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# ADDITIVE MANUFACTURING OF THIN-WALLED INCONEL 718 BRACKETS FOR EXTREME CONDITIONS

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## Abstract

The demand for components capable of withstanding extreme conditions, including high and low temperatures and corrosive environments, continues to grow. In the aerospace industry, where weight is a critical factor, there is a pressing need for lightweight components made from materials like Inconel 718. Furthermore, there is high economic as well as ecological cost associated with subtractive manufacturing of light components from advanced materials. The high material removal rates are taxing on the tools and a significant amount of raw material is unutilized.

This paper presents an approach to manufacturing thin-walled components from Inconel 718 using additive manufacturing techniques, which greatly reduces material waste. Additionally, with this approach, no complex fixturing is needed. Variants of the additive manufacturing approach are proposed and compared to subtractive manufacturing. The effectiveness of 3D printing is among other things dependent on the part orientation, therefore, several print orientations are compared. Finally, a sample component is manufactured using the DMLS method. The load case is simulated, and the simulation is verified in a use case. In conclusion, we propose an innovative approach for manufacturing thin-walled aerospace components from Inconel 718 with reduced reliance on skilled labour. This approach offers significant advantages in terms of material efficiency and cost-effectiveness.

**Keywords:** Inconel 718; additive manufacturing; 3D printing; aerospace components

## 1. Introduction

The highly demanding applications in the aerospace industry require the production of components that can withstand extreme temperature variations. These aerospace components must be lightweight for fuel efficiency while possessing exceptional mechanical properties to ensure safety and performance. Currently, materials from the ISO S group are commonly used in the construction of such components. In scenarios that demand high mechanical stress resistance across fluctuating temperatures and superior creep resistance, nickel superalloys like Inconel 718 are the preferred choice. [1], [2]

However, machining Inconel 718 presents a significant challenge. It places considerable stress on both the machine tools and cutting tools due to the immense forces required for material removal. Tool wear rates are much higher compared to materials from other ISO groups, necessitating lower cutting speeds and resulting in significantly reduced material removal rates. This combination leads to substantial cost escalation in the manufacturing of components from ISO S materials. Moreover, these costs are not just financial; they also have environmental implications, as the subtractive manufacturing of such parts consumes a significant amount of $CO^2$. Additionally, aerospace components often require high material removal rates to achieve the desired weight savings. [3], [4]

This is where additive manufacturing comes in as a transformative solution for aerospace components. Additive manufacturing has the advantage of using materials almost entirely in the final part, thereby eliminating wastage. Furthermore, it completely eliminates tooling costs, reducing the overall expense of production. Various methods can be employed to manufacture specimens from Inconel 718, with fused deposition modelling (FDM) and direct metal laser sintering (DMLS) being among the most prevalent. FDM requires debinding and sintering post-3D printing but provides slightly lower resolution compared to DMLS. DMLS, on the other hand, offers more precision, with layer heights as low as 0.02 mm, and delivers detailed parts. Although the DMLS process generally results in a final part, a heat treatment step is usually carried out after the build process. [5], [6]

This study focuses on the process of manufacturing a thin-walled bracket component. The primary objectives include achieving maximum weight reduction while maintaining performance and ensuring operational safety. Additionally, the bracket must endure extreme temperature variations and exhibit resistance to corrosion. In pursuit of these goals, Inconel 718 was selected as the material, and through an additive manufacturing process, we explored the production of this aerospace component.

## 2. Materials and methods

The process of additive manufacturing for the specimen utilized the EOS M290 DMLS metal 3D printing machine. Inconel 718 powder, provided by EOS GmbH, was the chosen build material. A combination of Materialise Magics and EOS Print software facilitated the print date preparation. Post 3D printing and heat treatment, the material's yield strength stands at a minimum of 1145 MPa. Initially, the specimen underwent solution annealing, which involved a one-hour exposure to a temperature of 954°C (1750°F), followed by an argon-cooled environment. Subsequently, the specimen experienced ageing treatment (Step 2), entailing an 8-hour hold at 718°C (1325°F). The next phase included furnace cooling to 621°C (1150°F) and a subsequent 18-hour maintenance at this temperature for total precipitation. The final phase incorporated cooling the specimen to room temperature in an argon atmosphere. [7]

| **Properties** | **Values** |
|---|---|
| Yield strength – Rp0.2 [MPa] | 1145 |
| Tensile strength – Rm [MPa] | 1375 |
| Hardness, HRC | 47 |

Table 1. Mechanical properties of 3D printed and heat-treated Inconel 718 sample in the vertical direction. [7]

The component's design and load case simulation were conducted using Fusion 360 software. Since the part was designed for additive manufacturing, it includes many features that would be difficult to produce using other methods. The comparison between additive manufacturing and machining was based on the speeds and feeds recommended for machining this material, as per the tooling catalogue from Iscar. As the final step, the component underwent testing in one of its intended use cases. It was subjected to a 6 Kg payload at room temperature and maintained under this load for 180 hours. Two basic manufacturing methods, additive manufacturing and subtractive manufacturing (milling) are considered in this research.

## 3. Results and discussion

The subtractive manufacturing method was considered first, utilizing a raw material block of Inconel 718 with a 1 mm allowance on three sides and 4 mm on the last side. This setup allows the part to be held in a standard machining vice. The machining time was estimated at 28 minutes, based on the cutting conditions from the tool manufacturer. A significant disadvantage of this process is the high material removal rate. Using the raw material mentioned above results in the removal of 61,591 $mm^3$ of material, equating to a 97.17% material removal rate.

It is important to note that the component design heavily relies on additive manufacturing. Consequently, some features are not ideal for milling and would require rework. Additionally, a second operation would likely involve complex fixturing, and the extensive material removal could complicate the machining process due to the cutting forces generated by milling. The wall thickness is designed to be 1 mm. [8]

For the DMLS additive manufacturing process, the specimen must be connected to the steel build platform, either directly or using support structures. The latter is chosen here to minimize raw material use. Two orientations were considered (See Fig. 1): orientation a) requires 758 $mm^3$ of support material, while orientation b) needs only 595 $mm^3$. Despite using the least amount of support material, functional surfaces must also be considered (critical surfaces highlighted in Fig. 1). Support structure removal is labour-intensive, and achieving high-quality surfaces can be challenging. For these reasons, orientation a) was deemed more suitable and used.

The additive manufacturing process results in 758 mm3 of material wasted in support structures, while the subtractive process removes 61,591 mm3 of material as chips. From the standpoint of material waste, the additive approach is superior.

Energy consumption is closely related to the carbon footprint, a crucial consideration in modern manufacturing. A significant portion of energy consumption in Inconel 718 manufacturing is associated with raw material production. The raw powder for additive manufacturing requires additional atomization of the bulk material, using more energy. The embodied energy of bulk Inconel 718 is approximately 321 MJ/kg. The additive manufacturing process adds approximately 55.6 MJ/kg for atomization. Therefore, raw Inconel 718 powder for 3D printing requires approximately 376.6 MJ/kg of energy. [9] The energy needed for the manufacturing process itself was not considered here, as there would be significant differences based on the device used. The energy consumption of machining centres can vary by orders of magnitude. The total energy consumption for the raw material for the subtractively manufactured specimen would be 167.76 MJ, while the additively manufactured part would require 7.79 MJ of energy.

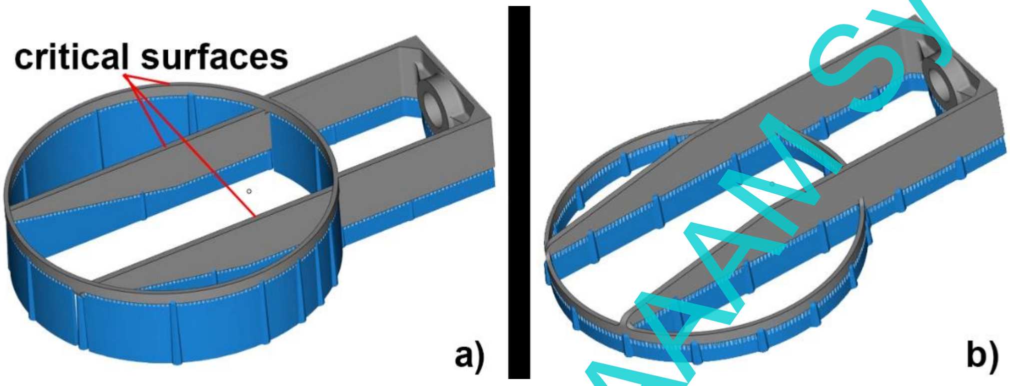

Fig. 1. Possible sample orientations with blue support structures

The integrity of the thin-walled design was rigorously evaluated using a static stress simulation. This step was crucial to ensure that the design could withstand the operational conditions it was intended for. The load case for the simulation was crafted based on the specific application requirements, where the component was expected to handle a 6 Kg cylindrical payload. To accurately mimic the real-world conditions, the bracket's connection to the rest of the assembly was also factored into the simulation. This connection was achieved through a single M6 bolt. The forces that this bolt would experience and transfer to the bracket during the operation were crucial parameters in the simulation. To maintain consistency and reliability in the results, a force of 1000 N was applied in the simulation. This value was derived from the ISO standard for a 10.9 class M6 bolt, ensuring that the simulation adhered to widely accepted engineering norms.

The results of the simulation indicate that the design was capable of supporting the specified 6 Kg payload. Moreover, the design demonstrated a minimum safety factor of 13.78. This safety factor, a measure of the structural capacity of the design beyond the expected loads, provided assurance that the component could reliably perform its function even under unforeseen dynamic events or slight overloads. In summary, the expanded analysis through static stress simulation not only validated the design's capability to handle the specified payload but also provided confidence in its structural integrity and safety under various conditions.

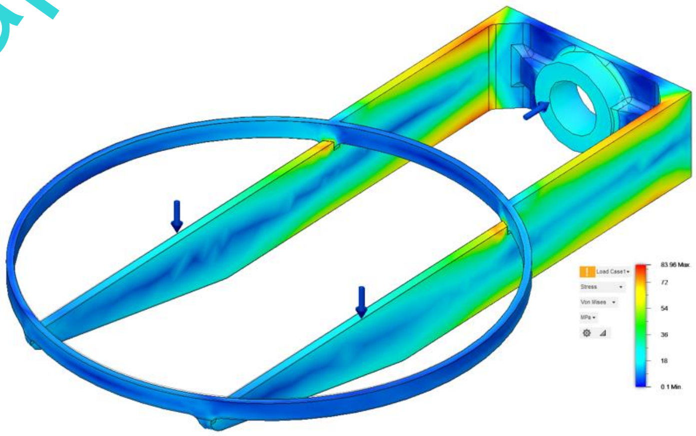

Fig. 2. Simulation of the sample load case

## 4. Conclusion

To conclude, a comparative analysis between additive and subtractive manufacturing processes was conducted for the fabrication of an aerospace bracket made from Inconel 718. The additive manufacturing approach was found to be superior in terms of energy consumption, requiring only 4.64% of the energy needed for milling. However, it's important to note that raw powder for additive manufacturing has about 14.76% higher embodied energy than the material for subtractive manufacturing. The energy savings for a general sample would be highly dependent on the material removal rate required.

For future research, thorough mechanical testing of the specimen must be conducted, with a particular focus on investigating the creep behaviour of the part. When considering the carbon footprint of a manufacturing process, various factors such as the geographical location of the manufactured raw materials, energy sources, and more need to be considered. A detailed future study focused on this topic is planned to gain a comprehensive understanding of the carbon footprint.

## 5. Acknowledgments

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