Original Article

Microstructure characteristic of spray formed 7055 Al alloy subjected to ballistic impact by two different steel core projectiles impact

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7055 aluminium (Al) alloy was synthesized by spray forming followed by hot extrusion, later subjected to (T6 & T74) aging treatments and its mechanical properties were examined. To investigate the ballistic behavior of the semi-infinite aluminum alloy target material, ballistic test with two different types of projectiles 7.62 mm soft steel core and 7.62 mm armor-piercing hard steel core projectiles were carried out. Excellent mechanical properties such as; higher strength UTS 708 MPa, fracture to elongation 12.8% and hardness 240 HV were achieved in the T6 condition owing to the MgZn2 phase and Al2Zr strengthening particles. Ballistic performance of the 7055-T6 target was superior to the T74 heat treated condition in terms of depth of penetration, crater diameter, strength, ductility and hardness. The target materials were deformed seriously against armor-piercing hard steel projectile impact as compared to soft steel core projectile. The microstructure was modified within the 1–1.5 mm area from the crater wall. The spray formed Al alloy have a good combination of strength and ballistic performance under the T6 heat treatment condition in comparison of T74 and other alloys produced by conventional forming methods.

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1. Introduction

Many investigators’ efforts supported the direction to design a lighter material that is suitable for ballistic protective applications [1,2]. Generally, different steel alloys are used as armor materials because of their combination of properties such as higher strength, ductility, and formability [3–5]. Prior investi-
tigations have shown that aluminum alloys can reduce the weight of a defensive structure by 25% with comparison to steel, because of its higher energy absorption capability [6,7]. Many researchers used several aluminum alloys to investigate the ballistic performance such as; AA5089, AA7039, AA7017, AA5083, and AA7085, etc., produced by traditional forming methods [1,8–11]. These studies confirmed that the ballistic impact properties of materials depend upon target material thickness, strength and hardness and impacted projectiles shape, angle and velocity [6,12]. Some experimental studies also reported on ballistic impact behavior of Al alloys target against API hard steel core projectiles impact [6,11]. However, ballistic behavior of a spray formed 7055 Al alloy against soft steel core and API hard steel core projectiles has not been investigated previously.

The Al-Zn-Mg base 7055 Al alloy has been widely used in automotive and aerospace industries due to its excellent mechanical properties, namely higher specific strength, fracture toughness, damage tolerance capacity, and ductility after suitable heat treatments [13–15]. However, 7055 Al alloy produced by a conventional forming method, exhibited cracks, macro segregation and coarse grains, due to the higher volume fraction of Zn and lower cooling rate of conventional casting [16]. In order to resolve the above stated problems, spray forming technique has gained much consideration because of the distinctive features such as refined microstructures, increased uniformity and extension of solid solubility. When we compared the spray formed Al alloy with other traditional formed alloys. The spray formed Al alloy exhibited superior mechanical properties due to higher cooling rate of spray forming method, which delivers a uniform chemical composition with refined grains [13,16,17]. Additionally, the spray formed 7055 Al alloy has the ability to replace several traditional aluminum alloys used in armour applications [9,18,19].

Some previous investigations revealed that the ballistic performance of materials can be influenced by mechanical properties like strength and hardness [20,21]. Because ballistic impact resistance of target materials usually increased with both increased strength and hardness [1]. In addition, for ballistic protection applications, the material should have excellent energy absorbing properties with the combination of strength, hardness, and low density. Al alloys, after addition of required alloying elements and appropriate heat treatment, may achieve the desired properties with respect to ballistic safety [19,22,23].

Conversely, a lot of work [13,24] was reported just on the mechanical properties of spray formed Al–Zn–Mg–Cu alloy. Lei et al. [13] and Pan et al. [25] were reported that the ultimate tensile strength (UTS) of spray formed 7055 Al alloy 684 MPa, 732 MPa and elongation about 17.3% and 7%, respectively. On the other hand, some of the studies on ballistic investigation of Al alloys (produced by conventional method) have been reported against 7.62 mm non-deformable API hard steel core projectiles. Mishra at al [11]. studied the ballistic behaviour of 7055 Al alloy produced by ingot metallurgy route against API hard steel core projectiles. To date, very limited literature is available on the ballistic performance of Al alloy against deformable soft steel core projectiles impact, which is normally used for applications like important vehicles and security checkpoints [26,27].

### Table 1 - Chemical composition of 7055 Al alloy.

<table>
<thead>
<tr>
<th>Material</th>
<th>Alloying elements (Wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7055</td>
<td>Zn  7.9  Cu  2.4  Mg  1.8  Zr  0.13  Fe  0.8  Si  0.3  Al  86.67</td>
</tr>
</tbody>
</table>

In this work, the mechanical properties and a detailed metallographic features of spray formed 7055 Al alloy is investigated after impact from 7.62 mm deformable soft steel core and non-deformable API hard steel core projectiles at T6 & T74 heat treatments. The microstructure features and mechanical properties of spray formed and heat treated 7055 Al alloy was characterized by using tensile testing, micro hardness, transmission electron microscopy (TEM), X-ray diffraction (XRD) and scanning electron microscopy (SEM) to established a broad understanding regarding the ballistic behaviour. Later, the ballistic test features such as; depth of penetration (DOP), penetration path diameter, adiabatic shear bands (ASBs), fracture mechanism, and grain size were investigated and characterized by OM and SEM. The micro-indentation method was used to identify the variation in target material strength after impact.

#### 2. Materials fabrication

7055 Al alloy was fabricated by a spray forming technique. The spray-formed ingots were prepared by Haoran Co. Ltd., Jiangsu, China. During process molten metal was atomized by nitrogen (N₂) between 700°C–750°C. The spray pressure 0.6–1.0 MPa, rotation speed 2–4 mm min⁻¹ and withdraw speed was about 45–55 r min⁻¹.

The chemical composition of spray formed 7055 Al alloy is shown in Table 1. Spray formed Al alloy ingots were extruded at 430°C and then cooled in air. The Al alloys were further solution treated at 470°C/1.5 h and followed through aging treatments (T6 and T74) as shown in Table 2. The specimens were used for ballistic testing, mechanical and metallographic characterization. The entire process flow chart of spray forming and heat treatment as shown in Fig. 1. The ballistic testing setup and projectile shape and dimension are displayed in Fig. 2. The tensile tests were completed according to ASTM E8 standard. All the tests were conducted at a constant strain rate of 0.001 s⁻¹ with the crosshead speed of 1.8 mm/min and at 25°C by using (INSTRON 5985). For accuracy, three tensile specimens were carried out at T6 and T74 aging treatment and average results are reported.

To explore the dynamic mechanical response of 7055 Al alloy under both heat treatments (T6 and T74), specimens were machined of Ø 5 mm × 5 mm and subjected to high strain rate compression at 3000 s⁻¹ and 4000 s⁻¹ with Split Hopkinson pressure bar. Micro-hardness tests on a LEICO 700 AT were also accomplished as per ASTM E140 to measure the hardness of 7055 Al alloy before and after impact. Micro-hardness tests were conducted using a Vickers hardness testing machine using a 100 g load and time was 10 s. Micro-hardness values of target materials were measured to observe the difference in hardness. These values were taken from the middle of the pen-
Fig. 1 – Schematic illustration of spray forming, extrusion, aging treatment of 7055 Al alloy.

Fig. 2 – (a) Schematic illustration of ballistic testing set up and (b) projectile shape and dimensions.

Fig. 3 – SEM micrographs of (a) spray formed 7055 Al alloy under T6 and (b) T74 aging treatments.
Table 2 – T6 and T74 heat treatment procedure of desire Al alloy.

<table>
<thead>
<tr>
<th>AL</th>
<th>Extrusion</th>
<th>Solution treatment</th>
<th>Quenching</th>
<th>Treatment</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>7055</td>
<td>430°</td>
<td>470° /1.5 h</td>
<td>Water</td>
<td>120° /24 h</td>
<td>Air</td>
</tr>
<tr>
<td>7055</td>
<td>430°</td>
<td>470° /1.5 h</td>
<td>Water</td>
<td>120° /6 h + 160° /24 h</td>
<td>Air</td>
</tr>
</tbody>
</table>

![Figure 4](image)

**Fig. 4** – (a-b) Tensile stress-strain analysis along ED of T6 and T74 heat treatment (c) dynamic compression curves of 7055 alloy under T6 and T74 conditions.

etration path and 1–1.5 mm distance from the crater at different points along the three lines. The microstructure of the 7055 Al alloys was investigated using SEM (Hitachi S-4800) and OM (ZEISS observer.AI m AXIO) before and after projectile impact. After high-velocity projectile impact, specimens were cut near the projectile penetration channels (i.e. the deformed area) to observe the microstructure for both heat treatment (T6 & T74) conditions. Specimens were ground, polished and etched by Keller’s reagent to reveal the microstructure. The grain size of Al alloy before and after ballistic impact was measured with nano measurer 1.2 software.

The ballistic impact tests were conducted according to depth of penetration (DOP) test method on spray formed and extruded semi-infinite ingot (in cylindrical shape) with size of 100 × 150 × 100 mm. Three ballistic tests were performed on each target materials to ensure the validity of results. Ballistic testing of the heat treated (T6 & T74) target materials was conducted along the extrusion direction with zero obliquity (normal angle). The ballistic testing of target materials was carried out with deformable soft steel core and non-deformable API hard steel core projectile with a standard gun barrel. To ensure the projectile stability, the gun was held stable on a rigid base stand. Testing was performed with 820 m/s (soft steel core projectile) and 815 m/s (API hard steel core projectile) impact velocity. The target materials were fixed with rolled homogeneous armor (RHA), which was used as a backing material during ballistic impact. The projectiles were fired from 8 m distance from the target materials and impact velocity of projectiles was measured from 1 m distance from the target materials. Further, the impact velocity was measured by infra-red light emitting diode photovoltaic cells. The microstructure features of Al alloy target material was investigated throughout the projectile penetration path by OM and SEM.

3. Results and discussion

3.1 Microstructure before ballistic impact

3.1.1 Scanning electron microscopy analysis

The microstructure of the target material after T6 and T74 aging treatment is shown in Fig. 3. There were observed recrystallized, un-recrystallized, sub grains, and elongated grains due to hot extrusion under both heat treatment conditions as shown in Fig. 3a-b. The average grain size of the Al targets at T6 and T74 treatments are 40 µm and 50 µm, respectively.
3.2. Mechanical properties

Stress-strain analysis of specimen subjected to compression and tension of the Al alloy targets along extruded direction are shown in Fig. 4. For accuracy three test of each alloy was carried out and their average is taken as shown in Fig. 4a–c and summarized in Table 3. The results indicated an increase in UTS, elongation, and hardness after extrusion followed by solution treatment and then T6 aging treatment. After T6 aging treatment, a good combination of UTS and elongation of the 7055 Al alloy was achieved in comparison of T74 heat treatment. The dynamic compression behavior of the consider alloy is presented in Fig. 4c. It is observed that 7055 Al alloy at T6 condition possess higher yield strength (YS) and ultimate compression strength (UCS) at 3000 s\(^{-1}\) and 4000 s\(^{-1}\) strain rates compared to 7055 Al alloy in the T74 condition as shown in Fig. 4c.

3.3. Transmission electron microscopy & XRD analysis

Fig. 5a shows the microstructure analysis of 7055 Al alloy at T6 aging treatment. It is consisted of elongated grains of average size 40 μm. The grain size slightly increased 50 μm in Fig. 5d after T74 treatment. Fig. 5b–c presents a high number of fine precipitates distributed homogeneously in the matrix under T6 treatment. Likewise, at T74 condition the precipitates are uniformly distributed but their size increased as shown in Fig. 5f. The average size of spherical precipitates in T6 heat treatment is 12 nm which increased to 14 nm after the T74 heat treatment as presented in Fig. 5f. Similarly, the volume
fraction of precipitates was increased for T74 in comparison to T6 heat treatment. The major precipitation was $\eta'$ and $\eta$ in 7055 Alloy. The width of precipitates free zone (PFZs) of T6 specimens was the narrowest as compared to T74 specimens as shown in Fig. 5b, e. The EDX mapping in Fig. 6 showed that the very fine particles are possibly of the $\eta'$-type phase through assessment of the Mg: Zn ratio by EDX. The Mg-Zn-rich zones have Mg: Zn in the ratio of 2:1 that backings the existence of $\eta$-type precipitates.

XRD of spray formed 7055 Al alloy at T6 condition was also undertaken, and revealed that MgZn$_2$ was the secondary phase in the 7055-T6 Al alloy as shown in Fig. 7, which was the main strengthening phase. At T6 aging treatment temperature was 120°C where Guinier–Preston zones grow and transform into the $\eta'$ phase. The $\eta'$ phase is more coherent with the Al solid solution matrix at 120°C. In the 7055 Al alloy, the $\eta'$ and Al$_3$Zr high-density nanoscale particles are responsible for higher strength. Above 120°C, the $\eta'$ particle size increases and transformed into the non-coherent phase $\eta$, and lose their coherency with the Al solid solution matrix [13,31,32].

4. **Ballistic tests**

Once the projectile hit the Al alloy target, it caused highly localized plastic deformation inside the target materials. Table 4 shows the parameters of Al alloy core and soft steel core projectile. During projectile impact, the formation of crater happened on the front impact surface. Fig. 8 show geographical views (projectile entry and stopped area) of Al alloy target materials under both aging conditions (T6 & T74) impacted with soft steel core and API hard steel core projectiles. Cavity type fracture occurred on the front surface of 7055 Al alloy impacted with soft steel core projectile. Conversely, API hard steel core projectile traveled inside the Al alloy target and formed a cylindrical hole (i.e. like API hard steel core projectile shape) in the target. Thus, the Al alloy target material had different fracture morphologies when subjected to soft and API hard steel core projectile.

The diameters of craters on all target materials were higher than the fired projectiles and were larger in T74 heat-treated material. The target materials impacted by two different steel core projectiles had different DOP and penetration path diameters. Fig. 9 shows the DOP and projectile penetration path diameter inside the target materials of impacted surfaces. The API hard steel core projectile remained un-deformed, but the soft steel projectile was deformed seriously after impact with target materials. The results indicated that ballistic protection resistance of 7055 Al alloy, in terms depth of penetration (DOP), crater diameter, strength and hardness, was higher for the T6 heat treatment condition. The DOP and crater front diameter of target material impacted by two different types of steel core projectiles as revealed in Table 5.

4.1. **Microstructure analysis after ballistic impact**

4.1.1. Optical microscopy analysis

When the soft steel core and API hard steel core projectiles hit the Al alloy targets, the microstructure was modified. Plastic deformation, small and distorted grains were observed in the two different aging treatments as shown in Figs. 10 and 11. The grains were strained along the projectile travelling paths and crater was formed on the target surfaces. This was initiated by the material’s deformation because of the displacement of the projectile inside the target Al alloy. In addition, the highly modified microstructure was observed in the deformed channels. However, 1 mm to 1.5 mm distance away from the penetration channels, the microstructure remained unchanged. Deformation only occurred near the deformed channels because of the collision between projectiles and target materials in this area. The microstructure of the Al7055-T74 target material was more affected by both types of high-velocity projectile impacts then Al7055-T6. During soft steel core projectile impact, the grain size of target material was reduced near the penetration channel from 40 $\mu$m to 11 $\mu$m at T6 and from 50 $\mu$m to 9 $\mu$m at T74 heat.
<table>
<thead>
<tr>
<th>projectile types (m/s)</th>
<th>Diameter (mm)</th>
<th>Hardness (HRC)</th>
<th>Mass (g)</th>
<th>Length (mm)</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>API hard steel core</td>
<td>6</td>
<td>62</td>
<td>4.94</td>
<td>27.5</td>
<td>815</td>
</tr>
<tr>
<td>Soft steel core</td>
<td>6</td>
<td>20</td>
<td>4.84</td>
<td>28.0</td>
<td>820</td>
</tr>
</tbody>
</table>

Fig. 8 – (a, b) 7055 Al alloy impacted with API steel core projectile at T6 and (c, d) at T74 heat treatments, (e–f) showing the target material impacted with soft steel core projectile at T6 and (g, h) at T74 heat treatment conditions.

Fig. 9 – DOP and projectile penetration path diameters of target material impacted with (a) API hard steel and (b) soft steel core under T6 and T74 conditions.

treatment conditions as shown in Fig. 12a-b. Similarly, in case of API steel core projectile the grain size was reduced from 50 μm to 7 μm and 40 μm to 4 μm under T6 and T74 conditions, respectively as revealed in Fig. 12c–d. The API steel core projectile had more effect on Al alloy target than the soft steel core projectiles due to their higher hardness. Metallography also revealed the existence of adiabatic shear bands (ASBs) near the penetration channels. ASBs [33,34] are
Table 5 – Crater front diameter and DOP of 7055 Al alloy under T6 and T74 conditions.

<table>
<thead>
<tr>
<th>Projectile types</th>
<th>Crater diameter (mm)</th>
<th>(DOP) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7055-T6</td>
<td>7055-T74</td>
</tr>
<tr>
<td>Armor piercing hard steel core</td>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td>Soft steel core</td>
<td>27</td>
<td>38.5</td>
</tr>
</tbody>
</table>

Fig. 10 – OM of 7055 Al alloy target plates stuck with (a, b, c) soft steel core at T6 and (d, e, f) at T74 conditions. (specimens were taken from a to c & d to f labeled on target material).

Fig. 11 – Optical micrographs of spray formed Al alloy target plates impacted by (a, b, c) API hard steel core at T6 and (d, e, f) T74 conditions. (specimens were taken from a to c & d to f labeled on target material).
observed about in very small extent of the period because of heat produced by impact loading caused in-homogeneities in the microstructure. ASBs induced deformation appeared along with the narrow bands because of heat confined through the contracted bands, rapid cooling, and loss of strength. In addition, these bands contain massively deformed and small grains. ASBs induced cracks in the 7055 Al alloy penetration path (near the crater edge) as the result of API hard steel projectile impact.
core projectile impact at T6 and T74 conditions as shown in Fig. 13a–c.

4.1.2. Scanning electron microscopy analysis

Once a projectile penetrated inside the target material, the energy was transferred into the targeted substrate. During that, friction energy and compressive stress caused crack initiation, propagation and deformation. During ballistic impact, high strain rate deformation was confined to the narrow bands (deformed channels) of target material initiating the catastrophic failure [6]. In order to protect the target materials from failure against ballistic impact, a target material was needed with higher strength, hardness, ductility and fracture toughness. Fig. 14a, c shows the surface fragmentation and Fig. 14b, d show fracture surface produced by adiabatic induced heating after the high-velocity projectile impact. Fig. 15a, b shows the shear fracture due to the tensile stress wave. The shear fracture indicates the projectile impact cycling loading in the target because of multiple deformations of tensile waves [35].

The presence of the shear fracture on the impact surface of the specimen confirmed the failure initiated by the replicated tensile stress waves from the edge of the penetration channel. Fig. 15c, d shows the compressed surface (where projectile stopped), it can be seen that melting and dragging of material existed due to projectile displacement. Fig. 16a, b indicates the quasi-cleavage and delamination pattern, like Charpy impact fracture surface for the T6 heat treated 7055 Al alloy. The fracture surface of the sample for the T74 condition displayed a complex nature of intergranular surfaces of fractured layers by transgranular depressions inside the fractured grains. In addition, tensile specimens showed typical ductile dimples which were fine and shallow at the surface (Fig. 16c), and coarse and flattened at the middle as depicted in Fig. 16d.

5. Hardness

Softening and hardening behavior of target plates impacted by two different steel core projectiles, near (deformed area) and far (un-deformed area) away from the projectile penetration channels were identified by micro Vickers hardness testing. Target materials impacted with API hard steel core projectile had maximum hardness values adjacent to the crater wall at both heat treatment conditions. Target materials impacted by soft steel core projectile also had different hardness values adjacent to deformed channels, and the maximum observed hardness is given in Table 6. Fig. 17a shows the hardness values after T6 & T74 aging treatments. Fig. 17b, c indicates the variation after impact in hardness values near the deformed channels of 7055 Al alloy. However, plates impacted by 7.62 mm API hard steel core had higher hardness near the projectile deformed channels. Likewise, target material impacted with soft steel core and API hard steel core
Fig. 15 – SEM (SE) images of target material impacted by (a, c) API hard steel core at T6 and (c, d) T74 aging treatments.

Fig. 16 – SEM (SE) images showing (a, b) Charpy impact and (c, d) tensile fracture images of spray formed Al alloy at T6 and T74 aging treatment.
had variation in hardness due to strain hardening and smaller grains near the crater wall. Conversely, further away from the crater wall, the micro-hardness decreased and reached the base hardness values of considered Al alloy.

6. Conclusions

The 7055 Al alloy was produced by a novel spray forming process for analysis of mechanical and ballistic behaviour under two different heat treatments. The ballistic behaviour of 7055 Al alloy were investigated against API hard steel core and soft steel core projectiles impact. The following conclusions were obtained:

- Higher Ultimate tensile strength 708 MPa, hardness 240HV and elongation 12.8% has been achieved with hot extrusion followed by solution treatment and T6 aging treatment. The MgZn2 strengthening phase particles were responsible for higher strength at T6.
- Spray formed and T6 heat treated 7055 Al alloy displayed better ballistic response in term of DOP, hardness, strength, ductility, and penetration path diameter against both type of projectiles.
- During impact the modified microstructures were observed through OM. However, the target materials remain unaltered and unchanged 1mm and 1.5mm far from the penetration channels after soft steel core and armour piercing hard steel core projectiles impact, respectively. In addition, adiabatic shear band and adiabatic shear band induced crack were observed in target materials against API hard steel core projectile impact. ASBs associated with adiabatic heating while the heat produced along the narrow bands and confined. This leads to the temperature rise, along with the narrow bands, caused in-homogeneities in microstructure, thermal softening and reduce the strength. ASBs induced cracks can be deleterious for the structure impacted by sudden loading.
- Micro-hardness result points out the difference in strength adjacent to the damaged areas.
- SEM investigation provided us essential evidence about shear fracture and surface fragmentation due to sudden impact (compressive stress) at the front area of penetration channels. At the projectile stop area dragging and melting of material was observed due to projectile displacement (inside the target materials) and heat produced by high velocity projectile impact.

Conflicts of interest

The authors declare no conflicts of interest.
Acknowledgments

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