An experimental study on the deformation behavior of Aluminium armour plates impacted by two different non-deformable projectiles

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Abstract

The present study describes the experimental results pertinent to the penetration of AA-2024, AA-6061 and AA-7017 plates with two different non-deformable steel projectiles. The diameters of the projectiles used for ballistic impact testing are 7.62 and 12.77mm. The projectiles are impacted on the aluminium targets of 70 mm thickness with velocities in the range of 840±10 m/s. The results presented include variation in damage pattern in experimental alloys with respect to different projectiles. The microstructures and micro-hardness values along the projectile penetration path have been investigated to understand the material deformation behaviour. Some observations relating to the adiabatic shear band formation have also been presented. From the ballistic testing experiments, it is observed that AA-7017 plates display higher ballistic resistance among the tested aluminium alloys. The ballistic performance of the aluminium alloy plates have been correlated with their respective mechanical properties.

1. Introduction

Aluminium alloys are extensively used in applications where weight is an important design criterion. These alloys are very popular in automotive and aerospace applications owing to their high strength, low density, good fracture toughness, good formability, ease of weldability for manufacturing purposes and excellent corrosion resistance. Based on these properties, these alloys are also candidate materials for ballistic applications wherein steels are normally chosen. In addition, several investigations have shown that the aluminium alloys can reduce the...
weight of a protective structure by approximately 25% in comparison to those of steels against a similar level of threat [1-2].

Ballistic impact is an immensely localized process. Heat generated during such severe and rapid impact may induce local thermal softening and microstructural instability. The research activities in the field of ballistic impact have been mainly focused on experimental tests, understanding the behaviour of materials under high strain rate loading and creation of analytical models. However, majority of these investigations to a certain extent lack the inclusion of starting microstructure and its subsequent modifications during projectile impact. In addition, material failure at high strain rates is a complex process involving many material parameters like strength, hardness, ductility, toughness, strain hardening co-efficient etc. Materials with a balanced combination of strength and toughness may display better ballistic performance in comparison to those only having higher strength or toughness [3]. It is, therefore, of interest to study the deformation behaviour of different aluminium alloys based on microstructural modifications in post impact materials.

In the present study, the ballistic behaviour of three different series of heat treatable aluminium alloys namely AA 2024, AA 6061 and AA 7017 plates subjected to the impact of 7.62mm and 12.7mm projectiles has been investigated. The changes in the microstructure, hardness and damage pattern in post impact samples with respect to the two different projectiles have been studied.

2. Experiments

The analysed chemical composition of the three aluminium alloys is given in Table 1. The aluminium alloys were received in the peak aged condition in the form of 70 mm thick plates. Microstructure characterization of the plates were carried out following standard metallographic techniques used for aluminium and its alloys and etched using Keller’s reagent (5ml HNO₃, 3ml HCl, 2ml HF and 190 ml H₂O). Mechanical properties of the alloys were evaluated by hardness and tensile properties measurements. Hardness of the plates was measured according to ASTM E 140-02 by using a Vickers hardness tester. 10 kg load was employed to determine the hardness of the plates. Tensile samples are machined according to ASTM 8 and tensile properties were evaluated at an ambient temperature on round tensile specimens (20 mm gauge length) using INSTRON 8500 testing machine at a crosshead speed of 1.0 mm/min. In case of each alloy, three tensile tests were carried out and average values of the properties are reported.

Ballistic tests were conducted in a small arms range using a standard rifle. All the tests were carried out at normal impact angle i.e. at zero obliquity. The plates were impacted with two different non-deformable steel projectiles. The detailed description of the projectiles is illustrated in Table 2. The angle of attack was normal to the target plates. The striking velocity of the projectiles was measured using infrared light emitting diode photovoltaic cell by measuring the time interval between the interceptions caused by the projectile running across two transverse beams placed 2 m apart. The velocities of impacts were within range of 840± 10 m/s. The projectiles were fired from a distance of 15 m. The testing arrangement is described elsewhere [4]. At least three shots were fired on each plate and three sets of plates were fired in order to get the ballistic behavior statistically. After ballistic testing, plates were cut into half across the craters and then subjected to standard metallographic procedure to reveal the post ballistic microstructures. The microstructures along the path of the projectile were examined in optical microscope. Vickers micro hardness values were obtained adjacent to the crater wall along the path of the projectile by using a Leica micro hardness tester at 100 gm load.

Table 1. Chemical composition of aluminium alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition (Wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 2024</td>
<td>Cu – 4.05, Mg – 1.43, Si – 0.43, Mn - 0.38, Fe - 0.32, Ti - 0.017, Pb - 0.031, Al - Balance</td>
</tr>
<tr>
<td>AA 6061</td>
<td>Mg – 1.2, Si – 0.8, Fe – 0.7, Cu – 0.4, Mn - 0.15, Cr – 0.35, Zn – 0.25, Ti – 0.15, Al – Balance</td>
</tr>
<tr>
<td>AA 7017</td>
<td>Zn – 5.2, Mg – 2.3, Si – 0.35, Cr - 0.35, Fe – 0.45, Mn - 0.2, Zr – 0.1, Al – Balance</td>
</tr>
</tbody>
</table>

Table 2: Some parameters of the projectiles

<table>
<thead>
<tr>
<th>Property</th>
<th>Projectile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.62mm</td>
</tr>
<tr>
<td>Core material</td>
<td>High hardness steel</td>
</tr>
<tr>
<td>Bullet length</td>
<td>26.53 mm</td>
</tr>
</tbody>
</table>
Diameter of high hardness projectile 6.06 mm 10.75 mm  
Core weight 5.342 gm 30.049 gm  
Striking velocity 840±10 m/s 840±10 m/s  
Kinetic energy 1.88 KJ 10.6 KJ

3. Results

The starting microstructures of the different aluminium alloy plates are given in Fig.1. The microstructural analysis demonstrates the typical features of heat treatable aluminium alloys consisting of large crystalline grains surrounded by hardening precipitates. All the alloy plates demonstrate unrecrystallised pancake shaped grain structure elongated along the rolling direction.

![Microstructure of aluminium alloy plates](image)

The representative engineering stress–strain curve of the three alloys exhibit typical nature of flow stress that increases continuously up to ultimate tensile strength (Fig. 2a). The nature of true stress–true strain curve also follows similar trend to those of engineering stress– strain curves (Fig.2b). The yield strength (σYS), ultimate tensile strength (σUTS), total elongation, hardness values of these alloys are summarized in Table 3. It is evident from Fig 2 and Table 3 that AA 7017 and AA 6061 plates display the highest and lowest strength (σYS, σUTS) values, respectively. The AA 2024 alloy plate exhibits highest value of ductility measured in terms of total elongation to failure followed by the AA 7017 and AA 6061 materials.

![Engineering stress-strain curves](image)

![True stress-strain curves](image)

Table 3. Mechanical properties of the three studied aluminium alloys

<table>
<thead>
<tr>
<th>Aluminium Alloy</th>
<th>σYS (MPa)</th>
<th>σUTS (MPa)</th>
<th>% Elongation</th>
<th>Hardness (VHN)</th>
<th>n1</th>
<th>n2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 2024</td>
<td>310±5</td>
<td>457±6</td>
<td>16.2±0.2</td>
<td>130±2</td>
<td>0.167</td>
<td>-165.4</td>
</tr>
<tr>
<td>AA 6061</td>
<td>250±3</td>
<td>294±4</td>
<td>11.3±0.4</td>
<td>107±4</td>
<td>0.113</td>
<td>-191.0</td>
</tr>
<tr>
<td>AA 7017</td>
<td>458±4</td>
<td>508±5</td>
<td>13.1±0.6</td>
<td>135±4</td>
<td>0.082</td>
<td>-117.0</td>
</tr>
</tbody>
</table>

Strain hardening behaviors of the three aluminium alloy plates are shown in Fig. 3. The material displays two typical slopes in log (true stress) vs. log (true plastic strain) curves. Strain hardening exponents (n) are calculated from the slopes of the curves at lower and higher strain regimes by using Ludwigson’s relation as shown in equation 1. [5].

\[
\sigma = K_1 \varepsilon^{n_1} + \exp(K_2 + n_2 \varepsilon) \quad \text{--------- (1)}
\]

Where \(\sigma\) and \(\varepsilon\) are true plastic stress and true plastic strain while \(n_1\) and \(n_2\) are strain-hardening exponents in higher
and lower strain regimes, respectively and $K_1$, $K_2$ are constants. The ‘$n_1$ and $n_2$’ values of different alloy plates are shown in Table 3. The AA 2024 alloy plate displays the highest strain hardening exponent value in high strain regime followed by AA 6061 and AA 7017 plates.

Fig. 3 True stress–true plastic strain curves on log scales up to UTS of the three aluminium alloys

The visual comparison of the aluminium alloy plates after ballistic impact against 7.62mm and 12.7mm projectiles is exhibited in Fig. 4 and 5. The damage mechanisms displayed by all the three alloy targets clearly indicates that the projectiles has entered into the plates by causing ductile hole enlargement. A close view of the front damage pattern against 7.62mm projectiles elucidates that the material flows out to form perfect petalling damage pattern in the front side of the AA 2024 and AA 6061 plates. In contrast, broken petal damage is observed in the front face of the AA 7017 plate. All the aluminium alloy plates have successfully stopped the 7.62mm projectiles. No bulging is observed at the rear face of any of the plates. On the contrary, all the aluminium alloy plates fail to stop the 12.7mm projectiles. The projectiles have penetrated through the AA 7017 plates. However, the projectile is seen to remain wedged in the plates. In the same time, a complete perforation is observed in AA 2024 and AA 6061 plates. The variation of ballistic performance of the AA 2024, AA 6061 and AA 7017 plates in terms of depth of penetration (DOP) against 7.62mm projectiles is given in Fig. 6. This clearly shows that the ballistic penetration resistance of the AA 7017 plate is superior to those of the AA 2024 and AA 6061 plates.

Fig. 4 (a) (b) (c) Front face of the aluminium alloy plates after ballistic impact against 7.62mm projectile (d), (e), (f) Close up view of the damage patterns

The impact craters of all the three alloys against both types of projectiles are examined in detail to observe the changes in microstructure. The post ballistic microstructures of the AA 2024, AA 6061 and AA 7017 plates impacted with 7.62 mm projectile are shown in Fig. 7 (a–c). The projectile penetration path can be broadly divided into two regions (A and B) from the prospective of observation of deformed grains (Fig.7). In region A, large material deformation is observed along with a few cracks. Severely distorted material flow lines are present in this region. In the region B, material flow lines are smooth and curved in the projectile penetration direction. Adiabatic shear bands (ASBs) are not observed in the microstructure of the craters formed by 7.62 mm projectile. Similar observations are made in the microstructures of craters formed by the impact of 12.7mm projectiles (Fig 8 a-c). The
microstructures of AA 6061 plates display the presence of extensive ASBs throughout the path of the projectile. A few ASBs are also seen in AA 7017 plates. However, no ASBs are observed in the crater region of AA 2024 plates. The inside microstructure of ASBs is seen to be different than the matrix (Fig. 7 b).

Micro hardness measurements are taken, starting from close to the crater wall and gradually moving away. The variation in micro hardness values of the AA 2024, AA 6061 and AA 7017 target plates against 7.62mm and 12.7mm projectiles are displayed in Fig. 7 d and Fig. 8 d, respectively. In AA 2024 impacted plates, there is an initial rise in the hardness value and then it decreases with distance from crater wall till it reaches the base hardness of the plate. For AA 6061 and AA 7017 plates, the hardness starts from a low value and gradually increases. Subsequently the hardness decreases with distance. The extent of rise in hardness is more in 12.7mm impacted craters than that of the 7.62mm.

![Fig. 5 (a) (b) (c) Front face of the aluminium alloy plates after ballistic impact against 12.7mm projectile (d), (e), (f) Rear face of the aluminium alloy plates after ballistic impact against 12.7mm projectile](image)

![Fig. 6. The variation of DOP values of AA 2024, AA 6061, AA 7017 plates against 7.62mm ammunition](image)

4. Discussion

The alloys AA 2024, AA 6061 and AA 7017 belong to the series of heat treatable aluminium alloys. These alloys acquire their optimum properties through a process of thermal treatment i.e. solution treatment followed by artificial aging. Aging process causes the formation of coherent precipitates leading to high strength and hardness of the material. The effect of thermal treatment process on the microstructure and mechanical properties of AA 2024, AA 6061 and AA 7017 plates has been studied thoroughly. It has been reported that Al₃CuMg, Mg₂Si, MgZn₂ precipitates are formed during artificial aging of AA2024, AA6061, and AA7017 plates, respectively [1,6-7]. The presence of fine precipitates in the microstructure of the present alloys is also observed (Fig.1). The variation in strength and hardness in present aluminium alloys can therefore be attributed to the amount of alloying additions and morphology of the precipitate phases. The AA 7017 plate displays the highest strength and hardness owing to
the presence of higher percentage of alloying elements in comparison to those of AA 2024 and AA 6061 plates.

During ballistic impact, the kinetic energy (KE) of the projectile is transmitted to the target plate. The KE of the 7.62mm and 12.7mm projectiles are calculated and given in Table 2. This reflects that the 12.7mm projectile carries almost six times higher KE than that of 7.62mm. It thus explains the failure of AA2024, AA6061 and AA7017 target plates to stop the 12.7mm projectiles. The AA 7017 plate displays the best ballistic resistance against both the projectiles in comparison to those of the AA 2024 and AA 6061 plates (Figs. 5 and 6). This can be ascribed to the higher strength and hardness associated with AA 7017 plates. When projectile impacts on a metallic plate, energy absorption takes place by plastic deformation. As a result, material properties which resist the flow of material improve the ballistic performance. Also, the increase in strength and hardness values of the target material provides resistance to the projectile and thus assists in its erosion and fracture. The ballistic performance therefore
improves with increase in strength and hardness of the material. Previous investigations have also pointed out similar correlations of ballistic properties with strength and hardness [8-9].

The post-ballistic microstructure gives a good indication of the energy absorption in the material during ballistic testing. When projectile strikes, large amount of KE is distributed over a relatively small volume of target material in a very short span of time. This leads to the deformation of material adjacent to the crater wall and formation of ASBs. In fact, the ASBs are produced due to inhomogeneity in deformation of material subjected to loads at very high strain rate. These are formed when the stress, strain and strain rate reaches to a critical condition in which thermal softening suppresses the strain hardening effect during plastic deformation of a material. The ASBs are prominently observed in the 12.7mm projectile impacted craters of AA 6061 and AA 7017 plates. In contrast, these are absent near crater wall of 12.7mm projectile impacted AA 2024 plates. This can be correlated with the higher uniform elongation and $n_1$ values of AA 2024 plate. High strain hardening exponent value prevents
localisation of deformation process and thus leads to a uniform deformation. The ASB region undergoes an instantaneous heating and rapid cooling due to their formation in a very short span of time. As a result, the microstructure within the ASBs is different from the matrix.

In the present study ASBs are not observed in the post ballistic microstructure of 7.62mm projectile impacted target plates. Due to higher thickness of the target plates, a larger volume of the material is involved in the absorption of the impact energy. Thus, the energy dissipated per unit volume of the material is not sufficient to form ASBs in case of plates impacted against 7.62mm projectiles.

The variation in hardness adjacent to the crater wall is a result of strain hardening caused by high applied strain-rate and simultaneous annealing effect by rise in temperature after projectile impact. In case of AA 6061 and AA 7017 plates, the initial drop in hardness adjacent to the crater wall suggests that the thermal softening effect is dominant mechanism during initial deformation. This is confirmed from the observation of ASBs in the post ballistic microstructure of these two alloy plates. This can be correlated with the low strain hardening exponent values of these two alloy plates. Due to low strain hardening exponent values, the material deforms in a non uniform way. Hence, the heat gets constricted in a narrow region and leads to thermal softening. The behaviour of micro-hardness curves for the three alloys is similar against both the projectiles. However, a higher rise in hardness values are observed in case of 12.7mm projectile impacted craters which can be attributed to higher KE of the 12.7mm projectile.

5. Conclusion

In this study, the ballistic performance of three different heat treatable aluminium alloys against 7.62 mm and 12.7 mm projectiles has been investigated. The main conclusions are given below.
1. The AA 7017 alloy exhibits the best ballistic performance among the studied materials.
2. Ballistic penetration resistance of the present alloys is in accordance with their strength and hardness values. It appears that the strength and hardness values are more dominant parameters against both the projectiles than the ductility.
3. An apparent difference is observed in the post ballistic microstructures and micro hardness observations of the alloys. The AA 2024 plate exhibits uniform deformation while an adiabatic mode of failure is detected in AA 6061 and AA 7017 plates.
4. The 12.7mm projectile has introduced larger material deformation in comparison to 7.62mm projectile.

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Reference