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Review

Processing and Mechanical Characterisation of Titanium Metal Matrix Composites: A Literature Review

Raviraj Shetty [1], Adithya Hegde [1,*], Uday Kumar Shetty SV [1], Rajesh Nayak [1,*], Nithesh Naik [1] and Madhukar Nayak [2]

[1] Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India
[2] Department of Mechanical Engineering, Shri Madhwa Vadiraja Institute of Technology and Management, Bantakal 574115, India
* Correspondence: adithya.hegde@learner.manipal.edu (A.H.); rajesh.nayak@manipal.edu (R.N.)

Abstract: Today, Discontinuously Reinforced Particulate Titanium Matrix Composites (DRPTMCs) have been the most popular and challenging in consideration with development and heat treatment due to their significant weight-saving capacity, high specific strength, stiffness and oxidising nature compared with other metals and alloys. Owing to their excellent capabilities, DRPTMCs are widely used in aerospace, automobiles, biomedical and other industries. However, regardless of the reinforcements, such as continuous fibres or discontinuous particulates, the unique properties of DRPTMCs have dealt with these composites for widespread research and progress around the domain. Even though DRPTMCs are one of the most studied materials, expedient information about their properties, processing, characterisation and heat treatment is still scattered in the literature. Hence, this paper focuses on a literature review that covers important research work that has led to advances in DRPTMCs material systems. Further, this paper also deals with broad details about the particulates, manufacturing processes and heat treatment processes.

Keywords: DRPTMCs; processing; characterization; heat treatment

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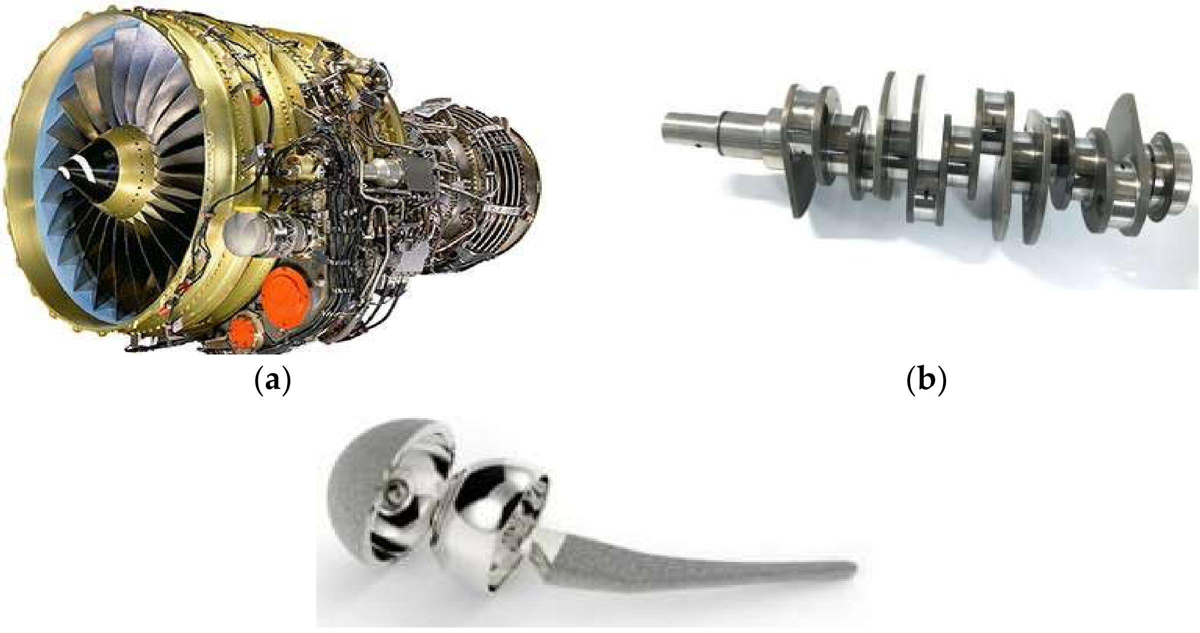
1. Introduction

The application of composite materials began during the Egyptian civilisation. Today, researchers are focusing on various matrix and reinforcement combinations with enhanced physical and mechanical properties. However, alloys are compositions made of two or more metallic elements [1,2]. To guarantee the stability of the dispersion phase, the matrix phase is a continuous phase in which a composite is created in a microstructure of metals and completely envelops the dispersed phase. Although the dispersive phase differs depending on the material, the matrix phase's significance remains constant in order to guarantee the appropriate execution of the dispersive phase. The strength of the bond in metals, which determines the rate of corrosion in Metal Matrix Composites (MMCs), can be strongly influenced by the effectiveness of the matrix phase [3,4]. Figure 1a—cshows examples of Titanium matrix composite applications [5–7].

High-tech industries like aerospace, defence, automotive, and civil engineering frequently use metal matrix composites (MMCs) as structural materials [8,9]. In particular, titanium alloy with reinforced particles is one such material. Particle-reinforced MMCs have the potential to provide superior mechanical qualities, such as increased specific strength and stiffness [10,11]. In order to increase the titanium matrix's stiffness, strength, hardness, and wear resistance while maintaining a quasi-isotropic behaviour that makes the standard reshaping process easier, ceramic materials are frequently utilised as reinforcement. Due to their superior mechanical qualities, silicon carbide (SiC) is one of the most often employed particles to reinforce titanium matrix [12]. The shape [13,14], size [15], volume fraction [16] and distribution of the reinforcements [17], along with the characteristics of the reinforcements and matrix materials [18,19], all influence the mechanical behaviour of particulate-reinforced MMCs. The mechanical characteristics of MMCs are influenced by the interfaces between the matrix and reinforcement materials [20,21]. Therefore, the total mechanical properties of the MMCs are greatly influenced by the load-carrying capacity of reinforced ceramic particles in the metal matrix [22] and the particle shape [23,24]. The toughness, strength, and ductility [25] of the composite are dramatically reduced by the debonding of reinforcements from the matrix. Cracks begin when the stress exceeds the interface's support capacity, typically at the points where the largest stresses are produced, such as the spherical reinforcements poles or the corners of triangular or rectangular particles. The damage spreads as the fracture widens along the matrix/particle contact and reduces the amount of load that the matrix transmits to the reinforcement or the strengthening effect of reinforcements. Last but not least, cavities grow out of interface cracks, and fracture is caused by the amalgamation of interfacial cavities. These mechanisms are widely acknowledged in polymer- and metal matrix-based composite materials [22,23], respectively [26,27]. Although titanium was first discovered in the 18th century [28], it was not until the middle of the 20th century that the titanium industry underwent substantial advancements. These modifications were brought about by the development of the gas turbine engine and resulted in the growth of industries specialising in the production of titanium sponges in the USA, Europe, and Japan [29], as shown in Figure 2a,b. Since then, the aerospace industry has dominated the use of titanium globally; both engines and airframe structures can use the metal. A very desirable combination of titanium's qualities includes exceptional fatigue resistance, a high strength-to-weight ratio, and great corrosion resistance. Such characteristics permit broad applications; the major limitation on further deployment is the high cost of extraction and processing. Although [30] the development of polymer-based composites and rising operating temperatures are issues for the aerospace industry, creative solutions like metal-matrix composites and titanium aluminides open up new possibilities for growth. Industries currently utilising these materials include biomedical, sports and marine sectors. Physical and mechanical properties are given in Tables 1 and 2.



(**a**) (**b**)

(**c**)

Figure 1. (**a**) Aircraft engine. (**b**) Titanium-MMC crankshaft (**c**) TMC cartilage implant [5–7].

(**a**) (**b**)

Figure 2. (**a**) Titanium Sponge (**b**) TMC Engine blade ring of aircraft [29].

Table 1. Physical properties of Titanium [31].

Element Properties—Titanium	
Atomic Number	22
Atomic Weight	47.867
Melting point	1600 °C
Boiling point	3287 °C
Density	4.5 g/cm^3
Oxidation states	+2, +3, +4
Electron configuration	[Ar]3$d^2$4s^2

Table 2. Mechanical properties of Titanium [32].

Natural Occurrence	Primordial
Crystal Structure	Hexagonal close packed
Thermal Expansion	8.6 µm/(m·K) (at 25 °C)
Thermal Conductivity	21.9 W/(m·K)
Electrical Resistivity	420 nω·m at 20 °C
Magnetic Ordering	Paramagnetic
Young's modulus	116 GPa
Shear Modulus	44 GPa
Poisson ratio	0.32
Moh's hardness	6.0
Vicker's hardness	830–3420 MPa
Brinell hardness	716–2770 MPa

2. Processing Methods of TMCs

Discontinuously reinforced titanium composites are produced majorly through the processes mentioned below.

2.1. Powder Metallurgy

Due to the strong chemical reactivity of titanium, standard ingot metallurgy methods are not suited for producing TMCs enhanced with ex situ additive particles. In order to create TMC components, powder metallurgy (PM) methods are frequently used. In fact, one of the best fabrication techniques for the creation of DRTCs is the PM processing route [33–35]. Homogeneous powder mixing and dispersion are the two most crucial factors in assuring the optimal performance of composites during the PM processing of DRTCs. The surface coating may occasionally be used to improve or guarantee homogenous dispersion [36]. The ultimate properties of the composites are determined by choice of distributed reinforcements, their size, shape, content, and the interfacial bonding between reinforcements and the matrix [37]. Depending on how the additives interact with the matrix, the reinforcements can be introduced into the matrix using either an ex situ or an in situ processing method [38,39]. Low porosity Ti/TiB composites have been synthesised using TiH_2 and TiB_2 powders via a hydrogen-assisted blended elemental powder metallurgy route. It resulted in the formation of highly dense structures because of incomplete in situ transformation of TiB_2 into the TiB phase [40]. While fabricating β titanium alloy matrix composite, it was found that nucleation of TiB and TiC particulates causes the formation of hard β phases of TiB and TiC, causing a substantial increase in the hardness of the composites. Ref. [41] evaluated the feasibility of using coated SiC and TiC as reinforcements with Titanium alloy in order to achieve homogenous mixing. It was noticed that hardness improved with an increase in sintering temperature, and the highest hardness value of 385 +/− 20 Hv was recorded. Ref. [42] concluded that there was an increase in the density of the sintered $Ti\text{-}^{nano}Al_2O_3$ composites with an increase in sintering time. Further, it also improved the hardness values and corrosion behaviour of the composite. Ref. [43] have used Artificial Neural Networks to predict the wear behaviour of titanium-nano graphene platelets (Ti-(GNPs)-Si_3N_4 produced through powder metallurgy. They concluded that sintering temperature holds the highest impact on the surface roughness and hardness of the composites, followed by sintering time. Ref. [44] fabricated titanium-graphene oxide (Ti-GO) through hot pressed sintering with varying (1–5%) Wt.% of graphene oxide. Because of the agglomeration of graphene oxide particles, there was a slight decrease in yield stress but a substantial improvement in hardness with a maximum hardness value of 457 Hv at 5 Wt.% of graphene oxide. Ref. [45] studied the effect of process input parameters on the hardness of titanium matrix composites processed through direct energy deposition-based additive manufacturing. Crack-free titanium matrix composites with a hardness of 700 Hv and density of 99.1% were achieved with 5 Wt.% Titanium Boride as reinforcement material.

2.2. Ex Situ Processing Technique

Ex situ processing methods are used to include thermodynamically stable ceramics in titanium, such as SiC, TiC, TiB, and ZrC. Except when external impacts are applied on purpose, as in mechanical milling, both the particle size and morphology of the added particles before and after sintering essentially remain unchanged. This is because no new compounds are created during sintering and consolidation [46]. In addition to producing DRTCs with improved mechanical qualities, ex situ production of these materials also enhances wear resistance and stabilises the friction coefficient during dry sliding [47]. The ex situ approaches for creating DRTC have not attracted much attention because of their own drawbacks, such as the inadequate bonding between the matrix and the reinforcement [48].

2.3. In Situ Synthesis Methods

During in situ processing, the titanium matrix's high reactivity is combined with additive elements like boron, carbon, and nitrogen to create in situ stable particulates or needle-like reinforcements, which are dispersed through a solid-state reaction. TiB2, B4C, Cr3C2, and Si3N4 are common starter additions for in situ processing. As an illustration, [49] titanium powder and TiB2 particles can interact during the sintering process to generate TiB whiskers, which are then disseminated throughout the matrix as reinforcement. In the case of in situ processing, increased interfacial bonding between the matrix and reinforcement leads to improved tribological performance. Additionally, composites created using in situ procedures have superior oxidation and creep resistance, high specific strength, and modulus [50,51]. To prevent the creation of interfacial defects, the in situ reactions must be carefully controlled.

2.4. Rapid Solidification Process

Rapid solidification technology has improved greatly over the last 20 years to become a promising fabrication method for DRTC processing [52–54]. Metallic powders are frequently produced in large quantities via the atomisation process. By atomising the melt with the reinforcements present, composite powder with the reinforcements can be created. One such instance was the remelting of a composite ingot made of Ti-6Al-4V (20 vol% TiC) employing induction heating and argon gas flow. The composite powder was then used to manufacture bulk composite material using hot isostatic pressing (HIP) at 900 and 950 °C, under 100 MPa for 4 h [55]. For the production of titanium metal and titanium inter-metallic matrix composites, Martin Marietta Laboratories has created a unique ingot metallurgical method [56]. During the casting process, the XDTM technology creates in situ ceramic reinforcements that are thermally stable, kinetically inert, and evenly spread within the melt. Ingots of Ti-48Al-2V and Ti-45Al with TiB2 reinforcement were created using this technology. Then, with the use of centrifugal atomisation and a rotating consumable electrode, powders of these composite materials were created. The atomisation procedure kept the ceramic particles that had formed in the ingot. It was discovered that the processing temperature had a significant impact on the size and scale of the TiB2 particle dispersion [57]. Similar to this, by consolidating rapidly solidifying Ti64 alloy with various levels of boron addition, [58] created in situ TiB-reinforced Ti64 composites. The Marko 5T melt-spinner was used to carry out the quick solidification procedure [59,60]. This approach is only applicable to reinforcements that should have a density similar to that of the matrix material. The atomisation process can result in non-uniform distribution of reinforcements in the composite powder due to particle aggregation if the density of the reinforcements differs significantly from that of the matrix. Rapid solidification leads to non-equilibrium, which opens the door to new alloying techniques, such as the incorporation of rare-earth alloying elements in titanium. Recent research by [61] has shown that plasma can be used as a chemical reactor to create in situ titanium composites using induction plasma technology. They stated that the chemical reaction between the components injected into the plasma could directly produce Ti64 reinforced with TiC or TiN particles. Figure 3 shows DRTCs' fabrication processes through the powder metallurgy route.

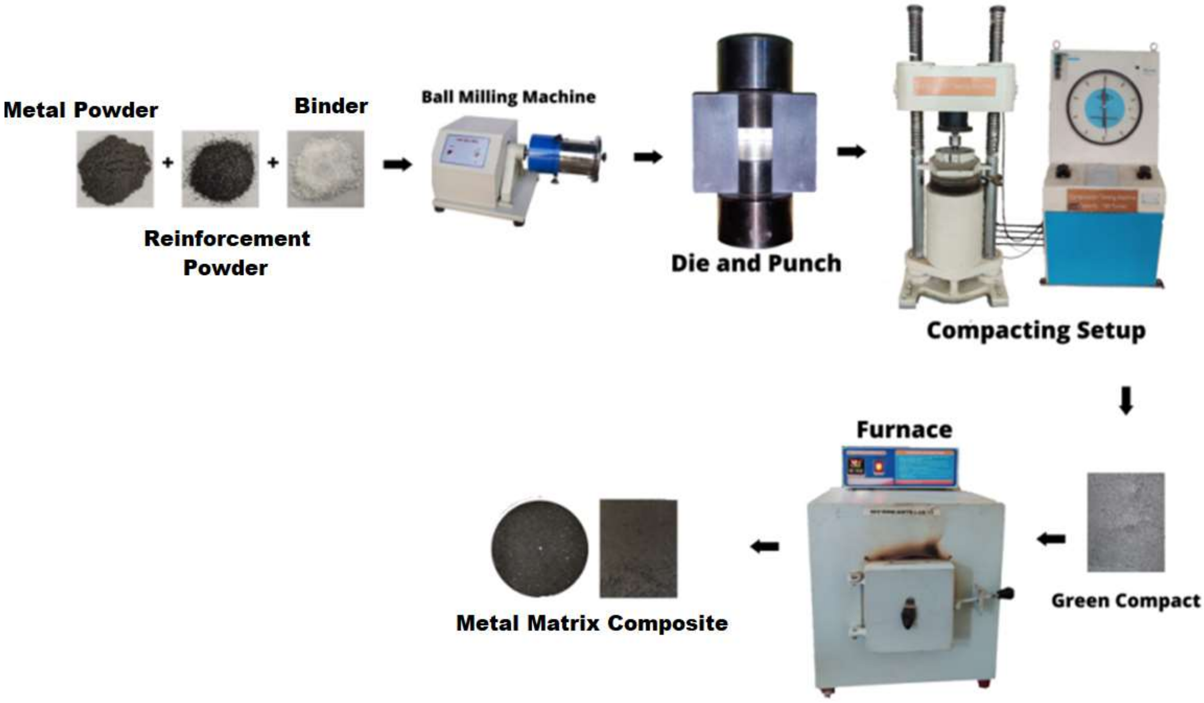


Figure 3. Powder metallurgy process.

3. Mechanical Properties of Titanium Matrix Composites

Multiple physical factors must be understood in order to characterise composite materials mechanically. Ref. [62] examined the mechanical behaviour of Ti-6Al-4V composites at 538 °C after they were strengthened with 10 wt% TiC particles made by cool and hot isostatic pressing, including their ductile and creep properties (CHIP). At strain rates ranging from around 10^{-5} to 10^{-3} s^{-1}, they discovered that the yield quality (YS) and extreme rigidity (UTS) of the composite were more notable than those of the matrix compound, and the composite's creep resistance was superior to that of the matrix compound. However, the composite material's extension was noticeably lower than that of the matrix compound. The results of the tensile test on the matrix compound showed dimpled breakage, while the results of the creep test on the matrix compound revealed interlatch and intercolony cracking particularly. The cleavage failure of the particles, followed by the bendable fracture of the matrix, regulated the failure of the tensile-tested and creep-tested composite material. By applying uni-axial strain at high temperatures, Ref. [63] conducted another study to examine the mechanical characteristics and fracture mechanism of in situ blended titanium composite. Their research shows that when the temperature rises, the ultimate tensile strength decreases and the ductility increases. The extreme tensile strength of the composite was significantly increased when compared to the matrix compound because the in situ generated reinforcement is particularly stable at high temperatures and can successfully strengthen the matrix combination. The temperature affected the fracture behaviour. Due to the fortifications breaking, the composites fail with modest strain at room temperature. As a result, the primary cause of the failure of composites is the debonding between the reinforcement and the matrix component. Using standard casting and hot working techniques, Ref. [64] examined the flexible characteristics of high-temperature titanium matrix composites reinforced with hybrid reinforcements. The ultimate strength of a composite is discovered to be considerably increased under all circumstances, although it decreases when the strain rate is lowered. The results of the aforementioned investigation show that interfacial debonding is more extreme and reduces the strength of composites. Their findings show that interfacial debonding is more severe and reduces the strengths of composites at higher temperatures or slower strain rates. Additionally, it is discovered that the materials become brittle under creep-rupture circumstances. The microstructure and mechanical characteristics of extruded pure Ti matrix composites supplemented with TiC particles were evaluated in the study [65]. Spark plasma sintering (SPS) and hot extrusion were used to create a titanium matrix composite (TMC) that was reinforced with inexpensive carbon black. Carbon dark particles were included in the SPS method for the in situ arrangement of TiC dispersoids. Using a wet process and a zwitterionic solution containing dark carbon spheres, two different types of titanium (Ti) powder, sponge and fine Ti, were coated with dark carbon particles. They discovered that the mechanical properties of these composites were enhanced by the addition of a little amount of carbon dark at 0:070:16 mass%. In comparison to extruded pure Ti with no fortification, the yield stress increases of the expelled sponge and fine TMC were 70.0 and 291 MPa, whereas the rigidity increases were 67 and 231 MPa, respectively. They discovered cracked surfaces on the TMC samples after tensile testing. Ref. [66] prepared a composite material made out of high-thickness polyethylene and inorganic colour (carbon dark and titanium dioxide). Titanium dioxide and carbon black were used in various amounts to create the filler (2–15 wt%). The results show that the mechanical properties may be changed consistently by using colours, carbon dark, and TiO_2 in the right quantities. With the high-thickness polyethylene, the weight fraction of the carbon blacks and titanium dioxide ranged from 0.0 to 15 wt%. After passing a high voltage through the composite, it was discovered that its resistivity had decreased. When compared to pristine high-density polyethylene, carbon black and titanium dioxide-high-thickness polyethylene composites exhibit considerable differences in the frequency range. Both carbon black and titanium dioxide/high-density polyethylene composites are shown to have improved thermal characteristics than that neat high-density polyethylene.

3.1. Static Properties

In general, the rule of mixtures can be used to determine the strength and stiffness of composites in the longitudinal direction if the parameters of the matrix and fibres are known. A number of researchers have measured the tensile characteristics of SiC-reinforced TMCs on composites made using various fabrication techniques and varied volume fractions of SiC fibre [67]. Figure 4 compares the ultimate tensile strength (UTS) of unreinforced alloys to that of several composite systems over the temperature range of 25 to 800 °C. Perhaps the most remarkable quality of unidirectional reinforced composites is high longitudinal strength up to high service temperatures. 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, whereas the UTS of traditional "+" alloy, titanium aluminides, and Ti-Al-Nb vary from 400 MPa to 1200 MPa at room temperature and from 250 MPa to 500 MPa at 800 °C. According to the literature [68], the strength increases gradually until the loading direction is not parallel to the fibre axis. Because of the weak fibre/matrix interaction, there is inadequate load transfer to the fibres, which results in low off-axis strength. It is interesting to note that this weak interface is required for acceptable fracture toughness at fibre/matrix interfaces in order to produce crack deflection [69]. Due to this significant fibre orientation effect, careful design strategies are required to optimise loads parallel to the fibre path and minimise them in other directions. The high cost of fibre-reinforced TMCs may outweigh the advantages gained from the usage of composites in the absence of such design adjustments.

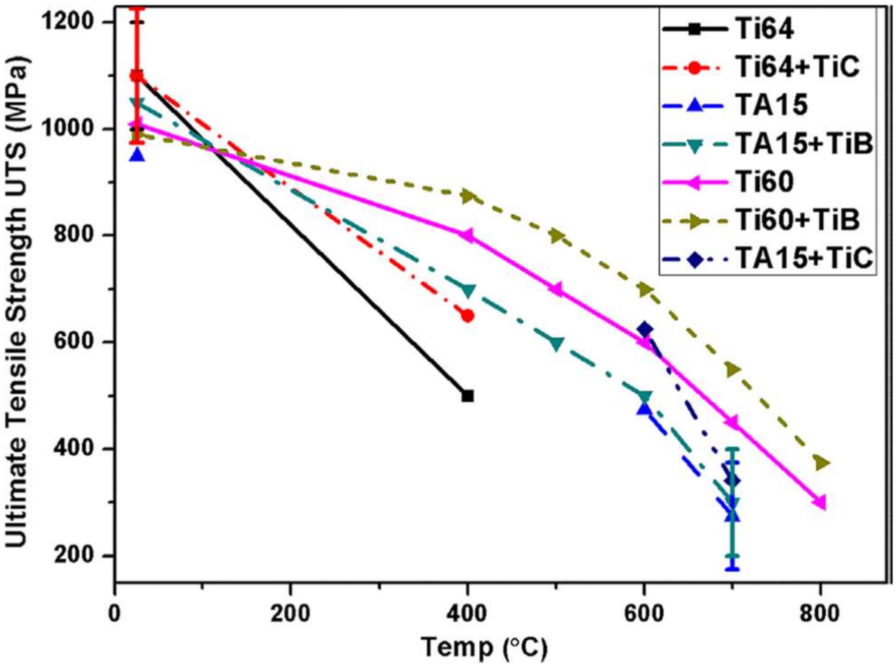


Figure 4. General overview of the UTS over a temperature range for different SiC fibre-reinforced composites [53–59].

The research [70,71] states that in situ generated TiB whiskers (TiBw), and TiC particulates (TiCp) are the most efficient reinforcements for DRTCs because of their high modulus and hardness, strong chemical compatibility with titanium, similar density, and thermal expansion coefficient. With monolithic alloys, Figures 4 and 5 compare the UTS of several reinforcing DRTCs created using various in situ synthesis techniques [53–59]. Figure 5 shows that DRTCs have greater tensile strength than monolithic alloys over a range of temperatures, with the difference becoming more noticeable at higher temperatures. Interestingly, compared to fibre-reinforced composites, the inclusion of ceramic particles or whiskers does not appreciably raise the UTS of metal or alloy (in the longitudinal direction). When it comes to DRTCs, the increase in UTS is primarily the result of dispersion-strengthening and hardening by uniformly dispersed small particles, or whiskers (in dispersion strengthening, secondary hard particles, or dispersoids, block the dislocation movement via the well-known Orowan looping mechanism). The dispersoids ex situ added are typically stable at high temperatures (in contrast to precipitation hardening, where precipitates are generated in situ via solution ageing). It is important to note that the strength of composites at high temperatures is not constrained by the fibre or particulate's insufficient strength. Instead, it is constrained by the matrix material's capacity to withstand high temperatures. The composite's service temperature limit is thus determined by the matrix material selected. The high-temperature strength of DRTCs is increased by increasing the volume percentage of reinforcement, albeit at the expense of ductility and oxidation resistance. Recent research [70] has demonstrated that adjusting the distribution of reinforcement is a successful method for concurrently enhancing the ductility, deformability, and high-temperature strength of DRTCs. They asserted that by carefully adjusting the reinforcement distribution, it is possible to achieve significantly higher tensile strength and service temperatures while also resolving the critical issue of extreme brittleness that surrounds DRTCs made by PM and enabling them to exhibit superior ductility. Numerous findings in the literature [64–66] also advocate the use of reinforcement combinations to maximise the advantages of individual reinforcements. In situ TiC particle, Ti3SiC2 bar, and ultrafine Ti5Si3 needle-reinforced Ti64 matrix composite were recently successfully designed and manufactured by [71]. The outcome showed that tailored reinforcement distribution was accomplished using larger-sized matrix powders, smaller-sized reinforcement powders, low-energy milling, and in situ hot reaction pressing. The (TiC + Ti3SiC2 + Ti5Si3)/Ti64 composites showed a strong mix of strength and ductility when compared to monolithic Ti64 alloy; in particular, the composites with 5.0 vol% reinforcements and made using 0.5 m SiC had a UTS of 1171 MPa and elongation of 5.3%. They asserted that the customised network structure, the hybrid strengthening impact, the size of the matrix region, and the solid solution strengthening effect were the key causes of this improvement in characteristics (Figure 5).

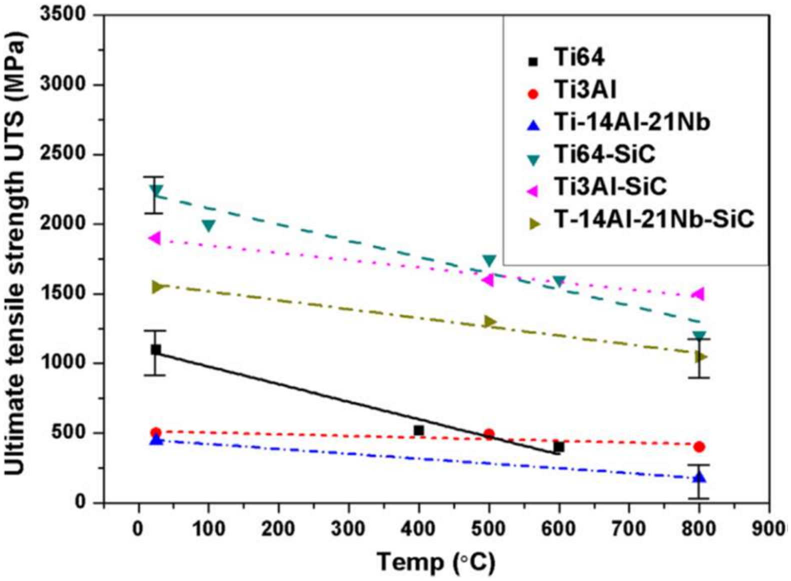


Figure 5. Ultimate tensile strength values of different DRTCs over a temperature range [71].

3.2. Wear Properties

Wear-resistant applications are another situation where DRTCs are preferable over fibre-reinforced composites. Due to titanium's low hardness, it and its alloys are typically regarded as being unsuitable for wear-resistant applications. The hardness of ductile titanium matrix is greatly increased by the addition of hard ceramic particles or fibres, and this increase in hardness is directly inversely related to the volume percentage of ceramic reinforcement. Due to their high price and anisotropic features, fibre-reinforced titanium composites have rarely been researched and used for wear-resistant applications. The wear and tribological characteristics of DRTCs have been documented by several researchers [65,68–72]. Ref. [72] investigated the wear and friction characteristics of titanium matrix (TiB + TiC) composites. Commercially pure (CP) Ti (Grade 2) was combined with granular B4C via vacuum induction melting. They came to the conclusion that the ideal reinforcement content to improve friction characteristics is 20%, and wear loss visibly decreased as reinforcement content increased. Recently, Ref. [73] achieved the successful fabrication of in situ TiBw/Ti64 composites with a network topology. According to their explanation, the TiBw network border served as a "barrier wall" and efficiently resisted abrasion, significantly improving the hardness and wear parameters compared to those of the Ti64 alloy. They also discovered that the network size has a significant impact on the wear attributes and process. As the network size increased from 60 to 200 micrometres, the wear mechanism changed from micro-cutting to brittle debonding. Wear loss increased from 4.654 mg to 6.110 mg, while the coefficient of friction (COF) increased from 0.164 to 0.188. They came to the conclusion that the best wear resistance was found in a composite with 8.5 vol% TiBw and a network size of 60 m. In a different work, Ref. [74] created a functionally gradient Ti-4Al-2Fe/TiB/TiC composite using spark plasma sintering (SPS). In situ, TiB was created using potassium tetrafluoroborate (KBF4) as a boron precursor, while TiC was created during the sintering process using graphite foils placed on either side of the compact as a carbon source. With ultrafine TiC on top, fine TiB needles close to the surface, and coarser TiB whisker-reinforced Ti (Ti-4Al-2Fe/TiBw) in bulk, the resulting microstructure has different characteristics. The bulk Ti-4Al-2Fe/TiB composite had a hardness of 7 GPa, but the TiC surface layer had a very high hardness of 20 GPa. As a result, the wear rate of the surface TiC layer was significantly lower than that of the bulk Ti-4Al-2Fe/TiBw composite, serving as an efficient wear protection. The two examples above demonstrate how application-specific wear characteristics can be achieved by carefully regulating the volume fraction of reinforcement and the microstructure of DRTCs.

3.3. Fatigue Properties

The insufficient fatigue resistance of monolithic lightweight alloys for numerous demanding applications, such as rotating components of jet engine compressors, is the primary factor pushing the development of TMCs [75]. One of the most crucial design factors in choosing materials for engine compressors is the fatigue behaviour under high stresses. Fatigue resistance can be significantly increased by using a high-stiffness ceramic reinforcement. Determining the fatigue behaviour of composites is not an easy process, however. Compared to homogeneous and isotropic materials like metals, their behaviour is more unpredictable. When assessing their fatigue behaviour, composites are frequently considered metals [76]. Due to a variety of factors, this strategy may cause numerous problems. In contrast to metals, where damage accumulates mostly locally, composites tend to accumulate damage more generally. Furthermore, failure typically does not result from the growth of a single macroscopic break. Additionally, a TMC material may sustain many kinds of damage, including fibre fracture, matrix cracking, and fibre matrix debonding. The complexity of the issue is heightened by the interactions between the damages and the various harm growth rates. In one type of composite, a failure mode that is dormant may become very active and even critical in another type of TMC material. Additionally, for various loading orientations, various primary damage mechanisms may be activated. Using common alloy testing procedures, the fatigue testing of DRTCs can still be measured with some degree of accuracy. However, some crucial factors should be taken into mind, especially for fibre-reinforced composites:

3.3.1. Reinforcement Type and Configuration

It is common knowledge that the size and volume percentage of the reinforcement has a significant impact on the fatigue strength of composites. Additionally, the uniform alignment of fibres for fibre-reinforced composites and the homogeneous discrete distribution of the reinforcing particles/whiskers/short fibres in the case of DRTCs have a major impact on fatigue behaviour. Numerous experimental findings have demonstrated that the spatial alignment and homogeneity of reinforcement have a negative impact on fatigue behaviour [77].

3.3.2. Manufacturing

The production procedures have an impact on the mechanical properties of composites. Any material preparation that can increase the matrix's resistance to crack propagation or the interfacial adhesion is likely to increase the composite's fatigue properties. The fatigue behaviours of composites under service circumstances are significantly influenced by parameters like surface state and roughness, just like in metals [78].

3.3.3. Loading Conditions in the Case of Fiber-Reinforced TMCs

As was already discussed, a composite material may experience various damage mechanisms based on the loading circumstances. It is mainly unknown how composite materials will behave in complex stress situations. Due to the expense and time required for testing, fatigue tests for composites are often conducted under the simplest loading conditions, namely constant stress under tension-tension loading [79]. Figure 6 shows a cross-section of the worn surface and a proposed illustration of the network-structured DRTC undergoing the sliding wear process.

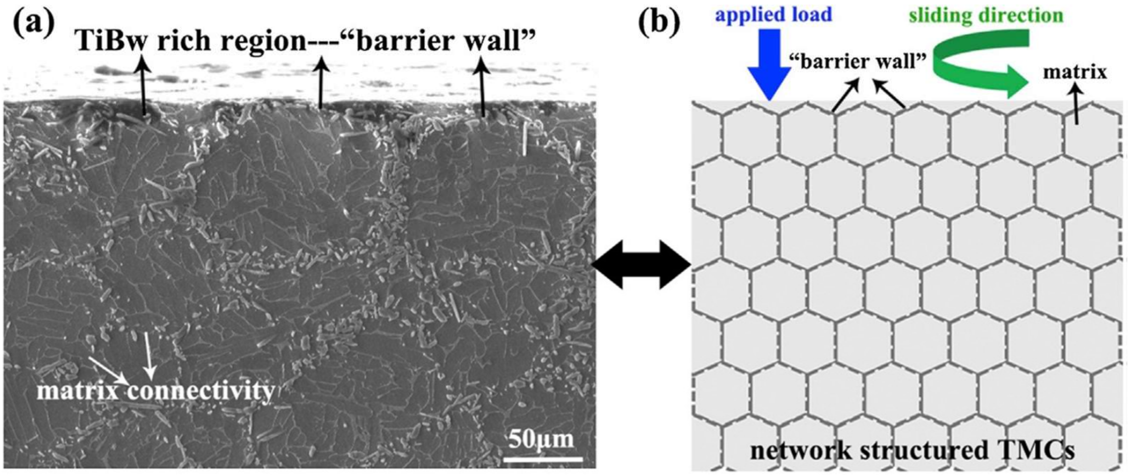


Figure 6. (**a**) Cross section of the worn surface; (**b**) Proposed illustration of the network structured DRTC undergoing sliding wear process [79].

3.3.4. Prior Impact Damage

The post-impact fatigue behaviour is still not fully understood, and the effects of low-velocity impact damage on the fatigue life and dependability of the affected structure are not clearly characterised. This characteristic of composite behaviour has been shown to be a significant barrier to the use of composites, particularly in the aerospace industry [80–82].

Figure 7 illustrates how using fibre-reinforced TMCs improves fatigue characteristics. TMCs have a much greater maximum cyclic stress than unreinforced materials both in the low cycle fatigue (LCF) regime and the high cycle fatigue (HCF). SiC/Ti64 has an endurance limit of 750 MPa as opposed to the unreinforced Ti64′s approximately 500 MPa. According to [83], the improvement in fatigue characteristics at higher temperatures is considerably more significant.

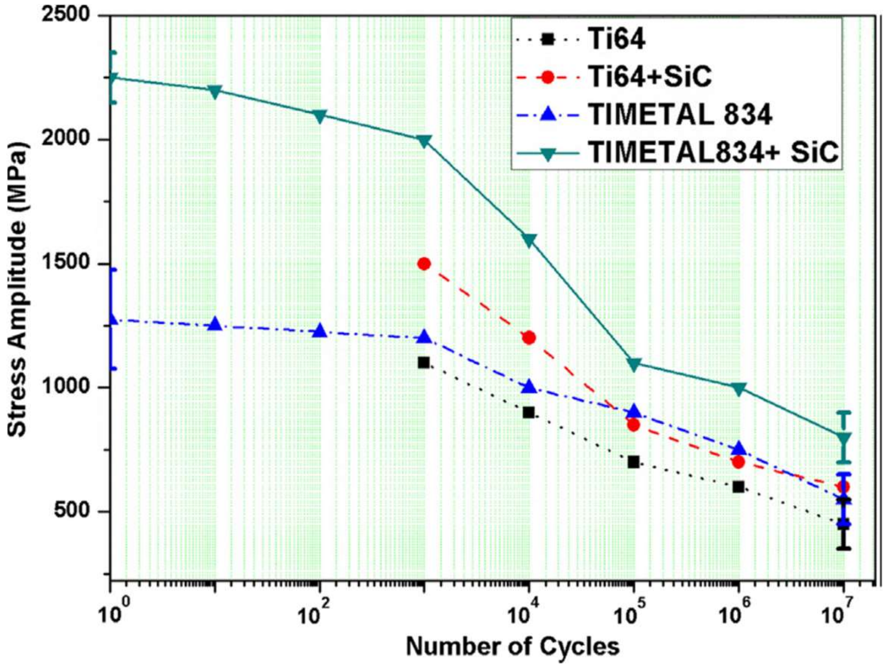


Figure 7. Fatigue behaviour of SiC fiber-reinforced TMCs [83].

3.4. Fracture Toughness

The orientation/distribution of fibre/particles in the matrix, the processing technique, and the interface properties all affect the fracture toughness of TMCs, as do many other mechanical properties. SiC fibre-reinforced TMCs have outstanding longitudinal tensile, fatigue, and creep properties, but their fracture toughness is less than that of typical titanium alloys. SiC-reinforced TiAl, in particular, experiences poor impact resistance and damage tolerance as a result of the titanium aluminide matrix's weak natural fracture toughness [84]. Combining two distinct alloys as the composite matrix is one method of increasing the fracture toughness of TMCs made of TiA matrix [85] employing the combination of a ductile Ti6Al4V alloy with a TiAl alloy as the matrix, while SiC fibre as reinforcement. They claimed that a hybrid matrix might significantly improve the fracture toughness of composites made of TiAl. The compliant Ti6Al4V layer acts as a layer to accommodate the residual stresses because it is ductile. Additionally, while maintaining the high-temperature characteristics and environmental resistance of the TiAl layer, the Ti-6Al-4V layer successfully prevents the spread of micro cracks started from the brittle layer. They came to the conclusion that by using such hybrid matrices, the resulting composites could be used at temperatures that were much higher than those possible with ductile titanium alloy matrix composites while also increasing the titanium aluminide matrix composites' damage tolerance. Recent research on Ti64-(SiCf/Al3Ti) laminated composite can be found in [86]. Foil-fiber lay-up process was used to create the composite, which was then sintered in a vacuum hot pressing furnace in the following order: Ti64, SiC, Al, SiC, Ti64. The mechanical testing that followed supports the judgement made by [87]. In the earlier papers [88–90], the toughening mechanisms for fibre-reinforced TMCs have been thoroughly investigated and reported. When it comes to fibre-reinforced composites, the toughening mechanisms may include fibre bridging, fibre/matrix interfacial debonding, which might result in fracture deflection or crack-arresting effects, and matrix plastic deformation. Ref. [89] investigated the uniaxial SiC fiber-reinforced Ti64 alloy's fracture toughness. They asserted that a plastic deformation zone arises before the fracture tip as a result of the applied force. Due to the various deformation capabilities of the matrix and the fibre, the interface of the matrix and fibre rebound as the load is raised, which causes fibre pull-out. The load is currently supported by the matrix and fibre pull-out. As a result, it is hypothesised that the characteristics of the matrix, fibre, and fibre pull-out mechanism are connected to the toughness of fibre-reinforced TMCs. They also attained a fracture toughness of about 50 MPa (for comparison, the fracture toughness of pure Ti and its alloys varies from 28 to 108 MPa). They also noticed that heat treatment causes the fracture toughness to decrease. A strong interfacial interaction between SiC fibres and the Ti64 matrix is thought to be the cause of this decline in fracture toughness [90].

4. Conclusions

This literature review in this paper provides a brief summary of the effect of processing parameters and mechanical characterisation of titanium matrix composites (TMCs). Despite the significant research, the application of TMCs in the automotive and aerospace sector can still be expanded upon by optimising its processing and behaviour traits. Therefore, there is a need for additional research studies in the area of TMC processing. This article gives a thorough analysis of the impacts of processing factors on TMCs based on a thorough review of prior work on various processing methods and mechanical characterisation of TMCs. Following are the conclusions that can be drawn from this literature review.

- From the literature, it was observed that among Powder Metallurgy, Ex situ, In situ, and Rapid Solidification for TMCs, Powder Metallurgy had been proven to be the best processing technique. Homogeneous powder mixing results in isotropic dispersion of reinforcements and the interfacial bonding between reinforcements and the matrix.
- It was also observed that the sintering temperature above 1000 °C resulted in Silicides and ternary carbide formation during the processing of TMCs in the powder metallurgy technique. Hence, these silicide and ternary carbide formations improved mechanical properties and wear resistance and also stabilised the friction coefficient.
- Further, during in situ processing technique, the titanium matrix is combined with additional elements like boron, carbon and nitrogen, which are dispersed through a solid-state reaction. The improved interfacial bonding between the matrix and the reinforcement results in higher specific strength and modulus and improved tribological performance.
- Finally, in the rapid solidification technique, particle aggregation during the atomisation process may result in a non-uniform distribution of reinforcements in the composite powder.

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