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A REVIEW ON PROCESSING ROUTES, PROPERTIES, APPLICATIONS, AND CHALLENGES OF TITANIUM METAL MATRIX COMPOSITE[†]

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Titanium is currently familiar for its light weight, high strength, and non-reactive nature over all the metals. Titanium metal matrix composites (TMCs) are very popular in the field of aerospace, automotive, defense, and biomedical because of their high specific strength, light weight, and biocompatibility nature. Some of the extensively used fabrication methods like powder metallurgy (PM), additive manufacturing (AM), and spark plasma sintering (SPS) have been reviewed here with some of the properties of TMCs. By varying various types of reinforcements, it is possible to achieve the required properties as per industrial and modern applications in TMC. This study also includes the consequence of sintering temperature on properties of TMCs like physical, mechanical, and structural. Titanium alloys are showing good mechanical and biomedical properties when reinforced with carbon fibers, borides, ceramics, and plenty of other materials as continuous fiber or discontinuous particulates and whiskers. In this paper, the applications of TMCs in aerospace, automobile, biomedical, and defense have been narrated. Besides all these favorable properties and applications, TMCs can't be used extensively in the said applications because of their high cost and difficulty in machining, that discussed in this paper over various challenges of TMCs. The cost reduction can be done by making Ti - super alloys. In addition, there is a necessity for an effective cooling system during the machining of TMCs to enhance machinability and some of the effective methods which may enhance the machinability of TMCs were also discussed.
Keywords: Ti MMC; PM; AM; SPS; Challenges
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INTRODUCTION

The surrounding world is filled with composite materials which help mankind to live a better life. Titanium-MMCs (TMCs) are of greater interest within the field of aerospace and automobile industries due to their lightweight and high specific strength, i.e., strength to weight ratio. The characteristics of composite materials are much better than the individual constituents. The essential concept is to integrate the reinforcement material into the matrix material to get some desirable properties. Metal matrix composites (MMCs) are a bunch of materials having metals or metallic alloys as their major component (matrix) and are reinforced (continuously or discontinuously) by other materials like metals, ceramics or polymers. These are very fashionable within the field of engineering due to some superior properties like high thermal and electrical conductivity, high strength and stiffness, high specific strength, lightweight, low coefficient of thermal expansion, biocompatibility, resistance to high temperature, etc [1-4]. The foremost common MMCs are made of aluminum, copper, titanium, magnesium, iron, and nickel. Titanium and its alloys are fast becoming a component of serious research interest for a good range of applications like automotive, aerospace industries, aviation, chemical industries due to its high specific strength, specific rigidity, and excellent mechanical properties [2]. The foremost commonly used aerospace Ti- MMC is ($\alpha+\beta$) alloy, Ti- 6Al- 4V [5]. Titanium alloys with a temperature capability approaching 760 ^{0}C, the TMCs offer a possible 50% weight reduction in hot compressor sections to use in airframe applications and aircraft engines [6]. The higher biocompatibility and corrosion resistance of TMCs lead it to be the primary choice in osteosynthesis systems utilized in oral, maxillofacial surgery, and tissue engineering [3, 7]. Again, 37 % porous chemically pure Ti (CP- Ti) and Ti- TiB composite samples produced by selective laser melting (SLM) have a coefficient of elasticity near that of human bone. Their compressibility, good wear resistance, and porosity made them a typical material in biomedical [1, 8].

The common reinforcement of TMCs is split into two groups based on the shape of reinforcements, i.e., continuously reinforced TMCs (CTiMCR) and discontinuously reinforced TMCs (DTiMCR) as shown in Fig. 1. Particulate, whisker (needle-shaped), and short fibers are employed as discontinuously reinforced composites, whereas long fiber and sheets are used as continuously reinforced composites. Sometimes, nanoparticles are used as reinforcements to produce light MMCs with high ductility, high hardness, and high toughness [9, 10]. Discontinuously reinforced titanium composites are usually composed of borides or carbides, embedded in titanium matrix [2]. Here the addition of appropriate reinforcement by a novel processing strategy is very important to optimize the mechanical properties of DRTMCs. The foremost prominent discontinuous reinforcements are TiC, TiN, TiCN, TiB_2, SiC, $Al_5Y_3O_{12}$, Al_2O_3, and Si_3N_4 in both whisker and particulate forms. Many of the reinforcements exhibit clean interfaces free from any diffusional alloying or reactions with the Ti matrix [8]. To get tailored unique distribution of

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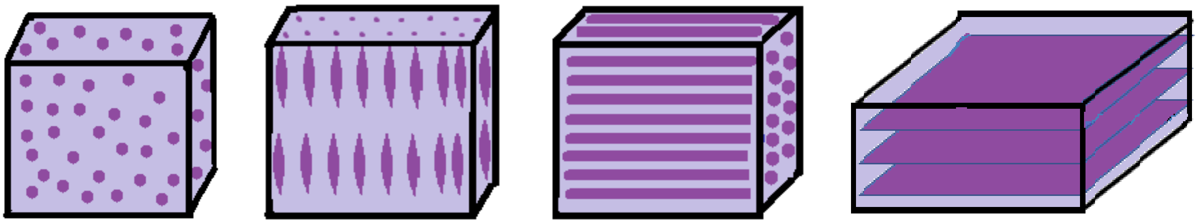
reinforcements inside TMCs, additive manufacturing and laser deposition techniques are very helpful [11]. Discontinuous (or particulate) reinforced composites are less expensive to fabricate and their properties are nearly isotropic. Continuously reinforced titanium matrix composites are expensive, due to high fiber costs and limited formability, and their properties are highly anisotropic. Particulate reinforced titanium matrix composites are being considered for wear, erosion, and corrosion-resistant applications [12, 13].



(a) Particulate (b) Whisker (c) Fiber (d) Layer

Figure 1. Reinforcement of TMCs (a) Particulate, (b) Whisker, (c) Fiber and (d) Layer

Ceramic particles as reinforcements on titanium metal matrix composites represent a possible improvement in its properties and an increase within the utmost service temperature. Reinforcing Ti with a steady ceramic phase can noticeably improve its modulus, hardness, wear resistance, additionally as yield strength but the resultant tensile ductility is sometimes poor or perhaps near zero [14-17]. The role of reinforcement in a metal matrix composite is to finish the shortcomings of metal and to make it an ideal choice for industrial applications. The coefficient of elasticity of metals is within the range of 45 GPa to 407 GPa. Its value is 106 GPa for Titanium which isn't sufficient for a few industrial applications. Thus, the reinforcement for TMC to increase the coefficient of elasticity has been discussed. The elastic modulus of the composite (E_C) is given by the addition of products of elastic modulus (E_M or E_R) and volume fraction (V_M or V_R) of different components:

$$E_C = E_M \times V_M + E_R \times V_R \tag{1}$$

The thermal expansion is not a greater challenge for metals (8.5×10^{-6} K^{-1}). So, the reinforcement can have a little less or very near value of the coefficient of thermal expansion to the metal. The values of Elastic modulus and Coefficient of thermal expansion of some common reinforcements are put together in the following Table 1.

Table 1. The relative properties of some of the reinforcements [9, 18-21].

Reinforcement	Elastic modulus (or Young's modulus) (GPa)	Coefficient of thermal expansion (10^{-6} K^{-1})
TiB	550	8.60
TiC	460	6.52 - 7.4
TiN	250	8.3 - 9.3
SiC	420	4.3 - 4.63
TiB_2	529	4.6 - 8.1
B_4C	449	4.5 - 4.8
Al_2O_3	350	8.1
Si_3N_4	320	3.2
Ti-6Al-4V	115	8.8
Graphene	~1000	-4.8
CNTs	~1000	21
La_2O_3	-	5.8 - 12.1
Alpha-Ti	105	8.8

FABRICATION TECHNIQUES

The fabrication technique is an important aspect of a material that determines the physical, mechanical, and biological properties of composite material along with its surface finishing and cost. Various types of techniques are used to manufacture TiMMCs, out of which powder metallurgy, additive manufacturing, and spark plasma sintering are very popular.

POWDER METALLURGY (PM)

In the PM fabrication technique, the metal removal process is usually avoided so that the yield loss is decreased while manufacturing the fabric which ends up lowering the prices and material wastage as compared to the casting process. It's an efficient process of controlling the components, i.e., matrix and reinforcement dispersion ratio in a very powder form using the varied jar, ball milling methods, etc within the composites [22, 23]. The powder metallurgy routes are applicable for advanced materials for Aerospace, like functionally graded materials. Titanium is reinforced with Carbon nanotubes (CNTs) and graphite via powder metallurgy and hot-extrusion (HE) [24]. PM processing is extremely useful within the production of military ground vehicles at a lower cost. Initially, the metallic powder of titanium is created within the metallurgy process. This process consists of two major parts: (i) preparation of starting material (mixing, milling, and mechanical alloying) and (ii) densification of the prepared powder mixture (cold or hot pressing, sintering, forging, etc.) [25].

MILLING AND MIXING PROCESS (MMP) OF PM

The pure form of titanium is taken in the cavity of ball milling with spherical steel balls inside it. Then the reinforcement particles were added to it. It grinds the mixture into fine powder. The schematic diagram of milling and mixing has been shown in Fig. 2.

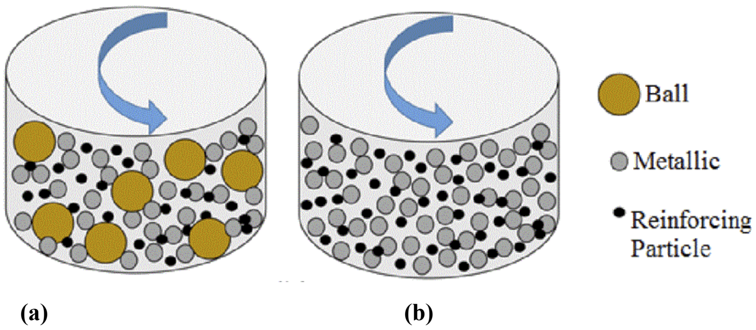


Figure 2. Mixing of metallic particles with reinforcements (a) Ball milling and (b) Regular mixing processes [26].

MECHANICAL ALLOYING (MA) OF PM

This is a popular method that is used for alloying materials which are difficult or impossible to combine through conventional melting methods. The mechanical alloying of Ti with graphite particles is shown in Fig. 3.

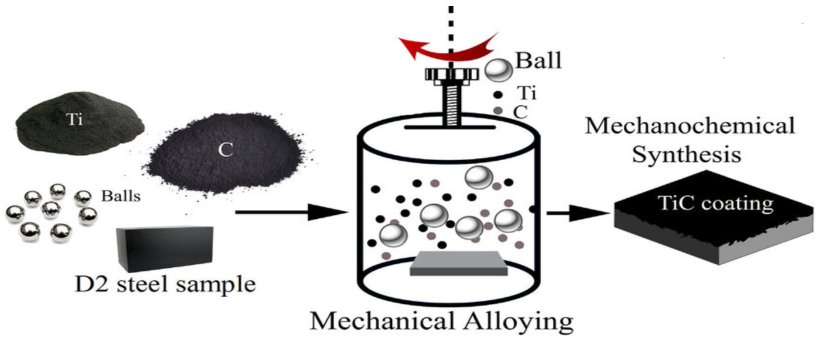


Figure 3. Schematic diagram of MA process to prepare TiC [27].

ISOSTATIC PRESSING OF PM

Isostatic pressing can be performed at (a) elevated temperatures, known as hot isostatic pressing (HIP), or (b) ambient temperatures, known as cold isostatic pressing (CIP). Hot isostatic pressing can be used to manufacture metal components directly or to densify parts from other powder metallurgy processes.

SINTERING PROCESS OF PM

It is the process of compacting the powder to form a solid mass material by applying pressure or heat without melting the material. So, the sintering temperature is less than the melting point. Change of powder to a solid mass or grain is shown in Fig. 4.

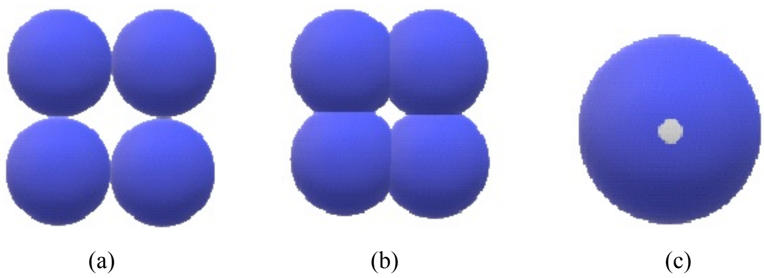


Figure 4. Different stages of the sintering process: (d) Before sintering, (e) During sintering, and (f) After sintering [28].

Before sintering, the grain size is small with big pores in between them. Whereas the grain size increases and the pore size decreases gradually during sintering. Finally, a big grain can be obtained with a small pore inside it. In this stage, the grain size is affected by the sintering temperature.

Table 2. Effect of sintering temperature on grain size [29].

Sample	Grain size at different Sintering temperature	
	1200 ^{0}C	1300 ^{0}C
Ti-5.1% (4140) alloy	71 ± 9 μm	97 ± 12 μm
Ti-7.1% (4140) alloy	98 ± 8 μm	121 ± 18 μm

Here, it was observed that with the temperature rise, the grain size increases. The increased grain size leads to a larger grain boundary. The strength of a material increases with its grain boundary. During the sintering process, the properties of the material vary with the sintering temperature. The variations of density, porosity, and micro hardness have been plotted in Fig. 5.

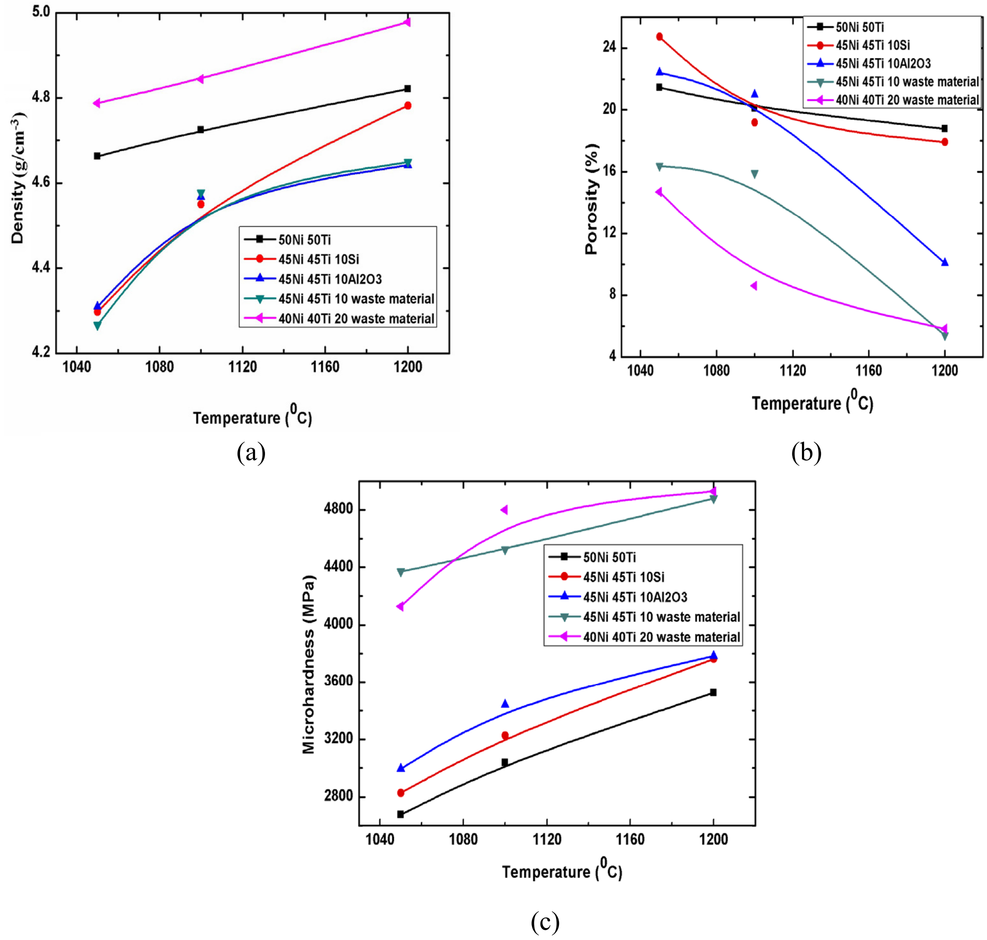


Figure 5. Variations of (a) density, (b) porosity, and (c) micro hardness with sintering temperature [30].

As the sintering temperature increases, the material starts softening and the grains (particles or molecules) seem to diffuse with the surrounding particles or molecules without melting. This happens because of the higher liquid phase transitions at higher temperatures. So, density increases, and porosity decreases with an increase in sintering temperature. As the porosity and air gap decrease with an increase in temperature, the micro hardness increases, and the material, with greater micro hardness value, can be used to manufacture different parts of automobiles and aircraft.

FORGING PROCESS (FP) OF PM

The schematic diagram representing powder metallurgy methods with their different processes and stages has been shown in Fig. 7.

It can be classified into three categories, i.e. (i) Cold forging: In this method forging is done at atmospheric or room temperature, (ii) Warm forging: In this method forging is done above atmospheric or room temperature but below the recrystallization temperature of matter and (iii) Hot forging: In this method forging is done above the recrystallization temperature of matter.

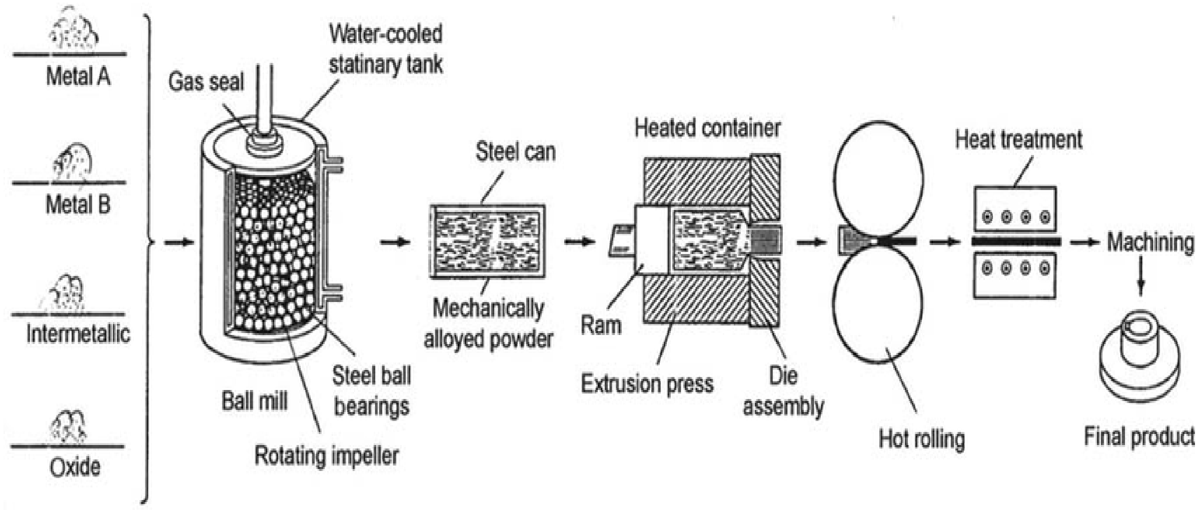


Figure 6. Different steps involved in the manufacturing of a product from powders by mechanical alloying [31].

ADDITIVE MANUFACTURING (AM)

It is a popular method to fabricate composite materials because of its low prototyping and manufacturing cost and also because of the easy method of fabrication. It needs a computer and 3D CAD (computer-aided design) software to sketch the fabric prototype. Once the 3D CAD sketch is produced, the AM manufacturing equipment starts the assembly process by reading the information from CAD files and adds layer upon layer of the fabric (in liquid or powder or sheet form) to fabricate a desired 3D stuff. The fundamental steps of AM method are creating a CAD 3D model, creating STL (standard tessellation language) files, manipulation of STL files in AM equipment, completing the method of building, removal and cleaning up, post-processing and implementation. AM is transforming the practice of drugs and making work easier for architects [32]. The productivity of fabric may be increased by AM fabrication technique. The common application of AM is to style the net-shaped plastic parts without the employment of high cost and time-consuming special tools, like injection molds [33]. AM process is generally utilized in the assembly of lightweight materials to scale back the burden of vehicles in automotive and aerospace applications due to its ability to create lightweight net-shaped frames; it is accustomed to manufacture complex honeycomb-shaped cross-sectional areas [34].

Some of the AM techniques used for the fabrication of TMCs are –

- Selective laser melting (SLM): It is an AM process that uses a high-density laser beam to melt and fuse the metallic powder in any specific region (point or line) or layer by layer. High power laser beam fuses the consecutive layers to form a 3D object by following CAD and STL files.
- Laser-engineered net shaping (LENS): It uses a high-power laser beam to form a highly dense product. The metallic or ceramic powder is injected into the hot molten pool of metal through the nozzle by following CAD. Directed energy deposition is another name of LENS (Fig. 7) and it is used to add some extra material to the existing component or to repair any instrument.

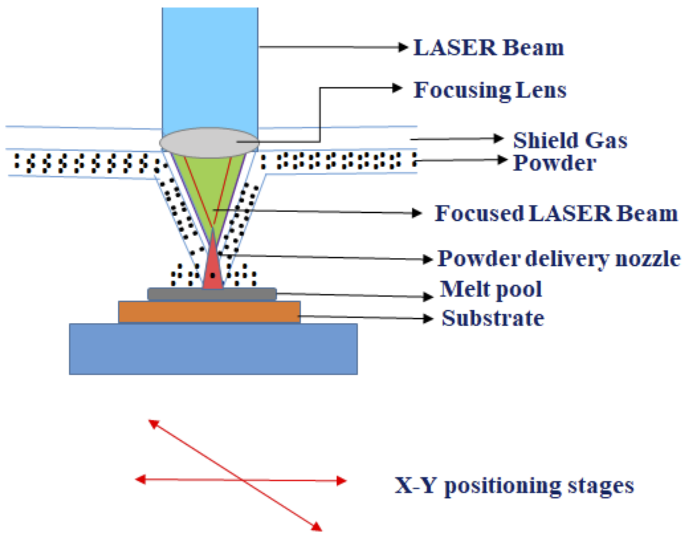


Figure 7. Schematic diagram of Laser engineered net shaping (LENS) [35].

- Direct laser deposition (DLD): It is a process of direct energy deposition (DED) that is very helpful in producing complex customized parts or repairing them. Some AM fabrication methods are presented in Table 3.

Table 3. AM techniques used for the fabrication of TMCs.

Matrix	Reinforcement	Method of fabrication
Ti	TiB	LENS [35], SLM [36]
Ti	TiC	SLM [37,38]
Ti	TiB and TiC	DLD [39]
Ti	TiC, unmelt SiC, $TiSi_2$, Ti_5Si_3	LENS [40]
Ti	TiN	SLM [41]
Ti	Ta	SLM [42]
Ti-6Al-4V	TiB_2	DED [43]
Ti-6Al-4V	TiN	LENS [44]
Ti-6Al-4V	TiB and TiN	LENS [45]
Ti-6Al-4V	Mo	SLM [46]

* SLM: Selective Laser Melting, LENS: Laser engineered net shaping, DLD: Direct Laser Deposition, DED: Direct energy deposition

SPARK PLASMA SINTERING (SPS)

It is an emerging powder consolidation technique during which uniaxial force and pulsed DC are employed under low air pressure. A schematic diagram of the SPS process with its different components is shown in Fig. 8.

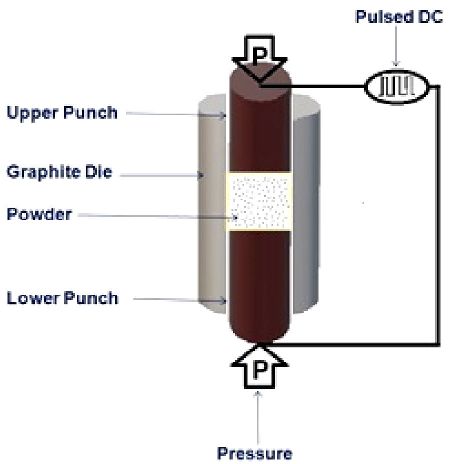


Figure 8. Schematic diagram of SPS [47, 50]

Instrumentation: the SPS process is administered within the SPS machine having the founded (i) vertical single-axis pressurization, (ii) water-cooled chamber, (iii) atmospheric control, (iv) vacuum exhaust unit, (v) Sintering DC generator, and (vi) SPS controller [47, 50].

EXPERIMENTAL PROCESS OF SPS

The sample powder is held between the punch and the graphite dies. The temperature is quickly raised to 1000 to 2500 ^{0}C (which is 200 to 500 ^{0}C less than the conventional sintering process) resulting in the formation of the high-quality sintered compact within 5 to 20 mins by the following vaporization, melting, and sintering [48]. During the sintering process, different atmospheres like hydrogen, inert gas, nitrogen, argon, natural gas, dissociated ammonia, and vacuum are used. Vacuum atmosphere is generally used for titanium for its high reactivity. The processing is carried out in 3 stages, i.e., Plasma heating, Joule heating, and Plastic deformation, shown in Fig. 9.

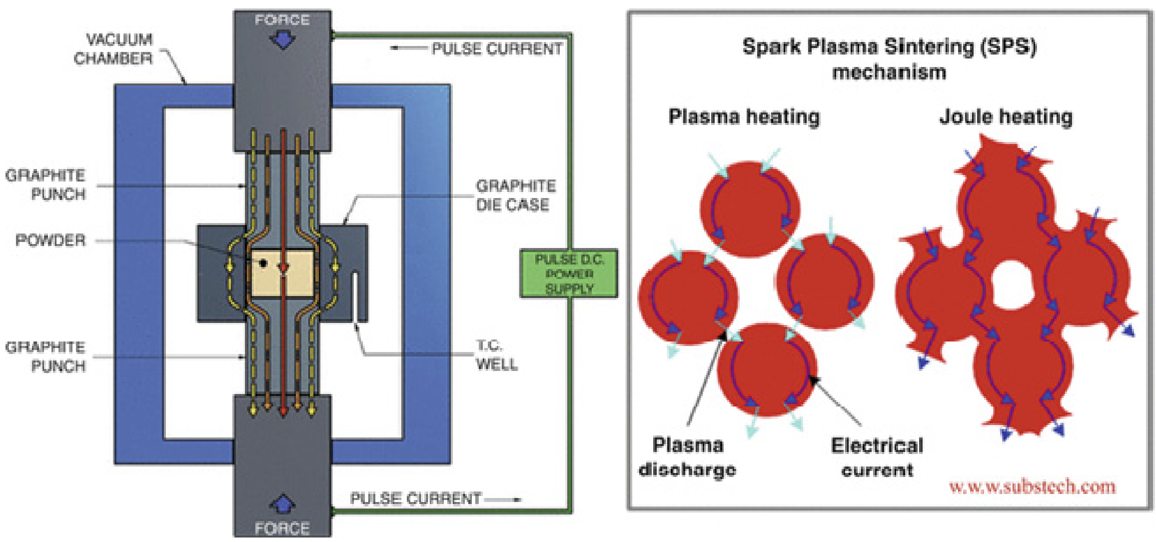


Figure 9. Pulsed DC along with the plasma heating and joule heating [49].

The details are given below.

a. Plasma heating: The electrical discharge among the powder particles results in heating of particle surface around 1000 to 2500 ^{0}C. The high temperature causes the vaporization of impurities to purify and activate the particle surface. Because of micro-plasma discharge, the generated heat is equally distributed among particles of the sample. Due to high temperatures, the particles melt and fuse to form a connection between them.

b. Joule heating: It is generated by pulsed DC which flows from particle to particle through the neck and causes diffusion of atoms and molecules enhancing their growth. The rapid rise and drop in temperature diminish the growth of material grain. So, this method can be used in the manufacturing of nanocomposites [50].

c. Plastic deformation: The soft material sample goes through plastic deformation under uniaxial force. The material is densified because of plastic deformation as well as diffusion. So, it is a better option for densification (around 94-99 % of theoretical value) of nanocomposites at a lower temperature than the conventional methods [48, 51-53].

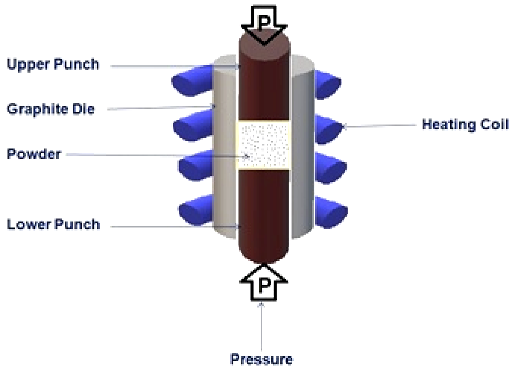


Figure 10. HP process with its different components [47, 50].

SPS is very similar to hot pressing (HP) in which an external heating source is used as shown in Fig. 10, but in SPS, an electric pulse is used to heat the sample powder from outside (through graphite dies) as well as from inside (by plasma discharge). SPS process is having very faster solute homogenization as compared to HP because of the joules heating. So SPS gives better results than HP [54]. The difference between the SPS (with pulsed DC) and HP (with external heating source) can be observed from fig 9 and fig 10. Even if the sintering temperature in SPS is less than the conventional sintering process, it plays a vital role in changing the mechanical properties of a composite material. Here the graphical plot of variations in density, hardness, and flexure strength with sintering temperature has been shown in Fig. 11. With a rise in sintering temperature, the number of pores decreases which results in the densification of the material. Hence density increases slightly as sintering temperature increases. The hardness of both samples (Fig. 11) was decreased with rising in sintering temperature. The two samples show the best 3-point-bending test result at 1150 ^{0}C as the flexure strength is maximum at this sintering temperature.

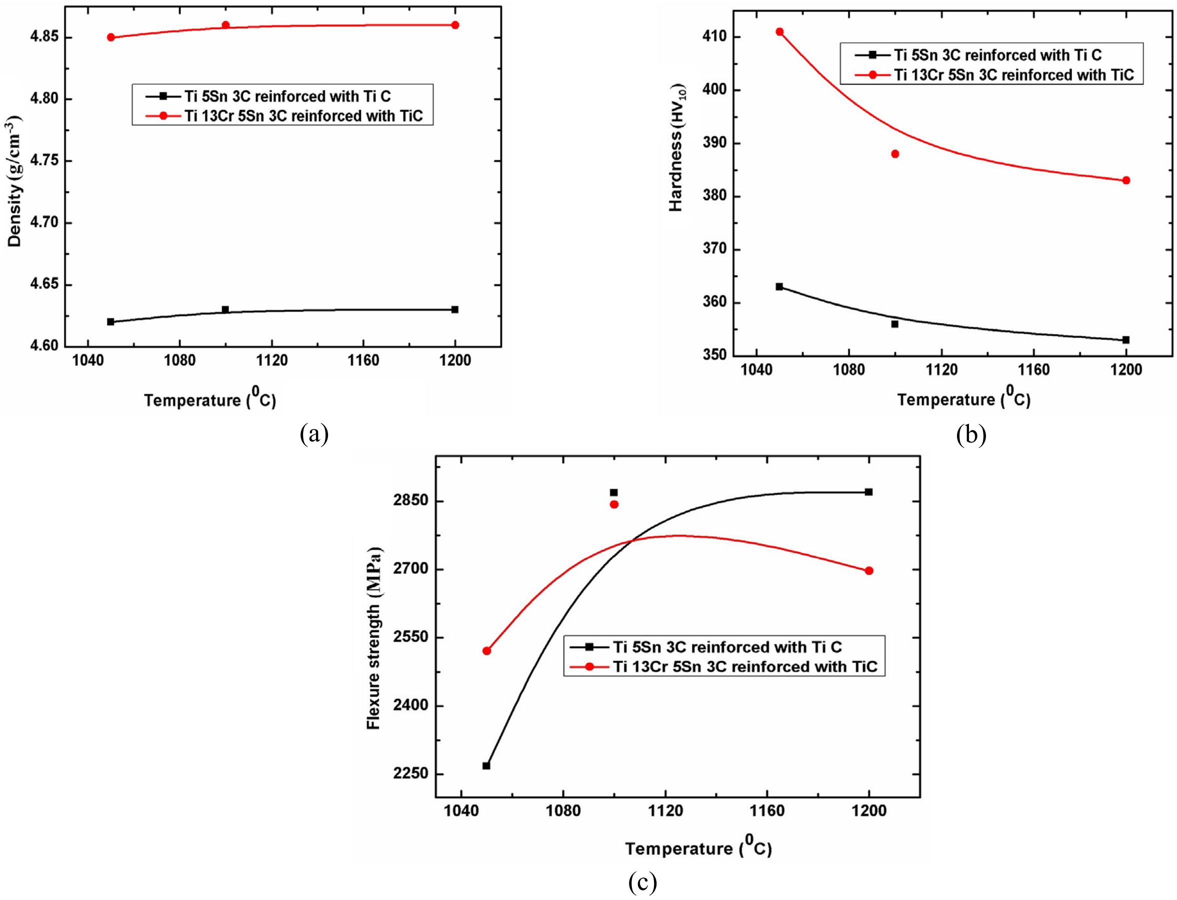


Figure 11. Variation of properties (a) density, (b) hardness, and (c) flexure strength of composites at different sintering temperatures in SPS [55].

PROPERTIES OF TMCs

Comparative Properties of Ti MMCs and Super alloys: TiMMC's have a metal strength greater than Aluminum Alloy if 6Al-4V titanium alloy is used. The values of some properties are presented in Table 4.

Table 4. Comparative properties of TMC, Ti-Al MMC, and super alloys.

Property	Conventional TiMMC	Ti Aluminide TiMMC	Superalloys
Density (g/cm^3)	4.04	4.18	8.3
0° Stiffness (GPa)	200	242	207
90° Stiffness (GPa)	145	200	207
Max use temp. (°C)	538	760	1090
0° CTE (°C^{-1} × 10^{-6})	7.20	7.92	13.0
90° CTE (°C^{-1} × 10^{-6})	8.91	9.18	13.0

* 0° → Along the direction of Fiber and 90° → Transverse to Direction of Fiber [6, 56, 57].

It has been observed that types of reinforcement, the quantity of reinforcement, and processing routes change the property of composite material. A quantitative study on the physical and mechanical properties of different TMCs with their processing routes is presented in Table 5.

Table 5. Physical and mechanical properties of different TMCs with their processing routes.

Matrix	Reinforcement with volume %	Processing route	Properties				References
			Density	Hardness	Strength (MPa)	Ductility %	
Ti	24% TiB	SPS	4.90 g/cm^3	710 HV	-	-	[58]
	38.5% TiB		4.75 g/cm^3	890 HV	-	-	
	20.6% TiB	HIP (PM)	4.92 g/cm^3	658 HV	-	-	
	38.3% TiB		4.90 g/cm^3	823 HV	-	-	
	17.6% TiB	PM	4.20 g/cm^3	424 HV	-	-	
	37.9% TiB		4.68 g/cm^3	618 HV	-	-	
Ti-64	Zr based MG	SLM	-	-	> 1000	20*	[59]
Ti	1.0 wt% CNTs	SPS+HE	-	292 HV	625	-	[60]
	2.0 wt% CNTs		-	336 HV	662	-	
	3.0 wt% CNTs		-	367 HV	853	-	
Ti-4.5 Al-6.8 Mo-1.5 Fe	5% TiB	HVC (PM)	97.90%*	335 HV	1038	2.19	[61]
	10% TiB		98.20%*	392 HV	1147	-	
	15% TiB		98.30%*	428 HV	741	-	
	20% TiB		96.10%*	445 HV	521	-	
Ti	4% TiB + 0.97% TiC	PM	-	-	876	14.2	[62]
	6.49% TiB + 1.61% TiC		-	-	995	7.8	
	10.93% TiB + 2.81% TiC		-	-	1138	2.6	
Ti	0.2wt% of MWCNTs	SPS	99.69%*	2 GPa	898	-	[63]
	0.4 wt% of MWCNTs		99.44%*	2.18 GPa	1092	-	
	0.6 wt% of MWCNTs		99.31%*	2.3 GPa	1052	-	
	0.8 wt% of MWCNTs		99.13%*	2.39 GPa	1015	-	
	1.0 wt% of MWCNTs		99.01%*	2.4 GPa	853	-	
Ti-6Al-4V	5% TiC	SPS	99.7%*	-	995		[64]
	10% TiC		99.6%*	-	1060		
Ti	0.5 wt% MLGs	SPS	-	15.39 GPa	-	-	[65]
	1.5 wt% MLGs		-	14.54 GPa	-	-	
Ti	B + 1 vol% CNTs	SPS	99.3%*	33 GPa	-	-	[66]
	B + 2 vol% CNTs		98.7%*	29 GPa	-	-	
	B + 4 vol% CNTs		97.6%*	28 GPa	-	-	
	B + 6 vol% CNTs		96.0%*	25 GPa	-	-	
Ti	0.5 vol% B4C	PM + HE	-	-	916	2.6	[67]
Ti-15Mo	TiB	SPS	-	22%*	1480	-	[68]

Matrix	Reinforcement with volume %	Processing route	Properties				References
			Density	Hardness	Strength (MPa)	Ductility %	
Ti-Ni	1 wt% of CCS	SPS	96.4%*	289.40 HV#	669.75	-	[69]
	3 wt% of CCS		98.9%*	296.81 HV#	686.90	-	
	5 wt% of CCS		99.9%*	319.71 HV#	739.90	-	

CNT: Carbon Nano Tube, MWCNT: Multiwalled carbon nanotubes, MLG: Multi-layer graphene, CCS: Carbonized coconut shell, HIP: Hot isostatic pressing, HE: Hot extrusion, HVC: High-velocity compaction, HV: Vickers Hardness, * Relative, # Micro hardness.

APPLICATIONS

There are many important applications of TiMMCs in various sectors such as Aerospace, Biomedical, Automotive, Defense, etc. that shown in Fig. 12.

AEROSPACE

TMCs are extensively used in the aerospace industries to make aircrafts lightweight, erosion-resistant, and protect the aircraft from foreign objects and birds.

- The usage of TMCs in US fighter aircraft [2]
- Ti-6Al-2Sn--4Zr-6Mo is used to manufacture an aero-engine which is having excellent creep resistance, heat resistance up to 450 ^{0}C and can be elongated up to 10% with a yield strength of 1105 MPa. Ti-5AI-2Sn-2Zr-4Mo-4Cr having a heat resistance of 350 ^{0}C with tensile strength and yield strength of 1250 MPa and 1150 MPa respectively. It is used to manufacture the shaft and fan with a greater damage tolerance ability [70].
- Rolls Royce starts manufacture of world's largest fan blades for an aircraft. The weight of the ultra-fan has been reduced up to 680 kgs. The weight reduction is due to the carbon titanium fan blades and composite casing [71].

BIOMEDICAL

Titanium could be a non-reactive, biocompatible, and corrosion-resistant metal that may be employed in bone and dental implants. It is resistant to body fluids.

- CP-Ti, Ti-6Al-4V, Ti–24Nb–4Zr–8Sn, Ti–TiB/TiC, and Ti-6Al-7Nb are the popular composites utilized in biomedicals as these materials show mechanical and biomedical properties almost like human bone [8].
- 37% porous CP Ti and Ti-TiB produced by the SLM process are having a modulus of elasticity near human bone [1].
- Porous ceramic reinforced Ti composites are produced by additive manufacturing complete all the strain of orthopedic implant applications at a lower cost [72].

AUTOMOTIVE

Mainly titanium is employed in automobiles for weight reduction. The weight reduction ultimately reduces the fuel and power consumption and air resistance of the vehicle.

- Titanium is employed to manufacture the engine valve train and connecting rods to reduce the inertial force in a reciprocating engine. The primary motive force in vehicles is provided by the electric motor. The nonmagnetic and relatively higher electrical resistance nature of titanium reduces the eddy current loss in electrical motors [73].
- Ti-6Al-4V is that the main component of connecting rods, intake valves, and wheel hubs because of its high tensile strength up to 1050 MPa and yield strength up to 950 MPa. Ti-6Al-4Sn-4Zr-1Nb-1Mo-0.2Si (Reinforced with 5% TiB) could be a material for the assembly of exhaust valves having a yield strength of 1150 MPa [74].
- Conventional TiMMCs supported strengthening with discontinuous TiB or TiC reinforcements have realized a wide application in automobiles.
- An exhaust valve with a non-porous cast Ti-44Al-8Nb-1B has been processed and examined using an X-Ray beam [75].

DEFENSE

The high ballistic impact resistance and high strength to weight ratio of titanium composites made it a good choice for armor and aviation material in defense. It can reduce the weight of the vehicle up to 40 -50% so that the fuel consumption will be less and the vehicle movement will be free.

- Ti-6Al-4V is having a greater ballistic resistance as compared to rolled homogeneous armor (RHA) steel. It is having a mass efficiency rating of 1.5 when the value for RHA steel is taken as 1 with a lesser weight.
- Ceramic reinforced titanium composites are showing good elastic modulus, good wear resistance, and high yield strength. A reliable armor material can be produced with a different defeat mechanism by ceramic reinforced Ti with TiB ceramic [15, 76].

- Layered composite material armor for helicopters has been developed with Titanium Alloy-Ceramics-Polymer-based lightweight composites which protect ammunitions to critical parts of the helicopters [77].
- TMCs can also be used in the production of body armors weighing only 8-10 kg (bulletproof jacket) and aviation on some parts of fighter jets, aircraft, and military ground vehicles.

Figure 12. Different applications of TiMMCs

VARIOUS CHALLENGES

Even if TMCs are having many unique properties, their use is limited in the automotive and aerospace industries because of the following reasons.

- High cost: Titanium is a high-cost metal as compared to aluminum and iron in the current market. So, it is used in those fields which can get more efficiency and weight reduction as compared to its cost as in the case of aerospace industries where the fly-to-buy ratio is analyzed before its use.
- Low availability of the material: The relative abundance of titanium on earth is just 0.63% whereas, the relative abundance of aluminum and iron is 8.1% and 5% respectively.
- Difficulty in machining: Due to high strength, low thermal conductivity, and chemical reactivity with the tool material at elevated temperature, it makes a hazard to the tool and reduces the tool life.
- Spring-back and chatter effect: The low young's modulus value of Ti alloys and composites leads to the spring-back and chatter effect resulting in the poor surface quality of the product.

The machining difficulties can be solved by using high-pressure coolant during cutting and drilling operations. But the coolants are of high cost. Current research focuses on the design of an effective cooling system. Some of the popular cooling systems are-

- Cryogenic liquid nitrogen: It reduces the cutting temperature (around 28 - 61%), the surface roughness (around 4.36- 51.67 %), thrust force (around 14%) of Ti-6Al-4V as compared to the wet coolant. It also increases the tool life [78].
- Minimum quantity lubrication: The drilling temperature decreases effectively by using the MQL method during the material removal process because it reduces the drill wear when drilling the compound stacks [79].
- Low-frequency vibration-assisted drilling: This technique helps reduce the mechanical and thermal load of the material removal process of carbon epoxy composite Ti-6Al-4V which is very useful in aerospace industries [80].
- Carbon dioxide-based cooling system: Vortex tube-based cooling system assistance machining can increase the effectiveness of the machining in terms of cutting temperature and surface roughness. In this method, different types of coolants can be used where CO_2 gas is providing better results [81]. This cooling system reduces the cutting temperature (around 46.6%) and surface roughness (around 46%) as compared to dry machining [82].

CONCLUSIONS

Titanium metal matrix composites (Ti-MMCs), as a replacement generation of materials, have various potential applications within the biomedical, defense, aerospace, and automotive industries. For a specific potential application, the manufacturing route is restricted. Such as SPS is a better method for the manufacturing of nanocomposites and dense materials. Similarly, additive manufacturing is used to reduce production costs and PM is used to manufacture armors at a lower cost. Depending upon the porosity of TMC, its application is specified in various fields. Porous materials are used in biomedical (37% Ti-TiB) whereas dense materials are used in automotive sectors (cast Ti-44Al-

8Nb-1B). Even if TMCs full fill many mechanical and biomedical requirements, their higher cost and machining difficulties limit their usages in different industries. For aerospace applications, it should have a good fly-to-buy ratio. Otherwise, it will affect the final production cost of aircraft. The cost of TMCs can be reduced to some extent by changing the processing route. But it is not sufficient to compete with other composites in the market. The cost reduction can also be done by making Ti alloys (producing a matrix material containing Ti with other metals like aluminum, iron, etc in nearly equal proportion just like in super alloys). An effective cooling system can overcome machining difficulties. Now-a-days research is going on to reduce the assembly cost of raw Titanium and designing of an effective cooling system. More insight into the research field of composites is required to know the reason for its high cost. Once the reason is very clear then the cost can be reduced which in turn increases the usage of high strength and light weight TMCs in different applications without any second thought.

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ОГЛЯД ШЛЯХІВ ОБРОБКИ, ВЛАСТИВОСТЕЙ, ЗАСТОСУВАННЯ ТА СКЛАДНИХ ПРОБЛЕМ, ЩО ПОВ'ЯЗАНІ З ТИТАНОВО-МЕТАЛЕВИМИ МАТРИЧНИМИ КОМПОЗИТАМИ

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На сьогоднішній день титан відрізняється своєю малою вагою, високою міцністю та нереактивною природою в порівнянні з усіма металами. Титаново-металеві матричні композити (ТМК) є дуже популярними в галузях аерокосмічної, автомобільної промисловості, в оборонній та біомедичній сферах через їх високу питому міцність, малу вагу та біологічну сумісність. Деякі з широко використовуваних методів виробництва, таких як порошкова металургія (ПМ), адитивне виробництво (АВ) та іскрове плазмове спікання (ІПС), були розглянуті в цій роботі з урахуванням деяких властивостей ТМК. Змінюючи різні типи армування, можна досягти необхідних властивостей відповідно до промислових та сучасних застосувань у ТМК. Це дослідження також включає наслідки впливу температури спікання на такі властивості ТМК, як фізичні, механічні та структурні. Сплави титану демонструють хороші механічні та біомедичні властивості при армуванні вуглецевими волокнами, боридами, керамікою та багатьма іншими матеріалами у вигляді суцільних волокон або переривчастих частинок та вусів (ниткоподібних кристалів). У цій роботі йдеться про застосування ТМК в аерокосмічній, автомобільній, біомедичній та оборонній сферах. Незважаючи на усі ці сприятливі властивості та застосування, ТМК не можуть широко використовуватися у зазначених галузях через їх високу вартість та труднощі в обробці. Зниження вартості можна здійснити шляхом виготовлення Ті – суперсплавів. Крім того, для покращення технологічної обробки існує необхідність у ефективній системі охолодження під час механічної обробки ТМК. Були також розглянуті деякі ефективні методи, які можуть поліпшити оброблюваність ТМК.

Ключові слова: Ті ММК; ПМ; АВ; ІПС; складні проблеми