# Ballistic Impact Behaviour of SiC Fibre Reinforced Titanium MMCs

N.J.Bowman[1] and M.P.Thomas[2]

[1]*Imperial College of Science Technology & Medicine,*
*Exhibition Road, London, SW7 2AZ, UK*
[2] *Structural Materials Centre, Defence Evaluation & Research Agency (DERA),*
*Farnborough, Hampshire, GU14 OLX, UK*

**SUMMARY:** The room temperature ballistic impact behaviour of four unidirectionally fibre reinforced titanium MMCs has been studied together with corresponding monolithic Ti alloys. Monolithic Timetal 834 exhibits a lower ballistic limit, and more brittle failure modes, than monolithic Ti-6-4, perhaps due to a limited ductility resulting from silicide precipitates. The MMCs exhibit ballistic limits significantly lower than the monolithic alloys, as a result of preferential crack growth along fibre/matrix interfaces. This crack growth results in targets splitting longitudinally at and above the ballistic limit. Ti-6-4 / Sigma SM1140+ MMC exhibits the best ballistic limit due to crack meandering and bifurcation. The ballistic limit in the Sigma SM1240 fibre reinforced MMCs is reduced compared to Ti-6-4 / SM1140+ because of the deleterious effect of cracks at the SM1240 fibre/matrix interface which grow into the matrix. Timetal 834 / SM1140+ MMC has a poor ballistic limit due to a weak fibre/matrix bond and an embrittled matrix.

**Keywords:** Titanium, MMC, ballistic impact, SiC fibres

## INTRODUCTION

The principal requirement for the next generation of military gas-turbine engines is the achievement of a significant increase in thrust to weight ratio (from the current 10:1 to around 15:1). Two methods available to achieve this are to increase the turbine entry temperature to increase power output, or to reduce the overall engine weight. Both these developments require the use of “step-change” engineering materials. One such material, SiC fibre reinforced Titanium Metal Matrix Composite (Ti MMC), offers improved specific strength, stiffness and high temperature performance over currently used monolithic titanium alloys.

One of the components which is generating much interest for the incorporation of Ti MMCs is the compressor blade. Aeronautical gas-turbines are a safety critical environment and damage to compressor components from impact events, such as bird strike and blade-offs, can have potentially disastrous effects. For this reason, it is imperative that the impact resistance and damage tolerance of Ti MMCs are fully characterised before blade components can be designed with confidence. The Defence Evaluation and Research Agency (DERA) is performing a programme to study impact tolerance of aero-engine materials. Within this programme, low speed impact testing (impact speed ~3.5 m/s) of Ti MMCs has already been

carried out using Charpy testing procedures [1]. The current paper extends this work by looking at high speed impact behaviour.

## MATERIALS AND PROCEDURE

The MMCs consist of Ti-6-4 (Ti-6Al-4V) or Timetal 834 (Ti-5.8Al-4.0Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si-0.06C) reinforced with either DERA Sigma SM1140+ (carbon coated) SiC fibre or DERA Sigma SM1240 (C/$TiB_x$ coated) SiC fibre. Panels were produced by the fibre-foil route and had nominal fibre volume fractions of 0.33. Fibre reinforcement was unidirectional. The MMC microstructures have been investigated in detail elsewhere [2]. Rectangular targets, of dimensions 50mm x 50mm were machined from panels using a diamond wafering blade (target thickness was approximately 1.3mm). A few targets of monolithic Ti-6-4 and Timetal 834 were also tested to act as a comparison. These were machined from plates made from alloy foils processed under the same parameters as the MMCs. Thus, they had identical microstructure to the matrices in the MMCs. Dimensions were identical to those of the MMC targets.

Ballistic impact testing was carried out using the DERA low speed gas gun facility. This facility allows projectiles to be fired at speeds of between 5m/s and 300m/s, and thus simulates the impact from ingested runway debris and birdstrike [3]. The projectiles were 9.5mm diameter steel ball bearings, with a nominal weight of 3.5g. The ballistic limit has been quantified for each material, and damage development has been examined by impacting specimens at energies below the ballistic limit. Damaged and failed targets have been examined in a JEOL JSM 840a Scanning Electron Microscope (SEM) with attached wavelength dispersive X-ray spectrometer (WDX). Sections of targets were also mounted, polished and examined optically.

## RESULTS AND DISCUSSION

### Monolithic Ti alloys

The results of the ballistic tests on monolithic Ti-6-4 are shown in Fig. 1. The ballistic limit was approximately 127 m/s impact velocity (28.3 J impact energy), as shown in Table 1.

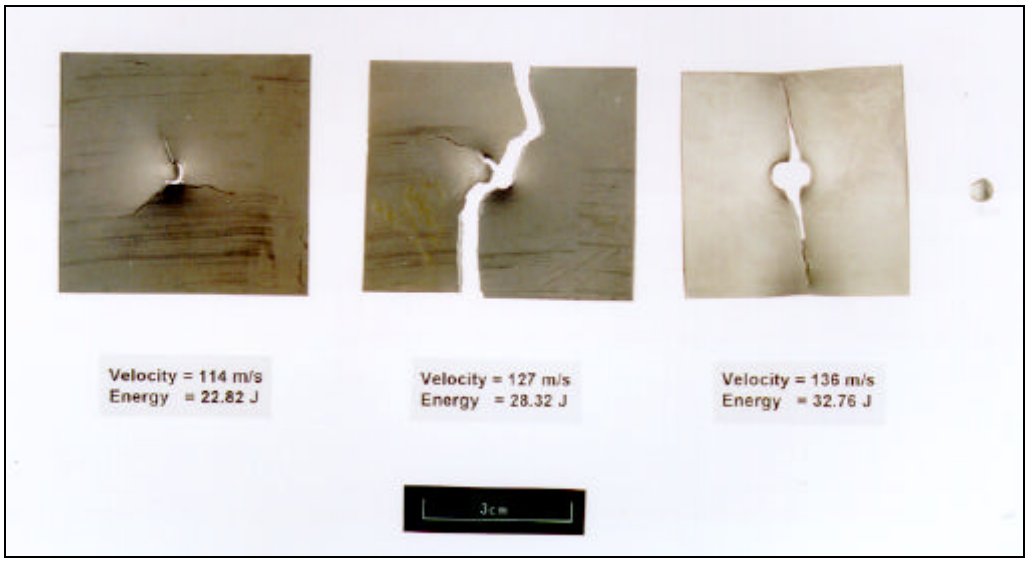



Fig. 1: Impact behaviour of monolithic Ti-6-4 targets

Failure was by gross cracking. This is in contrast to previous work on Ti-6-4 in which penetration of thicker targets occurs by plug formation [4,5]. The plug forms after intense localisation of plastic deformation, forming adiabatic shear bands [4-7]. Whilst adiabatic shearing still occurs in the current targets, as indicated by the shear voids on fracture surfaces (Fig. 2), this causes cracking of the targets rather than plug formation, most probably due to the use of thinner targets [8]. At impact velocities significantly above the ballistic limit, the failure mode of the monolithic Ti-6-4 begins to revert to plug formation, with less catastrophic cracking (Fig. 1).

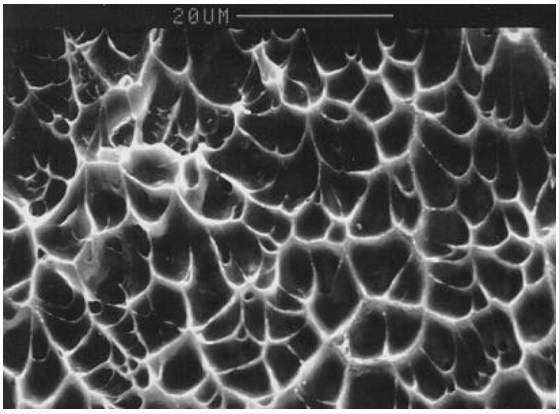



Fig. 2: Dimpling on the fracture surface of monolithic Ti-6-4 at the ballistic limit

The failure behaviour of monolithic Timetal 834 is shown in Fig. 3. The ballistic limit is lower than in Ti-6-4. Although no more targets were available to test at lower impact velocities, it is apparent that the ballistic limit of Timetal 834 is equal to, or lower than, 111 m/s impact velocity (21.6 J impact energy). Target cracking appeared to be more prevalent in Timetal 834 than in Ti-6-4. Testing at velocities higher than the ballistic limit resulted in Timetal 834 targets shattering into small pieces (Fig. 3), rather than reverting to plug formation as occurred in the Ti-6-4.


Fig. 3: Impact behaviour of monolithic Timetal 834 targets

Fracture surfaces of Timetal 834 have a different appearance to those of Ti-6-4 (Fig. 4). The fracture surface did not appear to have been formed in shear, ductile dimples were much smaller than in Ti-6-4, and areas of cleavage failure were present. Reduced ductility and brittle failure modes have previously been observed in this foil-bonded, monolithic Timetal 834 alloy during Charpy impact tests [1] and tensile tests [9]. The failure behaviour of the Timetal 834 may be linked to the presence of silicide particles in its microstructure [2]. Such particles are thought to reduce the ductility of Ti alloys [10].

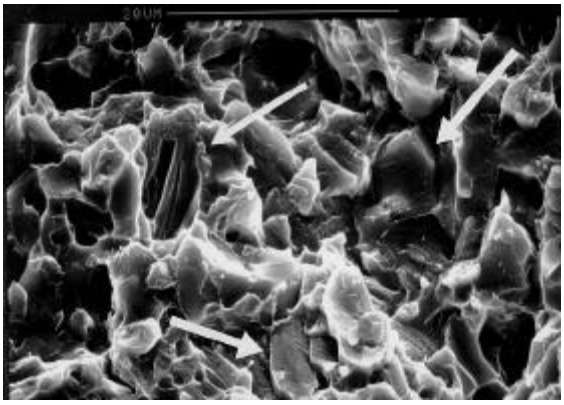


Fig. 4: Fracture surface of monolithic Timetal 834 at the ballistic limit, illustrating areas of cleavage failure (arrowed)

**Titanium MMCs**

Although all the MMCs failed in a similar manner to each other, the damage development and failure mechanism was different to that in monolithic Ti alloys. The ball bearing causes a small area of intense deformation of both matrix and fibres through the thickness of the target, immediately below the impact point. This is observed after the test as a concave, "dished" region (Fig. 5). Fibre cracking is only observed in this dished region. Matrix cracks initiate in this dished region on the rear face and grow towards the front face, meandering to pass preferentially through the weak fibre/matrix interfaces (Fig. 6). These cracks are a result of the large anisotropy in stiffness in these unidirectionally reinforced MMCs. Previous work has shown the Young's modulus along the fibre axis to be in the region of 200MPa [11], whilst the Young's modulus perpendicular to the fibre axis is only around 130MPa [12]. This anisotropy means that, when impacted, the targets will flex much more in the transverse direction than in the longitudinal direction. This results in high tensile stress being generated at, and near, the rear face of targets [3], which causes the initiation of the cracks.

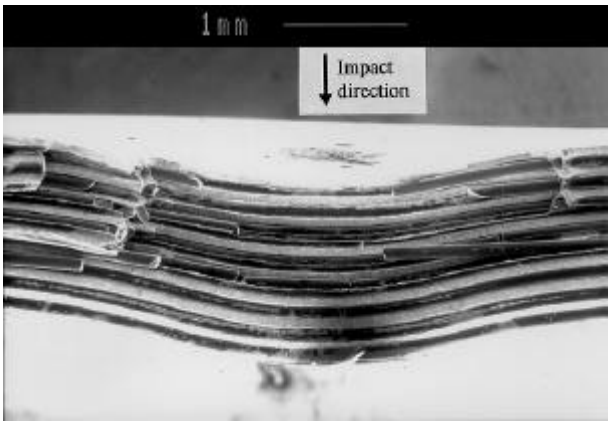



Fig. 5: Dished region (in profile) in Ti-6-4 /SM1240 (all MMCs similar).

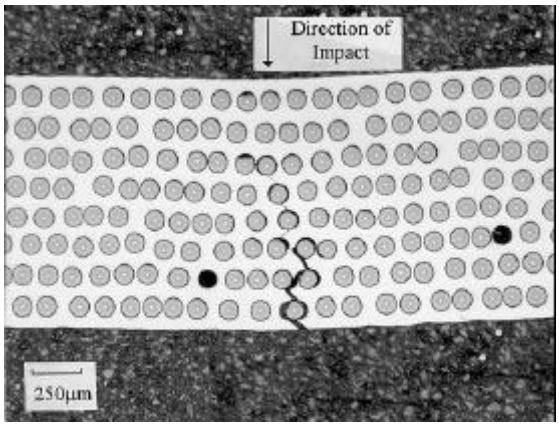



Fig. 6: Crack growing from rear face of Ti-6-4 / SM1140+ (all MMCs similar)

Once the front face has been reached, these cracks then grow longitudinally along the fibre/matrix interfaces, without further fibre damage. At higher impact velocities, complete splitting of the target occurs when the failed interfaces are connected by crack propogation through the matrix. Fig. 7 shows the example of the Ti-6-4/SM1140+ MMC. Delamination between plies is not observed, because of the unidirectional nature of the reinforcement [3].

Table 1: Impact results for monolithic Ti alloys and Ti MMCs at room temperature

| Material | Ballistic Limit Impact Velocity (m/s) | Ballistic Limit Impact Energy (J) | Damage |
|---|---|---|---|
| Ti-6-4 | 127.1 | 28.3 | Meandering cracks |
| Timetal 834 | ≤ 111.3 | ≤ 21.6 | Meandering cracks |
| Ti-6-4 / SM1140+ | 44.28 | 3.46 | Cleaved in two |
| Ti-6-4 / SM1240 | 41.17 | 2.98 | Cleaved in two |
| Timetal 834 / SM1140+ | 26.79 | 1.27 | Cleaved in two |
| Timetal 834 / SM1240 | 38.21 | 2.68 | Cleaved in two |

The MMCs' ballistic limit energies are an order of magnitude lower than for the monolithic alloys (Table 1). This fact, together with the longitudinal splitting failure mode and minimal fibre fracture, shows that the anisotropy of Young's modulus, and weak fibre/matrix interfaces, are having a deleterious effect on the ballistic impact resistance of these MMCs.

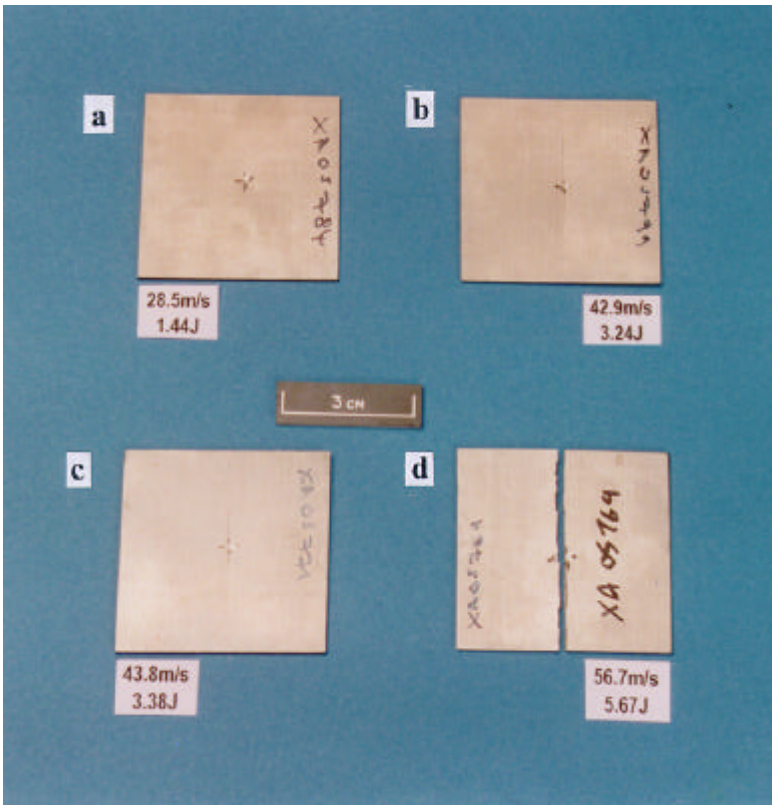
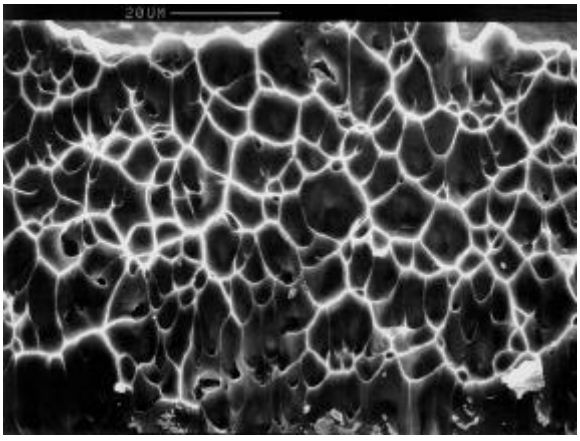


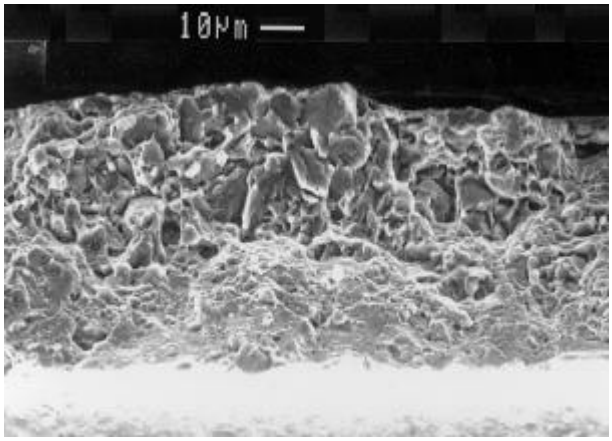

Fig. 7: Impact behaviour of Ti-6-4/SM1140+ (other MMCs similar)

Although the overall failure mechanism is the same for the four MMCs, their ballistic limits differ (Table 1). Ti-6-4/SM1140+ exhibits the highest ballistic limit. In this MMC, the crack

growing from the rear, tension, face frequently bifurcates (Fig. 6). This absorbs greater energy than in the case of a specimen with a single crack path. Timetal 834/SM1140+ exhibits the poorest ballistic limit. This MMC undergoes minimal crack bifurcation during growth from the rear face to the front face. It has also previously been noted that this MMC appears to contain a weaker fibre/matrix interface than the other three MMCs [12,13]. Thus, interfacial failure during longitudinal crack growth is likely to require less energy than that in the Ti-6-4/SM1140+ MMC.



a. MMCs other than Timetal 834/SM1140+




b. Timetal 834/SM1140+

Fig. 8: Matrix failure in the MMCs at the ballistic limit

Additionally, the matrix in Timetal 834/SM1140+ MMC may contain a high carbon concentration, caused by carbon diffusion from the fibre coating when the MMC is consolidated at the high temperatures necessary for the Timetal 834 matrix. This carbon contamination appears to increase matrix embrittlement over that in the monolithic Timetal 834 [11-13]. Whilst the matrix of the other three MMCs failed by ductile void growth and coalescence (Fig.8a), large areas of the matrix in the Timetal 834/SM1140+ MMC had a flat, faceted appearance indicative of cleavage cracking (Figure 8b), as was the case during Charpy impact testing [1].

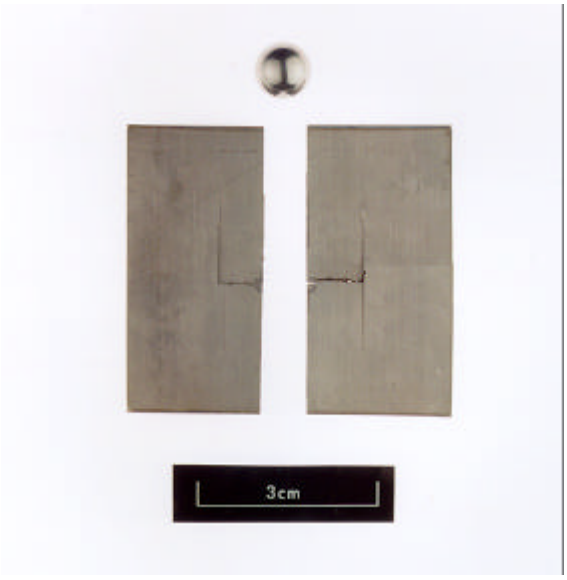



Fig.9: Secondary cracking in Timetal 834/ SM1140+ after high velocity impact

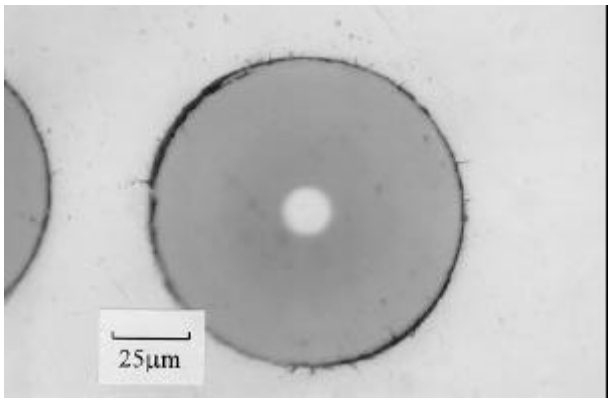
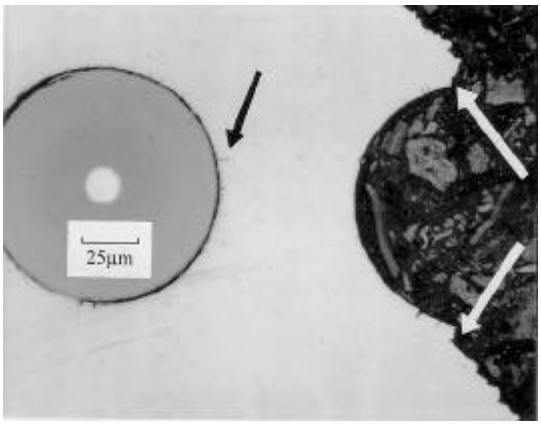


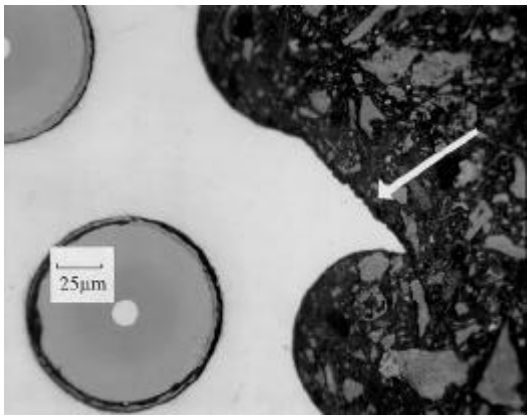

Fig.10: Interfacial cracks in SM1240 fibre reinforced MMCs, under the point of impact

Embrittlement of the matrix was further illustrated by impacting targets at a high impact velocity of 56.4 m/s (5.6 J impact energy). Whilst a Ti-6-4/SM1140+ target impacted at this speed simply cleaved in two, the Timetal 834/SM1140+ target exhibited matrix cracks perpendicular to the fibre axis, and additional longitudinal interfacial cracks (Fig.9). This combination of a brittle matrix and apparent weakness of the fibre/matrix interface could account for the poor ballistic resistance of the Timetal 834/SM1140+ MMC.

The ballistic limits of the two MMCs reinforced with SM1240 fibre are similar. These two MMCs are inferior to the Ti-6-4/SM1140+ MMC because of the behaviour of the fibre/matrix interface. In Ti-6-4/SM1140+ MMC, cracks are occasionally seen in the fibre carbon coating in the dished region, but they are deflected along the carbon/TiC interface and do not grow into the matrix. By contrast, in the two MMCs reinforced with SM1240 fibres, more interfacial cracking is observed, and in these MMCs the cracks grow into the matrix (Fig.10 and black arrow in Fig.11a). Matrix failure appears to initiate at these cracks as indicated by a small step on fracture surfaces near to prior fibre/matrix interfaces (white arrows in Fig.11a). The Ti-6-4/SM1140+ MMC does not show such steps (white arrow in Fig.11b).




a. Timetal 834/SM1240
(Ti-6-4/SM1240 similar)




b. Ti-6-4/SM1140+

Fig.11: Matrix failure in the MMCs at the ballistic limit

The poorer ballistic impact resistance of the Timetal 834 matrix, compared to the Ti-6-4 matrix, as measured on monolithic targets, is the cause of the Timetal 834/SM1240 MMC having marginally inferior impact resistance compared to Ti-6-4/SM1240 MMC. The fact that the difference in ballistic limit of these two MMCs is relatively small indicates that the fibre/matrix interface has the dominant effect on ballistic resistance, rather than the matrix alloy.

## CONCLUSIONS

1. Monolithic Timetal 834 has an inferior ballistic limit, and is more prone to cracking, than monolithic Ti-6-4. This may be due to the presence of silicide particles in the Timetal 834 reducing the ductility.
2. The ballistic impact resistance of unidirectionally reinforced Ti MMCs is significantly inferior to that of monolithic Ti alloys.
3. Failure of MMC targets at the ballistic limit is caused by catastrophic longitudinal splitting at the fibre/matrix interface.

4. Timetal 834/SM1140+ has a poor ballistic limit due to a weak fibre/matrix interface and embrittled matrix.
5. Cracks formed in the fibre/matrix interfacial region of SM1240 fibre reinforced MMCs grow into the matrix, having a deleterious effect on the ballistic limit.
6. Ti-6-4/SM1140+ exhibits a superior ballistic limit compared to the other MMCs due to crack meandering and bifurcation, and the lack of deleterious interfacial cracking.

## ACKNOWLEDGEMENTS

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