



Material characterization and performance of additively manufactured high temperature heat pump screw compressor rotors

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Abstract

Industrial processes with high heat energy demand account for approximately two thirds of total industrial energy use globally. These processes are mostly fossil fuel driven and offer significant potential for efficiency improvements. High-temperature heat pumps (HTHPs) are one of the most promising technologies that can replace (or be integrated into) existing heating processes. However, most systems on the market do not exceed heat sink temperatures ranging between 150 °C and 175 °C. To exceed this range limit and to be able to cover a wider range of applications, new components and manufacturing technologies must be evaluated to enable sustained operations at high temperatures.

This paper focuses on the design and manufacturing process of a twin-screw compressor by using selective laser melting (SLM) additive manufacturing process to produce the compressor rotors. The design target is to achieve a heat sink temperature of 200 °C with a temperature lift of 80 K. Therefore, material characterization tests were conducted with 3D-printed 18 Ni Maraging steel and 718 Inconel specimen. For both materials, specimens were printed in both horizontal and vertical build orientations to evaluate their material properties and compare them to a baseline material. Furthermore, the outcomes of the material tests were used in a coupled rotor-dynamics and fatigue model to simulate geometry deformation in a high-temperature environment, as found in an HTHP compressor. Based on the material test and simulation results, the best material and printing direction were selected, and the screw geometry was further optimized to enable efficient screw compressor operation at the design point of 205 °C discharge temperature.

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1. Introduction

With a global energy use of about 37%, industry is the energy usage sector with the highest individual demand [1]. In this share, heat intensive industrial processes account for approximately two thirds [2]. In 2022, just 5% of that heat demand was covered by electricity supplies in the United States while the remaining heat was provided by fossil-fuel based sources [3]. At the same time, electrically driven high temperature heat pumps (HTHPs) offer an energy-efficient alternative to the combustion of energy-dense fossil fuels. Also from an economic perspective, HTHPs for low quality heat (up to 100 °C) and medium quality heat (up to 200 °C) provide heat energy in a competitive range [4]. However, current high temperature heat pump designs with operating temperatures above 175 °C are often limited by the number of available working fluids for subcritical operation and the need for advanced cycle architectures and components [5], [6], [7]. Specifically, the compressor as key component of a vapor compression system requires additional attention. Some high temperature applications allow the use of commercially available compressors as shown with reciprocating

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compressor that were used for discharge temperatures up to 188 °C by Brendel et al. [8]. Other approaches focused on the redesign of compressor parts such as an optimized screw rotor [9]. However, a meaningful increase in efficiency and reliability for a HTHP compressor with discharge temperatures of 205 °C requires a significant redesign.

The given limitations of current compressor models can be overcome by expanding the design space with new manufacturing methods such as additive manufacturing. Initial efforts in applied HVAC&R and cryogenic systems have demonstrated the potential of metal additive manufacturing for advanced component design. Weiss et al. [10] introduced additive manufacturing in the design process of an Organic Rankine Cycle (ORC) expander turbines and nozzles and proved the feasibility of this manufacturing method, even for high-stress components operating at speeds above 24,000 RPM. Doll et al. [11] successfully used metal 3D printing for a submersible helium centrifugal pump. Their pump design showed that metal 3D printed parts can withstand even extremely low temperatures without problems. Wang et al. [12] even investigated metal 3D printing as an alternative manufacturing method for screw compressor rotors and reported a generally positive outcome. While the use of additive manufacturing in HVAC&R components is not completely new, the research in this field is not very developed yet. Most projects used additive manufacturing either to optimize the prototyping process or to compare it to conventional manufacturing techniques.

The current project goes beyond the existing body of work and the target is to design and manufacture a screw compressor for HTHP applications with internally cooled screws and demonstrate the quality control of the printed parts [13]. To identify the correct material for the application in a compressor, a series of mechanical and metallographic tests was conducted on additive manufactured metal samples. The measured mechanical properties were implemented in a numerical structural analysis to verify the theoretical predictions.

2. Additive manufacturing process

2.1. Powder Selection

At the outset of the material evaluation process, the basic decision had to be made which materials should be printed and tested. The selection was primarily based on the metal powder types available in the university's additive manufacturing facility, resulting in four candidate materials: 1. Titanium (Matsuura Titanium 6A14V Powder); 2. 18 Ni Maraging Steel (Matsuura Maraging II Powder – MAT-0114A); 3. Inconel 718 (Matsuura Nickel Alloy 718 powder – MAT-0116A); 4. Stainless Steel (Matsuura 316L Stainless Steel).

Based on an initial review of published material properties [14], [15], [16], [17], it was decided to not continue the investigation of stainless steel and titanium. The decision against titanium and stainless steel was made due to their insufficient high-temperature strength that significantly reduces for above 250 °C and 350 °C for stainless steel and titanium, respectively. Even though these temperatures are not going to be reached in the HTHP compressor, the change of the material properties close to these temperatures can negatively impact the long-term stability and lifetime of the components. Furthermore, stainless steel appears to be harder to finish mechanically in a milling or grinding process. The advantages of titanium's lower weight and stainless steel's corrosion resistance are properties that are not required for use as screw compressor rotors in industrial applications. In addition to this, the higher material powder costs cause an economic disadvantage.

Therefore, the decision was made to use 18 Ni Maraging Steel and Inconel 718. Additive manufacturing of both materials shows very beneficial properties for the use in HTHPs due to limited warping during the printing and controllable residual stresses. Additionally, both of the selected materials are comparatively easy to machine and allow post processing such as aging and heat treatment and are predicted to behave similar to the SAE1141 [18] steel that was used for rotors of the baseline compressor.

2.2. 3D-printing and specimen preparation

The specimens were printed in a laser powder bed fusion (LPBF) process which is a selective laser melting (SLM) process. The materials were manufactured in two different machines: the 18 Ni Maraging Steel was printed in a *Matsuura Lumex Avance-25* printer in a nitrogen gas atmosphere while the Inconel 718 was printed in a *Renishaw AM 400 Laser Melting System* in an argon gas atmosphere. Both printers operated with the settings shown in Table 1 to ensure comparable printing quality and outcomes.

Table 1. Printer settings

Laser Power	240 W
Spot Diameter	200 μm
Scan Speed	700 mm/s
Hatch Pitch	110 μm
Hatch Pattern Rotation	67 °/layer
Layer Thickness	50 μm

Besides using two different materials, two printing directions were also investigated. For each material, 10 test bars were printed in ZX direction (Figure 1), in the following they will be called vertical specimens. Furthermore, 10 test bars of each material were printed in XY direction as illustrated in Figure 1; they will be referred to as horizontal specimens in this report. The different orientations were selected to identify their impact on mechanical strength (tensile strength, shear strength) as well as the printing quality (accuracy, warping). It is worth mentioning that the horizontal print usually comes with an economic advantage. Since the powder bed must be built up over the whole build platform during the printing process, a vertical print requires not just more powder but also a longer time to create the bed layers. However, depending on the geometry, the horizontal print may require more support structures to avoid warping. The removal of the support structures causes additional machine time that should not be neglected in this comparison as well.

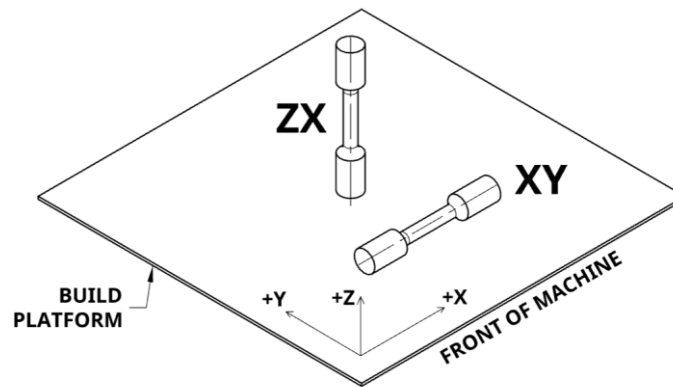


Figure 1. Printing Orientations according to ASTM standard F2971 [19]

The specimen were built as dog bone-shaped test bars and designed as cylindrical test specimen following the ASTM E8/E8M Standard [20] for round tension test specimen. The decision to use cylindrical test specimen rather than flat test specimen was made to allow the use of the same specimen for the tensile and the torsion tests and to keep them interchangeable. In addition to that, the cylindrical shape provides more stability in printing process of the vertical samples. The set of specimens made of 18 Ni Maraging steel were manufactured in the specimen size 2 with a gauge section diameter of 9 mm. Since the material appeared to be more resistant than expected during the initial tests the decision was made to progress with specimen size 3 with a gauge section diameter of 6 mm to remain within the specified operation boundaries of the test instrument and to decrease the overall test times. Since both sizes are small-size specimen dimensions that are proportional to the standard (specimen size 1) with a diameter of 12.5 mm, the test outcomes are directly comparable.

The ASTM E8/E8M standard does require the test bars to be machined and polished to the final dimension. The surface cannot remain in the pattern of the raw print. The reason for this is that surface imperfections, such as layer and surface imperfections, as well as remaining support structures can negatively influence the result of the mechanical tests. To ensure a smooth and uniform surface, the printed parts were machined on a lathe to the final standard conform dimensions. Due to the high quality of the machined surface and due to a limitation of equipment, the test surfaces were polished by hand. The vice zones were machined to a diameter of 15 mm for both specimen sizes due to the available vice grips of the testing machine. Of the 10 printed specimen for each material and each printing direction (40 specimen in total), 4 test bars were prepared for tensile testing and 3 test bars for the torsion testing. This number was taken based on the sample size of publications in the field and the experience of the personal that supported the mechanical tests. The remaining test bars were cut and used for metallurgical and material compatibility tests.

3. Mechanical Testing

The utilized testing machine was the *MTS 809 Axial/Torsional Test System*. This machine was selected for two reasons: (1) the maximum tensile strength of 100 kN was higher than the predicted ultimate tensile strength (UTS) for the tensile test bars and (2) the machine is not only capable of conducting tensile tests (ASTM E8/E8M [20]) but also able to conduct torsion tests (ISO 1352:2021 [21]) with a maximum torsion angle of $\pm 35^\circ$ as machine limit.

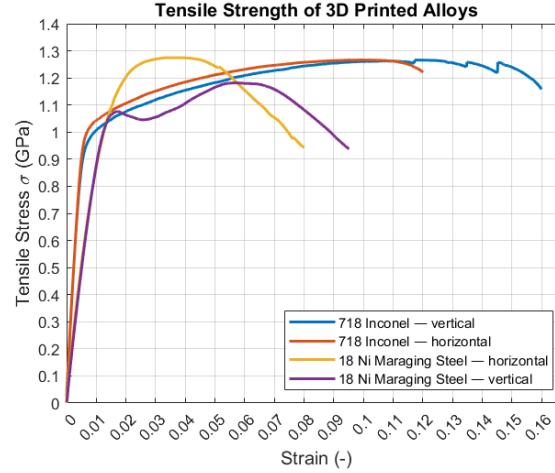


Figure 2. Summary of tensile test results of the investigated metal alloys and printing orientations

3.1. Tensile Test

Figure 2 shows the average results of the tensile tests that were conducted according to the ASTM E8/E8M standard with 4 specimens being tested for each of the two materials (18 Ni Maraging Steel, Inconel 718) and each of the two printing directions (horizontal and vertical). The diagram shows the tensile strain on the x-axis and the tensile stress on the y-axis. The data was calculated and processed from a raw data set for each test specimen that contained the recorded tensile force during the test, the test time, and the displacement. For the plotting and analysis step, the tensile strain ε is a dimensionless number and calculated as the ratio of the change in length ΔL over the original length L_0

$$\varepsilon = \frac{\Delta L}{L_0} \quad (1)$$

The tensile strength σ in Pa is calculated as the measured force F_σ in N over the cross-sectional area of the specimen A

$$\sigma = \frac{F_\sigma}{A} \quad (2)$$

Adjusted for a cylindrical specimen, σ is calculated using the diameter d in m

$$\sigma = \frac{4 \cdot F_\sigma}{\pi \cdot d^2} \quad (3)$$

Based on Eq. 3, the ultimate tensile strength σ_{UTS} for each data set can be calculated as by using the maximum recorded force $F_{\sigma, \max}$.

$$\sigma_{UTS} = \frac{4 \cdot F_{\sigma, \max}}{\pi \cdot d^2} \quad (4)$$

The results of the numerical calculation are reported in Table 2. The averaged tensile strength values are all in a range between 1.2013 and 1.2834 GPa. Overall, Inconel 718 appears to show more consistent test values, not just between the individual data sets but also between the horizontal and vertical print direction. 18 Ni Maraging Steel indicates larger outliers and an overall higher spread between horizontal and vertical printing direction.

Table 2. Numerical analysis of tensile test according to ASTM E8/E8M [20]

Material	Minimum Tensile Strength (GPa)	Average UTS (GPa)	Maximum Tensile Strength (GPa)	Range (%)
18 Ni Maraging Steel (horizontal)	1.2486	1.2637	1.3074	-1.19 / +3.46
18 Ni Maraging Steel (vertical)	1.0871	1.2013	1.2603	-9.51 / +4.91
718 Inconel (horizontal)	1.2292	1.2834	1.3013	-4.22 / +1.39
718 Inconel (vertical)	1.2606	1.2643	1.2685	-0.29 / +0.33

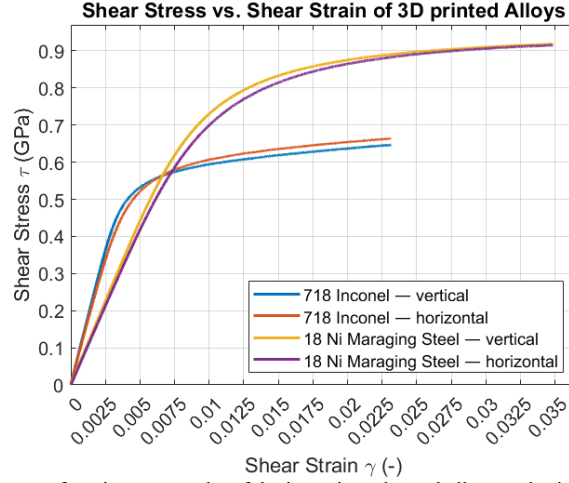


Figure 3. Summary of torsion test results of the investigated metal alloys and printing orientations

3.2. Torsion Test

Figure 3 shows the results of the torsion tests that were conducted according to the ISO 1352:2021 standard with a total of 3 specimens being tested for each of the two materials (18 Ni Maraging Steel, Inconel 718) and each of the two printing directions (horizontal and vertical). The diagrams show the shear strain on the x-axis and the shear stress on the y-axis. The data was calculated and processed from a raw data set for each test specimen that contained the recorded torsional force that was applied during the test, the test time, and the torsion angle or twist.

For the plotting and analysis step, shear strain γ is a dimensionless number and calculated as the ratio of lateral displacement Δx during the torsion test over the original height h

$$\gamma = \frac{\Delta x}{h} \quad (5)$$

Adjusted for a cylindrical specimen, γ is calculated using the radius r in m, the twist angle Θ in degrees and the gauge length L in m

$$\gamma = \frac{\pi \cdot r \cdot \theta}{180 \cdot L} \quad (6)$$

The shear strength τ in Pa is calculated as the applied shear force F_τ in N over the cross-sectional area of the specimen A

$$\tau = \frac{F_\tau}{A} \quad (7)$$

Adjusted for a cylindrical specimen, τ is calculated using the diameter d in m

$$\tau = \frac{4 \cdot F_\tau}{\pi \cdot d^2} \quad (8)$$

Based on Eq. 8, the maximum shear stress $\tau_{\max}$ for each data set can be calculated as by using the maximum recorded force $F_{\tau, \max}$

$$\tau_{\max} = \frac{4 \cdot F_{\tau, \max}}{\pi \cdot d^2} \quad (9)$$

Due to the limitation of the maximum twist angle $\Theta_{\max}$ at 35° , the fracture point of the samples in the torsion tests could not be reached. Since the slope of the graphs significantly reduced in all cases close to the 35° mark, this value was assumed to be the maximum shear strength. The values elaborated by this conservative approach are very close to the actual $\tau_{\max}$. Since the maximum value is not exactly reached, just the elastic and the plastic deformation phase without necking is visible in the graphs.

Table 3. Numerical analysis of torsion test according to ISO1252:2021[21]

Material	Minimum Shear Strength (GPa)	Average Shear Strength (GPa)	Maximum Shear Strength (GPa)	Range (%)
18 Ni Maraging Steel (horizontal)	0.9072	0.9162	0.9240	-0.98 / +0.85
18 Ni Maraging Steel (vertical)	0.9189	0.9190	0.9191	-0.01 / +0.01
718 Inconel (horizontal)	0.6531	0.6656	0.6747	-1.88 / +1.37
718 Inconel (vertical)	0.6438	0.6484	0.6517	-0.71 / +0.51

The results of the numerical calculation can be seen in Table 3. The average shear strength values are all in a range between 0.6484 and 0.9190 GPa. Both 18 Ni Maraging steel and Inconel 718 show very consistent test values, not just between the individual data sets, with deviations smaller than 2%, but also between the horizontal and vertical print direction. It stands out that in direct comparison to 18 Ni maraging steel, Inconel 718 has a notably lower shear strength.

3.3. Conclusions of the mechanical tests

The graphs in Figure 2 clearly show the three main phases of the sample deformation during the tensile tests: (1) It starts with the elastic deformation phase where the graphs increase with a very steep slope. In this phase the tensile stress increases strongly while the strain remains very small. If the force were removed at this point, the specimen would turn back to its original shape, similar to a spring. During the machine operation, the elastic deformation zone should never be exceeded; (2) After the so-called yield strength is exceeded, the plastic deformation begins. In this phase, the tensile strength increases until the ultimate tensile strength (UTS) reaches the peak of the graph. Phase 2 is also called strain hardening phase since the material gets stronger as it stretches. At this point, the specimen is plastically deformed, meaning it will not transfer back to its original length on its own, but the diameter of the specimen is not necked yet; (3) The last phase is characterized by necking, a localized thinning where the cross section shrinks quickly. On the graph, the material appears to be weaker but in reality, the true stress (stress adjusted for the necking diameter) of the material increases because the area is shrinking faster than the load drops. The strain increases until the fracture of the specimen occurs. However, the material properties show distinct differences, as shown in Figure 2. All investigated materials can be characterized as ductile. Overall, Inconel 718 performed better in the tensile strength test with higher tensile strength for both printing orientations, higher consistency (low deviation) and much higher fracture strain. The diagram also shows that other than the Inconel 718, the 18 Ni Maraging Steel very well shows different properties between the two printing directions. However, the deviations mostly appear in the plastic deformation zone while the trends for elastic deformation behave very uniform. It is important to point out that both materials far exceed the properties of the material SAE 1141 as it is used for the rotors of the baseline compressor [18].

For the torsion tests, summery graphs in Figure 3 shows the distinct differences between the materials. While both materials can be characterized as ductile, 18 Ni Maraging Steel is performing better in the torsion test with a notable higher shear strength for both printing orientations, higher consistency (low deviation) and much higher fracture strain. Inconel 718 is performing constant as well. However, the maximum shear stress values are about 0.15 GPa lower than the one of the 18 Ni Maraging Steel. While both materials exceed the properties of the SAE 1141 steel that is used in the baseline device 18 Ni Maraging Steel is the superior material based on the mechanical investigation.

4. Metallographic Testing

Metallography is the optical science of studying the microstructure of metals and alloys to understand its properties. To elaborate the printing quality but also gain knowledge about the metallurgical background of the mechanical test results and to understand them better, scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) tests were conducted.

4.1. SEM Imaging

Scanning electron microscopy (SEM) is a process in which a picture is generated with an electron microscope by scanning the surface with a focused beam of electrons. The electron scan operated in a raster scan pattern and the position of the beam is combined with the detected signal to produce an image. The process is applied when very high resolutions of up to 1 nanometer are needed. For this investigation it was used to analyze and compare the unmachined surface of the 3D printed specimens and as a preliminary step for the EBSD analysis

The electron microscope that was used for the investigation is the *Thermo Scientific Helios G4 UX Dual Beam*. The microscope is a conventional SEM, that means that it is operating with a working chamber pressure in high vacuum.

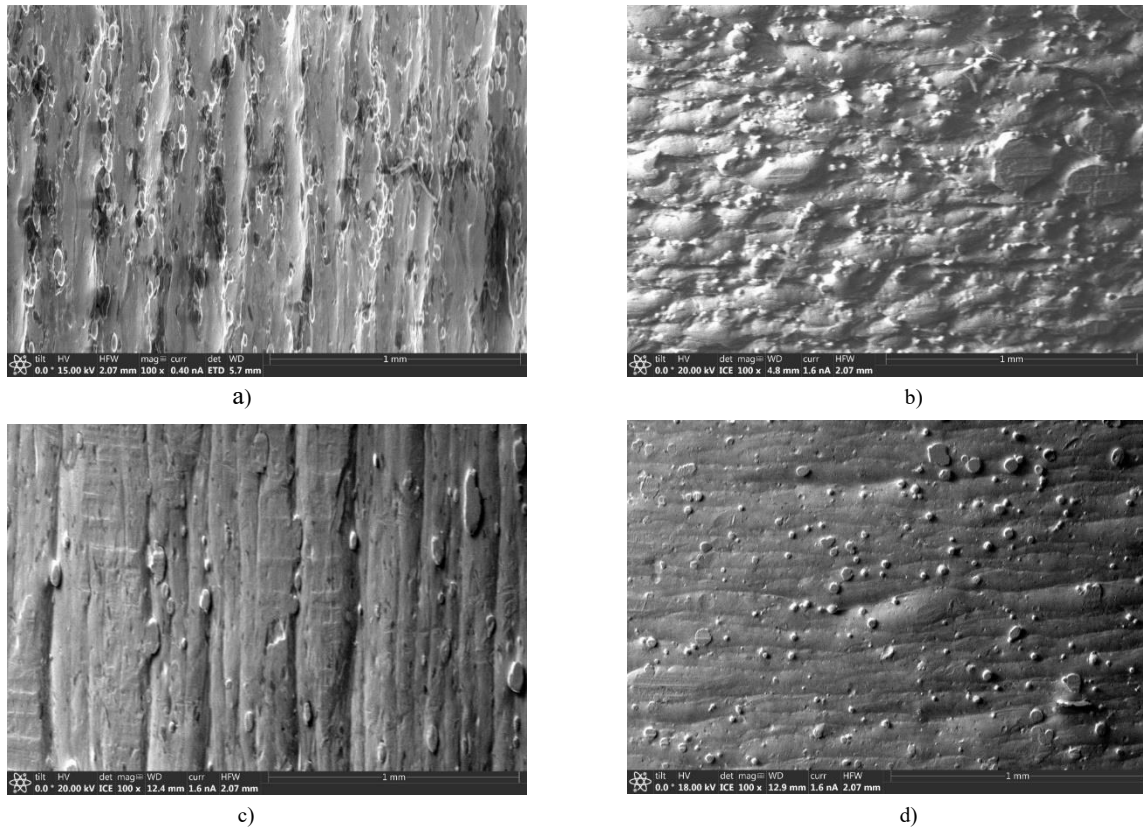


Figure 4. SEM pictures of the unmachined 3D printed surface: (a) 18 Ni Maraging Steel in horizontal direction, (b) 18 Ni Maraging Steel in vertical direction, (c) Inconel 718 in horizontal direction, (d) Inconel 718 in vertical direction

Figure 4 shows the unmachined surfaces of the 3D printed specimen with 1000x magnification. 18 Ni Maraging Steel shows a rougher surface with more and larger protrusions vertical print direction. However, the surface is even and consistent. Inconel 718 shows an overall better surface pattern with smaller and less protrusions. It is to mention though, that none of the prints provide a good enough surface quality to be used for a unmachined screw rotor. Polishing will be necessary.

Figure 5 shows the capabilities of SEM: By simply zooming in to a magnification of 6492x for 18 Ni Maraging Steel and 800x for Inconel 718, the grain structure and boundaries can be seen on the metal surface without additional measures such as etching. The only preparation that is needed is a high-quality polish of the surface.

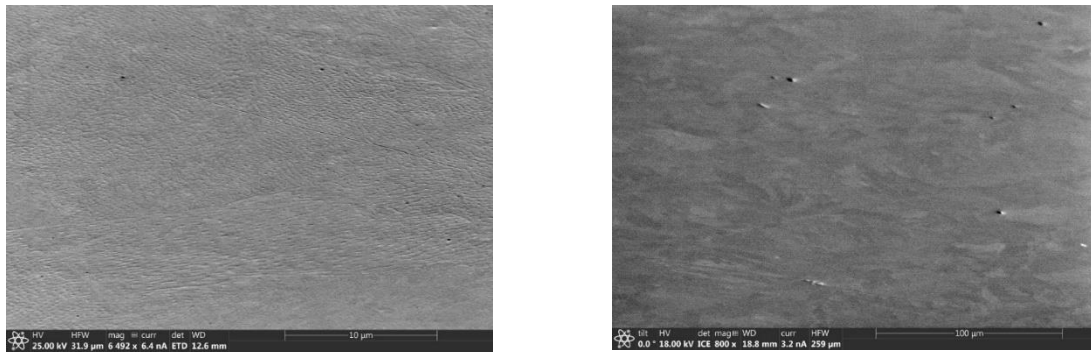


Figure 5. SEM of a polished surface: 18 Ni Maraging Steel (left), Inconel 718 (right)

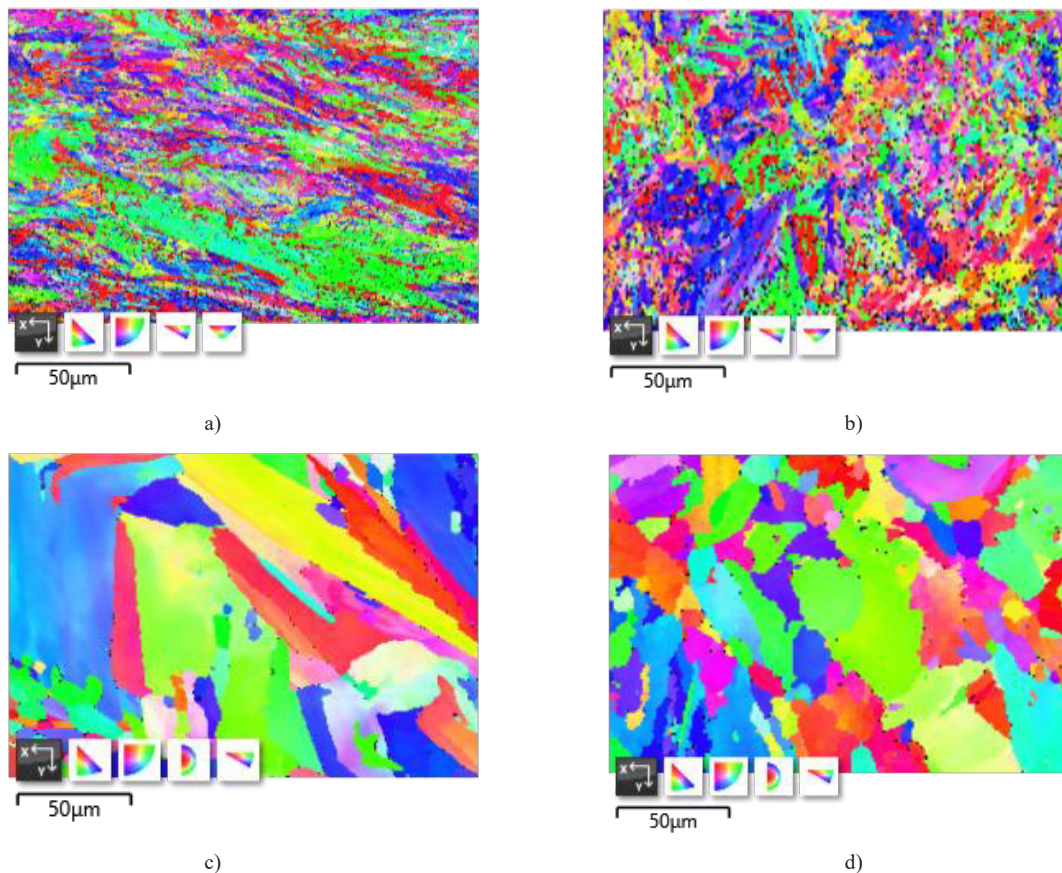


Figure 6. IPF X maps: (a) 18 Ni Maraging Steel (horizontal), (b) 18 Ni Maraging Steel (vertical), (c) Inconel 718 (horizontal), (d) Inconel 718 (vertical)

4.2. EBSD Processing

To closer investigate the grain size and orientation of the prints, an EBSD analysis was conducted. EBSD is a sub technique of SEM to analyze the crystallographic structure of materials, meaning the grain size, grain boundaries, grain orientation and grain pattern of a metal or material. In this case, the electron beam that hits the surface and is reflected from it is detected by a phosphor receiver screen. Based on the received beam and the known elements from the EDS step, the grain boundaries and orientations can be calculated based on the refraction of the beam.

The generated grain maps for each material are shown and the trends are described, a comparison will be made at the end. For each material and printing direction, the inverse pole figures (IPF) in Z direction are displayed. In the IPF maps, each pixel is colored according to the direction of a particular sample axis (e.g., surface or print direction) as seen in the crystal reference frame. The IPF maps highlight the preferred

orientation of the grains and the texture that comes with it. For example, if grains are mostly red or orange colored, the grains are oriented parallel to the samples reference direction which is usually an indicator for a strong texture along the investigated direction. Indicator for a strong metallic material with interconnected grain in all 3 coordinate directions is a small grain size and a consistent mix of red, green and blue based colors.

4.3. Imaging Analysis

Figure 6 a) and b) show the EBSD maps for 18 Ni maraging steel in horizontal printing direction and vertical printing direction respectively. From both directions, the material shows a thin and long grain structure as typical for the lath martensite structure as it usually appears in maraging steel. The constant grain pattern and the varying orientations, indicated by the darker red colors and the lighter green colors cause for structural stability in all 3 coordinate directions which might be the reason for the large shear strength of the material.

Differently behaves the microstructural pattern for Inconel 718. While the map shows lengthy shaped and heterogeneously distributed metal grains in the horizontal printing direction (Figure 6 c), it shows a smaller, and uniformly distributed grain pattern in the vertical printing direction (Figure 6 d). Also, the grain size of the Inconel 718 is noticeable larger than the one of the 18 Ni Maraging Steel. This correlates to the Hall-Petch relationships which claims that the yield strength of a polycrystalline material increases as the grain size decreases. This is because the grain boundaries act as barriers to the dislocation movement and, and a finer grain size means there are more boundaries to impede this movement. Mathematically, this can be described by

$$\sigma_y = \sigma_0 + k_y d_{\text{grain}}^{-1/2} \quad (10)$$

where σ_y is the yield strength in Pa, d_{grain} is the average grain size in m, σ_0 is the friction stress in N/m² and $k_{y\text{vis}}$ the Hall Petch coefficient (Pa m^{1/2}).

This relationship backs up the finding that the shear strength of Inconel 718 is significantly lower than the one of 18 Ni Maraging Steel. Also, the trend that Inconel 718 has a longer strain in the plastic deformation of the tensile strength correlated to this.

In summary, the mechanical and metallographic investigations lead to the outcome that 18 Ni Maraging Steel is better suitable for the application in a high temperature heat pump screw compressor. This conclusion then needs to be confirmed in a numerical model in the next step.

5. Numerical Model

The numerical model that was set up for this work is part of a broader research project that aims to develop an advanced internally cooled screw compressor for an HTHP. In the planned design, liquid refrigerant will be circulated through hollow screw rotors to enhance the thermal management and improve the performance of the compressor. The present structural study serves as a preliminary investigation and focuses on the baseline solid rotor geometry, which provides essential reference data for evaluate the influence of future design modifications. While the material study has only limited impact on the outcomes at this stage, the results will become more substantial once the hollow rotor design is introduced to the model. All simulations were conducted in COMSOL Multiphysics [22], and the system boundary conditions that will be elaborated closer in the following paragraphs are defined by the cycle calculations from Gadagkar et al. [7]. The analysis examined thermally induced deformation, and rotor dynamics at an operating speed of 5,000 RPM. Since 18 Ni maraging steel had the best performance during the mechanical tests, the material values were adjusted for this steel.

5.1. Thermal Expansion

The temperature induced stress (Figure 7 left) was evaluated by applying the temperature boundary conditions representative of the HTHP scenario. The rotor front face was fixed at the suction temperature of 129.6 °C, while the discharge side was set to 204.8 °C to establish a realistic axial temperature gradient. The resulting expansion increases from the suction toward the discharge end with maximum deformations of 0.24 mm in axial (z) direction and 0.067 mm in radial (y) direction. Therefore, 18 Ni maraging performed better than the previously applied SAE 1141 steel with fewer temperature induced thermal deformations. Although material effects remain secondary for the solid rotor, these deformation magnitudes provide an important baseline against which the future hollow-screw designs can be compared.

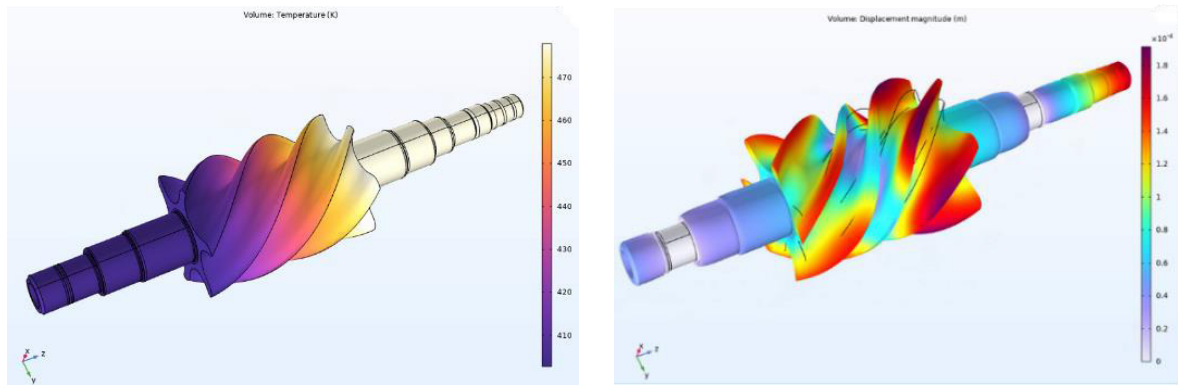


Figure 7. Overview of structural analysis on female rotor: Thermal stress (left) and surface deformation due to rotor dynamics (right)

5.2. Rotor Dynamics

The rotor dynamics (Figure 7 right) were evaluated at nominal operating speed of 5,000 RPM as they appear in the baseline compressor. The pressure-induced deformations were assessed by applying the suction pressure of 512 kPa and discharge pressure of 2650 kPa respectively, from the system model [7]. A linear axial pressure distribution was assumed for the simulation. Results indicate that the maximum dynamic deformation occurs near the rotor shaft due to the acting discharge conditions but also at the tips of the rotor edges due to the thinner material. While the material effects, are modest for the solid geometry in a direct material comparison, these findings become more significant once mass distribution, stiffness and damping properties change due to the hollow screw design.

6. Conclusion and Future Work

The presented work investigated the use of additively manufactured metals for the use in high-temperature screw compressors with discharge temperatures of above 200 °C. The investigation focused on two predefined materials 18 Ni maraging steel and Inconel 718 that were manufactured using laser powder bed fusion in both horizontal and vertical print directions. Their mechanical properties were quantified through standardized tensile and torsion testing. In addition to that, their microstructural characteristics were examined using SEM and EBSD. The resulting properties were applied to a numerical structural model of a baseline solid screw rotor to evaluate the temperature induced stress and the rotor dynamics of the part under the operating conditions of an HTHP.

Across the conducted experiments, 18 Ni maraging steel emerged as the superior material for high-temperature screw compressor rotor, showing a higher shear strength, consistent mechanical behavior and uniform lath-martensitic grain structure. In contrast, Inconel 718 proved good ductility and consistently high tensile strength but stood out negatively with a lower shear strength which could be related to the larger, less uniform grains during the metal characterization process. Numerical simulation further confirmed that 18 Ni maraging steel produces smaller thermal deformation than the baseline SAE 1141 steel providing a better foundation for future hollow screw design.

For future work, the findings of this paper will be extended to hollow, internally cooled screw rotor geometries. For these future investigations, the mass distribution, stiffness and thermal loading will have a much higher impact on the deformation of the rotor itself and therefore become more critical. Experimental validation using additively manufactured prototype rotors will be able to further confirm the performance of the compressor concept in general and the use of additively manufactured parts specifically.

Nomenclature

HTHP	High Temperature Heat Pump
UTS	Ultimate Tensile Strength (GPa)
HVAC&R	Heating Ventilation Air Conditioning and Refrigeration
ASTM	American Society for Testing and Materials
EBS	Electron Backscatter Diffraction
EDS	Energy-Dispersive X-Ray Spectroscopy
ISO	International Organization for Standardization
IPF	Inverse Pole Figure
LPBF	Laser Powder Bed Fusion
ORC	Organic Rankine Cycle
SAE	Society of Automotive Engineers
SEM	Scanning Electron Microscopy
SLM	Selective Laser Melting

Symbols

σ	Tensile Strength (Pa)
ε	Tensile Strain
τ	Shear Stress (Pa)
γ	Shear Strain
ΔL	Change in Length (m)
L_0	Original Length (m)
L	Gauge Length (m)
A	Area (m ²)
d	Diameter (m)
d_{grain}	Average Grain Size in (m)
Δx	Lateral Displacement (m)
h	Original height of specimen (m)
r	Radius (m)
F_{σ}	Tensile Force (N)
F_{τ}	Shear Force (N)
$F_{\sigma, \text{max}}$	Maximum Tensile Force (N)
$F_{\tau, \text{max}}$	Maximum shear Force (N)
σ_{UTS}	Ultimate Tensile Strength (Pa)
σ_{γ}	Yield Strength (Pa)
σ_0	Friction Stress (N/m ²)
τ_{max}	Maximum Shear Stress (Pa)
Θ	Twist Angle (°)
Θ_{max}	Maximum Twist Angle (°)
k_{γ}	Hall-Petch Coefficient (Pa m ^{1/2})

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