Chapter

Low-Cost Preparation Technologies for Titanium Alloys: A Review

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Abstract

The titanium industry has been developing for nearly 70 years since the birth of Ti-6Al-4 V alloy. Due to its high specific strength, high and low-temperature resistance, corrosion resistance and good biocompatibility, titanium alloy is used in aerospace, marine engineering, and biomedical fields. However, the high production cost of titanium alloys currently limits their widespread use like steel and aluminum alloys. Therefore, the low-cost preparation technology for titanium alloys becomes hot research in recent years. This chapter provides a comprehensive overview of low-cost preparation technologies for titanium alloys from four aspects: raw materials, melting, hot working and machining, and advanced technologies. This review would be of interest to scholars in related fields.

Keywords: low-cost titanium alloys, alloying elements, low-cost melting, hot working, wire and arc additive manufacturing (WAAM)

1. Introduction

Although titanium (Ti) is the tenth amplest element on earth and the fourth most ample structural metal after aluminum (Al), iron (Fe), and magnesium (Mg), it took about 160 years from its discovery to the industrial application of Ti-6Al-4 V alloy in 1954 [1]. This is because, despite its large reserves, titanium is also defined as a rare metal due to its strong affinity for elements such as O, C, and N, which makes it difficult to extract from its ores [2]. In the past 70 years since the birth of Ti-6Al-4 V, titanium alloys have developed into hundreds of types and have been widely used in various industries due to their high specific strength, high and low-temperature resistance, corrosion resistance, and biocompatibility [3]. The strength of titanium is similar to steel, but its density is about half that of steel, and compared with aluminum, titanium is five times stronger [4]. The high specific strength of titanium alloys and their high tolerance to extreme operating conditions have led to their widespread use in aerospace (aircraft, spacecraft, engine, etc.) and military applications (helicopter, unmanned aerial vehicles, guided missiles, etc.) [5–7]. About 60% of titanium alloys are used in aerospace in Europe and the United States [8]. Nowadays, people are increasingly concerned about reducing CO_2 emissions, and the light weighting of transportation is a key step in reducing CO_2 emissions [9]. Therefore, the automotive industry is showing a strong interest in the use of titanium alloys for the light weighting of structural components, which offers the possibility of lower fuel consumption and reduced CO_2 emissions, but are currently limited to racing cars and specialized vehicles [10–12]. Titanium alloy is also used in marine engineering as a corrosion-resistant and lightweight structural material (propeller, bathyscaph, etc.) [13, 14]. In addition, non-toxic, non-magnetic, and better biocompatibility make titanium alloy widely used in medical implants (joint prosthesis, skeletal repair, etc.) [15–17]. Based on the current industrial applications and foreseeable development potential, titanium and its alloys are gradually becoming the fourth generation of metal materials after copper (Cu), iron (Fe), and aluminum (Al), but its high application cost greatly limits its large-scale application like the previous three metal materials [4, 18, 19]. Therefore, for about the past 30 years, research has been driven by various industriesto make titanium alloys a common general-purpose metal by reducing their production costs [20–23].

The traditional production and manufacturing process of titanium alloy components are roughly the same as for steel, including production of titanium sponge, addition of alloying elements, melting and pouring of alloy ingots, hot working to prepare different types of titanium materials (plate, tube, bar, etc.), and machining to prepare the final titanium alloy components. According to statistics, the percentage of each factor in the overall cost composition of titanium parts is shown in **Figure 1** [24]. It can be seen that from titanium sponge to ingot accounts for about 30% of the total cost, which includes the preparation of titanium sponge, the addition of alloying elements, and the melting of ingots. The average prices of titanium metal and its alloyed elements are shown in **Table 1** [25]. The price of titanium metal is much higher than the general metal iron (Fe) and aluminum (Al), while the application of more alloying elements, such as V, Nb, Mo, will again increase the cost of raw materials. In addition, the molten state of titanium alloy has a large viscosity and poor filling mobility, which makes it easy to produce defects such as porosity during the solidification process [26]. On the other hand, the hot working and machining accounts for about 70% of the total cost of titanium alloys, which is a hardly desirable percentage. Titanium alloys tend to react with oxygen under hot working and form a hardened oxide layer on the surface, making this process require specialized equipment [27]. At the same time, due to its low thermal conductivity, it will make the heat generated during the machining process cannot be dissipated quickly, and the higher heat accumulation will accelerate the tool wear [28]. Poor machinability and electrical conductivity have also led to the classification of

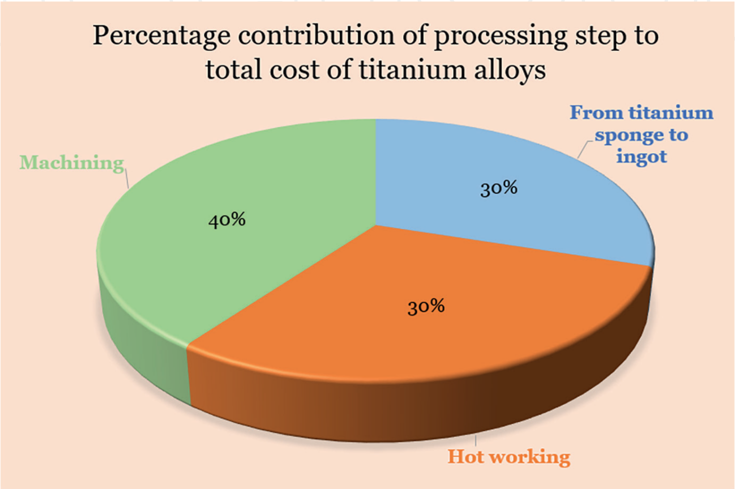

Figure 1.
Percentage contribution of processing step to total cost of titanium alloys [24].

Element	Price (USD/kg)	Role in phase stability
Ti	~11.9	
Al	~2.6	α-stabilizer
Fe	~0.6	β-stabilizer
V	~334.0	β-stabilizer
Nb	~96.5	β-stabilizer
Mo	~56.0	β-stabilizer
Ta	~534.4	β-stabilizer
Ni	~25.4	β-stabilizer
W	~16.2	β-stabilizer
Cr	~11.4	β-stabilizer
Co	~53.6	β-stabilizer
Mn	~3.5	β-stabilizer

Table 1.
The average prices of titanium metal and its alloying elements [25].

titanium alloys as difficult to machine materials [29]. The low molding rate of titanium parts and the large amount of remaining scrap being wasted are also a factor in the overall high cost of titanium alloys applications [30]. After the above analysis, we understand the various factors affecting the total cost of titanium alloys and realize that there are great challenges in the development of low-cost titanium alloys.

This chapter firstly reviewed the latest progress of low-cost titanium alloys from three aspects: raw materials, melting of alloy ingots, and processing and forming. Then, several new techniques for the low-cost preparation of titanium alloys are discussed and analyzed. Finally, the future development of low-cost titanium alloys is prospected and some suggestions are put forward.

2. Raw materials

2.1 Production of titanium

In the history of titanium production, from the birth of the Hunter process to the improved Kroll process using recyclable magnesium instead of sodium, it is still the most common method used in industrial production [31]. However, it is known from practical applications that the product obtained by the Kroll process is titanium sponge, which is six times more expensive than stainless steel production process [32]. After this problem was recognized, researchers continued to develop several new processes to reduce the cost of titanium feedstock, such as the Fray-Farthing-Chen (FFC) process [33], the Armstrong process [34], the Ono and Suzuki (OS) process [35], etc. The development of new processes for the production of titanium has been reviewed by researchers [36, 37]. This section will categorize all processes and then provide a brief overview and analysis. These new processes can be divided into two categories according to the metallurgical process: thermochemical processes and electrochemical processes. A summary of the various titanium production processes is shown in **Table 2**, including Kroll process.

To date, the vast majority of the world's titanium is produced by the Kroll process, which involves chlorination of titanium ore, purification of $TiCl_4$, magnesiothermic reduction, vacuum distillation, and electrolytic regeneration of Mg and Cl_2 [36]. We all know that the reduction of highly valence titanium compounds is a stepwise process. On the one hand, in order to minimize impurities in the final product, an excess of magnesium must be added to the magnesiothermic reduction process, which leads to a decrease in magnesium utilization. On the other hand, to ensure magnesium utilization leads to an increase of low valent titanium compounds in the final product

Processes classification	Processes name	Precursors	Advantages	Disadvantages	Refs.
Thermochemical processes	Kroll process	$TiCl_4$	Product with less oxygen content and metallic impurities	Low productivity; high cost of reductant; high energy consumption	[31]
	TiROTM process	$TiCl_4$	Continuous production	Easy introduction of oxygen	[38]
	Vapor-phase reduction process	$TiCl_4$	Continuous production	High oxygen content or high magnesium and chlorine content in Ti powder	[39]
	CSIR-Ti process	$TiCl_4$	Continuous production	Oxygen content is difficult to control	[40]
	Armstrong process	$TiCl_4$	Continuous production; excellent compressibility and denseness of Ti powder	Irregular powder morphology	[34]
	MHR process	TiO_2	Single-step reaction	High energy consumption and pollution	[41]
	PRP process	TiO_2	Highly scalable; controllable purity of Ti powder	High cost of reductant	[42]
	EMR process	TiO_2	Continuous production; high purity of Ti powder	Complicated process; difficult separation of metal and salt	[43]
	HAMR process	TiO_2	Low oxygen of Ti powder	High energy consumption	[44]
	HDH process	Ti sponge, Ti ingot, Ti mill products and Ti scrap	High purity of Ti powder; relatively inexpensive process	Irregular and angular powder morphology	[45]

Electrochemical processes	FFC process	TiO_2	Semi-continuous production; low oxygen of Ti powder	Low current efficiency; difficult separation of metal and salt	[33]
	OS process	TiO_2	Semi-continuous production; low oxygen of Ti powder	Low current efficiency; difficult separation of metal and salt	[35]
	USTB process	TiC_xO_{1-x} $(0 < x < 1)$	Semi-continuous production; low oxygen of Ti powder	Low current efficiency	[46]
	SOM process	TiO_2-containing flux	Single-step process	High process temperature	[47]

Note: CSIR: council of scientific and industrial research; MHR: metal-hydride Reduction; PRP: preform reduction process; EMR: electronically mediated reaction; HAMR: hydrogen-assisted magnesium reduction; HDH: hydride-dehydride; FFC: Fray-Farthing-Chen; OS: Ono and Suzuki; USTB: University of Science and Technology Beijing; and SOM: solid oxide membrane.

Table 2.
A summary of the various titanium production processes.

and a longer production cycle, which requires a choice between production efficiency, energy consumption and product quality. Overall, the disadvantages of Kroll process, including the expensive reducing agent Mg, long process route, low production efficiency, and high energy consumption (71.61 kWh/kg), resulted in a high price of \$7.4–\$10.3 per kg for titanium [4, 36]. The TiRO™ process [38], the vapor-phase reduction process [39], and the CSIR-Ti process [40] can all be seen as improvements of the Kroll process, and the Armstrom process [34] can be seen as an improvement of the Hunter process, using the same precursors and reductants, and they all attempt to develop a continuous production process with low energy consumption. Although the main precursor for titanium production is $TiCl_4$, there is also a class of processes that focus on TiO_2. Because TiO_2 can also be thermally reduced by metals, the commonly used reductants include Ca and Mg and are known as calciothermic and magnesiothermic methods, of which the MHR process [41], PRP process [42], EMR process [43], and HAMR process [44] are typical representatives. In addition to the thermochemical processes mentioned above, electrochemical processes have also received a great deal of attention, and typical representatives include FFC processes [33], OS processes [35], USTB processes [46], and SOM processes [47]. **Table 2** summarizes the advantages and disadvantages of the various processes, and by looking at the corresponding references you can gain a deeper understanding of the principles and processes of each process. Although many new processes have been developed over the decades in the hope of producing titanium cost-effectively, unfortunately, none of them have yet been able to replace the Kroll process in commercial applications. In fact, if it is a mature cost-efficient new process, firstly it should reach industrial production, secondly, the quality of the titanium metal produced by this new process should be the same or even better than Kroll process, and finally, the production cost of this new process should be significantly lower than that of Kroll process. It is clear that all the new processes that have been developed so far do not meet the yield, quality, and cost targets simultaneously, and there is still a long way to go to prepare low-cost titanium alloys from this step in the production of titanium.

2.2 Addition of alloying elements

Alloying elements also have a place in the raw material cost of titanium alloys. At present, the core idea of reducing the cost of titanium alloys from alloying elements is to use Ti-6Al-4 V alloy as the target and use cheap alloying elements instead of expensive alloying elements to reduce the cost of titanium alloy, while its mechanical properties are not lower than Ti-6Al-4 V alloy. This is because Ti-6Al-4 V alloy is still the most widely used titanium alloy today [48]. A great deal of corresponding research has been conducted in the United States, Japan, and China, and many low-cost titanium alloys have been developed and some have found practical application. A summary of the low-cost titanium alloys that have been developed in various countries is shown in **Table 3**.

Depending on their influence on the β-transus temperature, the alloying elements are classified as α-stabilizers, β-stabilizers, and neutral [49]. Generally, different strengthening effects are exhibited due to different alloying elements types, but some alloying elements can be replaced by others. The α-stabilizing elements include Al, O, N, and C, with Al being the most commonly used in titanium alloy design. The β-stabilizing elements can be divided into isomorphous-stabilizing elements and eutectoid-stabilizing elements. The isomorphous-stabilizing elements include V, Mo, Nb, Ta, etc., while the eutectoid-stabilizing elements include Fe, Cr, Mn, Ni, etc. Zr and Sn are neutral elements. As can be seen in **Table 1**, eutectoid

Country	Alloy designation	Chemical composition (wt %)	Low-cost features
United States	Timetal 62S	Ti-6Al-1.7Fe-0.1Si	Replace V with Fe
	ATI-425	Ti-4A1-2.5 V-1.5Fe-0.25O	Replace V with Fe
	Timetal LCB	Ti-1.5Al-6.8Mo-4.5Fe	Replace V with Fe-Mo alloy
	RMI VM	Ti-6.4Al-1.2Fe	Replace V with Fe
	Timetal CL4	Ti-5Al-3 V-0.6Fe-0.17O	Replace V with Fe
Japan	Ti-Fe-O-N alloys	Ti-1Fe-0.35O-0.01 N Ti-1Fe-0.4O-0.045 N Ti-1Fe-0.5O-0.05 N	Replace V with Fe; replace Al with O and N
	SP-700	Ti-4.5A1-3 V-2Mo-2Fe	Replace V with Fe-Mo alloy
	TFCA	Ti-4.3Fe-7.1Cr-3.0Al	Replace V with Fe-Cr alloy
	TFC	Ti-4.3Fe-7.1Cr	Reduce Al; replace V with Fe-Cr alloy
	KS Ti-531C	Ti-4.5Al-2.5Cr-1.2Fe-0.1C	Replace V with Fe-Cr alloy
China	Ti-8LC	Ti-6Al-1Mo-1Fe	Replace V with Fe-Mo alloy
	Ti-12LC	Ti-4.5Al-1.5Fe-6.8Mo	Replace V with Fe-Mo alloy
	Ti-35,421	Ti-3Al-5Mo-4Cr-2Zr-1Fe	Replace V with Fe-Cr alloy
	Ti-5322	Ti-5Al-3 V-2Cr-2Fe	Partially replace V with Fe-Cr alloy

Table 3.
A summary of the low-cost titanium alloys in various countries.

β-stabilizing elements are cheaper than isomorphous β-stabilizing elements, so people choose to use eutectoid β-stabilizing elements instead of isomorphous β-stabilizing elements for the design of low-cost titanium alloy. For example, in the early 1960s, the Ti185 (Ti-1Al-8 V-5Fe) alloy was developed through the addition of Fe [50]. Its high tensile and shear strength makes it an attractive fastening material. Since Fe is readily available and the cheapest, it is considered to be an ideal replacement element [51]. Fe is also one of the strongest β-stabilizing elements, and studies have shown that with the addition of Fe, the grain size of Ti-Fe system alloys decreases, which can improve the comprehensive properties of alloys [52, 53]. The use of Fe completely replaces V, such as the Timetal 62S (Ti-6Al-1.7Fe-0.1Si) alloy developed in the United States [54], and the addition of Si refines the grain. The cost of this alloy is reduced by 15–20% compared with Ti-6Al-4 V alloy without loss of strength and tensile properties, and has been used in military applications. In addition, the addition of Fe can facilitate hot working by reducing flow stresses, thus saving heat and power consumption [55]. Although you have many reasons to use Fe as an additive element for low-cost titanium alloys, it has been found that when Fe is added at more than 3%, segregation of Fe tends to occur, leading to the formation of intermetallic compounds (TiFe or Ti_2Fe) and beta flecks [56]. The intermetallic compounds tend to cause the alloys to lose their plasticity and also reduce their mechanical properties, while the beta flecks are often the preferred location for fatigue failure of the alloys [57]. To avoid the above, people choose to use Fe to partially replace V and Mo as isomorphous β-stabilizing elements, such as ATI-425 alloy (Ti-4A1-2.5 V-1.5Fe-0.25O) [58], Timetal LCB alloy (Ti-1.5Al-6.8Mo-4.5Fe) [59], Ti-8LC alloy (Ti-6Al-1Mo-1Fe) [60], and Ti-12LC alloy (Ti-4.5Al-1.5Fe-6.8Mo) [60]. Timetal LCB alloy was originally developed to replace Ti-1023 (Ti-10 V-2Fe-3Al) alloy with a cheaper Fe-Mo intermediate alloy instead of V. This alloy has proven to have high strength and good formability, with mechanical properties comparable to Ti-1023 alloy while costing about 80% of Ti-6Al-4 V alloy. The Ti-8LC and Ti-12LC alloys developed by China also use a cheap Fe-Mo intermediate alloy and incorporate pure titanium scrap in the melting process. These two alloys are currently listed in the Chinese national standard, corresponding to the grades TC28 and TC29. Ti-Fe-O-N series alloy is a typical low-cost titanium alloy developed in Japan, replacing Al and V with O, N, and Fe [61]. This series of titanium alloys is generally used in civilian applications because of its low price, as well as its low plasticity and poor high temperature performance. In addition, these alloys are also considered as potential materials for biomedical applications [62]. Incidentally, low-cost biomedical titanium alloys are also being developed rapidly [16, 63]. Also as relatively inexpensive eutectoid β-stabilizing elements Cr and Mn are of course used in the development of low-cost titanium alloys, such as Ti-3Al-2Fe-8.5Cr [64], Ti-6.0Al-4.5Cr-1.5Mn [65], and Ti-4.5Al-6.9Cr-2.3Mn [66].

Because the proportion of alloying elements in titanium alloys is relatively low, compared with the main element Ti, this method is limited in terms of cost reduction. During the literature search, it is clear that although researchers in various countries have designed a large number of low-cost titanium alloys and claimed that they have good prospects for application, very few of them are actually used. The authors believe that it is time to conduct in-depth fundamental research on the process, organization, and property relationships of the already designed low-cost titanium alloys to bring them to the level of industrial application as far as possible. Take Ti-5321 (Ti-5Al-3Mo-3 V-2Zr-2Cr-1Nb-1Fe) alloy as an example, since it was designed, developers have conducted extensive research on the alloy in terms of plane strain fracture behavior, and impact toughness, fracture toughness, deformation mechanism, and mechanical properties, which can lay a good foundation for pilot scale and even industrial applications [67–73].

3. Melting of alloy ingots

3.1 Recycling of titanium scraps

The recycling and reuse of titanium scrap can reduce the production cost of titanium alloys, which means that the actual utilization rate of the material is improved. Titanium scraps are first generated from the production of titanium metal. For example, when titanium sponge is produced using the Kroll process, 10–20% of inferior titanium sponge is produced during the reduction and separation process [30]. In addition, a large amount of titanium scraps will be generated during the processing of titanium alloy parts, especially in the aircraft industry, the finished product rate of general aviation parts is only about 10% [20]. It is obvious that recycling of titanium scrap is necessary, and according to statistics, the cost of titanium alloy ingots will be reduced by 0.7% for every 1% of titanium added after the recycling process [20]. These reviews [30, 74–77] are very useful for you to get a comprehensive understanding of the current technology and status of recycling of titanium scraps, and the authors will not repeat them here. Titanium scraps that meet the reuse criteria will be mentioned in Section 3.2.

3.2 Low-cost melting technologies

The low-cost melting of titanium alloy is mainly considered from two aspects, one is to increase the utilization of titanium scraps, and the other is to improve the melting efficiency and quality, while achieving the integration of meltage and refinement. The CHM (Cold Hearth Melting) technology developed in the United States basically solves both problems [20], including EBCHM (Electron Beam Cold Hearth Melting) technology and PACHM (Plasma Arc Cold Hearth Melting) technology. The biggest difference between the above two melting technology is the difference in heat source, and one is selected here for introduction. Compared with conventional vacuum arc remelting, EBCHM has the following outstanding advantages [20, 78]: (1) High-density impurities, low-density impurities, and volatile impurities can be removed to prepare pure titanium alloys; (2) low raw material requirements, 100% titanium scraps, and titanium alloys scraps can be utilized; (3) ingots can be produced by a single melting; and (4) the preparation of multiple forms of ingots can be achieved by adjusting the crystallizer to shorten the subsequent process flow. Since EBCHM works under high vacuum conditions, alloying elements (e.g., Al) are easily evaporated if their vapor pressure is higher than that of titanium. It is particularly important to control the content of aluminum, which is a key element in most titanium alloys. Using Langmuir equation and penetration theory, the evaporation process of Al during EBCHM of Ti64 alloy was calculated and the evaporation mechanism of Al was analyzed, and the results showed that the evaporation of Al is a double-controlled process, that is, surface evaporation and melt pool diffusion [78]. To control the evaporation of Al, the surface temperature of the alloys must be controlled. The influence of melting speed, electron beam output power, and other factors on ingot composition was determined by developing a mathematical model of Al evaporation kinetics during EBCHM, which provides a usable tool for melting ingots with specified compositions using EBCHM [79]. The aerospace materials standard of the United States requires aerospace structural parts made of titanium alloys must undergo an EBCHM melting. EBCHM is able to make full use of titanium scrap and obtain homogeneous titanium ingots by primary melting, thus reducing the production cost of titanium ingots in terms of both raw materials and energy, and has become the first choice of countries.

4. Hot working and machining

As shown in **Figure 1**, from titanium metal to alloy ingots accounts for 30% of the total cost of titanium alloy parts, which means that the savings from reducing the production cost of titanium metal, using cheap alloying elements instead of expensive alloying elements and using low-cost melting technology will only add up to much less than 30%. Correspondingly, the hot working and machining processes used for the final forming of titanium alloy parts account for approximately 70% of the total cost. Obviously, it is a big challenge to reduce the cost of hot working and machining. Researchers first thought of tackling this challenge by optimizing the process parameters. The appropriate hot working parameters for different titanium alloys need to be found accurately; otherwise, poorly performing titanium alloys will only increase the cost of their applications in disguise [80]. Temperature, strain rate, and strain are the most important parameters in the hot working. Titanium alloys are sensitive to the process parameters of hot working, and changes in parameters can alter their microstructural morphology, which in turn can lead to significant changes in actual alloys properties [81, 82]. In recent years, constitutive models [83] and processing maps [84] have gained more practical applications due to their accuracy in process parameter optimization. **Table 4** summarizes some studies on constitutive models and processing maps of titanium alloys during hot working. From the different studies presented in **Table 4**, it can be concluded that the main challenge of this approach is to select the most suitable constitutive models to accurately describe the stress-strain behavior during

Alloys	Parameters			Refs.
	Temperature (°C)	Strain rate (s^{-1})	Strain (%)	
Ti-6Al-4 V	900–1050	0.1, 1 and 10	80	[85]
Ti60	970–1120	0.01–10	80	[86]
CP-Ti	400–700	0.001–1	90	[87]
IMI-834	975–1100	0.1 and 1	80	[88]
Ti2448	750–850	0.001–63	70	[89]
Ti-6Al-4 V	800–1100	0.001–10	100	[90]
BT3-1	800–1060	0.0003–1	60	[91]
As-cast ATI 425	950–1150	0.001–1	50	[92]
Ti-3Al-3.7Cr-2Fe-0.1B	800–950	0.01–10	70	[93]
46Ti-46Al-4Nb-2Cr-2Mn	850–1050	0.0001–10	80	[94]

Table 4.
A summary of some studies on constitutive models and processing maps of titanium alloys during hot working.

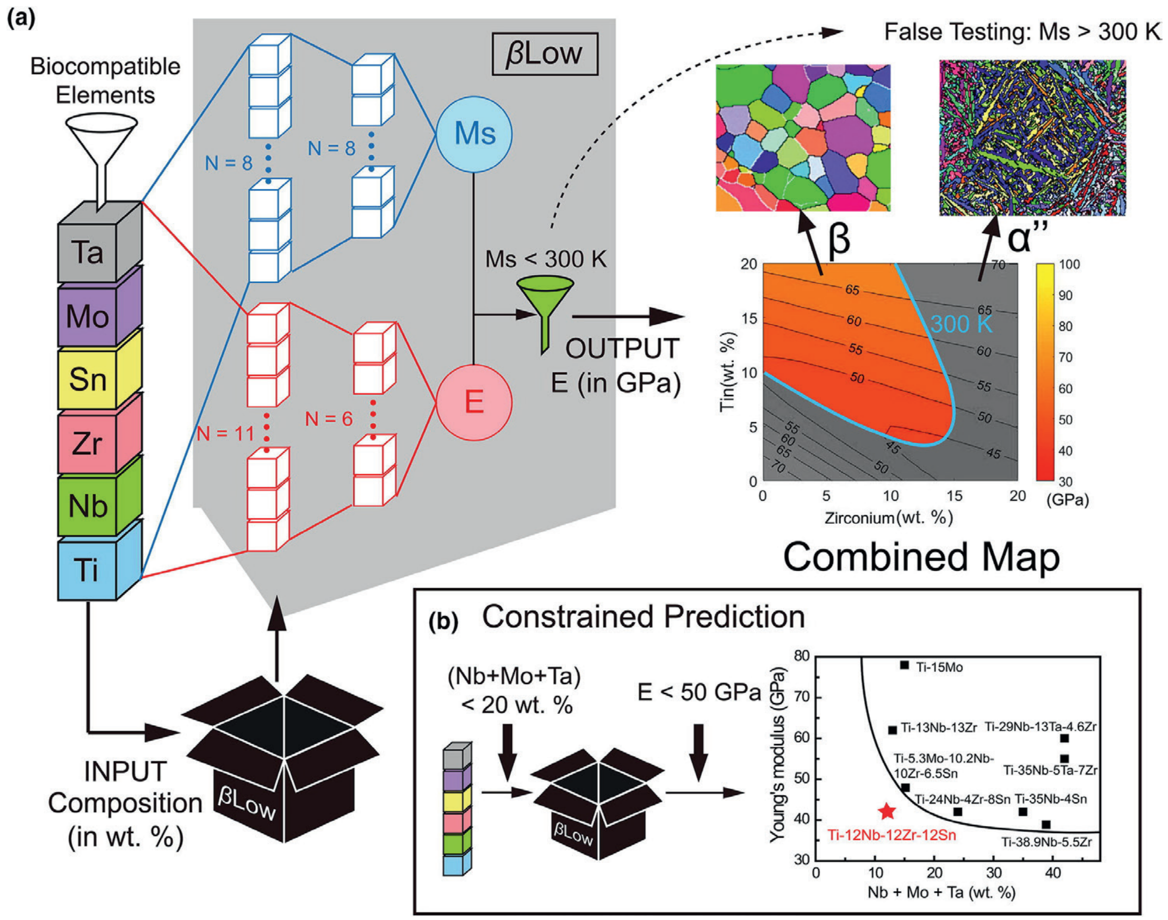

Figure 2.

Schematic diagram of artificial neural network assisted development of titanium alloys. (a) The operation process of alloy design is introduced in detail; and (b) prediction of low-cost titanium alloys by limiting high-cost elements to less than 20% [99].

the hot working. In addition, artificial neural networks based on machine learning have been applied to predict the hot deformation behavior [95], flow stress [96], microstructure evolution [97], and processing parameters [98] of titanium alloys. For example, a low-cost titanium alloy with bone-like Young's modulus was designed using neural networks, as shown in **Figure 2** [99]. And its Young's modulus and Ms. temperatures were predicted, and further experiments proved its high tensile strength and better biocompatibility. The process of titanium alloys development can be accelerated through the use of artificial neural networks, while reducing research costs.

If the cost of equipment is considered, steel and titanium co-production can be implemented [4], which can effectively use the existing mature equipment to greatly reduce the processing and manufacturing cost of titanium alloys.

5. Advanced low-cost preparation technologies

A large part of the high price of titanium alloys comes from the long and complex process from ingot to product. Advanced preparation technologies are dedicated to the preparation of titanium alloy products in a few simple steps, while achieving efficient manufacturing and improved raw material utilization. **Table 5** summarizes some studies of advanced low-cost preparation techniques of titanium alloys. The advanced technologies in the table can be divided into three categories, namely AM,

Alloys	Feedstock	Technologies	Refs.
Ti-xCu	Ti and Cu spherical powders	AM	[100]
Ti-xFe	HDH Ti powder and Fe powder	PM	[101]
Ti-6Al-4 V	Ti-6Al-4 V HDH powder	FAST-forge	[102]
Ti-xFe	Ti and Fe power	PM	[103]
Ti-xFe	HDH Ti powder and AISI 430 LHC powder	PM	[104]
Ti-35Nb	Ti and Nb power	SLM	[105]
Ti-6Al-4 V	Ti-6Al-4 V wire	WAAM	[106]

Note: AM: additive manufacturing; PM: powder metallurgy; FAST: field-assisted sintering technology; SLM: selective laser melting; and WAAM: wire and arc additive manufacturing.

Table 5.
A summary of some studies of advanced low-cost preparation techniques of titanium alloys.

PM, and FAST-forge, as SLM and WAAM are included in AM [105, 106]. The feedstock used in all technologies is metal powders, except for WAAM, which uses metal wire as feedstock. Compared with titanium sponge powder and titanium powder prepared by other methods in Section 2.1, HDH titanium powder containing Ti mill products and Ti scrap is preferred due to its low cost, low chlorine content, and good mechanical properties [45]. We note that Fe remains an important alloying element in advanced technologies, due to the fact that Fe, in addition to the advantages mentioned in Section 2.2, and helps to improve the sinterability of titanium alloys, making it more advantageous in PM [24]. Although alloying elements such as Ni, Cr and Cu are also used in powder form, the attraction of using Fe powder in advanced technologies is still the greatest, and expensive alloying elements, complex hot working, and difficult machining can all be solved at once.

AM is a process of manufacturing parts layer by layer and is a promising method for manufacturing near final (net) shape parts [100], which focuses on reducing the production cost of titanium alloy parts in terms of both improving the utilization of raw materials and preparing the final product in a short process. In the following, WAAM will be discussed and analyzed as an example. A complete WAAM process consists of three main aspects: the planning of the target part by software, the deposition of metal materials using the WAAM system, and post-treatment [107]. The cost data for the production of titanium alloy (Ti-6Al-4 V) parts using WAAM are shown in **Table 6** [108]. The capital cost is a one-time cost of approximately $130,000 to make up the basic hardware of WAAM. Also, welding wire (Ti-6Al-4 V) is an inexpensive feedstock, with prices ranging from $120 per kg to $300 per kg (depending upon wire diameter). The advantages of WAAM are high deposition rates, low equipment costs, and high material utilization. Compared with conventional subtractive manufacturing, the WAAM process can reduce manufacturing time by 40–60% and post-machining time by 15–20%, and save approximately 78% of raw materials [109]. In aerospace, the "Buy-To-Fly" (BTF) ratio is used as a cost lever to refer to the ratio of materials purchased to materials in the final product, and it is clear that a lower BTF ratio is advantageous [110]. The researchers compared the BTF ratio using WAAM with conventional titanium machining and can conclude that the BTF ratio of WAAM is significantly lower compared with conventional titanium machining methods [111–113]. The applications of titanium alloy parts prepared by WAAM are shown in **Figure 3** [107]. As an example,

Costs	Items	Amount of money (USD)
Capital cost	Six-axis robot	~60,000
	Power source and torch	~36,000
	Clamping tool	~12,000
	Enclosure	~24,000
Software cost	WAAMsoft	/
Material cost	Welding wire (Ti-6Al-4 V)	~120–300/kg

Table 6.
A summary of cost data for the production of titanium alloy (Ti-6Al-4 V) parts using WAAM [108].

WAAM3D Company produced a full-scale sample of a Ti-6Al-4 V pressure container for space exploration that is approximately 1 meter high and 8.5 kg in weight. By using WAAM, 65% time was saved and 80% less raw material was used to meet performance requirements [107]. By far, WAAM products are the most commonly used in the aerospace and nuclear industries. The low processing accuracy and large surface roughness limit its application in the electronics and biomedical industries compared with other metal powder-based AM, such as SLM [114].

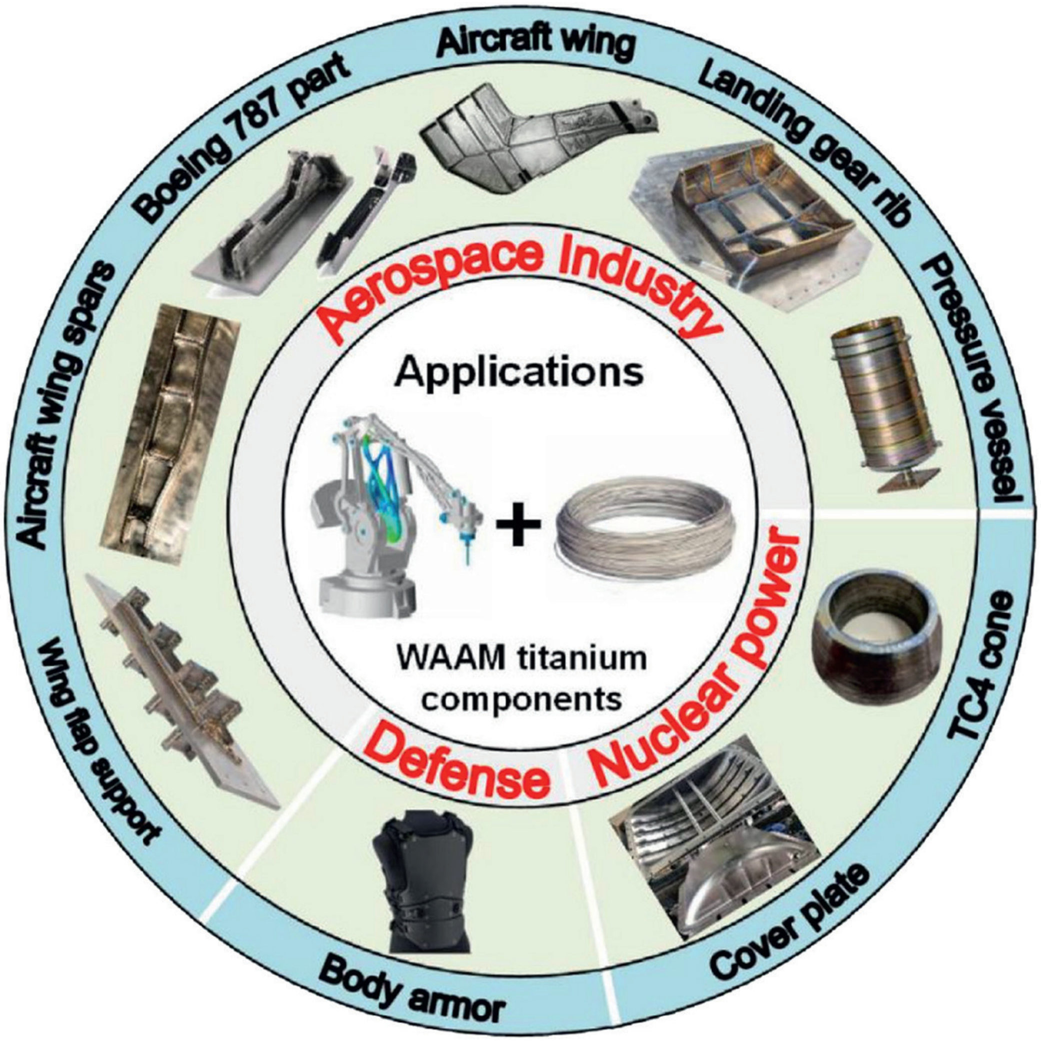

Figure 3.
The applications of titanium alloy parts prepared by WAAM [107].

6. Emerging technologies and climate

The greenhouse effect caused by CO_2 emissions is becoming increasingly evident. According to estimates, to achieve a global temperature rise limited to less than 2°C by 2100, CO_2 emissions must be reduced to less than 500 million tons per year before 2050 [115]. In recent years, several countries have developed a series of policies to address CO_2 emissions, such as carbon taxes and carbon trading schemes, all aimed at addressing the problem of climate degradation due to excessive CO_2 emissions [116–118]. It is clear that these policies will lead to changes in the industry, making the future of industrial production cleaner and more efficient. For the main process used to produce titanium, the Kroll process, researchers compared the environmental impacts of advanced technology equipment before and after its application, such as multi-pole electrolytic cells and inverted U-shaped reduction distillation furnaces [119]. The results show that the application of advanced technologies significantly improved the Kroll process' ability to save energy and reduce emissions, with 17% reduction in total electric power consumption, 90% reduction in particulate matter and CO gas emissions, and 21% reduction in overall environmental impact. In China, 74.4% of electricity is generated by coal, so a reduction in energy consumption in industrial production can also be seen as reducing carbon emissions [120]. Electrical discharge machining (EDM), which has the advantages of non-contact machining, non-macro-cutting force and high-machining hardness materials, has been maturely applied to the machining of titanium alloys [121]. According to the World Research Institute/World Business Council for Sustainable Development Greenhouse Gas Protocol, the total carbon emissions of the electricity used by an EDM machine are 23.57 tons of CO_2 equivalent. In order to save energy and improve EDM productivity, researchers developed a magnetic field-assisted EDM process (MF-EDM), and experimental results showed 61.43% reduction in energy consumption when using MF-EDM, equivalent to 9.09 tons reduction in CO_2 emissions [120]. Environmental friendliness is one of the major advantages of electrochemical methods. Unlike the preparation of titanium using electrochemical methods in Section 2.1, researchers used electrochemical methods to efficiently prepare Ti-Al alloy powders [122] and Ti-Al-V alloy powders [123] in one step, and at the same time, these titanium alloy powders can be directly used as raw materials for near-net forming of titanium alloy parts, such as powder metallurgy (PM) and additive manufacturing (AM). Through modeling and estimation, if the U.S. aircraft industry were to shift from conventional manufacturing (CM) to additive manufacturing (AM), cumulative energy savings of 1.2–2.8 billion GJ could be achieved in 2050, with associated cumulative greenhouse gases (GHG) reductions estimated at 92.1–215.0 million metric tons [112]. For any step of the full production process of titanium alloy parts, emerging technologies with environmental friendliness, low energy consumption, and low cost are the subjects of our research, and it is clear that we still have a long way to go.

7. Conclusions

In order to expand the application range of titanium and titanium alloys, the low-cost titanium alloys are one of the hot spots of research in the field of titanium alloys at present. This chapter provides a comprehensive overview of low-cost preparation technologies for titanium alloys from four aspects: raw materials, melting, hot working and machining, and advanced technologies. Raw materials include the production of titanium metal and the addition of alloying elements. Although there are many improved or alternative processes for the production of titanium, the Kroll process is still the most used in industry. Therefore, using cheap alloying elements instead of expensive ones is currently an effective way to reduce raw material costs. On the melting side, the recycling of titanium scraps and the application of CHM melting technology are together influencing the cost of alloy ingots. The use of the constitutive model, processing maps, and artificial neural networks can make the process parameters of hot working more accurate, and the co-production of steel and titanium can reduce the production cost of titanium alloys from equipment. Advanced preparation techniques for titanium alloys, such as AM and PM, are highly attractive because they generally have simple steps and can address multiple factors that lead to high costs in traditional titanium alloy preparation processes at once. Only technological progress in many aspects will enable titanium alloys to be used more widely, like steel and aluminum alloys. In addition, some emerging technologies for the preparation of titanium alloys and their contribution to the reduction of CO_2 emissions and energy consumption are presented.

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Conflict of interest

The authors declare no conflict of interest.

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