REVIEW OF RECENT FINDINGS ON INVESTMENT CASTING OF TITANIUM ALLOYS

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ABSTRACT: Recent findings on the investment casting of titanium alloys have been reviewed. Because of the reported high reactivity between the titanium alloy melt and the mould at increasing working temperatures (1670 °C), selecting a refractory mould for investment casting is critical. Calcium zirconate (CaZrO₃) and alumina (Al₂O₃) have been identified as the least reactive moulds for the investment casting of titanium alloys. The manufacture of a novel lower-cost cast titanium alloy based on the Ti-Al-Fe system (Ti-6Al-5Fe-0.05B-0.05C (all wt. %)) has been reported. When compared to the baseline Ti-6Al-4V alloy, this novel alloy had better castability. There is minimal understanding of the research of locally produced raw materials as either refractory moulds or binders for investment casting of titanium alloys, according to certain knowledge gaps. Furthermore, there is little understanding about the ideal mould preheating temperature for good investment casting of titanium alloy. Future research on titanium alloy investment casting should address the information gaps, as stated.

KEYWORDS: investment casting, titanium alloys, refractory mould, binder, pattern

1 INTRODUCTION

Investment casting is a kind of casting that uses a refractory shell and wax to create a finished product. It's also known as the "lost wax" or "precise casting" approach. Investment casting allows for near-net-shape manufacturing of complicated cast objects. According to Freitag et al. (2017), the high melting temperature of titanium alloys and their rapid reactivity during casting is very challenging. A simple investment mould is required that does not react negatively with the melt of titanium alloy. Several new mould materials have been created in previous studies to overcome the limits of traditional investment mould compounds. For example, an oxidation-expansion investment compound was created in which magnesium oxide or zirconia was employed as the major element and metallic zirconium was added to compensate for contraction attributable to solidification of the cast metal. There is now a need for simple and dependable investment casting technologies that allow for easy extraction of metal alloys from an investment mould that rarely reacts with the metal or a metal alloy. Bewlay et al. (2020) posited that traditional investment mould compounds utilized in the jewellery and dental prosthesis sectors, such as fused quartz, cristobalite, gypsum, or the like, are typically not suited for casting reactive alloys like titanium alloys. One explanation for this is that the titanium melt reacts with the investment casting mould.

The key requirements for a refractory mould cavity for investment casting are sufficient green unfired capacity to withstand wax removal without breakdown, sufficient fired strength to withstand metallic pressure, high thermal shock resistance to avoid crack formation throughout metal flowing, chemical inertness and minimal reactivity with the metals being cast to achieve adequate surface finishing and no alpha case creation on the surface of Ti and Ti alloys sections. The mould must also have sufficient permeability to enable the molten metal to flow freely through it, as well as thermal conductivity to permit heat to move through the mould wall, enabling molten metal to cool, and minimal expansion coefficient (Neto et al., 2017).

Because of the investment in casting technology, cast titanium alloys offer a broad variety of applications. Nickel and titanium alloys (also referred to as superalloys) are among the materials utilized in gas turbines. Titanium alloys are often used for compressor components in aviation engines, nickel alloys are ideal for hot portions of the engine of aircraft, and high strength steels are utilized for compressor housings and turbine housings, for example. Forged parts are frequently used in highly loaded or strained gas turbines, such as compressor components. Turbine parts are made...
of investment cast pieces (Bewlay et al., 2020). Furthermore, since the 1950s, titanium alloys have been extensively employed because of their superior properties, like specific resistance, resistance to corrosion, and bioactivity, among many others (Castellanos et al., 2017). Contemporary combustion turbines must meet the most stringent requirements in terms of dependability, weight, power, efficiency, and operational life. Material selection, the quest for new acceptable materials, and the search for new manufacturing processes play an essential part in fulfilling requirements and satisfying demand in the advancement of such turbines (Bewlay et al., 2020).

The need for more complex and demanding components is driving the growth of the investment casting industry, even though the technology is not particularly new. There is always a need to develop creative procedures to make high-quality investment castings that are quicker, more efficient, less costly, and provide higher value because of the huge demand for high-precision castings.

2 THE INVESTMENT CASTING METHOD

Investment casting is a technique for creating complicated parts with precise details. It includes covering a wax design with successive layers of ceramic slurries and stuccos to create a disposable ceramic mould. Pattern making, mould manufacturing, pouring, and finishing are only a few of the phases in the investment casting process, as depicted in Fig. 1 (Kobryn, 1996).

2.1 Investment casting pattern creation

Pattern creation is the initial stage in investment casting. By injecting the liquid, semi-solid, or hard wax or polymer into a durable mould, the pattern is obtained. Waxing mixtures (mixtures of resins, waxes, dyes, fillers, and plastics) and polymers (polyethylene, polystyrene amongst others) are among the materials used in pattern creation. Properties impacting insertion, withdrawal, assembly, handling, dimensional control, mould forming, burnout and dewaxing, environmental pollution, and economics must all be addressed when selecting a pattern material. Because waxes are simple to process and may be tailored to generate a broad variety of qualities, wax mixtures are more widely utilized than plastics (Kobryn, 1996).

2.2 Mould production

The pattern is initially immersed into a ceramic slurry bath comprising various proportions of wetting agents, binders, antifoam compounds, and fine refractory powders to make the ceramic shell mould. The design is withdrawn from the slurry, let to drain briefly, and then stuccoed in a fluid medium or by sprinkling with coarse ceramic powder. Another slurry-stucco layer is added once the coating has solidified by drying or chemical gelling. The immersing, stuccoing, and hardening processes are repeated until the required mould thickness is achieved. To seal the mould, a final layer of slurry coating is applied without stuccoing. The slurry coatings give the mould its strength and precisely copy the pattern's surface, while the stucco coats keep the slurry from running off, splitting, or peeling away, offering adhesion between adjacent layers, and quickly building up mould thickness.

The kind of refractory and binder used to build the mould is determined by the alloy being cast as well as the process conditions, like thermal gradients within the mould and time among others. Zircon, aluminium silicates, and fused silica are the most popular refractories used in investment castings. Since it is more refractory and far less reactive, alumina is widely used for casting superalloys. On the other hand, Zirconia, yttria, and thoria are often used in titanium investment casting (Colvin, 1994; Kobryn, 1996). For operations requiring extremely refractory binders, such as

![Flow chart illustrating the key processing phases of mould manufacturing, casting, post-cast processing, and inspection in the traditional investment casting process.](image-url)
directional solidification, binders could include ethyl silicate, colloidal silica, colloidal alumina, liquid sodium silicate, and colloidal zirconia. The shell is cured between 16 and 48 hours after the final layer is applied. This final drying may be aided by using a vacuum or a low-humidity environment. Dewaxing is the process of removing the design from the shell once it has cured fully. Flash dewaxing and autoclave are the two most common forms of dewaxing. Both have the purpose of melting the wax layer on the surface quickly before the remainder of the design warms up. This permits the residual wax to grow without placing excessive mould stress, which increases at a slower pace than the leftover wax. The casting alloys, refractories, and binders are employed to determine the combustion, drying, and preheat temperatures. Preheats for titanium casting moulds vary between 300 and 980 °C (Kobryn, 1996).

2.3 Titanium alloy casting

The mould is prepared for the main casting procedure after it has been sintered and warmed. Titanium alloys need more specific melting procedures due to their exceptional melting temperature and reactivity. To avoid oxygen and nitrogen contamination from the air, all-titanium melting processes are carried out in a vacuum or an inert environment. The most prevalent technique for melting titanium is vacuum arc remelting (VAR).

An electric arc melts a disposable titanium electrode into a copper crucible that is water-cooled in titanium VAR. The first piece of titanium to melt forms a protective skull atop the copper crucible. During the melting and pouring process, the skull stays solid, shielding the titanium melt from impurities (Kobryn, 1996). The casting process may begin when the molten charge has been prepared and the mould has been warmed.

2.4 Applications and features of titanium investment castings

Titanium investment castings have mechanical qualities that are like wrought titanium (Eylon et al., 1990). The ultimate tensile strength of 750 to 900 MPa, 0.2 per cent yield stress of roughly 835 MPa, and 6 to 12 per cent elongation to failure are typical features of investment cast titanium alloy (Ti-6Al-4V). Cast titanium's fatigue strength is lower than wrought titanium's fatigue strength. However, the cast titanium's poor fatigue characteristics are due to its high grain size and the inclusion of grain boundary alpha (Kobryn, 1996).

Titanium castings may be utilized for building structures of various shapes and sizes. However, investment casting cannot readily manufacture pieces with sections smaller than around 0.1” thick (Kobryn, 1996; Colvin, 1994). In essence, titanium investment castings are widely used in the aerospace industry, where enclosures, casings, struts, and blades for gas turbine jet engines are frequently used. Titanium castings can also be used in heat exchangers, medical prostheses, marine applications, and other applications involving excellent resistance to corrosion and resilience.

3 OVERVIEW OF CURRENT STUDIES ON TITANIUM ALLOY INVESTMENT CASTING (2017-2021)

According to the statistics of the examined studies on investment casting of titanium alloys between 2017 and 2021, publications in relevant areas grew by 370 articles from 2017 to 2018, (InvestmentCastingOfTitaniumAlloys, 2017 - 2018), as shown in Table 1 and Fig. 2.

Table 1. Recent research on titanium alloy investment casting

<table>
<thead>
<tr>
<th>Year</th>
<th>Publications on investment casting of titanium alloys</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>2,070</td>
<td>(InvestmentCastingOfTitaniumAlloys, 2017)</td>
</tr>
<tr>
<td>2018</td>
<td>2,440</td>
<td>(InvestmentCastingOfTitaniumAlloys, 2018)</td>
</tr>
<tr>
<td>2019</td>
<td>2,400</td>
<td>(InvestmentCastingOfTitaniumAlloys, 2019)</td>
</tr>
<tr>
<td>2020</td>
<td>2,330</td>
<td>(InvestmentCastingOfTitaniumAlloys, 2020)</td>
</tr>
<tr>
<td>2021</td>
<td>2,440</td>
<td>(InvestmentCastingOfTitaniumAlloys, 2021)</td>
</tr>
</tbody>
</table>
The number of published research on the subject under consideration, decreased somewhat in the following years, with 40 articles in 2019 and 70 articles in 2020. The number of publications on the topic was almost the same in 2021 as it was in 2017. (InvestmentCastingOfTitaniumAlloys, 2019 - 2021). Lack of interest may be a factor in the stagnating trend of publications on titanium alloy investment casting and related issues.

3.1 Previous research on titanium alloy investment casting

Investment casting of titanium alloys has been the subject of previous research. Figure 2 shows a summary of the works that have been reviewed. Freitag et al. (2017) effectively constructed CaZrO₃ investment casting moulds utilizing a water-based, silica-free binder method for the first time. They found that investment casting Ti-6Al-4V resulted in a cast component with an unusually low hardness increase. The silica-free CaZrO₃ investment casting moulds are thought to have enabled this finding. In another development, (Chamorro et al., 2017) carried out a study in which Ti-6Al-4V turbine blade-like geometries were cast in Al₂O₃ and ZrSiO₄ based investment shells at various preheating temperatures to determine the least reactive conditions. To prevent unexpected melt reactions, the cold crucible induction melting method was used. The results showed that the diffusion layer thickness was 50 m less in the less stable preheated ZrSiO₄ mould than in the more stable Al₂O₃. This development was because the reaction products in the outer layer slowed the transport of harmful elements, resulting in a thinner diffusion layer. In both heated and non-heated conditions, Al₂O₃ was found to be the least reactive mould material, while Gibbs' free energy concept was found to be the locus factor that defined the refractory stability for the mould-metal interaction analysis.

The influence of fluidity and surface reactivity of titanium alloy during investment casting via metal-mould reaction was investigated (Kim et al., 2017). The research looked at three distinct alloys: Ti-6Al-4Fe-0.25Si (TAFS), pure titanium (also known as commercially pure titanium, CP-Ti), and Ti-6Al-4V (T64). A spiral style of mould was also used for the fluidity testing. The alloys were melted and cast via induction skull melting, and investment casting was done using a ZrSiO₄ mould. The CP Ti had the longest fluidity length, whereas Ti-6Al-4Fe-0.25Si had the shortest. The thickness of the surface reaction layer (alpha-case) of Ti-6Al-4Fe-0.25Si, on the other hand, was the smallest, while that of CP-Ti was the thickest (Kim, et al., 2017). On the other hand, pre-wetting was used in between multilayer ceramic investment casting shells by O’Sullivan et al (2021) to increase porosity and permeability while maintaining flexural strength. The results revealed a rise in porosity, while green and fired flexural strength decreased by 8.7-15.6 per cent and 18.7-28.5 per cent, respectively, but hot strength increased by 20-25 per cent. When pre-wetting was applied between intermediate coatings, permeability improved by a factor of two, and mercury intrusion porosimetry revealed a stepwise rise in intrusion volume in the high-pressure regime. When bilayers of pre-wetting solution were applied, gas adsorption techniques confirmed the existence of micropores using the alpha-s method (O’Sullivan et al., 2021).
Table 2. Summary of previous studies on investment casting of titanium alloys

<table>
<thead>
<tr>
<th>S/N</th>
<th>Material Cast</th>
<th>Examined Casting Shell Mould (s)</th>
<th>Reported Best/Most Non-reactive Shell Mould (s)</th>
<th>REF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ti–6Al–4V</td>
<td>Dual H₂O-based free-silica CaZrO₃ slips with a max. the grain size of 1mm and 0.5mm</td>
<td>CaZrO₃</td>
<td>(Freitag et al., 2017)</td>
</tr>
<tr>
<td>2</td>
<td>Ti-6Al-4V</td>
<td>ZrSiO₄ and Al₂O₃ moulds</td>
<td>Al₂O₃</td>
<td>(Chamorro et al., 2017)</td>
</tr>
<tr>
<td>3</td>
<td>CP-Ti, Ti–6Al–4Fe–0.25Si, and Ti–6Al–4Fe–0.25Si</td>
<td>ZrSiO₄ mould</td>
<td>ZrSiO₄</td>
<td>(Kim et al., 2017)</td>
</tr>
<tr>
<td>4</td>
<td>Ti6Al4V, and γ-TiAl and</td>
<td>Fused Y₂O₃, ZrSiO₄, Al₂O₃, yttria (6%) stabilized ZrO₂ and yttria-stabilized ZrO₂ with 10% fine Y₂O₃ (3–7 µm).</td>
<td>Fused Y₂O₃ face coat at the detriment of fluidity</td>
<td>(Neto et al., 2017)</td>
</tr>
<tr>
<td>5</td>
<td>Ti and TiAl alloys</td>
<td>Fumed Alumina, Zirconia and fine Yttria (AFZrYc), Polymer and fumed alumina, fused yttria (AAFY), Fumed alumina (AFAL), and Polymer fused yttria (AY)</td>
<td>Shells Polymer and fumed alumina, fused yttria (AAFY) and fused yttria (AY)</td>
<td>(Neto et al., 2017)</td>
</tr>
<tr>
<td>6</td>
<td>Ti-6Al-4V alloy</td>
<td>Y₂O₃-SiO₂ (Y-Si) shell mould</td>
<td>Y₂O₃-SiO₂ (Y-Si) (shell mould with SiO₂ content between 15 and 20 wt.%)</td>
<td>(Wei et al., 2018)</td>
</tr>
<tr>
<td>7</td>
<td>Ti–6Al–4V</td>
<td>Y₂O₃-silica sol shell mould</td>
<td>Y₂O₃-silica sol</td>
<td>(Wei et al., 2019)</td>
</tr>
<tr>
<td>8</td>
<td>titanium melts</td>
<td>Aluminum-yttrium ceramics</td>
<td>α-Al₂O₃–Y₃Al₅O₁₂·α-Al₂O₃</td>
<td>(Shcherbakova et al., 2019).</td>
</tr>
<tr>
<td>9</td>
<td>Ti-48Al-2Cr-2Nb</td>
<td>Colloidal silica and refractory materials in the alumina and zircon mold</td>
<td>Rutile-containing alumina mould</td>
<td>(Lee et al., 2020).</td>
</tr>
<tr>
<td>10</td>
<td>Ti-6Al-5Fe-0.05B-0.05C (all wt.%) and baseline Ti-6Al-4V alloy.</td>
<td>ZrO₂ ceramic coating, and H13 steel mould</td>
<td>Ceramic coated H13 steel mould</td>
<td>(Liang et al., 2020)</td>
</tr>
<tr>
<td>11</td>
<td>CP titanium</td>
<td>Ethyl silicate as a binder, fused corundum Al₂O₃, zircon ZrSiO₄ and yttria-stabilized zirconium oxide ZrO₂, and fused corundum Al₂O₃.</td>
<td>Moulds containing zirconium oxide and zircon face layers and corundum backup layers</td>
<td>(Kaliuzhnyi et al., 2021)</td>
</tr>
<tr>
<td>12</td>
<td>Ti–6Al–4V</td>
<td>Calcium zirconate</td>
<td>Alginate-based spray-coated calcium zirconate</td>
<td>(Freitag et al., 2022)</td>
</tr>
<tr>
<td>13</td>
<td>Ti-5 wt% Cu melts</td>
<td>Refractory materials made of calcium-stabilized zirconia, solid-state produced calcium zirconate, and fused calcium zirconate</td>
<td>Fused calcium zirconate</td>
<td>(Song et al., 2022).</td>
</tr>
<tr>
<td>14</td>
<td>46Al–8Nb-Ti (at. %) intermetallic</td>
<td>Y₂O₃ doped BaZrO₃/Al₂O₃</td>
<td>-</td>
<td>(Duan et al., 2022)</td>
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</table>
Neto et al. (2017) conducted research to evaluate different materials for ceramic shell face coatings (i.e., Y₂O₃, ZrSiO₄, Al₂O₃, yttria (6 per cent) stabilized ZrO₂, and yttria-stabilized ZrO₂ with 10% fine Y₂O₃ (3–7 µm). For the alpha case and fluidity assessment, a test sample was created that simulated both compressor wheels and turbines and was built in a wax tree. Based on microhardness data, reactivity tests were done. The findings revealed that a fused Y₂O₃ face coat removed the alpha case while compromising fluidity, and y-TiAl castings had more misrun-blades than Ti-6Al-4V castings. The impact of ceramic-shell composition on properties such as flexural stress, friability, and dimensional correctness in investment casting of Ti and TiAl alloy was investigated by the same group of researchers. They concluded that all non-traditional ceramic shell mechanisms with interest for reactive alloys, based on fumed alumina binder and alumina sand for back-ups, had higher dimensional stability (low shrinkage or expansion) than older methods based on colloidal silica binder and zircon and alumino-silicates backups. With non-traditional alumina and polymer binders, as well as yttria flour and stucco, followed by alumina back-ups, improved mechanical strength, and decreased friability were achieved. They discovered that throughout the preheating cycle, the shells AFZrYc, AAFY, AFAL, and AY virtually maintained their sizes. These insignificant deviations in dimensions helped the production process achieve precise tolerances. However, because of their high flexural strength and low friability, the shells AAFY and AY were the most resistant (Neto et al., 2017).

Using ProCAST simulation software, a three-dimensional finite element analysis of counter-gravity investment casting was created to construct TiAl pieces with various cross-sections (Yang et al., 2018). The filling capacity and solidification behavioural patterns of the Ti-48Al-2Cr-2Nb alloy during the casting were numerically examined. Also, the impacts of filling pressure, melt superheating temperature and mould preheating temperature on filling integrity and casting defects were experimentally evaluated. The filling pressure influenced the filling capacity, according to the findings. At the same time, adequate elevation of the mould preheating and melt superheating temperatures was noted to increase the filling capacity. The as-cast morphology of the Ti-48Al-2Cr-2Nb alloy revealed that the size effect had a significant impact on phase composition and shape (Yang et al., 2018). Klotz et al. (2019) compared the applicability of several shell mould materials for titanium casting to traditional materials. They presented a novel corrosion-resistant substance based on calcium zirconate (CaZrO₃) for crucibles and shell moulds with the goal of increasing the casting quality of titanium alloys. 3 distinct crucible materials were used in tilt casting attempts into CaZrO₃ shell moulds. The findings were compared to a silica-containing commercial shell system. Hardness profiles and oxygen measurements were used to investigate the reactivity of the titanium melt as a function of melt temperature, component size, and shell mould temperature. The CaZrO₃ shell’s response was extremely low, indicating little oxygen concentration and hence poor surface hardness (Klotz et al., 2019).

The influence of remnant gas in a Y₂O₃–silica sol shell mould on interfacial interaction during Ti–6Al–4V alloy investment casting has been studied (Wei et al., 2019). By using various types of pore formers, two sets of shell moulds were created (i.e., nylon fibres, and spherical starch particles, respectively). The Ti–6Al–4V alloy was gravity cast in a vacuum using the cold crucible induction melting (CCIM) process. The Archimedean approach was used to determine the porosity of various shell moulds. The findings revealed that all specimens had a very mild direct chemical reaction. Surface flaws were mostly caused by the discharge of residual gas from closed pores. Open pores, on the other hand, had almost little effect on the contact response. Shcherbakova et al. (2019) looked at the challenges of using an aluminium-yttrium binder in the production of high-temperature melting crucibles and investment moulds that are thermochemically resistant to titanium melts. The findings demonstrated that using α-Al₂O₃–Y₃Al₅O₁₂–α-Al₂O₃ composition under high-temperature melting and pouring under vacuum eliminates physicochemical interaction and considerably reduces the alpha case layer on cast products, consequently enhancing their operational qualities.

The Ti-Al-Fe system has been used to create a reduced-cost cast titanium alloy (Ti-6Al-5Fe-0.05B-0.05C (all wt. percent)) (Liang et al., 2020). In comparison to the baseline Ti-6Al-4V alloy, the

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Composition</th>
<th>Porosity Type</th>
<th>Reference</th>
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<tbody>
<tr>
<td>15</td>
<td>Ti-45Al-2Mn-2Nb (at%) + 0.08 vol% TiB₂, and Ti-46 Al-2 Nb-2Cr-0.15B (at%)</td>
<td>Yttria inclusions introduced into TiAl parts</td>
<td>(Lin et al., 2018)</td>
</tr>
</tbody>
</table>
new alloy had lower material costs and better castability. Due to Fe partitioning, the new alloy's fine primary and secondary phase microstructure provides outstanding strength (1023 MPa yield stress and 1136 MPa maximum tensile stress) and ductility (3.7 percent extension) for structural applications. This lab-scale experiment has shown to be promising and should be further explored. The experimental casting apparatus, which included an induction skull melting (ISM) system, a gravity tilt pour system, and a ceramic-coated H13 steel mould, was utilized to make near-net-shape permanent metallic mould castings using the newly discovered titanium alloy. A prototype automobile connecting rod was cast using this configuration and with the help of casting process simulation (Liang et al., 2020). To model the multi-scale solidification process of CP titanium and two kinds of titanium alloys with varied solute contents, Zhang et al. (2022) used ANSYS and the cellular automaton-finite difference code μMatIC to achieve that. In a vacuum environment, investment casting of Ti–6Al–4V was done using the counter-gravity casting technique. The grain development mechanism of titanium alloys was observed to be dependent on the solute concentrations. With more solute, the grain development mode of titanium alloys changed from planar to dendritic. It was reported that in the investment casting of Ti–6Al–4V, equiaxed grains were formed independent of thickness, according to both prediction and experimental data. The grain size was observed to grow as the cast part's wall thickness increased.

In the case of the electron beam casting technique, the reaction between the titanium melt with refractory mould was investigated (Kaliuzhnyi et al., 2021). Fused corundum Al2O3, zircon ZrSiO4 and yttria-stabilized zirconium oxide ZrO2, as well as ethyl silicate as a binder, were utilized to create ceramic moulds. The moulds with face layers of zirconium oxide (Z1), zircon (ZS1), and backup layers of corundum had the least contact with the titanium melt, according to their findings. Corundum and titanium reacted to generate a 400-500 μm thick non-continuous reaction layer. A reactive layer with a thickness between 500 and 600 μm was created for shell moulds with zircon face and backup layers on the exterior of the castings. Also found in these strata was zirconium-silicon eutectic. The filling and solidification processes of the high Nb-TiAl alloy impeller investment casting were simulated using the casting simulation program ProCAST (Liu et al., 2021). The findings demonstrate that ProCAST software was more reliable in forecasting shrinkage cavity and porosity in high Nb-TiAl castings, and the process scheme was improved based on simulation and forecasting results to minimize significant shrinkage cavities and porosity in the casting. All the castings were filled, with tensile strengths of around 580 MPa at ambient temperature and 450 MPa at 850 °C (Liu et al., 2021).

Song et al. (2022) employed the cup test technique to investigate the corrosion behaviour of calcia-stabilized zirconia, solid-state manufactured calcium zirconate, and fused calcium zirconate refractory exposed to Ti-5 wt. per cent Cu melts at 1680 °C for 15 minutes. The three crucibles were discovered to have dissolved straight into the titanium melt, generating Ti (Zr, O) and CaZrO3 in the infiltration layer, and finally developing a porous Ti3O5 layer in the lining. Furthermore, contamination of Ti-5 wt. % Cu alloy (oxygen: 5.3 wt. %; zirconium: 6.01 wt. per cent; calcium: 0.42 wt. %) by fused calcium zirconate crucible was significantly lower than that of solid-state synthesized calcium zirconate (oxygen: 5.83 wt. per cent; zirconium: 6.14 wt. per cent; calcium: 0.43 wt. %) (Song et al., 2022). Because the standard dip-coating approach of the lost-wax process limits the surface quality and dimensional accuracy of titanium components produced by investment casting; Freitag et al. (2022) conducted research with the goal of improving surface quality by utilizing calcium zirconate slips and alginate gelation coatings. A homogenous spray coating was discovered using scanning electron microscopy and computed tomography. Functionally graded calcium zirconate shell moulds were made using an alginate-based spray coating. The microstructure of these moulds was discovered to be fine-grained, having holes in the lower micrometre range. A bridging zone and a homogenous distribution of coarse grain throughout the diameter were seen in the microstructure. They claimed to have achieved Ti6Al4V cast pieces without the presence of an alpha case layer (Freitag et al., 2022).

Using the Bridgman apparatus, research on directed solidification of Ti–46Al–8Nb (at. %) intermetallic in the Y2O3 doped BaZrO3/Al2O3 composite ceramic mould was carried out (Duan et al., 2022). The findings revealed that the leaking of the alloy melt was caused by macrocracks in the face coat of the mould. Furthermore, the alloy melt was discovered to infiltrate into the mould via large-size holes, increasing the oxygen content of the target alloy and forming inclusions in the alloy ingot containing O, Zr, Si, and Y elements (Duan et al., 2022). The reactivity at the interface between a Y2O3 SiO2 (Y-Si) shell mould and titanium alloys was studied (Wei et al., 2018). Prior to investment casting of Ti-6Al-4V alloy under vacuum using the
cold crucible induction melting (CCIM) process, a collection of shell moulds was made using Y$_2$O$_3$ sand and silica sol with various SiO$_2$ concentrations. When the SiO$_2$ concentration of silica sol was less than 20%, the thickness of reaction layers was less than 3 μm, according to the findings. When the SiO$_2$ concentration was raised to 25%, the reaction layer thickness grew dramatically to roughly 15 μm. When the SiO$_2$ level was at 15 to 20 weight per cent, a satisfactory balance between chemical inertness and mechanical performance was recorded. The dispersion of SiO$_2$ and the roughness of the shell's surface was identified to be the most important factor in determining the amount of reactivity between the shell mould and titanium alloy (Wei et al., 2018).

Based on simulations using ProCAST, Tian et al. (2017) improved the process variables throughout investment casting to reduce platform warping deformation. The influence of pouring temperature, shell mould preheating temperature, furnace temperature, and withdrawal velocity on the surface finish of the platform of the superalloy-DD6 turbine blade was then investigated using the single-factor method, orthogonal test, neural network, and genetic algorithm. By measuring the platform during blade casting, the correctness of the investment casting simulation was confirmed. The corresponding warping deformation was decreased by 21.8 per cent from 0.232295 mm to 0.181698 mm using the optimum process settings, according to simulation findings (Tian et al., 2017). The influence of yttria inclusions on the room temperature tensile characteristics of two investment cast TiAl alloys, viz: Ti-45Al-2Mn-2Nb (at%) + 0.08 vol% TiB$_2$ and Ti-46 Al-2 Nb-2Cr-0.15B (at%), was investigated (Lin et al., 2018). The findings demonstrated that yttria inclusion-induced tensile failure resulted in lower plastic strain and ultimate tensile strength. Yttria inclusions vary in size, shape (agglomerate or whole piece), and position (surface or internal), with those with bigger sizes or found at the specimen surface being more hazardous (Lin et al., 2018).

4 IDENTIFIED KNOWLEDGE GAPS

Certain knowledge gaps have been discovered after reviewing previous studies on titanium alloy investment casting. Some of the gaps are as follows:

1. There is limited information available on the use of locally derived raw materials as refractory moulds or binders in titanium alloy investment casting.

2. There is little understanding of the ideal preheating temperature of the mould for optimal investment casting of titanium alloy

5 CONCLUSION(S)

Several advancements in the investment casting of titanium alloys have resulted in the creation of less reactive moulds based on CaZrO$_3$ and Al$_2$O$_3$. It has been reported that a new low-cost cast titanium alloy system, Ti-6Al-5Fe-0.05B-0.05C (all weight per cent), has been developed. This innovative alloy exhibited higher castability than the standard Ti-6Al-4V alloy. Future studies on titanium alloy investment casting should address the knowledge gaps highlighted.

6 REFERENCES


The 14th World Conference on Titanium.


