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## Review

## Titanium metal matrix composites: An overview

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## ABSTRACT

Titanium matrix composites (TMCs) offer high specific strength and stiffness compared with steel and nickel-base materials. High-temperature TMCs can offer up to 50% weight reduction relative to monolithic superalloys while maintaining equivalent strength and stiffness in jet engine propulsion systems. Regardless of the reinforcements are continuous fibres or discontinuous particulates, the unique properties of TMCs have thrust them to the forefront of extensive research and development programmes around the world. Even though TMCs are one of the most studied and sought-after material systems, useful information about their properties, fabrication methods and design is scattered in the literature. This review covers important research work that has led to the advances in TMCs material systems. It also provides comprehensive details about common reinforcements, manufacturing processes, and reviews static and dynamic properties of some common TMCs. The review also presents common industrial applications of TMCs and highlights the promising outlook of TMCs.

## 1. Background

Titanium and its alloys are fast becoming a part of significant research interest for wide range of applications such as automotive and aerospace industries. These materials are light weight and generally have attractive properties such as high specific strength, excellent chemical resistance and excellent biocompatibility. The combination of such properties makes them an ideal candidate for structural, chemical, petrochemical, marine and biomedical applications [1,2]. However, Young's modulus, wear resistance and heat resistance of titanium materials are inferior to those of steel and Ni-based alloys [3,4]. Titanium metal matrix composites (TMCs) provide an alternative to overcome these shortcomings.

TMCs have been under significant development and evaluation in the past 30 years for use in aircraft engines and airframe applications [5,6]. The high specific modulus of TMCs is the main catalyst behind its usage for airframes applications, while the benefit of high specific strength has been the impetus for their adoption in engines industry. For example, TMCs based on titanium aluminides that have a temperature capability approaching 760 °C offer a potential 50% weight savings compared to nickel based superalloys for high temperature compressor applications [7,8].

The introduction of TMCs into high performance applications has however not been straightforward due to the complexities of fabrication

and high material and implementation costs. Nonetheless, consistent efforts in the earlier days of TMCs research were made, particularly by National Aeronautics and Space Administration (NASA), to increase its usage for industrial applications. The formation of Titanium Matrix Composite Turbine Engine Composite Consortium (TMCTECC) programme was one of such examples, where six US companies joined forces for development and implementation of TMCs into large gas turbine engines [7,9]. The current advancement and success stories of TMCs are only made possible due to those earlier efforts.

This paper provides a timely review of previous and current work and developments in TMCs and provides an overview of recent activities in this ever-evolving area covering reinforcements, processing, properties, and potential applications.

## 2. Common reinforcements

The common TMCs can be categorized into two groups depending on the form of reinforcements [10,11]:

- Continuously reinforced TMCs
- Discontinuously reinforced TMCs

Fig. 1 presents a schematic illustration of different categories of TMCs based on the type of reinforcement used while Tables 1 and 2

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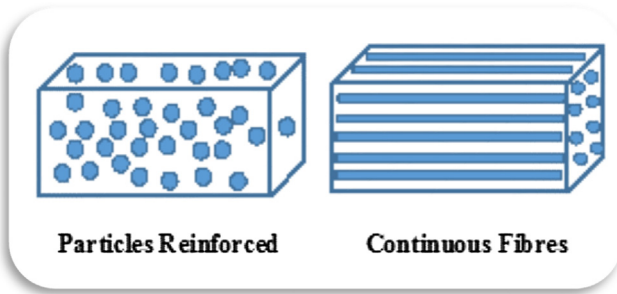


Fig. 1. Different types of reinforcements (Schematic). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1  
Different reinforcements for DRTCs.

Reinforcements	Melting point (°C)	Density (g·cm <sup>-3</sup> )	Elastic modulus (GPa)	The coefficient of thermal expansion (× 10 <sup>-6</sup> K <sup>-1</sup> )
TiB	2200	4.50	425–480	8.60
TiC	3160	4.99	440	6.52–7.15 (25–500 °C)
TiN	3290	3.97	420	8.30
SiC	2697	3.19	430	4.63 (25–500 °C)
TiB <sub>2</sub>	2980	4.52	500	4.60–8.10
Graphene	~ 3852	2.00	~ 1000	–
CNTs	~ 3379	1.70–2.00	~ 1000	–
B <sub>4</sub> C	2447	2.51	445	4.78 (25–500 °C)
La <sub>2</sub> O <sub>3</sub>	2217	6.51	–	5.8–12.1(100–1000 °C)

Table 2  
Different reinforcements for fibre reinforced TMCs.

Type	Name	Producer	Diameter (µm)	UTS (GPa)	Modulus (GPa)
SiC	SM 1140+	DERA-Sigma	106	3.4	400
SiC	SCS-6	Textron	140	4	400
SiC	SCS-Ultra	Textron	140	6.2	420
SiC	Trimarc	ARC	125	3.5	410
Al <sub>2</sub> O <sub>3</sub>	Sapphire	Saphikon Inc.	120	3.4	410

compare physical and mechanical properties of common reinforcements.

Early attempts to produce TMCs used boron reinforcing fibres coated with silicon carbide (SiC), commonly called Borosic fibre [5,12,13]. However, these fibres were extremely expensive, which ultimately led to discontinuation of the use of these fibres. In TMCs, the most common and widely used fibre is SiC fibre with a diameter between 100 and 142 µm – the optimal range resulting in superior dynamic properties [14]. The earliest fibre, SCS-6, was produced on a carbon core by Textron in the US. A second fibre, Sigma, was developed by British Petroleum and was produced in the UK by Defence Evaluation and Research Agency (DERA) and in the US by ARC (Trimarc) [15,16]. SiC fibre reinforced titanium composites saw a significant boom in the 80's and early 90's when NASA and GE aerospace sponsored and carried out compelling research to use such composites in aerospace applications [17–21]. Since then, the reports on fibre reinforced titanium composites have gradually decreased in number. Recently, BJS Ceramics GmbH has partnered with Fraunhofer Center to produce SiC fibres [22]. The ceramic fibre plant is expected to start up in January 2019. Apart from SiC fibres, carbon fibres have also been applied and studied for titanium composites. However, the use of such composites for high performance applications has not been well defined in the literature [23,24].

Discontinuously reinforced titanium composites (DRTCs) have

undergone fast development in recent years. In general, a DRTC is expected to exhibit higher specific strength, specific stiffness, wear resistance, thermal stability and high-temperature durability than its corresponding titanium alloy counterpart. These superiorities make them potential candidates for critical applications in the aerospace and automotive industries. Particle clustering in an isolated pattern, which significantly affects the mechanical properties of DRTCs, is one of the major challenges associated with DRTCs. Therefore, the majority of activities have been focused on the production of a homogeneous discrete distribution of the reinforcements, in the form of particles, whiskers or short fibres [25]. A number of different particulates have been selected as reinforcements for TMCs such as TiB<sub>2</sub>, TiN, B<sub>4</sub>C, ZrC, SiC, TiB, TiC, and Al<sub>2</sub>O<sub>3</sub>. Among these TiB and TiC are most widely used [26,27]. Apart from TiB and TiC, other reinforcements such as Si<sub>3</sub>N<sub>4</sub> [28], nano SiC [29], nano Al<sub>2</sub>O<sub>3</sub> [30] and carbon nanotubes [31] have also been reported in the literature. However, the practical importance of these reinforcements remains limited. For instance, Si<sub>3</sub>N<sub>4</sub> is considered unstable and many available reports suggest that it decomposes at high temperatures forming titanium silicides [32]. The main advantage of DRTCs over continuous-fibre composites is the low cost of production. New manufacturing technologies can now produce uniformly distributed particle reinforced composites at a lower cost than many types of continuous-fibre composites. Despite the ease of manufacturing, the applications for DRTCs have not yet emerged at the rate needed to meet the high expectations.

### 3. Common fabrication methods

#### 3.1. Continuous (long) fibre reinforced TMCs

##### A. Lay-up techniques

Processing of fibre reinforced TMCs using foil and fabric lay-up technique is probably the oldest. This process starts with alternating layers of woven fibre mats and 0.1–0.15 mm thick titanium alloy foils. The alternated fibre mats and titanium foils are stacked up and vacuum hot pressed (VHP) or hot isotactic pressed (HIP) to consolidate into a multilayer composite. However, high foil cost combined with high fibre cost, fibre distribution and the difficulty of fabricating useful component shapes are the main reasons behind limited applications of this method [33].

##### B. Induction plasma deposition

Induction plasma deposition (IPD) [34] is another method to produce TMCs and was first employed by GE Aircraft Engines [35]. It uses an inductively coupled radio frequency plasma generator to melt and spray deposit a fine-grained uniform microstructure of titanium matrix onto a fibre-wound drum [35]. During the IPD processing, fibre spacing is firmly maintained making it an excellent candidate for manufacturing TMCs monotapes (a single TMC ply). Furthermore, virtually any matrix metal or alloy that can be produced as powder can be deposited to produce MMC monotapes. However, there is a stringent composition requirement that the starting powder has to meet before it can be used in IPD process, particularly for titanium and its alloys [35].

##### C. Physical vapour deposition

Similar to IPD, physical vapour deposition (PVD) involves deposition of matrix material onto single fibre layer by the evaporation of metal matrices via electron beam or by magnetron sputtering. In either case, the resulting monotapes have excellent fibre distribution, with the thickness of the matrix coating determining the final volume fraction of the composite. This method can produce complex shape composites components with very high fibre volume fractions of up to 80% [36].

##### D. Tape casting

Tape casting of ceramic materials is well established and used to manufacture ceramic components in electronics. Tape casting of fibre reinforced TMCs was first demonstrated in the early 1990s [36]. The process starts with the formation of slurry, consisting of metallic powders (composite matrix) and polymeric additives in an organic solvent.

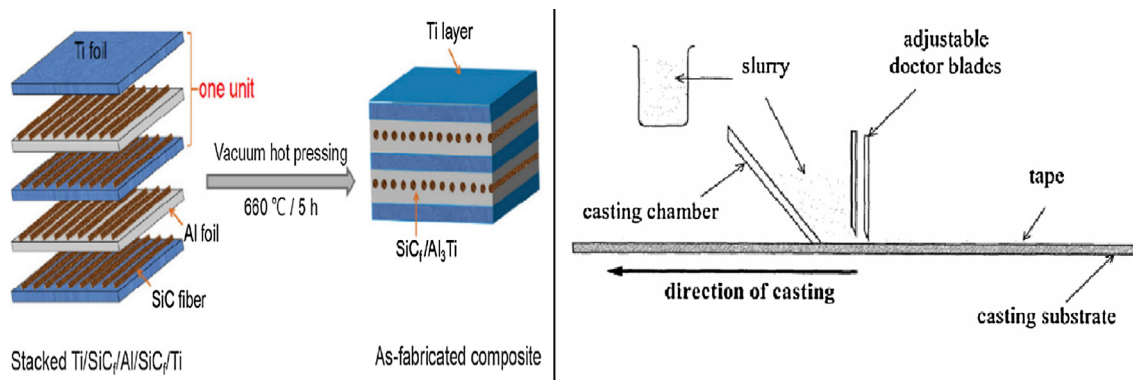


Fig. 2. Schematics of fibre reinforced TMCs fabrication methods, left: metal foil metallurgical technique for laminated composite production [40]; right: Tape casting [37]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The polymeric additives can be polycarbonate, polystyrene, acrylic, polyisobutylene or a copolymer or a mixture of such polymers, while the organic solvent may be an aliphatic or aromatic hydrocarbon. The additives in the tape hold the powder particles together and provide sufficient strength and flexibility to the tape [37]. The reinforcement is then coated with this slurry to form unconsolidated tapes. A doctor blade controls coating thickness. The unconsolidated tapes are then cut to preferred sizes, stacked, degassed and consolidated. The consolidation step involves a pre-burnout step to remove the additives from tapes followed by high pressure and temperature to create a homogeneous material. However, considering the reactive nature of titanium and the presence of polymeric additives, the contamination control is challenging [36,37].

Apart from the above-mentioned common techniques, hot pressing has also been tested to manufacture fibre reinforced TMCs [38]. Recently, Guo et al. [39] prepared hybrid ceramic composites comprising SiC (SCS-6)/Ti composite and  $ZrB_2$ -ZrC ceramic by sandwiching Ti/SiC (SCS-6)/Ti sheets and Zr +  $B_4C$  powder layers, followed by reactive hot pressing at 1300 °C. The subsequent testing showed that highly dense matrix can be achieved using this technique. Fig. 2 presents a schematic overview of two manufacturing processes used for fibre reinforced TMCs production while Fig. 3 presents cross-sectional SEM micrographs of the samples manufactured by these two processes.

### 3.2. Discontinuously reinforced titanium composites (DRTCs)

#### A. Powder metallurgy

The conventional ingot metallurgy processes are not suitable for the fabrication of TMCs reinforced with *ex situ* additive particles because of

the high chemical reactivity of titanium. Therefore, powder metallurgy (PM) processes are commonly employed to fabricate TMC components, Fig. 4. In fact, PM processing route is considered one of the most suitable fabrication methods for the production of DRTCs [25]. In PM processing of DRTCs, homogeneous powder mixing and dispersion are the two most important parameters in ensuring good performance of composites. In some cases, surface coating is applied to enhance or ensure homogeneous dispersion [25]. The selection of dispersed reinforcements, their size, morphology, content and the interfacial bonding between reinforcements and the matrix determine the final properties of the composites [25].

The reinforcements can be incorporated into the matrix by two types of method: *ex situ* and *in situ* processing [42], depending on whether or not the additives react with the matrix.

#### 3.2.1. Ex situ processing technique

In titanium, thermodynamically stable ceramics such as SiC, TiC, TiB, and ZrC are added using *ex situ* processing routes. Since no new compounds are formed during sintering and consolidation, there is essentially no change in both the particle size and morphology of the added particles before and after sintering unless external impacts are purposely applied such as in mechanical milling [42]. *Ex situ* fabrication of DRTCs not only results in superior mechanical properties but also improves the wear resistance and stabilizes the friction coefficient under dry sliding conditions [42]. Due to its own shortcomings such as the poor bonding between the matrix and the reinforcement, the *ex situ* methods for producing DRTC have not garnered significant attention. On the other hand, DRTCs fabricated by *in situ* synthesis methods are sought after due to their excellent properties, isotropic properties and

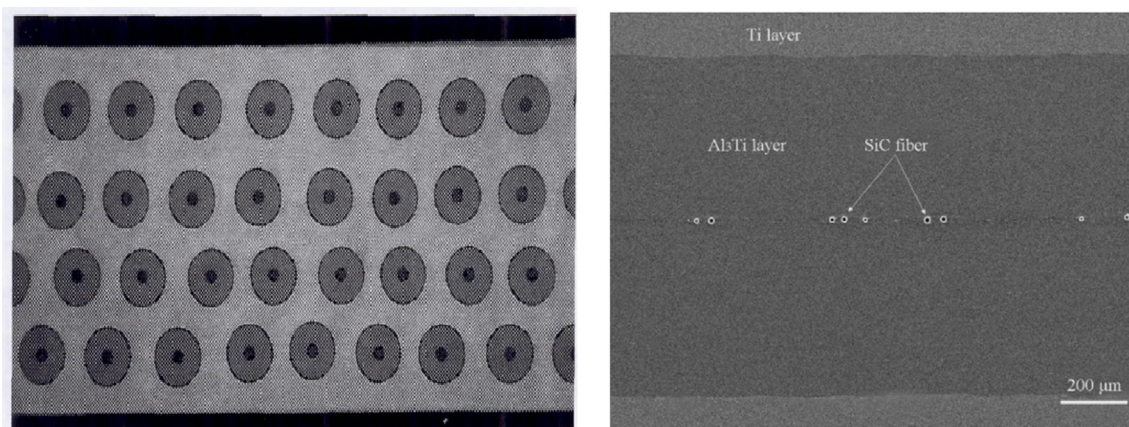


Fig. 3. (left) Cross-section of 0.036 in. thick 35 vol% fibre tape cast composite, Ti-21Al-23Nb - 140 + 325 powder, and SCS-6 fibres [41]; (Right) SEM micrograph of laminated structure of Ti-(SiC<sub>7</sub>/Al<sub>3</sub>Ti) composite [40].



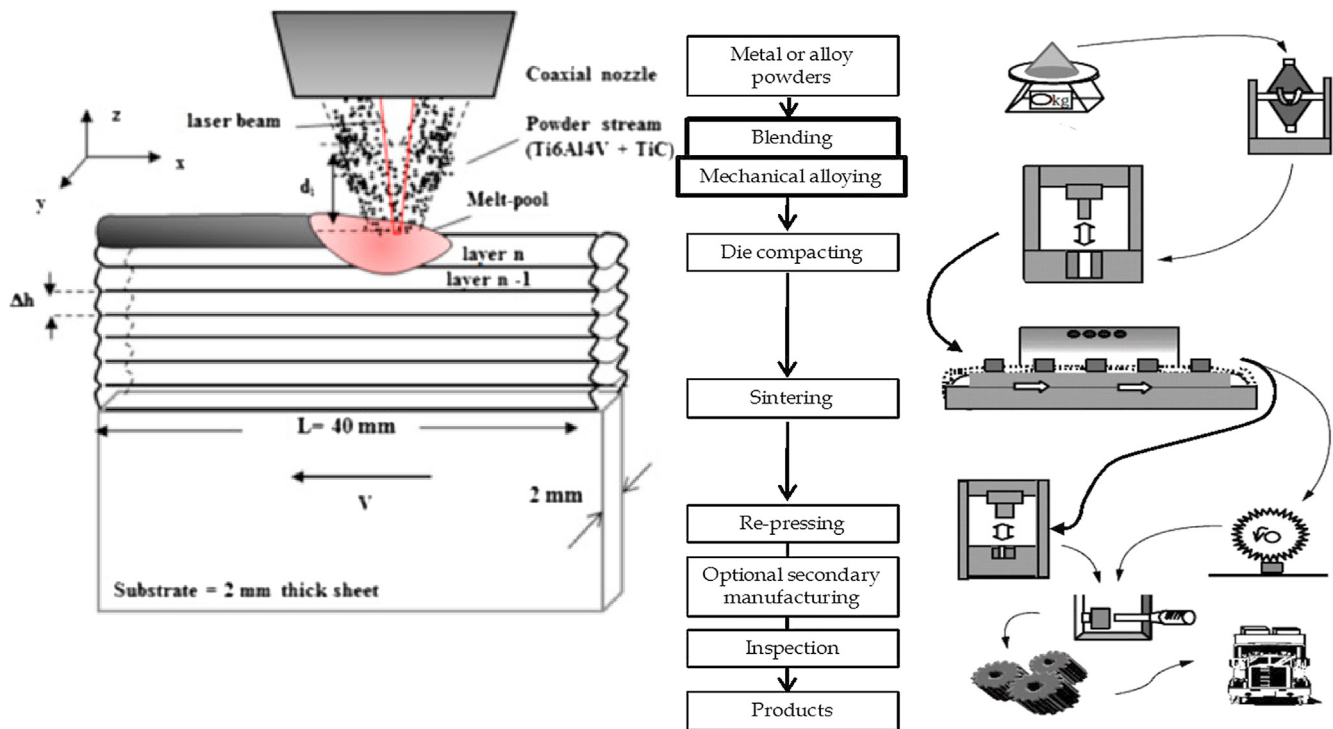


Fig. 4. Schematics of different DRTCs fabrication processes, left: Direct metal deposition laser process [55]; right: Powder metallurgy process [56]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

low cost.

### 3.2.2. In situ processing technique

During *in situ* processing, high reactivity of titanium matrix with the additive elements such as boron, carbon, nitrogen is used to form *in situ* stable particulates or needle-like reinforcements, which are dispersed through solid-state reaction. Some common starting additives for *in situ* processing are  $TiB_2$ ,  $B_4C$ ,  $Cr_3C_2$ , and  $Si_3N_4$ . For example, when  $TiB_2$  particles are used as additive, titanium powder can react with  $TiB_2$  particles during sintering, resulting in the formation of  $TiB$  whiskers and dispersed as the reinforcement in the matrix. The better interfacial bonding between matrix and the reinforcement in the case of *in situ* processing leads to enhanced tribological performance. Moreover, composites produced via *in situ* techniques exhibit high specific strength and modulus, as well as excellent oxidation and creep resistance [42]. However, the *in situ* reactions must be carefully controlled to avoid otherwise the formation of interfacial defects.

Apart from conventional powder metallurgy, self-propagation high-temperature synthesis (SHS) [43], additive manufacturing [44] (Fig. 4), and ingot metallurgy techniques [45] have also been used to produce *in situ* DRTCs.

Fig. 5 presents microstructures micrographs resulting from the two processes.

#### B. Rapid solidification process

In the past two decades, rapid solidification technologies have advanced significantly to become a potential fabrication technique for processing DRTCs [46–48]. Atomization is a common technique for mass production of metallic powders. If the reinforcements are added to the melt, composite powder containing the reinforcements can be produced by atomization. In one such example, a Ti-6Al-4V (Ti64, in short form) + 20 vol% TiC composite ingot was remelted using the induction heating process, and atomized by argon gas flow. The composite powder was then used to produce bulk composite material via hot isostatic pressing (HIP) at 900 and 950 °C, under 100 MPa for 4 h [49]. Martin Marietta Laboratories has developed a novel ingot metallurgy approach to produce both the titanium metal and titanium

intermetallic matrix composites [50]. The XD™ technology produces *in-situ* ceramic reinforcements during the casting process that are thermally stable, kinetically inert, and well dispersed within the melt during casting. Using this technology, Ingots of Ti-48Al-2V and Ti-45Al containing  $TiB_2$  reinforcement were produced. Powders of these composite materials were then produced using centrifugal atomization and a rotating consumable electrode. The ceramic particulates formed in the ingot were retained during the atomization process. The size and scale of the  $TiB_2$  particulate dispersion was found to be strongly dependent on the processing temperature [51]. Similarly, Fan et al. fabricated *in situ* TiB reinforced Ti64 composites by consolidation of rapidly solidified Ti64 alloy with different levels of boron addition. The rapid solidification process was carried out via Marko 5T melt-spinner [52]. However, this method is limited to the reinforcements that should have a density close to the matrix material. If the density of reinforcements is significantly different from that of matrix, the atomization process can lead to non-uniform distribution of reinforcements in the composite powder due to particles aggregation. The non-equilibrium associated with rapid solidification creates the potential for additional alloying strategies such as addition of rare-earth alloying elements in titanium [53].

Recently, researchers in Tekna group [54] have demonstrated that induction plasma technology can also be used to produce *in situ* titanium composites using plasma as a chemical reactor. They claimed that Ti64 reinforced with TiC or TiN particles can be obtained directly through the chemical reaction between the elements introduced into the plasma.

Table 3 presents advantages and disadvantages of different manufacturing techniques that are commonly use to fabricate TMCs.

## 4. Mechanical properties of common reinforcement TMCs

### 4.1. Static properties

In general, if the properties of the matrix and the fibres are known, strength and stiffness of composites in the longitudinal direction can be

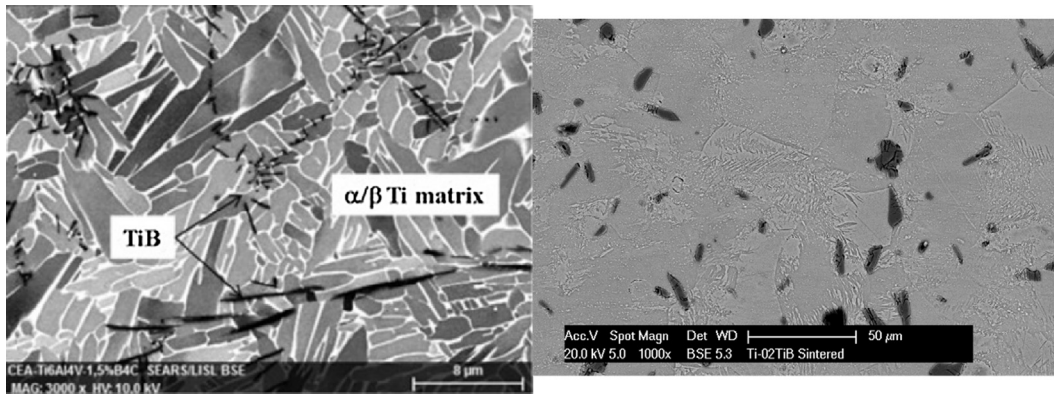


Fig. 5. (left) SEM micrograph of a Ti64 – 3% B<sub>4</sub>C TMC fabricated using direct metal deposition laser process [55]; (right) SEM micrograph of *in situ* PM TiB/Ti composite [57].

estimated by the rule of mixtures. The tensile properties of SiC reinforced TMCs have been measured by a number of investigators on composites with different volume fractions of SiC fibre fabricated by different methods [18,33,35,36,58–60]. Fig. 6 displays the ultimate tensile strength (UTS) of different composite systems over a temperature range of 25–800 °C, and compares it with the UTS of unreinforced alloys.

High strength in the longitudinal direction up to elevated service temperatures is perhaps the most outstanding property of unidirectional reinforced composites, Fig. 6. While the UTS of classical  $\alpha + \beta$  alloy, titanium aluminides and Ti-Al-Nb range from 400 MPa to 1200 MPa at room temperature and from 250 MPa to 500 MPa at 800 °C, the maximum strength of SiC reinforced TMCs is between 1500 MPa and 2300 MPa at room temperature and still as high as 1700 MPa at 800 °C. This improvement of strength falls sharply when the loading direction is not parallel to the fibre axis as explained in the literature [18]. The low off-axis strength is because of poor load transfer to the fibres due to the weak fibre/matrix interface. Interestingly, this weak interface is necessary to achieve crack deflection at fibre/matrix interfaces to obtain acceptable fracture toughness [18]. This strong fibre orientation effect creates the need for prudent design approaches to maximize the loads parallel to the fibre direction and to minimize it in other directions. In the absence of such design modifications, the high cost of fibre reinforced TMCs may overshadow the benefits realized from the use of composites.

Table 3

Generic overview of different manufacturing techniques for TMCs.

Techniques	Advantages	Disadvantages	Materials System Examples
Lay-up techniques	<ul style="list-style-type: none"> <li>Low-cost tooling, if room-temperature cure resins are used.</li> <li>Higher fibre contents, and longer fibres than with spray lay-up</li> </ul>	<ul style="list-style-type: none"> <li>Low resin content laminates cannot usually be achieved without the incorporation of excessive quantities of voids.</li> <li>Health and safety considerations of resin</li> </ul>	Fibre-reinforced TMCs
Physical vapour deposition	<ul style="list-style-type: none"> <li>The ability to deposit a variety of materials on the substrate or work-piece to confer specific properties</li> <li>Good adhesion of the film to the substrate.</li> <li>Operation at low temperatures, which is suitable for heat-sensitive substrates;</li> </ul>	<ul style="list-style-type: none"> <li>Higher costs</li> <li>The process requires complex machines that need skilled operators.</li> <li>The rate at which coating PVD operates is relatively slow</li> </ul>	Fibre-reinforced TMCs
Tape casting	<ul style="list-style-type: none"> <li>Water-based tape casting with inexpensive, non-toxic, non-flammable</li> </ul>	<ul style="list-style-type: none"> <li>Evaporation rate is low.</li> <li>High concentration of binder required.</li> </ul>	Fibre-reinforced TMCs
Powder metallurgy	<ul style="list-style-type: none"> <li>Near net shape</li> <li>Low cost and difficulties</li> <li>High production rates</li> <li>Uniform microstructure</li> </ul>	<ul style="list-style-type: none"> <li>Limited shapes and features.</li> <li>Difficult to produce large and complex shaped parts</li> </ul>	DRTCs
Rapid solidification process	<ul style="list-style-type: none"> <li>Direct and simple process.</li> <li>Noenvironment pollution.</li> <li>Low investment cost.</li> </ul>	<ul style="list-style-type: none"> <li>Required more proper maintained of machine</li> <li>Heat of input is high.</li> </ul>	DRTCs

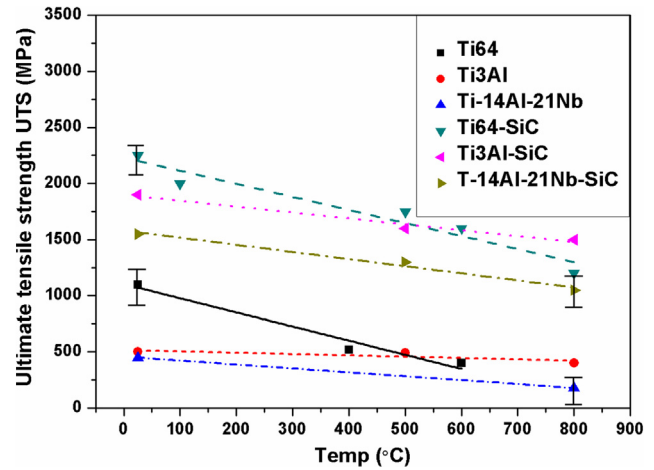


Fig. 6. General overview of the UTS over a temperature range for different SiC fibre reinforced composites [18,56,61]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Recently, Cui et al. [62] has shown that carbon fibres coated with graphene reinforced TiAl alloy composite can be fabricated by powder metallurgy, melt spun and vacuum melting. They claimed that the

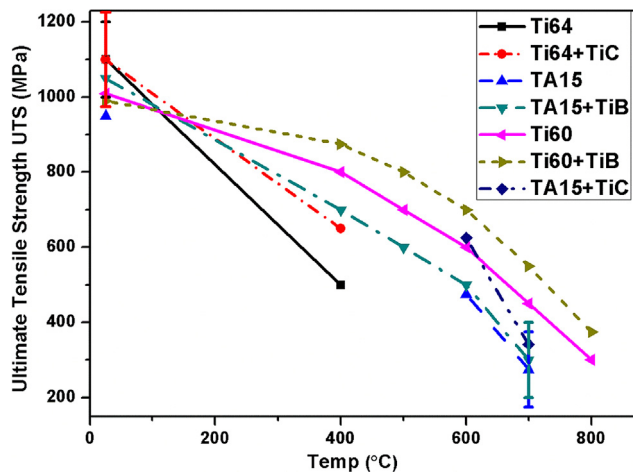


Fig. 7. UTS of different reinforcements DRTCs over a temperature range [59–66]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

designed composites showed excellent mechanical properties with microhardness of 426 HV<sub>0.1</sub>, average fracture strain of 26.27% and average strength of 2312 MPa. It can be envisaged that this approach opens up new opportunities to fabricate fibre reinforced TMCs in a simple manner.

According to the literature [26,27], *in situ* synthesized TiB whiskers (TiB<sub>w</sub>) and TiC particulates (TiC<sub>p</sub>) are considered the most effective reinforcements for DRTCs due to not only their good chemical compatibility with titanium, high modulus and hardness, but also similar density and thermal expansion coefficient with that of titanium. Fig. 7 compares the UTS of different reinforcements DRTCs made by different *in situ* synthesis processes with monolithic alloys [63–70].

It can be seen from Fig. 7, DRTCs show better tensile strength than monolithic alloys over a temperature range; the difference is more prominent at higher temperatures. Interestingly, the addition of ceramic particulates or whiskers does not increase the UTS of metal/alloy significantly compared to the fibre-reinforced composites (in longitudinal direction). In the case of DRTCs, the increase in UTS is mainly due to dispersion-strengthening and hardening by uniformly distributed fine particulates or whiskers (in dispersion strengthening, the secondary hard particles (dispersoids) block the dislocation movement, via the well-known Orowan looping mechanism. Compared to precipitation hardening where precipitates are formed *in situ* via solution ageing, the dispersoids *ex situ* added are usually stable at elevated temperatures).

It is worth noting that the strength of composites at high temperatures is not limited by insufficient strength of the fibre or particulate. Instead, it is limited by the high-temperature capability of the matrix material. Therefore, the choice of matrix material determines the service temperature limit of the composite. Increasing the volume fraction of reinforcement does increase high-temperature strength of DRTCs but at the cost of ductility and oxidation-resistance. Recently, Huang et al. [71] has shown that tailoring reinforcement distribution is one effective route to simultaneously improve ductility, deformability and high-temperature strength of DRTCs. They claimed that by tailoring reinforcement distribution not only the critical problem of extreme brittleness surrounding DRTCs fabricated by PM can be resolved to exhibit superior ductility, but also the strengthening effects at room temperature and high temperatures are remarkably enhanced to obtain much higher tensile strength and service temperature.

Many reports in the literature [72–74] also suggest using combinations of different reinforcements in order to achieve combined benefits of individual reinforcements. Recently, Liu et al. [75] successfully designed and fabricated *in situ* TiC particle, Ti<sub>3</sub>SiC<sub>2</sub> bar and ultrafine

Ti<sub>5</sub>Si<sub>3</sub> needle reinforced Ti64 matrix composite. The result showed that tailored distribution of reinforcements was achieved using matrix powders with a larger size, reinforcement powders with smaller size, low-energy milling and *in situ* reaction hot pressing. Compared with monolithic Ti64 alloy, the (TiC + Ti<sub>3</sub>SiC<sub>2</sub> + Ti<sub>5</sub>Si<sub>3</sub>)/Ti64 composites exhibited a good combination of strength and ductility; especially the composites with 5.0 vol% reinforcements and fabricated using 0.5 μm SiC resulted in the UTS of ~1171 MPa and elongation of 5.3%. They claimed this improvement in properties was mainly due to tailored network structure, the hybrid strengthening effect, the large size of matrix region and solid solution strengthening effect.

#### 4.2. Wear and tribology

Another area where DRTCs are the preferred choice over fibre reinforced composites is wear resistant applications. Titanium and its alloys are generally considered not ideal for wear resistant applications due to low hardness of titanium. The incorporation of hard ceramic particles/fibres in ductile titanium matrix significantly enhances its hardness, which is directly proportional to the volume percentage of ceramic reinforcement. The fibre reinforced titanium composite, due to their high cost and anisotropic properties, have rarely been studied and employed for wear resistant applications.

Several researchers have reported wear and tribological properties of DRTCs [73,76–80]. Kim et al. [73] studied friction and wear behaviour of titanium matrix (TiB + TiC) composites. They added granular B<sub>4</sub>C to commercially pure (CP) Ti (Grade 2) and used vacuum induction melting to synthesis TMCs. They concluded that the 20% content of reinforcement is the best way to improve the friction characteristics (Fig. 8a) and the wear loss clearly decreased as contents of reinforcement increased, Fig. 8b.

Recently, An et al. [81] have successfully fabricated *in situ* TiBw/Ti64 composites with a network structure by powder metallurgical process. They claimed that the TiBw network boundary acted as a “barrier wall” and effectively resisted abrasion, which remarkably enhanced hardness and wear properties compared with that of the Ti64 alloy, Fig. 9. Moreover, they found that the wear properties and mechanism largely depends on the network size. The wear mechanism varied from micro cutting to brittle debonding with the increase of network size from 60 μm to 200 μm. The coefficient of friction (COF) increased from 0.164 to 0.188 and wear loss increased from 4.654 mg to 6.110 mg. They concluded that composite with 8.5 vol% TiBw and network size of 60 μm exhibited the best wear resistance.

In another study, Chaudhari et al. [72] fabricated Ti-4Al-2Fe/TiB/TiC functionally gradient composite by spark plasma sintering (SPS). They used Potassium tetrafluoroborate (KBF<sub>4</sub>) as boron precursor to form *in situ* TiB while graphite foils were used on either side of the compact as a carbon source to produce TiC during sintering. The resulting microstructure had distinct features with ultrafine TiC on top, fine needles of TiB near the surface and coarser TiB whisker reinforced Ti (Ti-4Al-2Fe/TiB<sub>w</sub>) in the bulk. The TiC surface layer exhibited a very high hardness of 20 GPa as compared to 7 GPa of the bulk Ti-4Al-2Fe/TiB composite. The surface TiC layer thus acted as an effective protection against wear with wear rate was almost one order of magnitude lower than that of the bulk Ti-4Al-2Fe/TiBw composite. The above two examples show that by carefully controlling volume fraction of reinforcement and microstructure of DRTCs, application specific wear characteristics are attainable.

Table 4 compiles an overview of different properties for most studied DRTCs in the literature.

#### 4.3. Fatigue behaviour

The main driving force for the development of TMCs is the inadequate fatigue resistance of monolithic lightweight alloys for many demanding applications such as rotating components of jet engine



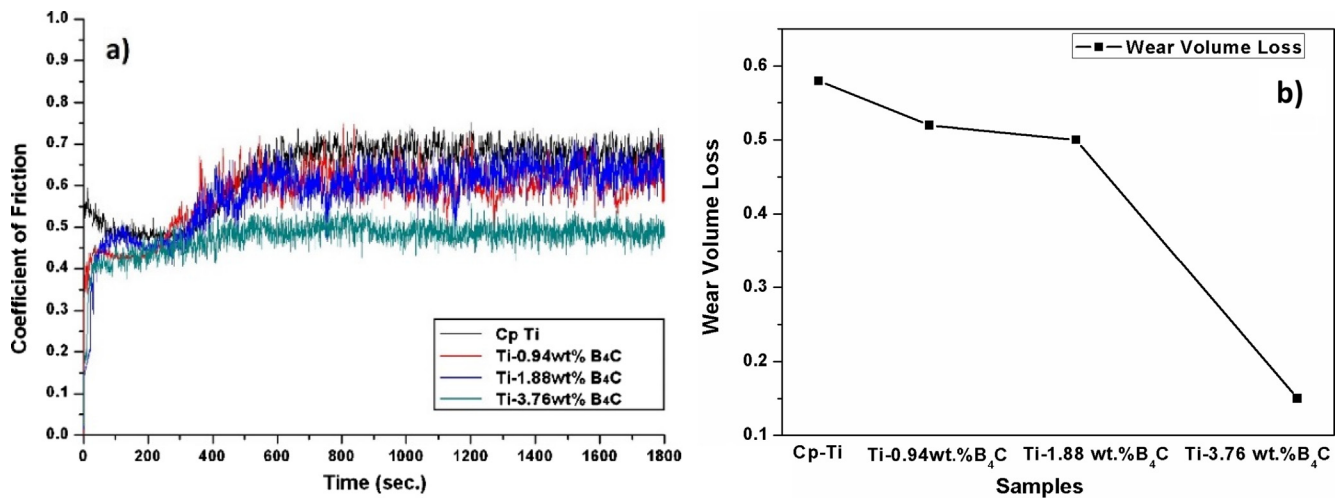


Fig. 8. (a) Friction coefficient of developed composites; (b) wear volume ( $\text{mm}^3$ ) of developed composites. [73]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

compressors [108]. The fatigue behaviour under high stresses is one of the most important design criteria in selection of materials for engine compressors. The use of a high stiffness ceramic reinforcement can result in a substantial increase in fatigue resistance. However, the determination of fatigue behaviour of composites is not a straightforward task. Their behaviour is more difficult to predict than that of homogeneous and isotropic materials such as metals. On many occasions, composites are treated as metals in evaluating their fatigue behaviour [109]. This approach can lead to several difficulties due to a number of reasons. Mainly, the accumulation of damage in composites is more of a general in nature rather than a localized fashion prevalent in metals. In addition, failure usually does not occur by the propagation of a single macroscopic crack. Also, there are different types of damage that can occur in a TMC materials, e.g., fibre fracture, matrix cracking, fibre matrix debonding. The interactions between the damages and the different damage growth rates increase the complexity of the problem. A mode of failure which is dormant in one type of composite may be very active and even critical in other type of TMC material. Moreover, there can be different dominant damage mechanisms active for different loading directions. The fatigue testing of DRTCs can still be reasonably accurately measured using standard testing methods of alloys. Nevertheless, some important considerations must be taken into account, particularly for fibre reinforced composites:

A: Reinforcement type and configuration

It is a well-known fact that volume fraction of reinforcement and its size critically affect the fatigue strength of composites. Furthermore,

the homogeneous discrete distribution of the reinforcing particles/whiskers/short fibres in the case of DRTCs and uniform alignment of fibres for fibre-reinforced composites have a significant influence on the fatigue behaviour. As numerous experimental observations have shown that inhomogeneity of the spatial arrangement/alignment of reinforcement is detrimental to fatigue behaviour [25].

B: Manufacturing

The mechanical properties of composites are functions of the manufacturing processes. Any material treatment or processing that can improve the resistance of the matrix to crack propagation or the interfacial adhesion is likely to improve fatigue properties of composite [110]. Just like in metals, factors such as surface state and roughness particularly influence the fatigue behaviours of composites in service conditions [111].

C: Loading conditions in the case of fibre reinforced TMCs

As mentioned earlier, different damage mechanisms can develop in a composite material depending on the loading conditions. Behaviour of composite materials under complex stress states is largely not understood. Fatigue tests for composites are usually carried out for the simplest loading conditions, namely constant stress in tension-tension loading due to costly and time-consuming nature of testing.

D: Prior impact damage

The influences of low-velocity impact damage on the fatigue life and reliability of the affected structure are not well characterised and the post-impact fatigue behaviour is still not fully understood. This aspect of composite behaviour has proven to be a major bottleneck for the

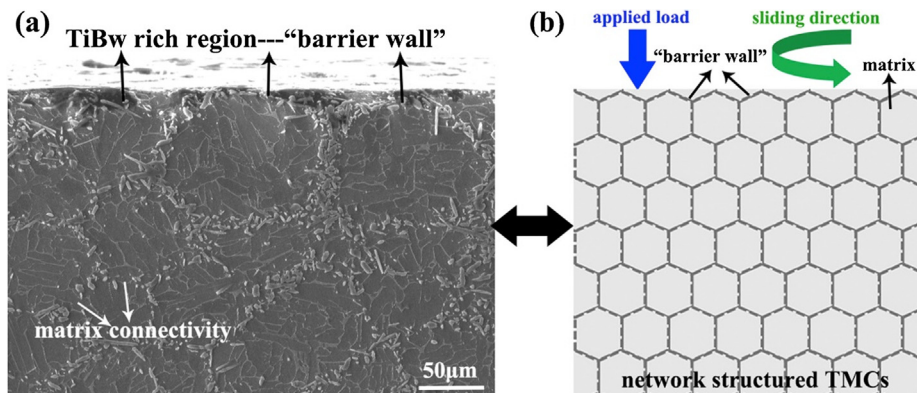


Fig. 9. (a) Cross section of the worn surface; (b) Proposed illustration of the network structured DRTC undergone sliding wear process [81]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 4**  
List of most studied DRTCs and their resulting properties in literature.

Matrix	Reinforcement & vol. %	Processing Route	Properties					References
			Density	Hardness	Strength (MPa)	Ductility %	Flexure Strength	
Ti	5% TiB	VAR + HS	–	–	787	12.5	–	[82]
Ti	15% TiB	VAR + HS	–	–	903	0.4	–	[82]
Ti-6Al-4V	10% TiB	MA + HIP	–	–	–	0.25	–	[83]
Ti-6Al-4V	11% TiB	GA + HIP	–	–	1470	3.1	–	[84]
Ti	20% TiB	PM	–	–	673	0	–	[84]
Ti-6Al-4V	20% TiB	MA + HIP	–	–	1170	2.5	–	[84]
Ti	67% TiB	RHP	–	1351	–	–	350	[85]
Ti-6.4Fe-10.3Mo	34% TiB	PM + HP	–	–	736	0.5	–	[86]
Ti-24.3Mo	34% TiB	PM + HP + HT	–	–	1105	0.9	–	[86]
Ti-53Nb	34% TiB	PM + HP + HT	–	–	724	1.7	–	[86]
Ti	40% TiB	SHS/PHIP	94.30%	82.7 HRA	140	–	193	[87]
Ti	50% TiB	SHS/PHIP	> 994%	–	224	–	449	[87]
Ti	60% TiB	SHS/PHIP	97.04%	84.3 HRA	280	–	515	[87]
Ti	70% TiB	SHS/PHIP	98.45%	87.8 HRA	248.8	–	416.4	[87]
Ti	80% TiB	SHS/PHIP	97.57%	86.7 HRA	207	–	277	[87]
Ti	100% TiB	SHS/PHIP	96.86%	87.1 HRA	103	–	225	[87]
Ti-6Al-4V	20% TiB	PM + E	–	–	1215	0.5	–	[88]
Ti-6Al-4V	20%TiB	MA + HP	–	–	1018	0.1	–	[88]
Ti-6Al-4V	40% TiB	PM + E	–	–	864	0	–	[88]
Ti-4Fe-7.3Mo	10% TiB	MA + SPS	99.60%	–	–	–	1007	[89]
Ti-6Al-4V	3.1% TiB	C + E + H	–	–	1156	–	–	[90]
Ti-22Al-27Nb	6.5% TiB	IM + HR + H	–	–	992	4	–	[91]
Ti-22Al-27Nb	6.5% TiB	PM + HR + H	–	–	1260	2.3	–	[91]
Ti	5 %TiB + 1.17% Y <sub>2</sub> O <sub>3</sub>	AM	–	52.5 HRC	–	–	–	[92]
Ti	5 %TiB + 3.49% Y <sub>2</sub> O <sub>3</sub>	AM	–	48.2 HRC	–	–	–	[92]
Ti	5 %TiB + 5.79% Y <sub>2</sub> O <sub>3</sub>	AM	–	45.5 HRC	–	–	–	[92]
Ti	5 %TiB + 8.64% Y <sub>2</sub> O <sub>3</sub>	AM	–	38.0 HRC	–	–	–	[92]
Ti	35% SiC fibre	MS	–	–	1163	–	–	[93]
Ti	8–10% Carbon Fibres	PM	99%	214 HV	674	–	–	[92]
Ti	TiB and TiC	RHP	–	–	1190	–	–	[26]
Ti	SiC particulate	HE	100%	–	–	–	–	[94]
Ti	0.18% CNTs	PM + E	–	275HV	682	34.2	–	[95]
Ti	0.24% CNTs	PM + E	–	278HV	704	38.1	–	[95]
Ti	0.35% CNTs	PM + E	–	285HV	754	34.8	–	[95]
Ti-6Al-2Zr-1Mo-1 V	5% TiC	LMD	–	–	925.87	4.32	–	[96]
Ti-6Al-2Zr-1Mo-1 V	10% TiC	LMD	–	–	845.27	1.23	–	[96]
Ti-6Al-2Zr-1Mo-1 V	15% TiC	LMD	–	–	806.38	1.33	–	[96]
Ti	9.50% (TiB + TiC)	VIM	–	239 HRB	–	–	–	[73]
Ti	14.03% (TiB + TiC)	VIM	–	259 HRB	–	–	–	[73]
Ti	22.72% (TiB + TiC)	VIM	–	306 HRB	–	–	–	[73]
Ti	15% TiB <sub>2</sub>	PM	99.6%	6.6 GPa	–	–	1160	[80]
Ti	24% TiB	SPS	4.90 g/cm <sup>3</sup>	710 HV	–	–	–	[97]
Ti	38.5% TiB	SPS	4.75 g/cm <sup>3</sup>	890 HV	–	–	–	[97]
Ti	20.6% TiB	HIP	4.92 g/cm <sup>3</sup>	658 HV	–	–	–	[97]
Ti	38.3% TiB	HIP	4.90 g/cm <sup>3</sup>	823 HV	–	–	–	[97]
Ti	17.6% TiB	PM	4.20 g/cm <sup>3</sup>	424 HV	–	–	–	[97]
Ti	37.9% TiB	PM	4.68 g/cm <sup>3</sup>	618 HV	–	–	–	[97]
Ti	1.0 wt% CNTs	SPS + HE	–	292 HV	625	–	–	[98]
Ti	2.0 wt% CNTs	SPS + HE	–	336 HV	662	–	–	[98]
Ti	3.0 wt% CNTs	SPS + HE	–	367 HV	853	–	–	[98]
Ti-4.5 Al-6.8 Mo-1.5 Fe	5% TiB	HVC	97.90%	335 HV	1038	2.19	–	[99]
Ti-4.5 Al-6.8 Mo-1.5 Fe	10% TiB	HVC	98.20%	392 HV	1147	–	–	[99]
Ti-4.5 Al-6.8 Mo-1.5 Fe	15% TiB	HVC	98.30%	428 HV	741	–	–	[99]
Ti-4.5 Al-6.8 Mo-1.5 Fe	20% TiB	HVC	96.10%	445 HV	521	–	–	[99]
Ti-21Al-29Nb	26.2% SiC fibre	FFF method	–	–	1013	–	–	[100]
Ti-21Al-29Nb	26.0% SiC fibre	FFF method	–	–	1037	–	–	[100]
Ti	4% TiB + 0.97% TiC	PM	–	–	876	14.2	–	[101]
Ti	6.49%TiB + 1.61% TiC	PM	–	–	995	7.8	–	[101]
Ti	10.93%TiB + 2.81% TiC	PM	–	–	1138	2.6	–	[101]
Ti	0.2 wt% MWCNTs	SPS	99.69%	2 GPa	898	–	–	[102]
Ti	0.4 wt% MWCNTs	SPS	99.44%	2.18 GPa	1092	–	–	[102]
Ti	0.6 wt% MWCNTs	SPS	99.31%	2.30 GPa	1052	–	–	[102]
Ti	0.8 wt% MWCNTs	SPS	99.13%	2.39 GPa	1015	–	–	[102]
Ti	1.0 wt% MWCNTs	SPS	99.01%	2.40 GPa	853	–	–	[102]
Ti-6Al-4V	5% TiC	SPS	99.70%	–	995	3	–	[103]
Ti-6Al-4V	10% TiC	SPS	99.60%	–	1060	3	–	[103]
Ti	0.5 wt% MLGs	SPS	–	15.39 GPa	–	–	–	[104]
Ti	1.5 wt% MLGs	SPS	–	14.54 GPa	–	–	–	[104]
Ti	B + 1 vol% CNTs	SPS	99.30%	33 GPa	–	–	–	[105]
Ti	B + 2 vol% CNTs	SPS	98.70%	29 GPa	–	–	–	[105]
Ti	B + 4 vol% CNTs	SPS	97.60%	28 GPa	–	–	–	[105]
Ti	B + 6 vol% CNTs	SPS	96.00%	25 GPa	–	–	–	[105]

(continued on next page)



Table 4 (continued)

Matrix	Reinforcement & vol. %	Processing Route	Properties					References
			Density	Hardness	Strength (MPa)	Ductility %	Flexure Strength	
Ti	0.5 vol% B <sub>4</sub> C	PM + HE	–	–	916	2.6	–	[106]
Ti	26% Ti <sub>3</sub> Al <sub>7</sub>	VHP	–	–	300	4.4	462	[107]
Ti	2% Si <sub>3</sub> N <sub>4</sub> fibres	PM	98.60%	401 HBW	–	–	–	[28]
Ti-6Al-4V	5% SiC particle	PM	–	460 HV	–	–	–	[29]
Ti-6Al-4V	10% SiC particle	PM	–	369 HV	–	–	–	[29]
Ti-6Al-4V	15% SiC particle	PM	–	315 HV	–	–	–	[29]

Note: SPS: spark plasma sintering; PM: Powder Metallurgy; HE: Hot Extrusion; VHP: Vacuum Hot Pressing; FFF: Fused Filament Fabrication; HVC: High Velocity Compaction LMD: Laser Melted Deposition; AM: Arc Melting; VIM: Vacuum Induction Melting; RHP: Rapid Hot Pressing; MS: Magnetron Sputtering; IM: Induction Melting; MA: Mechanical alloying; HT: Heat Treatment; VAR: Vacuum Arc Remelting; PHIP: Pseudo Hot Isostatic Pressing; HS: Hot Swaged; GA: Gas Atomization; SHS: Self-propagating High Temperature Synthesis.

application of composites especially in the aerospace domain [110].

This list is not exhaustive, but it gives an indication of challenges associated with fatigue testing of TMCs. Currently, there are no ASTM or ISO test methods for determining the fatigue characteristics of TMCs. Therefore, metals fatigue test standards such as ASTM E466 [112], E606 [113] are generally used for TMCs.

For unidirectional fibre reinforced metal matrix composites, Gouda et al. [114] found that the fatigue life is independent of the mean stress and proposed a simple model to predict an S-N curve, which can be employed for TMCs as well. This model accounts for two micro-mechanical damage modes during the fatigue, growth of matrix cracks in the direction perpendicular to the fibre axis (type A) and that of interfacial debonding (type B), Fig. 10.

Fatigue crack growth of type A is similar to the usual Mode I of growth observed in alloys in which the rate of crack growth as a function of  $\Delta K$ , the range of stress intensity factor, is sigmoidal between the limits of  $\Delta K_{th}$  (threshold level for crack growth) and  $K_{IC}$  (the fracture toughness of Mode I). An S-N curve computed from such crack growth rate data leads to the usual form of the S-N curve for alloys. However, for crack growth of type B, the shape of the S-N curve may be quite different [115]. If the interfacial debonding (or crack) progresses along a fibre with no weak points, then the growth of this interfacial debonding does not contribute to final fracture. If all fibres are of the perfect fibre type (no weak points), then the S-N curve will be flat, i.e., the endurance limit being the static strength. However, in actual unidirectional metal matrix composites, some fibres may be perfect, but the majority of fibres usually have weak points. Then the S-N curve will be a mixture of those of types A and B [115]. Since then, numerous fracture micro-mechanisms [116–121] under cyclic loading have been proposed, and different models have been developed to predict the

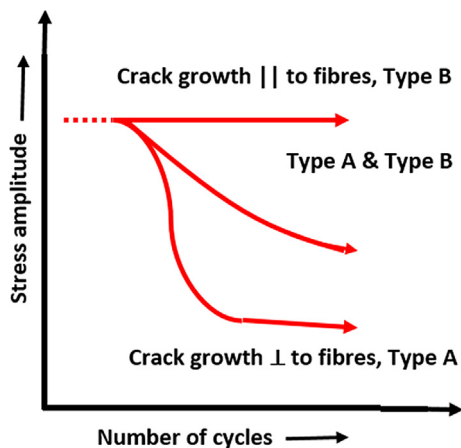


Fig. 10. Shapes of S-N curves in unidirectional composites as influenced by crack path - Gouda model [114]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relationships of fracture mechanism and crack growth rate in MMCs including TMCs [120,122–125].

As TMCs are primarily designed for improved fatigue strength, the fatigue behaviour of a TMC is usually superior to that of the unreinforced titanium alloy. This is particularly true for a unidirectional composite system [115]. Fatigue behaviour of SiC reinforced TMCs has been well studied, and document in literature; most of these studies came out of NASA research in the 80's and 90's on these composite systems [126–132] followed by other researchers [133–137]. Fig. 11 presents S-N curves for different SiC reinforced TMCs and compares it with monolithic alloys.

As shown in Fig. 11, the use of fibre reinforced TMCs has a positive effect on fatigue properties. The maximum cyclic stress for TMCs in the low cycle fatigue (LCF) regime as well as in the high cycle fatigue (HCF) is significantly higher than that of unreinforced materials. While the endurance limit of the unreinforced Ti64 is about 500 MPa, SiC/Ti64 reaches an endurance limit of 750 MPa. The improvement in fatigue properties at higher temperatures are even more significant, as was shown by Leyens et al. [138].

Johnson at the NASA Langley Research Centre carried out a thorough and fundamental study of fatigue damage initiation and propagation in continuous fibre-reinforced titanium-matrix composites at both room and elevated temperatures [142]. According to the author, the fatigue life of the unnotched laminates is the function of the stress range in the 0° fibres for isothermal, non-isothermal and thermo-mechanical fatigue conditions. However, this relationship (0° fibre stress range/cycles to failure) varies with temperature, indicating a fibre/matrix reaction effect or a cumulative strain effect at elevated temperatures. The author also showed that the strength of the interface

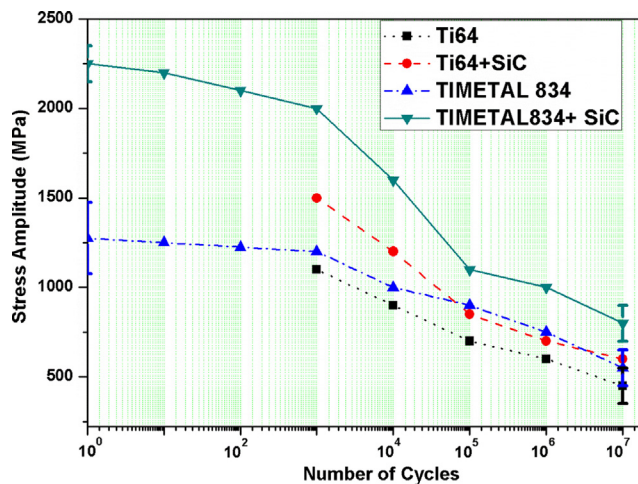


Fig. 11. Fatigue behaviour of SiC fibre reinforced TMCs [137–142]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the magnitude of the residual thermal stresses play a significant role in the laminate failure process. Interestingly, high interface strengths and high residual stresses are shown to reduce the laminate static and fatigue strengths. Moreover, in the case of notched samples, matrix cracking around notches occurs at low cyclic stress levels. It is suggested that due to the nature of such cracks they may appear as cosmetic defects. Nevertheless, they significantly reduce the residual strength, making these matrix cracks a serious consideration.

Recently, Stanley et al. [143] assessed fatigue crack growth resistance in continuous SCS-6 fibre reinforced Ti64 composites from unbridged defects at room temperature, 300 and 450 °C in air and in vacuum. They concluded that the crack arrest/catastrophic failure (CA/CF) transition of the composite is greatly affected by the initially applied stress intensity factor range ( $\Delta K_{app}$ ) value due to its effect on fibre failures. Moreover, they found out that the fibres in the first few rows are more important to reduce crack growth rates and to promote crack arrest.

Apart from SiC fibre, fatigue properties of coated SiC fibre reinforced TMCs have also been studied and reported in the literature. Guo et al., studied the fatigue behaviour of duplex metal (Cu/Mo and Cu/W) coated SiC fibre reinforced Ti-15-3 matrix composites [144]. They reported that the fatigue resistance of this fibre reinforced composite is improved by use of the duplex metal coatings and claimed that the number of cycles to failure for SiC/Cu/Mo/Ti-15-3 and SiC/Cu/W/Ti-15-3 is approximately double that for SiC/Ti-15-3, with SiC/Cu/Mo/Ti-15-3 showing the longest fatigue life. They postulated that both Cu/Mo and Cu/W coatings prevent interfacial debonding of the SCS coating layer from the SiC surface, and thus the fibre can retain its pristine strength. This enables fibre bridging [123,145] behind the matrix crack tip thus, reducing the crack growth rate of the matrix.

As mentioned earlier, the fatigue properties of TMCs are strongly influenced by the type and inherent properties of the matrix. Recently, Rahman et al. [146] fabricated and tested SiC fibre reinforced Ti-5Al-5Mo-5V-3Cr metal matrix composite. They claimed that the fatigue performance of the material exceeded that of MMCs developed using Ti-21S or Ti64 matrices. However, no fundamental study is presented about this improvement in fatigue performance.

The fatigue behaviour of discontinuously reinforced metal matrix composites and DRTCs strongly depends on the volume percentage of reinforcing particles [27,147]. According to the literature reports [148–150], as the weight percentage of reinforcing particles increases, the *S-N* curve shifts to higher stress amplitude and becomes nearly flat at very high cycles. This implies that below the fatigue limit the cycle number to failure becomes indefinitely large and the fatigue failure, in this case, will actually not take place. However, increasing the volume fraction of reinforcement has an adverse effect on ductility and fracture toughness of DRTCs [27]. Fatigue properties of DRTC reinforced with TiB<sub>w</sub>, TiC<sub>p</sub> have been studied and reported in the literature, albeit in less detail and volume compared to SiC reinforced composites [67,151–153]. Fig. 12 presents *S-N* curves for common reinforcement DRTCs and compares it with monolithic alloys.

When compared with fibre reinforced composites, the DRTC fatigue properties are evidently low as can be compared by Figs. 11 and 12. In another study [157], the authors showed that despite having superior static properties, the fatigue lives of TiB<sub>w</sub>/Ti & TiC<sub>p</sub>/Ti composites were shorter than a conventional Ti64 alloy. They also showed that TiC<sub>p</sub>/Ti had a lower fatigue crack resistance while TiB<sub>w</sub>/Ti had a better crack resistance than Ti64 alloy. Based on the results they concluded that the crack growth resistance in particulate reinforced titanium composites is mainly dependent on the particle shapes and sizes. Similarly, Tjong et al. [151] presented that the incorporation of ceramic reinforcement to Ti matrix leads to an improvement of high-cycle fatigue but deterioration in low cycle fatigue performance. In another study of fatigue crack nucleation and growth in a Ti-6Al-4V/TiB in-situ composite Soboyejo et al. [90] concluded that the TiB whiskers led to premature fatigue crack nucleation in the composite and did not promote

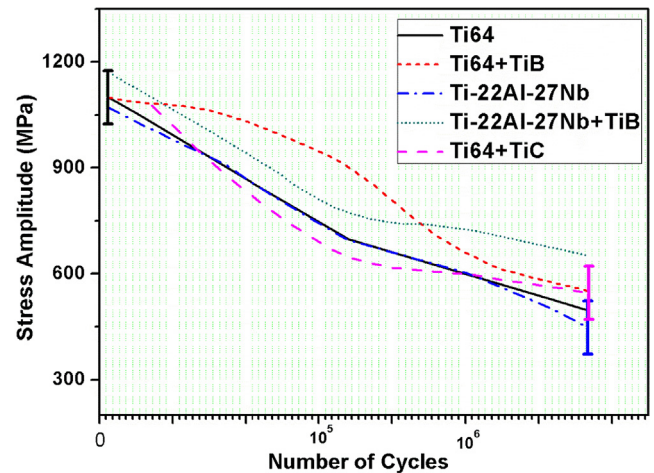


Fig. 12. Fatigue behaviour of different DRTCs [90,154–156]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

significant changes in the overall fatigue resistance. However, the studied composite system had better overall mechanical properties. Given the variation in fatigue properties of DRTC reported in the literature, it is arguable that the discontinuous reinforcement does not have a significant impact on fatigue properties of titanium composites and can be further enhanced by carefully tailoring the reinforcement and matrix microstructure.

The mechanics and mechanisms of fatigue behaviour, crack growth and failure for discontinuously reinforced composites have been documented in the literature. Llorca [158] presented a detailed overview of fatigue of particle and whisker reinforced metal matrix composites. In general, the ceramic reinforcement can significantly affect the threshold stress intensity range and fatigue crack growth rates of the DRTCs. The reinforcement influences the crack-tip deformation mechanisms such as crack closure, crack deflection and crack bridging. The net result of all these crack-tip processes is the reduction of the crack-tip stress intensity factor range ' $\Delta K$ ', which ultimately leads to lower crack growth rate [151]. This was verified in a study by Dubey et al. [159], who studied the fatigue crack propagation and fracture characteristics of in-situ titanium-matrix composites in detail. They found that for the studied composite systems Ti-6Al-2Fe-0.6B and Ti-8Al-1V-1Mo-0.6B, the crack followed a tortuous path with microstructurally induced deflections of the crack, the presence of fine microscopic cracks and uncracked ligaments bridging the fatigue crack. This manifests the importance of the particle size and shape of the reinforcement in determining fatigue properties of DRTCs, in addition to the volume fraction of particulate/whiskers. At any given volume fraction, the reinforcement interparticle spacing decreases with decreasing particle size and thus resulting in more barriers for the reversible slip motion that takes place during fatigue [160,161]. Likewise, narrowing of the particle size range distribution also results in higher fatigue life.

#### 4.4. Creep properties

Creep resistance of a material plays a significant role in determining its performance at elevated temperatures. Therefore for high-temperature applications, the assessment of creep behaviour of a potential TMC is a prerequisite for a component design engineer who wants to employ the TMC. The majority of metal matrix composites appear to possess the three distinct stages: the initial (primary), secondary (steady state) and tertiary - partly due to the fact that at high temperatures the matrix metal creeps, but the reinforcing fibres/particles creep unnoticeably. Among the above three stages, the secondary stage is considered most

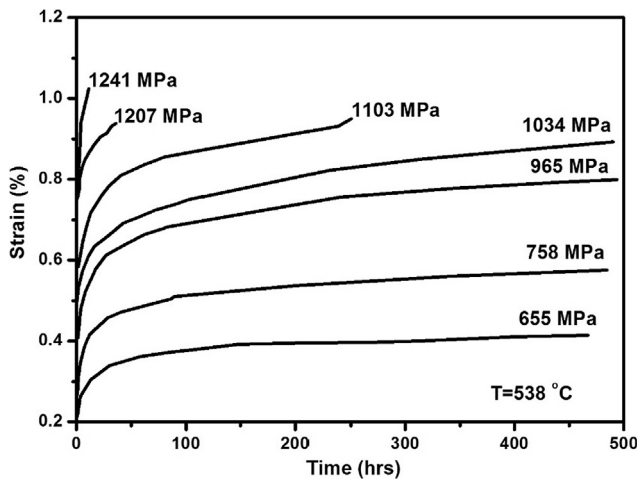


Fig. 13. Longitudinal creep behaviour of SiC (SCS-6)/Ti-6Al-4V. Good creep resistance is maintained up to 1034 MPa at 538 °C, redrawn from Ref. [168].

important since this stage primarily causes the creep strain (deformation). The slope of secondary stage is usually constant, and it is termed “steady-state creep” or simply “creep rate”. From an engineering design point of view, a reduction in the creep rate is desired in order to increase overall creep resistance. In the case of fibre reinforced TMCs, the load placed on the composite during creep exposure is mainly endured by the fibres. Since the commonly used fibres such as SiC have significantly higher creep resistance than any Ti matrix, the creep resistance of TMCs is substantially improved relative to the monolithic titanium alloys due to reinforcement hindrance to matrix creep.

Like fatigue, a number of factors affect the creep resistance of TMCs, including reinforcement strength and distribution/fibre orientation, chemical composition and creep behaviour of the matrix, properties of the reinforcement-matrix interface, residual stresses and environmental conditions. A detailed discussion on the creep behaviour of SiC fibre reinforced TMCs along with models to predict the creep rate is available in the literature [162–167]. Fig. 13 shows typical creep curves for SiC fibre reinforced Ti-6Al-4V.

It can be seen from Fig. 13 that at 538 °C loads as high as 1000 MPa can be applied without failure, further affirming the high-temperature capabilities of TMCs. Furthermore, the steady-state creep stage is shortened with increasing load and strain at rupture in each case is lower than 1%. Such values are comparable to the failure strain of the SiC fibres. Fig. 14 presents the Larson-Miller plot of the creep behaviour

of SiC reinforced Ti-24Al-11Nb and compares it with different monolithic alloys.

As can be seen from Fig. 14, TMCs exhibit significantly better creep resistance in longitudinal direction than any monolithic alloys. However, the creep resistance of the TMCs are highly anisotropic [61], again highlighting the importance of component design for TMCs commercial applications.

As mentioned earlier, mechanisms of creep failure for TMCs in the longitudinal direction have been well documented in the literature. According to Schwenker et al. [168], during the loading phase (at low stresses), load is gradually transferred from the matrix to the fibres. As a result of this load sharing, stress relaxation in the matrix occurs. At higher stresses, the highly loaded fibres break at locations where flaws are accumulated. The load at these locations is then transferred back to matrix, resulting in plastic deformation of the matrix. This plastic deformation of the matrix results in local stress re-distribution until an unbroken fibre can take up stresses, thus relieving the matrix. This fibre fracture occurs at a nearly constant frequency throughout the secondary stage. Hence, a secondary stage of nearly constant creep rate is achieved if the rate of load transfer from the matrix to the fibres and subsequent fibre rupture is in equilibrium with load re-distribution to the fibres. For continuing creep loads, this process occurs throughout the composite, which leads to multiple fibre rupture. Moreover, the frequency of fibre fracture and minimum creep rate increases with the applied stress. The final failure is a result of accumulated micro-damage to location where fibres break, reduction of fibre strength and interface degradation.

Although the main aim of developing DRTCs is to broaden the utilization field of titanium and its alloys by increasing their high-temperature properties such as oxidation resistance and primarily creep resistance, the improvements in creep properties are rather debatable. Fig. 15 compares the creep rates of pure Ti and Ti-6Al-4V with DRTCs.

The presence of reinforcing particles does increase the creep resistance of pure Ti metal; however, monolithic Ti-6Al-4V possesses creep properties better than even reinforced Ti-6Al-4V. Moreover, the creep resistance of pure Ti increases with increasing volume fraction of reinforcing particles. Tsang et al. [82] studied the effects of volume fraction of *in situ* TiB on creep properties of TMC and presented creep mechanisms. They stated that the creep mechanisms of unreinforced Ti and TiBw/Ti are associated with diffusion-controlled dislocation climb. Furthermore, they also established that two factors are responsible for an increase in creep strength of pure Ti-based composites: (1) a higher modulus induced by load transferring from matrix to stiffer reinforcement and (2) threshold stress induced by interaction between

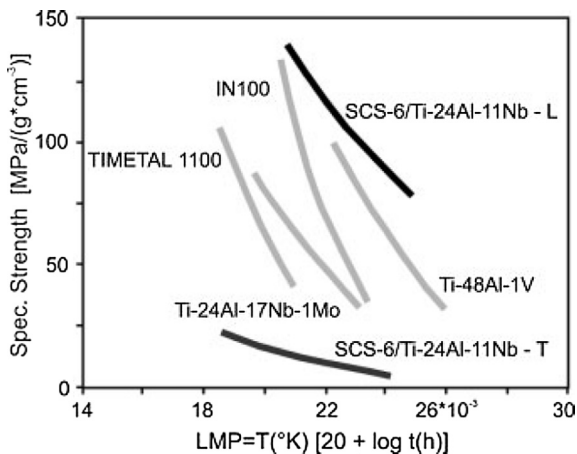


Fig. 14. Larson-Miller plot of the creep behaviour of monolithic titanium alloys, nickel-base alloy IN100 and fibre reinforced Ti-24Al-11Nb, redrawn from Ref. [61].

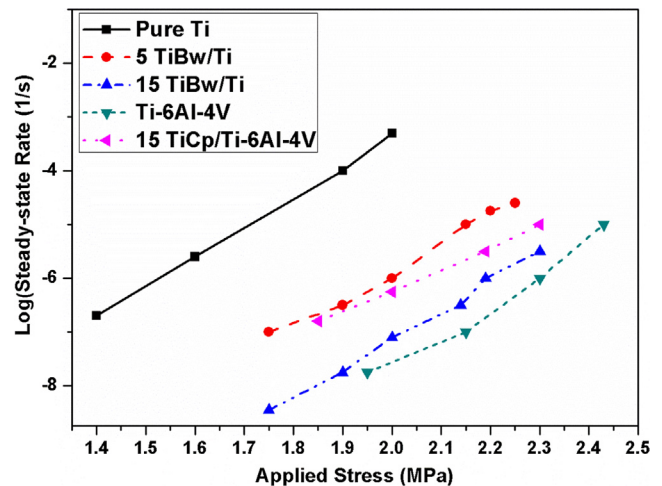


Fig. 15. A comparison of the creep rates between pure Ti and Ti-6Al-4V with DRTCs at 550 °C [169,170]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



dislocation and reinforcement [82]. The former mechanism is also suggested by Zhu et al. [171]. In the case of Ti-6Al-4V, the creep resistance is attributed to several factors including ( $\alpha + \beta$ ) morphology, grain size and volume fractions of each phases. The higher creep resistance of monolithic Ti-6Al-4V alloy, in this case, was apparently due to  $\alpha/\beta$  interfaces acting as obstacles to dislocation motion and to the initial average grain size of  $395 \mu\text{m}$ , which can contribute for the reduction of grain boundary sliding and dislocation sources [169]. *In situ* reinforcement formation can influence the above-mentioned parameters, thereby affecting the overall creep properties. Recently, Wang et al. [172] have shown that creep resistance of TiBw/Ti6Al4V composites can be significantly increased by architecting a network of TiB whiskers. They claimed that the network distribution of the TiBw reinforcement constrains the deformation of the Ti6Al4V alloy, which results in a lower creep rate. The final rupture occurs when the cracks on the TiBw are sufficiently large and the debonding between the TiBw and the Ti6Al4V matrix occurs at the TiBw-rich network boundary. The creep resistance of DRTCs hence can be significantly enhanced by carefully controlling the volume fraction and distribution of reinforcement inside the matrix and matrix microstructure itself.

It should be noted that Figs. 6–15 presents a general overview of UTS for a temperature range, wear resistance, fatigue lives and creep properties of TMCs. The actual value may vary depending on different parameters such as fabrication method, volume fraction of reinforcement and matrix compositions.

#### 4.5. Charpy impact behaviour

Initially, TMCs (fibre reinforced, in particular) were aimed at compressor discs, linkage and actuator struts of aeronautical gas turbines. Since then interest has grown towards their use in blades as well. Blades are however, susceptible to impact damage such as that from extraneous matter, e.g. bird strike [173]. Therefore, it is imperative for the blades to have sufficient impact strength. If the TMCs is to be used in the safety critical environment of the aeronautical gas turbine, it is essential that their impact properties be quantified and understood. However, the lack of available reports on impact behaviour of TMCs suggests that TMCs are not well suited for applications where impact strength is one of the main requirements. Fig. 16 compares the impact strengths of SiC fibre reinforced TMCs with monolithic Ti alloys.

The impact strength of fibre reinforced TMCs is reduced by an order of magnitude compared with the monolithic Ti alloys. This is because of

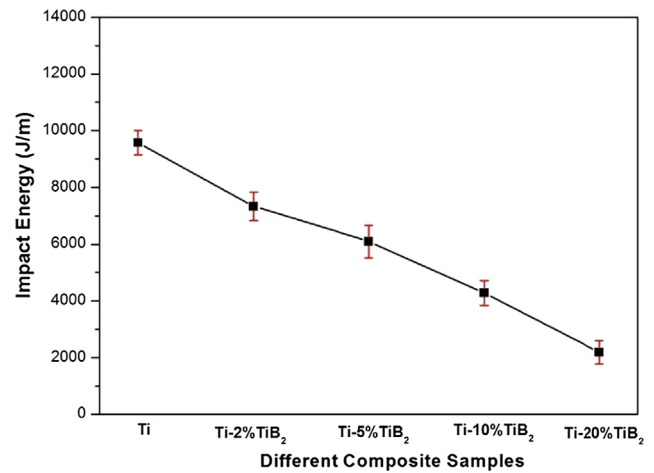


Fig. 17. Variation of impact energy with TiB<sub>2</sub> concentrations for different composites. The reduced impact energy with the weight fraction of the reinforcement is attributed to the brittleness of TiB and a less favourable TiB<sub>w</sub>/Ti interface (our own work). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the deleterious effect of the SiC fibres. SiC has a low impact strength, which generally varies between  $0.01$  and  $4.0 \text{kJm}^{-2}$  [174]. The SiC fibres crack under impact load, which then lead to interfacial cracking accompanied with sharp cracks that grow into matrix. This cracking first occurs in the fibres on the tension side of the samples at the time of impact. Similar observations were made for TiB<sub>w</sub> reinforced titanium composites as well during impact energy testing, Fig. 17.

#### 4.6. Fracture toughness

As with many other mechanical properties, the fracture toughness of TMCs depends on individual components properties, processing method, orientation/distribution of fibre/particles in the matrix and the interface properties. Although SiC fibre reinforced TMCs have excellent tensile, fatigue and creep properties (in longitudinal direction), their fracture toughness is comparatively inferior to conventional titanium alloys. SiC reinforced TiAl, in particular, suffers from poor impact resistance and damage tolerance due to inherently poor fracture toughness of titanium aluminide matrix [175].

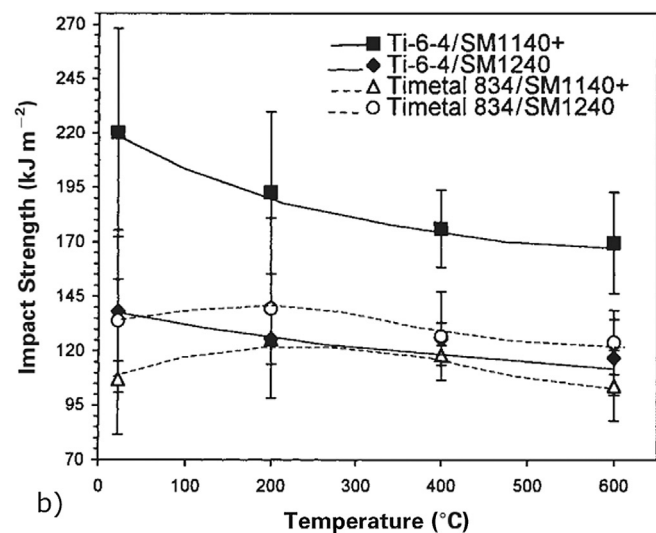
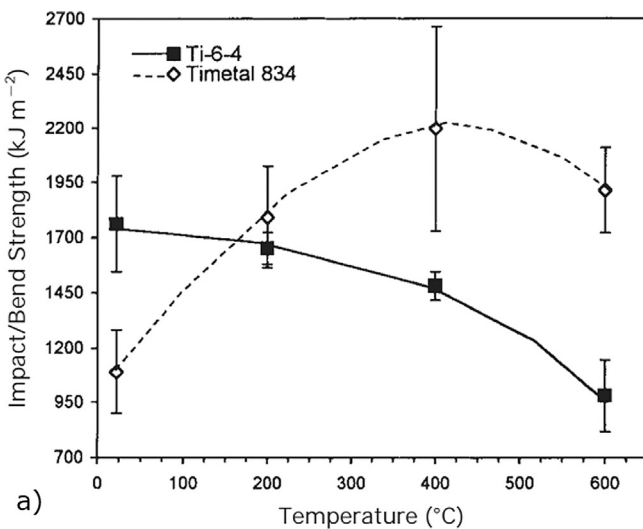


Fig. 16. (a) Impact/bend strengths of monolithic foil-bonded panels of two monolithic Ti alloys. The panels of alloys were fabricated under the same consolidation conditions as the TMCs; (b) Impact strengths of different SiC fibre reinforced TMCs along the longitudinal direction. Where, SM1140 + represents carbon coated SiC fibre while SM1240 represents C/TiB<sub>x</sub> coated SiC fibre. The volume fraction of SiC fibre was fixed at 0.33% in this study [173].

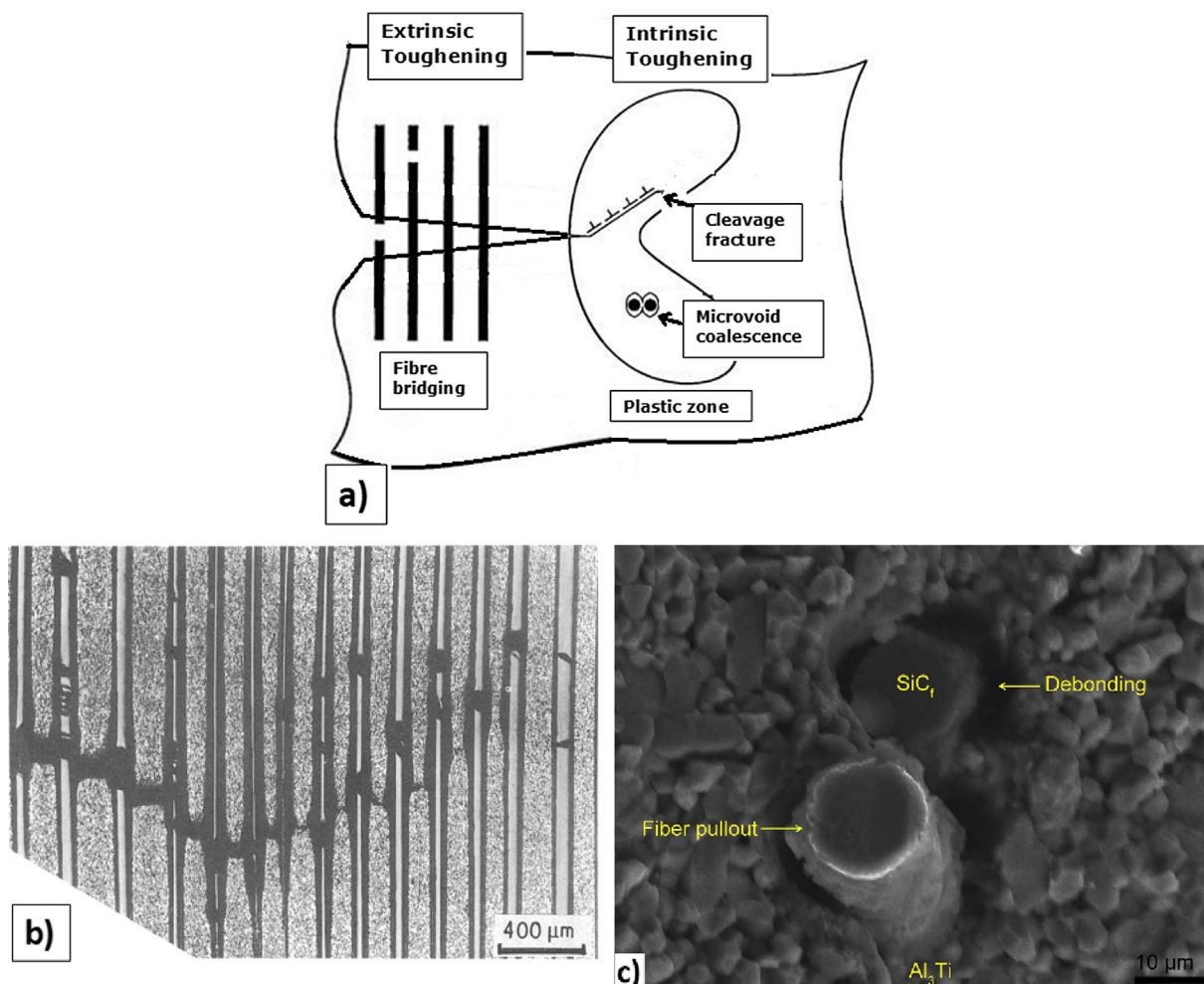
One way of improving the fracture toughness of TMCs based on TiAl matrix is by combining two different alloys as the composite matrix. Jeng et al. [175] used the combination of a ductile Ti6Al4V alloy with a TiAl alloy as the matrix, while SiC fibre as reinforcement. They reported that by using a hybrid matrix, the fracture toughness of TiAl based composites can be substantially increased. The ductile Ti6Al4V layer serves as a compliant layer to accommodate the residual stresses. Furthermore, the Ti6Al4V layer effectively suppresses the propagation of micro-cracks initiated from the brittle layer while maintaining the high-temperature properties and environmental resistance of TiAl layer. They concluded that using such hybrid matrices, the resulting composites can be used at a temperature well beyond those attainable in ductile titanium alloy matrix composites while improving the damage tolerance of the titanium aluminide matrix composites. Most recently, Lin et al. [176] have studied Ti64-(SiC<sub>f</sub>/Al<sub>3</sub>Ti) laminated composite. The composite was fabricated by foil-fibre lay-up technique (in the order Ti64-SiC-Al-SiC-Ti64) followed by sintering in a vacuum hot pressing furnace. The resulting mechanical testing affirms the conclusion drawn by Jeng et al. [175].

The toughening mechanisms for fibre reinforced TMCs have well studied and documented in the previous reports [177–179]. The toughening mechanisms in the case of fibre reinforced composites can be a combination of both extrinsic toughening by fibre bridging, fibre/matrix interfacial debonding that can trigger the crack deflection/

arresting effects and intrinsic toughening by matrix plastic deformation, Fig. 18.

Yanqing et al. [182] studied the fracture toughness of Ti64 alloy uniaxially reinforced with SiC fibres. They claimed that under the action of the applied load, plastic deformation zone forms ahead of the crack tip. As the load is further increased, the interface of the matrix/fibre rebounds due to different deformation ability of the matrix and the fibre and leads to fibre pull-out. At this time, the load is borne by the matrix and fibre pull-out. Therefore, it is suggested that the toughness of fibre reinforced TMCs is related to the properties of the matrix, fibre and the fibre pull-out mechanism. Moreover, they achieved fracture toughness of  $\sim 50 \text{ MPa}\cdot\sqrt{\text{m}}$  (for comparison, the fracture toughness of pure Ti and its alloys varies from 28 to  $108 \text{ MPa}\cdot\sqrt{\text{m}}$ ). They also observed that the fracture toughness decreases upon heat treatment. The reason for this fracture toughness degradation is attributed to a severe interfacial reaction between SiC fibres and Ti64 matrix [182].

In addition, Cooper et al. [179] stated that the diameter of fibre plays an important role on the fracture toughness of metal composites. They showed for the copper matrix composite that fracture toughness varies linearly with the diameter of the fibres at room temperature. As the fibre diameter decreased from 1 mm to  $40 \mu\text{m}$ , the work of fracture decreased from a mean value of  $10^8$  to just above  $10^7$  ergs.cm<sup>-2</sup>. Comparatively, a similar trend might be true for SiC fibre reinforced



**Fig. 18.** (a) Schematic illustration of extrinsic versus intrinsic toughness. Intrinsic toughening mechanism act ahead of the crack tip to promote crack advance while extrinsic mechanisms act behind the crack tip to impede crack advance [177]; (b) Crack propagation pattern of the SCS-6/Ti64/Ti-25Al-Nb3 at % [180]; (c) Fracture feature of SiC<sub>f</sub>/Al<sub>3</sub>Ti composite: debonding, pullout and breakage behaviour of SiC fibres were observed, which can improve the properties of the fibre reinforced composite by increasing the resistance to crack propagation and constraining microcrack extension [181]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

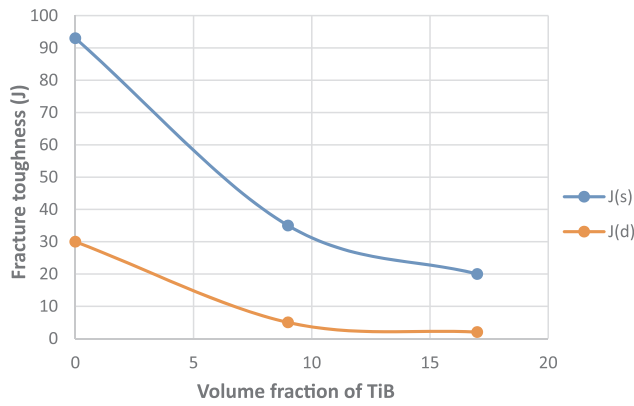


Fig. 19. Effect of TiB particle volume fraction on static  $J(s)$  and dynamic  $J(d)$  fracture toughness. Redrawn from Ref. [183]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

TMCs.

In DRTCs, toughening can be achieved by crack bridging resulting from the uncracked ligaments. Likewise, microcracks which are formed at reinforcement particles some distance ahead of the crack tip and have yet to link to the main crack may also play an important role by causing main crack deflection. Wang et al. [183] developed a relationship between microstructure and fracture toughness of Ti-6Al-2Sn-4Zr-2Mo alloy reinforced with TiB particles, Fig. 19.

As seen in Fig. 19, both static and dynamic fracture toughness decrease with increasing volume fraction of TiB particles. In particular, the decrease is more prominent at lower volume fractions. In comparison to dynamic fracture toughness, the impact of volume fraction of TiB on static fracture toughness is greater. They proposed that the common toughening mechanisms for titanium alloys do not work well for toughening the materials with TiB particles. It has been well known that toughening can be achieved by stress release arising from the nucleation of microcracks, shear ligament formation for linking the microcracks, and the decrease of the effective stress intensity factor caused by the crack deflection or crack-tip blunting. Instead, toughening in TiB-reinforced Ti alloys is achieved via debonding and shearing of TiB particles [183]. Since the resistance of TiB particles against crack propagation is small, TiB particles provide the crack propagation path with minimal crack deflection, Fig. 20. This trend increases with increasing the volume fraction of TiB particles thereby, further decreasing the fracture toughness.

Bhat et al. [85] compared the mechanical properties of Ti-TiB and Ti-(TiB + TiC) composites. In their work, the Ti-(TiB + TiC) composite demonstrated a non-uniform microstructure, while the Ti-TiB had a uniform microstructure with needle-shaped TiB particles. They implied

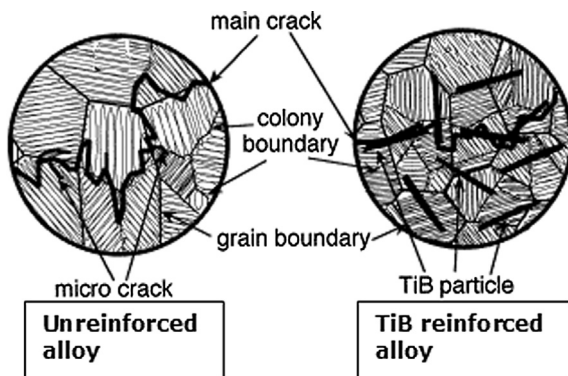


Fig. 20. Schematic illustrations of fracture mechanisms for monolithic and TiB reinforced alloy. Redrawn from Ref. [183].

that the presence of a large number of needle-shaped reinforcements in the fracture process confirms the effective load transfer from the Ti matrix to the reinforcement through the large interfacial area arising from the morphology of the reinforcement particles. Also, they observed the presence of tear ridges around the fractured needle-shaped particles indicating some amount of matrix deformation prior to the complete fracture. They concluded that the needle-shaped TiB reinforcement particles, help in improving the strength and fracture toughness of the composite by crack arresting [85]. Recently, Popp et al. [184] compared fracture toughness of different  $\alpha + \beta$  titanium alloy matrix composites containing carbide contents ranging from 0% to 15% by volume. They concluded that the composite containing 10% carbide results in excellent overall properties having a fracture toughness of 30.7 MPa. $\sqrt{m}$ . This was comparable to the fracture toughness of monolithic alloy, 40 MPa. $\sqrt{m}$ . DRTC based on Ti6Al4V alloy and 10 vol % TiCp has previously been reported by CermeTi® [185] and it is highly likely that they are already being used in commercial applications.

Although it has been suggested that the toughness of composites can be substantially increased by using nanoscale reinforcements such as carbon nanotubes, the results to date do not justify this claim. The importance of carbon nanotubes for TMCs has yet to be realised.

4.7. Anisotropy of fibre-reinforced TMCs

In general, fibre-reinforced composites show inferior properties under loading out of fibre axis, due to their specific morphology. This greatly impacts the tensile and compressive strengths, as well as the stiffness. However, due to the high-strength titanium matrix this effect is less pronounced for TMCs. Therefore, in spite of the existing anisotropy, a unidirectional reinforcement can be applied and sufficient properties in each direction can be obtained [61]. Table 5 shows the anisotropy ratio of TMCs in comparison with some other materials.

The properties in the transverse direction or normal to the fibres are dominated by the properties of matrix and interface. Fig. 21 shows the stress-strain response under transverse static tension loading. In region I, the composite is fully elastic and the stiffness is increased by the fibres. As the stress increases, shear stresses induced by the stress gradient exceed the shear strength of the interface in region II, which causes mode II failure of the interface. However, the crack surface is kept closed due to residual stresses and thus the stiffness is unchanged in this region [186]. If the applied stress exceeds the sum of the residual stress and the interface tensile strength, fibre and matrix separate (debonding) - region III, mode I failure. This is marked by a sudden drop in stiffness [187]. With further loading, the fibres bear no stress and the composite stiffness is lower than that of the unreinforced matrix material. Afterwards, the matrix deforms plastically, leading to a further decrease of Young's modulus in region IV. Similar damage mechanisms occur under creep and fatigue loading. However, they may occur at lower stresses.

4.8. Biocompatible TMCs

In recent times, TMCs are receiving increasing recognition as the potential biomaterials in the field of biomedical implants or devices [188–192]. The use of titanium and hydroxyapatite (HA) composites for biomedical applications has increased due to the resulting

Table 5  
Anisotropy ratio of different materials [61].

Material	$E_{\perp}/E_{\parallel}$	$\sigma_{\perp}/\sigma_{\parallel}$
Isotropic materials	1.0	1.0
Metals, rolled	~1.0	0.9 ~ 1.1
Glass fibre reinforced polymer (Unidirectional)	0.1 ~ 01.5	0.05 ~ 0.1
Carbon fibre reinforced polymer (Unidirectional)	0.02 ~ 0.1	0.02 ~ 0.1
TMC (Unidirectional)	0.7 ~ 0.8	0.15 ~ 0.2



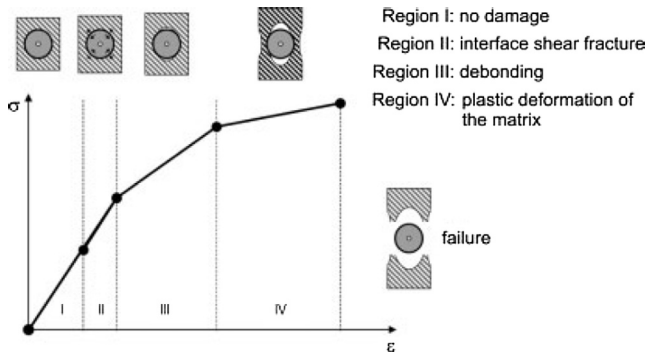


Fig. 21. Schematic of stress-strain response and damage events under transverse tension [61].

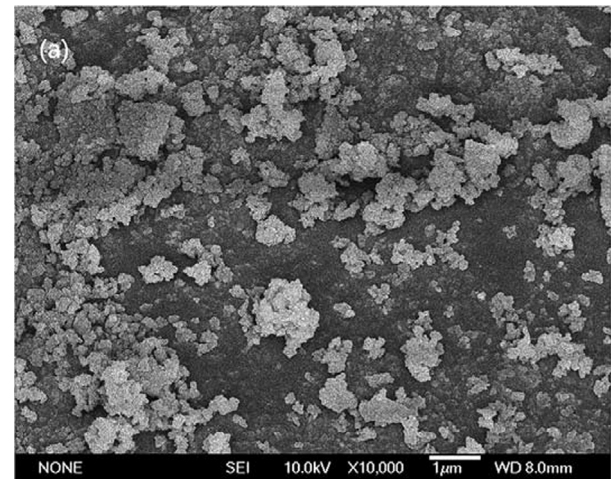


Fig. 23. Cross-sectional SEM micrograph of a Ti/HA composite manufactured by a 3D rapid prototype printer (LTY series, Shanghai Fochif Mechatronics Technology, Co, Ltd, China), taken from Ref. [200].

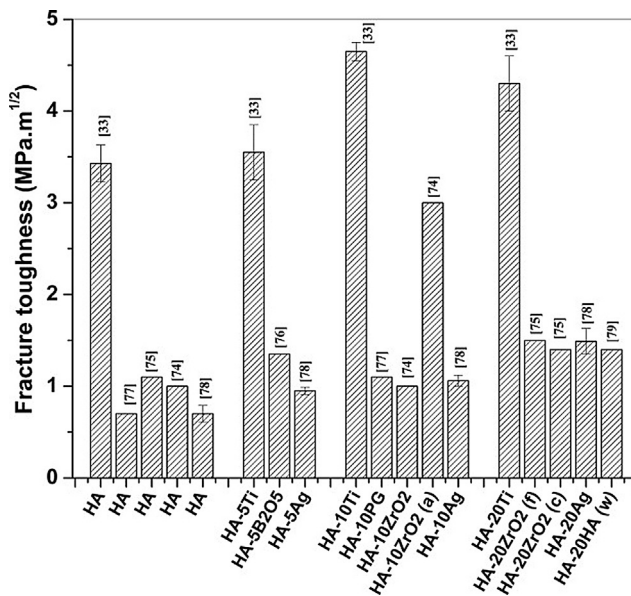


Fig. 22. A comparison of fracture toughness of HA-based composites. HA-Ti clearly outshines other ceramic-ceramic composites in terms of fracture toughness. Taken from Ref. [195] with permission.

advantageous combination of hydroxyapatite bioactivity and favourable mechanical properties of titanium. HA ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ ) is a bioceramic material frequently used for implants of human hard tissue because its chemical and crystallographic structure is similar to that of bone minerals [193]. Moreover, HA is nontoxic, bioactive and biocompatible, which results in better osseointegration between implants and bones [194]. However, a major limitation of using HA is its poor mechanical properties. On the contrary, Ti has superior mechanical properties and is considered a biocompatible metal- although its biocompatibility is not as good as that of HA. Consequently, with the purpose of creating high-efficiency biomaterials for medical implants, Ti-HA composites have been considered an encouraging group of materials, Fig. 22.

The simplest method to make Ti-HA composites is powder metallurgy [196–198]. Powder metallurgy uses powders from Ti and HA to obtain sintered composites with HA particles as “islands” in the Ti matrix. Recently, the FAST (field assisted sintering technique) has been used to prepare highly densified samples from the powder mixture within a short time [199]. In addition, additive manufacturing has also been utilized to fabricate these composites [200], Fig. 23.

## 5. Applications and future outlook

### 5.1. Typical applications

A report published by ex-NASA engineers in 2009 stated that the use of titanium composites in US fighter aircraft amounts to almost 40% for F-22, Fig. 24(a) [201]. With the development of new generation fighters such as F-35, it is worth assuming that this amount has likely been increased. Similarly, the lower drag brace for the landing gear of Royal Netherlands Air Force F16 is now made of SiC fibre reinforced TMC, Fig. 24(b) [202]. The TMC replacement offers 40% weight reduction compared to the original, which was made of high-strength steel. Additionally, the metallic composite materials have better corrosion and fatigue resistance than either steel or aluminium. Recently, Rolls Royce has tested a carbon/titanium composite fan system for the advanced ultra fan engine designs. The fan system includes carbon/titanium fan blades and a composite casing that reduce weight by up to 1500 lb per aircraft. This weight saving is equivalent to carrying seven more passengers at no cost. The engine design will also offer at least 20% less fuel burn and CO<sub>2</sub> emissions than the first generation of Trent engine, Fig. 24(c) [203].

Toyota Motors are now using connecting rods and engine valves made of DRTCs in their new vehicles, Fig. 25.

Dynamet Technology Inc., which is now merged with RTI international titanium segment, has shown previously that their in-house developed Ti metal matrix composites (CermeTi®) [185] is used in numerous applications from medical implant products to sporting knives, Fig. 26. Some additional industrial applications of TMCs are presented in Fig. 27.

### 5.2. Future outlook

#### A: New materials and industrial collaborations

In the past two decades, new industrial collaborations have been set up in order to develop and manufacture new materials systems for TMCs. For instance, FMW Composite Systems, Inc., in collaboration with Honeywell Aerospace proposed to develop a novel nano-dispersion reinforced TMC system that can operate at higher temperatures for impeller applications in advanced Army turboshaft engines. This project was funded by SBIR.STTR, America’s seed fund. Similarly, Lawrence Livermore National Lab and Pratt & Whitney made a Cooperative Research and Development Agreement (CRADA) to improve the ductility and toughness of high-strength, high-stiffness TiAl-base composite materials for commercial jet engines and U.S.

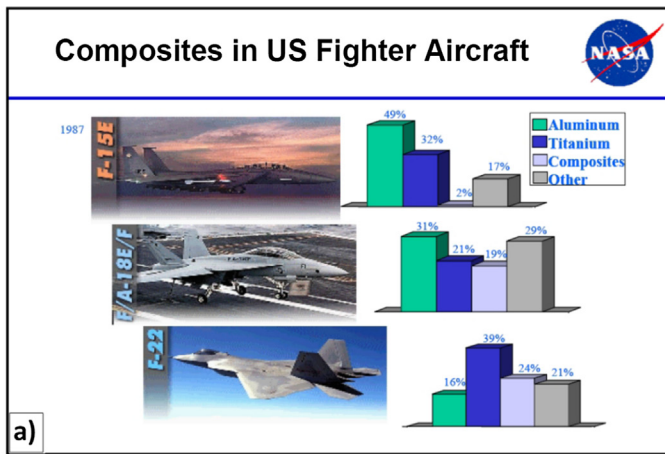


Fig. 24. (a) Usage of titanium composites in US fighter aircrafts [201]; (b) SP aerospace (Geldrop, The Netherlands) has developed a TMC lower drag brace for the landing gear on a Royal Netherlands Air Force F-16. It is the first application of an MMC landing gear part [202]; (c) Rolls Royce composite fan system for new engine designs [203]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

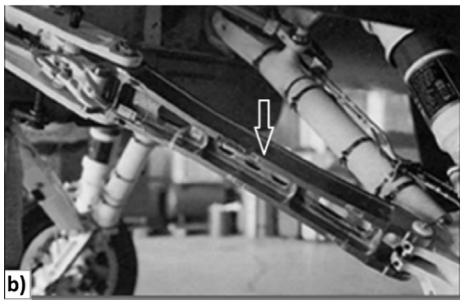


Fig. 25. (a) Engine connecting rod; (b) Engine intake valves, both made of DRTCs. Pictures courtesy of Central South University. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

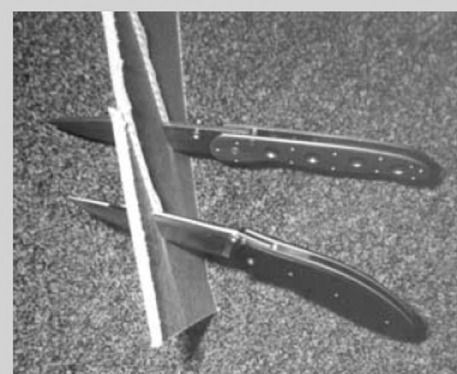
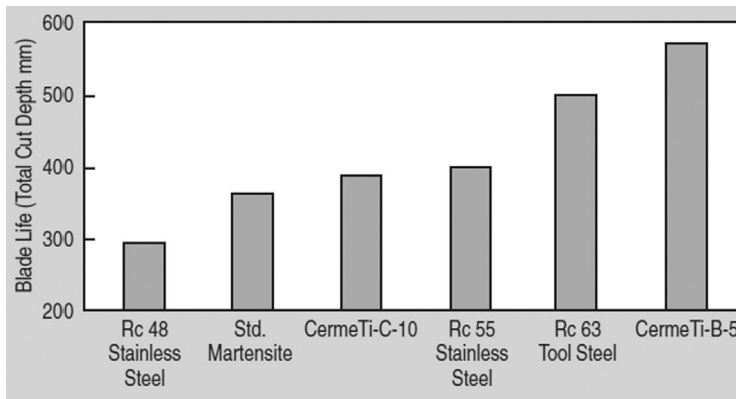


Fig. 26. Left: Comparison of sharpness retention by blades made of different, CermeTi-B-5 clearly outperforms all; Right: Sporting knives manufactured by Ken Onion Hawaii using CermeTi blades [185].



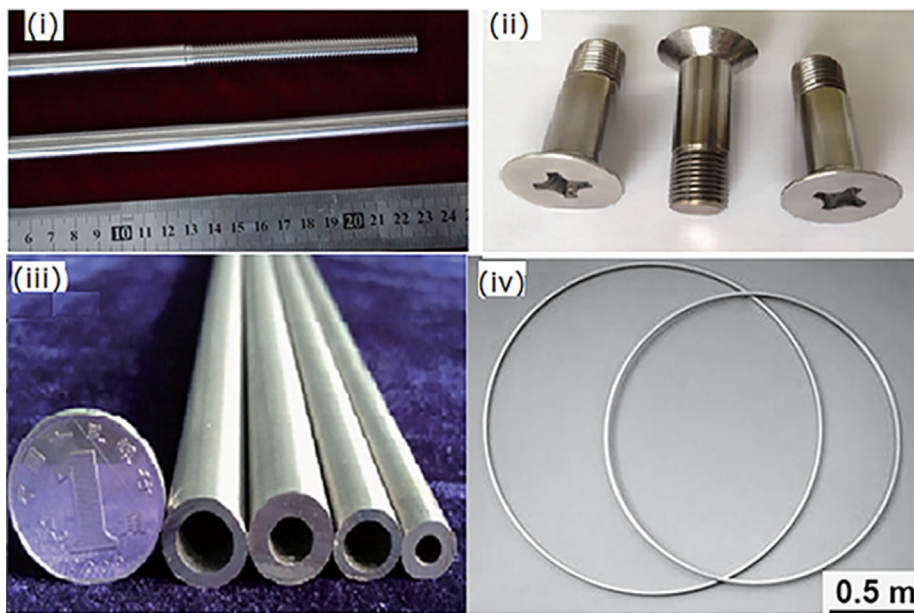


Fig. 27. (i) 8 vol%  $TiB_w$  / TC4 DRTC screw; (ii) 2 vol%  $TiB_w$  / TC4 DRTC fastener; (iii) The thin-wall pipes of DRTCs prepared by rotary forging technology; (iv) Two fibre-reinforced TMC rings of the type that could be incorporated into a rotating stage of an aircraft engine. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Department of Energy (DOE) Defense Program applications [204]. In another such collaboration, ORNL Manufacturing Demonstration Facility worked with XG Sciences, Inc. to develop composite material incorporating graphene platelets in a titanium matrix with the goal of improving thermal conductivity [205]. These developments are, however, not limited to industrial collaborations only. As stated earlier, individual research groups are also contributing soundly towards the development of new TMCs and further improving the properties of already established TMCs [39,62,206].

#### B: Manufacturing techniques

The surge of additive manufacturing (AM) technology in the past two decades has opened up new opportunities for the development of application-oriented TMCs. The most commonly used AM processes for composites are: Selective Laser Sintering/Melting (SLS/M), Laser Engineered Net Shaping (LENS), Fused Deposition Modeling (FDM), 3D Printing and Ultrasonic Consolidation. Among these SLS and LENS have seen some success in the development of TMCs – but only DRTCs. It should be noted that the production of fibre reinforced composites (mainly polymer based) are limited to Stereolithography (SL) and Laminated Object Manufacturing (LOM) techniques only. This is because in the powder-based AM techniques it is difficult to draw smooth layers to fibre-powder mixture. This gives rise to density variations and subsequently leads to reduced strength of final parts. Moreover, it is difficult to incorporate long fibres into processing [207]. Some of the common DRTCs manufactured by AM technology include: Ti/TiB [208,209], Ti/TiC [210], Ti/TiB + TiC [211], Ti/SiC [212], Ti/graphite/diamond [212], Ti64/TiB [213], Ti-48Al-2Cr-2Nb/TiC [214], and Ti-Cu/TiC [215]. Despite the fact that AM technology provides a promising platform for highly efficient fabrication of DRTCs and even though promising results have been reported in recent times, there are still some important aspects which require considerable attention and research. For instance, fatigue lives of AM fabricated titanium alloys, in almost every case, is lower than their wrought counterparts and require exhaustive post processing to achieve acceptable levels. This highlights that improvement of fatigue features for AM-produced DRTCs are even more challenging and may involve other complicating factors. Nevertheless, given the large volume of research activities currently aimed at AM technology, it is hoped that such challenges will be ironed out in the near future. Recently, Attar et al. [216] have reviewed the developments in AM of TMCs in detail. It is recommended that readers should consult it in order to learn more about AM of TMCs.

The developments in fabrication methods for TMCs are not limited

to DRTCs only. Hausmann et al. [217] developed a new lay-up technique to produce tubular samples of SiC reinforced TMC considering the anisotropic properties of composites. The industrial applications of their design have yet to be seen, but it shows that design-specific properties of fibre reinforced TMCs are achievable. Recently, studies on Ti metal-metal composites are also being carried out for potential applications in the field of biomedical [218–220].

In a nutshell, outstanding mechanical properties including high-temperature strength, stiffness and fatigue make fibre reinforced titanium matrix composites (TMCs) ideal candidate for demanding high technology applications, e.g., gas turbine engines, aerospace applications. However, the high material costs and strong fibre orientation effect result in their usage limited to niche applications only. On the other hand, DRTCs offer manufacturing flexibility at the cost of mechanical properties compared to fibre reinforced TMCs. Our ever-expanding appetite for the high strength-to-weight ratio of structural parts involved in military, aerospace or automotive applications in order to cut down fuel costs is continually feeding the research and development of TMCs. It is expected that this trend will remain the same in coming years.

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