Deformations on Hole and Projectile Surfaces Caused By High Velocity Friction During Ballistic Impact

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Abstract: In this study, the deformations caused by the ballistic impact on the MM composites and on projectile surfaces are examined. The hole section and grain deformation of unreinforced targets are also examined after impact. The relatively high complexity of impact problems is caused by the large number of intervening parameters like relative velocity of projectile and target, shape of colliding objects, relative stiffness and masses, time-dependent surface of contact, geometry and boundary conditions and material characteristics.

The material used in this investigation are 2024 and 7075 aluminum alloys as matrix reinforced with SiC and Al₂O₃ particles. The matrix materials are extensively used in defense applications due to its favorable ballistic properties, moderate strength, high corrosion resistance and super plastic potential. Two different composites were produced; one by casting and the other by lamination.

The ballistic tests of the composite targets were carried out according to NIJ Standard-0101.04, Temperature 21 °C, RH=65% with 7.62 mm projectiles. The bullet weight was 9.6 g and their muzzle velocities were in the range of 770–800 m/s. The projectiles consisted of a steel core, copper jacket and lead material. The composite targets were positioned 15 m from the rifle. The interaction between projectiles and the target hole created after impact were examined by light microscopy and photography. Different damage and failure mechanisms such as petalling, cracking, spalling, dishing, etc., were observed on the target body. On the other hand, dramatic wear and damages on the projectile surface were also observed. The targets were supported with Al-5083 backing blocks having 40 mm thickness.

Keywords: Ballistic, high velocity friction, laminated composite, grain deformation, tribology

1. Introduction

Reinforced aluminium composites are being increasingly considered for structural applications in the defence, aerospace and automotive industries, etc. [1]. MMCs have slowly replaced some of the conventional light weight metallic alloys such as the various grades of aluminium alloys in applications where low weight and energy conservation are important considerations. Some researchers investigated dynamic behaviours of MMCs. The dynamic fracture toughness of SiC whisker reinforced 2124 aluminium alloy is higher than the quasi-static fracture toughness but decreased as the volume fraction of reinforcement increased [2]. in materials with SiC particulate, the ductility increased rapidly with pressure and the mode of damage initiation by particle fracture, and composites with SiC whiskers showed whisker matrix decohesion and strain localization that resulted in shear fracture[3]. But very little dependence of the total elongation on the strain rate[4]. Reinforcing a ductile, tough metal with a strong ceramic is one method of achieving such an improvement in properties. Discontinuous reinforcements such as particulates or whiskers tend to produce composites
with a greater degree of isotropy in properties as compared with continuous fiber reinforcements [5]. Therefore, the response of the MMC composites to a dynamic loading is a very important property. Although composites have many advantages with regard to mechanical properties; such as higher modules of elasticity, strength, hardness and wear resistance. They have the disadvantage of lower fracture toughness which is affected by many factors such as reinforcement size, volume fraction, distribution, chemical composition and heat treatment of matrix material, etc. The size of the reinforcement and its volume fraction are important variables in determining the properties of a composite [6].

In this study, the deformations caused by the ballistic impact on the MM composites and on projectile surfaces are examined. The hole section and grain deformation of unreinforced targets are also examined after impact.

2. Materials and method

The relatively high complexity of impact problems is caused by the large number of intervening parameters like relative velocity of projectile and target, shape of colliding objects, relative stiffness and masses, time-dependent surface of contact, geometry and boundary conditions and material characteristics.

The material used in this investigation are 2024 and 7075 aluminum alloys as matrix reinforced with SiC and Al$_2$O$_3$ particles. The matrix materials are extensively used in defense applications due to its favorable ballistic properties, moderate strength, high corrosion resistance and super plastic potential. Two different composites were produced; one by casting and the other by lamination. The chemical compositions of the matrix material are given in Table 1.

| Material | Si (w%) | Fe (w%) | Cu (wt%) | Mn (wt%) | Mg (wt%) | Cr (w%) | Zn (w%) | Ti (w%) |
|----------|---------|---------|----------|----------|----------|---------|---------|---------|
| 2024     | 0.5     | 0.5     | 3.8–4.9  | 0.3–0.9  | 1.2–1.8  | 0.1     | 0.25    | 0.15    |
| 7075     | 0.4     | 0.5     | 1.2–2    | 0.3      | 2.1–2.9  | 0.18–0.28| 5.1     | 0.2     |

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3. Results and discussion

The deformation behaviour of a composite target is a very important factor regarding the ballistic performance under impact loading conditions. Failure mechanisms are affected by this behaviour and the ballistic performance depends on impact behaviour. The ballistic performance of a composite target depends not only on its hardness but also on its toughness. Generally, brittleness and toughness are contra dictionary properties. If the hardness increases, the brittleness also increases while the toughness decreases. Therefore, the toughness properties are inversely affected by the hardness of the composite. Because of these complex effects, the hardness and toughness properties of a composite target should form an optimum point. This can be achieved by arranging suitable composition and heat treatment of the matrix materials, the type, size, volume fraction, distribution and the shape of the reinforcement.

Fig. 1 shows the hole structure after a projectile is removed from hole. It can be seen that there are many SiC particles in the hole of the MMC. They were first shaken by the high-velocity projectile and then pulled off from the surface and became free particles. The freeing of particles is related to the strength of the bonding between particles and matrix material. When the surface of the hole is examined by macroscopy, it is observed that some galling and yielding surround of the hole can be met. Part of the impact energy is consumed and appear as plastic deformations. When a reinforced composite could not prevent the passing of a projectile, the exit side of the hole may or may not petal, depending on the back side properties of the target. The surrounding area of the hole can be yielded freely and petalling appears after the projectile exits the hole. If the target has lowe reinforcement or without reinforcement, the hole surface or surrounding of hole deformed easily and petalling is occured(fig.2 a). This deformation zone of the hole around is created by projectile puncing effect.

![Figure 1.](image)

**Figure 1.** The macro illustration of hole created on the composite target a) Hole with projectile b) The hole surface without projectile

When the impact behaviour of the unreinforced target is examined, it can be seen that any cracking or breaking of the target body is not observed other than the petalling flower-like created by the projectile on the back side of the hole (Figure 2(a)).
Figure 2. Created holes on unreinforced and laminated targets: (a) petalling, (b) plastic deformation at the surrounding of the hole, (c) deformed grains of body material, (d) laminate deformation near the hole section.

The petalling with some soft cracking around the hole is generated from the punching effect of the high velocity impact of projectile. This effect causes plastic deformation along the thickness of the body along the radial direction of the hole (Figure 2(b)). The thickness of the unreinforced target on the hole’s radial axis is increased by the punching, however, this increase does not reach the size of the hole diameter. This must be evidence of plastically compressed material structure on both sides of the hole. A certain area around the hole on the unreinforced sample is affected by this plastic deformation and a compression of area took place. At this area, aluminium grains between the projectile and undeformed body material are compressed by the projectile in the radial direction.

Figure 2(c) is evidence of this restricted deformed area. The grains close to the hole surface are also deformed in both the radial and axial directions. Therefore, these grains have a maximum length and a minimum thickness due to extensive deformation. It can be seen in Figure 2(d) that the main (macro) deformation direction is axial with the complex one occurring in all directions. Since the laminates have weaker bonding to each other compared with those of unreinforced and particle reinforced target bodies. All deformations occurring in the axial direction on all composite targets used in this study are caused mainly by the frictional forces generated from the friction between the hole and the projectile tip surfaces. When the reinforcement particles close to the hole surface are affected by the punching effect of a projectile, they are compressed as they are forced to move either with the matrix or by translation. They are freely transferred and buried in the matrix and/or projectile surface. Since the particles are harder than the surfaces of the hole and projectiles they can scratch both surfaces easily. The reinforcement particles buried and/or scratched into the surface of the projectile reduce its velocity significantly. This causes a strong friction between the hole and the projectile surface and leads to a deformation of grains surrounding the particles directed along the three axes. The evidence of particle and laminate reinforced composite and buried particle can be seen in Figure 3. The macro deformation of the laminates can be seen in Figure 4. When the projectile punches the laminates and apply a friction to the hole surface of a laminated composite, the laminates are compressed and pushed forward with the projectile tip. Therefore, they are deformed and fractured, and they compress the area around the tip. The laminates close to the back side of the target are affected by the compressing effects of projectile tip like a punch. While the projectile is moving in the hole in the composite body, many mechanical and chemical phenomena [7,8] occur because of the deformation and strong friction mentioned above.
2. c) 

2. d) 

![Image of microstructure with labels]

- Projectile direction
- Copper jacket
- Hole
- Same area
- Deformed grains
- Oxidized grains

![Image of microstructure with labels]

- Projectile direction
- SiC

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Figure 3. Deformations of the matrix material at the surrounding of reinforcement particles, (a) particle reinforced composite (with SiCs), (b) laminated composite

Figure 4. Deformation of laminates at surrounding the hole after friction and punching effects of projectile.
Now, we can examine casted target hole and the projectile surfaces impacted to composite target at high velocity. Fig. 5 shows clearly the frictional traces on the hole surface created by high-velocity projectile. These traces on this frictional area must have been created by the particles pulled out from the matrix area. When a projectile enters into a target, it meets with some particles and the projectile transfers these particles to another zone and/or some other particles adhere to the projectile surface while some are buried into the projectile surface. The particles can scratch both surfaces easily because they are harder than the surfaces of the hole and projectile. As new traces are scratched by the other particles following, some traces are built up over each other. It is also obvious that the path of the projectile in composite can be changed.

![Figure 5. Frictional traces on the hole surface](image)

It can be claimed that the stronger the friction, the smaller is the penetration depth. The projectile is first slowed down by the friction of SiC particles and then stopped by other particles embedding into both surfaces. The evidence to this friction mechanism can be seen in Fig. 6. This figure shows that the embedded particles stopped the projectile in the matrix. The hard SiC particles buried themselves into the jacket surface of projectiles and this led to dissipation of the kinetic energy of the projectile and its eventual stop. Fig. 6 b clearly shows that the final deformed shape of the matrix material resembles the particle form which caused the deformation. The plastic yielding is localised around the particles.

The projectile surface is scratched by the SiC particles and the plastic deformation takes place. There are many deep grooves caused by reinforcing particles on the friction surface parallel to the propagation direction.
Fig. 7 shows the some macro damage on the projectile tip caused by armour plate during impact. It can easily be seen that the projectile tip may have broken and blunted (Fig. 7a). This breaking often occurs if the projectile impacts a hard zone generated by collecting the hard Al2O3 particles onto the target surface. After the projectile tip enters the armour plate, it has to pass among the hard and coarse Al2O3 particles. Sometimes, this interaction caused to asymmetric forces on the nose of the projectile. These forces deflect projectile line of flight inside the target [9] and may be bend projectile nose (Fig. 7b). This phenomenon may be resembled projectile impact to an inclined plate [10]. It may also detach some parts from projectile nose by breaking, and big craters can be formed (Fig. 7c). Even when the projectile is very sharp, the interception capability of the composite target is very satisfactory. It can be seen from the figure that penetration of the projectile tip to the target is too hard and the projectile lost some parts from its nose. Some deep valleys generated from friction with Al2O3 particles can nose (Fig. 7d) also be observed on the tip.

**Figure 6.** Hard SiC particles buried into the jacket surface; (a) buried SiC particles, and (b) plastically yielding of matrix material at the surrounding SiC particle.
Figure 7. Damage on the projectile tip after impacting: (a) broken AK-47 steel projectile tip, (b) plastic deformation of the tip by bending, (c) crater on the tip nose by breaking, and (d) deep valleys on the tip nose.

The strong friction can lead to the deep grooves on both frictional surfaces. Figures show evidence that the wear mechanisms are predominantly abrasive. Melted zone is observed only on the hole surface. Some matrix material and some SiC particles are adhered to the surface of projectile strongly. Namely, the wear mechanisms are different on both hole and projectile surfaces. While the wear mechanisms are melting, adhesive and abrasive on hole surface, they are predominantly abrasive on the projectile surface. As the strong friction caused by reinforcement particles leads to the deceleration of the projectile in the armours, swelling at the surrounding area of the scratched grooves by particles also takes place. The deep grooves are swelled by plastic yielding to their edges or around the particles buried in the grooves [11].
4. Conclusions

1. The MMCs can prevent the penetration of a projectile through their body by consuming the projectile’s kinetic energy. The energy is consumed through the damage such as cracking, petalling, and some matrix deformation.

2. On the composite targets manufactured with relatively good toughness, some petals are observed at entrance and exit sides of the hole generated by the passing projectile.

3. When the projectile meets reinforcement particles in the composite body, the strong friction is generated between the projectile and hole surface. The velocity of the projectile is decreased suddenly at the inlet of the hole. Some reinforcement particles scratch the projectile surface by burying and the copper alloy jacket of the projectile is left in the hole by heavy deformation (swelling). This section is the largest section of the hole.

4. All composite types show a different deformation mechanism and different deformation rates by the fast punching effects of projectile. In the case of laminate composites, the laminates are fractured and deformed in the direction of projectile movement.

5. If the projectile pierces through and leaves the composite some petalling can be observed at the exit side of the hole. If a strong friction force is generated by the reinforcement particles, the projectile cannot pass through the composite and is kept inside composite.

6. While the wear mechanisms are different on the hole surface such as melting, adhesion and abrasion, on the projectile surface, wear mechanism is predominantly abrasive with some swelling.

7. The projectile nose is broken or deformed plastically when it impacts the composite target. If the composite has hard reinforcement particles such as Al2O3, the friction between projectile tip and hole surface becomes greater and the projectile surface is scratched by ploughing. Plastic damage or breaking of the tip nose leads to increasing the resistance to the projectile movement through the target hole

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