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Development of low-cost titanium alloys: A chronicle of challenges and opportunities

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Abstract

The production of titanium alloys became fully commercialized in the 1950s and that was precisely 145 years since titanium ores, ilmenite and rutile were first discovered. In the 2000s, up to 100 titanium alloys of different grades were already designed, but only 20% of these alloys are in use on a commercial scale. Despite this, there is growing interest in the design of new titanium alloys owing to the global demand for stronger, lighter and less-expensive alloys for engineering applications. This paper presents an overview of the different design strategies that were adopted in producing low-cost titanium alloys since the alloys already met two important demands, strength and lightweight. Some of the challenges and opportunities that are associated with these strategies are mentioned.

Introduction

Spanning over 100 years is the distance between the discovery of titanium ore and commercial utilisation of titanium and its alloys. This is largely attributed to the difficulties that are often encountered during the extraction of titanium from its ore. In fact, the metal was named after the titans because of its affinity for other elements, mainly oxygen and nitrogen, which explains why it is difficult to extract [1]. With the breakthrough of William J. Kroll in 1940 shortly after the attempt made by Matthew A. Hunter in 1910, titanium and its alloys soon became the metal of choice in the aerospace and military due to their good strength-to-weight ratio [1]. The major oxide of titanium, TiO_2 was also used as an important raw material in the paint industry [2]. As titanium continued to gain prominence, its application was extended from strictly aerospace to other land-based applications such as automotive and biomedical industries [3], [4].

The consideration given to titanium and its alloys in these sectors was due to their good resistance to corrosion in many industrial electrolytes, excellent biocompatibility and good strength up to 450 °C in the $\alpha+\beta$ type alloys [3], [4].

Despite the growing interest in titanium, high cost of production for the various alloy types remained an impediment against widespread applicability of titanium alloys [5]. In the last two and a half decades, the impetus for research on titanium has been reduction of manufacturing cost [3], [6]. While some author focussed on developing extraction process that is cheaper than the Kroll process, others concentrate on developing cost-effective design strategies that would make the manufacturing of the different titanium alloys and their products affordable. Although significant progress was made in developing different extraction processes that were cheaper than the Kroll process, the Kroll process still remain the mostly utilised method for extracting pure titanium from its ore on a commercial scale [7]. The final product from the Kroll process is titanium sponge and it is six times more expensive than stainless steel production process [7]. Since titanium powders are needed for alloy development, the hydrogenation-dehydrogenation (HDH) process was developed and remained one of the most recognised titanium powders used today [7]. To reduce cost, other alternative processes that allowed for production of titanium powder directly from the extraction process were developed. The Armstrong process [8], Australia's CSIRO process [9], United Kingdom's Fray Farthing Chen (FFC) Cambridge process [10], [11] and the South Africa's CSIR metallothermic process [12] are notable examples.

Since an extensive review of the titanium powder extraction has been presented by Fang et al. [13]. This review will focus more on the design strategies that were used in reducing the cost of manufacturing titanium alloys for engineering applications. These strategies are largely categorised as basic design concepts and advanced design concepts and are discussed in more detail in the subsequent sections.

Section snippets

Basic design strategies for developing low-cost alloys

The basic design strategies were the earliest ideas that were implemented to tackle the challenge of high cost of titanium alloys. The strategy involved identifying the critical factors that significantly contribute to the cost of producing titanium alloys. The different factors that contribute to the high cost of titanium alloys as established by SA materials [14] and Kraft [15] are presented in Fig. 1, Fig. 2. The factors include use of expensive and rare alloying elements, complex and…

Advanced design strategies for designing low-cost titanium alloys

The advanced design strategies involve addressing more than one factor that contribute to high cost of titanium alloys in one or two simple steps. The approach takes advantage of having titanium powder as raw material and the availability of robust powder metallurgy techniques. Table 4 presents some of the works done on low-cost titanium alloys using the advanced design strategies. The HDH titanium powder and the sponge titanium fines were the commonly used feedstock in making most of these…

Summary

The different strategies used in developing low-cost titanium alloys for land-based applications were classified into two broad groups, basic design concepts and advanced design concepts. The basic design concepts focus on tackling individual factor that contributes to the cost of producing titanium alloys. Substitution of expensive alloying elements with cheaper alternatives is one of the basic design strategies that was adopted to tackle the challenge of expensive raw materials when producing …

CRediT authorship contribution statement

Michael O. Bodunrin: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Funding acquisition. **Lesley H. Chown:** Supervision, Writing - review & editing, Conceptualization, Methodology, Resources, Funding acquisition. **Joseph A. Omotoyinbo:** Writing - review & editing.…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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>
> …The cost-effective aspect lies in the loose powder thermomechanical processing and the utilization of iron as the alloying element. Substitution of expensive alloying elements for cheaper raw material and reducing the processing step are key design strategies for the development of low-cost titanium alloy [39]. It is also important to mention that the results reported in this work for the mixing strategy could be applied to other loose powder thermomechanical methods.…

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> …Among all the strategies, the development of Fe-alloyed and V-free alloys opens the pathway to lowering the cost of wrought titanium products [1,2,17–34]. The substitution of expensive V with cheap element Fe not only reduces the cost of raw materials [17–19] but also decreases βtransus temperature [21]. The expanded β phase field gives rise to the enlarged forging/rolling temperature window and lowered the flow stress, thus facilitates the thermal-mechanical process and reduces the manufacturing cost [3,20].…

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Phase transformation and microstructure evolution of Ti6Al4V-0.55Fe alloy with different initial microstructure during continuous heating

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> …It is widely used in aerospace, petrochemical, biomedical and marine engineering fields [1–3]. For the development of Ti alloys, the mostly important considerations are improving the performance, exploring the civil market and reducing the cost [4–6]. Many experimental results have been concentrated on the microstructure and mechanical properties of Ti alloys.…

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