METAL MATRIX COMPOSITES AS POTENTIAL ARMOUR MATERIALS

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Abstract

To defeat a kinetic energy projectile the armour needs to be extremely hard on the surface, so as to blunt the projectile on initial impact. A ceramic material may be an ideal choice. However, to absorb and dissipate the complete kinetic energy of the projectile, the subsequent material has to be extremely tough with a very high work of fracture. It also needs to be a light weight material to keep the overall weight to a minimum possible value. A fibre reinforced polymer matrix composite can meet the requirement. The innermost layer needs to have a very high ductility so as to avoid any fracture and fragment formation which could be lethal. So it has to be a metallic material. Thus, the application requires a range of properties starting from that of a ceramic and ending with that of a metal. Metal matrix composites (MMCs) are essentially metals reinforced with ceramic reinforcements, which exhibit a combination of properties of both the constituents and could be tailored to suit the requirements. Discontinuously reinforced MMCs also have the added advantage of being amenable to conventional metal forming operations, which makes it easier to produce them in the required shapes. This paper would provide an introduction to MMCs and review the available literature on their evaluation for possible applications as armour materials. It would also present the results of the preliminary studies on the dynamic hardness measurements of discontinuously reinforced aluminium alloy composites which gives a good indication of their potential use as armour materials.

1. Introduction

Metal matrix composites (MMCs) are essentially metals with ceramic reinforcements, which exhibit a combination of properties of both the constituents and could be tailored to suit the requirements. MMCs have been developed for a variety of applications starting from sports goods to highly demanding defence and aerospace components. Depending upon the raw materials used and the processing route adopted, they can be made to suit the cost sensitive, high volume automobile applications or the performance oriented, low volume but highly critical, space applications. The ceramic reinforcements could be in the form of continuous fibres or discontinuous particulates, platelets, short fibres or whiskers. Discontinuously reinforced MMCs are being used for both structural and functional applications. Their superior specific strength and specific stiffness make them good structural materials for weight sensitive applications in aerospace and automobile fields. Their high temperature capabilities, lower coefficient of thermal expansion, better wear resistance and improved dimensional stability make them suitable for functional applications like brake discs and electronic packaging. Discontinuously reinforced aluminium alloy (DRA) composites have established themselves as a new class of advanced materials, which are now commercially available [1].

To defeat a kinetic energy projectile the armour needs to be extremely hard on the surface, so as to blunt the projectile on initial impact. A ceramic materials may be an ideal choice. However, to absorb and dissipate the kinetic energy of the projectile, the subsequent material has to be extremely tough with a very high work of fracture. It also needs to be a light weight material to keep the overall weight to a minimum possible value. A fibre reinforced polymer matrix composite can meet the requirement. The innermost layer needs to have a very high ductility so as to avoid any fracture and fragment formation which could be lethal. So it has to be a metallic material. Thus, the application requires a range of properties starting from a ceramic and ending with that of metal [2]. However, the present day armour against small arms is either steel or a combination of ceramic plates and a tough backing such as high strength aramid fibre (e.g.Kevlar®) fabric. The former means excessive weight on the personnel, while the latter suffers from the absence of multihit capability, which is very essential especially against the automatic weapons being employed. This is because the ceramic plates used in the latter kind of armour, which bear the brunt of the shot, shatter after the first hit and will not be available for protection if a second shot hits at the same spot, the chances of which are quite high with the automatic weapons [3]. MMCs are expected to have the multihit capability, since they are not as brittle as pure ceramics due to the metallic matrix which imparts certain amount of ductility and consequently fracture toughness to the composite. They are also expected to give significant weight savings vis-a-vis steel armour as both the constituents of the composites, namely the metallic matrix (e.g. aluminium) and the ceramic reinforcement (e.g. alumina, silicon carbide) have almost half the density of steel.

2. Metal Matrix Composites :

The metal matrix composites are conventionally classified into continuous fibre reinforced and discontinuously reinforced composites. Recent developments have however added some more special types of MMCs namely the layered or laminated composites, functionally gradient materials and interpenetrating network composites. While the conventional composites are well understood, the new developments need to be elaborated upon. The laminated composites are nothing but alternating layers of MMCs and the respective matrix metals or any other alloys. The aim of having this engineered microstructure is to enhance the damage tolerance and the fracture toughness of the composite [4,5]. The MMCs are otherwise brittle as compared to the respective matrix metals and the presence of alternating layers of the matrix metal diverts the crack path and also leads to other toughening mechanisms like crack bridging. Functionally gradient materials on the otherhand have continuously changing microstructure across the thickness of the composite, starting with a pure ceramic on one face and ending with a pure metal on the other side [6,7]. The purpose is to meet the conflicting requirements of the intended application. As explained earlier the materials property requirement to defeat a projectile changes as it traverses into the armour and gradually loses its velocity and dissipates its kinetic energy. In fact, such conflicting requirements are quite common in advanced technologies. Originally the functionally gradient materials were developed for heat shielding, where the surface temperatures reach as much as 2000K while the inside needs to be maintained at temperatures as low as 300K. The thickness allowed being about 10 mm, the thermal stresses are so high that no conventional monolithic material could withstand the same. The outer surface need to be highly insulating like a ceramic and the inner face has to be highly conducting like a metal [8]. The interpenetrating network composites consist of metal and ceramic phases both continuous and intermingled, the ceramic content reaching a high of about 85%. The continuous metallic phase improves the toughness and damage tolerance [9,10]. These composites are therefore an improvement over the ceramic faced armour, as they are expected to provide the multihit capability, as well as provide a weight advantage over the steel armour.

2.1 High Strain Rate Properties :

During ballistic penetration the material is subjected to deformation at very high strain rate (above 10^4 /s). therefore it is imperative to obtain the flow stress at this strain rate. Eventhough MMCs are candidate materials for many applications where high strain rate or ballistic impact loading is probable, not much data is available in the published literature on the high strain rate properties of these materials. However, whatever little information is available, it seems to suggest that they are potential materials for armour applications. Because mechanical properties vary significantly with strain rate, the use of static properties in the design and analysis of structures which undergo dynamic loading can on one hand lead to a very conservative overweight design, or on the otherhand can lead to designs which prematurely and unexpectedly fail. The use of quasi-static mechanical property data for high strain rate load situations is at best misleading, and at worst could possibly be disastrous.

Harding et al. [11] have evaluated 2124 Al alloy matrix composites reinforced with 15 and 25 volume percent of silicon carbide whiskers (2124 Al/15 & 20 vol. % SiC_w) at different strain rates ranging from quasi-static (~ 10^{-3} s^{-1}) to impact (~1500 s^{-1}).

Three different types of testing machines were used in this investigation to cover the entire range of strain rates namely a standard screw driven Instron for quasi-static tests (~ 10^{-3} s^{-1}), a hydraulic machine for intermediate rates (~10 s^{-1}) and a gas gun for impact loading at strain rates of ~1500 s^{-1}, however, the cylindrical specimen for testing was the same at all strain rates. The stress - strain curves obtained for 15 vol. % SiC and 25 vol. % SiC at the three different strain rates are reproduced in Figs. 1 (a) & (b) respectively. For both the composites, the strain at failure increased continuously with increasing strain rate while the flow stress at a given plastic strain is lowest at the intermediate strain rate and highest at the impact strain rate. A clear indication of the strain rate dependence of the yield stress, flow stress at a particular strain, the tensile modulus and the total failure strain can be seen from Figs. 2,3 & 4, which are based on the data derived from these curves. The lowering of the flow stress at the intermediate strain rate is an anomalous result. It was also observed that the dislocation density was an order of magnitude higher in the specimen tested at the lowest strain rate as compared to the one tested at the highest strain rate, which again needs explanation. The authors have concluded that assuming the increase in fracture to be genuine effects, it would seem necessary to relate the increased deformation to damage mechanisms involving an increase in volume rather than to plastic flow at a constant volume. Such mechanism might include micro-cracking or void formation which would need to play a greater role in the overall deformation process at high strain rates than under quasi-static loading. Whatever be the reason, the fact that the flow stress, the tensile modulus and the total strain to failure are at their maximum at the highest strain rate is a strong pointer to their potential as good armour material. The higher flow stress gives higher resistance to penetration, the higher modulus helps in dissipating the energy over a larger volume of the armour material, since the shock wave velocity in the material is directly proportional to the modulus and the higher total strain to failure would reduce fragmentation. In fact, the ballistic figure of merit M given by Stiglich [12] for a ceramic material :

$$M = \frac{EH}{\rho} \qquad \text{——} \quad (1)$$

where E is the modulus, H is the hardness and ρ is the density, also indicates that the ballistic performance of the material is directly proportional to the modulus and the hardness (which can be related to the flow stress) and is inversely proportional to the density. MMCs are known for their high specific modulus and high specific strength. Brian et al. [13] have also studied the high strain rate behaviour of 2080 Al reinforced with 20 vol. % SiC_p using the conventional Split Hopkinson Pressure Bar facility in the compression mode, and arrived at the following conclusions : (1) The specimens did not fracture over the range of strain rates upto 950 s^{-1}, although the compressive stresses exceeded 100000 psi. (2) Over the range of strain rate tested (592.4 s^{-1} to 952 s^{-1}) the yield stress increased by 31.3%, the yield strain increased by 68% and the elastic strain energy increased by 119% for the MMC.

2.2 Ballistic properties :

The relative effectiveness of different kinds of armour materials is best characterised by comparing their areal densities with that of rolled homogeneous steel armour (RHA) against a particular projectile. The areal density is the weight per unit area of the armour required to provide protection against a particular threat and is simply the depth of penetration of the said projectile in the armour multiplied by the density of the armour material. The mass effectiveness of different armour materials is thus the ratio of the areal density of RHA to that of the respective armour material. A mass effectiveness of 2.0 therefore means that the new armour can provide the same protection as RHA, at half the weight of RHA. The mass effectiveness of different types of light armour against 7.62 Armour Piercing (AP) bullet, which happens to be the most common threat against light armoured vehicles, is given in Table 1 [3]. As can be seen from this table, while aluminium armour alloys are slightly better than RHA, ceramic faced armours give significant weight savings over RHA. The boron carbide faced 6061 aluminium armour can give the same protection as RHA at less than one third of the weight of RHA. As mentioned earlier, the main disadvantage of the type of armour is the absence of multihit capability. One of the ways to solve this problem is by using smaller ceramic tiles such that the damage is confined to a smaller area. But then this introduces many weak points on the armour in the form of joints wherein the protection is expected to be inferior. Another shortcoming of this type of armour is that the ceramic facing is parasitic from the structural view point, in the sense that it does not add to the structural strength of the armoured vehicle. On the other hand, the weight of the ceramic facing is also to be borne by the underlying structure. It is also difficult to form the ceramic facing in complex contours. It is felt that all these disadvantages could be overcome by the use of MMCs, wherein the metallic matrix gives sufficient ductility and fracture toughness to the armour to provide multihit capability by avoiding shattering after the first hit. The MMCs can also form part of the vehicle structure and contribute to the structural strength. The ceramic reinforcement content can be adjusted to take advantage of the ceramic hardness and high modulus.

Bless et al. [14] have reported the ballistic impact behaviour of SiC reinforced 2014 Al and 6061 Al alloy MMCs. Projectiles used were 95% sintered tungsten alloy, having a double conical nose (40 and 10° half angles), with a major diameter of 7.7 mm and a mass of 22g. The nominal impact velocity was 1.2 km/s. The materials properties, shape and velocity of the projectile resembled those of several military tungsten alloy bullets that are used in 0.50 caliber and larger guns. Penetration resistance or ballistic performance was evaluated by calculating differential efficiency of the MMC materials using 6061-T651 aluminum as the reference materials as well as the backing material in the thick backing plate geometry shown in Fig.5. The differential efficiency factor (e_{Δ}) for the MMC material is computed from :

$$e_{\Delta} = W_{REF} - W_{R} / W_{A} \qquad ....(2)$$

where W_{REF} is the areal density of the reference armour (6061-T651 Al in this case) that will just stop the projectile, W_{A} is the areal density of the MMC plate and W_{R} is the penetrated areal density of the backing material (residual penetration multiplied by the density of the backing material). Values of e_{Δ} for the different materials tested by them are reproduced in Fig.6. The MMC plates as well as the matrix materials were confined in a steel frame to avoid excessive expansion and as can be seen from the data confinement itself improved the ballistic performance by about 50% over that of the unconfined 6061-T651 Al reference alloy. All the MMCs evaluated resulted in a differential efficiency factor above 3.0 indicating that these can give the same protection as the reference material at less than one third the weight of the reference material in the unconfined condition or at less than one half the weight of the reference material in the confined condition.

3. Preliminary results

Since adequate data is not available in literature on high strain rate flow behaviour of MMCs, a preliminary study is undertaken in this regard for 2124 Al alloy reinforced with SiC particulate reinforcement. The powder metallurgy processing of these MMCs has already been established at the Defence Metallurgical Research Laboratory, Hyderabad [15]. The unreinforced 2124 Al alloy produced by the same process was also evaluated for the purpose of understanding the effect of reinforcement. The Vickers hardness values were 99, 165 and 210 for 2124 Al, 2124 Al-15 vol.% SiC and 2124 Al-30 vol.% SiC respectively in the T6 heat treated condition. The dynamic indentation (DI) technique was used to evaluate the dynamic hardness of the material. The DI technique essentially involves a gas gun which allows a sphere to be impacted on to the specimen over a wide range of impact velocity. The samples were about 25 mm long, 21 mm wide and 15 mm thick. All samples were polished through 600 grit emery paper and ultrasonically cleaned prior to testing. These samples were then fixed to the sample holder of the gun and impacted normally with WC ball (4.76 mm dia.) over a range of velocities. The velocity V was varied by changing the gas pressure in the gas gun. The diameter (W) and depth (d) of the crater formed by the impact of the WC ball was measured. The W-V and d-V data so obtained becomes the basis for estimating the flow stress-strain relationship. Further details of the DI technique are available elsewhere [16].

The variation of penetration depth (d) with the impact velocity is shown in Fig. 7. It is to be noted that the penetration depth varies linearly with the impact velocity for unreinforced 2124 Al alloy as well as for SiC reinforced 2124 Al composite. As the non deforming projectile was used in the present investigation, the kinetic energy imparted to the target is constant for a given velocity for all the specimens. The rebound energy is negligible for ductile targets at the impact velocities exceeding 20 m/s [17]. The penetration data for AA 7039 Al alloy (cast and rolled) in T6 condition evaluated elsewhere [18] under identical conditions is also incorporated in Fig.7 for comparison. An interesting observation from Fig.7 is that the penetration depth is lower for 2124 Al alloy even without reinforcement as compared to 7039 especially at higher velocities. The extent of penetration is further reduced in 2124 alloy by the addition of reinforcement of SiC particulates. Increase in volume fraction has a direct correlation with the penetration resistance as seen in Fig.7. Given the fact AA 7039 alloy has been recognised as an armour material [3], the present data suggests that 2124 Al alloy reinforced with SiC composite can become a potential armour material with improved ballistic penetration resistance. However, more investigation is certainly required to realise the application of these MMCs as an armour material.

The evaluation of high strain rate flow behaviour on the basis of the data presented in Fig.7 is presently under progress at DMRL. A detailed investigation on the ballistic penetration of MMCs at velocities exceeding 200 m/s using a high velocity gas gun is also underway.

4. Conclusions

The available data from the literature and the results of the preliminary work carried out, indicate the potential of MMCs for armour applications. They are expected to provide a synergistic combination of hard ceramics and tough metals, thereby eliminating some of the drawbacks of the ceramic faced armours being used at present, such as the absence of multihit capability and parasitic nature of ceramic armour. In addition to the potential advantages of conventional MMCs, there is scope for further improvements in the form of laminated composites, functionally gradient materials and interpenetrating composites. Further work in this direction is a part of the ongoing activity at DMRL.

Acknowledgement

The authors would like to thank the Director, DMRL for encouragement and permission to publish this paper.

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Table 1
Mass effectiveness of different types of light armour against 7.62AP bullets at point blank range and normal impact [3]

Armour Type	Density kg/m³	Areal Density kg/m³	Mass Effectiveness
Steel Armour			
RHA (380 BHN)	7830	114	1.00
High Hardness Armour (550 BHN)	7850	98	1.16
Dual Hardness Armour (600-440BHN)	7850	64	1.78
Aluminium Armour			
5083 alloy	2660	128	0.89
7039 alloy	2780	106	1.08
2519 alloy	2807	100	1.14
Glass Fibre Laminates			
E-Glass	2080	115	0.74
S-Glass	2045	93	1.23
Ceramic Faced Armour			
Alumina (AD90)	3560	—	—
Alumina+5083Al	3125	50	2.28
Alumina+7020Al	3200	42	2.75
Alumina+E-Glass Laminate	2556	46	2.48
Alumina+Kevlar Laminate	2000	38	3.00
Boron Carbide	2450	—	—
Boron Carbide + 6061Al	2564	35	3.26
Titanium Diboride	4450	—	—

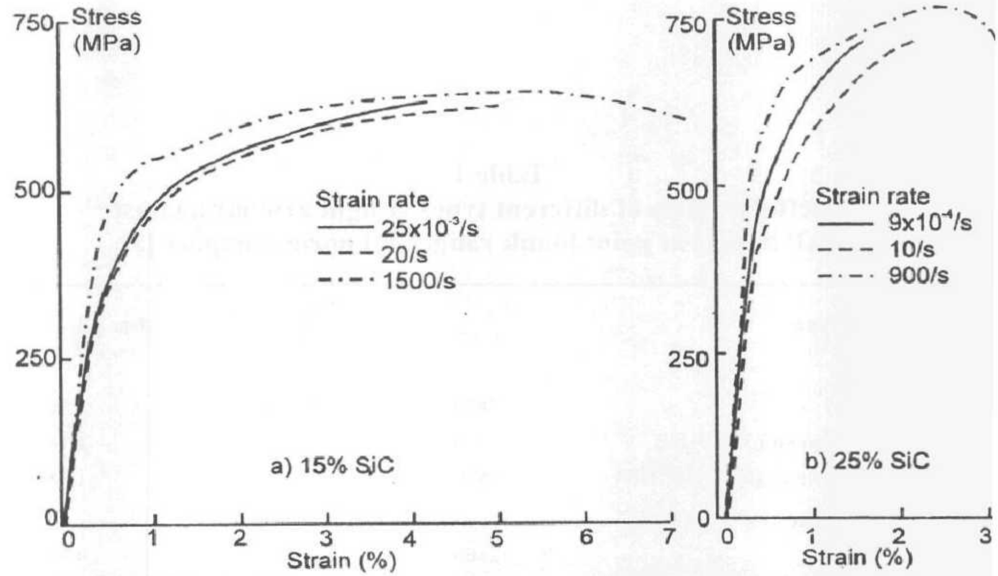

Fig. 1 - Effect of strain rate and volume fraction of reinforcement on the stress-strain curves of MMCs

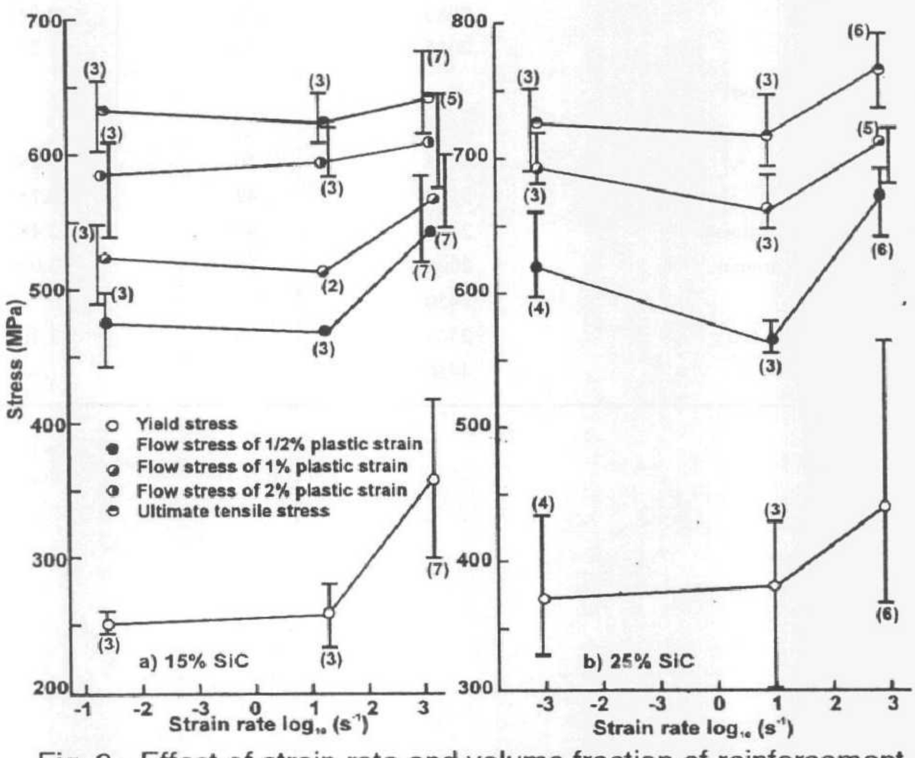

Fig. 2 - Effect of strain rate and volume fraction of reinforcement on the tensile yield stress, flow stress and ultimate stress of MMCs

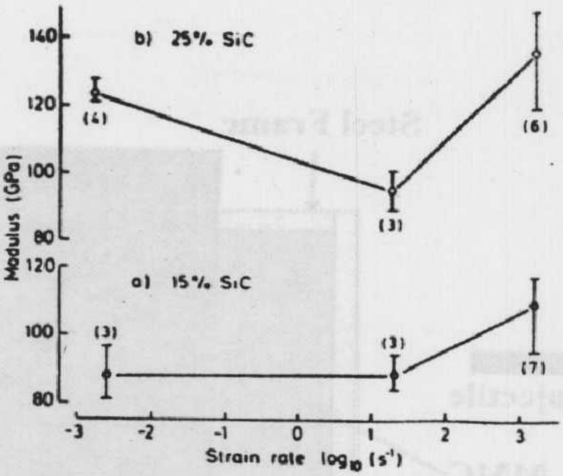

Fig. 3 - Effect of strain rate and volume fraction of reinforcement on the tensile modulus of MMCs

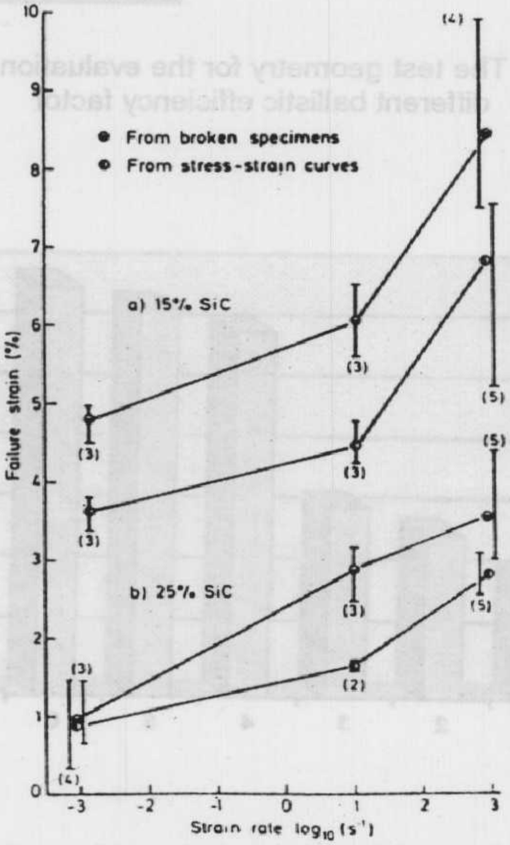

Fig. 4 - Effect of strain rate and volume fraction of reinforcement on the strain to failure of MMCs

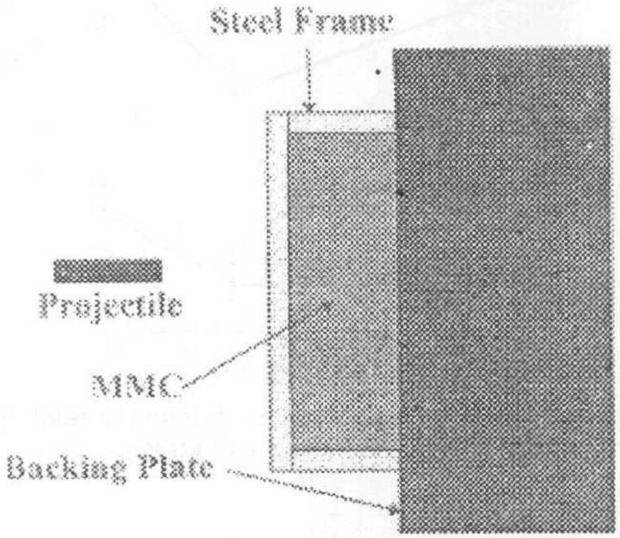

Fig. 5 - The test geometry for the evaluation of the different ballistic efficiency factor

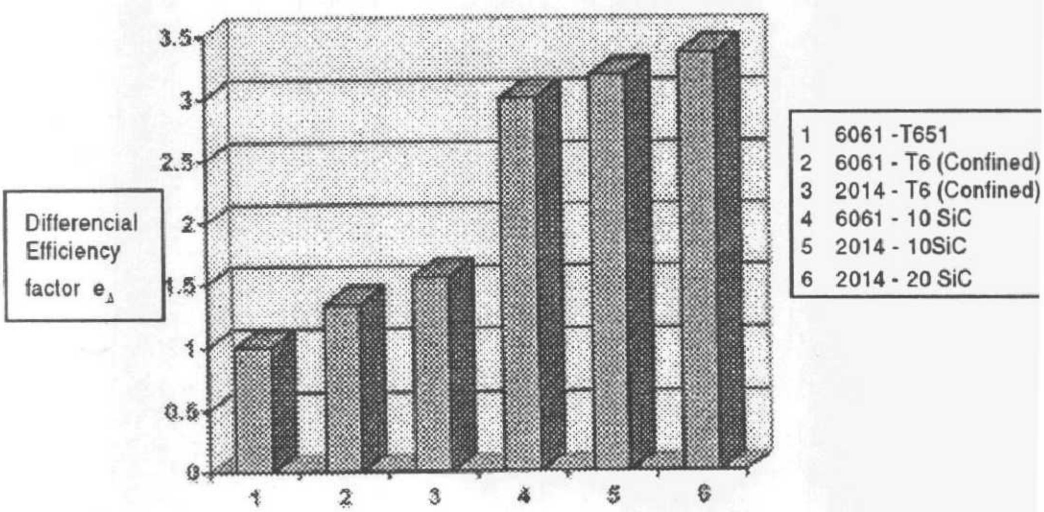

Fig. 6 - The differential ballistic efficiency factor for MMCs and unreinforced matrix materials [4]

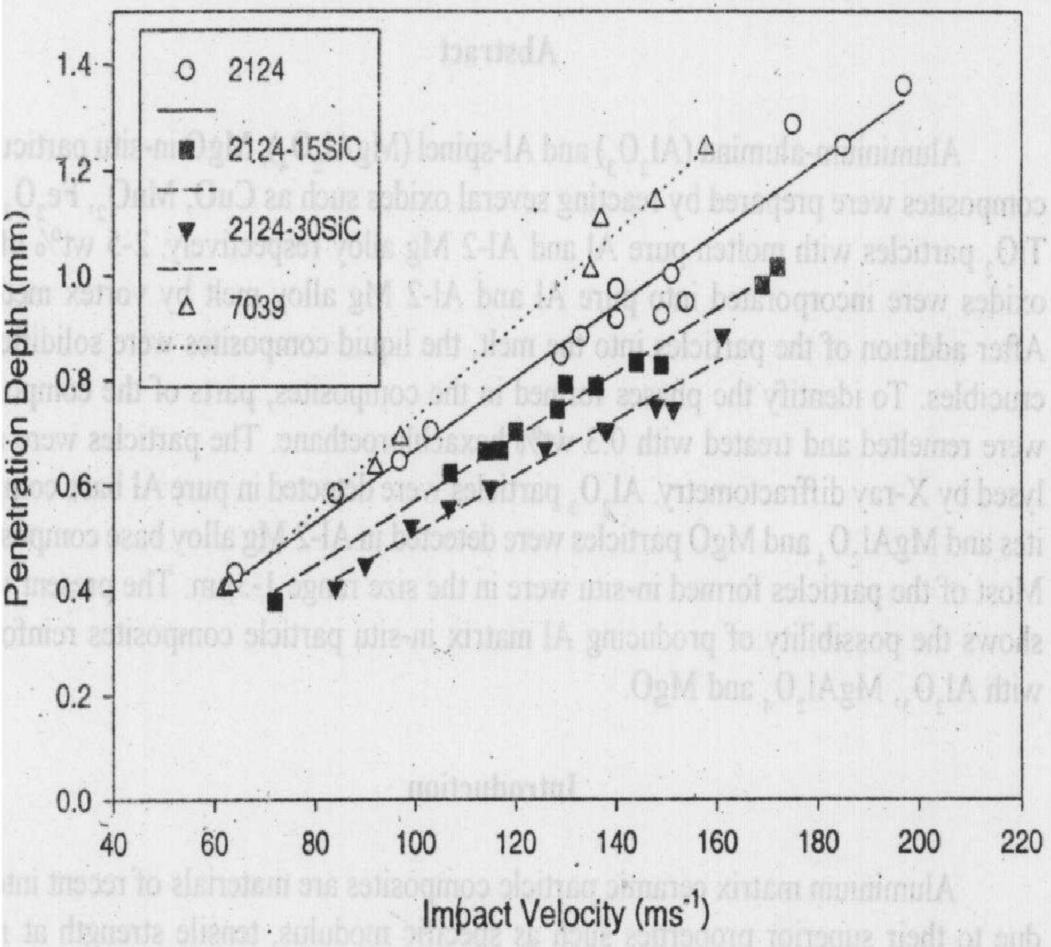

Fig. 7 - The penetration depth as a function of impact velocity in MMCs and unreinforced Al alloys