Damage Initiation and Evolution Analysis of Hot Extruded Recycled Aluminium Alloys (AA6061)

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Abstract. The effects of strain rate on the mechanical behaviour of recycled hot extruded aluminium alloys (AA6061) are investigated using uniaxial tensile tests in this work. The damage characteristics such as micro-cracks and micro-voids are analysed on the microstructure of the material using Scanning Microscope Electron (SEM). It is shown that the mechanical behaviour of the recycled AA6061 is influenced by the loading speed. Besides, the damage parameters such as the micro-cracks and micro-voids in the material are evolved significantly in such materials during finite strain deformation. It can be observed that the evolution speed of the micro-cracks and micro-voids in the materials is increasing with the increase in loading speed. Much work is still required to improve the recycled AA6061 as compared to the primary resources in terms of damage parameters initiation and evolution.

1. Introduction

The high demand of the primary aluminium alloys usage had been shifting the attention on the recycled aluminium alloys as the secondary resources. Nowadays, various recycling methods have been adopted in the production of recycled aluminium alloys capable of giving promising results. However, it is generally agreed that strain rates still a critical issue for consideration to ensure the identical engineering applications can be fulfilled as shown by the original solid-state form [1], [2]. At quasi-static rates of strain, this behaviour has been studied by a few researchers as published in [3], [4], [5] and [6]. Also, damage evolution in the recycled materials is still an existing open area to be studied in such materials.
Commercial aluminium alloys have been used extensively in aerospace and automotive industries due to its excellent profile such as low density, high specific modulus, excellent corrosion resistance and exhibits good machinability, formability and surface finish. Moreover, it also exhibits the potential of recyclability, where it can be fully and continuously recycled [5], [7]. However, during the production of aluminium alloys, it required a high amount of energy consumption, and it may bring to environment pollution [8], [9]. Therefore, a suitable replacement using recycled aluminium alloys as a secondary resource must be considered seriously.

The recycled aluminium alloys have produced from the aluminium scraps and chips. In previous, conventional technique that involved melting process is used to recycle the scrap and chips. However, some researchers found that the scraps and chips are not conducive and good for recycled using the re-melting process [10], [11]. Subsequently, solid-state recycling technique had been adopted. Figure 1 shows the comparison between the conventional and solid-state recycling technique to produce extruded recycled products. It can be noticed that the solid-state recycling technique required less procedure and less amount of new scrap will be produced in the recycling process [7], [12], [13].

However, there is a challenge on the recycled materials to achieve almost the same mechanical behaviour as the primary resources. This challenge due to the material degradation associated with the damage, such as the micro-crack and micro-voids in the recycled material. In fact, ductile fracture involves damage because of the nucleation, growth, and coalescence of those micro-cracks and micro-voids [14], [15].

In this paper, the recycle form of aluminium alloys (AA6061) was produced using a hot extrusion solid-state recycling technique. The specimens produced were tested at different strain rates via uniaxial tensile test, and the microstructure of the specimens was observed before and after the test. This approach allows for deep analysis on the damage behaviour of such materials undergoing finite strain deformation.

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**Figure 1.** Flowchart of Conventional Recycling Technique and Solid-state Recycling Technique [12]
2. Experimental Procedure

2.1. Specimen Preparation

The aluminium alloys AA6061 chips were milled from AA6061-T6 plate by using Sodick-MC430L high-speed machine. Acetone solution was used to clean the chips by utilizing ultrasonic bath, and the cleaned chips were dried in the thermal oven at 60 °C for about 30 minutes. Next, cold press machine was used to form a 30 mm diameter with approximate 90 mm height cylindrical shape billet at 120 bar. Then, the billet was pre-heated in a 500 °C furnace for 120 minutes. Subsequently, the billet was inserted into the 300 °C extrusion container and extruded. Lastly, the extruded product was cut into dog-bone shape according to ASTM E8 standard. The flow of the specimen preparation process is shown in Figure 2.

![Figure 2. The flow of Specimen Preparation using Hot Extrusion](image)

2.2. Uniaxial Tensile Test

The ASTM E8 dog-bone shaped recycled aluminium alloys (AA6061) specimens are tested in room temperature at three different loading speeds: 0.05 mm/min, 0.5 mm/min and 5 mm/min, using a uniaxial tensile machine. 25mm gauge length extensometer is used in order to obtain a more accurate result. The fracture surfaces after the tensile test are then observed under SEM. The test matrixes of the experiment are shown in Table 1.

| Temperature | Room Temperature |
|-------------|------------------|
| Specimen    | Loading Speed (mm/min) |
| 1           | 0.05              |
| 2           | 0.5               |
| 3           | 5                 |
3. Results and Discussion

3.1. Mechanical Properties

Figure 3 and Table 2 presented the tensile results of the recycled AA6061 at different loading speed. The results of Young’s modulus (E), yield strength and Ultimate Tensile Strength (UTS) are changing at different loading speed or strain rate. The UTS value is increasing; on the other hands, the performance of yield strength and Young’s modulus are decreasing with the increasing of loading speed. The recycled AA6061 behave more elastic with the increase in loading speed. It can be noticed that the most sensitive parameter to the loading speed or strain rate is Young’s modulus of the material, followed by UTS and yield strength.

Comparing with the primary resource, the mechanical performance of the hot extruded recycled AA6061 without heat treatment is poor than the as-received AA6061-T6, but it is still comparable with primary AA6061-T1. It can be noticed that the recycled AA6061 have some degradation on UTS value compared to AA6061-T1. The degradation of the mechanical performance might be caused by the micro-cracks and micro-voids within the recycled AA6061, which affected the bonding in the recycled material [16], [17]. The microstructure of the recycled material can be observed and analyzed in the following section.

![Figure 3. Tensile Test Results at Loading Speed of (a) 0.05 mm/min (b) 0.5 mm/min, (c) 5 mm/min](image-url)
Table 2. Summary of Tensile Test Result

| Specimen          | Loading Speed (mm/min) | E (GPa) | Yield Strength (MPa) | UTS (MPa) |
|-------------------|------------------------|---------|----------------------|-----------|
| 1                 | 0.05                   | 101.56  | 165.82               | 179.20    |
| 2                 | 0.5                    | 78.09   | 123.65               | 198.04    |
| 3                 | 5                      | 55.20   | 133.02               | 204.92    |
| AA6061-T1 [18]    |                        | 69      | 110                  | 210       |
| As-Received AA6061-T6 |                    | 70      | 270                  | 310       |

3.2. Microstructure

The tensile fracture surface of the recycled AA6061 was observed and analyzed by using SEM in this work, as illustrated in Figure 4. From the figure, the pores formed is the micro-voids and dimples in the fracture surface, and the lighter part which seems to be like strings is the crack propagation line [10], [19]. It can be observed that the amount of micro-voids and micro-cracks increase with increasing loading speed. At the highest loading speed, it can be observed that the voids and dimples are deeper while the quantity is higher than the one tested at lower loading speed.

In order to analyze the damage initiation and evolution, the microstructure before and after tensile loading is compared, as shown in Figure 5. Before undergoing tensile loading, the microstructure of the recycled AA6061 was smooth and fine. Less amount of micro-voids and micro-cracks can be noticed in the material. Contrarily, the formation of the micro-cracks and micro-voids due to the tensile loading is the main local damage initiation mechanism identified [20]. The micro-cracks and micro-voids evolved significantly in the recycled AA6061 undergoing tensile loading [21]. The evolution speed is increasing with the increment of loading speed or strain rate.

![Figure 4](image_url)

**Figure 4.** Microstructure of the Tensile Fracture Surface of Recycled AA6061 at Loading Speed of (a) 0.05 mm/min, (b) 0.5 mm/min, (c) 5 mm/min
Further, the results of the recycled AA6061 is compared to the primary resource. Figure 6 shows the comparison of the microstructure between the hot extruded recycled AA6061 and the as-received AA6061. Numerous dimples and micro-voids can be seen in both the fracture surface of the materials, and the fracture mode is categorized as ductile fracture deformation [10]. Undergoing the same loading speed condition at 0.5 mm/min, as-received AA6061 shows better results than the recycled material in terms of damage parameters development and evolution. The amount of micro-cracks and micro-voids in the primary resource is lesser than the recycled form, and the size of those damages can be seen smaller too. A lot of deep dimples and micro-voids can be found in the recycled AA6061 compared to the primary resource.

4. Conclusion

The results in this work show that the mechanical behaviour of the selected recycled material is dependent on the given loading speed as generally accepted. The material can withstand higher UTS value and behaves elastically with the increasing of loading speed. Based on the micrographs analysis, the microstructure of the undeformed hot extruded recycled AA6061 looks smooth, and not much
micro-voids and micro-cracks can be found. The damage parameters start to evolve due to the growth and coalescence of the voids and cracks. Moreover, it can also be observed that the loading speed influences the damage evolution. The voids and dimples that developed in the deformed recycled AA6061 at highest deformation speed are deeper and much higher than the one at lower loading speed.

In summary, much work still needed to enhance the capability of the recycled AA6061 as fulfilled by the primary resource. It is due to the damage parameters developed inside the recycled materials as proven in this work. In future works, heat treatment and aging are suggested to be included in the development process of the recycled material to improve the bonding between microstructures inside the recycled material.

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