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THE MANUFACTURING OF SINGLE CRYSTAL TURBINE BLADES

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ABSTRACT

Single-crystal nickel-based superalloy turbine blades represent one of the most technically demanding components in modern aerospace and power generation systems. This paper presents a comprehensive review of the materials, manufacturing processes, and future directions associated with their production. The thermodynamic motivation for operating at extreme temperatures is established through the Carnot efficiency framework, which drives the need for materials capable of sustained operation above 1100°C. The role of the γ/γ' microstructure in providing creep resistance is discussed, along with the contributions of key alloying elements, particularly rhenium and ruthenium. The investment casting process is reviewed in detail, encompassing wax pattern fabrication, ceramic shelling, de-waxing, sintering, and ceramic core leaching. The Bridgman-Stockbarger directional solidification technique and grain selector design are examined as the primary means of achieving single-crystal growth. Advanced cooling methods, including liquid metal cooling and gas cooling casting, are discussed in the context of large-component solidification. Common defects such as freckles and stray grains are analyzed alongside their formation mechanisms. Finally, emerging directions are surveyed, including silicon carbide ceramic matrix composites, additive manufacturing for repair, lattice mismatch optimization, and the strategic outlooks of GE Aerospace, Rolls-Royce, and Siemens Energy.

Keywords: Propulsion, Superalloys, Investment Casting, Single Crystal Growth

1. MATERIAL CONSIDERATIONS

Thermodynamics governs the efficiency of a gas turbine, η, with the limiting factor to gas turbine performance being the inlet gas temperature, T_{in}. This relationship is fundamentally described by the Carnot efficiency limit, $\eta = 1 - T_{out}/T_{in}$. Therefore, to improve the fuel efficiency of jet engines, a system must be designed that allows metal turbine blades to operate at temperatures far exceeding those achievable by traditional steels (1300–1400°C) [1]. This proves challenging not only from a thermal perspective but also from a mechanical perspective, as turbine blades often operate at speeds exceeding 10,000 RPM, making them highly susceptible to material degradation, especially creep at the elevated temperatures seen in turbines [2]. It is noted that in traditional polycrystalline metals, creep occurs primarily at the grain boundaries of the material. Because of these factors, both the material selection and the resulting microstructure are critical to the performance of gas turbine blades.

Because of these constraints, single-crystal nickel-based superalloys are used in modern gas turbine blades. The most common alloying elements in these superalloys are chromium, which adds oxidation resistance; and aluminum and titanium, which form the $Ni_3(Al, Ti)$ intermetallic compound γ', providing significant precipitation hardening [2]. The critical factor that dictates a nickel-based superalloy's temperature performance is its γ/γ' microstructure. This microstructure consists of a matrix of the γ phase, an FCC solid solution composed mostly of nickel with select alloying elements. This γ phase is interlaced with the γ' phase, which acts as a strengthening precipitate. The γ' phase has an $L1_2$ structure, an ordered FCC intermetallic phase in which nickel atoms occupy the faces of the unit cell, while aluminum or titanium atoms occupy the corners. A phase diagram highlighting the γ and γ' phases is shown in Figure 1. The γ' precipitates impede the movement of dislocations while providing properties unique to the γ/γ' microstructure. The first of these is the coherent lattice interface between the γ and γ' phases; this coherency prevents the γ' precipitates from coarsening rapidly, which is beneficial as smaller, more numerous precipitates are more effective at blocking dislocations [1]. Additionally, the yield strength of the γ' phase atypically increases with temperature up to approximately 800°C [4]. Heat provides the activation energy for dislocations to cross-slip from primary slip planes to planes where movement is more restricted, forming immobile Kear-Wilsdorf locks. This allows the γ/γ' microstructure to maintain operational integrity at temperatures much higher than traditional alloys while exhibiting superior creep resistance.

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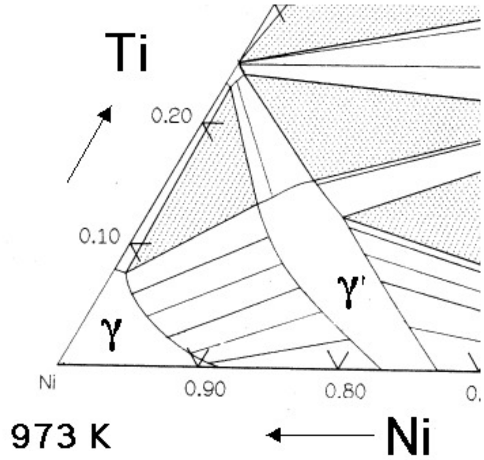

FIGURE 1: Nickel-Aluminum-Titanium Phase Diagram Showcasing Both the γ and γ' Phases at 973 K [3]

Additional alloying elements have been introduced to further increase the performance of nickel-based superalloys. In particular, rhenium (Re) has been added to the γ phase to slow dislocation movement [5]. Rhenium is the slowest-diffusing transition metal in nickel; by partitioning into the γ matrix, it retards dislocation motion both within the phase and at the γ/γ' phase boundary. However, increasing rhenium concentration has limitations, as it can promote the formation of brittle Topologically Close-Packed (TCP) phases that act as crack nucleation sites. To mitigate this, ruthenium (Ru) was introduced in newer generations of alloys to stabilize the microstructure and retain rhenium in solution, preventing the formation of these brittle phases [6]. Table 1 shows the progression of nickel-based superalloy generations.

TABLE 1: Evolution of Single Crystal Nickel-Based Superalloy Generations

Generation	Example Alloy	Alloying Element	Temp
1st Gen	PWA 1480	0% Re	Baseline
2nd Gen	CMSX-4	3% Re	+30–35°C
3rd Gen	CMSX-10	6% Re	+30°C
4th Gen	EPM-102	2–3% Ru (+ Re)	+15–20°C

To tailor the microstructure to produce γ' precipitates within a γ matrix, specific heat treatment processes must be employed. Allowing the cast metal to cool without intervention is not sufficient for creating a precise microstructure, as alloying elements remain segregated, yielding γ' precipitates that are irregular in shape and size, which reduces their effectiveness at impeding dislocation motion [7]. To dissolve these irregular precipitates from the casting process, the cast blade is heated to below the melting point of the material but above the γ' solvus temperature, producing a single-phase γ alloy [7]. Once single-phase, the blade is quenched, causing the $L1_2$ γ' microstructure to nucleate. Because the cast is quenched rather than slow-cooled, this results in many small γ' precipitates that do not have time to grow by diffusion. To grow the γ' precipitates to a size more effective at impeding dislocation motion, the blade is held at an elevated temperature, typically around 1000–1100°C [8].

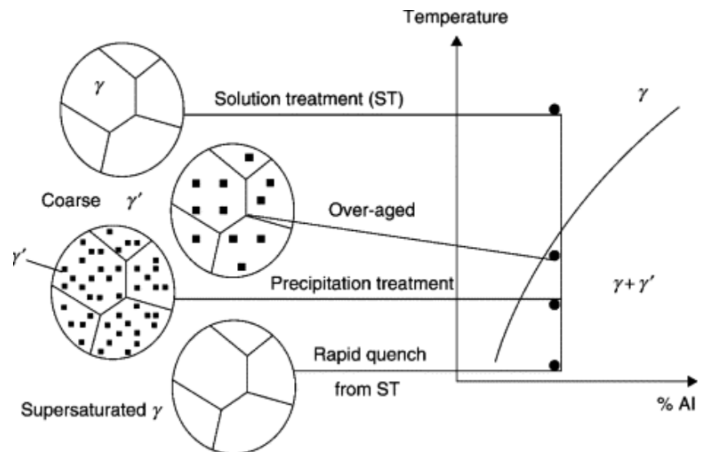

FIGURE 2: Schematic of the γ/γ' Heat Treatment Process Showcasing Homogenization, Quench, and Precipitate Coarsening [9]

2. CASTING PROCESS

Single-crystal turbine blades use investment casting to achieve fine dimensional tolerances and surface finishes. Investment casting is also well suited for components with complex shapes, as seen in the profile of turbine blades and their internal cooling channels. This process, however, comes with severe economic burdens, as a set of 40 single-crystal turbine blades can cost upwards of $600,000 with a lead time of over one year [10–12].

The manufacturing process begins with the creation of a wax pattern. For hollow blades in particular, molten wax is first injected into a metallic die that contains a ceramic core. The core serves as a replica of the internal cooling passages and allows for minimal machining of the final cast part [10]. For large-scale aerospace applications, these patterns are assembled into large clusters that maximize the number of individual blade patterns that can be processed in the furnace simultaneously. Conversely, large industrial gas turbine blades are often processed individually due to their larger size [10].

The wax assembly, whether individual or clustered, is repeatedly dipped into ceramic slurries with sand applied over the slurry. This process builds, layer by layer, a robust shell around the wax. Once a desired shell thickness has been reached, the wax and ceramic shell assembly is placed in a steam autoclave, which melts and removes the wax pattern from the ceramic mold [10]. Ceramic is chosen as the mold material due to its thermal properties, which allow the high-temperature nickel superalloy to be cast without damaging the mold. These requirements include creep resistance under the temperature and weight of the molten metal, as well as sufficiently uniform thermal conductivity to support the directional solidification required for single-crystal growth. Alumina-based ceramics are typically preferred for turbine-blade applications due to their thermal and mechanical properties [13].

At the time of wax removal, the ceramic mold is held together only by green-state binders. In this condition, the mold would not be able to support the weight of molten metal. To increase the structural integrity of the mold, it is sintered in a high-temperature kiln, enabling atomic diffusion across particle boundaries [14]. Careful consideration must be given to the duration of sintering, as low porosity in the mold, which increases with the extent of inter-particle diffusion, can prevent air from escaping when liquid metal is introduced [14].

Before the molten metal is poured, the mold must be preheated. Introducing molten nickel-based superalloy into a room-temperature mold would cause extreme thermal shock, potentially leading to mold failure [15]. Preheating the mold also aids in the development of a single-crystal structure, as elaborated in Section 3, *Single Crystal Growth* [15].

TABLE 2: Process Flow of Investment Casting for Gas Turbine Blades [16, 17]

Process	Function
Wax Injection	Defines external and interior geometry
Ceramic Shelling	Creates mold for the cast part
De-waxing	Removes wax pattern from ceramic mold
Sintering	Consolidates ceramic shell and core
Preheating	Prepares mold for molten metal

The thermal performance of the internal ceramic core is perhaps the most important factor in turbine blade casting. The cooling structures formed using ceramic cores are often geometrically complex and would incur significant machining costs if not implemented during casting [13]. These ceramic cores must also withstand metal pouring and temperatures exceeding 1500°C without deformation, necessitating careful material selection and the use of silica-, alumina-, and zirconium-based materials [18]. Research by Gromada *et al.* identifies an optimized core composition of 69 wt% silica, which provides leachability; 13 wt% zirconium silicate, which enhances refractory properties; 12 wt% alumina, which increases high-temperature stability; and 6 wt% borosilicate glass as a binder. This composition yields a low coefficient of thermal expansion (2.56×10^{-6} K^{-1}) and a low surface roughness (1.8 μm). In particular, the use of borosilicate glass as a binder is necessary for dimensional stability under high-pressure molding processes [19]. Additionally, the inner layer of the ceramic shell must be chemically resistant to the nickel-based superalloy, which is particularly challenging in single-crystal casting, in which the metal remains molten for an extended period of time [16].

Once solidification is complete, the ceramic core remains trapped within the internal cooling passages. To remove the ceramic cores without damaging the casting, chemical leaching is employed. Leaching attacks the tetrahedral structure of silica through an alkali-silica reaction, which causes silica to absorb water and crack, allowing the core to be removed [20]. Typical alkaline solutions used for chemical leaching are sodium hydroxide (NaOH) and potassium hydroxide (KOH), with KOH being more common as it yields high-surface-area, porous cleavages. The potassium silicate byproduct of KOH-based leaching is several orders of magnitude more viscous than the sodium silicate produced when NaOH is used, resulting in a diffusion-controlled reaction process [20].

3. SINGLE CRYSTAL GROWTH

Once the nickel-based superalloy is poured into the mold, directional solidification is used to produce a single-crystal turbine blade. The most prevalent industrial method for achieving this is the Bridgman-Stockbarger technique [10]. In this method, the mold rests on a water-cooled copper chill plate within a vacuum furnace. The furnace is divided into two regions: a hot zone held above the metal's liquidus temperature and a cold zone held well below the liquidus temperature [10].

Solidification begins at the copper chill plate, where equiaxed grains nucleate. The ceramic mold is then slowly withdrawn from the hot zone into the cold zone at a controlled velocity. This movement creates a thermal gradient across the superalloy. The ratio of the temperature gradient to the withdrawal velocity determines the stability of solidification; this ratio must be sufficiently high to prevent constitutional supercooling, which would otherwise produce stray grains [17].

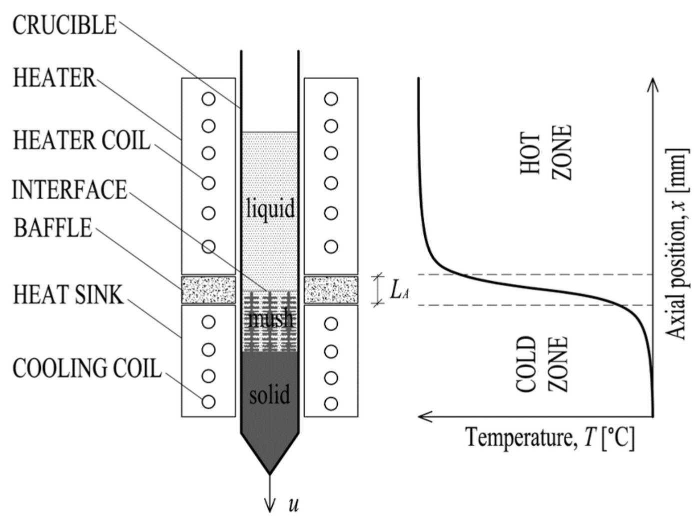

FIGURE 3: Schematic of the Bridgman-Stockbarger Technique Highlighting the Hot Zone, Cold Zone, and Thermal Gradient [21].

To transition from columnar grains to a single crystal, a specialized grain selector geometry is integrated into the mold. The grain selector, frequently a spiral or "pigtail" configuration, physically restricts the solidification front so that only a single grain enters the final turbine blade cavity [15]. It consists of three distinct zones: the starter cavity, a small chamber that rests directly on the water-cooled copper chill plate; the neck, a narrow passage that limits the number of grains advancing upward; and the spiral, which provides the final geometric filtering [22]. When the molten superalloy contacts the chill plate, numerous small grains nucleate at the cold interface. As the mold is withdrawn from the furnace, these grains grow upward, with grains whose [001] crystallographic axis is aligned with the steep thermal gradient growing faster than those that are misaligned. Grains not aligned with the vertical temperature gradient eventually intersect the mold walls and cease to grow. By utilizing a complex geometry such as a spiral, wall interference is maximized, selectively impeding misaligned grains and creating a bottleneck that ensures only one grain remains to seed the entire turbine blade [14, 22].

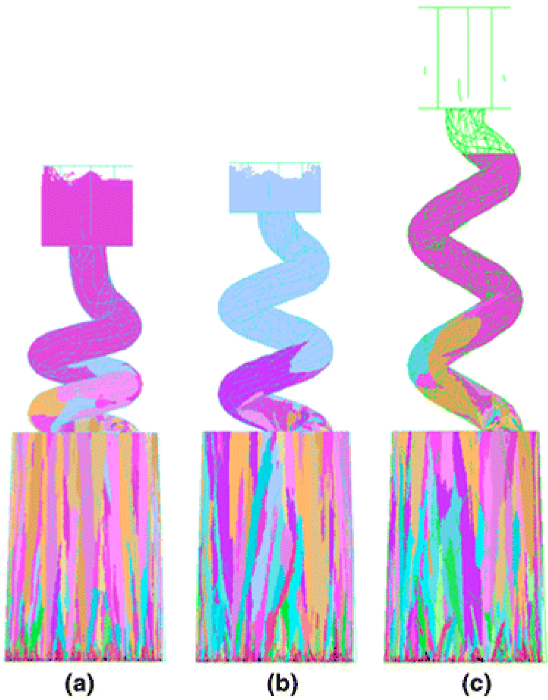

FIGURE 4: Columnar grain growth and selection mechanics in three different spiral grain selector geometries [23].

The performance of a grain selector is measured by its selection efficiency—the vertical distance required to reduce the solidification front to a single grain—and the crystallographic orientation of the resulting crystal. This performance is governed by critical geometric variables: the wire diameter d, the spiral diameter D, and the pitch S [22]. If the wire diameter d is too large, multiple grains may grow side-by-side through the entire selector, resulting in a multicrystalline defect. Conversely, excessively thin wire diameters are susceptible to ceramic mold fracture or cold-shut defects during the pour. A larger pitch S, characterized by a looser coil, is less efficient at blocking misaligned grains but may be used to mitigate radiant heat transfer from the chill plate, which can otherwise degrade the thermal gradient driving directional solidification [24]. Finally, the selector is designed to align the [001] crystallographic axis with the longitudinal axis of the blade. This orientation results in a lower elastic modulus along the primary stress axis, which significantly improves the thermal fatigue life of the component by reducing stress during thermal expansion and contraction [2].

As turbine blade size increases, the limitations of the chill-plate-based solidification method become apparent. Reduced temperature gradients can lead to defects such as freckles, which are small, discrete grain boundaries within the blade. This necessitates the development of more aggressive cooling methods, such as liquid metal cooling (LMC) and gas cooling casting (GCC) [10, 11].

LMC replaces the cold zone, which relies on radiative cooling, with a bath of molten metal, typically tin or aluminum [10]. This dramatically increases heat transfer from the solidifying superalloy through the addition of convection, enabling faster withdrawal rates, increased thermal gradients, and a refined microstructure [11]. Research by A. Elliott *et al.* shows that LMC effectively eliminates freckle defects in large turbine components where the conventional Bridgman process cannot establish a sufficient thermal gradient. LMC has its limitations, however, as it requires a floating thermal baffle to isolate the hot zone from the cold end, and demands greater precision in solidification front tracking than conventional Bridgman setups [11].

GCC, on the other hand, injects an inert gas, such as argon, below the furnace to enhance cooling. This approach is less efficient than LMC but carries a reduced risk of metal-on-metal contamination or mold cracking from hydrostatic pressure [10, 25]. It has also been shown that GCC can achieve heat transfer coefficients comparable to those of LMC, thereby enabling the production of larger single-crystal turbine blades with higher casting yields [25]. GCC has additionally been shown to reduce primary dendrite arm spacing by up to 100 μm at the base of the turbine blade compared to conventional Bridgman cooling [26].

Primary dendrite arm spacing (PDAS, λ) is the most important microstructural characteristic in determining the mechanical integrity of a cast turbine blade, as it governs the distribution of the γ and γ' phases. PDAS in the Bridgman process is described by the following relation: $\lambda_1 = k \cdot G^{-1/2} V^{-1/4}$ where G is the temperature gradient and V is the withdrawal velocity from the hot zone to the cold zone. PDAS values also increase as the solidification front moves away from the chill plate, often rising by approximately 20% over the length of the turbine blade [26, 27].

4. SOLIDIFICATION DEFECTS AND MECHANICS

The most common defect in modern single-crystal turbine blades is the freckle. Freckles are small chains of equiaxed grains aligned with the direction of gravity [28]. They result from natural convection within the mushy zone during solidification, as seen in Figure 3 [29]. As the superalloy solidifies, heavy alloying elements such as rhenium segregate from the melt into the solid phase, while lighter alloying elements such as aluminum and titanium are retained in the liquid. This creates a density inversion within the mushy zone, in which less dense liquid lies beneath denser liquid, triggering buoyancy-driven fluid flow [17]. This flow disrupts solidification within the mushy zone, causing the formation of equiaxed grains [30].

Investigations into third-generation nickel-based superalloys, which feature higher rhenium content, show that freckle formation is highly dependent on the casting's position relative to the heat source [17]. Regions of the casting exposed to a lower temperature gradient are more susceptible to freckle formation [17]. This is particularly problematic for production yield, as freckles cannot be removed through heat treatment, ultimately requiring the scrap of the affected casting [30].

Stray grains are another defect commonly found in modern turbine blades. They are randomly oriented crystals that nucleate independently of the single crystal, often at the extremities of the blade base, due to locally elevated cooling rates caused by blade geometry [31]. The formation of stray grains depends on the superalloy's undercooling capacity, with a larger undercooling tendency increasing the likelihood of stray grain nucleation. Nickel-based superalloys, such as MM247LC, exhibit low undercooling capacities and are therefore difficult to cast as single-crystal turbine blades without stray grains [31].

With material science considerations, casting processes, single crystal growth, and defects discussed, the advantages and disadvantages for single-crystal turbine blade manufacturing are summarized in Table 3.

5. FUTURE OF TURBINE BLADE MANUFACTURING

The future of turbine blade development is multifaceted, with the aim of advancing both the metallurgical and thermodynamic performance of the component. From a thermodynamic standpoint, a critical factor in creep performance is the lattice mismatch between the γ and γ' phases, denoted δ. A large misfit between the matrix and precipitate lattices promotes what is known as a rafting structure, in which the γ' precipitates coalesce into plates oriented perpendicular to the loading direction, enhancing dislocation blocking [32]. Recent research has demonstrated a linear correlation between the log of the creep rupture time $\ln(t_r)$ and the lattice mismatch, governed by the relation

$$\ln(t_r) = \ln(\delta^{3/2})$$

at high temperatures [32]. Current research efforts focus on understanding this effect in nickel-based superalloys containing more than ten alloying elements and on incorporating manufacturing processes that enhance lattice mismatch in production settings [32, 33].

Beyond incremental improvements to metallic alloys, the industry is increasingly exploring non-metallic materials for the next generation of turbine blade components. Of particular interest are silicon carbide fiber-reinforced silicon carbide matrix composites (SiC/SiC), which offer a density approximately one-third that of traditional nickel-based superalloys [34]. This reduced density can be leveraged to increase turbine speed under the same centrifugal force [35]. The primary appeal of SiC/SiC composites is their ability, as ceramics, to withstand significantly higher temperatures than metallic alloys without requiring the complex internal cooling systems currently employed [34, 35].

SiC/SiC composites differ fundamentally from superalloys in their mechanical behavior. Superalloys gain strength rapidly when cooled below their operating temperature, a trend common across metallic systems [35]. SiC/SiC composites, by contrast, exhibit a more stable strength-temperature relationship, enabling simpler cooling mechanisms to maintain blade performance [35].

SiC/SiC and other ceramic composites face significant challenges before they can be employed in commercial turbine systems. Environmental barrier coatings (EBCs), which are required to protect the ceramic composite from degradation in the high-moisture combustion environment, are still under development [36]. Until a suitable coating is available, ceramic composites cannot be deployed in turbine systems [36]. Additionally, while ceramic composites are more damage-tolerant than monolithic ceramics, they remain susceptible to microcracking, particularly at lower temperatures [34]. This is especially concerning given the brittle nature of ceramic composites. Despite these limitations, GE Aviation has successfully tested rotating ceramic composite low-pressure turbine blades, representing a major milestone in the development of ceramic composites for aviation applications [36, 37].

From a manufacturing standpoint, additive manufacturing (AM) is being studied as a means of fabricating and repairing single-crystal blades [10, 12]. Producing a single crystal via additive manufacturing is inherently difficult, as the extreme cooling rates and layer-by-layer construction process create conditions favorable for the nucleation of stray grains, which would sacrifice the creep benefits of a single-crystal structure [12, 38]. Despite this challenge, researchers at NIMS and Osaka University have successfully grown single-crystal nickel components using a large-radius flat-top laser beam [38]. Unlike conventional lasers used in metal AM processes, which create deep, bowl-shaped melt pools, the flat-top laser produces a more uniform temperature gradient and a shallower melt pool, allowing individual grains to grow in the same direction [38]. Additive manufacturing also allows for the programming of crystallographic orientation through a process called single-crystal twisting, in which the hatch angle, or the overlap between sintered layers, is continuously rotated [39]. This enables deterministic strengthening in the direction of applied stress [39].

While these recent developments are promising, the most compelling near-term application of AM in turbine manufacturing is repair [12]. Turbine blades are often scrapped when small cracks develop, even in non-critical areas [12]. Repairing them using additive manufacturing offers a cost-effective alternative [12]. Currently, directed energy deposition (DED) and laser powder bed fusion (LPBF) are being investigated as methods to deposit new material onto damaged blade tips with grain structures that are crystallographically coherent with the base material [12].

Given the large quantities of rare metals used as alloying elements in turbine blade manufacturing, there is growing

TABLE 3: Advantages and Disadvantages of Single-Crystal Turbine Blade Manufacturing

Advantages	Disadvantages
Elimination of grain boundaries significantly improves creep resistance at high temperatures	Extremely high production cost (up to $600,000 per batch) and long lead times
Ability to operate at temperatures exceeding 1100°C, improving engine efficiency	Complex and tightly controlled manufacturing process requiring specialized equipment
Excellent mechanical properties due to optimized γ/γ' microstructure	Susceptibility to defects such as freckles and stray grains, reducing yield
Investment casting enables complex geometries and integrated internal cooling channels	Difficult quality control; many defects cannot be repaired and require scrapping
Directional solidification allows crystallographic alignment for improved fatigue life	High sensitivity to process parameters (thermal gradient, withdrawal rate)
Advanced cooling methods (LMC, GCC) enable scaling to larger components	Use of expensive and scarce alloying elements (e.g., rhenium, ruthenium)

Property	Ni. Superalloys	SiC/SiC
Density	~8.7–9.2 g/cm^3	~2.5–3.0 g/cm^3
Max Temperature	~1100°C	~1316°C
Failure Mode	Creep	Crack deflection

TABLE 4: Comparison of Nickel Superalloys and SiC/SiC CMCs [34, 35]

interest in recycling both rhenium and ruthenium for both sustainability and economic reasons [40, 41]. Rhenium, currently valued at approximately $2,600/kg and used in concentrations of 3–6% in current-generation nickel-based superalloys, provides a particularly strong economic incentive for recovery [40–42]. As a result, closed-loop recycling systems are being established that return scrapped components from manufacturing plants to specialized recyclers, which use targeted metallurgical processes to extract both rhenium and ruthenium [40, 41, 43].

Finally, turbine blade manufacturing presently is, and will continue to be, concentrated primarily within three companies: GE Aerospace, Rolls-Royce, and Siemens Energy. GE Aerospace, through programs such as RISE (Revolutionary Innovation for Sustainable Engines), is focusing on compact engine cores utilizing both single-crystal superalloys and ceramic composites to achieve a 20% net reduction in fuel consumption [44, 45]. Rolls-Royce's strategy centers on the development of the UltraFan engine, a next-generation design proposed to run on renewable fuels with a 25% improvement in fuel efficiency [46]. Notably, the turbine blades are constructed from carbon composite titanium with a titanium leading edge to reduce weight, a significant departure from conventional superalloy blades [46]. Siemens Energy has finalized a $1 billion investment to expand its U.S. manufacturing base, with particular focus on facilities in Florida and North Carolina [47, 48]. Siemens is also investing in sustainability initiatives, specifically addressing the Energy Trilemma of affordability, reliability, and sustainability, with a target of producing gas turbines capable of burning 100% hydrogen as a sustainable fuel source [47, 48].

REFERENCES

[1] Reed, R.C. *The Superalloys: Fundamentals and Applications*. Cambridge University Press (2006).

[2] Pollock, T.M. and Tin, S. "Nickel-based superalloys for advanced turbine engines." *Journal of Propulsion and Power* Vol. 22 (2014). DOI 10.2514/1.18239.

[3] Bhadeshia, H. K. D. H. "Nickel Based Superalloys."

[4] Takeuchi, S. and Kuramoto, E. "Temperature and orientation dependence of the yield stress in Ni3Al." *Acta Metallurgica* Vol. 21 No. 4 (1973): pp. 415–425.

[5] Mottura, A. and Reed, R.C. "What is the role of rhenium in single crystal superalloys?" *MATEC Web of Conferences* Vol. 14 (2014). DOI 10.1051/matecconf/20141401001.

[6] Tian, N., Meng, T., Sun, S., Zhang, S. and Dang, D. "Creep Behavior of a Single Crystal Nickel-Based Superalloy Containing High Concentrations of Re/Ru." *Crystals* Vol. 14 (2024). DOI 10.3390/cryst14110983.

[7] Müller, L., Glatzel, U. and Feller-Kniepmeier, M. "Thermodynamics and kinetics of phase transformations in Ni-base superalloys." *Acta Materialia* Vol. 48 No. 11 (2000): pp. 2731–2745.

[8] Caron, P. and Khan, T. "Influence of microstructure on the creep properties of a nickel-based single crystal superalloy." *Materials Science and Engineering* Vol. 61 (1983): pp. 173–184.

[9] Álvarez Tejedor, T., Singh, R. and Pilidis, P. *Modern Gas Turbine Systems*. Woodhead Publishing (2013).

[10] Dexin, M.A. "Novel casting processes for single-crystal turbine blades of superalloys." *Frontiers of Mechanical*

FIGURE 5: Photo of the UltraFan Turbine Blade, Showcasing the Titanium Leading Edge With the Full UltraFan Engine in the Background [49].

Engineering Vol. 13 No. 1 (2018). DOI 10.1007/s11465-018-0475-0.

[11] Elliot, A. "Directional solidification of large cross-section nickel-base superalloy castings via liquid-metal cooling." Ph.D. Thesis, The University of Michigan. 2005.

[12] Angel, N. and Basak, A. "On the fabrication of metallic single crystal turbine blades with a commentary on repair via additive manufacturing." *Journal of Manufacturing and Materials Processing* Vol. 4 (2020). DOI 10.3390/jmmp4040101.

[13] Pradyumna, R. and Baig, M. "Ceramic Cores for Turbine Blades: A Tooling Perspective." *International Journal of Mechanical and Industrial Engineering* Vol. 3 (2013). DOI 10.47893/IJMIE.2013.1135.

[14] Campbell, J. *Complete Casting Handbook*. Butterworth-Heinemann (2015).

[15] Versnyder, F. and Shank, M. "The development of columnar grain and single crystal high temperature materials through directional solidification." *Materials Science and Engineering* Vol. 6 (1970). DOI 10.1016/0025-5416(70)90050-9.

[16] Lacaze, J. and Hazotte, A. "Directionally Solidified Materials: Nickel-Base Supperalloys for Gas Turbones." *Textures and Microstructures* Vol. 13 (1990).

[17] Liu, X., Long, A., Zhang, H., Ma, D., Song, M., Wu, M. and Guo, J. "Experimental and Numerical Investigation on the Formation Mechanism of Freckle Defects in a Novel Third-Generation Nickel-Based Single Crystal Superalloy Turbine Blade." *Crystals* Vol. 16 (2026). DOI doi.org/10.3390/cryst16040245.

[18] Maristany, E., Cordero, Z., Boyer, J. and Grant, L. "Economics of 3D printing ceramic cores for gas turbine investment castings." *Additive Manufacturing Letters* Vol. 10 (2024). DOI 10.1016/j.addlet.2024.100223.

[19] Gromada, M., Tluczek, A. and Cygan, R. "Silica-based ceramic cores for high-pressure turbine airfoil blades in aircraft engines." *Processing and Applications of Ceramics* Vol. 18 (2024). DOI 10.2298/PAC2403299G.

[20] Adetunji, D. "Chemistry and physics of the ceramic core leaching process." Ph.D. Thesis, University of Birmingham. 2019.

[21] Mooney, R. P., Gabalcova, Z., Lapin, J. and Mcfadden, S. "An experimental-numerical method for estimating heat transfer in a Bridgman furnace." *Applied Thermal Engineering* Vol. 67 (2014). DOI 10.1016/j.applthermaleng.2014.02.048.

[22] Higginbotham, G. J. S. "From saplings to single crystals." *Materials Science and Technology* Vol. 2 No. 5 (1986): pp. 442–460.

[23] Dai, H.J., Dong, H.B., D'Souza, N., Gebelin, J.-C. and Reed, R.C. "Grain Selection in Spiral Selectors During Investment Casting of Single-Crystal Components: Part II. Numerical Modeling." *Metallurgical and Materials Transactions A* Vol. 42 (2011). DOI 10.1007/s11661-011-0757-1.

[24] D'Souza, N., Jennings, P. A. and Green, N. R. "Directional solidification of Ni-base superalloys: Part I. Role of thermal gradient on the morphology of the {111} liquidus surface." *Metallurgical and Materials Transactions A* Vol. 31 (2000): pp. 2877–2884.

[25] Konter, M., Kats, E. and Hofmann, N. "A Novel Casting Process for Single Crystal Gas Turbine Componenets." *Superalloys* (2000)DOI 10.7449/2000/Superalloys_2000_189_200.

[26] Szeliga, D., Piechowicz, L., Lisiewicz, M. and Wiechczynski, A. "Directional Solidification of Single-Crystal Blades in Industrial Conditions Using the Developed Gas Cooling Casting Method." *Metallurgical and Materials Transactions A* Vol. 55 (2024). DOI 10.7449/2000/Superalloys_2000_189_200.

[27] Kostic, S., Aleksandar, G. and Valcic, A. "Primary and secondary dendrite spacing of Ni-based superalloy single crystals." *Journal of the Serbian Chemical Society* Vol. 74 (2009). DOI 10.2298/JSC0901061K.

[28] Liu, X., Long, A., Zhang, H., Ma, D., Song, M., Wu, M. and Guo, J. "Experimental and Numerical Investigation on the Formation Mechanism of Freckle Defects in a Novel Third-Generation Nickel-Based Single Crystal Superalloy Turbine Blade." *Crystals* Vol. 16 (2026). DOI 10.3390/cryst16040245.

[29] Bhadeshia, H. K. D. H. "Freckles in Nickel Based Superalloys."

[30] Hong, J., Ma, D., Wang, J., Wang, F., Sun, B., Dong, A., Li, F. and Bührig-Polaczek, A. "Freckle Defect Formation near

the Casting Interfaces of Directionally Solidified Superalloys." *Materials* Vol. 16 (2016). DOI 10.3390/ma9110929.

[31] Ma, D., Zhao, Y., Xu, W., Xu, F., Wei, J. and Zang, H. "Comparative Investigation of the Undercooling Capacity and Single-Crystal Castability of Some Ni-Based Superalloys." *Crystals* Vol. 13 (2023). DOI 10.3390/cryst13010057.

[32] Chen, C., Wang, Q., Dong, C., Zhang, Y. and Dong, H. "Composition rules of Ni-base single crystal superalloys and its influence on creep properties via a cluster formula approach." *Scientific Reports* Vol. 10 (2010). DOI 10.1038/s41598-020-78690-8.

[33] Aoki, Y., M. Arai, K. Chikugo, Koizumi, Y. and Harada, H. "Proceeding of the Internation Gas Turbine Congress." *Scientific Reports* (2003).

[34] Karadimas, G. and Salonitis, K. "Ceramic Matrix Composites for Aero Engine Applications—A Review." *Applied Science* Vol. 13 . DOI 10.3390/app13053017.

[35] Boyle, R. J., Gnanaselvam, P., Parikh, A. H., Ameri, A. A. and andV. K. Nagpal, J. P. Bons. "Design of Stress-Constrained SiC/SiC Ceramic Matrix Composite High Pressure Turbine Blades." *ASME Journal of Engineering for Gas Turbines and Power* Vol. 143 (2021). DOI doi.org/10.1115/1.4049776.

[36] Presby, M. J., Harder, B. J. and Lee, K. N. "Environmental Barrier Coatings for Gas Turbine Engines." *Mechanical Engineering Magazine Select* Vol. 147 (2025). DOI 10.1115/1.2025-Sept4.

[37] Aerospace, GE. "GE Successfully Tests World's First Rotating Ceramic Matrix Composite." (2015).

[38] Jodi, D., Kitashima, T., Koizumi, Y., Nakano, T. and Watanabe, M. "Manufacturing single crystals of pure nickel via selective laser melting with a flat-top laser beam." *Additive Manufacturing Letters* Vol. 3 (2022). DOI 10.1016/j.addlet.2022.100066.

[39] Bareis, J., Wahlmann, B. and Korner, C. "Single crystal twisting in additive manufacturing." *Progress in Additive Manufacturing* Vol. 10 (2025). DOI 10.1007/s40964-025-01158-6.

[40] Recycling, Okon. "Rhenium Recycling Process: Sources, Techniques Challenges." (2025).

[41] Materials, Quest. "Source of Rhenium Scrap for Recycling: A Comprehensive Guide." (2025).

[42] Survey, U.S. Geological. "Mineral Commodity Summaries: Rhenium." (2025).

[43] Rathore, N. and Panwar, N. L. "Environmental impact and waste recycling technologies for modern wind turbines: An overview." *Waste Management Research* Vol. 41 (2022). DOI 10.1177/0734242X221135527.

[44] Aerospace, GE. "GE Aviation's roadmap to future flight." (2022)URL https://www.geaerospace.com/news/articles/farnborough-airshow-sustainability-technology/ge-aviations-roadmap-future-flight.

[45] Aerospace, GE (2018). GE's Next Chapter.

[46] Rolls-Royce. "UltraFan technology programme: The next evolution of aviation." (2023). URL https://www.rolls-royce.com/innovation/ultrafan.aspx.

[47] Energy, Siemens. "Siemens Energy is investing $1 billion and creating highly skilled jobs in the United States." (2026). URL https://www.siemens-energy.com/global/en/home/press-releases/siemens-energy-is-investing--1-billion-and-creating-highly-skill.html.

[48] Energy, Siemens. "Decarbonization Pathways for Gas Turbines." (2026). URL https://assets.siemens-energy.com/dam/51aba4eb-30bc-4582-b48a-b1e9009c4c8f/H2_GF_GT-White-Paper_released-pdf_Original%20file.pdf.

[49] Gardner, Ginger. "Rolls-Royce starts manufacture of world's largest fan blades, made with composites, for UltraFan demonstrator." (2020).