specimen



(a) (b)

(c)

Fig. 5 – Stress-strain curves of recycled AA6061-T5 at different temperature: (a) 100 °C; (b) 200°C; (c) 300 °C



(a) (b)

Fig. 6 - Stress-strain curves of recycled AA6061-T5 at various temperature at loading speed of: (a) 1.5 mm/min; (b) 15 mm/min

In the present study, it can be observed that the total elongation at a lower strain rate is smaller compared to the elongation obtained at higher strain rate. It should be noted that the increment of fracture elongation is influenced by the strain rate hardening or work hardening. Local strain rate hardening controls the necking evolution and diffuses the necking regions at high strain rate, causing the necking area becomes stronger compared to other areas. Consequently, the elongation increases with the increment of strain rate. Generally speaking, it can be accepted that flow stress, and total elongation of such recycled material is strain-rate dependent. In other words, the material capable of sustaining a finite plastic strain deformation without fracture (good ductility) at a higher strain rate 5.8 x 10^{-3} s^{-1} compared to strain rate 5.8 x 10^{-4} s^{-1} within the elevated temperatures. However, there is no specific trend of response to temperature changes. In other words, there is no direct correlation between temperature towards yield strength and elastic's modulus of the material.

The response of recycled AA6061 under elevated temperatures is shown in Fig. 6. As can be seen, there is no specific trend of response towards temperature changes at the beginning of the plastic yielding. The trend of flow stress at the plastic region is not consistent with the increases in temperature. However, softening effects is observed in the specimen with the increment of temperature at plastic region as the plastic modulus is still exist as evident in Fig 6. Softening effect is normally observed during the decreases in stress as the elongation increases upon onset of the yield point. Therefore, it can be accepted in general that the flow stress decreases with increasing temperature.

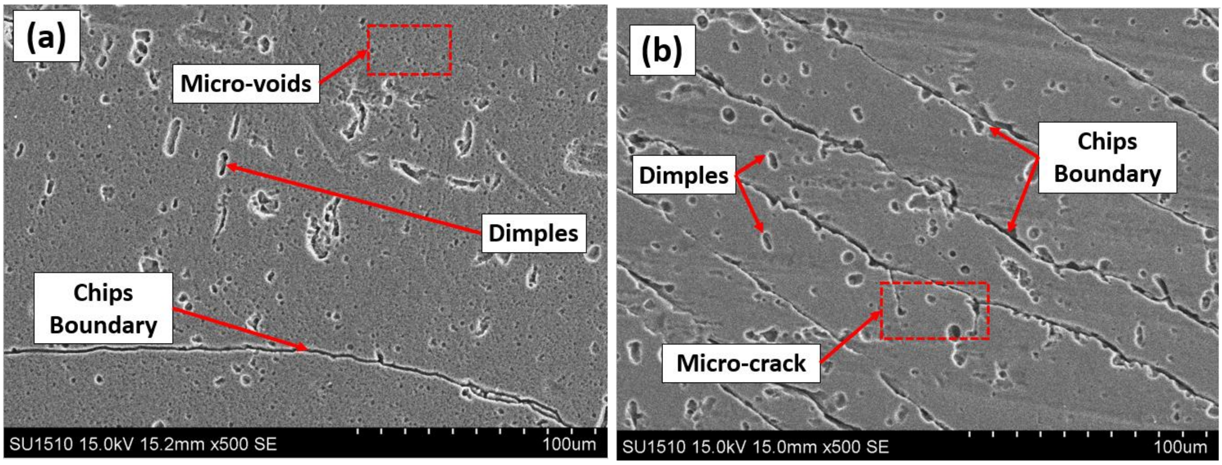


Fig. 7 - SEM micrographs of recycled AA6061 (a) before and (b) after (100 °C, 5.8 × 10^{-4} s^{-1})

3.2 Damage Initiation and Progression

Fig. 7 presents a sample of scanning electron microscope (SEM) micrographs of the specimen before and after (temperature=100 °C, strain rate= 5.8 × 10^{-4} s^{-1}) loading deformation. The damage, such as micro-voids, is initiated at the specimen before deformation (Fig. 7 (a)). The chip's boundary indicates the bonding between the chips in the material. The more and obvious the chip's boundary line, the weaker the bonding behaviour and strength of the material. It can be seen that chip's boundary is observed in the specimen before loading deformation, which indicated that the bonding between the chips is not fully bond even after going through the hot press forging recycling process. Furthermore, the chip's boundary is enhanced with the force applied and micro-crack is formed (Fig. 7(b)) due to the coalescence and growth of the micro-voids. The crack propagation happens by joining of micro-voids and finally results in the fracture of the specimen. Simultaneously, it can be observed that the micro-voids in Fig. 7(b) are lesser compare to Fig 7(a) and the dimples getting more after the loading deformation. This observation clearly shows the evolution of the damage where the micro-void is growth and evolve into a dimple. The dimples and voids growth and coalescence become crack during the loading deformation.

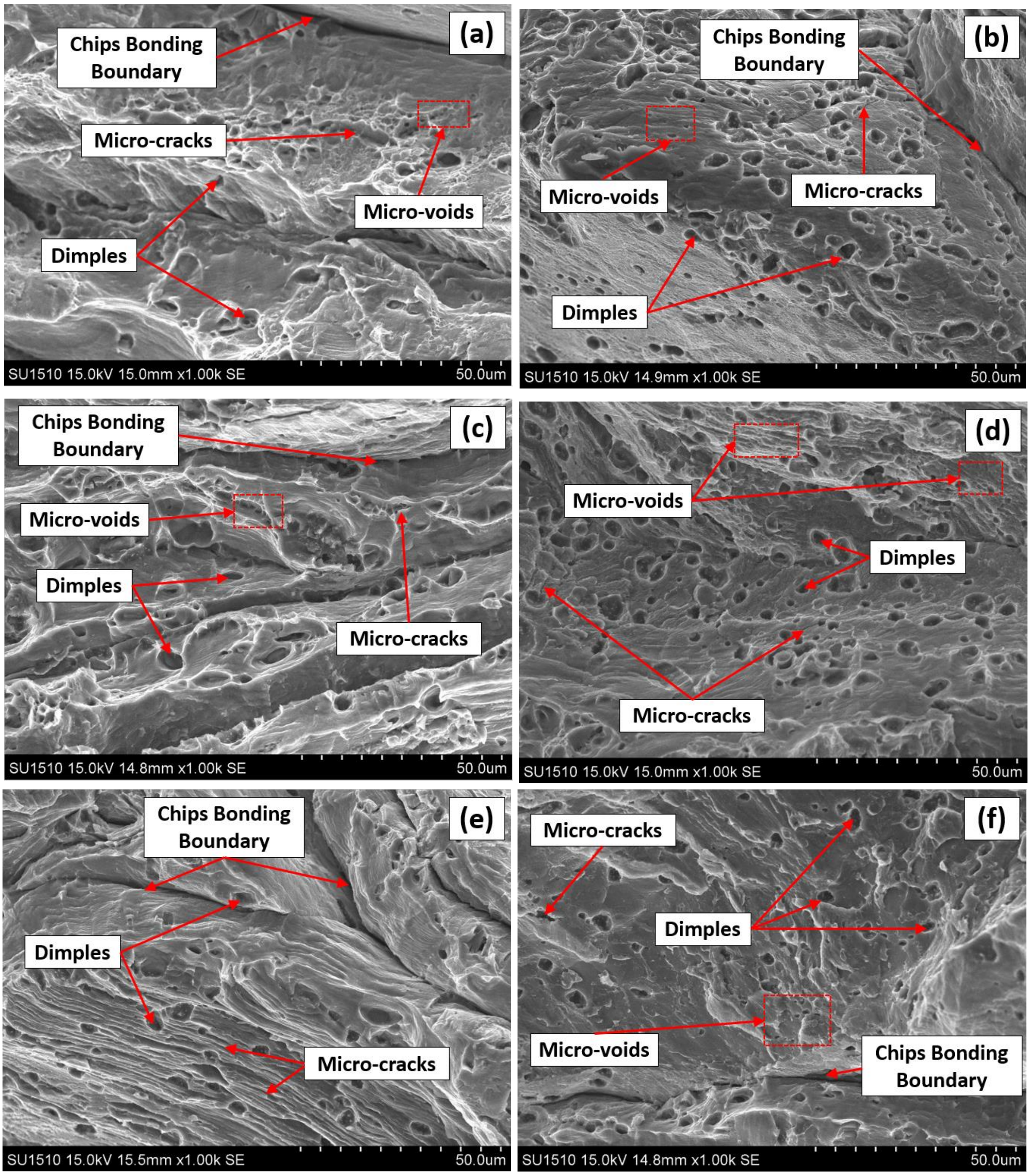


Fig. 8 - SEM micrographs of fracture surface of specimen tested at: (a) 100 °C & 5.8 × 10^{-4} /s; (b) 100 °C & 5.8 × 10^{-3} /s; (c) 200 °C & 5.8 × 10^{-4} /s; (d) 200 °C & 5.8 × 10^{-3} /s; (e) 300 °C & 5.8 × 10^{-4} /s; (f) 300 °C & 5.8 × 10^{-3} /s

The fracture surface of recycled specimens tested at different testing settings under SEM with x1000 magnification is depicted in Fig. 8. Noticeable chips bonding boundary is observed on the fracture surface; particularly the specimen tested at low strain rate deformation, which indicated that the bonding of the chips might be not fully completed. Similar observations of visible chips boundary and micro-voids in the recycled AA6061 chips were obtained by [18], [19]. By comparing the micrographs of the deformed specimens at the same temperature, it is noticed that the micro-voids are growth and coalescence, resulting in the formation of dimples and micro-cracks with an increasing strain rate.

According to the study by Bobbili et al. [9], during dynamic loading condition, the increase in quantity and the size of the dimples may result in ductility enhancement. It is also noticed that at a constant strain rate, a higher testing temperature prompts an increase in the quantity and size of the dimples. Still, the differences are not very obvious and significant. In Fig 8 (b), (d) and (f), the fracture surface shows a rough morphology with many deep and large dimples distributed randomly and densely among the surface. In contrast, in Fig 8 (a), (c) and (e), less amount of dimples is observed and are not densely distributed. Generally, dimples were formed perhaps by the dislocation mechanism where during the tensile deformation, dislocation shifted towards the grain boundary and enhanced the dislocation density and resulting in intergranular fracture [20].

Fig. 9 shows the optical microscopic micrographs of recycled AA6061 after loading deformation at different temperature with the same strain rate of $5.8 \times 10^{-4}\,s^{-1}$. It can be observed that the gap between the grain boundaries is getting wider with the increases in temperature. According to interpretation by Yusuf et al. [12], the closer the gap between the grain boundary indicated that the welding between the chips is enhanced. Moreover, in the study by Russell and Kok [21] which compared the tensile behaviour of single crystal and polycrystalline aluminium with different grain size. They concluded that the smaller the grain size could lead to a denser space barrier (the gap between the grain boundary) to dislocation which capable of enhancing the strength of the material.

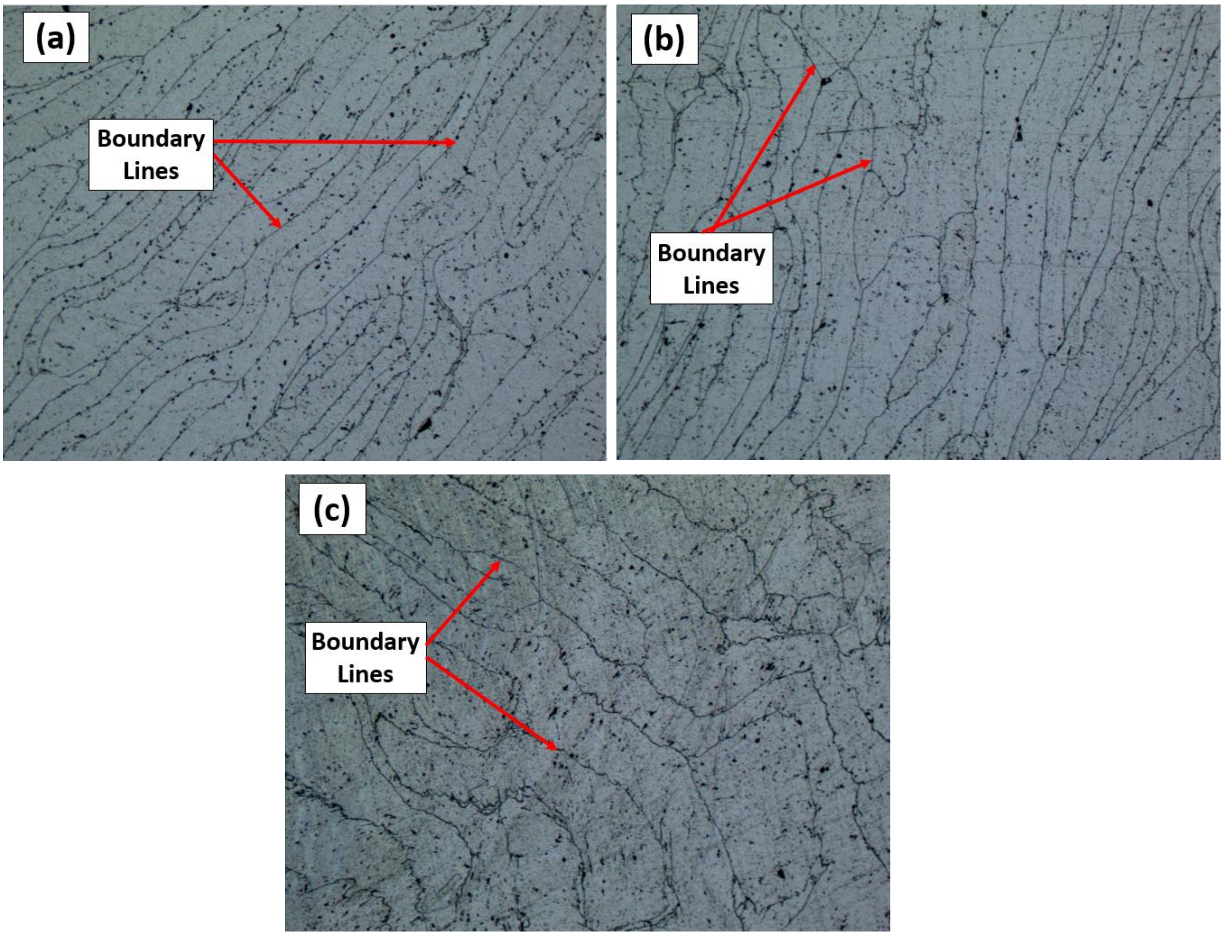


Fig. 9 - OM micrographs of recycled AA6061 at strain rate of 5.8×10^{-4} at temperature of: (a) 100 °C; (b) 200 °C; (c) 300 °C

4. Conclusion

This paper investigates the tensile behaviour of recycled aluminium alloy AA6061 at different strain rates and temperatures. In short, it can be concluded that the recycled AA6061 exhibit a strain-rate dependent response. The flow stress is increasing with the increases in strain rate. The total elongation of the recycled AA6061 is proportional to the increment in strain rate. The increment of the total elongation is generally due to the strain rate hardening or work hardening effect. Also, softening effect is observed proportional to the increment of temperature after the plastic deformation. According to the SEM micrographs of the fracture surface, the quantity of the micro-voids is enhancing. The micro-voids are growth and coalescence, resulting in the formation of dimples and micro-cracks with the increase in strain rate. There are no much differences with the increases in temperature. From the observation under an optical microscope (OM), the gap between the grain boundaries is getting broader with the increases in temperature. In general, the closer the gap between the grain boundaries, the better strength properties of the material.

Acknowledgement

Authors wish to convey sincere gratitude to Universiti Tun Hussein Onn Malaysia (UTHM) for providing the financial means during the preparation to complete this work under Geran Penyelidikan Pascasiswazah (GPPS), Vot U74 and UTHM Contract Research Grant, Vot H276.

References

[1] B. L. Chan and M. A. Lajis, "Direct Recycling of Aluminium 6061 ChipThrough Cold Compression," *Int. J. Eng. Technol.*, vol. 15, no. 04, pp. 4–8, 2015.

[2] M. Irfan *et al.*, "The Effect of Microstructures and Hardness Characteristics of Recycling Aluminium Chip AA6061 / Al Powder on Various Sintering Temperatures," *Int. J. Integr. Eng.*, vol. 10, no. 3, pp. 53–56, 2018.

[3] A. L. Noradila, Z. Sajuri, J. Syarif, Y. Miyashita, and Y. Mutoh, "Effect of Strain Rates on Tensile and Work Hardening Properties for Al-Zn Magnesium Alloys," *Int. J. Mater. Eng. Innov.*, vol. 5, no. 1, pp. 28–37, 2014.

[4] 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.

[5] V. Panov, "Modelling of Behaviour of Metals at High Strain Rates," Ph.D. Thesis, Cranfield University, 2006.

[6] Y. Wicaksana and S. Jeon, "Strain Rate Effect on the Crack Initiation Stress Level under Uniaxial Compression," in *9th Asian Rock Mechanics Symposium*, pp. 1–9.

[7] Y. Cao, J. Ahlström, and B. Karlsson, "The Influence of Temperatures and Strain Rates on the Mechanical Behavior of Dual Phase Steel in Different Conditions," *J. Mater. Res. Technol.*, vol. 4, no. 1, pp. 68–74, 2015.

[8] M. K. M. Nor and I. M. Suhaimi, "Effects of Temperature and Strain Rate on Commercial Aluminum Alloy AA5083," *Appl. Mech. Mater.*, vol. 660, pp. 332–336, 2016.

[9] R. Bobbili, V. Madhu, and A. K. Gogia, "Tensile Behaviour of Aluminium 7017 Alloy at Various Temperatures and Strain Rates," *J. Mater. Res. Technol.*, vol. 5, no. 2, pp. 190–197, 2016.

[10] A. Ahmad, M. A. Lajis, N. K. Yusuf, S. Shamsudin, and Z. W. Zhong, "Parametric Optimisation of Heat Treated Recycling Aluminium (AA6061) by Response Surface Methodology," in *AIP Conference Proceedings*, 2017, vol. 1885, no. 1, pp. 1–7.

[11] A. Ahmad, M. A. Lajis, and N. K. Yusuf, "On the Role of Processing Parameters in Producing Recycled Aluminum AA6061 Based Metal Matrix," *Materials (Basel).*, vol. 10, no. 1098, pp. 1–15, 2017.

[12] N. K. Yusuf, M. A. Lajis, and A. Ahmad, "Hot Press as a Sustainable Direct Recycling Technique of Aluminium : Mechanical Properties and Surface Integrity," *Materials (Basel).*, vol. 10, no. 8, p. 902, 2017.

[13] ASTM Standard G131, "Standard Practice for Cleaning of Materials and Components by Ultrasonic Techniques," *ASTM Int.*, no. Reapproved, pp. 1–5, 2002.

[14] ASTM E8/E8M, "Standard Test Methods for Tension Testing of Metallic Materials," *ASTM Int.*, pp. 1–27, 2012.

[15] ASTM E21, "Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials," *ASTM Int.*, pp. 175–182, 2012.

[16] N. A. Latif, Z. Sajuri, and J. Syarif, "Effect of Tensile Strain Rates on Flow Stress for Extruded AZ31 and AZ61 Magnesium Alloys," *Int. J. Automot. Mech. Eng.*, vol. 14, no. 1, pp. 3812–3823, 2017.

[17] N. Ma'at, M. K. M. Nor, and C. S. Ho, "Effects of Temperature and Strain Rate on the Mechanical Behaviour of Commercial Aluminium Alloy AA6061," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 54, no. 1, pp. 21–26, 2019.

[18] Mohamed Adel Taha Mohamed Abbas, "Characteristics of Solid State Recycling of Aluminum Alloy (AA6061) Chips by Hot Extrusion," in *The International Conference of Engineering Sciences and Applications*, 2016, vol. 1, pp. 316–323.

[19] A. I. Selmy, M. I. A. El Aal, A. M. El-Gohry, and M. A. Taha, "Solid-State Recycling of Aluminum Alloy (AA-6061) Chips via Hot Extrusion Followed by Equal Channel Angular Pressing (ECAP)," *Egypt. Int. J. Eng. Sci. Technol.*, vol. 21, no. 10, pp. 33–42, 2016.

[20] Z. Zheng, X. Zhang, L. Xie, L. Huang, and T. Sun, "Changes of Microstructures and Mechanical Properties in Commercially Pure Titanium after Different Cycles of Proposed Multi-Directional Forging," *Metal*, vol. 9, no. 2, pp. 175–186, 2019.

[21] A. M. Russell and K. L. Lee, *Structure Property Relations in Nonferrous Metals*. John Wiley & Sons, Inc., 2005.