# 2. Literature Review

## 2.1.Introduction

The presented chapter gives a detailed review of research work reported by different researchers in the field of development Titanium (Ti) and Hydroxyapatite (HAp) based composite scaffold for tissue engineering applications. The chapters review about different processing techniques employed in the fabrication of metallic (Ti) and ceramic (HAp) based composite along with their advantages and disadvantages. Thus, this chapter creates an insight of processing techniques of metallic and ceramic based bio-scaffolds.

## 2.2.Titanium and Its Alloys

As discussed earlier in Chapter 1 Titanium (Ti) is the ninth most abundant element in the lithosphere as it is a constituent of practically all crystalline rock. It has two crystal structures i.e. hexagonal closed packed structure and body centered cubic structure which depends on temperature and nature of alloying element. The upcoming section of the chapter presents a comprehensive study on different methods of preparing Ti based foam using powder metallurgy technique and details of physical and mechanical properties obtained.

## 2.3. Methods of Preparing Titanium Based Foam Using Powder Metallurgy Technique

Ti based materials have low thermal conductivity and high reactivity with surrounding environment due to this it's machining and melting as well as casting becomes difficult. Therefore the Ti components are generally machined from forged Ti blanks at a low speed, in this procedure about 95% of the raw materials are lost as a scrap and recycling of these scrap is still a challenge [1]. In order to reduce the stress shielding effect in Ti based implants incorporation of pores is a promising solution but manufacturing porous Ti structure is not technically easier or simple. However, researcher community have developed number of manufacturing technique to develop porous Ti structure

In order to reduce the effect of stress shielding, elastic moduli of the implant should be reduced. The use of porous material is suggested to mitigate this problem. The use of porous material in artificial joint replacement is an attractive field of research as it includes different methods and materials which can be used to reduce stiffness mismatch. In the present study, the different methods of synthesis of porous Titanium alloy scaffold are described.

### 2.3.1. Space Holder Technique

Space holder technique is one of the important powder metallurgy processes having the ability to control the size of pores, pore shape, amount of porosity, etc because these parameters generally depend on the size of space holder particles. The basic requirement of this process is that the particle size of the metal powder should be less than the particle size of the space holder. This method involves the addition of space holder particles with the metal powder followed by mixing such that both the material mixes throughout uniformly. Then the mixture is compacted uniaxially in order to form a green pellet. The green sample is pre-sintered at an optimized temperature (low temperature) so that complete removal of space holder particle can take place and it also leads to the initial sintering of metal particles. Finally, the pre-sintered samples are sintered at an elevated temperature in an inert atmosphere in order to avoid oxidation of the metal. The schematic representation of the replication process for preparing porous Ti is shown in Fig 2.1. There are several materials that have been used as a space holder which includes bio-wastes, metals like magnesium granules, urea, ammonium hydrogen carbonate, some water-soluble materials (like sucrose, potassium chloride, and sodium chloride), Paraformaldehyde, etc. The factors to be considered before selecting any space holder are its affinity with titanium, the minimum amount of left out residue after burning and easy processing. Complete removal of space holder material from the substrate is the main problem associated with the space holder technique because the presence of any residue may import any sort of detrimental effect which may result in the reduction of bio-compatibility. The use of materials like NaCl and Sucrose is suggested because it can be removed completely when treated with water [2].

Kim et al. used sacrificing magnesium granules as space holder particles because magnesium ions are directly involved in numerous biological mechanisms in our body such as they regulate channelizing of ions, DNA stabilization, enzyme activation and stimulation of cell growth and proliferation [3]. So the problems associated with space holder like partial removal of space holder particle is completely mitigated. Kim et al. used magnesium particles of size 20 to 100 mesh with 0.5 wt % ethanol as a binder. The mixture of Ti and Mg were compacted uniaxially followed by the removal of space holder particles by dipping them alternatively in hydrochloric acid and ethanol for 24 hours. Sintering the green samples at an elevated temperature of 1300ºC for 2 hours in high vacuum results in the formation of the controlled pore of porosity 50 to 71% and pore size of 132 to 262µm. The mechanical testing of the samples reveals that the compressive strength and the rupture strength are in the range of 59 to 280 MPa and 85 MPa respectively. Z. Esen and S. Bor [4] processed titanium foam using magnesium as space holder particle, the porosity being in the range of 45 to 70%, the pore size of 525µm and Young’s modulus value ranging from 0.42 to 8.8 GPa. Table 2.1

shows the mechanical property of porous Ti prepared by using metallic pore former under different conditions.

Bio-waste like rice husk is a rich source of silica and its low temperature combustion property can be utilized by using it as a space holder material. Due to the amorphous nature of silica and its high relative reactivity along with carbon for thermal reduction, rice husk can be a favourable candidate for the synthesis of low-temperature porous material [5, 6]. Table 2.1 shows different materials that can be used as a space holder material for preparing porous Ti for orthopedic application.

Apart from the above space holders, there are many other materials that have been used by various researchers to produce porous titanium scaffolds. Dabrowski et.al. [7] used the Paraformaldehyde of mean diameter 500µm as a space holder for the production of porous titanium. The reason behind choosing such space holder was its ability to decompose completely at low temperatures. The resulting porous titanium has a porosity of 60% to 70% and Young's modulus of 1GPa to 8GPa which is very much close to that of cancellous bone.

Several research works suggest urea as an effective space holder material which has a tendency to decompose at low temperature resulting in the formation of a pore. Vasconcellos et al. [8] synthesized porous titanium with three-dimensionally interconnected pores of pore size 480µm and total porosity of 36%. Wenjuan et al. [9] used urea of size 200-600 µm as a space holder and polyethylene glycol as a binder to synthesize porous titanium scaffold with the porosity of 55 to 75% and pore size of 200 to 500 µm. The mechanical test of the porous scaffold reveals that Young's modulus is in the range of 3-6.4 GPa which is close to that of natural bone. It has also been noticed that the rapid decomposition of urea at low temperatures causes rough control over porosity. The needle-like shape of urea particles provides sharp corners and notches to the pore which leads to stress concentration and deteriorate mechanical properties. Sometimes it is also found that the remaining urea in pores makes implant unfit for use [10]. Xiang et al. [11] prepared porous titanium having porosity in the range of 44 to 77% by using ammonium acid carbonate as a space holder material. The fabricated porous titanium scaffolds have a pore size of 200 to 500 µm with young's modulus and compressive strength value between 2.1 to 3.4 GPa and 60 to 140 MPa, respectively. Apart from the above space holder materials, there are several other materials that can be used as a pore former which fulfils the basic requirement that a pore former should satisfy the complete removal of residue to form a porous scaffold through dissolution in water and having low economic value. In this class, the best-suited materials that can be used as a pore former are sucrose and sodium chloride. Kohl et al. [12] discussed the excellent adhesion and proliferation of cells when NaCl is used as a space holder material. Also, if there is any left out residue in the scaffold will not affect the in vivo performance of titanium and its alloy. Chen et al. [13] proposed a new and highly biocompatible space holder material for the manufacturing of porous titanium having open and interconnected pore morphologies. Spherical sugar pellets were used to synthesize porous Ti of porosity 20 to 54% and pore size ranging from 212 to 500 µm. The Young's modulus of the scaffold is between 12.1 to 18.5 GPa which is very close to that of natural bone.

Polymethyl Methacrylate (PMMA) is also used as a space holder material for the preparation of a porous scaffold. Li et al. [14] used PMMA to produce a macro pore size of 200-400 µm and porosity in the range of 10-65%. The green compact was heated at 250-450ºC for the complete removal of SH particles. The compressive strength and elastic modulus were observed in the range of 32-530 MPa and 0.7-23.3 GPa respectively. Table 2.1 summarizes the mechanical property obtained by using different types of porous materials.

**Table 2.1** Mechanical Properties of Ti scaffold prepared by space holder technique

| Space Holder Material | Porosity (%) | Pore Size (μm) | Young's Modulus (GPa) | Yield Strength (GPa) | Ultimate Strength (MPa) | Compressive Strength (MPa) | Ref. |
|---|---|---|---|---|---|---|---|
| **Molybdenum Wire** | 32-47` | NR | 23-62 | 32% -192<br>37% -157<br>47% -76 | NR | NR | [15] |
| **Mg** | 45-70 | 525 | 0.42-8.8 | 15-116 | NR | NR | [4] |
| **Mg** | 50-71 | 262-132 | NR | NR | NR | 59-280 | [16] |
| **Mg** | 30-50 | NR | 15.4-44.2 | 30%- 221.7<br>40%- 117 | NR | NR | [17] |
| **Ti Fibers** | 35-84 | 150-600 | 2-4.2 | NR | 200-600 | NR | [18] |
| **Rice Husk** | 50-60 | 100-550 | NR | NR | NR | 17-70 | [5] |
| **Rice Husk** | 24.88-35.5 | NR | NR | NR | NR | 440-938 | [6] |
| **RH** | 15-34 | NR | 6-15 | NR | NR | 116-396 | [19] |
| **Sucrose** | 20-54 | 212-500 | 18.5-30<br>16.4-40<br>12.1-50 | NR | NR | NR | [13] |
| **Urea** | 36 | 480 | NR | NR | NR | NR | [8] |
| **Urea** | 55-75 | 200-500 | 3-6.4 | NR | 10-35 | NR | [9] |

### 2.3.2. Replication Method

Synthesis of porous Ti with the help of replicating polymeric sponge followed by high temperature sintering is a unique technique. This process offers to fabricate scaffold with high porosity, highly interconnected microspores with identical shape and size. The porous structure produced via this method has pore shape and size similar to that of cancellous bone [20–24] . In this technique controlling the rapid drying of the coated slurry plays a crucial role. Cachinho et al. [25] described a unique method of preparation of a porous titanium scaffold in which scaffold was prepared by replication of sponge followed by reactive sintering. The main advantage of this method is the easy production of complex shapes at a low cost. Due to the use of sacrificing polymeric sponge the pore formed in the scaffold is interconnected, which is the basic requirement of human bone ingrowth and vascularisation of newly formed tissue [26]. These types of porous structures are generally used in dental implants, permanent osteosynthesis plates and intervertebral discs [27]. Cachinho et al. [25] reported use of 45 vol% $TiH_2$ powder with mean particle size of 15.6 µm and specific surface area of 0.5336$m^2$/g. The polymeric sponge blocks were dipped into the slurry and infiltrated. After the removal of excess slurry, the samples are dried at room temperature for a period of 24 hours. The sintering of samples at a low heating rate of 1ºC/min with dwelling at 500ºC for 2 hours and 1000º C for 4 hours results in the formation of a highly porous titanium scaffold with a porosity of 75% and pore size of 100 to 600 µm. The porosity in the range of 100 to 600 µm is appropriate for the growth of new bone tissues and transport of the body fluids. Further, in order to improve biological properties, the porous titanium is coated with Hydroxyapatite and heat-treated at 700ºC. Li et al. [28] synthesized porous $Ti_6Al_4V$ alloy by replication method using 70 wt% of $Ti_6Al_4V$ powder in water and ammonia solution. High-temperature sintering of the samples results in the formation of open-cell porous titanium struts with a porosity of 88% and a compressive strength of 10 MPa. It should be noticed that the second deposition of powder slurry on the previously sintered scaffold followed by re-sintering results in an increase of density and compressive strength to 36 MPa. Wang et al. [29] in his study proposed an improved sponge replication method, to maintain fast drying rate and appropriate viscosity of Ti slurry a novel solvent consist of ethanol and water was used. This slurry was used for multiple Ti coatings and the Ti scaffold prepared posses compressive strength of 83.6±4.0 MPa with porosity of 66.4±1.8 %.

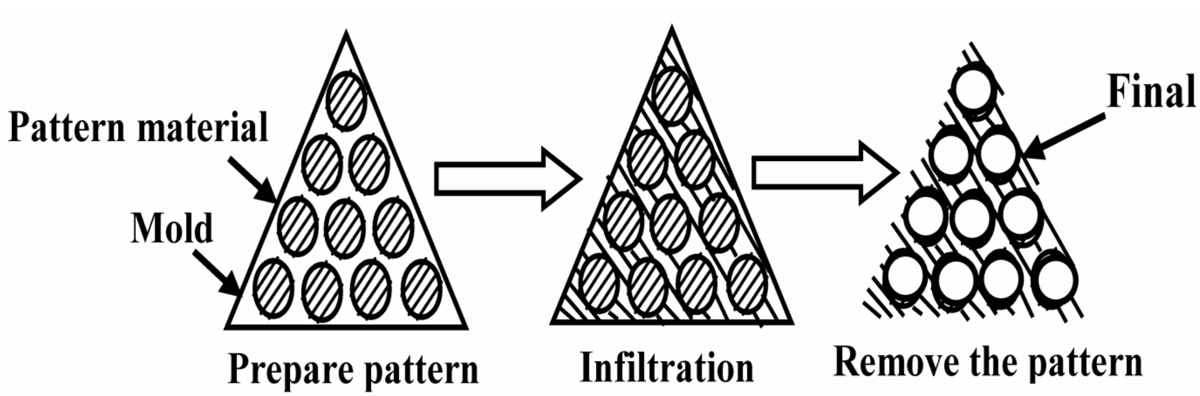


**Fig.2.1** Representation of the replication process for preparing porous Titanium [30]

### 2.3.3. Entangled Metal Wire Technique

Porous Ti implants fabricated via conventional method possess low toughness and tensile strength. The major drawback of these techniques is the difficulty in avoiding contamination and impurity phases in Ti while processing. Sometimes presence of undesirable cracks and metallographic defects in sintered Ti struts makes them brittle and thus they fails to bear tensile load [31]. Also, the porous Ti fabricated by powder metallurgy using space holder and plasma spray technique has low ductility that may break in the body's environment when subjected to uncertain overloading and accident [32]. In order to improve these mechanical properties a novel technique was introduced commonly known as Entangled Metal wire Technique (EMWT). In this technique Ti wire of diameter about 0.08 to 0.27 mm is used as raw material and this wire is coiled around 1.5 mm-diameter rod to form a coiled spring like structure. The coiled structure is stretched equably such that the distance between two spirals (screw pitch) reaches the external diameter of the coil. Now this stretched coil is entangled around a 1 mm-diameter rod to form a pre compacted sample. Finally, this pre-compacted sample is compacted with the help of piston in a cylindrical die [33]. Mechanism of fabrication and sample porous Ti scaffold prepared by entangled metal wire technique is shown in Fig 2.2 and Fig 2.3. Several researchers has fabricated porous Ti scaffold using EWMT, Zou et al. in 2007 [18] prepared open cell porous Ti with porosity in the range of 35 to 84% by sintering Ti fibers of 200 µm diameter in vacuum. The Ti fibers were curved into a helix with the help of a screw and then this helix is arranged in a cylindrical form followed by compaction and vacuum sintering at 1250ºC for 2 hours. The resulting porous scaffold has the pore size of 150-600 µm, Young's modulus was in the range of 3.5-4.2 GPa and compressive strength in the range of 100-200 MPa. Liu et al. [34] in 2010 fabricated entangled Ti wire material through different procedures one with normal wire and another with coiled wire, its compressive and pseudo-elastic hysteresis behaviour was investigated [34]the details of the properties obtained are discussed in Table 2.2. Jiang et al. [35] in 2015 fabricated an entangled porous Ti composite filled with biodegradable magnesium melted at 700 °C under protective environment of $SF_6$ and $CO_2$ with an aim to improve the fixation bonding between implant and host bone. Bisphenol A glycidyl methacrylate (BisGMA) is suggested as a bonding material to provide strong bonding strength and helps in fixing the free nodes of the entangled structure [36]. Wang et al. in 2017 [15] proposed a novel technique for the fabrication of three-dimensional porous Ti scaffold. This method was a combination of two different methods in which entangled Molybdenum wire was used as a space holder and Ti liquid was cast in a vacuum environment followed by etching off SH particle in aqua-regia solution. The resulting porous scaffold has three-dimensional interconnected pores with porosity in the range of 32-47% and exhibits elastic modulus in the range of 23-62 GPa and yield strength in the range of 76-192 MPa as shown in **Table 2.2**.

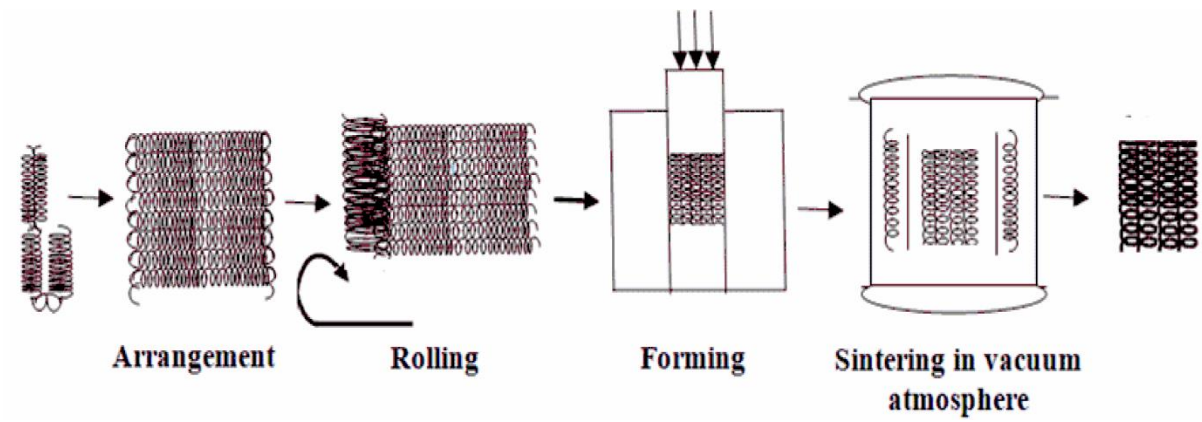


**Fig.2.2** Mechanism behind working of entangled metal wire technique

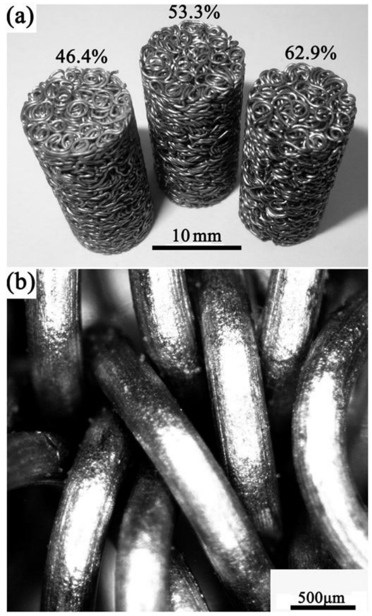


**Fig.2.3** Porous Ti samples prepared by entangled metal wire technique addoted from [35]

**Table 2.2 Mechanical Property of Porous Ti Prepared by Entangled Metal Wire Technique**

| Method | Material used | Porosity (%) | Pore Size (μm) | Young's Modulus (GPa) | Yield Strength (GPa) | Ultimate Strength (MPa) | Compressive Strength (MPa) | Flexural Strength (MPa) | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| **EWMT** | **Entangled Molybdenum Wire** | 32-47 | 0.4 mm | 23-62 | 76-192 | NR | NR | NR | [15] |
| **EWMT** | **Ti Wire** | 35-84 | 150-600 | 2-4.2 | NA | 200-600 | NR | NR | [18] |
| **EWMT** | **Entangled Ti Wires** | 44.2-81.2 | NA | 0.03-2.25 | NR | NR | NR | 9.8-324.9 | [37] |
| **EWMT** | **Entangled Ti Wires** | 53.4-55 | NR | 0.03-1 | 3-3.5 MPa | NR | NR | NR | [32] |
| **EWMT** | **Entangled Ti Wires** | 37.1-53.6 | NR | 22-47 | NR | NR | 175-246 | NR | [35] |
| **EWMT** | **Entangled Ti** | 40-55 | 100- | 0.4-1.4 | 12.9-52.5 | NR | NR | NR | [36] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Wires** | | 400 | | MPa | | | | |
| **EWMT** | **Entangled Ti Wires** | 44.7-57.9 | 50-200 | 1.05-0.33 | 75-24MPa | 108-47.5 | NR | NR | [31] |
| **EWMT** | **Entangled Ti Wires** | NR | NR | 0.05-6.33 (Flexural Elastic modulus) 0.03-2.25 (Compressive Elastic modulus) | NR | NR | 2.3-147.8 | 9.8-324.9 | [37] |
| **EMWT** | **Normal Entangled Ti Wires** | 77.6±0.2 -47.8±0.4 | | 135.3±2.9-816.5±8.4 MPa | 2.6±0.1-31.1±0.8 MPa | NR | NR | NR | [34] |
| | **Coiled Entangled Ti Wires** | 77.6±0.2 -47.8±0.4 | | 27.4±0.5-623.2±5.8 MPa | 1.1±0.1 – 19.1±0.5 MPa | NR | NR | NR | |

### 2.3.4. Spark Plasma Sintering (SPS) and Hot Pressing (HP)

The conventional sintering or pressureless sintering process involves heating of Ti and its alloys at an elevated temperature of 1200 to 1400ºC and a high vacuum of the order of $4 \times 10^{-4}$ to $6 \times 10^{-6}$ Pa for a long time about 24 to 48 hours [38] for densification and homogenization [39, 40]. Even after this lengthy procedure, achieving pore-free homogeneous microstructure is a challenge [39]. Also, the product produced is costly which limits the usage of Ti and its alloy in biomedical application. Spark Plasma Sintering (SPS) and Hot Pressing (HP) are the advanced powder consolidation techniques using pressure assisted sintering.

SPS is an advanced sintering technique which uses pressure-assisted pulsed-current for sintering for the production of the porous Ti samples. In this process electrically conducting powder is loaded in electrically conducting die, this die will act as a heating source when it is subjected through a pulsed direct current. Thus, this powdered sample will be heated from both sides under uniaxial pressure [41]–[44] and due to this fast heating, enhanced mass transfer and rapid consolidation of powder takes place [45]. There are two theories behind the consolidation mechanism of commercially pure (CP) Ti. According to first hypothesis the surface of the powder particles are cleaned and activated by spark discharges generated between metallic powdered particles and thus, promoting mass transport for sintering [46], [47]. Another hypothesis suggests that the densification of powder is due to particle deformation because as the temperature increases the yield strength of the powder particles decreases [48]. SPS is also known by other names such as field assisted consolidation technique [49], electrical field activated sintering [47], plasma-activated sintering [50] and electrical discharge compaction [51] . All of this technique involves very fast sintering of metallic powder under the action of electrical discharge with rapid heating and pressure application. Similarly, in HP the metallic powder is sintered with the help of electrical resistance in a closed die under uniaxial pressure. There are different heating methods like induction heating; electric conduction/ convection/ radiation heating that can be used in HP [52– 54]. Ibrahim et al. [55] synthesized porous Ti and its alloy by using a cost-effective SPS technique. In this process, porous Ti with different porosities was successfully synthesized by the powder metallurgy technique using $NH_4HCO_3$ as a space holder and $TiH_2$ as a foaming agent. SPS is used to consolidate powder at 16 MPa under pressureless condition. The experimental results showed that pure Ti samples achieved full relative density at a relatively low temperature of 750ºC and at a pressure of 16 MPa. The porosity of 53% and Young's modulus of 40 GPa was achieved in case of pressureless sintering at a temperature of 1000ºC. A comparative study of Properties of porous Ti synthesized by SPS and HP reported by different authors are mentioned in Table 2.3**.**

### 2.3.5. Microwave Sintering

The electromagnetic waves having a frequency in the range of 300 MHz to 300 GHz are referred to as Microwaves. The most commonly used microwaves for material processing have frequencies of 2.45 GHz and 915 MHz [56]. When materials interact with microwaves they convert electromagnetic energy into heat energy within the material. The main advantage of microwave sintering is the complete sintering of the material without any formation of impurities such as oxides. This method can be used for the sintering of ceramics, metals and composites, taking advantage of time and energy-saving, economical processing, and environment-friendly processing [57]. The following Table 2.3 demonstrates the processing conditions and physical and mechanical properties obtained using SPS, hot pressing and microwave sintering.

**Table 2.3 Processing Conditions and Mechanical Property of Porous Ti Prepared by SPS and Microwave Sintering**

| Material Type | Sintering Temperature (ºC) | Time and Pressure | Porosity (%) | Pore Size (µm) | Young's Modulus (GPa) | Yield Strength (GPa) | Compressive Strength (MPa) | UTS (MPa) | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| **Spark Plasma Sintering** | | | | | | | | | |
| **Pure Ti** | 750 | 16 MPa | Fully densed | NR | 125 (approx.) | NR | NR | NR | [55] |
| **Pure Ti** | 1000 | Pressureless | 53 | NR | 40 | NR | NR | NR | |
| **Ti5Mn alloy** | 950 | Pressureless | 56 | NR | 35 | NR | NR | NR | |
| **Ti5Mn alloy** | 1100 | Pressureless | 21 | NR | 51.83 | NR | NR | NR | |
| **Pure Ti** | 700 | | 30-70 | 125-800 | 6.2-36.1 | 27.2-94.2 | NR | NR | [58] |
| **β-alloy Ti-45Nb (Gas Atomized)** | 1000 | 10 min, 30 MPa | 0.5±0.1 (Vol %) | NR | 72±0.9 | 550±5 MPa | NR | NR | [59] |
| **β-alloy Ti-45Nb (Milled)** | 1000 | 10 min, 30 MPa | 4.0±0.2 (Vol %) | NR | 72±0.5 | 867±26 MPa | NR | NR | [59] |
| **Ti-6Al-4V** | 700 | 3 min, 30 MPa | 32.4±0.2 | NR | NR | NR | 125±5 | NR | [60] |
| **Pure Ti** | 600 | 3 min, 30 MPa | 31.9±0.4 | | NR | NR | 113±8 | NR | [60] |
| **CP Ti (Grade 1) Powder** | 900 | 5 min, 60 MPa | NR | NR | NR | 340 MPa | NR | 445 | [61,62] |
| **Cryomilled nanocrystalline CP Ti** | 850 | NR | NR | NR | NR | 770 MPa | NR | 840 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **(Grade 2) Powder** | | | | | | | | | |
| **CP Ti (Grade 3) Powder** | 900 | 5 min, 60 MPa | NR | NR | NR | 595 MPa | NR | 720 | |
| **Wrought titanium grade 4** | NR | 3 min, 80 MPa | NR | NR | NR | 480-635 MPa | NR | 655-690 | |
| **Hot Pressing (HP)** | | | | | | | | | |
| **Ti-45Nb (Gas Atomized)** | 600 | 30 min, 700 MPa | 0.7±0.2 | NR | 70±1 | 447±17 | NR | NR | [59] |
| **Ti-45Nb (Milled)** | 600 | 30 min, 700 MPa | 3.7±0.1 | NR | 70±0.7 | 940±34 | NR | NR | [59] |
| **Microwave Sintering** | | | | | | | | | |
| **Ti6Al4V/MWCNTi powder** | 1620 | | | 25 | NA 10.87±2.46 | 145.48±27.28 | 270.41±24.97 | | [57] |

## 2.3.6. Casting Technique

There are different casting techniques which can be used to produce porous titanium for orthopedic application. Among them, freeze casting, reverse freeze casting, slip casting and gel casting method are used most often. Freeze casting technique (FCT) has the ability to tailor the pore structure of porous material such as porosity, pore size, pore shape and orientation [63, 64]. In FCT the pore morphologies are generally determined by matrix powder kind, solvent type and frozen temperature gradient. FCT is generally used for ceramic particles because they have ability to keep themselves stable in slurry whereas metallic powders have tendency to sediment due to their higher density and large particle size as compared to ceramic powder [65]. In order to get uniform porous structure some dispersant and binders are added in slurry to ensure stable suspension [66]. Deionized water and liquid camphene are the common choice of solvent that are generally used in FCT [67]. Ti foams produced using freeze casting of aqueous slurry were aligned with elongated pores and were created after removing the ice dendrites grown unidirectionally during directional solidification [68, 69] journal of alloy and . It is observed that due to the presence of oxygen content from Ti particles and water there is a possibility of embrittlement of porous Ti foam, to mitigate this problem use of camphene as an alternative freezing vehicle is proposed [64, 65, 70]. Jung et al. [71] prepared a porous Ti scaffold using FCT by freezing Ti/camphene slurry in rotation at 44 ºC for 12 hours which is just below the solidification point of Ti/camphene slurry as shown in Fig 2.4. The porosity range and mechanical property of porous Ti prepared by this method are mentioned in the Table 2.4. Wang et al. [72] prepared a novel antibacterial bio-mimetic porous Ti implant using FCT. The bone integration properties were investigated by cell proliferation assay. An increase in the proliferation, differentiation and adhesion activity of osteoblasts compared to the unmodified porous or dense titanium implants were the major finding. Yook et al. [73] presented a new approach to camphene-based freeze casting and referred to it as reverse freeze casting (RFC) for overcoming the problem associated with FCT. This method is used to produce highly aligned porous biomaterials with strong and large pores. The mechanical property of the porous Ti obtained from different casting techniques are mentioned in Table 2.4. Inspite of number of advantages there are certain limitations associated with casting techniques like most metal powders can't be used for freeze casting method and also when camphene is used as freezing vehicle the degree of alignment becomes a critical issue because the freezing rate of camphene is slow and the dendrites don't have enough space to grow up [73, 74, 75]. The maximum pore size that can be produced by FC method is about 300 μm [73].

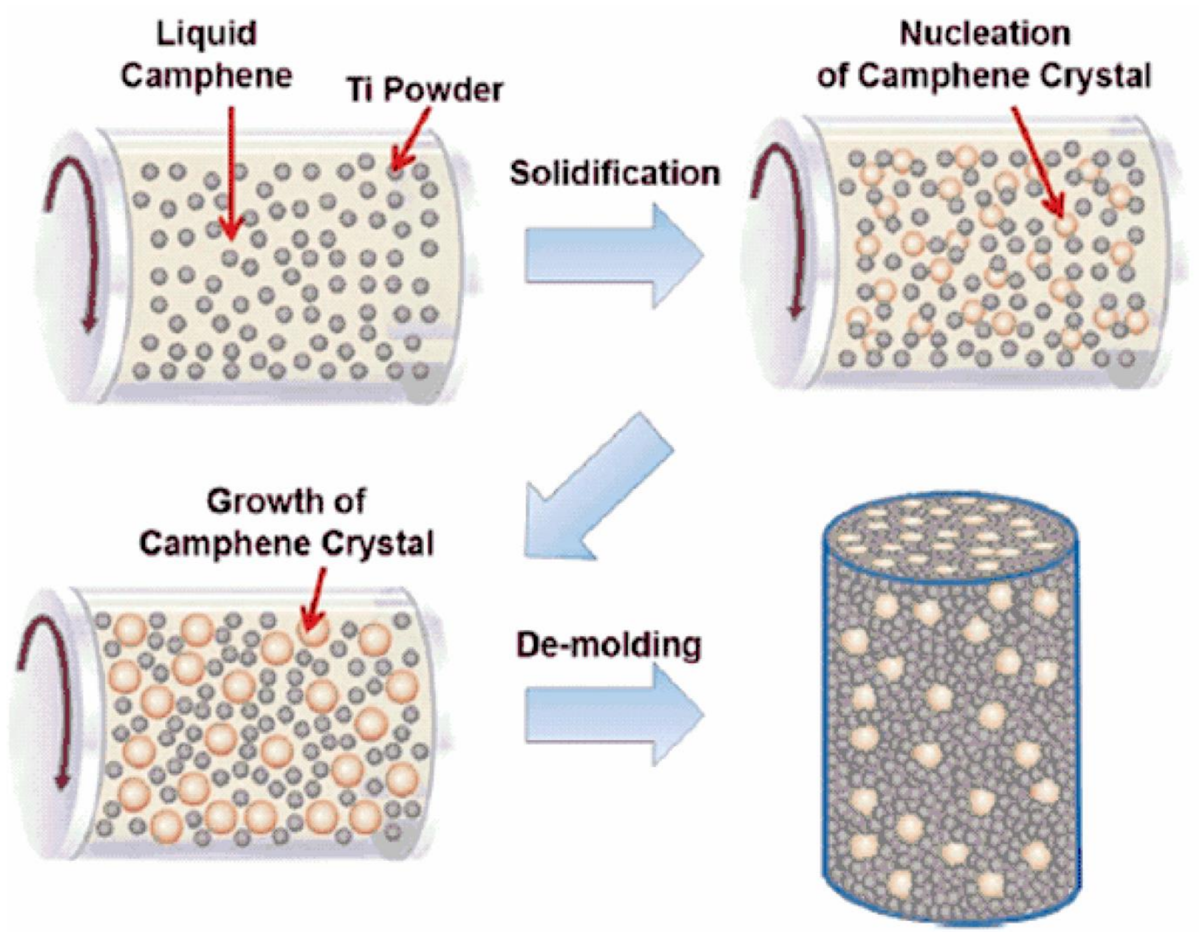


**Fig.2.4** Schematic diagram showing the creation of large interconnected pores using dynamic freeze casting [71]

### 2.3.7. Metal Injection Moulding (MIM)

Metal injection molding (MIM) is a Net-shape processing technique having potential to produce complex and porous geometries on which bone cell can attach and grow. MIM is generally recommended for mass production of complex shapes with high geometrical accuracy [76]. This process involves mixing of metal powder, binder, solvent, and lubricant to form a compound and this compound is injected into a mold followed by sintering [77]. For Ti and its alloys all the processing steps like mixing, de-binding, and sintering should be done carefully in closed environment in order to prevent from oxidation [78]. The ideal sintering temperature of 1500 °C is suggested to get best combination of low elastic modulus and high tensile strength [79]. MIMed binary Ti-12Mo alloy sintered at 1100 °C possess elastic modulus of 45 GPa while tensile strength and elongation were insufficient when compared with commercial alloys [80], [81]. Similarly, when the alloy is sintered at 1400 °C for 8 hr the elastic modulus was 54 GPa with sufficient elongation (10%) and strength [76]. Addition of Zirconium (Zr) and Tin (Sn) in MIMed binary Ti- Niobium (Nb) alloy is recommended by different researchers as Zr have tendency to increase tensile strength and elongation without effecting elastic modulus [82] and addition of Sn reduces the elastic modulus (75-90 GPa) [83]. Zhao et. al. [84] reported that addition of Nb up to 22% decreases elastic modulus and increases strength in Ti-Nb binary alloys. In spite of number of advantages there are some challenges for MIMed Ti components like high cost of low oxygen fine (≤45 μm) Ti spherical powder, oxidation of green Ti compacts from binders during MIM cycle [78]. It also reported that presence of undesirable $Ti_2C$ particles after sintering in the temperature range of 1300-1500 °C causes poor elongation (<5%). The mechanical property of the porous Ti obtained from MIM techniques are mentioned in Table 2.4.

**Table 2.4 Physical and Mechanical Property of Porous Ti Prepared by MIM and Different Casting Techniques**

| Method Used | Porosity (%) | Pore Size (μm) | Young's Modulus (GPa) | Yield Strength (Mpa) | Ultimate Strength (Mpa) | Compressive Strength (Mpa) | Ref. |
|---|---|---|---|---|---|---|---|
| **MIM** | 75 | NR | NR | NR | NR | NR | [85] |
| **MIM** | 42.4-71.6 | 300 | 3.03-0.28 | NR | NR | 17.5-316.6 | [86] |
| **FCT** | 64 | 143-271 | NR | NR | NR | 110±17 | [70] |
| **FCT** | 52-71 | 95-362 | NR | NR | NR | 57±4 to 183±6 | [71] |
| **FCT** | 58.32±1.08 | 126.17 | 1.7 | NR | NR | 58.51±20.38 | [72] |
| **FCT** | 50±2 to 67±3 | NA | NR | NR | NR | 58±8 to 162±10 | [67] |
| **FCT** | 57-65 | NR | NR | NR | NR | 40-60 | [63] |
| **FCT** | 49-63 | NR | NR | NR | NR | 81-253 | [64] |
| **FCT** | 33 | NR | NR | NR | NR | 196 | [87] |
| **RFC** | 51-69 | 500 | 2-5 | NR | NR | 121-302 | [73] |

***NR: Not reported**

### 2.3.8. Rapid Prototyping (RP)

RP is a computer-assisted technique that uses a computer-aided design (CAD) with computer-aided manufacturing (CAM) models to build predefined microstructure, macrostructure [88] and controlled hierarchical structure. The major requirement of this technology is control over scaffold pore structure including pore size, shape, volume and interconnectivity [89]. It is a layer by a layer fabrication process in which the selected part is built in a CAD file then the file is sliced along Z-axis in a virtual environment and for each slice a machine-specific tool path is generated. There is generally three most popular technique which is used for biomedical application (1) Electro-optical system selective laser melting (EOS-SLM), (2) Electron beam melting (EBM) and (3) Laser Engineered net shaping ($LENS^{TM}$). Table 2.5 shows mechanical property of porous Ti prepared by Rapid Prototyping technique.

**Table 2.5 Physical and Mechanical Property of Porous Ti Prepared by Rapid Prototyping Techniques**

| Method Used | Porosity (%) | Pore Size (μm) | Young's Modulus (GPa) | Yield Strength (MPa) | Ultimate Strength (MPa) | Compressive Strength (Mpa) | References |
|---|---|---|---|---|---|---|---|
| **3D Printing** | 70 | NA | 20.5 | NA | 104 | NA | [90] |
| **Rapid prototyping** | 60-87 | NR | NR | NR | NR | 10-100 | [91] |
| **LENS** | 17-58 | 800 | 2.6-44 | NA | 24-463 | NR | [92] |
| **LENS** | 23-70 | 60-700 | 12.1-18.5 | NR | NR | NR | [88] |

## References


[1] M. Qian, W. Xu, M. Brandt, and H. P. Tang, "Additive manufacturing and postprocessing of Ti-6Al-4V for superior mechanical properties," *MRS Bull.*, vol. 41, no. 10, pp. 775–783, 2016, doi: 10.1557/mrs.2016.215.

[2] Pradyot Patnaik, *Handbook of Inorganic Chemicals*, vol. s8-X, no. 245. 2003. doi: 10.1093/nq/s8-X.245.192c.

[3] M. Nabiyouni, T. Brückner, H. Zhou, U. Gbureck, and S. B. Bhaduri, "Magnesium-based bioceramics in orthopedic applications," *Acta Biomater.*, vol. 66, pp. 23–43, Jan. 2018, doi: 10.1016/J.ACTBIO.2017.11.033.

[4] Z. Esen and Ş. Bor, "Processing of titanium foams using magnesium spacer particles," *Scr. Mater.*, vol. 56, no. 5, pp. 341–344, 2007, doi: 10.1016/j.scriptamat.2006.11.010.

[5] X. Wang, Z. Lu, L. Jia, and F. Li, "Preparation and properties of low cost porous titanium by using rice husk as hold space," *Prog. Nat. Sci. Mater. Int.*, vol. 27, no. 3, pp. 344–349, 2017, doi: 10.1016/j.pnsc.2017.04.014.

[6] X. sheng Wang, Z. lin Lu, L. Jia, and J. xian Chen, "Preparation of porous titanium materials by powder sintering process and use of space holder technique," *J. Iron Steel Res. Int.*, vol. 24, no. 1, pp. 97–102, 2017, doi: 10.1016/S1006-706X(17)30014-6.

[7] B. Dabrowski, W. Swieszkowski, D. Godlinski, and K. J. Kurzydlowski, "Highly porous titanium scaffolds for orthopaedic applications," 2010, doi: 10.1002/jbm.b.31682.

[8] Luis Gustavo Oliveira de VasconcellosYasmin Rodarte CarvalhoCarlos Alberto Alves Cairo, “Porous titanium scaffolds produced by powder metallurgy for biomedical applications,” *Mater. Res.*, vol. 11, no. 3, 2008, doi: https://doi.org/10.1590/S1516-14392008000300008.

[9] W. Niu, C. Bai, G. B. Qiu, and Q. Wang, “Processing and properties of porous titanium using space holder technique,” *Mater. Sci. Eng. A*, vol. 506, no. 1–2, pp. 148–151, 2009, doi: 10.1016/j.msea.2008.11.022.

[10] D. S. Li, Y. P. Zhang, X. Ma, and X. P. Zhang, “Space-holder engineered porous NiTi shape memory alloys with improved pore characteristics and mechanical properties,” *J. Alloys Compd.*, vol. 474, no. 1–2, p. L1, 2009, doi: 10.1016/j.jallcom.2008.06.043.

[11] C. Xiang, Y. Zhang, Z. Li, H. Zhang, Y. Huang, and H. Tang, “Preparation and compressive behavior of porous titanium prepared by space holder sintering process,” *Procedia Eng.*, vol. 27, no. 2011, pp. 768–774, 2012, doi: 10.1016/j.proeng.2011.12.518.

[12] M. K. M. Kohl, M. Bram, H.P. Buchkremer, D. Stover, T. Habijan, “Production of Highly Porous Near-net-shape Ni-Ti Components for Biomedical Applications,” pp. 295–298, 2008.

[13] Y. Chen, D. Kent, M. Bermingham, A. Dehghan-Manshadi, and M. Dargusch, “Manufacturing of biocompatible porous titanium scaffolds using a novel spherical sugar pellet space holder,” *Mater. Lett.*, vol. 195, pp. 92–95, 2017, doi: 10.1016/j.matlet.2017.02.092.

[14] B. Q. Li, C. Y. Wang, and X. Lu, "Effect of pore structure on the compressive property of porous Ti produced by powder metallurgy technique," *Mater. Des.*, vol. 50, pp. 613–619, 2013, doi: 10.1016/j.matdes.2013.02.082.

[15] D. Wang, Q. Li, M. Xu, G. Jiang, Y. Zhang, and G. He, "A novel approach to fabrication of three-dimensional porous titanium with controllable structure," *Mater. Sci. Eng. C*, vol. 71, pp. 1046–1051, 2017, doi: 10.1016/j.msec.2016.11.119.

[16] S. W. Kim, H. Do Jung, M. H. Kang, H. E. Kim, Y. H. Koh, and Y. Estrin, "Fabrication of porous titanium scaffold with controlled porous structure and net-shape using magnesium as spacer," *Mater. Sci. Eng. C*, vol. 33, no. 5, pp. 2808–2815, 2013, doi: 10.1016/j.msec.2013.03.011.

[17] Y. Chen *et al.*, "Mechanical properties and biocompatibility of porous titanium scaffolds for bone tissue engineering," *J. Mech. Behav. Biomed. Mater.*, vol. 75, no. July, pp. 169–174, 2017, doi: 10.1016/j.jmbbm.2017.07.015.

[18] S. Z. Chunming Zou, Erlin Zhang, Mingwei Li, "Preparation, microstructure and mechanical properties of porous titanium sintered by Ti fibres," *J Mater Sci Mater Med*, vol. 19, no. 1, pp. 401–405, 2008.

[19] M. K. Yadav, V. Pandey, Jyoti, A. Kumar, K. Mohanta, and V. K. Singh, "Mechanical and biological behaviour of porous Ti–SiO2 scaffold for tissue engineering application," *Ceram. Int.*, 2021, doi: 10.1016/j.ceramint.2021.04.242.

[20] J. H. Lee, H. E. Kim, and Y. H. Koh, "Highly porous titanium (Ti) scaffolds with bioactive microporous hydroxyapatite/TiO2 hybrid coating layer," *Mater. Lett.*, vol.

63, no. 23, 2009, doi: 10.1016/j.matlet.2009.06.023.

[21] J. P. Li, S. H. Li, C. A. Van Blitterswijk, and K. De Groot, “A novel porous Ti6Al4V: Characterization and cell attachment,” *J. Biomed. Mater. Res. Part A*, vol. 73A, no. 2, pp. 223–233, May 2005, doi: 10.1002/JBM.A.30278.

[22] J. H. Lee, H. E. Kim, K. H. Shin, and Y. H. Koh, “Improving the strength and biocompatibility of porous titanium scaffolds by creating elongated pores coated with a bioactive, nanoporous TiO2 layer,” *Mater. Lett.*, vol. 64, no. 22, pp. 2526–2529, Nov. 2010, doi: 10.1016/J.MATLET.2010.08.038.

[23] A. Manonukul, M. Tange, P. Srikudvien, N. Denmud, and P. Wattanapornphan, “Rheological properties of commercially pure titanium slurry for metallic foam production using replica impregnation method,” *Powder Technol.*, vol. 266, pp. 129–134, Nov. 2014, doi: 10.1016/J.POWTEC.2014.06.030.

[24] H. C. Hsu, S. K. Hsu, S. C. Wua, P. H. Wang, and W. F. Ho, “Design and characterization of highly porous titanium foams with bioactive surface sintering in air,” *J. Alloys Compd.*, vol. 575, pp. 326–332, Oct. 2013, doi: 10.1016/J.JALLCOM.2013.05.186.

[25] S. C. P. Cachinho and R. N. Correia, “Titanium scaffolds for osteointegration: mechanical, in vitro and corrosion behaviour,” *J. Mater. Sci. Mater. Med.*, vol. 19, no. 1, pp. 451–457, Jan. 2008, doi: 10.1007/S10856-006-0052-7.

[26] V. Karageorgiou and D. Kaplan, “Porosity of 3D biomaterial scaffolds and osteogenesis,” *Biomaterials*, vol. 26, no. 27, pp. 5474–5491, 2005, doi:

10.1016/J.BIOMATERIALS.2005.02.002.

[27] M. Barrabés, P. Sevilla, J. A. Planell, and F. J. Gil, "Mechanical properties of nickel–titanium foams for reconstructive orthopaedics," *Mater. Sci. Eng. C*, vol. 28, no. 1, pp. 23–27, Jan. 2008, doi: 10.1016/J.MSEC.2007.02.001.

[28] J. P. Li, S. H. Li, K. De Groot, and P. Layrolle, "Preparation and characterization of porous titanium," *Key Eng. Mater.*, vol. 218–220, pp. 51–54, 2002, doi: 10.4028/WWW.SCIENTIFIC.NET/KEM.218-220.51.

[29] C. Wang, H. Chen, X. Zhu, Z. Xiao, K. Zhang, and X. Zhang, "An improved polymeric sponge replication method for biomedical porous titanium scaffolds," *Mater. Sci. Eng. C*, vol. 70, pp. 1192–1199, Jan. 2017, doi: 10.1016/J.MSEC.2016.03.037.

[30] Y. Li, C. Yang, H. Zhao, S. Qu, X. Li, and Y. Li, "New Developments of Ti-Based Alloys for Biomedical Applications," *Materials (Basel).*, vol. 7, no. 3, p. 1709, 2014, doi: 10.3390/MA7031709.

[31] G. He, P. Liu, and Q. Tan, "Porous titanium materials with entangled wire structure for load-bearing biomedical applications," *J. Mech. Behav. Biomed. Mater.*, vol. 5, no. 1, pp. 16–31, Jan. 2012, doi: 10.1016/J.JMBBM.2011.09.016.

[32] G. Jiang and G. He, "Enhancement of the porous titanium with entangled wire structure for load-bearing biomedical applications," *Mater. Des.*, vol. 56, pp. 241–244, Apr. 2014, doi: 10.1016/J.MATDES.2013.11.019.

[33] Q. Tan, P. Liu, C. Du, L. Wu, and G. He, "Mechanical behaviors of quasi-ordered entangled aluminum alloy wire material," *Mater. Sci. Eng. A*, vol. 527, no. 1–2, pp. 38–44, Dec. 2009, doi: 10.1016/J.MSEA.2009.07.022.

[34] P. Liu, Q. Tan, L. Wu, and G. He, "Compressive and pseudo-elastic hysteresis behavior of entangled titanium wire materials," *Mater. Sci. Eng. A*, vol. 527, no. 15, pp. 3301–3309, Jun. 2010, doi: 10.1016/J.MSEA.2010.02.071.

[35] G. Jiang, C. Wang, Q. Li, J. Dong, and G. He, "Porous titanium with entangled structure filled with biodegradable magnesium for potential biomedical applications," *Mater. Sci. Eng. C*, vol. 47, pp. 142–149, Feb. 2015, doi: 10.1016/J.MSEC.2014.11.014.

[36] Y. Liu, G. Jiang, and G. He, "Enhancement of entangled porous titanium by BisGMA for load-bearing biomedical applications," *Mater. Sci. Eng. C*, vol. 61, pp. 37–41, Apr. 2016, doi: 10.1016/J.MSEC.2015.12.018.

[37] G. He, P. Liu, Q. Tan, and G. Jiang, "Flexural and compressive mechanical behaviors of the porous titanium materials with entangled wire structure at different sintering conditions for load-bearing biomedical applications," *J. Mech. Behav. Biomed. Mater.*, vol. 28, pp. 309–319, Dec. 2013, doi: 10.1016/J.JMBBM.2013.08.016.

[38] K. Asaoka, N. Kuwayama, O. Okuno, and I. Miura, "Mechanical properties and biomechanical compatibility of porous titanium for dental implants," *J. Biomed. Mater. Res.*, vol. 19, no. 6, pp. 699–713, Jul. 1985, doi: 10.1002/JBM.820190609.

[39] Y. F. Yang, S. D. Luo, G. B. Schaffer, and M. Qian, "Sintering of Ti–10V–2Fe–3Al

and mechanical properties," *Mater. Sci. Eng. A*, vol. 528, no. 22–23, pp. 6719–6726, Aug. 2011, doi: 10.1016/J.MSEA.2011.05.041.

[40] O. M. Ivasishin and D. G. Savvakin, "The impact of diffusion on synthesis of high-strength titanium alloys from elemental powder blends," *Key Eng. Mater.*, vol. 436, pp. 113–121, 2010, doi: 10.4028/WWW.SCIENTIFIC.NET/KEM.436.113.

[41] V. Mamedov, "Spark plasma sintering as advanced PM sintering method," *Powder Metall.*, vol. 45, no. 4, pp. 322–328, 2002, doi: 10.1179/003258902225007041.

[42] G. Xie *et al.*, "Frequency effect on pulse electric current sintering process of pure aluminum powder," *Mater. Sci. Eng. A*, vol. 359, no. 1–2, pp. 384–390, Oct. 2003, doi: 10.1016/S0921-5093(03)00393-9.

[43] G. Xie, O. Ohashi, K. Wada, T. Ogawa, M. Song, and K. Furuya, "Interface microstructure of aluminum die-casting alloy joints bonded by pulse electric-current bonding process," *Mater. Sci. Eng. A*, vol. 428, no. 1–2, pp. 12–17, Jul. 2006, doi: 10.1016/J.MSEA.2005.10.029.

[44] S. W. Wang, L. D. Chen, Y. S. Kang, M. Niino, and T. Hirai, "Effect of plasma activated sintering (PAS) parameters on densification of copper powder," *Mater. Res. Bull.*, vol. 35, no. 4, pp. 619–628, Mar. 2000, doi: 10.1016/S0025-5408(00)00246-4.

[45] Y. F. Yang and M. Qian, "Spark plasma sintering and hot pressing of titanium and titanium alloys," *Titan. Powder Metall. Sci. Technol. Appl.*, pp. 219–235, Jan. 2015, doi: 10.1016/B978-0-12-800054-0.00013-7.

[46] M. Omori, "Sintering, consolidation, reaction and crystal growth by the spark plasma system (SPS)," *Mater. Sci. Eng. A*, vol. 287, no. 2, pp. 183–188, Aug. 2000, doi: 10.1016/S0921-5093(00)00773-5.

[47] J. R. Groza and A. Zavaliangos, "Sintering activation by external electrical field," *Mater. Sci. Eng. A*, vol. 287, no. 2, pp. 171–177, Aug. 2000, doi: 10.1016/S0921-5093(00)00771-1.

[48] M. Eriksson, Z. Shen, and M. Nygren, "Fast densification and deformation of titanium powder," *http://dx.doi.org/10.1179/174329005X71939*, vol. 48, no. 3, pp. 231–236, Sep. 2013, doi: 10.1179/174329005X71939.

[49] X. Zou, H. Li, M. Bünger, N. Egund, M. Lind, and C. Bünger, "Bone ingrowth characteristics of porous tantalum and carbon fiber interbody devices: an experimental study in pigs," *Spine J.*, vol. 4, no. 1, pp. 99–105, Jan. 2004, doi: 10.1016/S1529-9430(03)00407-8.

[50] J.A. Schneider, R.S. Mishra, A.K. Mukherjee, "Plasma activated sintering of ceramic materials," *Ceram. Trans.*, vol. 79, pp. 143–151, 1996.

[51] K. O. M.I. Lifland, "Properties of titanium dental implants produced by electro-discharge compaction," *Clin. Mater*, no. 17, pp. 203–209, 1994.

[52] W. B. E. A. Bose, "Hot Consolidation of Powders and Particulates," *Met. Powder Ind.*, 2003.

[53] K. P. W. W. Schatt, "Powder Metallurgy: Processing and Materials," *EPMA-European*

*Powder Metall. Assoc.*, 1997.

[54] R. K. Malik, "VACUUM HOT PRESSING OF TITANIUM-ALLOY POWDERS.," *Prog Powder Met.*, vol. 31, pp. 277–288, 1975.

[55] A. Ibrahim, F. Zhang, E. Otterstein, and E. Burkel, "Processing of porous Ti and Ti5Mn foams by spark plasma sintering," *Mater. Des.*, vol. 32, no. 1, pp. 146–153, Jan. 2011, doi: 10.1016/J.MATDES.2010.06.019.

[56] S. D. Luo, M. Qian, and M. Ashraf Imam, "Microwave sintering of titanium and titanium alloys," *Titan. Powder Metall. Sci. Technol. Appl.*, pp. 237–251, Feb. 2015, doi: 10.1016/B978-0-12-800054-0.00014-9.

[57] C. Y. Tang *et al.*, "In situ formation of Ti alloy/TiC porous composites by rapid microwave sintering of Ti6Al4V/MWCNTs powder," *J. Alloys Compd.*, vol. 557, pp. 67–72, Apr. 2013, doi: 10.1016/J.JALLCOM.2012.12.147.

[58] F. Zhang, E. Otterstein, and E. Burkel, "Spark plasma sintering, microstructures, and mechanical properties of macroporous titanium foams," *Adv. Eng. Mater.*, vol. 12, no. 9, pp. 863–872, 2010, doi: 10.1002/adem.201000106.

[59] R. Schmidt *et al.*, "Powder metallurgical processing of low modulus β-type Ti-45Nb to bulk and macro-porous compacts," *Powder Technol.*, vol. 322, pp. 393–401, 2017, doi: 10.1016/j.powtec.2017.09.015.

[60] M. Kon, L. M. Hirakata, and K. Asaoka, "Porous Ti-6Al-4V Alloy Fabricated by Spark Plasma Sintering for Biomimetic Surface Modification," *J. Biomed. Mater. Res.*

- *Part B Appl. Biomater.*, vol. 68, no. 1, pp. 88–93, 2004, doi: 10.1002/jbm.b.20004.

[61] M. Zadra, F. Casari, L. Girardini, and A. Molinari, "Microstructure and mechanical properties of cp-titanium produced by spark plasma sintering," *http://dx.doi.org/10.1179/174329008X277000*, vol. 51, no. 1, pp. 59–65, Mar. 2013, doi: 10.1179/174329008X277000.

[62] O. Ertorer, T. D. Topping, Y. Li, W. Moss, and E. J. Lavernia, "Nanostructured Ti consolidated via spark plasma sintering," *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 42, no. 4, pp. 964–973, Apr. 2011, doi: 10.1007/S11661-010-0499-5.

[63] Y. Chino and D. C. Dunand, "Directionally freeze-cast titanium foam with aligned, elongated pores," *Acta Mater.*, vol. 56, no. 1, pp. 105–113, Jan. 2008, doi: 10.1016/J.ACTAMAT.2007.09.002.

[64] S. W. Yook, B. H. Yoon, H. E. Kim, Y. H. Koh, and Y. S. Kim, "Porous titanium (Ti) scaffolds by freezing TiH2/camphene slurries," *Mater. Lett.*, vol. 62, no. 30, pp. 4506–4508, Dec. 2008, doi: 10.1016/J.MATLET.2008.08.010.

[65] H. Do Jung, S. W. Yook, H. E. Kim, and Y. H. Koh, "Fabrication of titanium scaffolds with porosity and pore size gradients by sequential freeze casting," *Mater. Lett.*, vol. 63, no. 17, pp. 1545–1547, Jul. 2009, doi: 10.1016/J.MATLET.2009.04.012.

[66] S. Deville, "Freeze-Casting of Porous Ceramics: A Review of Current Achievements and Issues," *Adv. Eng. Mater.*, vol. 10, no. 3, pp. 155–169, Mar. 2008, doi: 10.1002/ADEM.200700270.

[67] L. Yan, J. Wu, L. Zhang, X. Liu, K. Zhou, and B. Su, "Pore structures and mechanical properties of porous titanium scaffolds by bidirectional freeze casting," *Mater. Sci. Eng. C*, vol. 75, pp. 335–340, 2017, doi: 10.1016/j.msec.2016.12.044.

[68] J. C. Li and D. C. Dunand, "Mechanical properties of directionally freeze-cast titanium foams," *Acta Mater.*, vol. 59, no. 1, pp. 146–158, Jan. 2011, doi: 10.1016/J.ACTAMAT.2010.09.019.

[69] S. Deville, E. Saiz, and A. P. Tomsia, "Ice-templated porous alumina structures," *Acta Mater.*, vol. 55, no. 6, pp. 1965–1974, Apr. 2007, doi: 10.1016/J.ACTAMAT.2006.11.003.

[70] S. W. Yook, H. E. Kim, and Y. H. Koh, "Fabrication of porous titanium scaffolds with high compressive strength using camphene-based freeze casting," *Mater. Lett.*, vol. 63, no. 17, pp. 1502–1504, Jul. 2009, doi: 10.1016/J.MATLET.2009.03.056.

[71] H. Do Jung, S. W. Yook, T. S. Jang, Y. Li, H. E. Kim, and Y. H. Koh, "Dynamic freeze casting for the production of porous titanium (Ti) scaffolds," *Mater. Sci. Eng. C*, vol. 33, no. 1, pp. 59–63, Jan. 2013, doi: 10.1016/J.MSEC.2012.08.004.

[72] G. hui WANG, H. FU, Y. zhong ZHAO, K. chao ZHOU, and S. hong ZHU, "Bone integration properties of antibacterial biomimetic porous titanium implants," *Trans. Nonferrous Met. Soc. China*, vol. 27, no. 9, pp. 2007–2014, Sep. 2017, doi: 10.1016/S1003-6326(17)60225-5.

[73] S. W. Yook *et al.*, "Reverse freeze casting: a new method for fabricating highly porous titanium scaffolds with aligned large pores," *Acta Biomater.*, vol. 8, no. 6, pp. 2401–

2410, 2012, doi: 10.1016/J.ACTBIO.2012.03.020.

[74] Y. M. Soon, K. H. Shin, Y. H. Koh, W. Y. Choi, and H. E. Kim, "Assembling unidirectionally frozen alumina/camphene bodies for aligned porous alumina ceramics with larger dimensions," *J. Eur. Ceram. Soc.*, vol. 31, no. 3, pp. 415–419, Mar. 2011, doi: 10.1016/J.JEURCERAMSOC.2010.09.019.

[75] Y. Higuchi, Y. Ohashi, and H. Nakajima, "Biocompatibility of Lotus-type Stainless Steel and Titanium in Alveolar Bone," *Adv. Eng. Mater.*, vol. 8, no. 9, pp. 907–912, Sep. 2006, doi: 10.1002/ADEM.200600124.

[76] C. Suwanpreecha, E. Alabort, Y. T. Tang, C. Panwisawas, R. C. Reed, and A. Manonukul, "A novel low-modulus titanium alloy for biomedical applications: A comparison between selective laser melting and metal injection moulding," *Mater. Sci. Eng. A*, vol. 812, no. March, p. 141081, 2021, doi: 10.1016/j.msea.2021.141081.

[77] T. Deguchi, M. Ito, A. Obata, Y. Koh, T. Yamagishi, and Y. Oshida, "Trial production of titanium orthodontic brackets fabricated by metal injection molding (MIM) with sintering," *J. Dent. Res.*, vol. 75, no. 7, pp. 1491–1496, Nov. 1996, doi: 10.1177/00220345960750070901.

[78] A. Dehghan-Manshadi, D. StJohn, M. Dargusch, Y. Chen, J. F. Sun, and M. Qian, "Metal injection moulding of non-spherical titanium powders: Processing, microstructure and mechanical properties," *J. Manuf. Process.*, vol. 31, pp. 416–423, 2018, doi: 10.1016/j.jmapro.2017.12.004.

[79] D. Zhao, K. Chang, T. Ebel, H. Nie, R. Willumeit, and F. Pyczak, "Sintering behavior

and mechanical properties of a metal injection molded Ti–Nb binary alloy as biomaterial," *J. Alloys Compd.*, vol. 640, pp. 393–400, Aug. 2015, doi: 10.1016/J.JALLCOM.2015.04.039.

[80] J. Takekawa and N. Sakurai, "Effect of the Processing Conditions on Density, Strength and Microstructure of Ti-12Mo Alloy Fabricated by PIM Process," *J. Japan Soc. Powder Powder Metall.*, vol. 46, no. 8, pp. 877–881, Aug. 1999, doi: 10.2497/JJSPM.46.877.

[81] W. Xu *et al.*, "Mechanical properties, in vitro corrosion resistance and biocompatibility of metal injection molded Ti-12Mo alloy for dental applications," *J. Mech. Behav. Biomed. Mater.*, vol. 88, pp. 534–547, Dec. 2018, doi: 10.1016/J.JMBBM.2018.08.038.

[82] A. B. Nagaram and T. Ebel, *Development of Ti-22Nb-xZr using Metal injection moulding for biomedical applications*, vol. 704. 2016. doi: 10.4028/www.scientific.net/KEM.704.334.

[83] E. Yılmaz, A. Gökçe, F. Findik, and H. Özkan Gülsoy, "Characterization of biomedical Ti-16Nb-(0–4)Sn alloys produced by Powder Injection Molding," *Vacuum*, vol. 142, pp. 164–174, Aug. 2017, doi: 10.1016/J.VACUUM.2017.05.018.

[84] D. Zhao *et al.*, "Microstructure and mechanical behavior of metal injection molded Ti–Nb binary alloys as biomedical material," *J. Mech. Behav. Biomed. Mater.*, vol. 28, pp. 171–182, Dec. 2013, doi: 10.1016/J.JMBBM.2013.08.013.

[85] H. Guoxin, Z. Lixiang, F. Yunliang, and L. Yanhong, "Fabrication of high porous

NiTi shape memory alloy by metal injection molding," *J. Mater. Process. Technol.*, vol. 206, no. 1–3, pp. 395–399, Sep. 2008, doi: 10.1016/J.JMATPROTEC.2007.12.044.

[86] L. jian CHEN, T. LI, Y. min LI, H. HE, and Y. hua HU, "Porous titanium implants fabricated by metal injection molding," *Trans. Nonferrous Met. Soc. China (English Ed.*, vol. 19, no. 5, pp. 1174–1179, 2009, doi: 10.1016/S1003-6326(08)60424-0.

[87] P. Jenei, H. Choi, A. Tóth, H. Choe, and J. Gubicza, "Mechanical behavior and microstructure of compressed Ti foams synthesized via freeze casting," *J. Mech. Behav. Biomed. Mater.*, vol. 63, pp. 407–416, Oct. 2016, doi: 10.1016/J.JMBBM.2016.07.012.

[88] B. V. Krishna, S. Bose, and A. Bandyopadhyay, "Low stiffness porous Ti structures for load-bearing implants," *Acta Biomater.*, vol. 3, no. 6, pp. 997–1006, Nov. 2007, doi: 10.1016/J.ACTBIO.2007.03.008.

[89] S. Kurtz, K. Ong, E. Lau, F. Mowat, and M. Halpern, "Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030," *J. Bone Joint Surg. Am.*, vol. 89, no. 4, pp. 780–785, 2007, doi: 10.2106/JBJS.F.00222.

[90] G. E. Ryan, A. S. Pandit, and D. P. Apatsidis, "Porous titanium scaffolds fabricated using a rapid prototyping and powder metallurgy technique," *Biomaterials*, vol. 29, no. 27, pp. 3625–3635, Sep. 2008, doi: 10.1016/J.BIOMATERIALS.2008.05.032.

[91] P. Heinl, C. Körner, and R. F. Singer, "Selective Electron Beam Melting of Cellular Titanium: Mechanical Properties," *Adv. Eng. Mater.*, vol. 10, no. 9, pp. 882–888, Sep.

2008, doi: 10.1002/ADEM.200800137.

[92] W. Xue, B. V. Krishna, A. Bandyopadhyay, and S. Bose, "Processing and biocompatibility evaluation of laser processed porous titanium," *Acta Biomater.*, vol. 3, no. 6, pp. 1007–1018, Nov. 2007, doi: 10.1016/J.ACTBIO.2007.05.009.