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BALLISTIC STUDIES OF LIGHTWEIGHT MATERIALS – A REVIEW

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Abstract: A recent development in the material studies provides beneficial application of lightweight alloys such as aluminium, magnesium as well as composites and metal matrices. The alloys are experimentally improved by increasing hardness in the ballistics testing using projectiles, makes them viable for the areas such as aerospace, military, defence, automobiles and so on. So the study is made on different approaches. First, by comparing different types of non-ferrous alloys and projectiles regarding sizes, structures. Second, the materials with heat treatment are also studied for investigating the hardness property by overcoming successful penetration on non-ferrous alloys. Third, material to be improvised by use of numerical studies such as 3D models, empirical models and software such as ANSYS, ABAQUS and AUTODYN, etc. Finally, the aim of this paper is to review the recent progress ballistic studies of lightweight materials and to provide a best choice of material for further on-going research.

Keywords: lightweight materials, ballistics, heat treatment, numerical studies

1. INTRODUCTION

Ballistic testing is a field of science which deals with the study of impact objects such as a bullet, bombs, projectiles, etc. Ballistic research had been carried out in the lightweight material to utilize these materials in the defence industries. Technological improvisations had paved solution on constructing the lightweight and compact defence tankers for military applications. Many of the non-ferrous alloys dominated their role in the application of fields such as aerospace and military especially in the construction of defence tankers [14]. Few lightweight materials such as aluminium, magnesium and composites are substitution material for steel and rolled homogenous steel (RHS) because of its less density compared to steels. The impact strength of the material is analysed from the ballistic behaviours, failure mechanisms such as hole growth and crack which are important to study [19]. The hardness is an essential property to determine the ballistic performance [1, 2]. The study is carried out in non-ferrous alloys of desirable compositions for withstanding various projectiles of cross-sections [3] [4]. Ballistic experiments involve the loading of the work piece in the target area and the projectile strike in required velocity. The series of apparatus had equipped in various experiments to test the material and obtain readings and result out of it. Moreover, the numerical study is carried on models depicting the experimental procedure necessary to obtain a result on deformations and perforations [8, 17]. From numerical investigations, they found there is a close correlation with the experimental results [5].

This paper reviews the published journals in the field of ballistic studies of lightweight materials. It includes the few non-ferrous and composite materials on their ballistic performances and failure mechanisms. Few studies compare the experimental and numerical ballistic behaviour of lightweight materials against the different projectiles and velocities.

2. BALLISTIC EXPERIMENTAL DETAILS

Study of ballistics was done for various lightweight materials on predicting their limits on different projectiles. The experiments involve the study of the characterisation of the materials on strength, hardness, energy absorption before and after the ballistic impact.

While the size and structure of the projectile material vary accordingly and to be tested on the targets for impact energy generated on them. The experimental test involves series of procedure that is to be carried out with visual inspections and investigations, however carrying out ballistic test with precaution such as the remote location of the test area, noise cancellation devices are used in preventing from hearing impairments. The lightweight material such as aluminium alloys, magnesium alloys and composites are reviewed on the type of alloys tested against the projectiles.

Fig. 1. AM60 magnesium alloy with dimensions: Ø95×10 mm [12]

The aluminium alloys experimented on many articles includes AA2014-T652 forged plate [6], 6061-T6 and 7075-T6 aluminium plates [7], AA6070 [8], 1100-H14 [9], 5754-H111 [3], AA6061-T651 [10], AA5083-H116 [11] respectively. The magnesium alloys includes AM60 alloy [12], AZ31B alloy [13], AZ91 alloy [14], AMX602 alloy plate [1]. The pictorial representation of AM60 magnesium alloy is shown in Figure 1 [12]. The composites materials tested on articles includes EN AC-44200 alloy [15], GLARE (Glass Laminate Aluminium Reinforced Epoxy) [16], AA6063 with four different thicknesses considered while honeycomb cores are with hexagonal 5052 aluminium alloys [17], GLARE 3 composites which consist of 2024-T3 Aluminium as facing plates reinforced with E-Glass fibres and CY 219 Huntsman epoxy resin [4]. Hexoloy silicon carbide [18], boron carbide reinforced Al 6061 aluminium alloy [19], 4/3, 6/5 and 2/1 GLARE material [20]. The structure of the aluminium alloy sandwich panel with honeycomb cores is shown in Figure 2 [17].

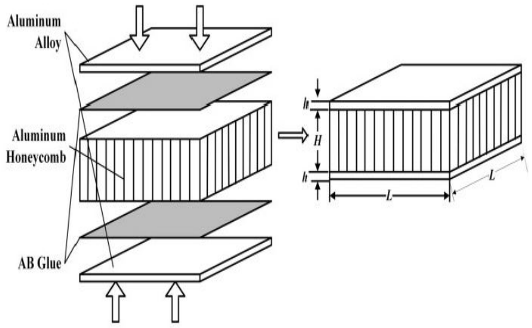

Fig. 2. Aluminium Alloy Sandwich Panel with Honeycomb Cores [17]

The various projectile equipped in the ballistic operations are double nose projectile structure[9], conical, hemispherical and blunt projectile [3] are shown in Figure 3.Parabellum and NATO projectile (displayed in Figure 4) [21], 7.62 mm calibre - ogival-nose - steel jacketed with hard tungsten core armour piercing (AP) projectile[22], 5.56 mm FMJ NATO projectile [5], 5.56×45 mm SS109 projectile [15], flat projectile[16], the flat-ended steel projectile [4], 15CDV6 steel [18], 50 calibre projectile [23], C30 steel (shown in Figure 6) [24], M80 of 7.62×51 mm [19].

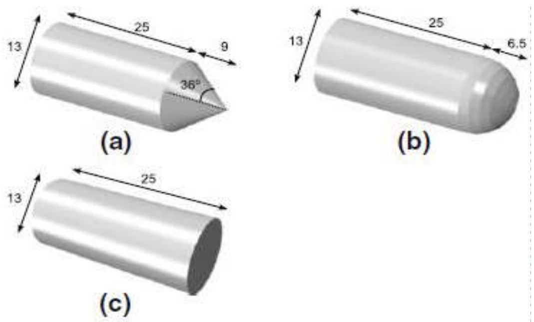

Fig. 3. The specification of the: a) conical, b) hemispherical, c) blunt projectile

Fig. 4. a) Parabellum Projectile, b) NATO Projectile [21]

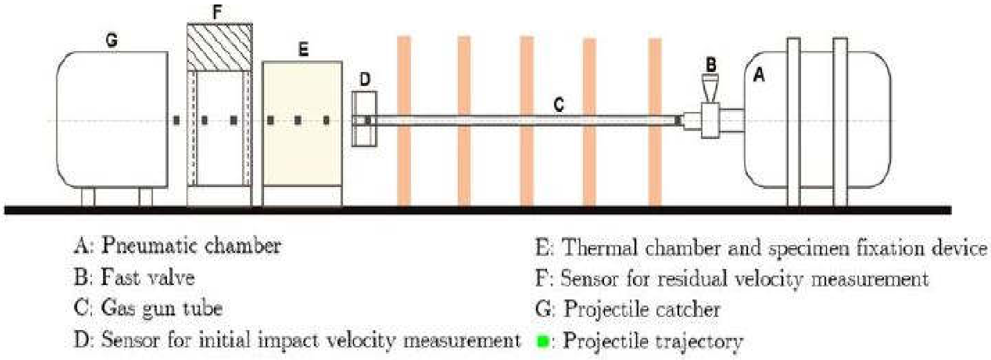

Fig. 5. Schematic representation of gas gun triggering experiments [25]

Reviewing among the articles, there are experimental setup made out of which some are tested using gas guns [25] and some with impact testing machines [12]. The schematic diagram of the gas gun setup is illustrated in Figure 5 [25]. While the 9250 HV Dynatup Instron impact tower is shown in Figure 7 [12].

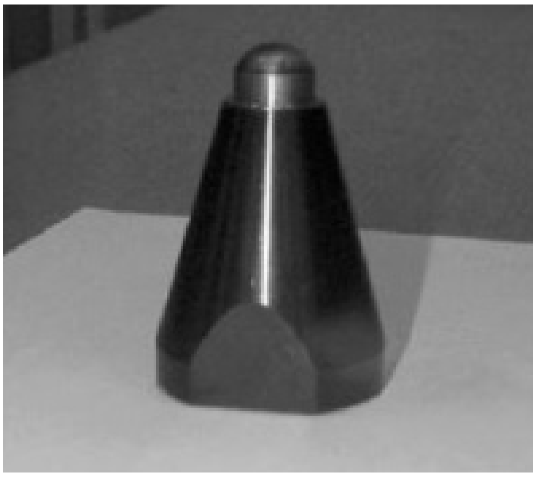

Fig. 6. C30 steel projectile [24]

Fig. 7. The 9250HV dynatup instron impact tower [15]

3. STUDIES OF BALLISTIC TEST ON ALUMINIUM ALLOYS

Prince Sharma et al. [6] conducted a test on AA2014-T652 which results in providing the perforation of target by hard steel projectile with a velocity of 834 m/s whereas soft iron projectiles do not perforate with the velocities less than 937 m/s. It results in extensive fragmentation and conical crater formation on the rear side of the work piece. Figure 8 shows the numerical ballistic penetration channel of Al6061 alloy with different velocities.

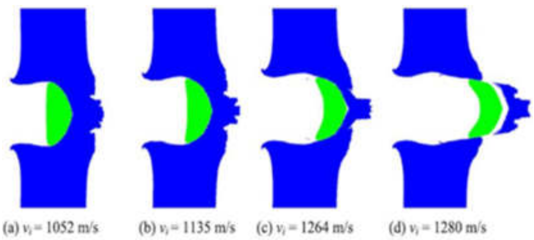

Fig. 8. Numerical model on penetration of soft iron projectile [6]

Senthil et al. [26] worked on the AA2024 target on blunt nose projectile which shows a gradual increase in ballistic resistance in increase with target thickness. The numerical and experimental values are almost the same for 1.27 mm thickness and slightly change of 29% from the numerical values to the experimental test on 3.18 mm target thickness. The values become insignificant for increasing thickness up to 19.05 mm respectively. Charles E. Anderson et al. [7] done the comparison of two aluminium alloys such as Al-7075-T6 and Al-6061-T6 and found out the difference in strength is 85%. The deformation changes slightly according to the thickness level. But the crack appears different in failure process results in comparative ballistic velocities of 366 m/s and 330 m/s on 7075-T6 and 6061-T6. J.K. Holmen et al. [8] investigated the heat-treated aluminium alloys and its effect on the ballistic properties where projectile limit is based on the thickness of the target and independent of the material and perforation in aluminium is compared with the steel and found to be better than steel where areal mass is taken in account, so the presence of scale effect provide such increased perforation resistance than steel plates. The target plates of 20 mm thickness are tested with APM2 bullets at different velocities as shown in Figure 9 [8].

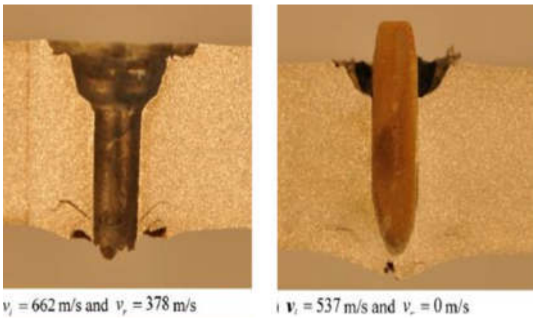

Fig. 9. Target plates of 20 mm tested with APM2 bullets at different velocities [8]

Iqbal et al. [9] studied the ballistic behavior of aluminium alloy using different projectiles. It is noted that the petal formation is found only on the conical-blunt projectiles and not on other projectiles such as single-nose blunt, single-nose conical. The highest penetration limit for 0.82 mm is observed against blunt-blunt projectile. While single-nose is highest penetration limit for 1.82 mm respectively. Rodriguez-Millan et al. [3] compared the ballistic limit of AA 5754-H111 and AA6082-T6 plates and found out the AA5754 is efficient than AA6082-T6, when the conical and hemispherical projectiles while the behavior is opposite for blunt projectiles. Evren Ozsahin et al. [10] researched the application of coatings on the aluminium for better ballistic performances. Penetration depth is found to appear on the coated alloy with bulging on the rear side making it ballistic efficient than the uncoated alloy especially at the higher impacts such as 390 m/s and higher due to presence of Co-Mo-Cr coatings rather than the Zirconium. LIANG Xiao-Peng et al. [27] discussed the micro structural evolution of 2519-T87 aluminium alloys with different stages in projectile penetration. The entering stage, stable-running stage and leaving stage which discusses adiabatic shear band and micro bands which are a larger amount in leaving the stage with the less adiabatic shear band while the micro hardness is increased. Jamal-Omidi et al. [11] studied aluminium alloy on low-velocity impact. Though the low-velocity impact calculated by the numerical is less predictable due to deflections, the use of Johnson-Cook model to prevent the spring back effect by providing the time deflection in the numerical study that coordinates with the experimental reading. Thus, the stiffness of different aluminium alloy is considered and the numerical modeling approach presented in the paper is quite accurate and reliable for analyzing the target plate with less impact velocity. Bendarma et al. [25] study found that temperature plays a significant role in the mechanical behavior also the projectile nose is closely associated with the ballistic limit and failure mode evaluation. For conical projectile, the energy produced due to residual stress at room temperature is 26 J and decreased to 18 J of energy at 300 which is shown in Figure 10 [25].

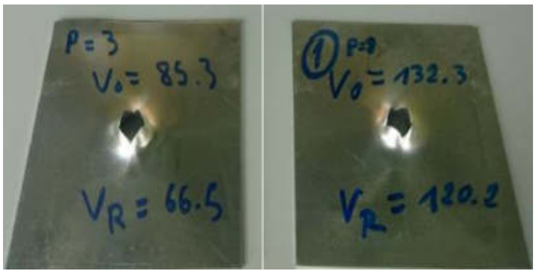

Fig. 10. Experimental observation of failure patterns on aluminium alloy, v_0= 85.3 m/s & 132.3 m/s [25]

4. STUDIES OF BALLISTIC TEST ON MAGNESIUM ALLOYS

Tadeusz Szymczaket al. [12] provided the result of impact energy within the range of 260-540J in friction zones of the test piece. The number of a crack in the region increases with ballistic perforation. Mohamed Faizal Abdullah et al. [21] tested the AZ31B alloy by addition of the lead content with varied percentage while the target is impacted with parabellum and NATO projectile. The magnesium can be feasibly used in ballistic applications with the dependence of hardness of the alloy. The hardness of the alloys with different lead content is compared with their hardness and the optimum amount that can be added to the AZ31B alloy is 1% Pb as it is shown in Figure 11 [21]. HE Huan-ju et al. [14] done test on AZ91 with impact situations where two types of the alloy are used cast and the other one is by solid solution and age-treatment. The result discusses the strain rate in both alloys where the casted AZ91 had less failure stress than solution ageing state and the fracture is occurred due to different strain rates. Bo Zhang et al. found that a unique localized shear observed in Mg-Al-Mn alloy under the ballistic impact, consistent with the detailed microstructure characterization of 'deformed twin'. Dynamic recrystallization and precipitation occur at the TBRs (Twin Boundary Regions) even as the inner area of twins indicates elongated grains. Unique slender shear bands that are composed of recrystallized grains and precipitates fashioned at the obstacles of twins. Teyfik Demir et al. [28] studied the ballistic performances of AA7075-T651 and AA5083 with the 7.62 mm AP projectiles where the best ballistic performance is obtained from 7075-T651.

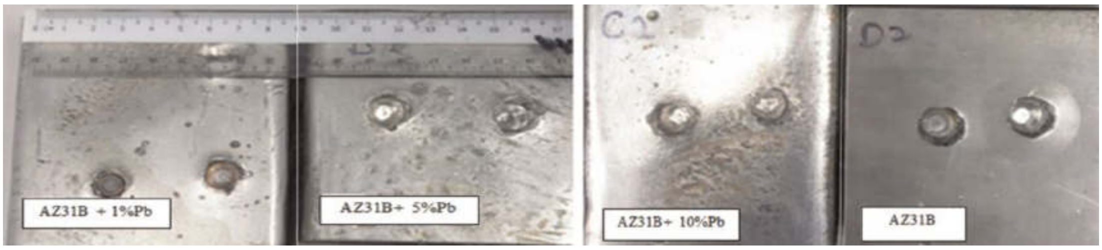

Fig. 11. Different work piece tested with 9×19 mm Parabellum projectile [21]

The increase in hardness gradually happens with an increase in the thickness of the work piece due to various applied heat treatments. But in the case of steel specimen, the increased hardness not only increased the ballistic performance but also broken in a brittle manner. Thus aluminium alloy7075-T651 is found to be lightweight and reduction in size by 25% when compared to rolled homogeneous armour steel. Ezhil Vendhan et al. [5] analysed AZ31B magnesium alloy with the projectile and found out that the ballistic effect is interdependent of velocity and target thickness which acts as the main factor for constructing armour. As the Impact kinetic energy increases from 1569 J to 3888 J the residual kinetic energy decreases from 120 to 40 J. The numerical simulations using AUTODYN software were made on the target to correlate with the experimental results done by Tyrone et al. [1] provides an out view of the ballistic penetration as it is shown in Figure 12 [5].

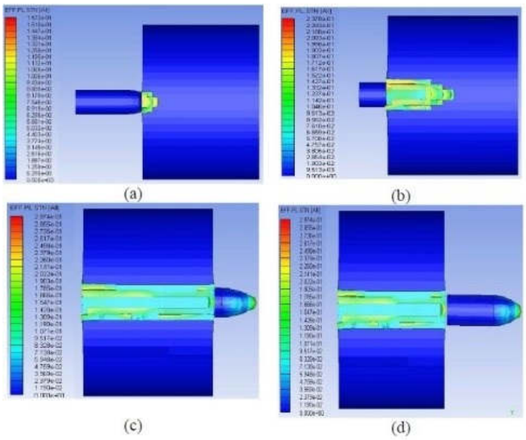

Fig. 12. Numerical simulations of projectile on magnesium AZ31B alloy [5]

M. F. Abdullah et al. [2] implemented the usage of Carbon-Nano Tube (CNT) for improving impact resistance on AZ31B magnesium alloy together with lead (Pb) addition. The graph is represented on the comparison of normal alloy and alloy with CNT and Pb which is shown in Figure 13 [2]. Ballistic performance is improved when tested with 5.56 mm FMJ NATO projectile. Therefore the addition of lead provides increased protection on military and defence. Tyrone L. Jones et al. [1] updated the ballistic performance of various non-ferrous alloys includes aluminium and magnesium alloys. It mainly compared AZ31B and AA5083 alloys tested with APM2 projectile. The projectile is tested on the target plate at 0 and 30 where the magnesium fails at initial and initially has higher ballistic resistance than AA5083 alloy at 30. But AMX602 fail to meet the ballistic resistance on APM2 projectile. Therefore AZ31B provides better ballistic performance at 26.6 mm thickness.

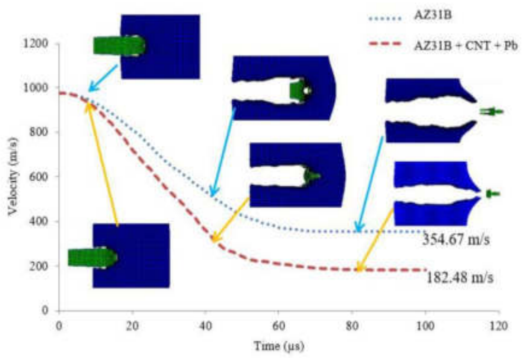

Fig. 13. Comparison of normal alloy and alloy with CNT and Pb [2]

5. STUDIES OF BALLISTIC TEST ON COMPOSITES

Adam Kurzawa et al. [15] discussed the use of metal-matrices in providing ballistic protection in which the ceramics and plastic fibre tend to change mechanical properties over the projectile testing. Hence the use of metal matrices such as corundum ceramics (Al_2O_3) made of ceramics and aramid laminate with 4mm thickness. It tends to show higher ballistic on use of SS109 impact projectile and which meets the expectation of ballistic performance. Hamed Zarei et al. [16] conducted the experimental analysis on GLARE5 targets using flat and conical projectiles. It also includes the numerical investigation using finite element software, LS-DYNA. Both the numerical and experimental results coincide. Thus the ballistic performance increases with a decrease in projectile mass. However, the result is different when the projectile diameter increases. QN Zhang [17] conducted the ballistic study on Aluminium alloy sandwich panels with honeycomb cores by conducting series of quasi-static and impact perforation tests which is provided on Figure 14. When the test is carried out on conical nosed projectile, the perforation causes tearing failure and dissipates most energy, therefore the honeycomb structure provides more ballistic performance on a conical-nose projectile.

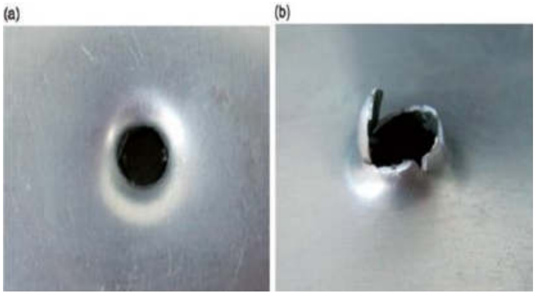

Fig. 14. Perforation of projectile through sandwich panels: a) front side, b) rear side [17]

Hadi Sabouri et al.[4] tested the 2/1 and 3/2 GLARE3 targets on flat end projector and also tells that the aluminium alloy with higher thickness have better ballistic performance such that medium thickness is preferred over the thin regions. Also, the projectile impact of 3/2 GLARE targets is the same for the front as well as the rear side. J.L. Zinszner et al.[18]conducted experiments of ballistic impact on Hexoloy ceramic tile and this paper deals with the characterization of dynamic fragmentation which means spitting of particles occurs during an impact test. They compared the experimental data with a DFH (Denoual, Forquin, Hild) anisotropic damage model predictions. Eyup Yeter et al.[23] proposed the use of Epoxy/Kevlar reinforced with aluminium and testing up with projectile. While the thickness of the material increased from 5 mm to 15 mm, the residual velocity decreases from 9.6% to zero. The perforation of the projectile through time interval is accurately done in this method. The hybrid models show reduced or even zero residual stress in the target when compared to conventional alloys. Z.L. Chang et al. [29] focused on the failure process of ceramic reinforced aluminium alloy and their configuration at a very high-speed impact. The numerical simulations are compared and analyzed for higher accuracy in the results from ANSYS/AUTODYN software. Halil Karakoc et al. [19] tested the addition of boron carbide reinforced with aluminium alloy where the thickness of 12.7 mm and 25.4 mm are focused on the mechanical behaviors. At 12.7 mm thickness, ductile behavior is noted with radial cracks whereas for 25.4 mm does not withstand the ballistic impact. The successful performance is obtained from hot rolled dual-layered composites with 5%wt and 15%wt on the composites. A. Seyed Yaghoubi et al. [20] conducted experimented and numerical studies on GLARE 5 fiber materials and provided a solution to the damages due to various thicknesses. Interfacing debonding on aluminium layer bending causes impact energy dissipations. The use of Lambert – Jonas equations helps in determining the low velocity of the projectile through numerical simulations which are difficult to obtain on experimental methods. The thicker specimen has maximum contact force whereas it is contact force is minimum for thin specimens. Therefore increase in the impact velocity makes the contact force suppressed.

6. SUMMARY AND CONCLUSIONS

The outcome of this literature review paper and other papers related to ballistic studies depicts the subsequent observation aspects which relate to lightweight materials for their defence applications. The study mainly involves discussion of the projectile perforation to the targets and the examinations are done on the effect of projectile by measuring velocity through the infra-red spectroscopy and chronograph [15]. The further examinations are done to find the failure modes in light weight alloys such as microstructure evaluation and impact study [21]. The Numerical comparisons are also done to find the residual stress in the system through the use of models such as Johnson-Cook model and Recht-Ipson model [5]. The aluminium is compared with the steel and found to be better than steel based on projectile perforation resistance [8]. While coating of the provides better resistance to the impact projectile thus ductile hole is reduced [10]. For magnesium alloy, AZ31B , it is light weight and has more resistance to projectile impact than the other magnesium alloy, hence it is suited for ballistic operation [1]. The dynamic recrystallization in magnesium alloy allows the material structure to be refined and gives more resistance to penetration[30]. The magnesium alloys can also be used as armor [5]. The composites such as metal matrices provides higher ballistic which meets the expectation of ballistic performance [15]. Thus the composites are light weight while magnesium acts as a substitute for aluminium due to its less density and can be applicable in defense industries such as constructing of defense tankers.

By concluding the review made on various manuscripts, the following main points are to be highlighted with remarks are discussed below.

1. The overview of ballistic research is focussed on aluminium alloys which has high ballistic performances and dominated the chart by impact resistance. The future research can be focussed on the welded joints and their behaviour associated with the ballistic impacts.
2. The usage of magnesium alloys are increases consistently on the improved performances of

ballistic test. The magnesium has the property of low density which makes the future research focussed on application of it in the field of defence. Many researchers have contributed the improvement of this alloy by various techniques to improve its hardness on withstanding high velocity impact projectiles.

3. The composites exhibit good ballistic characteristics when reinforced with non-ferrous alloys such as aluminium and magnesium alloys. It also paves solution for creating light weight armour and their resistance to very high velocities. The composites includes the metal matrices, hybridized and in form of sandwiched structure. The composites provide equivalent hardness and penetrant resistance in comparison with the base alloy on slightly less in weight and density. Further research will be focussed in the studies of ballistic effect especially on angle of attack, metal laminated composite with different light weight alloys of permanent and temporary joints.

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