Hot Tension and Creep Ranking of 3D printed ODS Nickel-base Superalloys

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Introduction

Inconel 718 (IN718) is a widely used Ni-based superalloy known for its high-temperature strength and durability, making it a key material in aerospace and energy applications. While IN718 maintains excellent mechanical properties up to 650ºC, its strength diminishes beyond this temperature due to the dissolution of γ'' precipitates, limiting its applicability in extreme environments. Recent research has focused on enhancing the high-temperature performance of IN718 through oxide dispersion (ODS) and carbide dispersion strengthening [1], which can stabilize the microstructure and improve mechanical resistance. Additionally, heat treatment and hot isostatic pressing (HIP) have been explored as methods to refine the alloy's microstructure stability further and optimize its mechanical properties. Alloy Y, an optimized version of TSNA-6, is a local transformation-strengthened NASA alloy (TSNA) designed for high-performance jet engine turbine disk applications. Transformation strengthening in TSNA alloys promotes the formation of both η and χ phases, dynamically-forming ordered defect phases that can actively strengthen [2], [3]. This study aims to rank the creep resistance and strength of ODS IN718, ODS Alloy Y, and non-ODS Alloy Y and determine if superior strengthening is observed when compared to the latter.

This study utilizes hot profilometry-based indentation plastometry (PIP), a miniaturized test method for evaluating the mechanical properties of metallic materials. The minimum specimen size is 10mm x 10mm x 3mm. Inverse finite element analysis is employed to predict the stress-strain curve of a material from indentation data. Creep ranking tests are performed under load control, where the LVDT displacement over time is recorded and the indentation depth is compared between samples. This technique offers a significant advantage over traditional high-temperature mechanical testing by reducing the time, cost, and volume of material required to evaluate a candidate alloy. A very small quantity of powder can be synthesized, used to 3D printing specimens, and explore heat treatments, enabling a high-throughput experimental pathway to connect chemistry, microstructure, and performance.

Research Objective

The objective of this study is to investigate the mechanical properties and microstructural evolution of ODS IN718 and ODS Alloy Y at 700°C to assess the effectiveness of oxide dispersion strengthening and transformation strengthening at elevated temperatures. The goal is to determine which alloy exhibits superior resistance. The following tasks are completed.

1. Hot tensile and creep ranking tests are performed via Hot PIP of miniature samples to assess mechanical properties. The 2D and 3D shape of the indentation is extracted via digital microscopy.
2. Optical and scanning electron microscopy (SEM) and transmission electron microscopy (TEM) of the deformed region below indentations are performed to evaluate microstructural evolution.

Materials and Methods

Three alloys are evaluated: ODS IN718, aged ODS Alloy Y, and aged Alloy Y non-ODS. All three specimens were HIPed, with a treatment of 1200ºC for four hours at 100MPa. Aged Alloy Y was aged at 855ºC for four hours, followed by 775ºC for eight hours, and finished with air cooling [4]. For indentation testing, specimen faces were polished to 1200-grit as per system requirements.

Hot PIP is performed using a 1 mm indenter tip. The specimen is placed below the tip, on the heated stage. Hot tension and creep tests are performed at 700ºC with a soak time of five and fifteen minutes, respectively. Temperature is measured via three K-type thermocouples embedded in the cartridge heaters. Specimen temperature is calculated based on sample thickness, with thermal conductivity set to 11.4 W/m-K based on literature [5]. Specimen temperature is verified via a welded K-type thermocouple and shown to be within ±8°C.

In the hot tension test, a fixed displacement rate of 3.018 µm/s is set (by default). The indenter encounters the sample, and then the indentation process begins. The indentation continues until the penetration depth reaches 200 µm (a penetration ratio of 20%), at which point the test is stopped and the sample is air-cooled. After cooling, the sample surface is cleaned, and a profilometry is used to capture the residual indentation profile in the x-, y-, xy-, and yx-directions across the indent to identify potential anisotropy. The load-displacement and residual indentation profiles are transferred to an inverse finite element analysis software to generate stress-strain curves utilizing the Voce Plasticity Law.

In the creep ranking testing, a fixed load is applied to a specimen on top of a pre-existing indent from a hot tension test. Load is 50% of the final load of the hot tension test, applied for eight hours (or until an indentation depth of 200 μm is reached). An LVDT displacement versus time graph is produced by the system (penetration depth as a function of time).

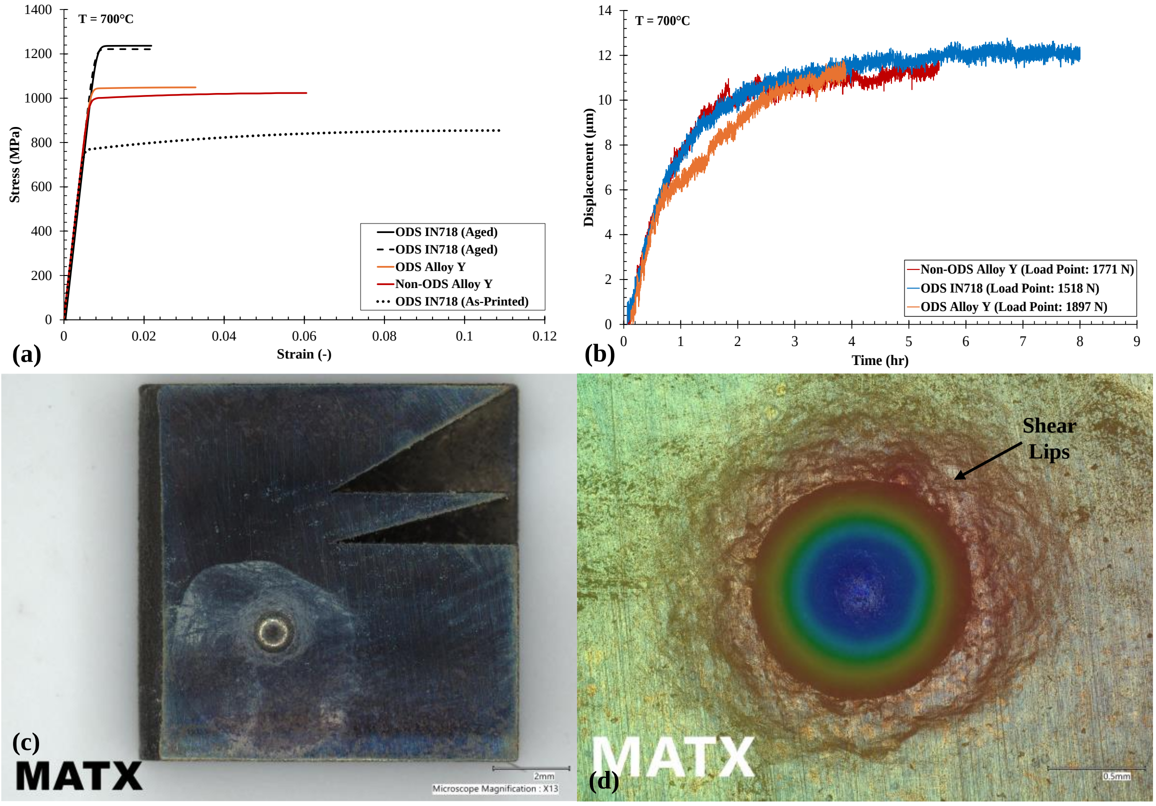

Figure 1: Test Results of (a) hot tension engineering stress-strain curve, (b) creep ranking curves at 700°C, (c) 2D indentation profile, and (d) 3D topology map of representative sample after creep testing

Results

The test results for ODS IN718, ODS Alloy Y, and non-ODS Alloy Y at 700°C are summarized in Figure 1. The engineering stress-strain curves obtained from hot tension tests are provided in Figure 1a. Both Alloy Y specimens show minimal strain hardening. ODS Alloy Y appears to be stronger than its non-ODS counterpart. ODS Alloy Y had a yield strength of 1044 ± 35 MPa and a tensile strength of 1049 MPa, with a confidence bound of +29 / -16 MPa. non-ODS Alloy Y had a yield strength of 1001 ± 22 MPa and a tensile strength of 1024 MPa with a confidence bound of +21 / -15 MPa. Due to specimen preparation issues, the stress-strain curve for ODS IN718 could not be plotted, and the alloy is to be reprepared and tested. However, preliminary HotPIP testing on aged and as-printed ODS IN718 samples shows a tensile strength ranging from 850 MPa to 1250 MPa at 700°C, where heat treatment promotes the precipitation of the strengthening gamma prime phase. The tensile strength of hot-rolled, annealed, and aged IN718 is 904 MPa [6, p. 718].

As seen in Figure 1b, all specimens exhibit similar creep ranking behaviour. Creep ranking is evaluated as follows. The material with the highest creep resistance exhibits the least amount of indentation creep. Applied load should also be considered, where if the creep load applied is higher for a specific material and the indentation creep rates are identical, the material with the higher load has better creep resistance. Loads in ODS alloy Y, non-ODS Alloy Y, and ODS IN718 are subjected to 1897, 1771, and 1518 N, respectively. These outcomes, where the creep ranking behaviour is similar and ODS Alloy Y is tested at the highest load, suggest it has the strongest creep resistance. Note, the IN718 creep test ran for a complete 8-hour test, whereas ODS Alloy Y and non-ODS Alloy Y tests were interrupted at 3.89 and 5.53 hours, respectively. Additional tests should be performed to compare creep ranking curves of similar duration.

Optical microscopy of the indent is shown in Figures 1c and 1d; the indent diameter is measured as 1.12 mm (12% larger than the 1 mm indenter) with a depth of 183.19 μm. The indent is spherical, indicating material isotropy.

Conclusions

This study covers the mechanical and microstructural behavior of three HIPed alloys at 700°C via HotPIP and Creep Ranking tests. Results showed that ODS Alloy Y appears to have higher creep resistance than the others. Retesting of ODS IN718 is ongoing, after which the tensile properties of the three alloys will be fully compared. SEM and TEM-FIB shall be performed below the indent to identify the effects of the indentation on microstructure and detect the presence of precipitation strengthening phases γ'/γ'' and transformation strengthening phases η and χ, respectively.

References

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