UNDERSTANDING THE INVESTMENT CASTING PROCESS FOR METAL PARTS AND CAST COMPONENTS

CRISTINA PUPĂZĂ[1], ALEXANDRA ȘOICA[2], SUSANA ECATERINA APOSTU[3], MIHAELA AURELIA TOMESCU[4]

Abstract: Investment casting is a precision manufacturing technique widely used for producing complex metal components with tight tolerances and excellent surface quality. Although the process is well established, recent advances in ceramic shell materials, wax pattern technologies and digital simulation continue to improve dimensional accuracy and reduce defect rates. This paper provides an integrated overview of the investment casting process and examines its application through a case study involving a stainless-steel pump impeller used in industrial fluid-handling systems. The study focuses on material selection, ceramic shell behavior, solidification conditions and the influence of geometry on casting reliability. The results highlight the importance of controlled shell permeability, optimized gating design and accurate prediction of shrinkage to achieve consistent component performance. The case study demonstrates how a combination of traditional techniques and modern modeling tools can deliver high-quality impellers with reduced post-processing requirements. The conclusions outline future directions for process optimization and the role of digitalization in supporting next-generation casting technologies.

Keywords: investment casting, lost wax casting, precision manufacturing, ceramic shell mold, metal alloys.

1. INTRODUCTION

Investment casting is one of the oldest metallurgical manufacturing techniques, yet it remains a highly relevant process for producing precision metal components used in modern engineering applications. Its origins date back thousands of years, but its continued evolution has allowed it to compete with, and often outperform, other casting

[1] *Assistant Ph.D. Eng., University of Petrosani, cristinasuciu@upet.ro*
[2] *Assistant Ph.D. Eng., University of Petrosani, alexandrasoica@upet.ro*
[3] *Lecturer Ph.D. Eng., University of Petrosani, susanaapostu@upet.ro*
[4] *Lecturer Ph.D. Math., University of Petrosani, MihaelaTomescu@upet.ro*

methods when fine detail, dimensional accuracy and surface quality are required. Today, investment casting is widely applied in sectors such as energy, automotive, chemical processing, marine engineering and heavy industrial machinery. Many of the parts used in these fields include complex internal channels, thin curved blades, contoured surfaces or intricate mechanical features that would be difficult or uneconomical to achieve through machining alone. This combination of historical foundation and modern applicability makes investment casting an ideal subject for both academic research and industrial improvement [1,2].

The process is built around the creation of a highly accurate wax or polymer pattern that serves as a one-to-one replica of the final part. Because the wax pattern is eliminated during the dewaxing stage, the ceramic mold produced around it becomes a negative of all external and internal geometrical features. This gives the process its well-known ability to reproduce very fine details. Once the ceramic mold is built, metal is poured into the cavity under controlled thermal and mechanical conditions, and after cooling the ceramic shell is removed to reveal the cast component. Compared with sand casting, which typically produces rougher surfaces, or die casting, which is limited to lower-melting-point alloys, investment casting offers a route for producing smooth, dimensionally consistent components in steel, superalloys, titanium and other demanding materials.

Although the basic steps of wax patterning, shell building, dewaxing and pouring remain unchanged, research over the last several decades has steadily improved their precision. One of the main challenges is maintaining dimensional accuracy throughout the process. Wax patterns tend to shrink when cooled, and the ceramic shell undergoes thermal expansion during heating and sintering. Each of these effects must be understood and compensated for. Modern pattern formulations include fillers and additives to stabilize shrinkage, while ceramic shells are engineered with controlled permeability and thermal behavior to withstand the stresses of the casting cycle. This level of refinement has allowed investment casting to be used for components that require tolerances measured in tenths of a millimeter[3,4].

Another important development has been the introduction of simulation tools that model mold filling, heat transfer and solidification. Before simulation became common, engineers had to rely largely on experience and iterative prototyping to refine a casting design. Today, software can predict where shrinkage porosity may form, how turbulence might affect surface finish and which areas of the component are likely to solidify last. These insights are invaluable for improving gating design, adjusting mold thickness and selecting optimal pouring temperatures. Simulation has reduced trial-and-error work and helped lower production cost, especially for complex parts such as turbine blades, impellers and precision housings.

The field has also seen increasing integration of additive manufacturing. 3D printing enables the production of highly detailed patterns directly from digital models, eliminating the need for machining or injecting complex wax assemblies. This is particularly beneficial for components with internal features that cannot be fabricated conventionally. Printed patterns also support rapid prototyping, allowing engineers to test new geometries without committing to expensive tooling. For industrial applications, especially those involving curved flow passages or optimized aerodynamic surfaces, these digital tools offer significant advantages in both speed and flexibility.

Stainless-steel pump impellers represent an excellent example of how these developments influence real-world manufacturing. Impellers are essential components in fluid-handling systems, where efficiency depends on maintaining exact blade geometry. Any distortion or surface defect can disrupt flow behavior, increase turbulence or reduce pump performance. Investment casting is often the preferred method for producing impellers because it can faithfully capture blade curvature, surface smoothness and fine details around the hub and shroud. However, impeller production also highlights the difficulties of the process. Thin blade sections cool at different rates than the central hub, raising the risk of internal stresses, distortion or isolated porosity. Ceramic shells must be strong enough to withstand metallostatic pressure while also allowing controlled gas escape. Alloy selection must consider both castability and in-service corrosion resistance. These points make the impeller an ideal case study for understanding the balance between materials, process parameters and dimensional control [5,6].

Overall, while investment casting has deep historical roots, it remains a dynamic field shaped by continuous technological improvement. Advances in materials science, simulation and automation are helping industry meet the growing demand for precise, high-performance metal components. This paper builds on this context by examining the process in detail and applying it to the industrial casting of a stainless-steel pump impeller, highlighting the practical interaction between traditional techniques and modern innovations.

2. METHODOLOGY AND RESULTS

The stainless-steel pump impeller examined in this study was produced from AISI 316L, a widely used austenitic stainless steel known for its strong corrosion resistance, good mechanical properties and stable behavior during casting.

Fig.1. The stainless-steel pump impeller

This alloy is particularly suitable for components exposed to water, chemicals or abrasive fluids, making it a common choice in industrial pumping systems. The low carbon content reduces the risk of carbide precipitation during solidification, which improves ductility and weldability while supporting the formation of a clean, homogeneous microstructure. In addition, the alloy's high chromium and molybdenum content enhances pitting resistance and ensures long-term durability in aggressive environments. Its good fluidity at high temperatures and predictable solidification behavior also make AISI 316L well suited for investment casting of thin-walled components such as pump blades, where dimensional accuracy and structural integrity are critical.

The patterns used for the impeller were manufactured from an industrial injection-molding wax designed for dimensional stability and low ash content. Wax formulation is critical in investment casting because any internal stress or shrinkage in the pattern directly affects the geometry of the ceramic mold. The selected wax exhibited controlled shrinkage, smooth surface characteristics and sufficient mechanical strength to withstand handling without deformation. For gating and riser attachments, a slightly harder wax grade was used to ensure rigidity during assembly.

Fig.2. The ceramic shell molds

The ceramic shell mold consisted of six layers, each serving a different purpose. The primary coat used a fine zircon-based slurry, chosen for its low reactivity with molten stainless steel and its ability to maintain sharp detail along the blade surfaces. The outer backup layers were made from aluminosilicate stucco, which provided the bulk mechanical strength required to support the impeller's complex shape during pouring. Rheological control additives were included in the slurry to ensure uniform viscosity, strong adhesion between layers and proper permeability during metal flow. The combination of zircon face coat and refractory backup layers created a balanced structure capable of resisting thermal shock, metal pressure and deformation.

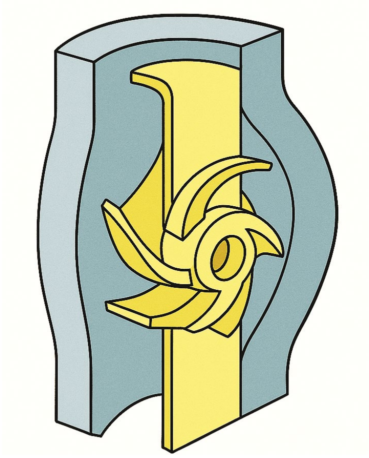

Fig.3. Section of the mold

The process began with wax pattern injection, where molten wax was pressed into precision metal dies. The impeller's blades were inspected for thickness variation, surface defects and geometric distortion. After inspection, the gating system was assembled. Gates were placed to guide the molten metal smoothly toward the blade passages, minimizing turbulence and avoiding areas that commonly develop shrinkage cavities. The assembled patterns were then cleaned and prepared for shell coating.

Shell building was performed in a controlled environment to avoid moisture-related defects. The pattern cluster was repeatedly dipped into the ceramic slurry, drained and coated with refractory stucco. Each layer was allowed to dry fully before the next was applied. Maintaining consistent humidity and airflow was essential to preventing cracks or delamination in the shell. After six layers, the shell had the required permeability, structural stability and thickness.

The dried shell was subjected to steam autoclave dewaxing, which removed the wax without causing rapid shell expansion or cracking. Using steam rather than thermal burnout at this stage reduces mechanical stresses on the shell and minimizes the risk of microcracks that could later propagate during pouring. Steam dewaxing also improves venting channels within the mold, allowing more consistent gas evacuation once the metal enters the cavity. After dewaxing, the empty ceramic molds were preheated to drive off residual moisture and to achieve the correct thermal profile before metal pouring, ensuring that thermal shock is minimized and that the shells maintain stable mechanical strength throughout the process[7].

Molten AISI 316L stainless steel was melted using an induction furnace and held at a controlled temperature of 1580 °C to ensure proper fluidity and reduce viscosity during mold filling. The shell molds were preheated to approximately 900–950 °C to encourage uniform metal flow into thin blade sections and to prevent premature solidification along the edges. Pouring was carried out under gravity, allowing the metal to fill the complex geometry smoothly and reducing the risk of turbulence-induced surface defects. Once solidified, the ceramic shell was removed using mechanical vibration and high-pressure water jets, ensuring the preservation of fine blade details without damaging the casting.

Post-processing included gate removal, grinding, surface finishing and final dimensional inspection. Radiographic examination was performed to detect internal porosity or shrinkage defects, while coordinate measuring equipment (CMM) was used to assess blade geometry relative to the design model and verify conformity with aerodynamic and hydraulic requirements.

The analysis of the impeller castings provided several insights into how process variables influence component quality. First, the geometric complexity of the blades made them highly sensitive to variations in shell temperature and local cooling rates. Sections near the leading edges cooled faster, sometimes producing uneven microstructures that required tighter thermal control during pouring. Maintaining uniform shell preheat temperatures significantly reduced distortion and improved blade symmetry, especially in areas with small radii and thin curvature.

The study also highlighted the role of ceramic shell permeability. Shells with insufficient permeability trapped gas during pouring, creating small surface defects on the blade tips and along the shroud. Adjusting the stucco grain size, improving slurry rheology and ensuring consistent layer buildup reduced these defects. The zircon face coat proved effective in preventing metal–mold reactions, preserving surface integrity, reducing oxidation and minimizing the formation of inclusions that could act as corrosion initiation sites during service.

A major improvement was achieved by redesigning the gating system. Early castings exhibited shrinkage near the hub, where solidification was constrained by thicker metal sections. By enlarging the feeder and repositioning the gate entry, directional solidification was better controlled, reducing shrinkage volume by more than half. This modification also increased the stability of the thermal gradient, improving microstructure uniformity across the blades [8,9].

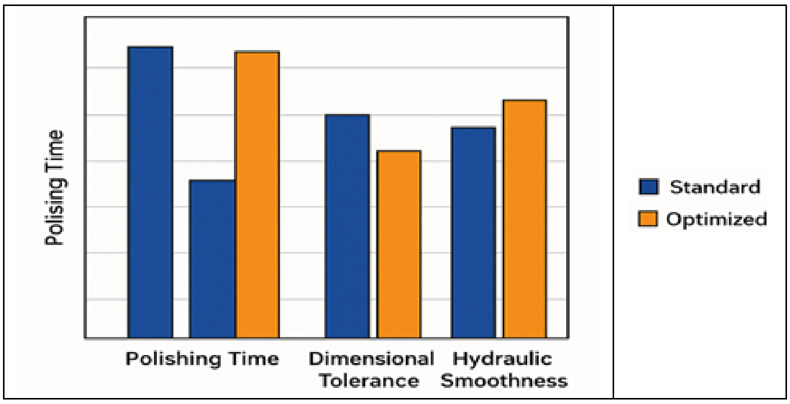

Fig.4 Improved impeller manufacturing

Surface roughness measurements showed that the optimized ceramic slurry contributed to notable improvements, reducing polishing time and enhancing flow efficiency once the impeller was installed. Impellers produced under the refined process conditions showed tighter dimensional tolerances, fewer internal defects and smoother hydraulic profiles. These improvements were reflected in more uniform wall thicknesses along the blade passages, which helped maintain consistent fluid velocity during operation. The enhanced surface finish also reduced the likelihood of cavitation damage, a common issue in high-speed pumping systems. Overall, the refined casting parameters contributed to longer service life and improved operational reliability of the impeller.

CONCLUSIONS

The study confirms that investment casting remains a highly capable manufacturing route for producing complex stainless-steel components, particularly when strict dimensional accuracy and controlled surface quality are required. Through the analysis of an AISI 316L pump impeller, the research highlights how material selection, ceramic shell architecture and optimized process parameters work together to ensure reliable casting performance. Although the basic stages of the lost-wax process are well established, the results demonstrate that small refinements in wax formulation, shell permeability and gating design can significantly influence the final quality of the component.

One of the most important findings concerns the behavior of the ceramic shell. Its multilayer structure, consisting of a zircon primary coat supported by aluminosilicate backup layers, proved essential for maintaining both mechanical strength and surface fidelity. The study shows that controlling the permeability and thickness of these layers has a direct impact on gas evacuation during pouring, thereby reducing surface defects and preventing local reactions between the molten alloy and the mold materials. The stability of the shell during preheating and pouring was also critical, minimizing dimensional distortion of the thin impeller blades.

The results further underline the value of an optimized gating system. By adjusting the feeder size and repositioning gate entry points, directional solidification became more predictable, effectively reducing shrinkage porosity near the hub and improving microstructural uniformity across the component. This demonstrates how geometric considerations and thermal behavior must be addressed together when designing castings with uneven section thicknesses. In industrial practice, these improvements translate into fewer rejected parts and reduced post-processing time.

Another contribution of the study is the confirmation that digital tools offer substantial advantages when producing complex components such as impellers. Simulation of mold filling, shrinkage behavior and cooling rates allows engineers to identify potential defects early and adjust the design before production begins. Combined with controlled shell building and modern wax formulations, these tools help stabilize critical dimensions and support consistent process repeatability.

Overall, the case study highlights that the integration of traditional investment-casting techniques with modern modeling and process optimization results in higher casting quality, reduced variability and improved hydraulic performance of the final impeller. Continued digitalization, including advanced simulation, automated inspection and potentially additive-manufactured patterns, is expected to play an increasingly important role in developing the next generation of precision cast components.

REFERENCES

[1]. Campbell J., *Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques and Design*, 3rd Edition, Butterworth-Heinemann, Oxford, 2020.

[2]. Ravi B., *Metal Casting: Computer-Aided Design and Analysis*, 2nd Edition, Prentice Hall, New Delhi, 2005.

[3]. **Beeley P.R.,** Smart R.F., *Investment Casting*, The Institute of Materials, London, 1995.

[4]. **Stefanescu D.M**., *Science and Engineering of Casting Solidification*, 2nd Edition, Springer, New York, 2009.

[5]. **ASM International**, *ASM Handbook, Volume 15: Casting*, ASM International, Materials Park, Ohio, 2008.

[6]. **Davis J.R.** (Ed.), *Stainless Steels*, ASM Specialty Handbook, ASM International, 1994.

[7]. **Qu X.H., Wang X.H.,** *Ceramic Shell Mold Technology for Precision Investment Casting*, Journal of Materials Processing Technology, 2010.

[8]. **Șoica A., Apostu S., Pupaza C**., "Design and Simulation of Mechanical Structures Using FEM (Finite Element Method)," Journal of Research and Innovation for Sustainable Society (JRISS), Vol. 7, Issue 1, Thoth Publishing House, 2025, pp. 126. ISSN 2668-0416.

[9]. **Șoica A., Apostu S**., "The Influence of Execution Technology on the Precision Turning of Mechanical Parts: Case Study on Manufacturing a Complex Component Using a Three-Axis CNC Lathe with Active Tooling," Journal of Research and Innovation for Sustainable Society (JRISS), Vol. 7, Issue 1, Thoth Publishing House, 2025, pp. 31. ISSN 2668-0416.