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Comparative Analysis of Inconel 718 and Inconel 625 for Rocket Nozzles: Performance, Durability, and Manufacturing Influence

Mohamed Abdullah K*, Kavyassree G†, Srimathi S‡

[2,3,4]*Department of Aerospace Engineering, SNS college of Technology, Tamil Nadu, India*

[2]*Project Associate at Aeroin SpaceTech Private Limited, Chennai, Tamil Nadu, India*

Abstract: Rocket nozzles operate under extreme thermal loads, high-velocity gas flow, and mechanical stresses, making material selection crucial for performance and durability. Inconel 718 and Inconel 625 are widely used nickel-based superalloys due to their high temperature strength, oxidations resistance, and mechanical reliability. However, a direct comparison of their erosion resistance, thermal stability, and manufacturability for rocket nozzle applications remains limited. This review consolidates research on their microstructural behavior, welding characteristics, and additive manufacturing feasibility to assess their suitability for propulsion systems. While Inconel 718 offers superior strength, creep resistance, and phase stability, Inconel 625 provides better flexibility, oxidation resistance, and weldability. Additionally, the influence of fabrication techniques, phase transformations, and structural integrity on long-term performance is examined. The findings provide valuable insights into performance trade-offs and material selection strategies, supporting advancements in rocket nozzle design and manufacturing for next-generation aerospace applications.

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1. Introduction

Rocket nozzles are essential components in propulsion systems . These magical parts are responsible for converting high-pressure, high-temperature gases from the combustion chamber into high-velocity exhaust to generate thrust. Their performance depends on both geometric design and material selection, which impact thermal stability, erosion resistance, and mechanical durability under extreme conditions. The de Laval nozzle, a widely used design in rocket propulsion, plays a crucial role in efficiently accelerating exhaust gases to supersonic speeds. It consists of a convergent section, throat, and divergent section, which work together to optimize the conversion of thermal and pressure energy into kinetic energy. The convergent section compresses and accelerates the exhaust gases, the throat forces them to reach Mach 1 (sonic velocity), and the divergent section expands the flow, further increasing velocity to supersonic levels (Mach >1).

* Project Associate, Aeroin SpaceTech Private Limited, Chennai, Tamilnadu-600100. **Contact:** mohamedabdullah.aeroin@gmail.com.
† UG Scholar, Department of Aerospace Engineering, SNS college of Technology, Tamil Nadu, India.
‡ UG Scholar, Department of Aerospace Engineering, SNS college of Technology, Tamil Nadu, India.
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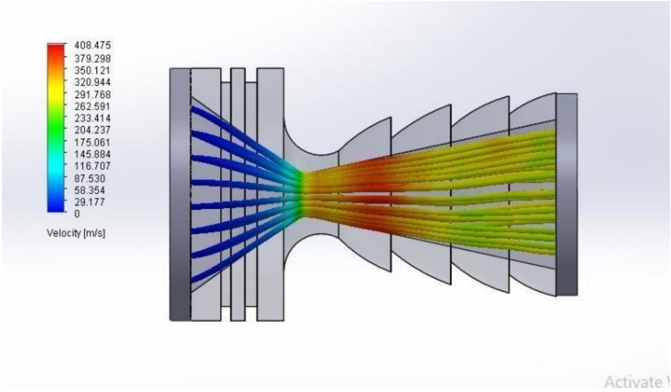

Figure 1 CFD Image

However, the extreme thermal loads, high-velocity gas flow, and chemical erosion inside the de Laval nozzle impose severe stresses on the material, making material selection critical. Rocket nozzle materials must exhibit exceptional thermal resistance, oxidation protection, creep resistance, and mechanical strength to withstand these harsh conditions while ensuring long-term durability.

Among high-performance materials, nickel-based superalloys such as Inconel 718 and Inconel 625 have been widely adopted due to their superior high-temperature performance. While Inconel 718 provides higher creep resistance and structural stability, Inconel 625 offers better flexibility and oxidation resistance, making material selection dependent on specific propulsion system requirements. Advancement in fabrication techniques, including welding, casting, and additive manufacturing, further influence the microstructure, phase formation, and mechanical behavior of these materials. Thus, a comprehensive evaluation of mechanical, thermal, and erosion properties is necessary to optimize rocket nozzle performance.

This review consolidates existing research on Inconel 718 and Inconel 625, identifying key performance trade-offs, material limitations, and advanced manufacturing strategies for next generation aerospace propulsion systems

2. Literature Review

Ramakumar et al. (2017) studied the welding characteristics of Inconel 625 and Inconel 718, focusing on the formation of Laves phase and its impact on mechanical properties. They found that niobium segregation during welding led to the formation of brittle Laves phase, reducing strength and ductility. Post-weld heat treatment (PWHT) was suggested to dissolve this phase and improve toughness. Additionally, the study highlighted that the use of pulsed current gas tungsten arc welding (PCGTAW) helped minimize heat input, leading to refined microstructures and improved weld quality.

S. Pratheesh Kumar et al. (2021) study talks about making Inconel 625 and Inconel 718 using Direct Energy Deposition (DED), a type of additive manufacturing. It looks at important properties like strength, fatigue resistance, and creep behavior. The results show that Inconel 718 is stronger, but Inconel 625 is more flexible. The study also explains how changing the DED process settings affects these properties. Heat treatment after printing makes the materials stronger and reduces internal stress. In the end, the study suggests that properly processed DED Inconel alloys can be just as good or even better than traditionally made ones.

Gedlu Solomon et al. (2020) study focuses on the design and analysis of a rocket nozzle to optimize thrust and efficiency. The research used mathematical methods like interpolation and iteration to determine key design parameters, including expansion ratio and throat area. For a chamber pressure of 966.2 psi, an expansion ratio of 8 was chosen to ensure optimal performance. The study also examined different nozzle materials, considering erosion and thermal stress cracking. The final selection was Columbium Carbide-Tungsten due to its durability in high-temperature conditions. The results confirmed that the designed nozzle achieved high efficiency with a Mach number of 2.574 and an exit velocity of 2,225.3 m/s.

Gradl, P. R., et al. (2019) Additive manufacturing techniques were investigated to fabricate channel wall nozzles using Blown Powder Directed Energy Deposition (DED) with Inconel 625. Mechanical properties, thermal performance, and hot-fire testing were conducted to evaluate the material’s suitability for regeneratively cooled rocket nozzles. The results showed that Inconel 625 maintains high-temperature strength up to 1,200°C, with oxidation and corrosion resistance in LOX/RP-1 combustion environments. Hot-fire testing revealed stable performance, with no structural failures after multiple cycles. Some surface roughness and thermal distortions were observed, but post-processing methods like hot isostatic pressing (HIP) improved material consistency. The study concluded that Inconel 625 is a viable material for large-scale additively manufactured propulsion components, enabling cost effective and efficient nozzle production

3. Methodology

This review follows a structured methodology to evaluate Inconel 718 and Inconel 625 for rocket nozzle applications. The analysis includes material selection, properties evaluation, microstructural analysis, and manufacturing considerations to determine their suitability for high-temperature propulsion environments. The methodology is based on existing literature, experimental studies, and industry reports, focusing on thermal stability, corrosion resistance, mechanical behavior, and fabrication feasibility of these nickel-based superalloys.

3.1 Material Selection

The selection of Inconel 718 and Inconel 625 is based on their extensive use in aerospace and propulsion systems, where materials must endure extreme temperatures, high-velocity gas flow, mechanical stress, and chemical erosion. The primary selection criteria include thermal resistance, oxidation and corrosion protection, mechanical strength, erosion resistance, and manufacturability.

To further understand material behavior, microstructural analysis was conducted to examine phase formation, grain structure, and carbide precipitation. Inconel 718 relies on γ' and γ'' strengthening phases, while Inconel 625 exhibits solid solution strengthening with carbide formation. These structural differences play a key role in their high-temperature performance and durability in rocket nozzle applications.

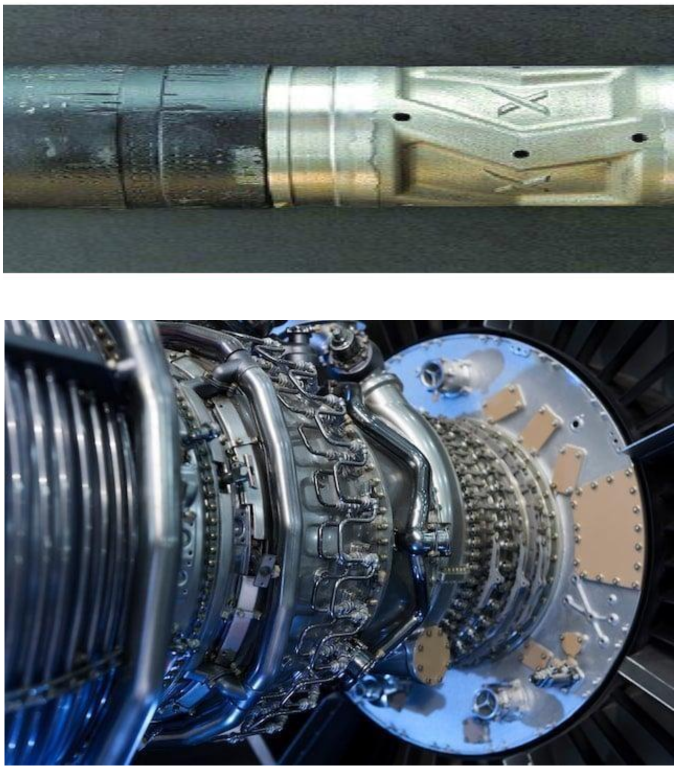

Figure 2(a): Schematic Representation of Nozzles Made from material Inconel 718 and Inconel 625

CRITERIA	INCONEL 718	INCONEL 625
Thermal resistance	High(1573K)	Moderate(1473K)
Oxidation resistance	Moderate	High
Corrosion resistance	Good	Excellent
Strength	Very high	Moderate
Creep resistance	High	Moderate
Erosion resistance	High	Moderate
Manufacturing ability	Moderate	High

Table 1: Selection Criteria for Rocket Nozzle Materials

3.2 Properties Evaluation

To further understand material behavior, microstructural analysis was conducted to examine phase formation, grain structure, and carbide precipitation. Inconel 718 relies on γ' and γ'' strengthening phases, while Inconel 625 exhibits solid solution strengthening with carbide formation. These structural differences play a key role in their high-temperature performance and durability in rocket nozzle applications. Comparative thermal and mechanical properties analysis was conducted to assess the behavior of Inconel 718 and Inconel 625 under rocket nozzle operating conditions. These properties include melting points, thermal conductivity, tensile strength, creep resistance, and oxidation performance, as they significantly influence nozzle durability and efficiency.

3.2.1 Thermal and Mechanical Properties

Thermal resistance and mechanical strength are crucial for nozzle materials, as they must withstand continuous heating and cooling cycles, extreme aerodynamic forces, and highspeed exhaust flow. The mechanical behavior of Inconel 718 and Inconel 625 is assessed in terms of tensile strength, yield strength, creep resistance, and fatigue resistance, all of which affect nozzle longevity and reliability.

Property	Inconel 718	Inconel 625
Density(g/cm^3)	8.19	8.44
Melting point	1260-1336	1290-1350
Thermal conduct	11.4	9.8
Tensile strength	1035-1375	760-1035
Yield strength	725-1035	414-827
Hardness	30-40	20-30

Table 2: Thermal and Mechanical Properties of Inconel 718 and Inconel 625

3.2.2 Corrosion and Oxidation Resistance

Rocket nozzles are exposed to oxidizing and corrosive exhaust gases, which can degrade material integrity over time. Inconel 625 exhibits superior oxidation and corrosion resistance, making it highly effective in highly reactive environments, whereas Inconel 718 relies on a protective oxide layer to maintain stability at elevated temperatures. This analysis provides insight into the expected lifespan and degradation mechanisms of each material in nozzle applications.

3.2.3 Erosion and Wear Performance

Nozzles experience high-speed gas flow-induced erosion, which can lead to material loss, reduced efficiency, and shorter service life. Inconel 718 is more resistant to mechanical erosion, whereas Inconel 625 offers better thermal shock resistance. Data from previous studies was analyzed to compare erosion rates and material wear under simulated propulsion conditions.

3.3 Microstructural Analysis

A microstructural evaluation was conducted to understand the grain structure, phase composition, and carbide formation in Inconel 718 and Inconel 625. These aspects directly influence thermal resistance, mechanical strength, and oxidation stability. Inconel 718 exhibits a precipitation-hardening mechanism through γ' and γ'' phases, which significantly enhance creep strength and fatigue resistance. Inconel 625, on the other hand, strengthens through solid-solution hardening, with Niobium-stabilized carbide.

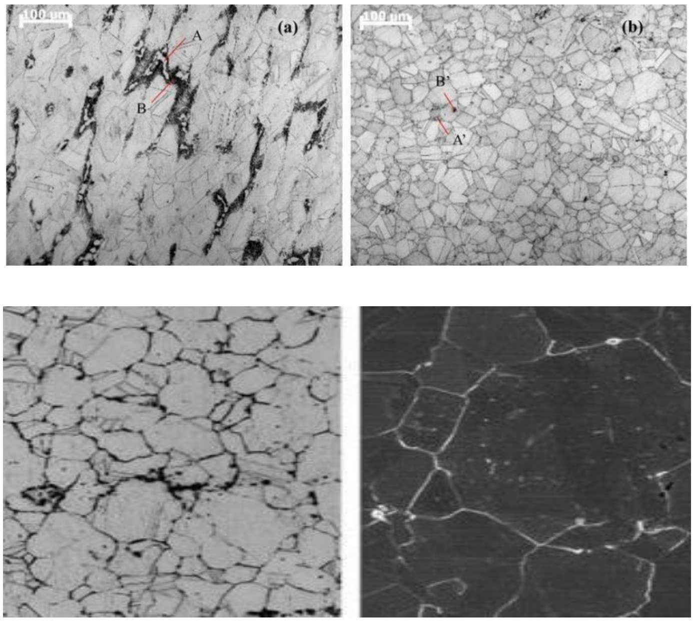

Figure 2(b): Microstructural Comparison of Inconel 718 and Inconel 625

4. Results and Discussions

4.1. Thermal and Oxidation Resistance

4.1.1. Temperature Distribution and Oxidation Behavior

Thermal analysis indicates that Inconel 718 retains heat longer due to its lower thermal conductivity, leading to localized thermal stresses in areas of high heat flux. In contrast, Inconel 625 dissipates heat more efficiently, reducing thermal gradients and improving overall nozzle longevity. Oxidation studies show that Inconel 625 forms a stable Cr_2O_3 (chromium oxide) layer, enhancing resistance to oxidation and hot-gas corrosion. Inconel 718, while stable at high temperatures, exhibits slightly higher oxidation rates due to the formation of Nb-rich oxides, which are less protective over extended operational periods. This makes Inconel 625 a better choice for long-duration missions where oxidation is a concern.

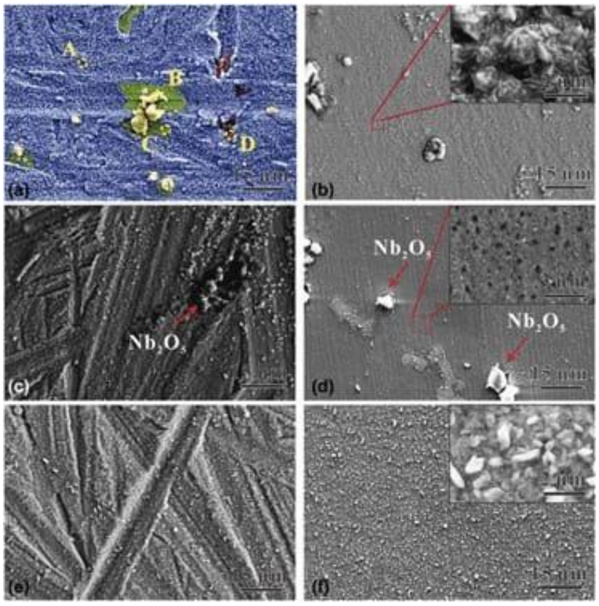

Figure 3(a): Temperature distribution and oxidation resistance comparison of Inconel 718 and Inconel 625

4.2. Mechanical Performance

4.2.1. Creep and Fatigue Resistance

From the stress-strain analysis, Inconel 718 exhibits a higher tensile strength of approximately 1240–1370 MPa, compared to Inconel 625's 830–1035 MPa. This makes Inconel 718 more suitable for high-load applications where structural stability is essential. However, Inconel 625 offers superior fatigue resistance due to its solid solution strengthening mechanism, which helps it withstand thermal cycling and stress variations. In applications where nozzles undergo repeated heating and cooling cycles, Inconel 625 maintains better structural integrity, reducing the risk of thermal fatigue failure.

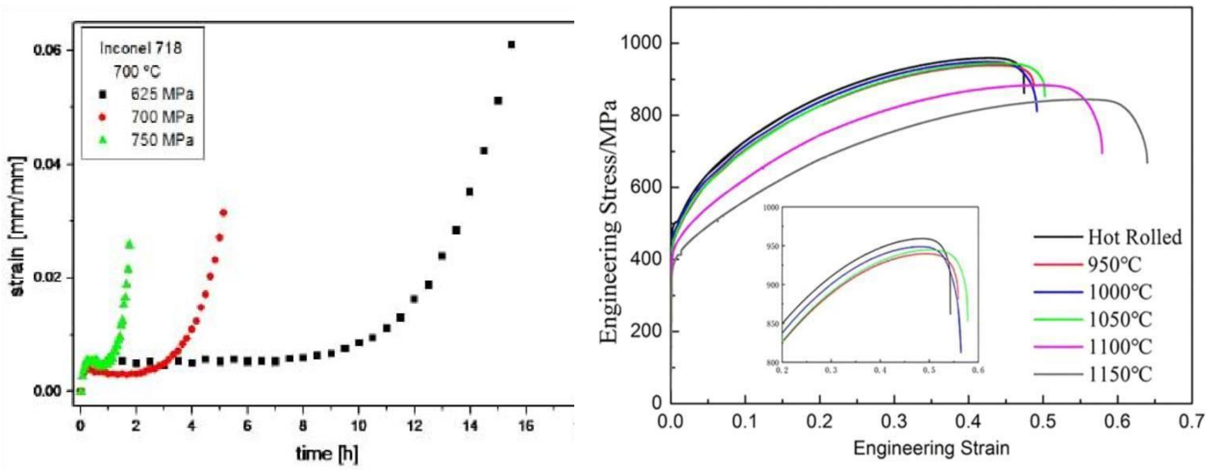

Figure 3(b): Stress-strain and creep behavior of Inconel 718 and Inconel 625

4.2.2. Erosion and Structural Stability

Erosion resistance is a critical factor in nozzle material selection, as high-speed exhaust gases can degrade the inner nozzle walls. Inconel 718, with its precipitation-hardened structure, is more resistant to particle erosion, making it ideal for nozzle throats, where gas velocity and pressure are highest. In contrast, Inconel 625, while slightly more susceptible to erosion, compensates with greater flexibility, allowing it to absorb mechanical stress without significant structural damage. This makes Inconel 625 a preferred material for nozzles with complex geometries or regenerative cooling channels, where structural adaptability is crucial.

4.3. Manufacturing Feasibility

4.3.1. Additive Manufacturing and Weldability

The weldability and additive manufacturing (AM) feasibility of these materials significantly impact their suitability for modern propulsion systems. Inconel 625 exhibits excellent weldability, forming clean and defect-free welds with minimal post-processing requirements. Inconel 718, however, is prone to Laves phase formation during welding, requiring post-weld heat treatment (PWHT) to restore mechanical integrity. For additive manufacturing, Inconel 625 maintains better as-printed properties, with minimal porosity and cracking issues. Inconel 718 requires additional heat treatment to refine the grain structure and eliminate residual stresses, which may increase manufacturing complexity and costs. Applications utilizing complex nozzle geometries or integrated cooling channels benefit more from Inconel 625, whereas high-stress structural components favor Inconel 718 due to its higher mechanical strength.

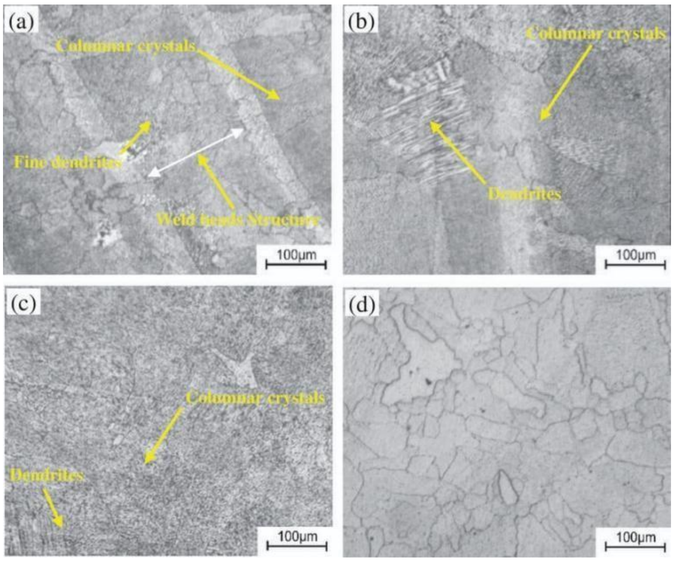

Figure 3(c): Microstructural comparison of welded and AM-processed Inconel 718 and Inconel 625

5. Conclusion

The study highlights the significance of material selection in rocket nozzle applications, particularly comparing Inconel 718 and Inconel 625 in terms of mechanical strength, corrosion resistance, and manufacturing feasibility.

- Inconel 718 exhibits superior mechanical strength, high creep resistance, and excellent erosion resistance, making it ideal for high-stress environments such as nozzle throats, where intense pressure and supersonic gas flow occur. Its precipitation-hardening mechanism enhances structural stability, but it requires post-weld heat treatment (PWHT) to mitigate Laves phase formation during fabrication.
- Inconel 625, in contrast, demonstrates exceptional corrosion and oxidation resistance, making it well-suited for long-duration missions and extreme thermal environments. Its solid solution strengthening mechanism provides better flexibility and fatigue resistance, ensuring durability in oxidizing and chemically reactive conditions. Additionally, Inconel 625 is more adaptable to welding and additive manufacturing, making it preferable for complex nozzle geometries.
- The selection of material depends on the specific propulsion requirements—Inconel 718 is the preferred choice for structural strength and erosion resistance, while Inconel 625 is better suited for environments requiring high corrosion resistance and manufacturability.

Optimizing material choice based on mission-specific demands is crucial for enhancing nozzle performance, lifespan, and overall propulsion efficiency. Future research can focus on hybrid materials, coatings, and improved manufacturing processes to further optimize rocket nozzle durability and efficiency.

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7. Conflict of Interest

The author declares no competing conflict of interest.

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