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WALLCOLMONOY

The Development and Optimisation of Manufacture for High-Pressure Turbine Blades

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MECHANICAL AND MANUFACTURING ENGINEERING



Declaration of Authenticity

'This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.'

Signed:

A handwritten signature in black ink, appearing to be 'Rup' or similar, written in a cursive style.

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Any inadequacies that remain in this work are my own – sorry!

Abstract

This report presents a comprehensive investigation into the investment casting processes aimed at developing the complete manufacture and enhancing the quality and efficiency of the High-Pressure Turbine (HPT) Blades manufacturing process. The primary aim of this research is to establish a repeatable and reliable route of manufacturing HPT Blades, ensuring consistent provision of high-integrity components to customers while solidifying Wall Colmonoy Limited's (WCL) reputation as a trusted supplier. The study encompasses an analysis of potential materials for HPT blade manufacturing, selection of the appropriate alloy, establishment of key parameters within the investment casting process, and identification of root causes of defects with mitigation strategies. Through examination and optimization of parameters such as pour temperature, pour rate, transit time, and gating design, significant strides have been made towards standardizing and optimizing the manufacturing route for HPT Blades. Furthermore, insights gained from defect analysis have facilitated the implementation of continuous improvement initiatives aimed at reducing defect rates and enhancing overall quality. The findings presented in this report offer valuable insights and recommendations for stakeholders in the aerospace industry, providing a roadmap for achieving consistent quality, reliability, and efficiency in the production of critical components. Moving forward, continued research and collaboration will be essential in driving innovation and further advancing investment casting technology to meet the evolving demands of the aerospace manufacturing sector.

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Glossary

CAD	Computer Aided Design
DPI	Dye Penetrant Inspection
FPI	Fluorescent Penetrant Inspection
Gating	Small opening or passage in the mould that allows molten metal to enter the cavity from the runner system.
GOM	Optical 3D scanning technology used to accurately capture the geometry of objects.
HPT	High Pressure Turbine
HPTB	High Pressure Turbine Blade
NRE	Non-recurring Engineering
RT	Radiographic Testing
Runner	A channel or pathway through which molten metal flows from the sprue
SEM	Scanning Electron Microscope
Shell	The ceramic coating covering the wax patterns and trees.
Sprue cavity.	The main channel through which molten metal is poured into the mould
Stucco	A fine-grained refractory material, that is applied to the surface of the wax pattern to create a ceramic shell.
Tree	A structure used to hold multiple wax patterns.
VIC	Vacuum Investment Casting
VIM	Vacuum Induction Melting
Wax Pattern	A replica of the desired metal part made from wax.
WCL	Wall Colmonoy Limited

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1. Introduction

High pressure turbine blades are being considered for manufacture for a small new aerospace engine. The manufacture of this type of component is new for Wall Colmonoy, so the need to develop a stringent method of manufacture is vital to expand into new sectors, such as aerospace/defence.

High-pressure turbine blades (HPTBs) stand as critical components within gas turbine engines utilized in aerospace and defence applications. Operating under extreme conditions of temperature, pressure, and mechanical stress, their performance is pivotal for ensuring the overall efficiency and reliability of propulsion systems.

HPT blades are intricately designed aerofoils made typically from advanced materials like nickel-based superalloys. They are mounted on the rotor of the high-pressure turbine section.

These blades play a crucial role in extracting energy from the high-pressure and high-temperature gases produced by combustion. As the gases expand through the turbine, they impart kinetic energy to the blades, causing them to rotate and drive the connected shaft, which powers various components such as compressors, generators, or propellers.

The geometry of high-pressure turbine blades is meticulously engineered for optimal performance under extreme conditions of temperature, pressure, and aerodynamic forces. They have an aerofoil shape with a curved profile to efficiently harness energy from the gas flow. The blades are designed with specific angles of attack, camber, thickness, and twist to maximize aerodynamic efficiency and minimize losses due to drag and turbulence.

Manufacturing high-pressure turbine blades is a thorough process that demands precision, durability, and advanced engineering techniques. Among the methods utilized in this manufacturing process are, investment casting, vacuum melting, 3D printing of the wax patterns, heat treatment, and simulations of molten metal fluid flow. These methods collectively enable the production of the blades that meet stringent performance requirements while pushing the boundaries of material science and manufacturing technology.

Investment casting, a versatile manufacturing method, has long been instrumental in producing complex components with high precision and intricate details for various industries, including aerospace, automotive, and medical sectors. This report aims to delve

deep into the intricacies of investment casting processes, particularly focusing on enhancing quality and efficiency through analysis and optimization techniques.

The initial sections of this report will set the stage by providing an overview of investment casting, its historical evolution, and its significance in modern manufacturing industries. By understanding the fundamentals of investment casting, including its advantages, limitations, and applications, readers will gain valuable insights into the context of the subsequent discussions.

Building upon this foundation, the report will then delve into a detailed examination of a specific case study involving a series of trial runs aimed at validating simulation accuracy, ensuring consistent high-quality production of blades, and identifying root causes of defects. Through preparation of simulations, adherence to detailed parameters, and iterative refinement efforts, the trial runs provide a rich source of data and insights into the complexities of investment casting processes.

The report will explore various methodologies employed in the trial runs, including 3D printing of wax patterns, precision vacuum investment casting, and comprehensive inspection techniques. By analysing the outcomes of these methodologies and their impact on quality and efficiency, identified will be key areas for improvement and optimization within the investment casting process.

In addition to examining the technical aspects of investment casting, the economic implications have also been considered, with a cost analysis comparing different trial runs and highlighting the importance of minimizing defects for sustained profitability.

Overall, this report seeks to contribute to the existing body of knowledge on investment casting processes by offering insights, recommendations, and best practices for enhancing quality and efficiency. Through a multidisciplinary approach encompassing engineering, materials science, and business management principles, the report aims to provide a comprehensive framework for production of high-pressure turbine blades in modern manufacturing environments.

1.1 Aims and objectives of the project.

1.1.2 Aims

To establish a repeatable and reliable route of manufacture of HPT Blades.

With the data obtained during this project, WCL are looking to establish a repeatable and reliable route of manufacture HPT Blade so that they can consistently provide quality, high integrity components to our customer, gaining a reputation as a trusted supplier along the way.

As the specific area of these components are relatively new ground for WCL, the information obtained will serve well for future projects in the defence sector, potentially unlocking new opportunities for more complex, high profit projects.

1.1.3 Objectives

This research has the following objectives:

1. To analyse potential materials for use in manufacturing HPT blades and select the appropriate alloy for production.
2. To establish key parameters within the investment casting process.

The HPT Blades are made via the investment casting process where wax patterns are coated in a ceramic shell, melted to leave an empty mould, and then filled with molten metal to create the final part. The key parameters to be established are:

- Pour temperature of the molten metal.
- Pre-heat/burn-off time.
- Pour rate.
- Transit time between pre-heat over and furnace.

3. Find the root cause of any defects within the manufactured parts and mitigate or eliminate them where possible. Defects are a consistent problem with investment casting within WCL, but with continuous improvement initiatives within the castings department, these have been reduced to <5% overall. The manufacture of HPT Blades is new ground, and with the added complexity compared to typical components, such as the Insert seen in section 1.2.5, there is expected to be higher fallout for this project.

4. To improve the efficiency of manufacture, resulting in lower costs/higher profit.

1.2 Reasons and relevance of the project

So that the need for this project is fully understood, the reasons for, and the relevance of this project are discussed in this section.

1.2.1 Market Opportunity

The defence industry offers a compelling market opportunity for precision components department due to its inherent stability and growth potential. Governmental spending on national security ensures a consistent demand for military equipment and related components, shielding manufacturers from the volatility often observed in other sectors. The Government have recently committed to increasing defence spending by 2030 to 2.5% of GDP. This delivers an additional £75 billion by the end of the decade (Sunak, 2024). Defence contracts typically span several years, providing manufacturers with a predictable revenue stream and enabling long-term planning and investment. Additionally, the global reach of defence operations presents opportunities for manufacturers to expand into new markets and establish strategic partnerships with international defence entities.

1.2.2 Technological Advancements

Military equipment demands the highest levels of precision and reliability, driving continuous technological advancements within the defence industry. Entering this sector, we will be compelled to innovate and develop cutting-edge solutions to meet the stringent requirements of defence contracts. An example of this is the DragonFire Laser system which the MoD have developed with its partners, which demonstrates the process of leveraging technological advancements to gain a strategic edge on the frontline (GOV, 2024). This environment fosters the cultivation of expertise in advanced manufacturing techniques, materials science, and quality control processes. Furthermore, collaboration with defence agencies often leads to the development of proprietary technologies, enhancing the manufacturer's competitive advantage and positioning them as leaders in the field of precision engineering.

1.2.3 Diversification of Portfolio

Diversifying into the defence industry will offer Wall Colmonoy the opportunity to mitigate risks associated with market fluctuations and dependency on specific sectors, which can be caused by wars and conflicts, technological changes, concerns over inflation, amongst others (Hall, 2023). By expanding the portfolio to include defence contracts, WCL can

balance their revenue streams and reduce vulnerability to economic downturns. Additionally, defence contracts tend to demonstrate counter-cyclical tendencies, providing a buffer against recessionary pressures. This diversification strategy not only enhances the resilience but also opens avenues for growth and expansion into new markets, both domestically and internationally.

1.2.4 Strategic Partnerships and Collaborations

Strategic partnerships and collaborations play a crucial role in the successful entry of precision components manufacturers into the defence industry. There are 17 strategic partners of the MoD (GOV, 2024). By forging alliances with established defence contractors, WCL can gain access to specialized knowledge, resources, and funding that are essential for navigating the complexities of defence projects. Collaborations with defence agencies enable technology transfer and facilitate supply chain integration, allowing WCL to leverage the expertise and capabilities of the defence sector while enhancing our own competitiveness. Furthermore, joint ventures and consortiums provide opportunities for manufacturers to pool resources, share risks, and pursue larger defence contracts that may be beyond their individual capacities (PricewaterhouseCoopers, 2024). Overall, strategic partnerships and collaborations are instrumental in maximizing the opportunities presented by the defence industry and ensuring the long-term success of precision components manufacturers in this sector.

1.2.5 Batch Comparison of HPT Blades and “Insert” component.

To understand the benefits of expanding into the defence sector, this subsection delves into the difference between one of WCLs highest volume components, the ‘Insert’, which is used within the glass bottle making industry, and the HPT Blade this project is based on.

Table 1 below, depicts the price, typical profit, total price, and total profit between the two components in question.

Component	Selling Price	Typical Profit	Typical Batch Size	Total Price	Total Profit
HPT Blade	£300	£171	75	£22,500	£12,825
Insert	£5	£0.55	2000	£10,000	£1,100

Table 1 - Blade & Insert Profit Comparison

Inserts, shown in Figure 1, vary in size but are the highest volume part WCL produces – Made of nickel the selling price of these parts tends to range between £2.50 and £7.50 (£5 has been used for comparison's sake) – Each insert sold for £5, but with just an 11% net profit there is only 55p net profit per part.



Figure 1 - Castellated Insert

The selling price of the HPT Blade, shown in Figure 2, is £300 which comes with a profit of £171 per part if the typical net margin is met.



Figure 2 - Typical HPT Blade

A typical batch of Inserts (2000) and a typical batch of HPT Blades (75) will have a total price of £10,000 and £22,500, respectively but profits of £1,100 and £12,825, respectively.

This shows that you would have to make over 23,000 (~12 batches) of inserts to get the same amount of profit as one batch of 75 Blades.

Historically, the glass container industry has supplied WCL with a high volume of work but were sold at a relatively low margin. Aerospace/Defence on the other hand has traditionally low turnover but sold at a high margin as seen in Table 2.

Sector	2019	2020	2021	2022	2023	Net Margin
Glass Container	1.89	1.78	1.346	1.665	1.756	11%
Aerospace	0.233	0.15	0.109	0.256	0.301	57%

Table 2 - Aerospace & Glass Container Net Margin Comparison

The average turnover from 2019-2023, as-cast had a turnover of 1.687 million pounds compared to almost 210 thousand pounds for Aerospace turnover. Depicted in Table 3.

The average profit for as cast is £185,570, compared to £119,586 for the aerospace sector, between 2019-2023. That means that as-cast has 8x turnover of aerospace, and only 1.55x the net profit margin. A visual representation can be seen in Figure 3.

Sector	Turnover £	Profit £
Glass Container	1,687,000	185,570
Aerospace	209,800	119,586

Table 3 - Aerospace & Glass Container Turnover/Profit Comparison

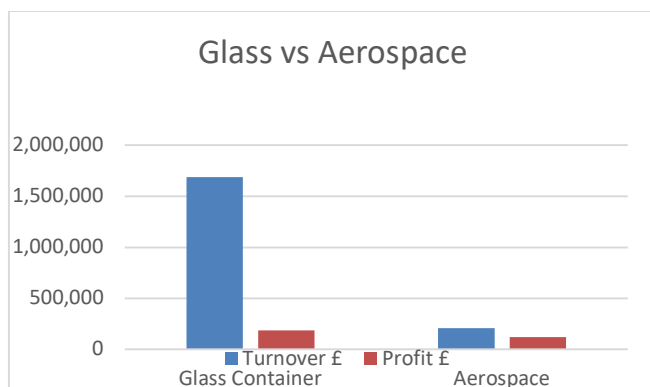


Figure 3 - Glass vs Aerospace Comparison Graph

Expanding into the defence sector promises greater profitability for WCL compared to its current high-volume product line in the glass container industry. Analysis shows that while the glass industry provides higher turnover, the aerospace and defence sectors offer significantly higher profit margins per unit. This shift would enable WCL to capitalize on higher-margin products, diversify its revenue streams, and enhance overall profitability and competitiveness.

2. Timing Plan

In this section, the timing plan is outlined, providing a comprehensive roadmap for the execution of the project, and compared with how that original plan deviated as the project progressed.

The initial Gantt charts has 6 distinct sections, which are detailed below:

1. Material Analysis,
2. Trial 1
3. Trial 1 Analysis
4. Trial 2
5. Trial 2 Analysis
6. Completion/Full Production

The Gantt charts shown in Figure 4 & Figure 5 both depict the first three sections. Figure 4 shows the initial plan and Figure 5 shows how the final plan differed.

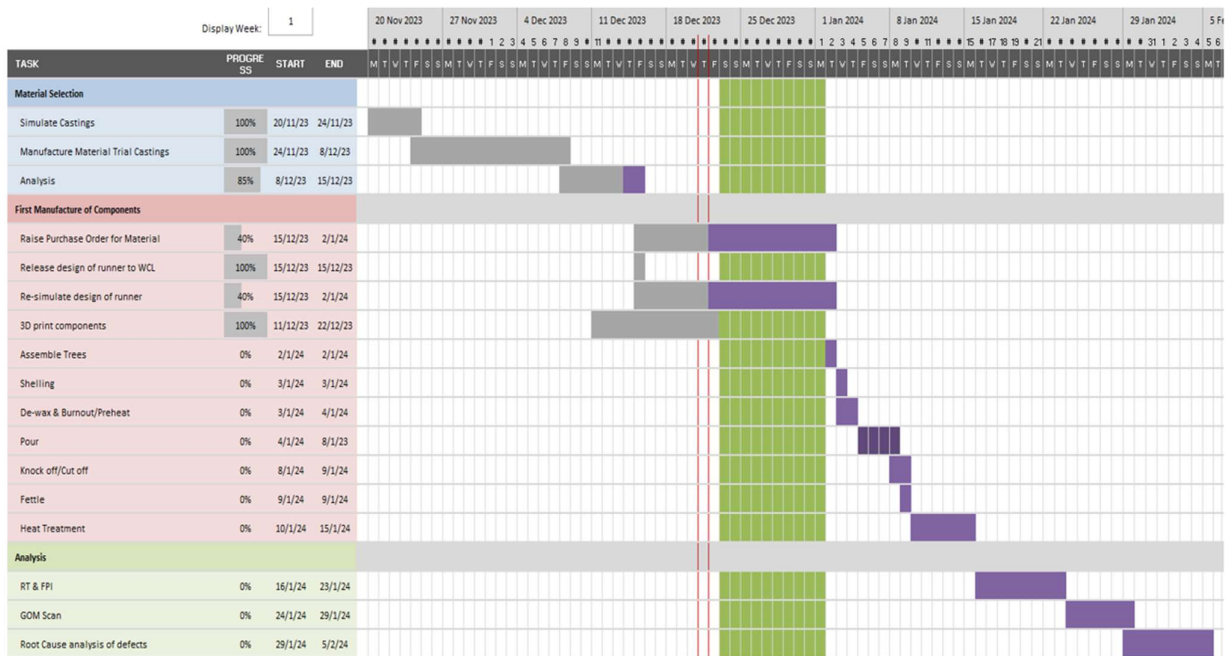


Figure 4 - Initial Plan Gantt Chart (First Half)

Section 1, Material Analysis – This section contained the analysis between the two materials in question, including simulations of castings, manufacture of castings and tensile bars, and

analysis of each material. Tasks 1 and 2 remained on schedule, consistent with the original plan. However, Task 3 encountered a delay, completing on 24/12/23 instead of the scheduled 15/12/23, due to an issue with the SEM in Wall Colmonoy.

Section 2, Trial 1 – Initially scheduled to commence on 11/12/23 and conclude on 15/1/24, this section experienced a delay of nine days due to an extended overrun in material analysis. Despite this setback, progress was made during the investment casting process, with the section ultimately completing on 17/1/24, two days behind schedule.

Section 3, Trial 1 Analysis – Originally planned to run from 16/1/24 to 5/2/24, this section commenced on 18/1/24 and concluded on 13/2/24, eight days behind schedule, primarily due to a late start and prolonged GOM scanning.

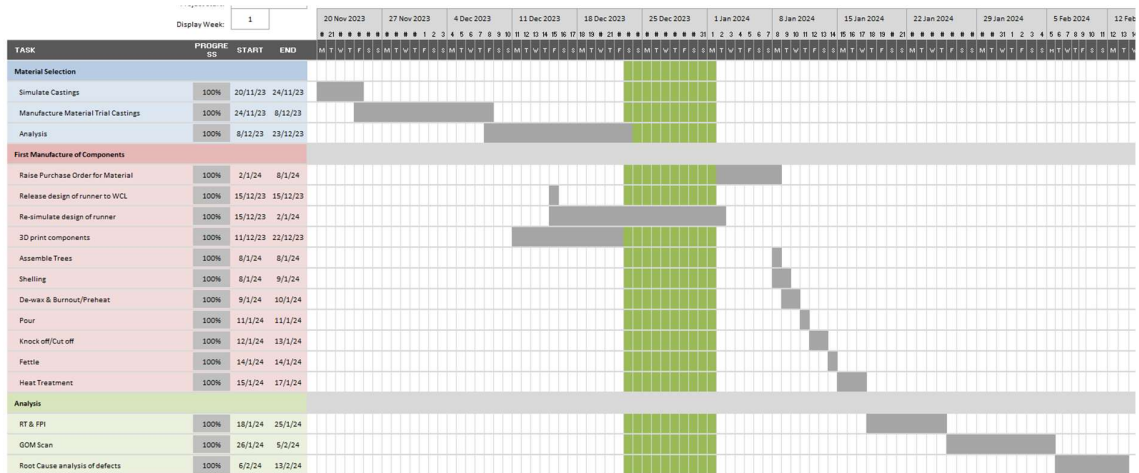


Figure 5 - Final Plan Gantt Chart (First Half)

The Gantt charts in Figure 6 & Figure 7 depict sections 4-6 of the project.

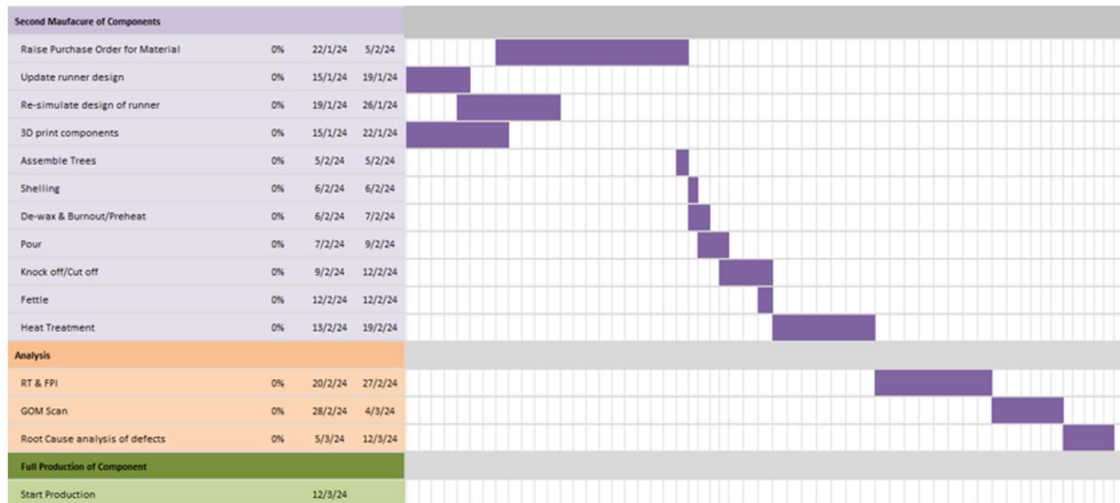


Figure 6 - Initial Plan Gantt Chart (Second Half)

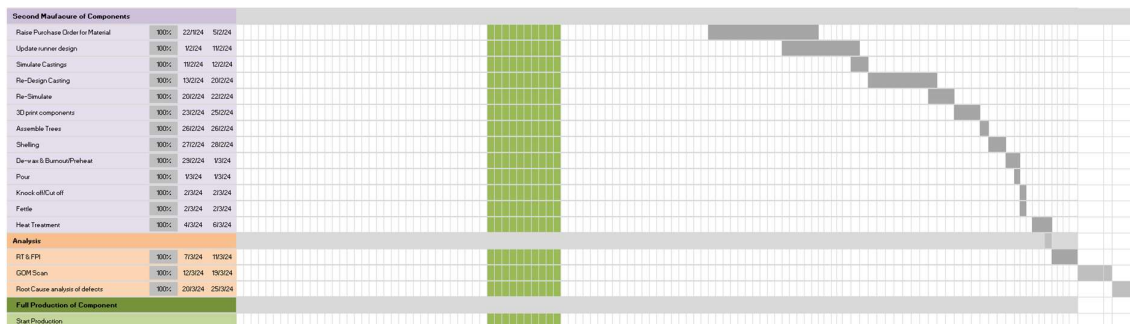


Figure 7 - Final Plan Gantt Chart (Second Half)

Section 4 marks the start of Trial 2, the second round of blade manufacture. Initially scheduled to begin on 16/1/24, it was delayed due to the late completion of the first three sections, starting on 22/1/24 instead. Although the trial progressed well during the investment casting process, issues arose with the blades after a tree redesign, necessitating component redesigns and re-simulations. Originally planned to conclude on 19/2/23, this section finished on 6/3/24, 16 days behind schedule.

Consequently, Section 5 commenced 16 days late on 7/3/24, reaching completion on 25/3/24.

Originally planned to span from 20/11/23 to 12/3/24, totalling 113 days, the project concluded on 25/3/24, extending to 126 days due to complications in material analysis, delayed GOM analysis, and blade redesigns, resulting in a 13-day overrun.

Despite encountering delays throughout various sections of the project, it can be concluded that being over schedule at this stage was not detrimental. The primary reason being that the delays occurred during research phases rather than during full-scale manufacturing and they still resulted in the creation of working parts that could be sold to the customer.

The delays allowed for thorough analysis, problem-solving, and refinement of the manufacturing process. For example, issues with blade design and simulations were identified during Trial 2, leading to necessary component redesigns and re-simulations. These adjustments ultimately contributed to the production of improved, more reliable components.

Therefore, despite the project extending beyond the original timeline, the delays were not negative as they occurred during research and development stages, ensuring that the final product would meet quality standards and customer expectations, with the addition of quality parts being able to be sold to the customer for testing before full manufacture is commissioned.

3. Literature Review

This literature review will provide an overview of the current research on the selection between two superalloys for the development of fast make small engine turbine blades. It will also review the existing literature on the manufacture of the wax using 3D Printing, Investment Casting, Vacuum Induction Casting, High Pressure Turbine Blades, Non-Destructive Testing and Simulation Software.

3.1 Superalloys

Superalloys have played a pivotal role in the aerospace industry, particularly in enhancing high-temperature strength and creep resistance, making them indispensable for critical components within operational engines (Whittenberger, 1992). High temperature strength typically refers to a material's ability to retain a significant portion of its mechanical properties, such as yield strength and tensile strength, at temperatures above 500°C. Creep resistance, on the other hand, is quantified by measuring a material's resistance to deformation or elongation over time when subjected to constant stress at elevated temperatures, commonly above 400°C (Yu et al., 2013), with jet engines reaching temperatures of 850°C to 1700 °C (Soloiu et al., 2021). Among these components, high-pressure turbine (HPT) blades are of paramount importance, and the choice of materials for their construction is a critical decision in the aviation industry. This literature review explores the performance comparison of two prominent nickel-based superalloys, Inconel 738LC and MAR-M-002, with a specific focus on their suitability for high-pressure turbine (HPT) blades, which is the focus of this report.

Having a rich history in aerospace engineering, dating back to the mid-20th century when superalloys were first introduced to meet the demands of high-temperature and high-stress environments within operational engines (Sims et al., 1987). The International Nickel Company's research on Alloy IN-738 in 1981 marked a significant milestone in the development of superalloys (Harada et al., 1982). These materials are characterized by their unique combination of γ/γ' precipitation, and additional complex refractory metal carbide precipitation, strengthening mechanisms (Starink, 2001). Superalloys undergo a process called precipitation hardening, where certain phases or compounds precipitate out of the material matrix as it is heated and cooled. In these alloys, the primary strengthening mechanism involves the formation of a γ' (gamma prime) phase within the γ (gamma) phase matrix. The γ' phase is a fine, coherent precipitate that significantly strengthens the material, enhancing its high-temperature performance. In addition to the γ/γ' precipitation mechanism,

superalloys often contain refractory metal elements such as tantalum, tungsten, niobium, or molybdenum. These metals form carbides (e.g., tantalum carbide, tungsten carbide) within the alloy matrix during processing. These carbides act as additional strengthening agents, contributing to the overall mechanical properties and high-temperature performance of the material (Dahlen & Fischmeister, 1980) (Selvig et al., 2010). The γ/γ' phase strengthening is particularly important for achieving exceptional high strength and high-temperature creep resistance, key attributes for this projects HPT Blades, used in hot zones of operational engines (Dahal et al., 2020). A comparison of stress rupture strength in relations to temperature for nickel-based superalloys, against Magnesium, Aluminium and Titanium alloys can be seen in figure 8 (Mouritz, 2012).

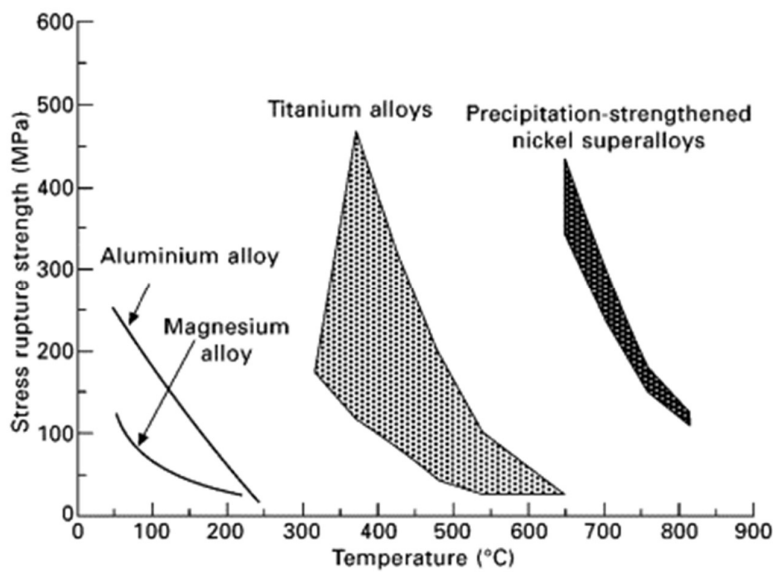


Figure 8 - Alloy Stress Rupture Comparison

The understanding of material properties, including tensile performance and microstructural characteristics, is crucial in the aerospace industry. Researchers like (Ming, 1995) and backed by (El-Bagoury et al., 2008) have emphasized the impact of solution heat treatment on material properties. As stated by (Khawaja & Moatamedi, 2014), tensile strength and elongation values are critical indicators of a material's performance under mechanical stress, making them valuable in evaluating the suitability of superalloys for high-pressure turbine blades (Theska et al., 2022). Microstructural analysis as seen in this report provides insights into the distribution of phases within the material and their impact on mechanical properties (Dahal et al., 2020). The presence of γ/γ' hardening mechanisms and the formation of complex MC carbides within the microstructure can significantly influence a material's performance.

Inconel 738LC and MAR-M-002, the two superalloys being investigated in this report, have a carbon content of 0.09-0.13 and 0.13-0.17 respectively. Carbon, as an alloying element, influences the microstructure and properties of these alloys. While high carbon content has been extensively studied (Idowu et al., 2006) (Selvig et al., 2010).

Low carbon content in nickel-based superalloys can lead to reduced precipitation of carbides and other secondary phases (Selvig et al., 2010). The absence of carbides may also promote solid solution strengthening, contributing to enhanced mechanical properties, such as yield strength and fatigue resistance (Behera & Sahoo, 2020).

The influence of low carbon content on mechanical properties varies depending on alloy composition and processing conditions. Generally, low carbon levels are associated with improved ductility and toughness, especially at elevated temperatures (Starink & Thomson, 2001). According to (Dahlen & Fischmeister, 1980) this can be attributed to the suppression of carbide precipitation, which reduces susceptibility to embrittlement mechanisms such as grain boundary cracking and intergranular fracture, which has been verified by (Formenti, et al., 2005).

Nickel-based superalloys with low carbon content exhibit superior high-temperature performance compared to their higher carbon counterparts, with some low carbon superalloys can withstand operating temperatures as high as 1,000°C, with some lower carbon superalloys maintaining their hardness and wear resistance up to around 600°C, but their performance may degrade at higher temperatures (Formenti, et al., 2005). Reduced carbide precipitation minimizes microstructural instabilities, such as sigma phase formation and sensitization, which can degrade mechanical properties and corrosion resistance at elevated temperatures (Zhou et al., 2022). Consequently, alloys with low carbon content demonstrate enhanced long-term stability and reliability in high-temperature environments (Idowu et al., 2006).

The beneficial effects of low carbon content make nickel-based superalloys particularly suitable for critical aerospace components, such as HPT Blades, where high-temperature performance and mechanical reliability are paramount (Sawant et al., 2008). Future research directions may include further optimization of alloy compositions and processing techniques to maximize the benefits of low carbon content while addressing specific application requirements and challenges (Zhou et al., 2022) (Nawrocki et al., 2023).

The information detailed in this subsection will aid the selection of an appropriate superalloy for production.

3.2 Additive Manufacturing (3D Printing)

3D printing, also known as additive manufacturing, involves the creation of three-dimensional objects by depositing successive layers of material (Roebuck, 2012). This technology is evolving rapidly, with 3D printers becoming faster, more cost-effective, and easier to operate, leading to their increased adoption in manufacturing companies. By enabling the production of parts and assemblies using various materials with distinct mechanical and physical properties in a single build process, 3D printing fosters innovation (Hong, 2015). Advanced 3D printing techniques allow the creation of models that closely mimic the functionality of product prototypes. The process begins with a 3D computer file, which the printer translates into a series of cross-sectional slices. These slices are then printed layer by layer to form the final 3D object (Roebuck, 2012). The speed in which prototypes can be modified, without expensive tool modifications, which ultimately may not work lends itself to being the perfect method for wax creation in the development stage in any investment casting development project, and therefore for the HPT Blades.

The versatility and efficiency of 3D printers have led to their widespread use across diverse fields, thanks to their quick productivity, user-friendly interfaces, and cost-effectiveness (Thomas et al., 2021). Utilizing software integrated into 3D printers, components can be automatically produced from 3D models designed within various software applications such as AutoCAD, Autodesk Inventor, or SolidWorks, minimizing the need for human intervention beyond initiating the printing process. However, limitations exist, with some printers having constraints on materials, path patterns, and layer thicknesses (Tserovski, 2019) (Intech Open, 2016).

One prevalent method of 3D printing is Fused Deposition Modelling (FDM), where a 3D printer extrudes material layer by layer to form the desired component (Protolabs, 2024). The process involves loading thermoplastic filament into the printer, which is then melted in the nozzle once it reaches the required temperature. An extrusion head attached to a 2-axis system moves in the X and Y directions, while the printer plate moves in the Z direction, depositing the melted material layer by layer at predetermined locations. Multiple passes are often necessary to fill an area completely without leaving holes. After each layer is completed, the build platform descends, and a new layer is deposited, repeating the process until the part is finished (Balasubramanian & Senthilkumar, 2020) – This details how the Blades will ultimately be printed.

Post-processing requirements vary based on the size and complexity of the printed part, typically involving sanding, and polishing to remove excess material and achieve the desired

finish (C.K Chua Kah Fai Leong, 2010). One challenge encountered with the FDM method, particularly with Wall Colmonoy's Ultimaker 3 Extended, is the difficulty of removing excess material from complex features of a part, leading to time-consuming finishing processes, which may have a negative effect on manufacture of the Blades. Delamination of the printed layers can also be a problem, with the effects not necessarily seen until it's too late (Balasubramanian & Senthilkumar, 2020), an issue encountered during this project.

Advancements in additive manufacturing (AM) technologies have enabled the rapid prototyping and optimization of gating system designs for investment casting applications (Vaezi et al., 2011). AM techniques such as 3D printing allow for the creation of intricate gating system geometries with precise control over dimensions and flow characteristics. Research has demonstrated the feasibility of using AM for rapid iteration and optimization of gating system designs, leading to improved casting quality and reduced lead times in the manufacturing process (Balasubramanian & Senthilkumar, 2020). Figure 9, provided by (ProtoFab, 2019) depicts the process flow for additive manufacture.

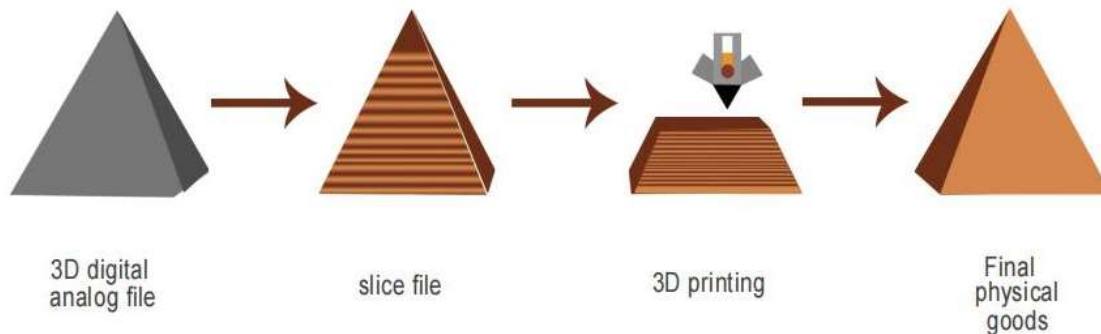


Figure 9 - 3D Printing Process Flow

3.3 Investment Casting

Investment casting, also known as the lost wax process, stands as one of the earliest methods developed for metal casting (Engineered Casting Solutions, 2011). This process has been used in WCL since 1979 and is well understood. Its capacity to cast hard and high-melting-point alloys to near net shape has positioned it as a vital casting technique (Belal, et al., 2008), which is ideal for the manufacture of the blades, which have complex geometry. The initial stage of investment casting involves creating the wax pattern, representing the

desired component with shrinkage allowance. Traditionally, waxes are formed through injection moulding into metal dies, although advancements have allowed for patterns to be produced through additive manufacturing processes as well (Thomas & Gilbert, 2014), with the latter will being initially used in this project. Subsequently, the wax patterns are assembled onto a wax cluster or tree, which serves as the runner system for the molten metal. This tree is then moved to the mould room, where it undergoes a series of steps involving dipping in ceramic slurry, coating with fine ceramic sand, and drying. The number of coating cycles varies based on factors such as component geometry, shell composition, and pouring temperature (Bond, 2023). Once the drying process is complete, the wax is removed from the mould either through autoclaving or firing, leaving behind a cavity (Horton, 2008) (Campbell, 2004). The moulds are then preheated in an oven to cure and burn out any wax residue left from the de-waxing process. Subsequently, the molten metal is poured into the mould, left to solidify, and cool, and then the shell of the mould is removed as the components are cut from the cluster (Campbell, 2011).

Figure 10, provided by (Metaltek, 2023) illustrates the basics of the process.

- A = Wax creation
- B = Assembly
- C = Coating
- D = De-wax/Burn out
- E = Pouring
- F = Knock off/Fettling

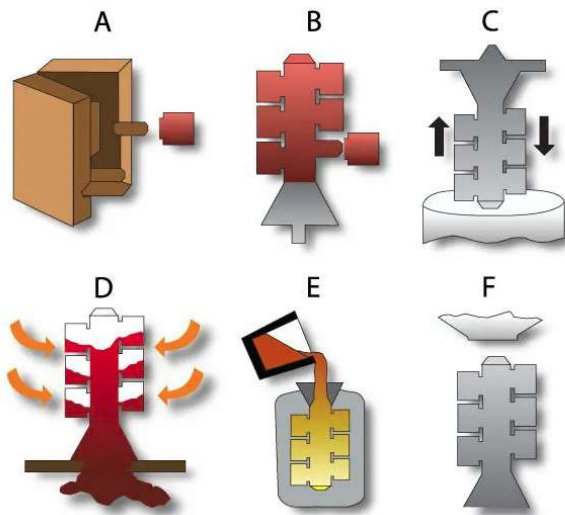


Figure 10 - Investment Casting Illustration

Tree-type gating systems play a crucial role in investment casting design, facilitating the flow of molten metal into the mould cavity while minimizing defects such as shrinkage and porosity (Bhatt et al., 2014). Research conducted by (Piwonka, 2023) and (Vrátný &

Herman, 2019) in this domain has concentrated on optimizing gating system configurations, including sprue, runner, and gate dimensions, to ensure uniform metal flow, decrease turbulence, and diminish defects in the final casting. Computational fluid dynamics (CFD) simulations and experimental studies have been utilized to analyse the flow characteristics of molten metal within gating systems and refine design parameters accordingly, which directly relate to one of the key parameters that are to be established.

A primary objective of tree-type gating system optimization is the mitigation of solidification-related defects like shrinkage and gas porosity (Li et al., 2004) (Annettes, 2015). Investigations from (Raza, 2015) and (Piwonka, 2023) have delved into the impact of gating system design on the cooling rate and solidification behaviour of molten metal, aiming to minimize defect formation and enhance casting quality (Bidwell, 2023) a problem which became evident in the casting trials detailed in this report. Strategies such as employing ceramic foam filters, chill inserts, and heat sinks have been explored to regulate solidification and decrease defect occurrence in critical regions of the casting (Kanyo et al., 2020).

3.4 Vacuum Casting

Vacuum investment casting (VIC) is a specialized casting process that involves the use of a vacuum environment during the investment casting process. This technique offers several advantages over traditional investment casting methods, including improved casting quality, reduced porosity, and enhanced surface finish, whilst mitigating oxidation (Campbell, 2011) (Swift & Booker, 2013). In recent years, VIC has garnered significant attention in various industries, including aerospace, automotive, and medical, due to its ability to produce complex and high-quality components with tight tolerances, such as HPT Blades (Ravichandran et al., 2022). Figure 11 shows the furnace used in WCL.

One key aspect of vacuum investment casting is its influence on the solidification behaviour and microstructure evolution of cast components. Research by (Miller, 1958) and (Belk, 1963) has focused on explaining the effect of vacuum conditions, such as pressure and



Figure 11 - Vacuum Furnace

temperature, on the solidification process and resultant microstructural characteristics, which has since been confirmed by (Kay, 2003). Studies have shown that the vacuum environment promotes a more uniform cooling rate and reduces the formation of internal defects, such as shrinkage porosity and gas porosity, leading to improved mechanical properties of the castings (Dlouhý et al., 2007) (Ravichandran et al., 2022).

Furthermore, the role of mould materials and process parameters in vacuum investment casting has been extensively investigated by (Belk, 1963) and (Miller, 1958). Various mould materials, such as ceramic shells and refractory metals, have been evaluated for their suitability in VIC applications, considering factors such as thermal stability, gas permeability, and mould strength (Kanyo et al., 2020). Additionally, optimization of process parameters, including mould preheating temperature, casting temperature, and cooling rate, has been investigated to achieve desired casting properties and minimize defects, (Hendricks et al., 1991)(Krane et al., 1998)(Nawrocki et al., 2015), which are explored in the report.

Research efforts have focused on the development of advanced techniques and technologies to enhance the efficiency and reliability of vacuum investment casting processes (Thompson, 2022). Computational modelling and simulation techniques, such as finite element analysis (FEA) and computational fluid dynamics (CFD), have been employed to predict the flow behaviour of molten metal, optimize mould design, and simulate solidification phenomena (Abeni et al., 2021) (Fang & Li, 2023). These modelling approaches aid in the optimization of process parameters and the design of gating and feeding systems to minimize defects and improve casting yield.

In addition to process optimization, research has also addressed the post-casting treatments and surface finishing techniques applicable to vacuum investment castings (Glover & Davis, 1996). Heat treatment processes, such as precipitation aging - which is an important part of the development of the HPT Blades, and stress relieving, are commonly employed to improve the mechanical properties and dimensional stability of cast components (Ming, 1995) (El-Bagoury et al., 2008). Surface finishing techniques, including shot blasting, vibratory finishing, and chemical etching, are utilized to achieve desired surface roughness and cosmetic appearance (Bidwell, 2023).

3.5 Non-Destructive Testing

Dye penetrant testing, acid etching, and radiographic inspection are widely used non-destructive testing (NDT) techniques for assessing the quality and integrity of precision

components in various industries, including aerospace, automotive, and manufacturing (McMinn, 2024). These techniques play a crucial role in detecting surface and subsurface defects, ensuring compliance with quality standards, and preventing catastrophic failures (Swain et al., 2020).

Dye penetrant inspection (DPI), also known as liquid penetrant inspection (LPI), is a widely employed NDT method used in WCL for detecting surface-breaking defects in precision components (McMinn, 2024). The process involves applying a coloured or fluorescent dye to the surface of the component, allowing it to penetrate surface discontinuities by capillary action (Escudier & Atkins, 2019). After a specified dwell time, excess dye is removed, and a developer is applied to draw out the trapped dye from the defects, making them visible under ultraviolet (UV) light or white light. Numerous studies such as some carried out by (Cawley, 2001) and (Luk et al., 2007) have demonstrated the effectiveness of dye penetrant testing in detecting defects such as cracks, porosity, and laps in precision components, with high sensitivity and reliability.

Acid etching, or chemical etching, is another commonly used technique for inspecting precision components, particularly those manufactured from metal alloys (McMinn, 2024). The process involves immersing the component in an acidic solution, which selectively removes material from the surface, revealing any surface irregularities or defects (Bidwell, 2023). Acid etching is particularly effective for identifying surface anomalies such as inclusions, porosity, and grain boundaries. Research has focused on optimizing etching parameters, including etchant composition, temperature, and immersion time, to achieve consistent and reliable results (Cartz, 2003) (Bieder et al., 2008). Additionally, advances in image processing techniques have facilitated quantitative analysis of etched surfaces, enabling precise characterization of defects and their distribution (Gupta et al., 2022).

Radiographic testing (RT), utilizing X-rays or gamma rays, is a powerful NDT technique for examining the internal structure of precision components (McMinn, 2024). Radiography can detect subsurface defects such as voids, inclusions, and internal cracks, providing valuable insights into component integrity without the need for disassembly (Mix, 2005). Recent studies by (Sharma et al., 2023) have investigated the use of digital radiography (DR) and computed tomography (CT) techniques to enhance the resolution and accuracy of radiographic images, enabling detailed three-dimensional (3D) analysis of complex components, depicted in Figure 12. Advancements in radiographic imaging software have facilitated automated defect detection and analysis, streamlining the inspection process and improving efficiency (Saboonchi et al., 2021).

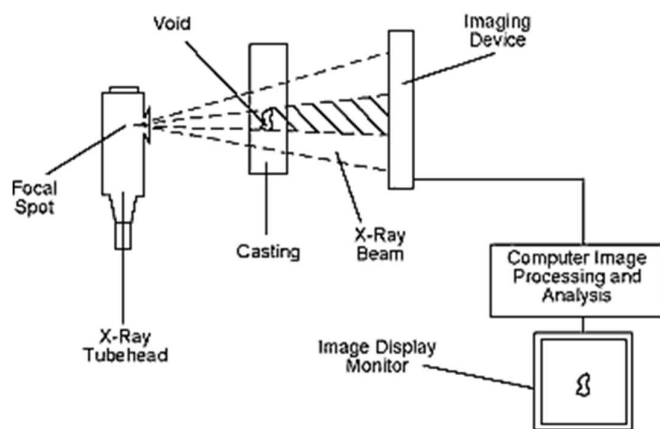


Figure 12 - Radiographic Testing Illustration

In addition to individual techniques, research has focused on the integration of multiple NDT methods to provide comprehensive inspection coverage and enhance defect detection capabilities (Dwivedi et al., 2018).

Combined approaches, such as dye penetrant testing followed by radiographic inspection or acid etching complemented by ultrasonic testing, offer synergistic benefits by leveraging the strengths of each technique to overcome their respective limitations from (Brekow, 1996) to (Lim et al., 2013). Furthermore, efforts have been made to develop advanced NDT systems and equipment, including automated inspection systems, robotic manipulators, and portable devices, to facilitate inspection of precision components in diverse environments and applications (Schulenburg, 2021) (Mineo & Javadi, 2022). Advancements in measurement technology such as GOM scanning, uses a scanner head which emits a light source that projects a sequence of parallel patterns onto the surface of the scan target. As the light interacts with the object's surface, the patterns undergo distortion. Subsequently, cameras capture these distorted patterns and transmit the images to the 3D scanning software for further processing and analysis.

Used in this project, GOM allows for the digitization of intricate components, capturing geometries with unprecedented detail, ensuring a comprehensive digital representation, and allows for the simultaneous measurement of multiple components within a single scan. The digitization of complex parts not only revolutionizes manufacturing processes but also opens new possibilities for innovation and advancement across industries (Zeiss, 2023).

Wall Colmonoy currently utilise DPI in house, and have trained inspectors to carry out the task, however, radiographic testing and GOM analysis must be subcontracted out as the equipment is not available in WCL. The information gathered by these tests will aid in root cause analysis of any defects found.

3.6 High Pressure Turbine Blades

A 3D model of the blade being manufactured in this project can be seen in Figure 13.



Figure 13 - HPT Blade (3D Model)

The design of HPTBs entails intricate considerations aimed at optimizing aerodynamic efficiency, structural integrity, and heat resistance. Leveraging computational fluid dynamics (CFD) simulations and advanced modelling techniques, engineers strive to refine blade profiles, leading-edge cooling channels (Riznyk & Artushenko, 2013), and aerofoil shapes, aiming for enhanced performance and fuel efficiency. Concurrently, ensuring structural robustness under high mechanical loads and thermal gradients remains a paramount concern (Arts, 2009)

Material selection for HPTBs is a critical determinant of their ability to withstand the harsh operating conditions encountered in aerospace and defence environments. Nickel-based superalloys continue to dominate this domain owing to their exceptional high-temperature strength, creep resistance, and corrosion properties (Carta et al., 2023). Recent research endeavours have delved into alloy development, exploring the incorporation of refractory metals and ceramic reinforcements to further enhance performance and durability while simultaneously addressing concerns regarding weight and manufacturing costs.

Manufacturing processes for HPTBs have undergone significant evolution to meet the demands of intricate geometries, stringent tolerances, and uncompromising quality standards. Advanced methodologies such as additive manufacturing (AM), colloquially known as 3D printing, offer promising avenues for rapid prototyping, customization, and the fabrication of complex internal cooling passages (Riznyk & Artushenko, 2013) (Chatterjee et al., 2023). Furthermore, advancements in precision machining, laser drilling, and surface finishing technologies have contributed to improving dimensional accuracy, surface quality, and fatigue resistance of HPTBs.

The performance assessment of HPTBs necessitates a comprehensive approach, encompassing experimental testing, computational modelling, and in-service monitoring. Rigorous testing protocols, spanning static and dynamic mechanical assessments, thermal cycling trials, and aerodynamic evaluations, are conducted to validate design assumptions and gauge blade performance under simulated operational conditions (Zubanov et al., 2023). Concurrently, in-service monitoring systems like health and usage monitoring systems (HUMS) offer real-time insights into blade health, vibration levels, and operational parameters, enabling predictive maintenance strategies and optimization of operational efficiency (Aust & Pons, 2022).

Despite notable advancements, several challenges persist in the development and deployment of HPTBs for aerospace and defence applications. Key among these challenges is the ongoing quest for further enhancements in material properties, particularly in areas such as fatigue resistance and environmental durability (Šmíd et al., 2020). Additionally, the development of advanced cooling technologies remains imperative to augment thermal management capabilities and prolong component lifespan (Riznyk & Artushenko, 2013). Furthermore, addressing the escalating demand for higher thrust-to-weight ratios, improved fuel efficiency, and reduced emissions necessitates ongoing research endeavours focused on lightweight materials, advanced coatings, and innovative blade geometries (Zubanov et al., 2023). A Finished HPT Blade can be seen in Figure 14.



Figure 14 - HPT Blade

3.7 Simulation Software

Investment casting, renowned for its intricacy and precision in producing metal components has become increasingly reliant on advanced simulation software to forecast metal flow behaviour and anticipate defects like shrinkage porosity. Employing finite element analysis (FEA) and computational fluid dynamics (CFD) principles to solve metal flow dynamics, solidification behaviour, and defect formation. These simulations provide engineers with visualizations and analyses of molten metal interactions within moulds and cooling systems, essential for designing robust casting processes which will be employed during the report.

Accurate representation of metal flow is critical for defect-free castings. Advanced simulation software integrates complex rheological models and boundary conditions to model fluid dynamics, turbulence, and heat transfer within mould cavities. Insights into flow velocities, pressure gradients, and solidification fronts facilitate defect prediction, including shrinkage porosity, misruns, and cold shuts.

Each software employs distinct methods to simulate the model and casting processes, and these methodologies can significantly impact the accuracy of results, computing time, and other variables. The finite difference method (FDM) divides the geometry into cubes, creating a structured grid pattern, which enhances the efficiency of meshing operations (Clearly, et al., 2002). However, the cubic structure may not accurately represent the geometry, leading to potential inaccuracies, as demonstrated in the Simtec (2016) example show in Figure 15. For instance, when computing the temperature distribution of a thin-walled cylinder, the cubic structure may fail to achieve a homogeneous temperature distribution across the diameter, as noted by Oscar-Yu (2002).

The finite element method (FEM) utilizes an unstructured mesh, allowing for more accurate meshing of complex geometries. Consequently, FEM computes thin sections and intricate shapes more accurately than FDM. However, the generation of the element mesh in FEM can become complex due to the intricate nature of the elements. Although vendors now provide built-in automatic mesh generation modules, generating an FEM mesh requires greater computing power compared to FDM due to the complexity of the elements.

When comparing the finite volume method (FVM) with FDM, a key advantage of FVM is its ability to work without a structured mesh (Warey, 2007), making it suitable for complex geometries akin to FEM. FEM is commonly employed for both structural mechanics and thermal/flow simulations, enabling the computation of residual stresses in addition to thermal and filling defects (Autodesk, 2011). In contrast, FDM is primarily utilized for thermal/flow

problems, although Rente and Oliveira (2003) mention its use in calculating solid stress. The diagram below provides a comparison of the structures of each method when meshed.

ProCAST, the package currently used in WCL runs on FEM, which lends itself to the complex geometry seen in the HPT Blade.

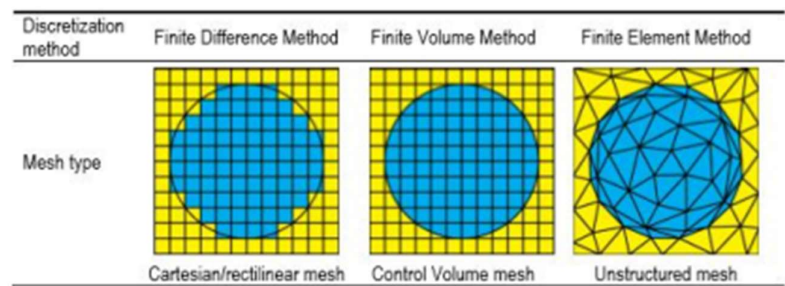


Figure 15 - Finite Methods Comparisons

Shrinkage porosity, a common defect in investment casting, stems from insufficient feeding of molten metal during solidification. 3D simulation software analyses solidification patterns to forecast shrinkage porosity, pinpointing vulnerable regions, optimizing gating, and feeding systems to prevent defects. Accurately estimating solid fraction during solidification is vital for defect prediction and process optimization. Simulation software tracks solidification fronts and calculates solid fractions based on thermodynamic properties and cooling rates, aiding in identifying potential defects like microporosity and hot tearing (Semiatin & Altan, 2010). The Niyama criterion, pivotal for investment casting optimization, assesses casting susceptibility to hot tearing. Simulation software evaluates Niyama criterion adherence by scrutinizing stress distributions, thermal gradients, and material properties, empowering designers to adjust gating and cooling designs to minimize hot tearing risks (Ivanina & Monastyrsky, 2021).

Despite advancements, challenges persist in accurately modelling transient phenomena and Multiphysics interactions. Addressing computational complexities and optimizing solver performance remain paramount. Future directions may include integrating machine learning for data-driven modelling, leveraging parallel computing for accelerated simulations, and implementing cloud-based platforms for collaborative analysis (Tomita et al., 2024).

4. Methodology

The purpose of this section is to provide a comprehensive overview of the key processes involved in the manufacturing and production of components through simulation, 3D printing of wax patterns, and investment casting.

4.1 Simulation

The initial assembly moulds were designed using the 3D modelling software, Spaceclaim, which was directly imported into ProCast using the IGES file format. Images of the Blades 3D model can be found in Appendix 10.9. The CAD model underwent meshing utilizing the Visual Mesh module of ProCast. Mesh sizes were tailored accordingly, focusing primarily on the casting area while the tree received significantly less emphasis. This approach is anticipated to reduce computing time by minimizing the number of elements within the model. This process was aided by Declan Bale, an engineer in WCL.

The software and method employed for the simulation is due in part to its availability in WCL, but also the success it has had in previous projects within the company. Whilst other simulation packages are available, the availability and success of ProCast means no other simulations were considered.

After meshing the surface and volume of the model, the next task involved inputting the simulation materials, conditions, and parameters. This task was completed using the Visual-Cast module of ProCast. Below is an overview of the simulation conditions:

- 20°C environment temperature – Average ambient temperature in the foundry.
- 1050°C pre-heat temperature – Highest temperature that can be achieved for pre-heat by WCL ovens.
- 1570°C pouring temperature – Customer and literature recommendation.
- 5kg/s pouring rate - Ideal standard within the software and confirmed by (Campbell, 2004) that keeping fluid flow under the critical velocity of the metal will mitigate turbulence, and in turn the likelihood of entrapped oxides.
- Alloy: MAR-M-002 – Material chosen for manufacture, detailed in Section 5.
- Pouring Cone Material: Refractory Alumina – Widely used in WCL.

- Shell Material: Molochite – Widely used in WCL.

4.2 3D printing of Wax

The manufacturing process begins with the creation of a pattern, which has been additively manufactured from PLA, a material readily available and used for prototype work in Wall Colmonoy. PLA stands for Polylactic Acid. It's a biodegradable thermoplastic polymer derived from renewable resources such as corn starch or sugarcane. PLA is one of the most popular materials for 3D printing due to its ease of use, wide availability, and environmental friendliness according to (Arbelaiz et al., 2022).



Figure 16 - Ultimaker 3 Extended 3D Printer.

3D printing allows for rapid iteration and prototyping of wax patterns without the need for expensive and time-consuming tooling. Design changes can be quickly implemented and tested, reducing development time and cost.

Traditional tooling methods require expensive moulds or dies to be manufactured, 3D printing can be a more cost-effective solution, especially for low-volume production runs. There are no tooling costs associated with 3D printing, making it ideal for small batch or custom production.

4.3 Investment casting

4.3.1 Wax room

Multiple patterns are attached to a central wax sprue to form a cluster, also known as a "tree". This arrangement optimizes the use of the ceramic shell and facilitates efficient casting of multiple parts in a single mould. Along with the components, the tree has 2 tensile bars attached, which be used for further material analysis of the poured material.



Figure 17 - Semi-Assembled Tree

4.3.2 Mould room

The assembled trees are then automatically dipped WCL's Robotic Shelling Cell, seen in Figure 18, and coated in a ceramic slurry, which consists of finely ground refractory material called Molochite, suspended in a liquid binder, which has been studied by (Campbell, 2011) and (Horton, 2008) amongst others. After each dip, the wet shell is coated with a fine ceramic stucco to build up the shell thickness. The shell-building process involves multiple layers to achieve the desired thickness and strength. Details as given in Appendix 10.1. WCL has utilised this method for almost 4 decades, resulting in confidence of how the process works.

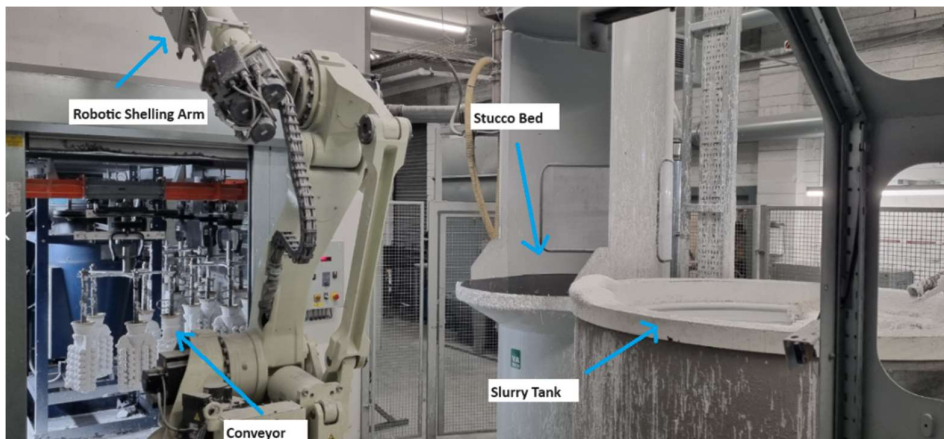


Figure 18 - Robotic Shelling Cell

4.3.3 Dewax

Once the ceramic shell has been built up and dried, it undergoes a dewaxing process to remove the wax pattern from the shell. This is achieved using an autoclave shown in Figure 19. In the autoclave, steam is used to melt and remove the wax at a pressure of 9 Bar leaving behind a cavity in the ceramic.

4.3.4 Pre-Heating

The ceramic trees are then preheated in a furnace to 1050°C for a minimum of 2 hours. This is double what Wall Colmonoy standard practice is for typical, investment cast trees to coincide with research by (Hendricks et al., 1991) and (Krane et al., 1998) which state that a longer duration burn-out will decrease the likelihood of ash residue. Preheating helps to minimize thermal shock and aids to ensure uniform metal flow during the casting process, as well the burning out of any leftover wax residue left behind in the de-waxing process. Figure 20 shows WCL's oven.



Figure 19 – Autoclave (De-Waxer)



4.3.5 Pouring

Figure 19 - Pre-Heat Oven

Once preheated, the ceramic tree is ready to receive the molten metal. The metal is melted in a separate vacuum induction furnace seen in Appendix 10.2 and poured into the preheated ceramic shell through a pouring cup attached to the sprue. Once solid (determined via visible radiant energy emission reduction) the vacuum furnace is opened to further cool the part through air conduction cooling.

The trial parameters mirrored those of the simulation:

- Pre-heating temperature: 1050°C
- Melting temperature: 1570°C
- Foundry temperature: 20°C

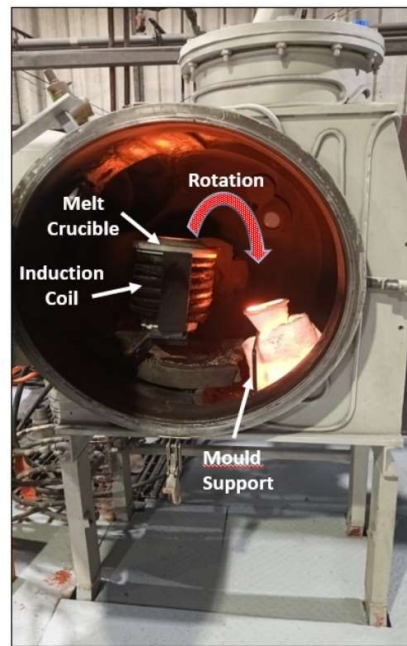


Figure 20 – Open Vacuum Furnace

4.3.6 Knock off.

Once the metal has fully solidified and cooled, depicted in Figure 22, which, obtained from thermodynamic assessment by (Starink & Thomson, 2001) shows the equilibrium of phase present in MAR-M-002 the ceramic shell is removed from the cast part. This is done manually by an operator who uses a small hammer to lightly tap the mould until all ceramic has been removed. Extreme care must be taken as to not damage the components. This was accomplished by adequately training personnel.

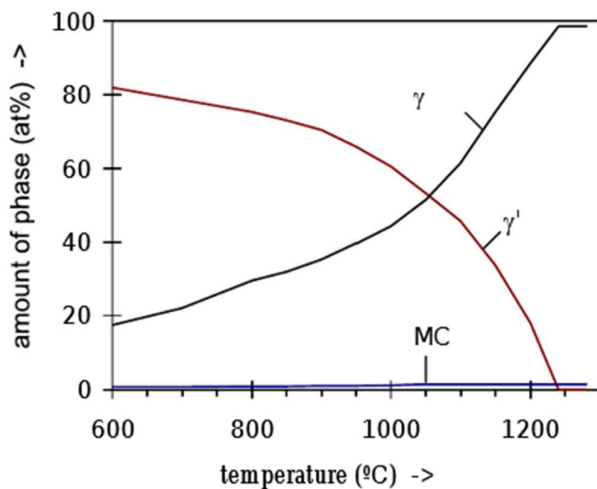


Figure 21 - Phase/Time Relationship Graph

4.3.7 Cut off/Fettling.

The ceramic is removed from the trees and the components are removed from the runner system. The components are then lightly fettled to ensure the feed is flush at a distance and speed sufficient to ensure no significant heat was imparted into the component to make any microstructural changes as detailed by (Nalbant et al., 2007).

4.3.8 Investment Casting Process Flow

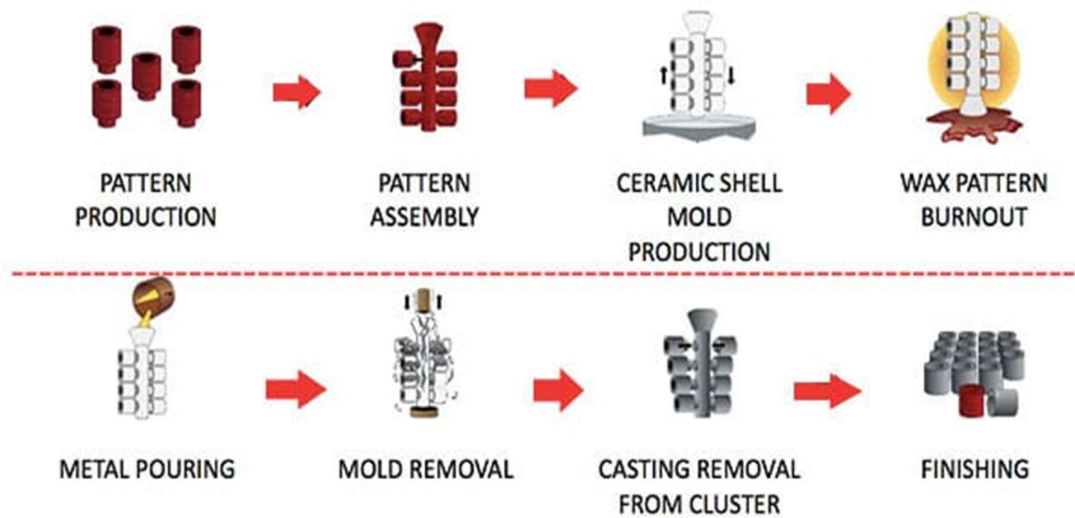


Figure 22 - Investment Casting Process Flow Diagram

4.3.9 Heat Treatment

The components then undergo heat treatment at 870°C for 16 hours, image of the furnace shown in Appendix 10.3. Aging the alloy at 870°C allows for the precipitation of fine secondary phases within the matrix, which increases the strength and hardness of the material according to (Ming, 1995). The prolonged duration of 16 hours ensures sufficient time for the precipitation process to occur and for the precipitates to reach their optimum size and distribution. (El-Bagoury et al., 2008).

4.3.10 Microstructural Analysis

Some of the cast blades are investigated for their corresponding microstructure for comparison to the mechanically tested microstructure of the tensile samples. A blade was sectioned via EDM methods and subsequently ground and polished to a mirror finish. In Figure 24, the areas of interest of the blade aerofoil are clearly indicated.

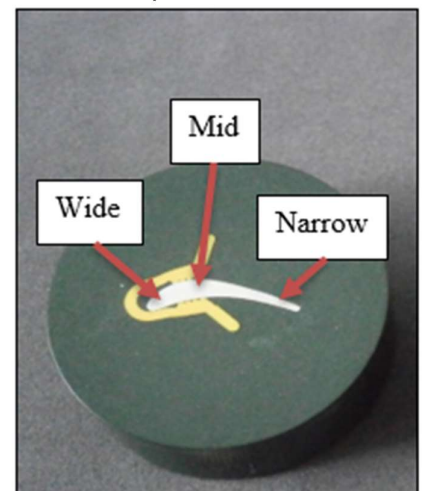


Figure 23 - Cross Section Areas of Interest

4.3.11 Inspection

The parts then had to pass various inspection steps before they could be deemed acceptable. Inspection and testing procedures shall be in accordance with BS.HC100. The processes are listed below:

- Visual Inspection – Trained inspection operators visually inspect each part for any noticeable surface defects. Any noticeable defects classify as a failed part.
- Fluorescent Penetrant Inspection (FPI) - The surface of the part is cleaned to eliminate any impurities. Then, the penetrant is applied to the surface, followed by the removal of excess penetrant. A developer is applied to draw out any trapped penetrant, and the parts are left to dwell for 4 hours, as per customer Acceptance Standard (DXK10396). Indications are carefully observed during inspection, followed by the analysis of results for interpretation and evaluation. The surface is cleaned in readiness for the proceeding inspection steps. A typical FPI part can be seen in Appendix 10.4. Acceptance Standard DXK10396 indicates that surface defects under 500 nanometres(nm) are acceptable.
- Radiographic Testing (X-Ray) – The surface of the part is again cleaned to remove any contaminants that could obscure the X-Ray image. The parts are placed in a chamber where X-rays pass through the material, where a detector captures the X-ray pattern. Trained inspectors analyse the images for defects. A typical x-ray of one of the blades can be seen in Appendix 10.5. Acceptance Standard DXK10396 indicates that subsurface defects under 0.5 micrometres (μm) are acceptable.
- GOM (3D Measuring System) – A 3D scanning system to capture high-resolution, three-dimensional data of the object's surface. The scanner captures data points across the surface of the object, creating a detailed point cloud or mesh representation of its geometry. Multiple scans are performed from different viewpoints, and aligned to create a single, coherent 3D model of the object. Once the 3D data is captured and aligned, it can be analysed using specialized software to extract measurements, compare against CAD (Computer-Aided Design) models, or perform quality control inspections. Only one part from each tree is required for GOM analysis , as per customer Acceptance Standard (DXK10396). A detailed overview of GOM Analysis can be found in Appendix 10.8.

Due to the sensitivity of this project, only a sample of each the inspection details can be provided. Samples can be seen in Appendix 10.4 & 10.5.

Similarly, customer Acceptance Standard (DXK10396) cannot be depicted.

4.3.12 Data Collection

Data has been collected throughout the project and has been collated into spreadsheets and graphs for visual aid. The data was then compared and analysed, resulting in appropriate conclusions.

5. Main Body

The main body of this report details the physical work that was carried out. This section contains material selection, which is followed by the initial trial manufacture, and finally the second trial manufacture which builds on the first trial.

5.1 Material Analysis

In order to manufacture the best possible blade, the correct material had to be selected from two options provided by the customer, Inconel 738LC1 and MAR-M-002. This section investigates these cast materials investigated to inform the decision on the alloy of choice for the future casting of HPT Blades for aerospace engineered components. Through a combination of microstructural examination and mechanical data the study has determined some performance differences of the alloys for further evaluation. A typical cross section of a jet engine can be seen in Figure 25 (Mazurkiewicz & Smolik, 2015).

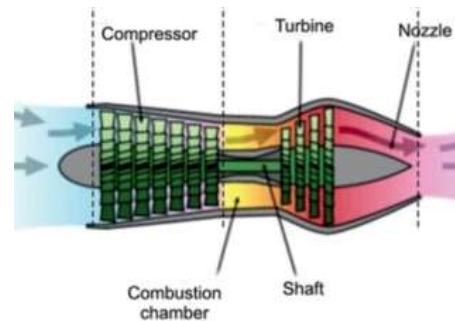


Figure 24 - Typical Turbine Cross-Section

5.1.1 738LC1 and MAR-M-002

Inconel 738LC and MAR-M-002 are nickel-based superalloys that combine the γ/γ' precipitation with additional complex refractory metal carbide precipitation strengthening mechanisms to create alloys that have exceptional high strength and high temperature creep resistance making them indispensable for aerospace engine components, particularly within the hot zones of an operational engine as detailed in Section 3.1. Alloy performance data is required to further inform the design decision. Material properties such as tensile performance in accordance with ASTM E8/E8M-16a Fig.9 (ASTM, 2020) and some guideline microstructural evaluation can be essential when correlating previously known in-service performance of nickel super-alloys and the adherence of previously unapproved manufacturing locations and processes to the tight conditions for successful casting of engine components. Vacuum cast source material was used for the casting trials, the chemical analysis of the source materials can be seen in Table 4. This investigation has included the use of the investment casting process; a low-cost, high-quality method for producing quality, reproducible components in high volume, detailed in Section 3.3, and

vacuum casting to ensure the material composition is retained due to the presence of highly reactive elements.

5.1.2 Method

Precision Vacuum Investment Casting Investment casting of the HPT Blades combined the use of additively manufactured wax parts seen in Figure 26, from the supplied part model file, referred to as HPT Blade, courtesy of Rolls Royce. The design was set by the customer, however modifications for manufacturability were permitted subject to customer approval. In order to ensure the parts had the highest chance of being 100% dense with no cavity fill problems the designed investment tree was simulated using ProCAST software which used finite element analysis and input process parameters such as metal pour temperature and shell temperature at the point of pour to estimate the condition of the parts for their solidification condition. Ensuring the parts are fully filled before solidification begins and the parts are provided liquid metal during the solidification process is essential, and is confirmed by the simulations, see Figure 27.



Figure 25 - 3D Printed Blades

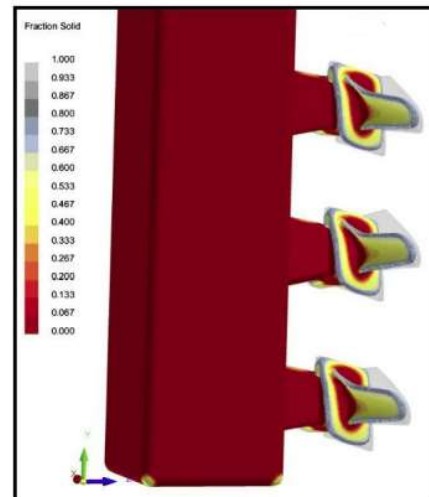


Figure 26 - Initial Material Analysis Simulation

Following the successful qualification of the tree design, complicated given the need for the tensile test bar the blades were assembled onto the designed wax tree, and the shelling; a process by which a thermos-mechanically robust, highly adherent, and smooth, metallurgically inert ceramic material is bound to the outside of the designed material in a designed number of layers. The void space is then created by the autoclave removal of the low melting point wax in order to provide the designed cavity for liquid metal filling, please

see Figures 25 & 26.

		Carbon	Cobalt	Chromium	Molybdenum	Tungsten	Tantalum	Niobium	Aluminium	Titanium
MAR-M-002	Spec	0.13-0.17	9.00-11.00	8.00-10.00	0.5	9.00-11.00	2.25-2.75	<0.1	5.25-5.75	1.25-1.75
	Test value	0.145	9.93	9.02	0.06	9.83	2.665	<0.01	5.57	1.53
Inconel 738LC	Spec	0.09-0.13	3.00-9.00	15.70-16.30	1.50-2.00	2.40-2.80	1.50-2.00	0.60-1.10	3.20-3.70	3.20-3.70
	Nominal	0.11	8.5	16	1.75	2.6	1.75	0.9	3.4	3.4
	Test value	0.077	8.47	15.62	1.71	2.48	1.79	0.82	3.45	3.44
		(Al+Ti)	Boron	Zirconium	Iron	Manganese	Silicon	Sulfur	Hafnium	Nickel
MAR-M-002	Spec		0.01-0.02	0.03-0.08	<0.5	<0.2	<0.2		1.30-1.70	Balance
	Test value		0.015	0.054	0.05	<0.02	<0.01		1.6	
Inconel 738LC	Spec	6.50-7.20	0.007-0.012	0.03-0.08	<0.05	<0.02	<0.3	<0.015		Balance
	Nominal	6.8	0.01	0.05	LAP	LAP	LAP	LAP		(61)
	Test value	6.89	0.01	0.03	0.07	0.01	0.03	<0.001		Bal

Table 4 - Superalloy Chemical Analysis

Each tensile test specimen and HPT Blade was then removed by disc cutting at a distance and speed sufficient to ensure no significant heat was imparted into the component to make any microstructural changes as detailed by (Nalbant et al., 2007). Final inspection of the parts ensured that the fill quality was as expected, certainly in the majority of parts and the materials were suitable to go for further evaluation with no visible casting defects. For this section of the project only, just visual inspection was required, as test specimens were being used for material property analysis.

5.1.3 Tensile Test

Tensile Data Tensile test bars, as-cast, were removed from the process were machined in accordance with ASTM E8/E8M-16a Fig.9, Specimen 1, (ASTM, 2020) results, and comparison to recognised alloy data (INCO, 2020), can be seen in Table 5.

	Vacuum Cast MAR-M-002	
Test	Published Data	Average (3 Replications)
Proof Stress (Rp0.2)	660	855
Tensile Rm	780	913
Elongation/%	14	5
Reduction of area/%	N/A	4
	Vacuum Cast Inconel 738	
Test	Published Data	Average (3 Replications)
Proof Stress (Rp0.2)	951	715
Tensile Rm	1096	868
Elongation/%	5.5	5
Reduction of area/%	N/A	7

Table 5 - Superalloy Tensile Data

The tensile data suggests that the MAR-M-002 has a considerably higher proof stress, Rp0.2, and a marginally higher ultimate tensile test, Rm. The as-cast bars for MAR-M-002 are also returning higher strength data than predicted from the literature. The higher strength returns of the MAR-M-002 comes with a reduction in the elongation values. The Inconel 738LC material has returned test data that is lower than the test data published by (INCO, 2020), but it is consistent to previous test data seen at WCL. Data sheet shown in Appendix 10.6.

5.1.4 Microstructural Analysis

Tensile bar and HPT Blade samples were taken and sectioned to provide test specimens for subsequent metallographic analysis. In each of the alloys the presence of the γ/γ' hardening mechanism can be seen. The lighter areas in the SEM micrographs will be the γ/γ' phase, a hardened Ni₃(Ti, Al) material which gives a characteristic dendritic solidification pattern from the nucleation and growth of crystals of the phase, the darker grey areas are characteristic of the eutectic γ phase which form in between the γ' dendrites due to depletion of the Al/Ti content in the resulting liquid metal and then fast cooling of the generally nickel solid solution

material, Figures 28 & 29 depict the microstructure of MAR-M-002 at x500 & x1500 magnification, respectively

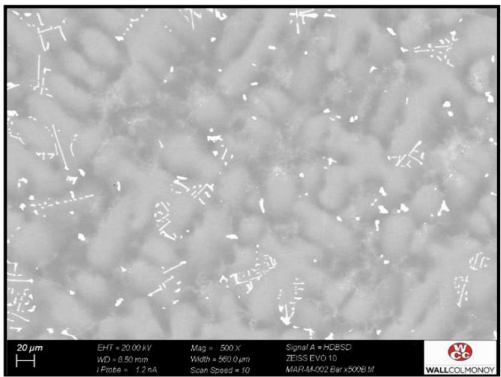


Figure 28 -SEM Image Tensile Bar MAR-M-002 (x500)

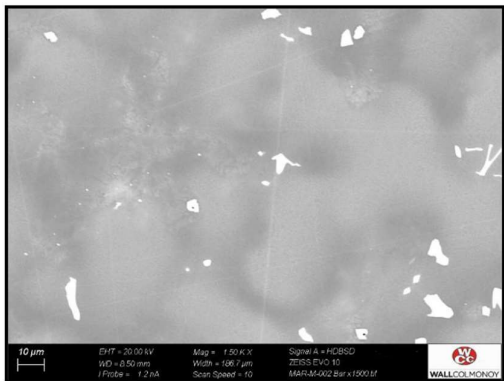


Figure 27 - SEM Image Tensile Bar MAR-M-002 (x1500)

Whilst Figures 30 & 31 depict the microstructure of Inconel 738LC at x500 & x1500 magnification, respectively.

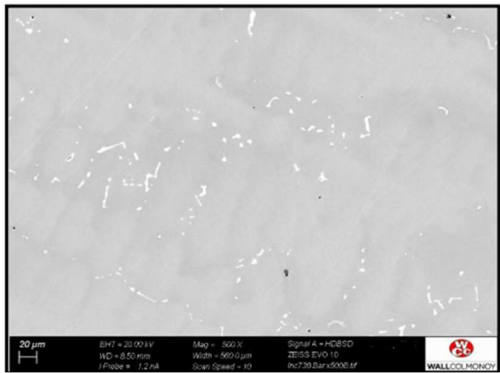


Figure 30 - SEM Image Tensile Bar Inconel 738LC (x500)

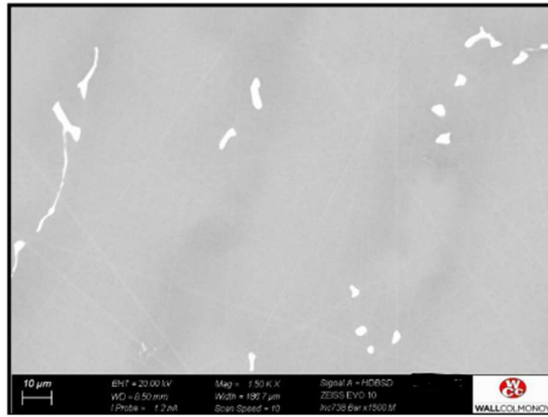


Figure 31 - SEM Image Tensile Bar Inconel 738LC (x1500)

5.1.5 Alloy Selection

After a comprehensive investigation into the performance of Inconel 738LC1 and MAR-M-002 cast materials for high-pressure turbine (HPT) blades in aerospace applications, it has been determined that MAR-M-002 exhibits superior mechanical properties, notably a considerably higher proof stress (Rp0.2) and slightly higher ultimate tensile strength (Rm) compared to Inconel 738LC1 as seen in Table 5. Despite a reduction in elongation values, MAR-M-002 demonstrates higher strength characteristics, surpassing even the literature predictions (INCO, 2020). Additionally, microstructural analysis confirms the presence of the γ/γ' hardening mechanism in both alloys. Given these findings, MAR-M-002 emerges as the preferred material for the future casting of HPT blades, offering enhanced performance and reliability crucial for aerospace engine components operating in high-stress, high-temperature environments. Further evaluation and testing can now proceed with confidence in the selection of MAR-M-002 as the alloy of choice.

5.2 Trial 1

Now that the appropriate alloy, MAR-M-002 has been selected, efforts turn to the first of two trial manufactures.

5.2.1 Aim

The aim of Trial 1 was to prove that the simulations are correct and can be trusted, and that the blades can be consistently made to a high quality. This is in addition to identifying the root cause of any defects found in the components.

5.2.2 Preparation of Simulation

Declan Bale aided with the preparation of the simulation. Focusing on the mesh sizes, the castings were meshed at the minimum of 1mm per element size, with less emphasis on the shell material, and significantly less on the tree itself. This is to reduce the computational time by decreasing the number of elements in the less important areas, and therefore decreasing the calculations required. Table 6 illustrates the mesh sizes implemented.

ID	Name	2D Element Size	Max Solid Element Size	Solid Transition Factor	Solid Shape Factor	Surface/2D Elms(Solid Elms)
1	HPT_Blade	1	10	1	2	0/11108(55513)
2	HPT_Blade	1	10	1	2	0/11108(55527)
3	HPT_Blade	1	10	1	2	0/11108(55486)
4	HPT_Blade	1	10	1	2	0/11108(55534)
5	HPT_Blade	1	10	1	2	0/11108(55527)
6	HPT_Blade	1	10	1	2	0/11108(55466)
7	HPT_Tree	4.11313	14.3116	1	2	0/166298(690220)
8	Shell	1.59312	11.7636	1	2	0/148678(1006492)

Table 6 - Simulation Mesh Sizes

The objectives of the simulation run were then inputted within the software, thermal and flow modules were activated.

5.2.2.1 Simulation Results

The simulation results were positive, showing no shrinkage within the components, implying that there will be no cavities within the castings. The transparent sections show in Figure 32 suggests that the metal has solidified evenly, whilst the purple areas, seen in the centre of the tree depict where the porosity is likely to be present. This simulation has qualified the design to enter production.

5.2.3 Investment casting Costings

The investment casting process was consistent with steps detailed in 4.2 and 4.3.

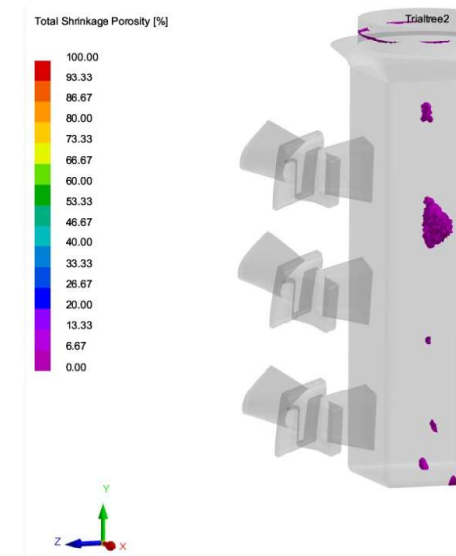


Figure 32 - Trial 1 Shrinkage Simulation

Section Cost:

3D Wax Cost: • Components - £15 (each)

- 6 parts per tree
- 5 trees per batch

10x6x5 = £450 of waxes per batch.

Wax Room/Mould Room/De-Wax = £516 per batch – taken from WCL cost calculator. Figure 33 depicts a fully coated tree ready for de-wax.



Figure 33 – Coated Tree

Pre-Heat/Melting/Pouring = £2500 – taken from WCL cost calculator

Knock-Off/Cut-Off/Fettling = £63 – taken from WCL cost calculator.

Figure 34 depicts a 'knocked off' tree.

Heat Treatment = £500 – taken from WCL cost calculator.



Figure 34 – Poured Tree

5.2.4 Pouring Parameters

Pouring: The trial parameters mirrored those of the simulation:

- Pre-heating temperature: 1050°C
- Melting temperature: 1570°C
- Foundry temperature: 20°C

However, the foundry temperatures deviate slightly from the simulation due to environmental factors. A tolerance of $\pm 10^\circ\text{C}$ is applied to the pre-heat and melting temperatures. Since the environment temperature is uncontrollable, further case studies are necessary to assess the impact of temperature fluctuations on the process. See Section 7.

Trial Run 1	Oven Temp	Time in Oven (Pre- Heat) (m)	Time to heat metal (m)	Metal Temp (°C)	Transport Time (s)	Pour Time
Tree 1	1050°C	120	8.3	1570 $\pm$ 10	5	5kg/s
Tree 2	1050°C	~131	8.15	1570 $\pm$ 10	4	5kg/s
Tree 3	1050°C	~142	8	1570 $\pm$ 10	6	5kg/s
Tree 4	1050°C	~153	7.58	1570 $\pm$ 10	17	5kg/s
Tree 5	1050°C	~164	7.55	1570 $\pm$ 10	5	5kg/s

Table 7 - Trial 1 Pouring Parameters

As seen in Table 7, the oven temperature during burn out remained consistent for the whole trail run, only reducing slightly for a brief moment each time the trees were removed prior to pouring.

The time each tree was kept in the oven at 1050°C from 2 hours (the pre-set minimum) to 2 hours and 44 minutes , over double the standard time detailed in WCL standard working practice, consistent with the recommendations of (Hendricks et al., 1991) and (Krane et al., 1998). This time range was consistent with the time it took to orient the tree in the furnace, melt the material between pours, and remove the tree post pouring. The pour time was consistent at 5kg/s, taking around 2 seconds to pour each tree fully – Consistent with the simulation. The transport time is the time it takes for the tree to be removed from the oven and orientated in the furnace. It was the intention to keep these times as low as possible, whilst maintaining safety standards. Tree 4 however took over 3 times the average time for transportation due to an unforeseen event in the foundry. Appendix 10.7 depicts the route from the pre-heat oven to the furnace.

5.2.5 Microstructural Analysis

Figures 35-38 show the areas of the blade at the locations detailed in Section 4.3.10. The microstructure is most clearly representative of the grain refinement process that is obtained due to the increased cooling rate of the cast aerofoils. The increased cooling rate is obtained due to the reduced liquid metal volume of the part compared to the volume required to produce the tensile bar specimen. The net total energy ($MCp\Delta T$) of the HPT Blade volume of liquid metal is distributed into the surrounding ceramic shell material during the liquid metal fill; bear in mind that once filled the blade material is static, meaning the net cooling rate is significantly increased, before radiant cooling takes over as the dominant cooling mechanism for the metal & ceramic shell system. (Theska et al., 2022) (Dahal et al., 2020) (Selvig et al., 2010)

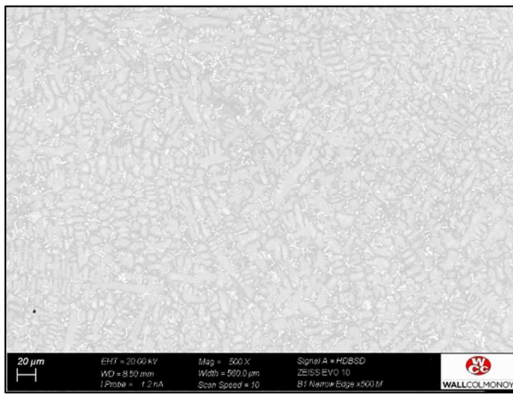


Figure 35 – Trial 1 SEM Image Narrow Edge (x500)



Figure 36 – Trial 1 SEM Image Mid-Section (x500)

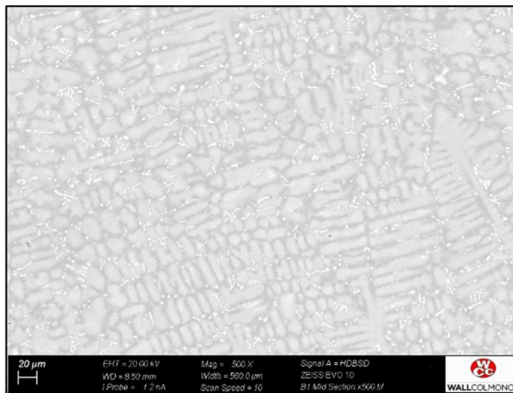


Figure 37– Trial 1 SEM Image Mid-Section (x500) (x1500)

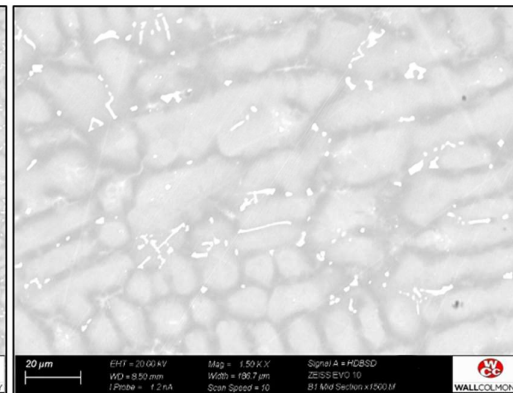


Figure 38 – Trial 1 SEM Image Mid-Section

5.2.6 Inspection

The parts were then sent for visual inspection, followed by FPI, X-Ray and one part from each tree sent for GOM analysis. All of which were previously detailed in section 4.3.11.

The cost for each inspection step is shown below:

- DPI - £10/part
- X-Ray - £40/part
- GOM - £120/part (1 part per tree)

5.2.6.1 Inspection Results

Tree 1: 1 from 6 parts failed inspection, with a subsurface defect over $0.5\mu\text{m}$ being detected by X-Ray. (~17% Defect Rate)

GOM Analysis: Pass

Tree 1	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Pass	Pass
Part 2	Pass	Pass	Pass
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Pass
Part 5	Pass	Pass	Pass
Part 6	Pass	Pass	Fail

Table 8 - Inspection, Trial 1, Tree 1

Tree 2: 2 from 6 parts failed inspection, one showing a surface defect over 500 nm during dye penetrant inspection, and one with a subsurface defect over $0.5\mu\text{m}$ highlighted by x-ray. (33.3% Defect Rate)

GOM Analysis: Pass

Tree 2	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Pass	Pass
Part 2	Pass	Pass	Pass
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Fail
Part 5	Pass	Fail	Pass
Part 6	Pass	Pass	Pass

Table 9 - Inspection, Trial 1, Tree 2

Tree 3: 1 from 6 parts failing on X-Ray, similar to Tree 1. (~17% Defect Rate)

GOM Analysis: Pass

Tree 3	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Pass	Fail
Part 2	Pass	Pass	Pass
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Pass
Part 5	Pass	Pass	Pass
Part 6	Pass	Pass	Pass

Table 10 - Inspection, Trial 1, Tree 3

Tree 4: All parts failed. (100% Defect Rate)

GOM Analysis: N/A – GOM analysis was not carried out for this tree due to complete failure.

Tree 4	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Fail	Fail
Part 2	Pass	Fail	Fail
Part 3	Pass	Fail	Fail
Part 4	Fail	N/A	N/A
Part 5	Fail	N/A	N/A
Part 6	Fail	N/A	N/A

Table 11 - Inspection, Trial 1, Tree 4

Tree 5: All parts passed. (0% Defect Rate)

GOM Analysis: Pass

Tree 5	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Pass	Pass
Part 2	Pass	Pass	Pass
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Pass
Part 5	Pass	Pass	Pass
Part 6	Pass	Pass	Pass

Table 12 - Inspection, Trial 1, Tree 5

5.2.6.2 Analysis

It was evident to see that the increased transit time on Tree 4 had catastrophic results on the quality of each component. Further work must be done, detailed in Section 7, to quantify and understand this phenomenon fully, but this phenomenon is well documented by (DasGupta, 2008) and (Campbell, 2011), who state pouring molten metal into moulds that temperatures are below the solidification temperature of the molten metal before complete filling will lead to cold shut and shrinkage defects. Parts 1-3 all passed a visual inspection, but failed dye penetrant and x-ray tests with surface and sub surface defects.

Trees 1,2 and 3 all had one part fail on X-Ray, and after analysing a sample of each failed part in the lab, it was determined that the sub surface defects were due to ash residue, determined by WCL lab technician Finn Rees. This residue is likely to have been left over from the de-wax and pre-heat process steps according to research conducted by (Hendricks et al., 1991) and (Krane et al., 1998).

Tree 2 also had a part fail during dye penetrant inspection. A microcrack was present on the face of part 5. This could be an outlier; however further investigation will be needed in the future if this type of defect persists. See Future Work Section 9.

Tree 5 has all parts pass each inspection step and meet the customer Acceptance Standard (DXK10396).

The first trial run had a 33.3% defect rate, however 20% of those defects can be directly attributed to the increase transit time for Tree 4.

When Tree 4 was removed from the statistics, the overall defect rate dropped to 16.7%.

Good Parts = 20

Failed Parts = 10.

Overall defect rate for Trial 1 was 33.3%.

5.2.7 Cost of Trial 1

The manufacturing costs were aggregated throughout the process to gain an understanding of the benefit of getting this project right. The cost for the investment casting process, from assembly through to fettling were lifted directly from WCL costing calculator, along with the cost for the heat treatment and DPI, which are both routinely preformed within the company. The 3D printing of the wax blades got its costs from a previous project in WCL, with updated consumable prices. The costs for X-Ray and GOM analysis were both subcontracted out to specialist companies. These costs are detailed in Section 5.2.6.

A breakdown of the costing per batch can be seen below in Table 13

Costing	3D Printing Wax (£)	Assembly / Mould Room (£)	Pre-Heat / Melting / Pouring (£)	Fettling (£)	Heat Treatment (£)	Dye Penetrant (£)	X-Ray (£)	GOM (Dimensional Analysis) (£)	Total Cost (£)	Cost Per Part (£)
Trial 1	450	516	2500	63	500	300	1200	600	6129	204.3

Table 13 - Trial 1 Cost Per Batch

A breakdown of the costings per blade can be seen below in Table 14.

Costing	3D Printing Wax (£)	Assembly/Mould Room (£)	Pre-Heat /Melting /Pouring (£)	Fettling (£)	Heat Treatment (£)	Dye Penetrant (£)	X-Ray (£)	GOM (Dimensional Analysis) (£)	Total (£)
Trial 1	15	17.2	83	2.1	16.7	10	40	20	204

Table 14 - Trial 1 Cost Per Blade

The total cost of manufacture for each blade in Trial 1 was £204.

5.3 Trial 2

The first trial showed that high quality blades could be manufactured, and the simulation results were accurate, with the majority of the components passing the inspection criteria.

5.3.1 Aim

The aim of this trial was to minimise any defects found in Trial 1, whilst simultaneously increasing efficiency.

It was highlighted during the first trial that increasing the transit time for the tree between burn-out and insertion into the furnace had a catastrophic effect of the component's quality. Operators have been instructed to keep this time down to a maximum of 6 seconds, whilst maintaining safety standards, ensuring all walkways are clear, and there is no thoroughfare during the process. The time of 6 seconds was determined by being the next highest time taken in transit which appeared to not have a negative effect on the cast blades. Future work is needed to quantify the exact effect of the cooling rate, detailed in Section 7.

The fact that the trees were not poured 5 seconds after leaving the pre-heat oven, as was stated for this simulation, and were transported into the furnace where the ambient temperature would keep it at an acceptable temperature, albeit an unmeasurable one did not seem to affect the quality of the castings, seen in Section 7.

With the first run being relatively successful, the attention must now be turned to making the process more efficient, and therefore more profitable. To achieve this, it was proposed that the number of components per tree be increased, improving the yield per melt. This however did not come without its complications. To increase the number per tree, a new tree design was required that would accommodate the higher quantity.

The new tree was designed and approved by Declan Bale who modified tried tested trees currently used in WCL by simulating larger versions of these historical trees ensuring an adequate molten metal pool within the body to feed the blades. This new design allowed an increase from 6 parts per tree, to 15 parts per tree, over doubling the output per pour. See Figure 39 and Figure 40 for a comparison between Trial 1 tree, and the new Trial 2 tree.

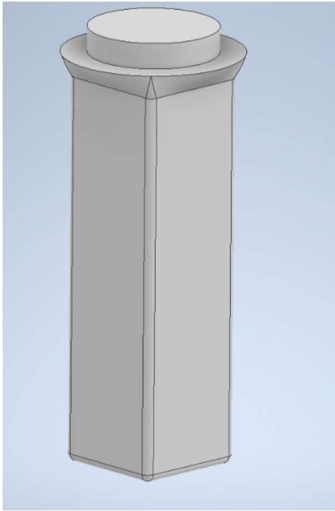


Figure 39 – Trial 1 Tree

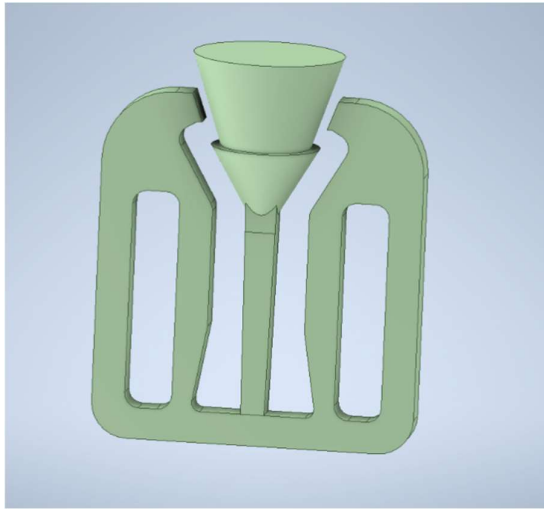


Figure 40 – New Trial 2 Tree

5.3.2 Preparation of the Simulation

Utilising the same methodology as the initial trial, the model underwent meshing in Visual Mesh. The component was meshed with 1mm elements, while larger elements were applied to mesh other volumes. Again, this approach aimed to reduce computational time by decreasing the number of nodes for calculation in the less important areas. Following meshing, materials and parameters were inputted into the Visual Cast module of ProCast, as per Trial 1.

5.3.2.1 Simulation results

As shown in Figure 41, the simulation results were not positive. The purple-coloured area in this image suggests shrinkage porosity in each of the simulated parts. Further evaluation was required to understand the mechanisms of this before any design or process change could take place.

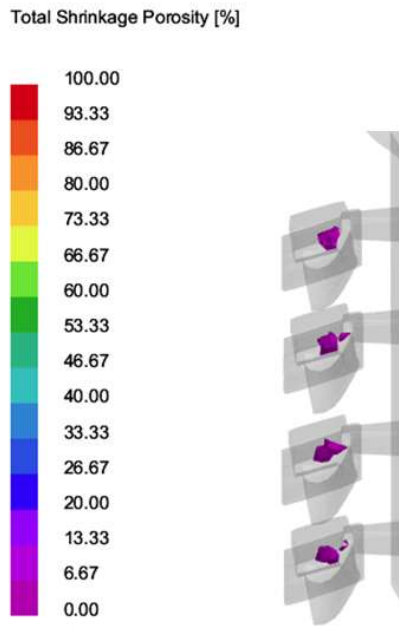


Figure 41 – Trial 2 Initial Shrinkage Simulation

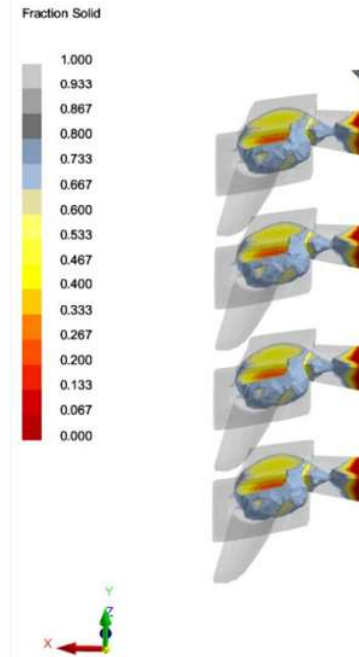


Figure 42 – Trial 2 Initial Fraction Solid Simulation

The solid fraction results illustrated in Figure 42 reveal the molten metal that remains un-solidified within the assembly. Transparent regions in the figures indicate areas where the metal has solidified. The colour scale ranging from grey to red signifies the degree of solidification, with grey indicating closer proximity to solidification than red.

It's evident that the non-solidified sections are segregating from the primary pool of molten metal. Consequently, there exists a region of molten metal within the components that lack sufficient feeding. Consequently, shrinkage is not adequately counteracted through feeding metal, potentially leading to shrinkage porosity within the component.

The Niyama criterion, which detects central line contraction in simulations of directionally solidifying alloys, can be applied in 3D simulations to predict the likelihood of defects such as shrinkage, porosity, or cracking during the casting process (Monroe et al., 2014) (Tavakoli & Davami, 2009).

The simulation considers factors such as temperature gradients, solidification rates, and fluid flow patterns within the mould.

The Niyama criterion can be incorporated into the simulation to predict regions of the casting where solidification may be prone to defects. This is particularly important in areas with

complex geometries or varying wall thicknesses, where cooling rates may vary significantly (Ivanina & Monastyrsky, 2021).

The Niyama criterion can help identify regions of the casting where porosity is likely to occur due to insufficient feeding of molten metal or gas entrapment during solidification (Ivanina et al., 2022). By analysing the local stress and strain conditions seen in Figure 43, the likelihood of porosity formation was predicted and preventive measures such as redesigning gating systems or modifying process parameters can occur.

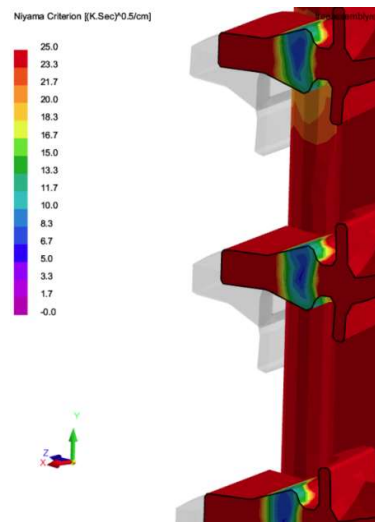


Figure 43 – Trial 2 Niyama Criterion Simulation

5.3.2.2 Updated Blade Design Simulation

The findings were reported to the end customer, who approved a design change of the 3D printed component from side fed to end fed, with a change to feeding system size. As seen in figures 44 & 45, there is a vastly greater taper on the newly designed end fed blade. According to research conducted by (Raza, 2015) and (Piwonka, 2023), making the feed taper wider will aid in reducing shrinkage within a component.

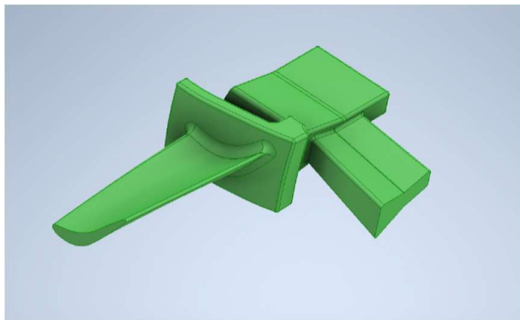


Figure 44 – Old 3D Blade Model

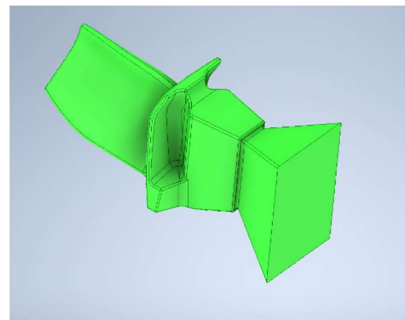


Figure 45 – Updated 3D Blade Model

The first simulation run featuring the newly designed, end-fed parts yielded positive outcomes, agreeing with the literature, as evidenced in Figure 46. Meshing was conducted with consistent element sizes for each component as per previous simulations, maintaining uniform conditions throughout. Notably, there are no purple regions within the components, indicating the absence of shrinkage porosity. The results indicate that the sole area exhibiting purple coloration is the centre of the tree, as anticipated. This intentional design allows for sufficient feeding of the critical component, resulting in a theoretically 'good' casting.

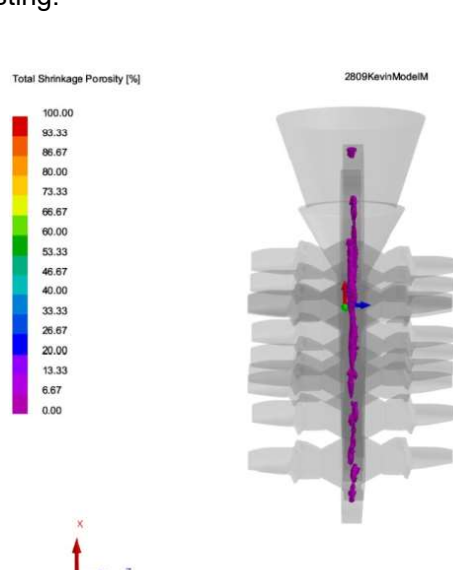


Figure 46 – Trial 2 Updated Shrinkage Simulation

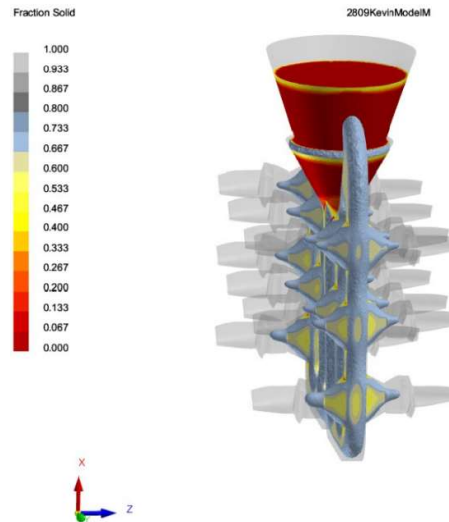


Figure 47 – Trial 2 Updated Fraction Solid Simulation

The solid fraction results demonstrate favourable feeding characteristics. The molten pool within the casting remains adequately fed throughout the solidification process, thereby mitigating shrinkage porosity in the final casting. Please refer to Figure 47 for visual representation.

According to (Campbell, 2004), turbulent flow whilst pouring will likely cause oxide films, which are visibility similar to shrinkage porosity. The velocity magnitude results from the simulation were analysed, the figure shows a purple to red scale, purple being zero metres per second (m/s) to red at 5.5 m/s. It can be seen in Figure 48 that the molten metal pours into the tree at a steady 0.365/s, implying that defects due to turbulent flow will not be

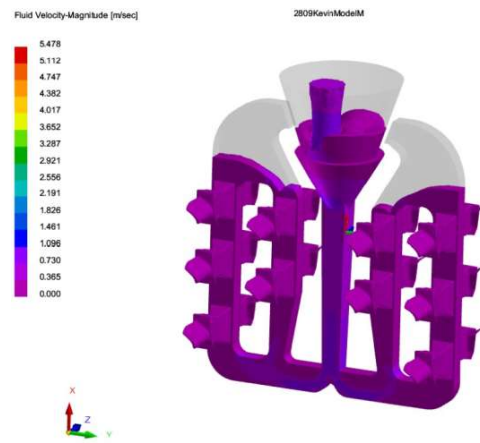


Figure 48 – Trial 2 Velocity Magnitude Simulation

an issue as again, stated by (Campbell, 2004), the critical velocity of the metal is 0.5m/s, after this velocity the metal is likely to have entrapped oxides.

5.3.3 Investment casting Costings

The investment casting process was consistent with steps detailed in 4.2 and 4.3.

Section Cost:

3D Wax Cost: • Components - £15 (each)

- 15 parts per tree
- 5 trees per batch

$15 \times 15 \times 5 = £1125$ of waxes per batch.

Mould preparation remained consistent with Trial 1. Cost = £1050 - Taken from WCL cost calculator.

Pre-Heat/Melting/Pouring = £3000 – Taken from WCL cost calculator.

Knock-Off/Cut-Off/Fettling = £89 – Taken from WCL cost calculator.

Heat Treatment = £500 – Taken from WCL cost calculator.

5.3.4 Pouring Parameters

Pre-Heating - The ceramic trees are then preheated in a furnace to 1050°C for a minimum of 4 hours. The time has been doubled as an attempt to reduce ash defects seen in run one. This is backed by (Hendricks et al., 1991) and (Krane et al., 1998) who state that a longer duration burn-out will decrease the likelihood of ash residue.

Pouring - Once preheated, again the ceramic tree is ready to receive the molten metal. Similar to Run 1, The parameters of the trial were again, run equivalent to the simulation, with a tolerance of $\pm 10^\circ\text{C}$ is placed on the pre-heat and melting temperatures. Again, the environment temperature cannot be controlled.

- Pre-heating temperature: 1050°C
- Melting temperature: 1570°C
- Foundry temperature: 20°C

Trial Run 2	Oven Temp	Time in Oven (Pre- Heat) (m)	Time to heat metal (m)	Metal Temp (°C)	Transport Time (s)	Pour Time
Tree 1	1050°C	240	8.25	1570 ± 10	5	5kg/s
Tree 2	1050°C	~250	8	1570 ± 10	4	5kg/s
Tree 3	1050°C	~260	8	1570 ± 10	5	5kg/s
Tree 4	1050°C	~270	7.59	1570 ± 10	6	5kg/s
Tree 5	1050°C	~280	7.56	1570 ± 10	5	5kg/s

Table 15 - Trial 2 Pouring Parameters

As shown in Table 15, careful attention was given to the transit time between the pre-heat oven and the Vacuum furnace as it was witnessed that the increased time taken for Tree 4 in Trial Run 1 had demonstrably negative effects.

5.3.5 Microstructural Analysis

In the same way as the first trial, a blade was sectioned via EDM methods and subsequently ground and polished to a mirror finish. Figures 49-52 depict the specific regions of the blade under consideration. The microstructure observed therein predominantly reflects the grain refinement process resulting from the heightened cooling rate experienced by the cast aerofoils.

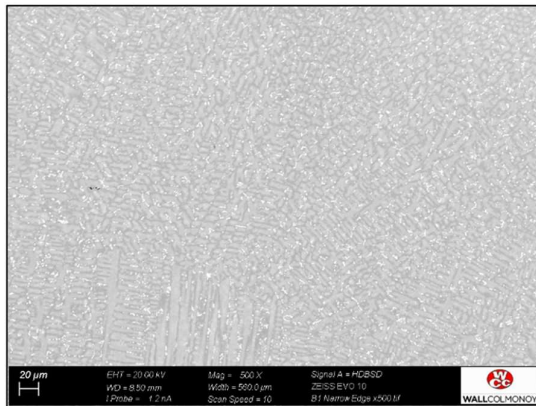


Figure 49 – Trial 2 SEM Image Narrow Edge (x500)

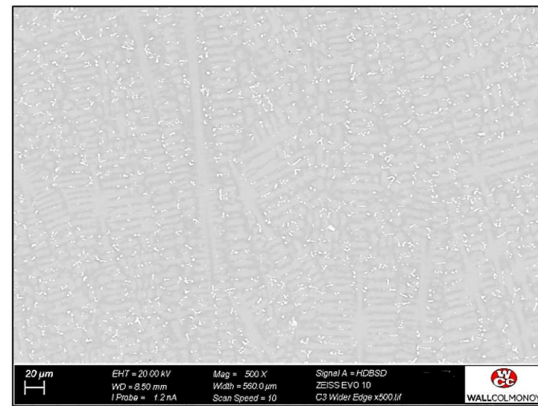


Figure 50 – Trial 2 SEM Image Wide Edge (x500)

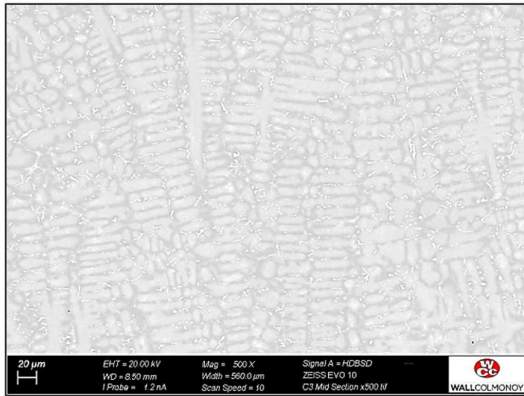


Figure 51 – Trial 2 SEM Image Mid-Section (x500)

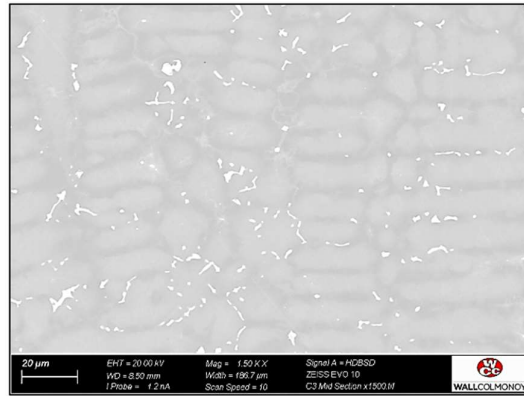


Figure 52 – Trial 2 SEM Image Mid-Section (x1500)

5.3.6 Inspection

The inspection process remained the same as the first trial run, which included visual inspection, LPI (£10/part), X-Ray (£40/part) and GOM analysis for 10% of the blades (£120/part).

5.3.6.1 Inspection Results

Tree 1: 3 from 15 parts failed inspection, one showing a surface defect over 500nm during dye penetrant inspection, and two with a subsurface defect over 0.5µm highlighted by x-ray. (20% Defect Rate).

GOM Analysis: Pass

Tree 1	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Pass	Pass
Part 2	Pass	Pass	Pass
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Pass
Part 5	Pass	Pass	Fail
Part 6	Pass	Pass	Pass
Part 7	Pass	Pass	Pass
Part 8	Pass	Pass	Pass
Part 9	Pass	Pass	Pass
Part 10	Pass	Fail	Pass
Part 11	Pass	Pass	Pass
Part 12	Pass	Pass	Pass
Part 13	Pass	Pass	Fail
Part 14	Pass	Pass	Pass
Part 15	Pass	Pass	Pass

Table 16 - Inspection, Trial 2, Tree 1

Tree 2: 2 from 15 parts failed inspection, one showing a surface defect over 500nm during dye penetrant inspection, and one with a subsurface defect over 0.5µm highlighted by x-ray. (13.3% Defect Rate).

GOM Analysis: Pass

Tree 2	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Pass	Pass
Part 2	Pass	Pass	Pass
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Pass
Part 5	Pass	Pass	Pass
Part 6	Pass	Pass	Pass
Part 7	Pass	Pass	Pass
Part 8	Pass	Pass	Pass
Part 9	Pass	Pass	Fail
Part 10	Pass	Pass	Pass
Part 11	Pass	Pass	Pass
Part 12	Pass	Pass	Pass
Part 13	Pass	Pass	Pass
Part 14	Pass	Pass	Pass
Part 15	Pass	Fail	Pass

Table 17 - Inspection, Trial 2, Tree 2

Tree 3 : 2 from 15 parts failed inspection, one showing a surface defect over 500nm during dye penetrant inspection, and one with a subsurface defect over 0.5µm highlighted by x-ray. (13.3% Defect Rate).

GOM Analysis: Pass

Tree 3	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Pass	Pass
Part 2	Pass	Pass	Pass
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Pass
Part 5	Pass	Pass	Pass
Part 6	Pass	Pass	Pass
Part 7	Pass	Pass	Pass
Part 8	Pass	Pass	Pass
Part 9	Pass	Pass	Pass
Part 10	Pass	Pass	Pass
Part 11	Pass	Pass	Pass
Part 12	Pass	Pass	Fail
Part 13	Pass	Pass	Pass
Part 14	Pass	Pass	Pass
Part 15	Pass	Fail	Pass

Table 18 - Inspection, Trial 2, Tree 3

Tree 4: 2 from 15 parts failed inspection, one showing a surface defect over 500nm during dye penetrant inspection, and one with a subsurface defect over 0.5µm highlighted by x-ray. (13.3% Defect Rate).

GOM Analysis: Pass

Tree 4	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Pass	Pass
Part 2	Pass	Pass	Fail
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Pass
Part 5	Pass	Pass	Pass
Part 6	Pass	Pass	Pass
Part 7	Pass	Pass	Pass
Part 8	Pass	Pass	Pass
Part 9	Pass	Pass	Pass
Part 10	Pass	Pass	Pass
Part 11	Pass	Fail	Pass
Part 12	Pass	Pass	Pass
Part 13	Pass	Pass	Pass
Part 14	Pass	Pass	Pass
Part 15	Pass	Pass	Pass

Table 19- Inspection, Trial 2, Tree 4

Tree 5: 1 from 15 parts failed inspection, one showing a surface defect over 500nm during dye penetrant inspection. (7% Defect Rate).

GOM Analysis: Pass

Tree 5	Visual Inspection	Dye Penetrant	X-Ray
Part 1	Pass	Fail	Pass
Part 2	Pass	Pass	Pass
Part 3	Pass	Pass	Pass
Part 4	Pass	Pass	Pass
Part 5	Pass	Pass	Pass
Part 6	Pass	Pass	Pass
Part 7	Pass	Pass	Pass
Part 8	Pass	Pass	Pass
Part 9	Pass	Pass	Pass
Part 10	Pass	Pass	Pass
Part 11	Pass	Pass	Pass
Part 12	Pass	Pass	Pass
Part 13	Pass	Pass	Pass
Part 14	Pass	Pass	Pass
Part 15	Pass	Pass	Pass

Table 20 - Inspection, Trial 2, Tree 5

5.3.6.2 Analysis

As seen in the above Tables 16-20, none of the components failed visual inspection or dimensional analysis. There was however 10 individual parts which failed to meet the quality criteria as per customer Acceptance Standard (DXK10396).

5 parts from the 75 manufactured parts has subsurface defects highlighted via X-Ray inspection. These parts were again analysed in the laboratory by Finn Rees, and just as seen in Trial 1, ash residue was found internally within the parts. This is a 7% defect rate. An X-ray image can be found in Appendix 10.5.

5 parts from 75 parts failed Dye Penetrant (LPI) inspection. Again, similar to Trial 1, these parts all exhibited a microcrack on the surface of the blade. These defects have persisted

through both trials implying that there must be a root cause, which will require further work to identify, seen in Section 7. An example of LPI can be seen in Appendix 10.

Good Parts = 65

Failed Parts = 10

Overall defect rate 13.3%.

5.3.7 Cost of Trial 2

Again, the costs for the manufacture of the new and improved blades and tree were calculated in the same manner as Sections 5.2.6 & 5.2.7.

A breakdown of the costing per batch can be seen below in Table 21.

Costing	3D Printing Wax (£)	Assembly/Mould Room (£)	Pre-Heat /Melting /Pouring (£)	Fettling (£)	Heat Treatment (£)	Dye Penetrant (£)	X-Ray (£)	GOM (Dimensional Analysis) (£)	Total (£)
Trial 2	15	14	40	1.2	6.7	10	40	12.8	134.9

Table 21 - Trial 2 Cost Per Batch

A breakdown of the costing per blade can be seen below in Table 22.

Costing	3D Printing Wax (£)	Assembly / Mould Room (£)	Pre-Heat / Melting / Pouring (£)	Fettling (£)	Heat Treatment (£)	Dye Penetrant (£)	X-Ray (£)	GOM (Dimensional Analysis) (£)	Total Cost (£)	Cost Per Part (£)
Trial 2	1125	1050	3000	89	500	750	3000	900	10114	134.853

Table 22 - Trial 2 Cost Per Blade

The total cost of manufacture for each blade in Trial 1 was £134.90.

6. Discussion

6.1 Comparison of Trial Results

6.1.1 Quality

As depicted in Figure 53, there was a clear improvement in quality between the trial runs. The blue bars represent Trial 1, and the red bars represent Trial 2.

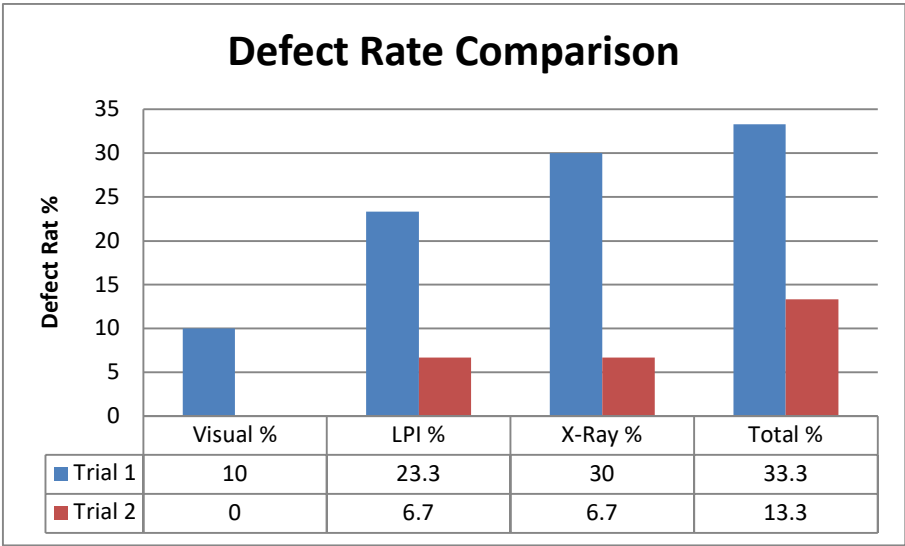


Figure 53 – Defect Rate Comparison

6.1.1.1 X-Ray

There was almost a 4.5 times improvement in the sub service defect rate caused by residual ash trapped within the trees prior to pouring. These results further confirm research conducted by (Hendricks et al., 1991) and (Krane et al., 1998), which state that longer burn-out/pre-heat can help mitigate this type of defect. Although a vast improvement was seen, the problem still persists, albeit in a lower frequency. Research conducted by (Krane et al., 1998) states that poor quality wax can be a cause of ashy residue.

6.1.1.2 Dye Penetrant

Again, there was an improvement with the defect rate between both trials. No controls were put in place to mitigate the micro cracks seen from trial 1, but the persistence of these infers there is a root cause. Research by (Wang et al., 2013), and more recently by (Mandolini et al., 2023) states that weak adhesion between layers in the 3D printed wax patterns can

result in delamination, where layers separate from each other. Delamination can lead to dimensional inaccuracies and surface roughness with the steps between the filament layers potentially leading to stress concentrations when the metal is contracting once poured into the casting.

6.1.1.3 Visual Inspection

A total of three parts failed visual inspection over the course of both the trials, with all of these coming from Tree 4, Trial 1, as to which the reason was confirmed as the increased transit time between pre-heat and pouring, which allowed the mould to cool to below the solidification temperature of the molten metal before complete filling (DasGupta, 2008) and (Campbell, 2011). Future work is required understand and quantify this fully. Detailed in Section 7.

6.1.2 Costing

As show in Figure 54, increasing the number of parts per tree decreases the production costs from £204/part, in Trial 1, to £134.9/part in Trial 2, which was almost a 34% decrease. The red line depicted in the graph represents Trial 2, and clearly indicates less cost per part throughout most of the process steps. It is important to note that GOM analysis was conducted at one part per tree for Trial 1, and at 10% for Trial 2. Moving forward the GOM analysis will always be conducted at a 10% of manufactured parts rate, as per customer acceptance standards.

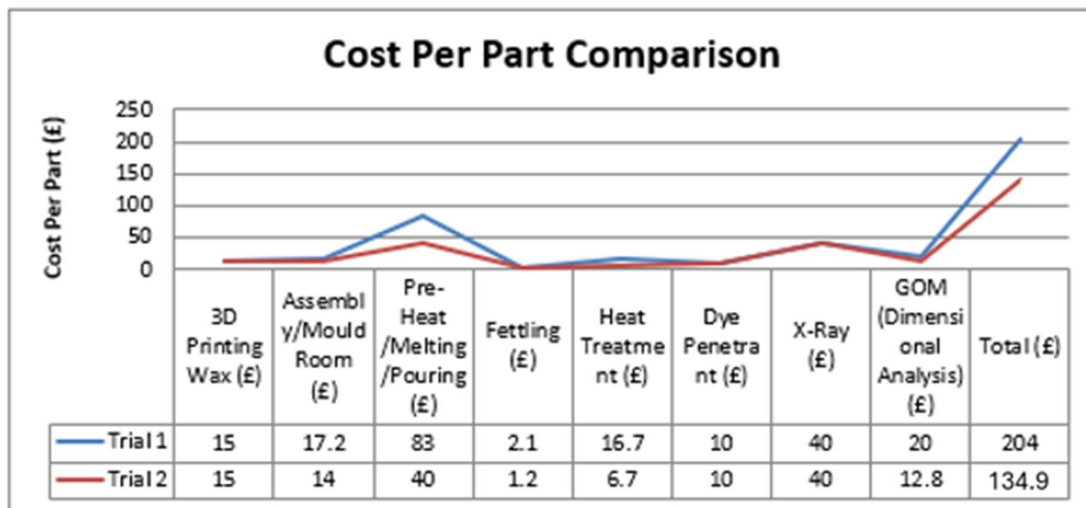


Figure 54 – Cost Per Part Comparison

Table 23 shows the hypothetical total profit made by each Trial*. Trial 1 made £96 per part, and a total of £2,880 profit, which is a margin of 32%. Trial 2 made £165.1 per part, and a total of £12,382.50 profit, which is a margin of 55%. It is important to note that these figures are calculated at a 0% defect rate, so do not consider any scrap parts. Although this would be ideal, the nature of investment casting there is always a likelihood some sort of defect failure within the process.

Target Price £300					
	Cost Per Part (£)	Total Cost (£)	Profit Per Part	Profit %	Total Profit
Trial 1 (x30 Parts)	204	6120	96	32%	2880
Trial 2 (x75 Parts)	134.9	10125	165.1	55%	12382.5

Table 23 - Hypothetical Manufacturing Profit

***Trials are made up of different batch sizes, so profit is not directly proportional.**

Table 24 depicts the actual costs of each trial with defects accounted for. It paints a different picture to Table 23 which highlights the importance of keeping defects to as close to zero as possible. With the failed parts accounted for Trial 1, made -£120 loss. This however being a development project, the lessons learnt from this trial will go on to improve future projects.

Trial 2, however still managed to maintain a healthy 48% profit margin.

Target Price £300										
	Cost Per Part (£)	Total Cost (£)	Parts (Good)	Parts (Fail)	Defect Rate	Total Cost of Parts (Good) (£)	Total Cost of Parts (Fail)(£)	Total Selling Price of Parts (Good) (£)	Total Profit (£)	Final Trial Margin
Trial 1 (x30 Parts)	204	6120	20	10	33.30%	4080	2040	6000	-120	-2%
Trial 2 (x75 Parts)	134.9	10125	65	10	13.30%	8768.5	1349	19500	9375	48%

Table 24 - Actual Manufacturing Profit

6.1.2.1 Cost of Project

The total cost of manufacture for this project was £16,245. This figure covers the manufacturing exclusively, and does not cover the time of contributors, simulations, and material analysis. These areas that were not covered in the manufacture costs were covered by the customers NRE activities.

With the total manufacturing costs of £16,245, and the total selling price of the blades of £25,500, this project made a manufacturing profit of £9,255.

7. Conclusion

This report has undertaken a comprehensive analysis of investment casting processes, with a specific focus on enhancing the quality and efficiency of manufacturing High-Pressure Turbine (HPT) Blades. The aims and objectives set forth at the outset of this research have guided the exploration of various aspects of investment casting, from material selection to process optimization and defect mitigation.

Throughout this study, a thorough analysis of potential materials for HPT blade manufacturing was conducted, leading to the selection of the appropriate alloy for production. MAR-M-002 stood out as the most appropriate material for future HPT blade casting, delivering superior performance and reliability essential for aerospace engine components functioning in demanding high-stress, high-temperature environments.

By establishing key parameters within the investment casting process, including pour temperature, which did not differ for the literature and simulation research, pour rate which remained at the recommended rate of the simulation at 5kg/s, and gating design which required optimisation which increased the taper allowing better feeding of the blades resulting in reduced shrinkage. The most significant parameter that was established was the transit time between pre-heat and insertion into the furnace. It was demonstrated that the increased transit time, which resulted in an increased cooling rate had a negative effect on the blades, which agreed with the literature. With establishing these parameters significant strides have been made towards standardizing and optimizing the manufacturing route for HPT Blades.

The investigation into root causes of defects within manufactured parts has provided valuable insights for defect mitigation strategies. Despite the inherent challenges associated with investment casting, particularly in the production of complex components like HPT Blades, continuous improvement initiatives have been identified and implemented to reduce defect rates and enhance overall quality.

The increased pre-heat time positively affected the rates of ash residue found within some of the blades, which agreed with the literature. However, some defects did persist, such as microcracks on the surface of some blades, as well as residual ash within the blades, although the latter was greatly reduced once the mitigation detailed previously had been put in place.

Future work is required to try and eliminate these defects altogether, potentially by changing the type of wax used and transitioning away from 3D printed waxes to more traditionally

created waxes, involving tried and tested patternmaking with a traditional aluminium tool. This approach would incur a large upfront cost but would eliminate defects caused by delamination of layers that sometimes occur during 3D printing.

The comparison between Trial 1 and Trial 2 reveals a notable enhancement in quality across various inspection methods. The analysis of X-Ray results indicates a significant reduction in the occurrence of sub-surface defects attributed to residual ash, albeit with some lingering issues suggesting the need for further investigation into wax quality.

Similarly, the improvement observed in dye penetrant testing highlights progress in addressing micro-cracks, although the persistence of these defects underscores the importance of addressing root causes such as weak adhesion in 3D printed wax patterns. Visual inspection identified specific challenges related to cooling times during the casting process, particularly evident in Trial 1.

While three parts failed visual inspection, the understanding of the root causes, as highlighted by previous research, lays the groundwork for future improvements in process control and optimization. Overall, these findings underscore the iterative nature of process improvement and the necessity of continuous research and development efforts to enhance quality and efficiency.

The analysis of Trials 1 and 2 provides valuable insights into the cost dynamics and profitability of the manufacturing process. The transition from Trial 1 to Trial 2 illustrates a significant improvement in production efficiency, as evidenced by the substantial decrease in cost per part and the corresponding increase in profit margins.

The comparison between the theoretical profits depicted in Table 22 and the actual profit detailed in Table 23 emphasizes the critical importance of minimizing defects in the manufacturing process. While Trial 1 incurred losses due to a relatively high defect rate, Trial 2 managed to maintain a healthy profit margin despite some defects, underscoring the resilience of the improved production strategy.

The evaluation of project costs, including manufacturing expenses and selling prices, reveals a significant manufacturing profit of £9,255. Although this figure does not encompass all project related NRE expenditures, it highlights the overall success of the manufacturing endeavour.

By addressing these objectives, this report not only contributes to the advancement of investment casting processes but also holds implications for broader industrial applications. The findings and recommendations presented herein serve as a valuable resource for Wall

Colmonoy Limited (WCL) and other stakeholders in the aerospace industry, offering a roadmap for achieving consistent quality, reliability, and efficiency in the production of critical components.

Looking ahead, further research and development efforts are warranted to build upon the insights gained from this study. Continued collaboration between academia, industry, and research institutions will be essential in driving innovation and pushing the boundaries of investment casting technology. With a steadfast commitment to continuous improvement and a focus on excellence, the aerospace manufacturing sector can continue to meet the evolving demands of the global market while ensuring the highest standards of quality and performance in its products.

This report represents a significant step forward in WCL's quest for excellence in investment casting processes, laying the foundation for future advancements, and reaffirming the importance of rigorous research and innovation in shaping the future of aerospace manufacturing, and becoming a trusted supplier within the industry.

7. Future work

While this dissertation has made significant strides in establishing a repeatable and reliable route for manufacturing high-pressure turbine (HPT) blades, there are several avenues for future research and improvement.

1. Material Optimization: Further investigation into potential materials for HPT blade manufacturing can enhance performance and durability. Exploring novel alloys or composite materials may offer superior mechanical properties, thermal resistance, and corrosion resistance, contributing to the overall efficiency and longevity of turbine engines.

2. Process Parameter Refinement: Continuous refinement of key parameters within the investment casting process is essential for optimizing efficiency and quality. Fine-tuning parameters such as pour temperature, pour rate, and gating design can minimize defects and improve yield rates, ultimately reducing production costs and enhancing component quality. Particular focus is to be spent on transit time between pre-heat oven and furnace. The literature had stated that pouring molten metal into moulds that temperatures are below the solidification temperature of the molten metal before complete filling will cause defects such as porosity, shrinkage, and cold shut. Heat transfer calculations will need to be done to quantify the rate of temperature loss to gain insights on how long the pre-heated moulds can be subjected to atmospheric temperatures before cooling to a critical temperature. Specialist equipment can also be used to measure the temperature differences.

3. Defect Analysis and Mitigation: Identifying root causes of defects within manufactured parts and implementing effective mitigation strategies remain ongoing priorities. Utilizing advanced inspection techniques, such as non-destructive testing and advanced imaging, can provide deeper insights into defect mechanisms, enabling targeted improvements in manufacturing processes and materials. A focused on completely removing the surface and subsurface defects found within the trials. An investigation into wax materials can be done to remove ash residue defects, after significant strides were made in reducing the defects by following the literature and increasing the burn-out time.

4. Potential for physical tooling: The potential for physical tooling will be explored, which will remove the reliance on 3D printed waxes, and eliminate any defects that have been associated with them. A cost benefit analysis is to be completed to assess the viability of this option.

5. Collaborative Research Initiatives: Collaboration with industry partners, research institutions, and regulatory bodies can foster innovation and knowledge exchange in

aerospace engineering. Participating in collaborative research initiatives can provide access to specialized expertise, resources, and funding opportunities, accelerating advancements in HPT blade manufacturing and aerospace propulsion technology.

8. References

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10. Appendix

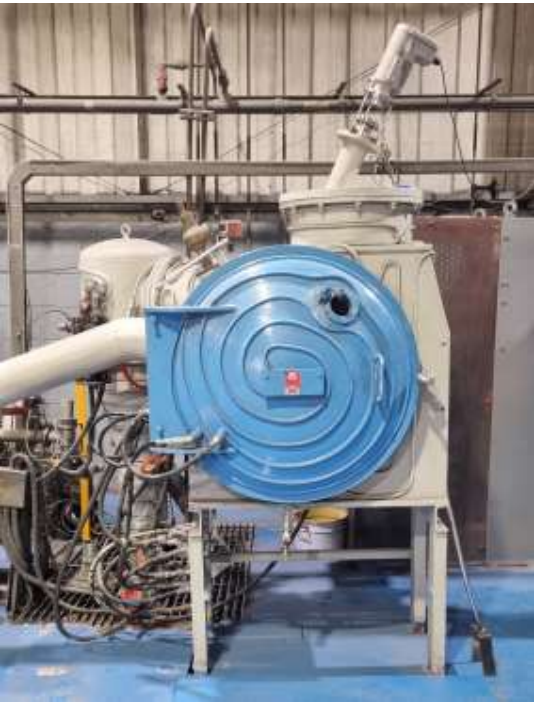
10.1 Slurry Properties



The slurry properties recorded below meet the requirements for mould production

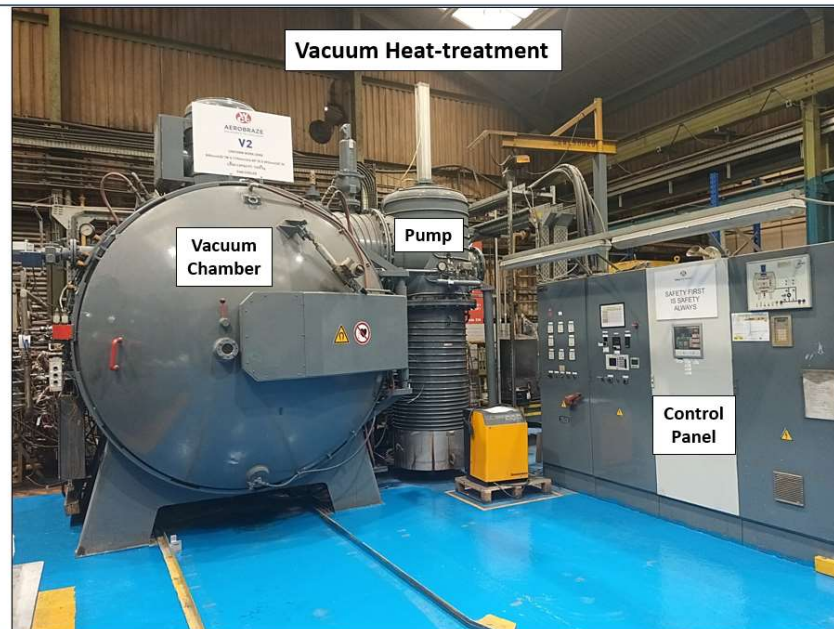
Test	Slurry Type		
	Prime	Intermediate	Back-up
Elco #5 Viscosity (s) :	16.4	12	13
Density (g/ml):	3.17	1.66	1.69
pH:	9.38	9.62	9.74

10.2 Vacuum Induction Furnace

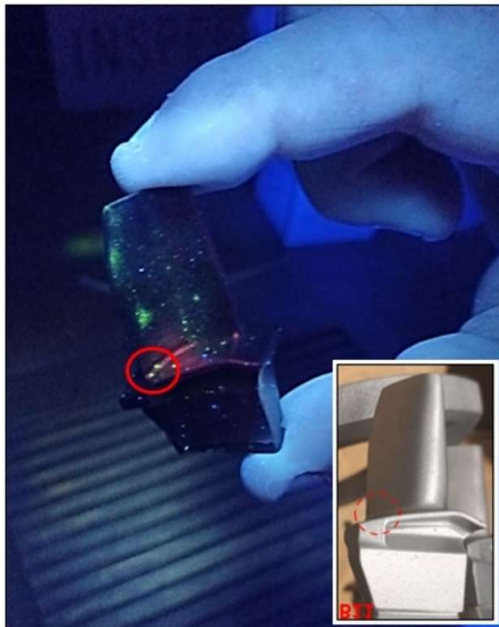


10.3 Vacuum Heat Treatment

Precipitation Heat Treatment: 870°C for 16hrs



10.4 Dye Penetrant Inspected Blade



10.5 X-Ray Inspected Blade



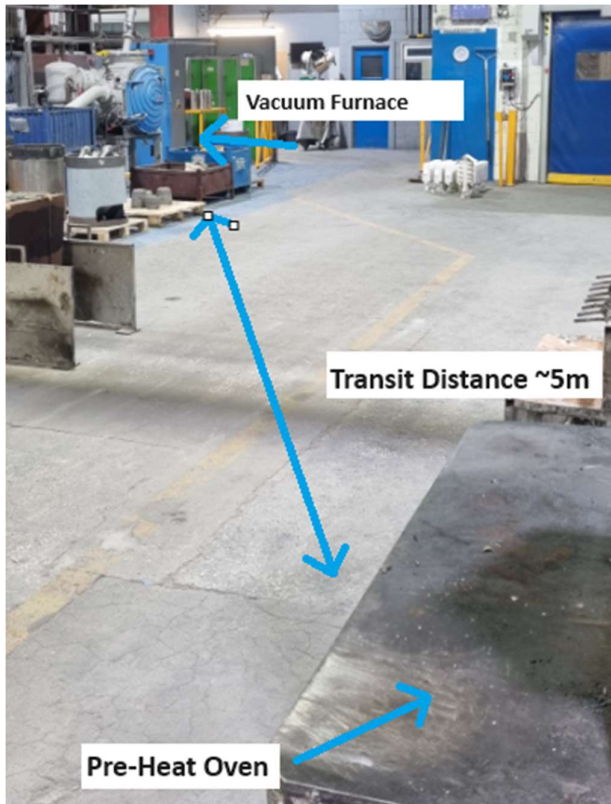
10.6 Inconel Data Sheet

TABLE VII Short-Time Elevated Temperature Tensile Properties of Alloy IN-738				
Temperature °F	Yield Strength (0.2% Offset) psi	Tensile Strength psi	Elongation (2 in.) %	Reduction of Area %
70	138,000	159,000	5.5	5
1200	132,000	153,000	7	7
1400	115,000	140,000	6.5	9
1600	80,000	112,000	11	13
1800	50,000	66,000	13	15

TABLE VIII Stress-Rupture Properties of Alloy IN-738C				
Temperature °F	Stress psi	Life hr	Elongation %	Reduction of Area %
1350	90,000	212	6	8
1500	40,000	3314	5	5
1700	33,000	95	8	14
1800	22,000	66	12	18

TABLE IX Stress-Rupture Properties of Alloy IN-738				
Temperature °F	Low Carbon IN-738LC		High Carbon IN-738C	
	Stress, psi, for Rupture in		Stress, psi, for Rupture in	
	1000 hr	10,000 hr	100 hr	1000 hr
1350	80,000	62,000	96,000	78,000
1500	46,000	33,000	66,000	48,000
1700	19,000	12,000	31,000	20,000
1800	12,000	7,000	19,000	12,000

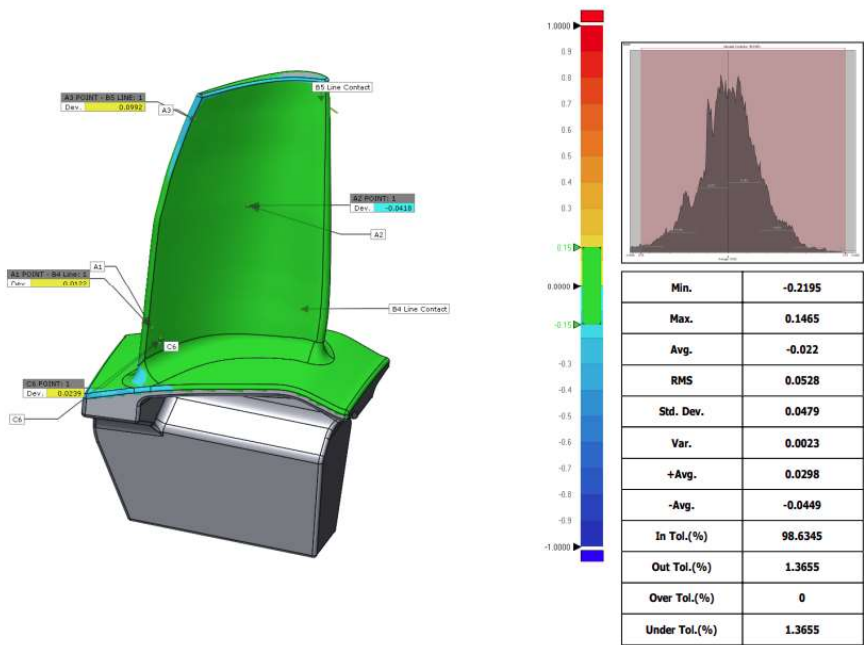
10.7 Transit Route



10.8 GOM Analysis

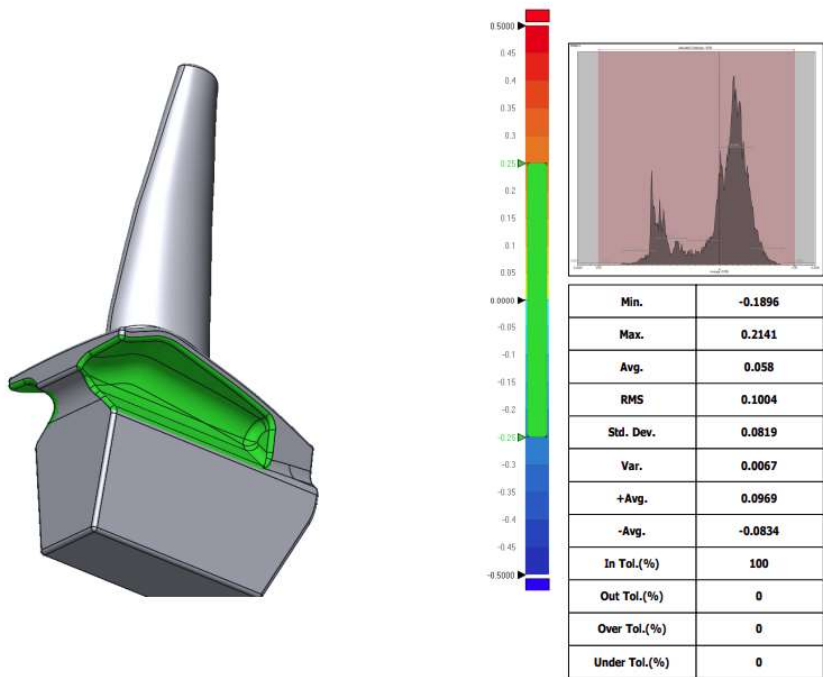
10.8.1 Cast HPT Blade

Cast HPT Blade : Blade I



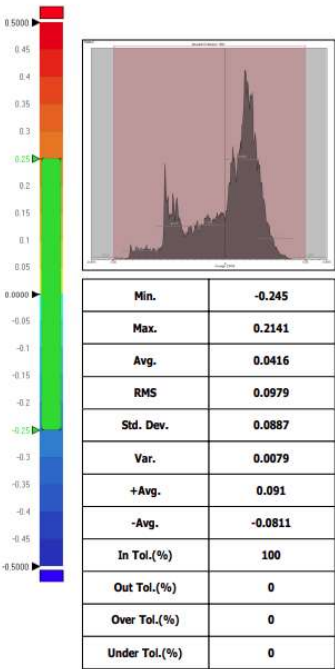
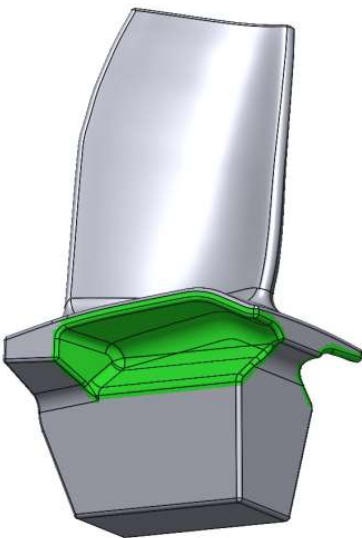
10.8.2 Middle A

Cast HPT Blade : Middle A



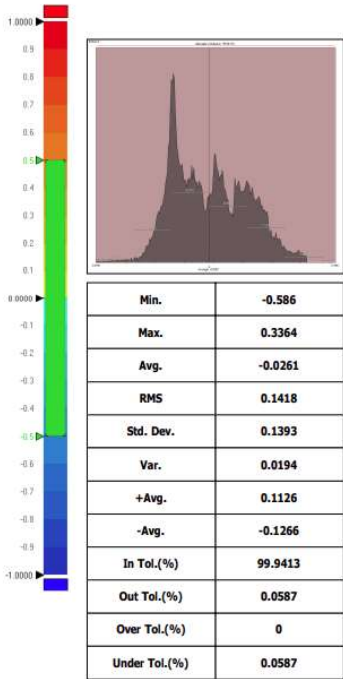
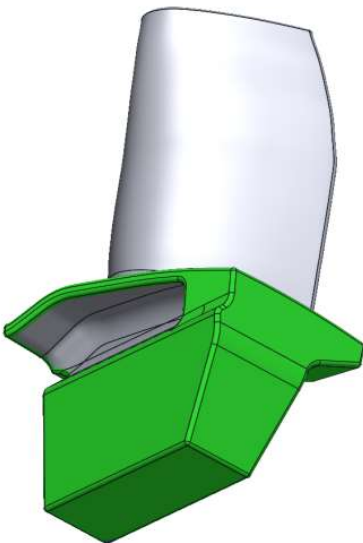
10.8.3 Middle B

Cast HPT Blade : Middle B



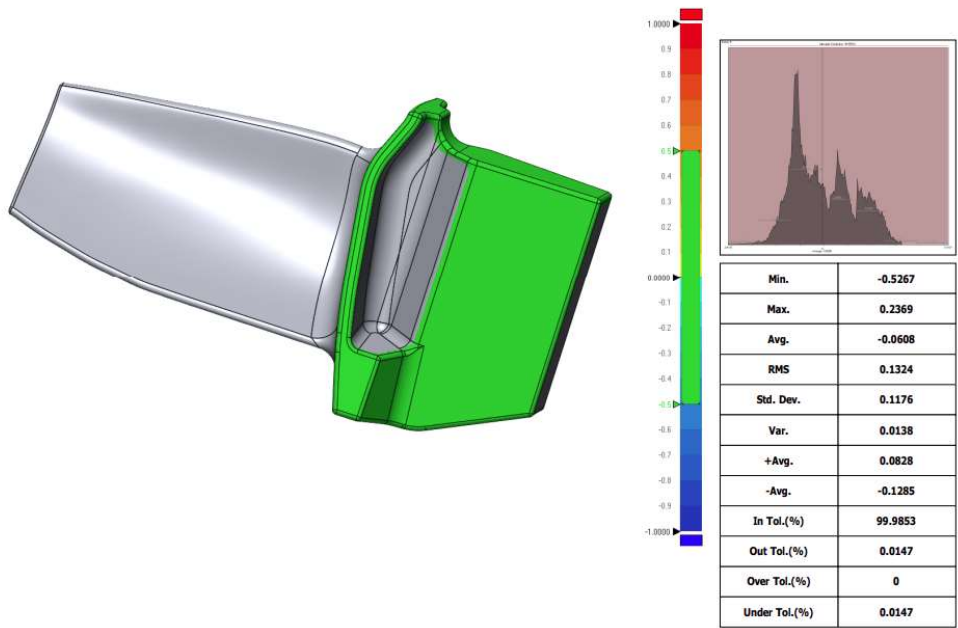
10.8.4 Bottom A

Cast HPT Blade : Bottom A



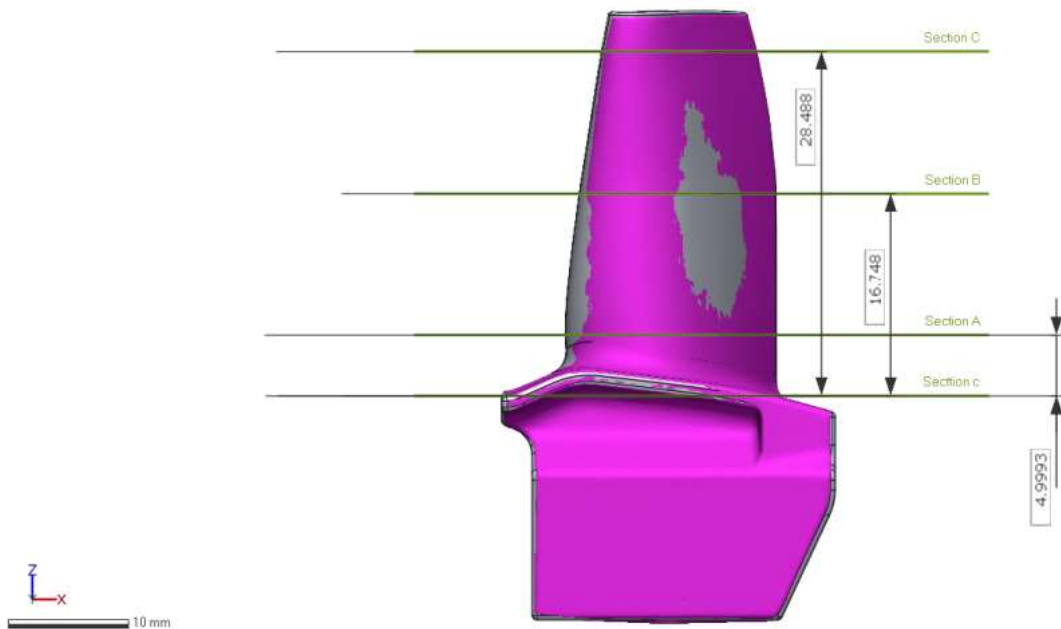
10.8.5 Bottom B

Cast HPT Blade : Bottom B



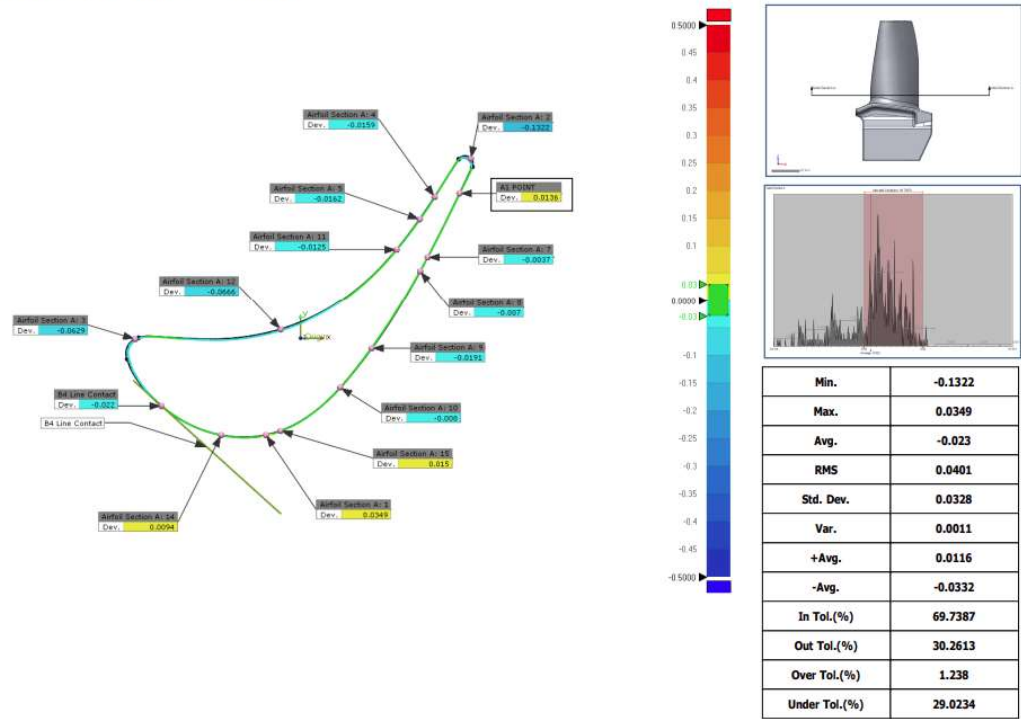
10.8.6 Planes A,B,C

Cast HPT Blade : Planes A, B, C



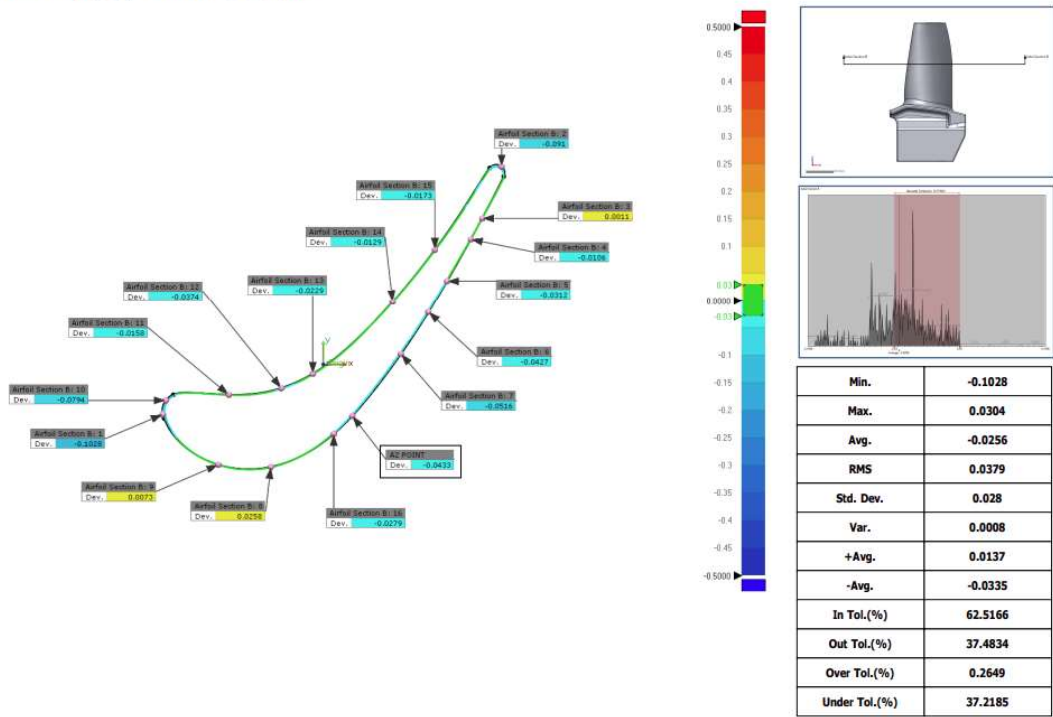
10.8.7 Airfoil Section A

Cast HPT Blade : Airfoil Section A



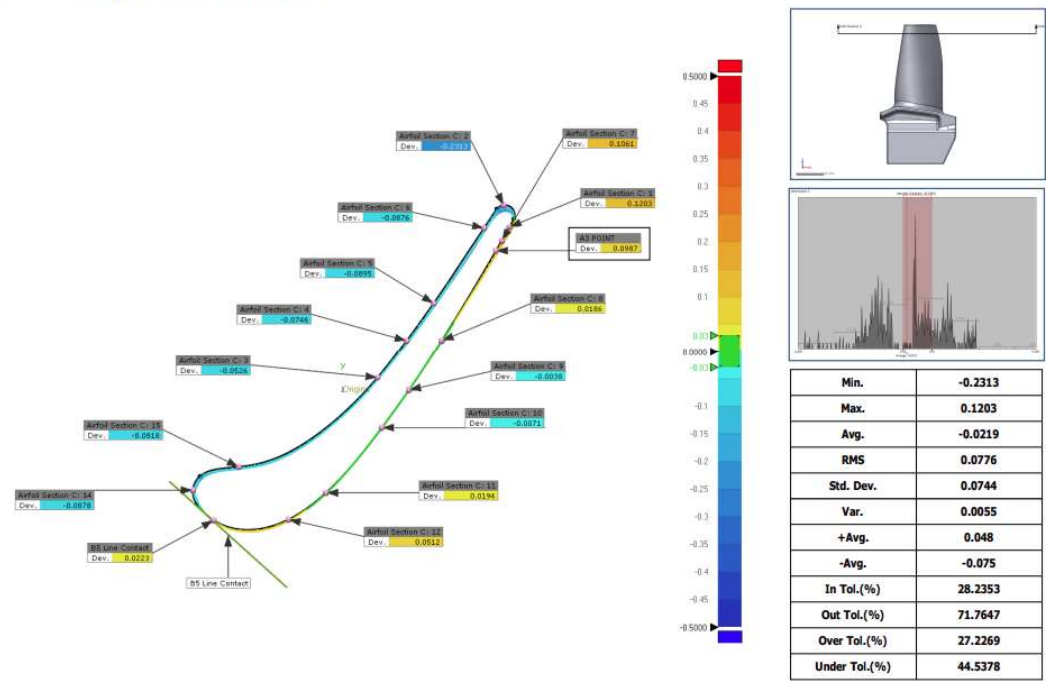
10.8.8 Airfoil Section B

Cast HPT Blade : Airfoil Section B



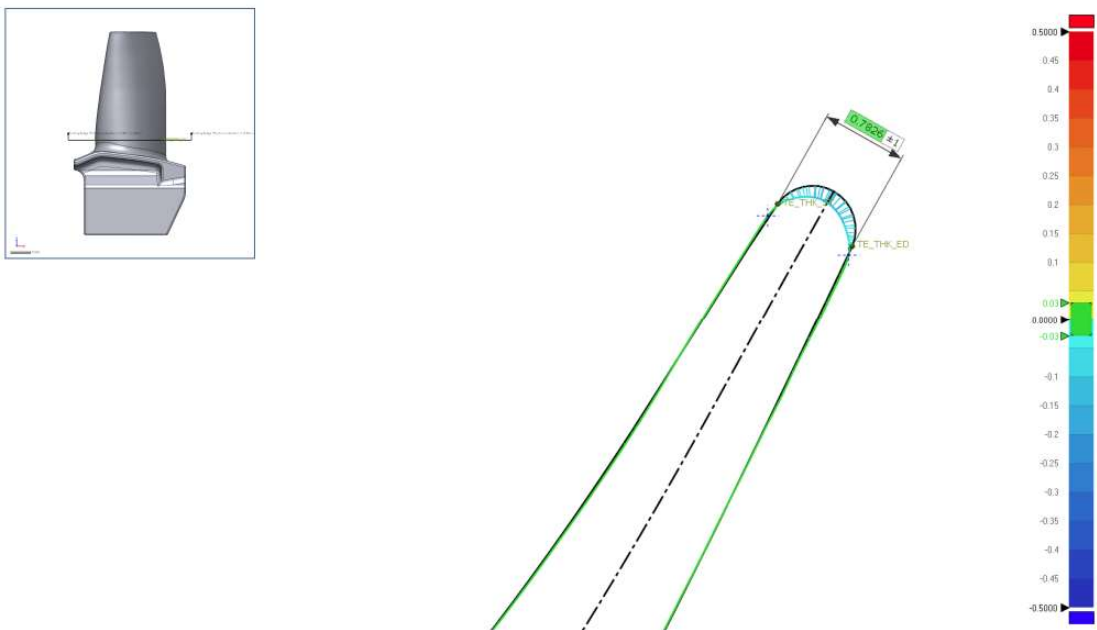
10.8.9 Airfoil Section C

Cast HPT Blade : Airfoil Section C

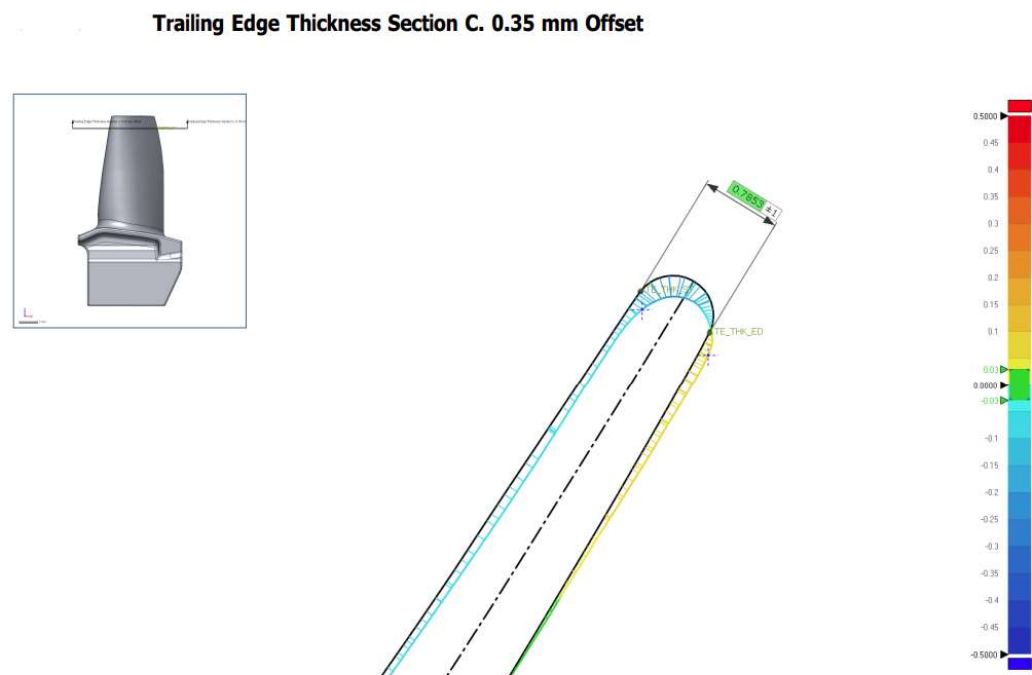


10.8.10 Trailing Edge Thickness Section A

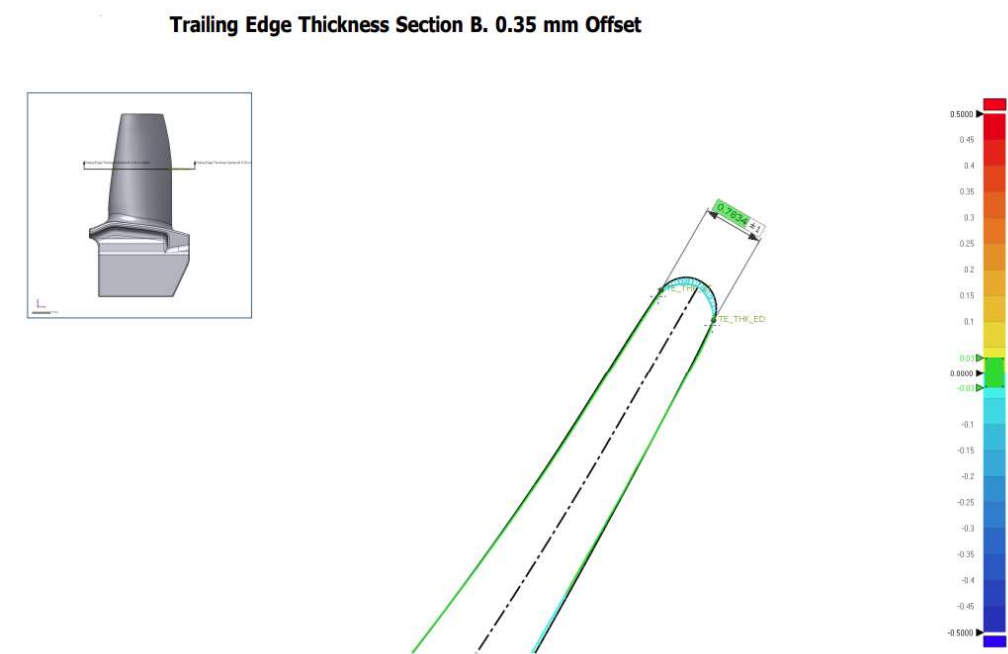
Trailing Edge Thickness Section A. 0.35 mm Offset



10.8.11 Trailing Edge Thickness Section B



10.8.12 Trailing Edge Thickness Section C



10.9 3D Models

