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High-Velocity Impact Penetration Behavior of Recycled Aluminum Alloy 6061: A Brief Look

Irfan Alias Farhan Latif[1], Mohd Khir Mohd Nor[1*]

[1]Crashworthiness and Collisions Research Group (COLORED), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA

*Corresponding Author

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Abstract: Aluminum demand is projected to increase in the future. To help meet the demand, recycling aluminum has been employed for quite some time. Conventional recycling of aluminum leads to CO_2 and greenhouse gas emissions. Therefore, direct recycling techniques such as hot press forging are being used and researched to provide an alternate recycling route that leads to even lower emissions, material losses, and energy consumption. The recycled aluminum 6061 alloy obtained from hot press forging is relatively new. Hence, not much is known about its capabilities and properties, including its impact penetration behavior. In this study, recycled 6061 aluminum alloy plates of 5 mm obtained through hot press forging are used in high-velocity impact tests using a single-stage gas gun to test the material's penetration behavior. Two tests are carried out at velocities ranging from 141 to 308 m/s, all resulting in full penetration. The material was observed to have decent energy absorption capabilities, ranging from 70% to 81%. The penetration behavior, however erratic, shows signs of both ductile and brittle failure modes.

Keywords: Recycling, aluminum, hot press forge, impact penetration, energy absorption

1. Introduction

Aluminum is a material that is frequently used in many aspects of modern society, such as the military, transportation, power, food, and chemical industries, due to its abundant availability and excellent properties. The use of aluminum in our society is only expected to grow as time advances. By the year 2040, global aluminum demand is projected to continue to grow, reaching as much as 90 million metric tons per year, with an additional 70 million metric tons of demand met by recycled aluminum [1]. However, aluminum processing incurs some CO_2 and greenhouse gas emissions. About 2% of the annual global CO_2 emissions are attributed to aluminum production [2]. However, aluminum has excellent recyclability [3], which can be utilized to recirculate the aluminum in use.

Aluminum is most commonly recycled by conventional means of melting and reforging the scrap. However, this approach produces greenhouse gas emissions, requires extensive energy usage, and results in material loss [4]. Research into direct recycling techniques has been going on for a while. These techniques allow recycling without melting the aluminum scrap, countering the negative effects of conventional aluminum recycling techniques. One of the most promising direct recycling techniques is the hot press forging technique [5], [6]. This technique, as the name implies, utilizes a hot press forge in which aluminum scrap is reshaped at temperatures just below the melting point (also known as recrystallization temperature).

The hot press forge has been used in many projects and has been optimized for recycling aluminum alloy 6061. Parameters such as the operating temperature of the forge, the operating pressure of the forge, the size of aluminum scrap chips, the holding time, and more have been tested and optimized to produce the best possible recycled aluminum 6061 specimens (these parameters are listed below) [5], [7]- [12]. The specimen produced using the optimized parameters was

*Corresponding author: khir@uthm.edu.my

found to have an ultimate tensile strength of around 250 MPa [13]. The elongation-to-failure percentage is around 12% [13]. The microstructure of the recycled material was investigated, and it was found to have much weaker chip bonds with plenty of voids and gaps [11]. The tensile behavior of the recycled aluminum 6061 was also studied at temperatures of 100°C, 200°C and 300°C [12]. Taylor cylinder impact tests were also carried out using the recycled material, and the recycled material showed signs of mild ductility [14]. The impact resistance and penetration behavior of the recycled aluminum 6061 alloys are yet to be investigated. The results of the Taylor cylinder impact tests do show promising signs for the recycled material. This particular gap in the knowledge base of the recycled aluminum 6061 alloy is the subject of this paper.

2. Materials and Equipment Setup

To investigate the penetration behavior of recycled aluminum 6061 alloy material, high-velocity impact tests are performed. A single-stage gas gun setup based on the NIJ-018.01 standard is used to perform the tests [15]. The test setup shown in Fig. 1 uses helium gas in a pressure vessel to propel a projectile towards the chamber box, which houses the target plate. The impact event is captured by a high-speed camera. A paper scale is placed in the background of the camera shot to mark the location of the projectile at a specified time and the distance travelled during this period. The impact velocity and residual velocity after impact are calculated through frame-by-frame analysis. The projectile used for testing is a hemispherical stainless-steel bullet of 13 mm in length, 8.5 mm in diameter, and 5.3 g in mass. Compatible plates of size 100x100 mm are needed for the test setup. These plates are prepared using the hot press forge recycling technique.

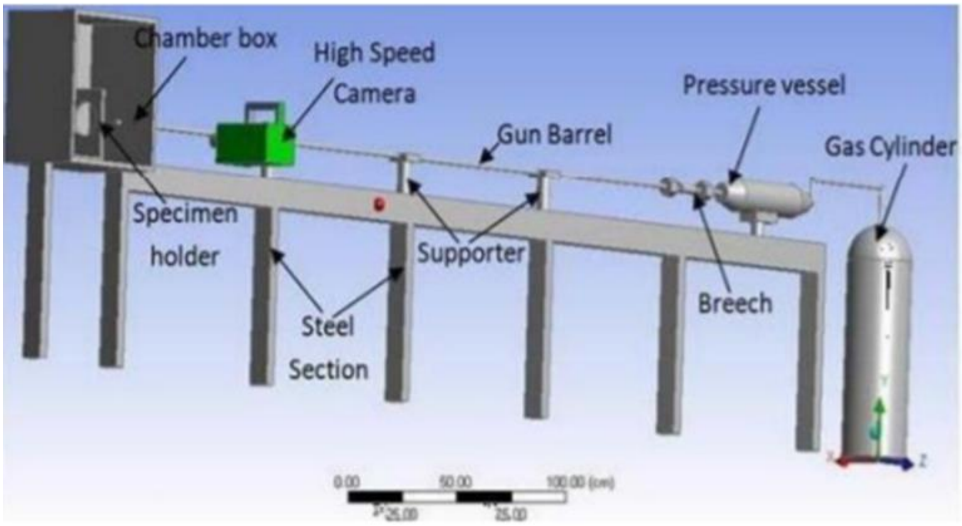


Fig. 1 - Single stage gas gun setup [16]

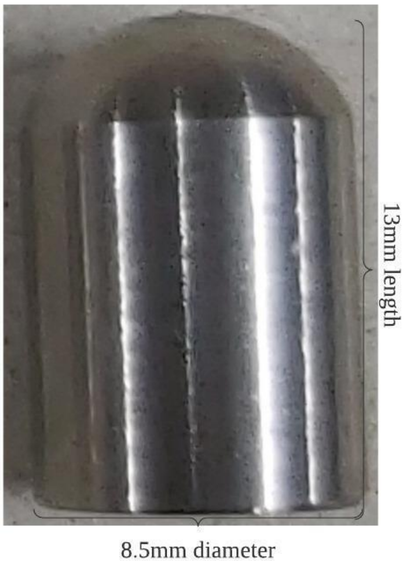


Fig. 2 - Hemispherical impactor used in tests

The process starts with preparing chips with the optimum parameters for the best results. The chips are of an average size of 5.2 mm length x 1.097 mm width x 0.091 mm thickness and were prepared using a CNC (computer numerical control) machine with a feed rate of 0.005 mm/tooth, 1 mm depth of cut, a 10 mm diameter tool, and a cutting speed of 377 m/min [14]. The chips are gathered and cleaned up in an ultrasonic bath using acetone as the solution. The chips are then dried in a thermal oven at a temperature of 60 °C for 30 minutes. The chips are then used to produce the required plates using the hot press forging process. The optimal operating parameters for the hot press forge are detailed in Table 1.

Table 1 - Optimal parameters for hot press forge [8], [11]

Optimal Parameter	Value
Operating Temperature	530 °C
Operating Pressure	47 MPa
Holding Time	2 hours

The plate is taken out of the forge when ready and quenched at a 100 °C/s quench rate. Artificial thermal ageing is done by putting the plate in a thermal oven for 120 minutes at a temperature of 175 °C. In terms of analysis, the impact velocity and the residual velocity are calculated by doing frame-by-frame analysis of the impact footage taken from the high-speed camera. The energy absorption capability of the plate is calculated by subtracting the kinetic energy of the bullet after impact from the kinetic energy of the bullet before impact. With the simple assumption of no energy loss, it can be said that the remaining energy is absorbed by the plate. The equation is shown below:

$$\frac{1}{2}mv_B^2 - \frac{1}{2}mv_A^2 = Ep \tag{1}$$

where Ep is the energy absorbed by the plate, m represents the mass of the bullet, v_B represents the velocity of the bullet before impact and v_A is the velocity of the bullet after impact (residual velocity). The plates are also 3D-scanned after impact to allow for accurate characterization of the deformation behavior. An example of how the profile is captured is shown in Figure 3. The test setup is capable of performing impacts at around 400 m/s velocity. In this paper, recycled plates of 5 mm thickness are tested.

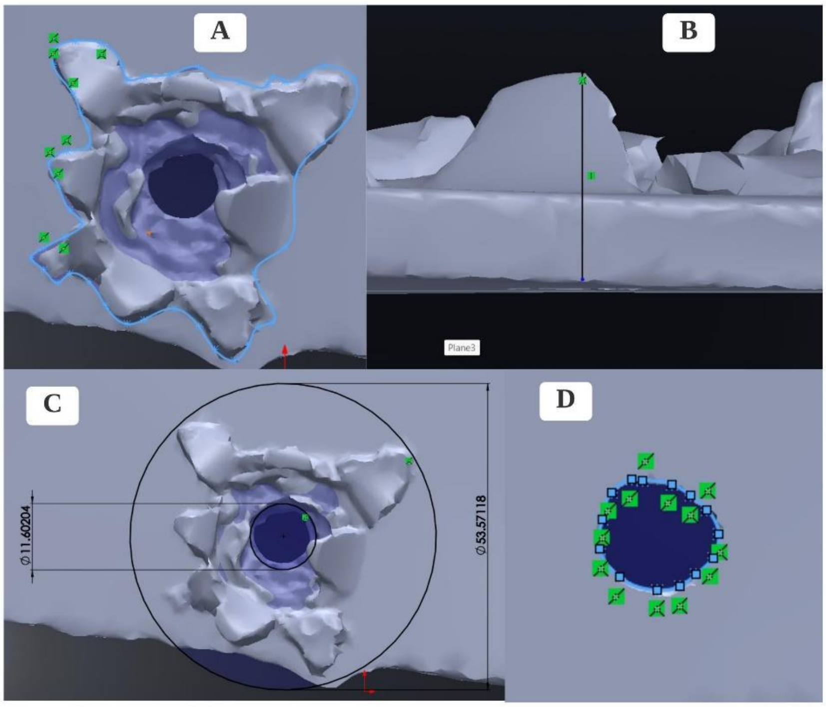
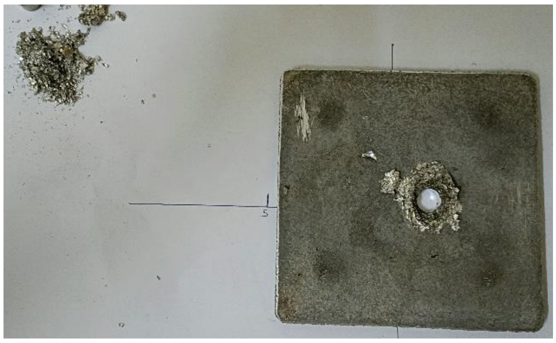


Fig. 3 - 3D scan deformation profile capture (a) deformation profile of the exit wound; (b) maximum depth of the crater; (c) bullet hole diameter and; deformation zone; (d) deformation profile of the entry wound

3. Results

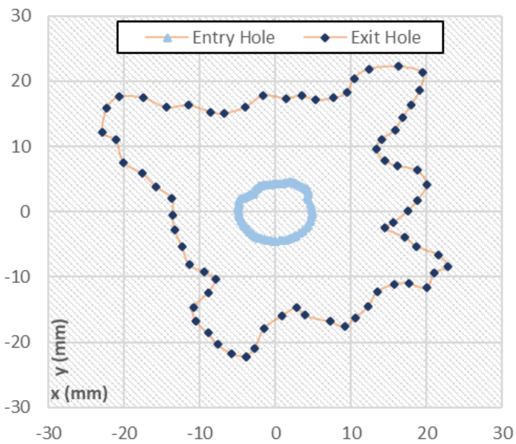
Two tests were performed using the 5 mm recycled plates. The resulting deformation is shown below in Figures 4 and 5. The velocities and the kinetic energy analysis of each test event are shown in Table 2. All two impact events resulted in full penetration, with the lowest velocity impact of 141 m/s and the highest of 308 m/s. From impact events 1 to 2, the jump in impact velocity is around 45%. A similar relation is observed for residual velocity from impact events 1 to 2, with a jump of 42%, suggesting the relationship between impact velocity and residual velocity is somewhat linear, at least at the testing ranges. The energy absorption capability is observed to drop just 3% from impact events 1 to 2. It can be said that the absorption capability of the plate remains around 80% in the range of 141 and 308 m/s impact events.

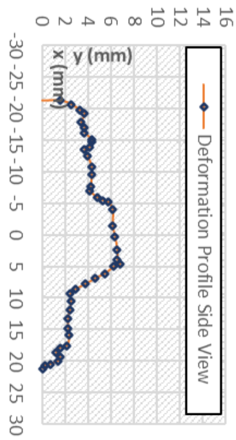
(a) 5mm; 141 m/s



(b) 5mm; 308 m/s

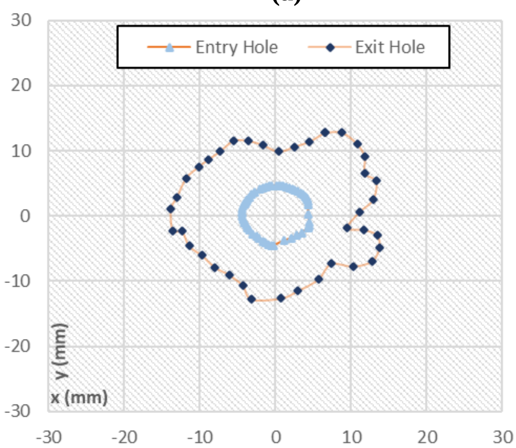
Fig. 4 - Pictures of deformation (a) impact event 1; (b) impact event 2

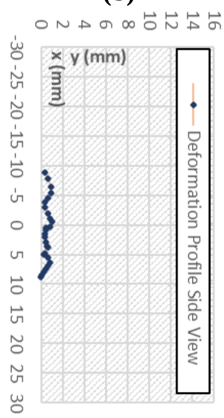




(5mm; 141 m/s)

(a) (b)





(5mm; 308 m/s)

(a) (b)

Fig. 5 - Deformation profile of recycled AA 6061 plates (a) bullet entry and exit hole profiles; (b) side view of the deformation

Table 2 - Impact velocities and kinetic energy observations

#	Impact velocity (m/s)	Residual velocity (m/s)	Kinetic energy absorbed by plate (%)
1	141	60	81
2	308	142	79

In terms of deformation, maximum deformation was observed in impact event 1, where most energy was absorbed by the plate. The deformation area of the exit wound of the plate was measured to be 1144 mm squared, where impact 2 resulted in 514 mm squared. The difference in energy absorbed appears to be minor. However, with the increase in impact velocity of 45%, a similar percent decrease in the area of the deformation can be seen. It can thus be summarized that as the velocity of impact increases, the resulting deformation appears more localized to the area of impact.

An observation of note is the mode of failure of the material. It can be argued by observing the pictures of the deformations in Fig. 4 that the material shows signs of petaling in the first impact event. However, the petals contain only the material from some separated layers on the back side of the plate. The petals are not initiated from the bullet entry hole area, which suggests spalling also occurs as material seems to be separating post-impact in layers. Plugs of the same diameter as the bullet are also observed, but the plug itself contains very little material that is barely staying put as gaps visible to the naked eye are observed. There are signs of fragmentation as well. Much of the material is ejected post-impact in the form of fragmentation, which consists of chips of varying sizes and minute-sized grains as well. Radial fracture can also be seen in between petals, but it's not the prevalent mode of fracture. In the second impact event, the deformation is much more concise and localized. Only petals are seen to be formed in a similar fashion to the first impact event, which had a total of 5 petals. The fragmentation debris is also much more granular in size. No plug was observed in the second impact event as well. As the velocity of impact increases in the second impact event, the bullet travels through the material faster, leading to a higher strain rate. An argument can be made that this leads to the minimal deformation profile of the second impact event. Overall, the material does show signs of both ductile and brittle fracture modes. It shows signs of mild ductility with some brittle material characteristics.

It is evident even with the naked eye that the chip bonds are not great. To understand the failure mode of the material better, a microstructure analysis is needed. The impact resistance of the material could be identified as all the tests resulted in complete penetration. However, from the given data, it can be said that the critical impact velocity (the velocity at which the plate is completely penetrated) of the 5 mm recycled aluminum plate is lower than 141 m/s for the chosen impactor.

4. Conclusion

From the test results, it can be observed that the penetration behaviour shown by the recycled plate is a mixture of various modes both ductile and brittle. Full penetration was observed for all the test events. The material exhibits decent energy absorption with the cost of significant damage to its structure. A linear relationshio between residual velocty and the impact velocity is observed. The deformation modes are somewhat consistent with all tested velocities whereas the deformation profile seems to be decreasing in area with an increase to the impact velocity.

Compared to primary aluminium 6061 alloys, the recycled plates show much less impact resistance. The recycled aluminium 6061 alloy plates can not be considered in the same applications as their primary counterparts as they display significantly different (weaker) impact behaviour. However, there still lies the possibility of the material being considered strong when it is impacted by projectiles of lower mass at low velocities.

Acknowledgement

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