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Advancements and Applications of Investment Casting Technology in Aerospace Industries: A Review

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Abstract

A conventional method for producing intricate and superior metal components is investment casting. It utilizes a wax pattern, a refractory shell, and molten metal to create a near-net-shape product. This method has been around for more than 5,000 years and is still relevant in various industries today, especially in aerospace. Investment casting, also known as lost-wax casting, is essential to the aerospace industry's ability to produce complex, high-performance parts. The review paper aims to provide valuable insights into the role of investment casting in meeting the demanding requirements of aerospace parts production. The paper discusses the historical development of investment casting techniques, focusing on recent innovations that have enhanced efficiency, precision, and cost-effectiveness. Additionally, the review discusses recent advancements in investment casting technology, such as the integration of computer-aided design and simulation tools, which have enhanced efficiency, precision, and cost-effectiveness. Overall, this review provides valuable insights into the current state and future prospects of investment casting in modern aerospace engineering, showcasing its significance in achieving performance, reliability, and sustainability objectives. All things considered, the paper highlights how important investment casting is to the aerospace sector. It enables the production of lighter, more efficient components for commercial and defense aircraft, contributing to achieving performance, reliability, and sustainability goals. Further research and advancements in materials, process optimization, and simulation hold the potential to address future challenges in aerospace engineering.

Keywords: Investment casting, aerospace industries, casting application, ceramic substance, alloys

INTRODUCTION

Investment casting, often known as lost-wax casting, is a manufacturing process used to create intricate and complex metal parts. Investment casting is one kind of casting that uses wax and a refractory shell to create a finished product. Complex cast objects can be manufactured nearly precisely to shape thanks to investment casting. Melted metal is poured into a ceramic mold, which is created by encircling a wax pattern with a refractory substance. The completed part is revealed after the ceramic mold is broken away after the metal has set.

The first step in the procedure is to create a wax pattern that closely resembles the final part's desired shape. Several techniques, such as manual sculpting or injection moulding, can be used to create this pattern. Multiple wax patterns, known as a pattern cluster or tree, are attached to a central wax rod to form a pattern assembly. A ceramic substance is subsequently applied to this assemblage to form a shell around the designs. To create the layers of the ceramic shell, a precise wax design is dipped into

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the slurry four to six times. A predetermined amount of hours are spent controlling the humidity, temperature, and ventilation for every shell coat [1] (Figure 1).

The following primary steps comprise the investment casting production process, which combines manual, semiautomated, and controlled operations:

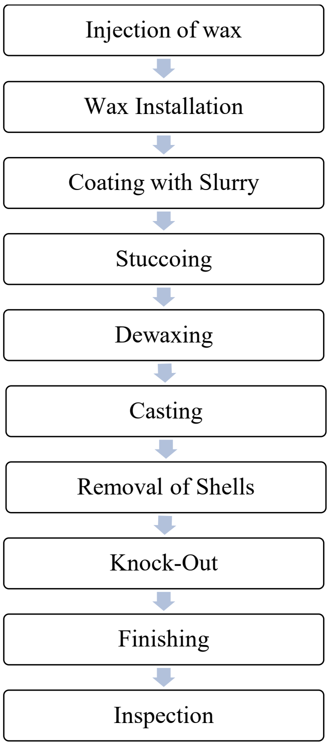

Figure 1. The key processing phases in the traditional investment casting process.
Reference: *Paper-4 (https://www.researchgate.net/publication/363418827)*

A manufacturing technique known as investment casting dates back more than 5,000 years to China and Ancient Egypt. It is used to cast a great deal of things, including high-performance, high-quality industrial parts. This makes them suitable for use in automotive, aerospace and biomedical industries. Research in this area has stated that "it is becoming imperative that the investment casting industry improves current casting quality and reduces manufacturing costs" and that "optimization of the mechanical and physical properties of the ceramic shell will be fundamental to achieving these aims". Titanium alloys were initially cast in the year 1950, and today the chemical, aerospace, and energy industries employ these alloys extensively. One manufacturing method for creating titanium components with a near-net shape is investment casting [2].

Recently, the present authors have proposed a new tool for the physical simulation of investment casting of complex shape parts from Ni-based super alloys. Super alloys based on nickel were created as metallic materials that could withstand high temperatures and creep in an oxidizing environment. They have been widely employed as nozzle guiding vanes, blades, rotating parts, etc. in aircraft and power production turbines. Typically, investment casting has been used to create these parts, which is a significant manufacturing technique for creating components with complex shapes.

LITERATURE REVIEW

1. When compared to prior years, the majority of investment casting foundries have seen an increase in casting production. The investment casting industry in India grew by roughly 10% to 12% in 2011. A lot of these foundries have robotic shelling systems and contemporary wax injection machines. They produce machinery, pumps, and industrial valves primarily, accounting for

around 44% of the Indian investment casting market. In the sphere of defense, investment casting was used at HAL, Koraput in India in the 1960s to create turbine blades and vane assemblies for MIG aircraft. Currently, there is a wide range of applications for investment cast graphite fiber-reinforced metal matrix composites in the aerospace and racing car industries. Due to their special qualities, titanium and zirconium alloys are used in high-performance structures and the aerospace industry. Even super alloys based on nickel are cast using the vacuum investment casting method [3].

2. Applications of cast aluminium alloys in aerospace, including the investment casting forward access door (FAD) of the Boeing 737 produced by PPC Corporation of America, the precision casting of aluminium alloy used for the baggage compartment door and flap tracks, and the superior cabin casting made in the United States by Hitchcock Company. In particular, cast aluminium alloys such as Ale Silicon (Si), Ale Copper (Cu), and Ale Magnesium (Mg) alloys are frequently utilized in aircraft. One significant indicator of a nation's level of industrial manufacturing is the aerospace sector. The materials that are frequently utilised in the aircraft industry include steels, composites, titanium (Ti) alloys, and aluminium alloys. The aerospace industry prefers titanium alloys because of their exceptional high-temperature performance and high specific strength, which even matches steels in strength. However, considering the manufacturing cost and comprehensive understanding of material properties, Al alloys still have higher application potential. The weight percentage of various structural materials used in large commercial aircraft [4] (Figure 2).

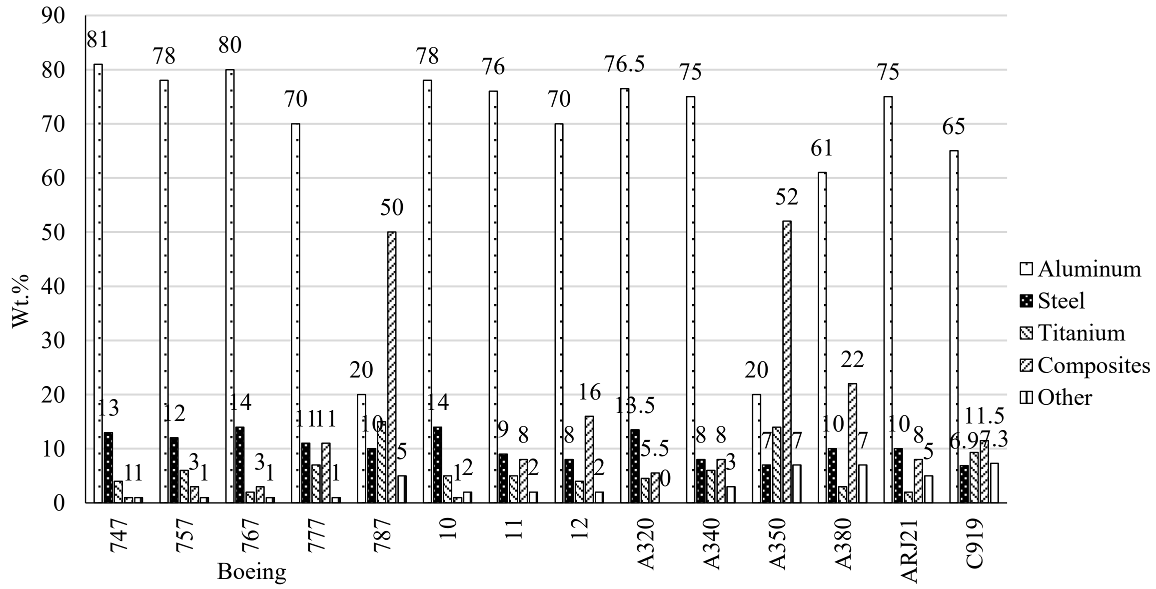

Figure 2. Material composition (Wt.%) of various aircraft structures across different manufacturers. Reference: Paper-2 (D)

3. The alloy known as Lockalloy is made up of 38% aluminum and 62% beryllium. As a typical example of alloys based on beryllium aluminum, it was utilized as a structural metal in the aerospace sector and has been used extensively as an engineering material. It has many benefits:
   i. elevated strength-to-weight ratio
   ii. stability in dimensions
   iii. High specific heat and thermal conductivity
   iv. High modulus as the temperature rises quickly.

   As a result, we decided on Lockalloy and effectively created and developed a brand-new, robust, textured Be-Al alloy via investment casting shown in Table 1.
4. Summary of the current titanium alloy investment casting studies (2017–2021)

Table 1. The current titanium alloy investment casting studies (2017–2021)

Year	Publications on investment casting of titanium alloys	Ref.
2017	2,070	(Investment Casting of Titanium Alloys, 2017)
2018	2,440	(Investment Casting of Titanium Alloys, 2018)
2019	2,400	(Investment Casting of Titanium Alloys, 2019)
2020	2,330	(Investment Casting of Titanium Alloys, 2020)
2021	2,440	(Investment Casting of Titanium Alloys, 2021)

Reference: *Paper-4 (https://www.researchgate.net/publication/363418827)*

1. Rapid investment casting (RIC) based on AM (Additive Manufacturing) has become widely accepted in casting industries due to rapid production of patterns without any tooling requirements. When production volume is limited, material extrusion of wax-like patterns can lower an IC process's cost and lead time, according to an estimate from our partner IC foundry. The RIC (Rapid Investment Casting) process in our case study cost about $100 per bracket, including post-processing, casting, and 3D printing of the wax-like patterns. The lead time for the fabrication of the wax-like patterns was less than two weeks. On the other hand, the creation and manufacturing of conventional pattern dies for the identical brackets can require 40–50 weeks and cost roughly $40000 altogether [5].

   In the early 21st century, civilization relied heavily on gas turbine engines for both air travel and a sizable amount of global power production. Unless something changes, this has been the situation for the last 50 years and is probably going to stay that way for the next 50 years shown in Table 2 [6].

Table 2. A Comparison of Key Technological Advancements their Innovation Challenges

Concept	Invention	Innovation	Gap (Years)
Ball-point pen	1888	1946	68
Zip fastener	1891	1923	32
Fluorescent lighting	1901	1938	37
Helicopter	1904	1936	32
Kodachrome	1921	1935	14
Television	1923	1936	13
Investment casting	c. 4000 B.C.	1942 (aero engine)	c.6000
I.C. for jet engines	1943	1948	<5

Reference: *Paper-6 (https://blayson.com/wp-content/uploads/2020/05/2009-Brno-Future-Trends-in-Investment-Casting-Dr-D-A-Ford.pdf)*

The development of investment castings happened incredibly quickly, despite the fact that it took an incredibly long period to bring many common goods to market. A clandestine report on the success of the experimental foundry established at the Rolls-Royce factory in Scotland to produce parts using the "Mediaeval Cire-Perdue" process created by the Austenal Laboratories in the USA was released by the British Ministry of Aircraft Production in November 1943. "It is now definitely established that castings in Vitallium, Stellite, Nimonic 80, and other alloys can be produced by the process to limits of accuracy of plus or minus 0.002" with an extremely fine surface finish, completely eliminating the necessity for machining operations," the report stated.

2. Investment casting rose to prominence in the casting business thanks to jet propulsion for both military and commercial aeroplanes. This casting technique is utilised for a wide range of high-tech industrial applications, from small castings of 30 kg to heavy castings of 300 kg. This procedure is more costly than sand casting in terms of casting methods, however the equipment is comparatively less expensive. However, for complex patterns that cannot be cast in any other

way, investment casting is still primarily used. Investment casting is frequently utilized in spacecraft, jet engines, and other applications. Despite its strong reliance on the aircraft industry, this sector is expanding its horizons by finding new applications. Typical aerospace investment castings include bearing cages, cargo systems, exterior and interior sensors, motion control and actuation systems, landing and braking components, hydraulic fluid system components, and interior components [7].

3. After examining a variety of bibliographies, the material properties of Hastelloy X were determined. The ASM International Handbook Committee (1990), the Department of Defence of the United States' Military Handbook on Metallic Materials for Aerospace (1998), and the thermodynamic database contained in CompuTherm LLC was acquired by ProCAST (2012). Lastly, the material attributes from the thermodynamic database specified have been applied. The Scheil microsegregation model, which presupposes that no diffusion occurs in the solid phase and that the chemical composition is equal to the average values of the normal range established for this kind of alloy, was used to compute these properties. The material properties defined for the mould have been estimated based on the information found in several journal articles: Browne and Sayers (1995), Connolly et al. (2000), Kovac et al. (2008), O'Mahoney and Browne (2000), Rafiqueand Iqbal (2009); within some confidential information extracted from prior research projects.
4. Aerospace turbine blade castings are one of the most difficult components to develop and manufacture due to the extreme environments of temperature and pressures in which type operate. Complex aerofoil forms are hollowed out to provide for cooling and temperature management within the parameters established by the super alloy materials based on nickel. The only method that can produce these hollow components is investment casting, which is a very intricate procedure that includes cooling and other steps [8].
5. Since the 1950s, the investment casting process has been a significant means of producing parts for the aerospace industries. It provides superior surface polish and tolerances along with design flexibility. For intricate geometries. The increasing need for lighter and more intricate engineering components, especially in the aerospace industry, is making the manufacturing process more complicated. Due to worldwide rules aiming at lowering emissions and fuel consumption, there is an increasing need to minimize the weight of cast components [9].
6. The global investment casting market was valued at USD 16.55 billion in 2022 and is expected to increase at a compound annual growth rate (CAGR) of 5.0% between 2023 and 2030. The market for investment-cast goods is expected to increase as more people fly by aviation, supporting the production of new commercial aircraft. The increase in passenger traffic is closely related to the global growth in GDP and per capita income, which has increased demand for new commercial aircraft. For example, Airbus delivered 611 commercial aircraft in 2021, an increase of 8% over 2020. In a similar vein, in 2021 Boeing delivered 340 commercial aircraft [10].

CONCLUSIONS

In the aerospace industry, investment casting has become a vital production process because it can create complex, high-performance parts with excellent surface polish and little need for machining. Through historical breakthroughs and contemporary advances like computer-aided design (CAD), simulation tools, and quick investment casting based on additive manufacturing (AM), the overview illustrates how this age-old technique has changed over time. When it comes to casting complex geometries and high-strength materials like titanium and nickel-based super alloys, these developments have greatly improved efficiency, accuracy, and cost-effectiveness. The aerospace industry, driven by the increasing demand for lighter, more efficient components, continues to benefit from the unique advantages of investment casting. Applications ranging from turbine blades to structural components in commercial and defense aircraft underline its indispensable role in achieving performance, reliability, and sustainability objectives. The ongoing research and technological progress in materials, process optimization, and simulation further underscore the potential of investment casting to meet future challenges in aerospace engineering.

Acknowledgment

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