A Review Paper on Aluminium Targets Subjected to Ballistic Loading

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ABSTRACT

In this paper, a review work on different ballistic performances analyzed experimentally by previous researchers on aluminium targets subjected to various impact velocities is discussed. Many authors have carried their research work in the area of ballistics by conducting experiments using the gas gun setup. Velocities that ranges between 35 and 950 m/s are discussed. Parameters like projectile velocity, target thickness, projectile shape, projectile material, target material, microstructure of target material are varied to study the ballistic performance.

KEY WORDS: Aluminium target, ballistic resistance, impact velocity, residual velocity.

1. INTRODUCTION

Steel is the material that is accepted globally as a primary constituent for the construction of military vehicles because of the features, such as high strength, high energy absorption, greater toughness, good machinability, weldability and high hardness (Ade, 1991; Madhusudhan reddy, 1996). Nowadays, due to the increase in mobility of the military vehicles it has become very crucial to select suitable armor material. Therefore, material with lowest density that resists the threat successfully is required. A number of various materials can be considered for substituting the steels, especially with alloys of magnesium, aluminium and titanium. As magnesium is self-explosive and titanium is of high cost, aluminium and its alloys has a greater chance to encroach where ferrous alloys have dominated. Aluminium alloys offer excellent properties in terms of light weight, stiffness, strength, resistance to corrosion and high energy absorption.

Over the past ten years considerable amount of research work has been directed toward aluminium based armours having improved ballistic properties. In this paper, a review work is done to study the ballistic performances analyzed experimentally by previous researchers on aluminium targets subjected to various impact velocities. Particularly gas gun setup is used for conducting the ballistic experiments. Parameters like projectile velocity, target thickness, projectile shape, projectile material, target material, target microstructure are varied by different authors. The next rest of the paper is organized as follows. In section 2, the literatures about the ballistic study by different authours are presented and conclusions are given in section 3.

2. METHODS & MATERIALS- LITERATURES

Thin aluminium plates: The ballistic performance of Al plates of 1mm thick by varying the fixity as 100%, 75%, 50% and 25% around the circumference of target at low velocity were studied (Tiwari, 2014). The target material used is 1100-H12 Al plate of 1mm thick. Ogive and blunt projectile of Ø19 mm were impacted.

The variation in boundary condition do not have any significant effect on the failure mode of the target. The results are plotted in the fig 1 and 2. The Ballistic Limit Velocity (BLV) increased by 7.1%, 15.4% and 24.5% for75%, 50% and 25% fixity compared with 100% fixity for ogive nosed projectile. Similarly for blunt nose projectile 5%, 12.7% and 21.6% increase is found. The target failed because of ductile hole enlargement for ogive projectile and due to shear plugging for blunt projectile.
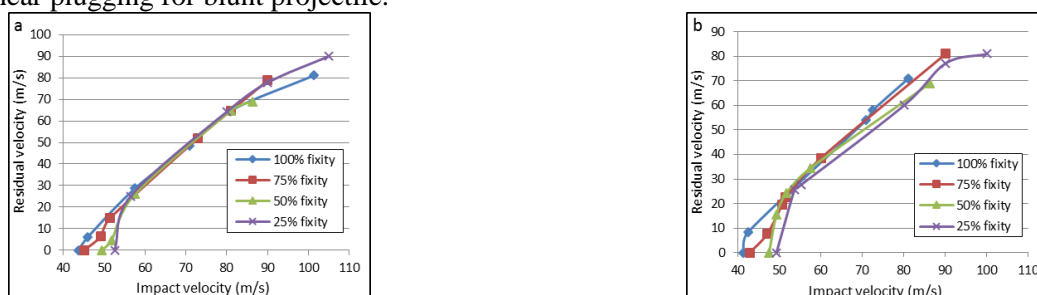

Figure.1. Impact Vs residual velocity plot for 100%, 75%, 50% and 25% fixity condition (a) blunt nosed projectile (b) Ogive nosed projectile

As the region of fixity decreases the global deformation increases and hence the energy absorption capacity of the target increases. Thus 25% fixity offered maximum ballistic resistance followed by 50%, 75% and 100%.

The effect on ballistic performance due to varying target to projectile diameter ratio (D/d) is investigated experimentally (Tiwari, 2015). Projectile diameter of 19mm of both ogive and blunt nosed were used. The materials used for the target is 1100-H12 Al sheets of 1mm thick. The span diameter, D is varied and the projectile diameter, d is kept constant throughout the experiments. The various D/d ratio used study are 3.6, 5, 7.9, 10 and 15.

Figure.2. Plot between impact Vs residual velocity for D/d of 3.6, 5, 7.9, 10 and 15 (a) blunt nosed projectile (b) nosed projectile

A Prominent effect is found on the BLV as the D/d ratio increases from 3.6 to 10 particularly against blunt nosed. When ogive nosed hits the target, cracks are initiated at the tip of the projectile, propagated and petals were formed. For blunt nosed, cracks were developed around the target causing the ejection of plug. The BLV was found to increase with an increase in span diameter. For the blunt nosed, BLV increased by 13.98%, 25.8%, 32.26% and 38.71% when compared with BLV of D/d=3.6. For ogive, BLV increased by 2.11%, 5.38%, 6.32% and 8.66% compared with BLV of D/d=3.6.

The behavior of AA7075-T6 of 1.5mm thick during the impact of spherical steel projectiles were studied (Castillo, 2011). The targets that are initially subjected to uniaxial in-plane tensile preloads are used. In this work, 12 specimens with preloads and 12 without preloads were impacted by steel projectiles of Ø12.5mm between velocities 100m/s and 300m/s.

In preloaded and unloaded plates, insignificant differences were detected between the residual velocities measured and the ballistic limits. However, the failure mode is differed when the impact velocity was more than the ballistic limit. Catastrophic failure is witnessed on the preloaded plates, whereas in unloaded plates this phenomenon did not occur. A preloading of 38% in the mechanical strength of the target material is sufficient for the catastrophic failure of the loaded plates.

Study on Damage Mechanism: The AA6061-T6 plates were subjected to two types of bullets and its ballistic resistance is tabulated (Manes, 2014).
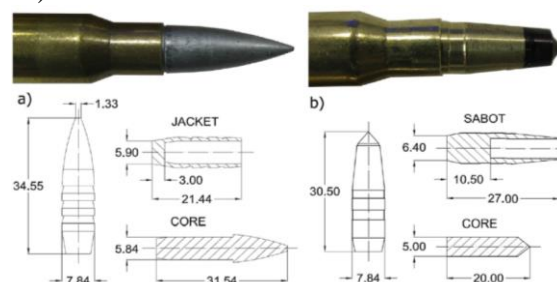

Figure.3. Bullet profile (a) Steel penetrator in copper jacket (b) Tungsten carbide in a brass sabot

Table.1. Consolidated DoP values

Depth of penetration in the 76.2 mm plate and 101.6 mm plate		
Bullet	Target thickness (mm)	DOP (mm)
AP steel	76.2	46.35
	101.6	46.45
AP tungsten	76.2	38.11
	101.6	41.29

The two penetrators resulted in different damage mechanism. Near the entry holes, the steel bullet caused front petal formation, whereas the other penetrator caused very thin petals. Similar damage is caused in the exit holes for both the bullets. The tungsten carbide cored bullet penetrates less deeply than the steel bullet in all of the experimental tests, because of the minor mass of the penetrating part.

The anti-penetration and damage mechanism of explosively welded steel/Aluminium plates of 5mm thick impacted by spherical and cubical projectiles is experimented (Wang, 2013). Spherical steel projectile of 6mm diameter and cubical projectile of 4.2mm side length were used. 3040 steel and Ly12-Al were used in the study. It was found that, even though the thickness distribution with steel as front plate and aluminum as rear plate are different, the failure modes of the targets are nearly identical. For both spherical and cubical projectile, the damage caused in the steel plate is shearing and plugging, and in aluminum it is ductile deformation. It is observed that the spherical projectile perforate more easily than the cubical at same kinetic energy.

Surface modification by FSP: The surface modification of AA7075 (Base metal) using boron carbide (B$_4$C) powders of size 160µm, 60µm and 30µm were presented (Madhusudhan reddy, 2016). Friction stir processing (FSP) is done by using this ceramic powders for fabricating the surface composites. The targets were fabricated in two

stages first using a flat tool and then by tool with pin. The target were tested with Ø7.62mm lead bullets at 830 ± 10 m/s. From the table, it can be established that the friction stir processed AA7075 alloy targets successfully stopped the projectile whereas the uncoated base metal was perforated completely. The targets with finer grade B_4C particles have better ballistic performance compared to the others.

Table.2. DoP values of surface composite as per

Target	DoP
Base metal	34
B_4C-160µm	30
B_4C-60µm	29
B_4C-30µm	24

The enhancement in ballistic resistance of AA7075 using FSP is studied (Srinivasa rao, 2015). The surface of the target was subjected to FSP to a depth of 3 mm. At first a straight cylindrical tool without pin was used to compact the B4C powders in the previously drilled holes. The diameter of the tool is 20mm. Then a second tool is used with a pin length of 3mm and Ø6mm. This tool was inserted into already processed surface. The ballistic testing of FSPed plates was carried out with Ø7.62mm lead bullets with a velocity of 830±10 m/s.

Table.3. DoP values of surface composite (Sudhakar, 2016)

Condition	DoP	Crack length
Base	34	no crack
B_4C 160 µm	30	80
B_4C 60 µm	29	45
B_4C 30 µm	24	40
B_4C 30 µm + MoS_2	12	15

The FSP results in fine and uniform microstructure and contains carbide particles in the matrix. The FSP of AA7075 alloy along with B_4C powder improved the ballistic resistance. The particle size of B_4C affect the ballistic resistance of base metal, and the maximum ballistic resistance was achieved with particle as given in the table. It is also seen that by adding molybdenum disulphide into B_4C, there is further improvement the ballistic resistance.

Effect of Ceramic particles: The effect of morphology and microstructure on the ballistic impact of B_4C/2024Al composite were studied (Gaohui, 2014). Ballistic test were carried out on B_4C/2024Al composites with 55% volume fraction of ceramic particles. The B_4C particle of average size 17.5µm was used. Heat treatments were introduced as: solution treatment at 495°C for 1 h, followed by aging at 160°C for 10 h. The 7A52 Al was used as backing target and the armor piercing bullets of dimension 7.62 x 51 mm were used.

To study the mechanism of bullet penetration in extruded AA6061-T6 sandwich panels in both empty and alumina filled cases experiments were conducted (Wadley, 2013). The projectile used is of 12.7 mm diameter hard steel projectile. The mechanisms of penetration of the empty sandwich structure involve plug formation. Filling the spaces with the alumina core led to severe projectile fragmentation and plastic deformation as the impact speed was increased.

Study on microstructure: The micro structural evolution of target material 2519-T87 Al alloy were experimented (Lan, 2012). The distribution of micro-hardness near the crater is studied after the impact. The targets were obliquely impacted by WO-109C type projectile of 7.62mm diameter, impact velocity is 816m/s and impact angle is 42°. The target thickness is 20mm. The adiabatic shear bands (ASB) are more at the entering stage, while micro-bands are less when compared to the stable-running stage and the leaving stage. During the stable-running stage, the ASB decreases as the micro-bands increases. Here the micro-hardness is the lowest among the three stages. Large amount of micro bands and small ASBs are present in the leaving stage.

The Al6061-T6 plates of different thickness impacted by two different 7.62mm APP were studied from a metallographic point of view (Manes, 2014). The material behavior of the target after the ballistic impact is studied by optical microscopy and scanning electron microscopy. During the impact some of the phenomenon like formation of ASBs, softening and hardening, creation of petalling, plugging as well as the localized failure mechanism were observed. It was noticed that tungsten core bullet seems more damaging for the structural integrity of Al6061- T6 plates. During complete penetration the target material dissipate the energy better and when the bullet is arrested it increases localized material softening that results in formation of ASBs. Both bullets exhibit ductile hole enlargement failure behavior.

Effect of surface coating: The impact resistance of AA6061 T651 due to the influence of plasma spray coating were investigated (Evren, 2010). Using plasma spray technique, two different types of surface coating were applied to the target. The ballistic performance of both uncoated and coated using 9.00 mm Parabellum bullets was tested. The penetration depth on the front face and the bulging on the rear face were measured in both coated and uncoated

plates. From the results improvement on the ballistic resistance of coated plates were clearly seen. The Co-Mo-Cr coating is more efficient than the ZrO_2 coating for higher impact velocities of 390 m/s and above.

The conclusions derived from this work as follows: (1) The ballistic performance of AA7075-T651 plates is the highest and for the AA6061-T651 plates is the lowest. (2) The ballistic resistance is improved for the coated plates. (3) Co–Mo–Cr coating is more efficient against bulging and penetration for AA2024-T351 and AA6061-T651 plates. (4) For AA7075, the ZrO_2 coating is superior as compared with Co–Mo–Cr coating.

Friction Stir weld effects: The effect of friction stir welding (FSW) of aluminium plate AA7010-T7651 on the properties and failure mechanisms were studied (Prangnell, 2011). FSW of thick plate leads to wide heat affected zone (HAZ). However, only 20% reduction in the ballistic limit (V_{50}) is found in the HAZ. It is noted that the maximum V_{50} was associated with the highest level of hardness. It reaches prior to change in failure mechanism from ductile hole enlargement or plugging with a fragment simulation projectile.

The Al7039 alloy plates were experimented which were used as armor materials (Erdem, 2016). The plates were subjected to T6 treatment and were joined double-sided by FSW. The micro-hardness and microstructure of the welded plate were investigated. The finest grain structure and the lowest harness is presented in the stir zone was determined. The grain size is 2−6μm and the hardness is HV 80.9. APP bullets of Ø7.62mm were shot to the base metal (BM), heat affected zone (HAZ), and thermomechanically affected zone+stir zone (TMAZ+SZ) to determine the ballistic properties of welded plates.

The ballistic limits V_{50} of the BM is 14.75%, TMAZ+SZ is 15.3% and HAZ is 17.9% and these values were found to be lower than that of the standard plate. The ballistic limits V_{50} of the TMAZ+SZ and the HAZ were 0.87 and 3.64% lower than that of the BM. Although the hardness of the SZ was the lowest, the ballistic limit V_{50} of this zone was more compared with that in HAZ.

Effect of Heat treatment: The ballistic resistance of 2519A aluminium alloy on the effects of T9I6 thermo-mechanical process were presented (Gang, 2014). Because of the T9I6 treatment, the yield strength, tensile strength and elongation of 2519A aluminum alloy turns to be very high. The BLV of 2519A-T9I6 alloy of 30mm thick plate is 715m/s. The interrupted ageing contributes to these excellent properties of the alloy. During interrupted ageing, the precipitation of Guinier Preston (GP) zone is finer and denser. This results in well precipitated strengthening phase.

The ballistic limit velocity test of the 2519A-T9I6 alloy was conducted at room temperature. The 2519A-T9I6 aluminum alloy plate of 30mm thickness was shot vertically at impact velocity of 818 m/s and the V_{50} was 715 m/s. compared with tests conducted in static or quasi-static condition, the impacted behaviors of materials are totally different. Grain morphology varies near the sidewalls of the crater and large grains were located around a number of small grains, which is an abnormal grain growth behavior. Abnormal grain growth happens under certain conditions, and it would lead to significant differences between the grain sizes. Adiabatic shear banding (ASB) could be found and micro-cracks accompanied by ASB appear in some areas.

The effect of heat treatment on the ballistic resistance of AA7075 plates were studied (Mishra, 2011). The plates were subjected to three different heat treatment namely under-aging, peak aging and over-aging. Large differences in the mechanical properties are observed in the plates. Maximum strength and hardness is observed in the peak-aged plate followed by the under-aged and overaged plates. The ballistic resistance of the heat treated plates are evaluated by impacting projectiles at a velocity of 820m/s. The thickness of the plates were 5 and 10mm. Similar ballistic penetration is observed in under-aged and peak-aged materials. This result is superior to the over-aged material. During the metallographic examination, formation of ASB induced cracks and few transformed ASBs were observed.

The ballistic resistance of AA6070 in different temper conditions, namely annealed (O), naturally aged (T4), peak strength (T6) and overaged (T7) were discussed (Borvik, 2013). The thickness of the target is 20mm. Ballistic test using Ø7.62mm APM2 projectiles were experimented and the BLV values were obtained. From the tests it was concluded that the annealed (O) condition was most ductile and no fragmentation due to the ballistic loading. The peak strength condition (T6) was the least ductile and fragmentation was seen. The results tells that despite fragmentation, strength is the most important feature than the ductility of the target for the ballistic impact.

The resistance to perforation of AA6070 plates of 20 mm thick subjected to medium velocity impacts were experimented (Holmen, 2016). The plates were made of four different tempers and were impacted with both ogive and blunt nosed cylindrical projectiles of Ø20mm. From this experiment it was conclude that material strength is not the most important parameter to resist penetration and perforation. Ductility is seen to be most important than that of strength, since fragmentation occurs for the temper with the highest strength and the lowest ductility. The experiments further confirmed that the capacity of a plate when impacted by blunt-nosed projectiles is lower than it is for ogive-nosed projectiles due to the formation of ASBs.

Parametric study: The impact of metallic sandwich structures with aluminium foam core for ballistic protection were discussed (Lu, 2010). Quasi-static and impact tests were carried out to study the ballistic performance. During

the test, effects of several parameters like thickness, impact velocity, and density of the foam core and projectile shapes were considered. The ballistic limit and energy absorption of the targets are identified.

The sandwich specimens consisted of two aluminium alloy skins and a core made from aluminium foam, and impacted by three projectiles with different shapes: flat ended, conical an hemispherical nosed. The perforated specimens showed similar damage patterns: the front face exhibits a circular crater without global deformation. A localized tunnel is evident in the foam core directly below the point of impact and through the thickness. On the back face, a round hole is visible with a number of petals, but without significant global deflection.

It is found that the dynamic perforation can raise the perforation energy that has a linear relationship with the impact velocity. Thicker skins and the cores with higher thickness and density are prone to produce higher ballistic limit. Blunt projectiles result in a larger petalling area and tend to increase the ballistic limit and energy dissipation.

Ballistic impact tests of AA2024 anisotropic aluminium sheet plate were performed (Seidt, 2013). Normal impact tests with titanium alloy and tool steel projectiles were carried out with impact velocities ranging from 190 to 299m/s. The thickness of the target material used is 3.175mm for AA2024-T3 and 12.7mm thick for AA2024-T351 plate.

The ballistic impact of 7.62x51mm soft-core ball of 9.5g projectiles on aluminum tubes were experimented (Manes, 2013). The tubes are made of AA-6061-T6 and simulate actual components of a helicopter tail rotor drive shaft. The initial and residual velocities of the bullets were measured. Also the shape and dimensions of the damage, and the residual stresses in the components is measured. The length of the target specimens is 760mm and it's a thin walled cylindrical shaft with an Ø63.5 as external diameter and 1.7mm thick. The impact velocity is similar in all 28 impact tests, with an average value of 844m/s. The residual velocity varies slightly and depends on the type of damage produced.

3. RESULTS & CONCLUSIONS

The present paper reviewed the research activities in concern with ballistic experiments that were carried out in various types of target materials. The effect of surface modification with coating and ceramics particles, the study about the damage mechanism, frictions stir and heat treatment effects and the parametric study about the bullet shape and size has been highlighted in this work. In contrast to the reported observations, improved ballistic resistance has been attained by adding the ceramic powder to the aluminium, magnesium alloys. Thus there is significant scope to determine the influence of ceramic powder on the projectile penetration.

REFERENCES

Ade F, Ballistic qualification of armour steel weldments, Weld J, 70, 1991, 53-54.

Andrew Manes, Pagani M, Saponara M, Mombelli D, Mapelli C, Giglio M, Metallographic characterization of Al6061-T6 aluminium plates subjected to ballistic impact, Materials Science & Engg A, 608, 2014, 207-220.

Andrew Manes, Serpellini F, Pagani M, Saponara M, Giglio M, Perforaation and penetration of aluminium target plates by armour piercing bullets, Internation journal of impact engineering, 69, 2014, 39-54.

Demir Teyfik, Ubeyli Mustafa, Orhan Yıldırım R, Investigation on the ballistic impact behavior of various alloys against 7.62 mm armor piercing projectile, Mater Des, 29, 2008, 2009-2016.

Evren Ozsahin, Suleyman Tolun, Influence of surface coating on ballistic performance of aluminum plates subjected to high velocity impact loads, Materials and Design, 31, 2010, 1276-1283.

Evren Ozsahin, Suleyman Tolun, on the comparison of the ballistic response of coated aluminum plates, Materials and Design, 31, 2010, 3188-3193.

Iqbal M A, Tiwari G, Gupta P K, Bhargava P, Ballistic performance and energy absorption characteristics of thin aluminium plates, International journal of impact engineering, 77, 2015, 1-15.

Jinxiang wang, Nan zhou, Damage mechanism and anti-penetration performance of explosively welded plates impacted by projectiles with different shapes, Marerials and design, 49, 2013, 966-993.

Liang xiao peng, Li hui zhong, Huang lan, Hong tao, M A Bing, Liu yong, Micro structural evolution of 2519-T87 aluminum alloy obliquely impacted by projectile with velocity of 816 m/s, Trans nonferrous met. Soc. China, 22, 2012, 1270-1279.

Madhusudhan Reddy G, Mohandas T, Ballistic performance of high strength low-alloy steel weldments, J Mater Process Technol, 57, 1996, 23-30.

Madhusudhan Reddy G, Mohandas T, Tagore GRN, Weldability studies of high strength low alloy steel using arstenitic fillers, J Mater Process Technol, 47, 1995, 213-228.

Shirley K. Garcia-Castillo, Sonia Sanchez-Saez, Enrique Barbero, Behavior of uniaxially preloaded aluminium plates subjected to high-velocity impact, Mechanics Research Communications, 38, 2011, 404-407.

Sudhakar I, Madhu V, Madhusudhan reddy G, Srinivasa rao K, Enhancement of wear and ballistic resistance of armour grade AA7075 aluminium alloy using friction stir processing, Defence technology, 11, 2015, 10-17.

Sudhakar I, Madhusudhan reddy G, Srinivasa rao K, Ballistic behavior of boron carbide reinforced AA7075 aluminium alloy using friction stir processing–An experimental study and analytical approach, Defence technology, 12, 2016, 25-31.

Tiwari G, Iqbal M A, Gupta P K, Gupta N K, The ballistic resistance of thin aluminium plates with varying degrees of fixity along the circumference, International journal of impact engineering, 74, 2014, 46-56.

Wadley H N G, Dharmasena K P, O'Masta M R, Wetzel J J, Impact response of aluminum corrugated core sandwich panels, International journal of impact engineering, 62, 2013, 114-128.

Zhisong zhou, Gaohui wu, Longtao jiang, Ruifeng li, Zhongguo xu, Analysis of morphology and microstructure of B_4C/2024Al composites after 7.62 mm ballistic impact, Materials and design, 63, 2014, 658-663.