Mechanical properties of nanostructured nickel based superalloy Inconel 718

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Abstract. This paper will describe the investigations of a nanostructured (NS) state of nickel based INCONEL® alloy 718. This structure was generated in bulk semiproducts by severe plastic deformation (SPD) via multiple isothermal forging (MIF) of a coarse-grained alloy. The initial structure consisted of γ-phase grains with disperse precipitations of γ″-phase in the forms of discs, 50-75 nm in diameter and 20 nm in thickness. The MIF generated structures possess a large quantity of non-coherent plates and rounded precipitations of δ-phase, primarily along grain boundaries. In the duplex (γ+δ) structure the grains have high dislocation density and a large number of nonequilibrium boundaries. Investigations to determine mechanical properties of the alloy in a nanostructured state were carried out. Nanocrystalline Inconel 718 (80 nm) possesses a very high room-temperature strength after SPD. Microcrystalline (MC) and NS states of the alloy were subjected to strengthening thermal treatment, and the obtained results were compared in order to determine their mechanical properties at room and elevated temperatures.

1. Introduction
It is well known [1] that by SPD an average grain size of metals and alloys can be refined to a NS state (<1 µm). In nickel-iron superalloy Inconel 718, that is widely used in aircraft engine manufacture, ultra-fine grain and NS states allow the fabrication of components by superplastic deformation at higher strain. Components operating at elevated temperatures are subjected to heat treatment to have strengthening coherent disperse particles of second phase precipitated. Mechanical properties of NS Inconel 718 are reported elsewhere [2]. But the data on mechanical properties of NS Inconel 718 after heat treatment are missing, and that is why such results are important.

The goal of the present paper is to investigate structure and mechanical properties of NS Inconel 718 subjected to strengthening heat treatment.

2. Material and methods
The material selected for this study was hot-deformed and precipitation hardened with strengthened phase γ” (bct, Ni3Nb) nickel based alloy Inconel 718 (Ni-18Cr-0.6Al-1.1Ti-18Fe-5Nb-2.9Mo-0.1Co, %Wt.) produced by Pratt & Whitney. The testing samples of alloy for SPD via MIF were machined from 250 mm diameter billets. MIF is a process in which a billet is compressed between flat dies on all three orthogonal directions during a sequence of forging passes with gradual decrease of temperature.
Bulk samples were produced on 630 ton-force press with decreasing deformation temperature from 950 to 800°C and to 575°C for processing, MC and NS states, respectively.

Deformation at high temperatures results in the transformation of \( \gamma'' \)-phase into orthorhombic \( \delta \)-phase. MC and NS forged billets were subjected to annealing at 980°C/1 hour, aging at 720°C/8 hours, furnace cooling to 620°C, hold at 620°C for total aging time of 18 hours. [3]. Tensile properties were determined at room temperature and 650°C, using sheet samples, with gauge dimensions of 5 mm x 2 mm x 15 mm. Stress rupture life and fatigue strength were determined using samples with gauge dimensions \( \Phi \)3 mm x 18 mm and \( \Phi \)4 mm x 25 mm, respectively.

Optical microscopy and transmission electron microscopy (JEM-2000EX) were used to investigate the microstructure.

3. Experimental results and discussion

3.1. Initial microstructure
MIF of bulk samples from investigated alloy carried out to various strains resulted in the formation of MC and NS states with mean grain sizes: 1 \( \mu \)m and 0.08 \( \mu \)m (figure 1). The TEM and SEM [4] studies have shown that the duplex structure consists of \( \gamma \)-phase and high temperature modification of \( \text{Ni}_3\text{Nb} \) - \( \delta \)-phase. Plates of \( \delta \)-phase with non-coherent boundaries are distributed uniformly. The NS state is characterized by higher dislocation density and non-equilibrium \( \gamma/\gamma \) boundaries [5]. Carbides with a mean size of 5 \( \mu \)m are present.

![TEM image of Inconel 718 produced by MIF with mean grain size: (a)-1 \( \mu \)m; (b)-0.08 \( \mu \)m.](image)

3.2. Mechanical properties of alloy after MIF at room temperature
According to the Hall-Petch relationship the strength of metals and alloys increases with decreasing grain size [1]. Tensile properties of Inconel 718 after MIF with various grain sizes are shown in table 1. The NS (\( \gamma + \delta \)) alloy exhibits very high room-temperature strength, which is much higher than that of the (\( \gamma + \gamma'' \)) alloy subjected to the strengthening thermal treatment. At the same time, increase in strength of this alloy in a NS state is accompanied by some reduction of ductility.

3.3. Mechanical properties after heat treatment
The studies on microstructure after carrying out the standard heat treatment [3] of MC and NS alloys showed that it resulted in the generation of uniform structure, the average grain sizes of \( \gamma \)-phase being 3.9 and 4.6 \( \mu \)m, accordingly. The difference of initial structural states is inherited after carrying out thermal treatment. From figure 2 it is evident that after heat treatment (HT) some quantity of globular
δ-phase is present in grain boundaries, which retards grain growth during annealing. Volume fraction of δ-phase is 2.9% for MC state after heat treatment and 3.3% for NC state.

| Grain size (µm) | Phases  | Ultimate strength (MPa) | Yield strength (MPa) | El (%) | RA (%) |
|----------------|---------|-------------------------|----------------------|--------|--------|
| 1.0            | γ + γ″  | ≥1276\(^a\)             | ≥1034                | ≥12    | ≥15    |
| 0.3            | γ + δ   | 1184                    | 920                  | 21.9   | 22.2   |
| 0.08           | γ + δ   | 1560                    | 1300                 | 5.1    | 11.0   |
|                | γ + δ   | 1920                    | 1845                 | 4.8    | 6.1    |

\(^a\) Mechanical properties after heat treatment [6].

\(^b\) [4].

The data on mechanical properties of the heat treated alloy are presented in table 2. These data evidently correspond to the material specification requirements. It is obvious that the initial nanostructure leads to maximum strength for the alloy at room temperature.

![Figure 2. Microstructure of Inconel 718 after MIF and heat treatment: (a) – MC+HT; (b) – NS+HT.](image)

**Table 2.** Mechanical properties of Inconel 718 after MIF and heat treatment.

| State     | Ultimate strength (MPa) | Yield strength (MPa) | El (%) | RA (%) | Grain sizes (µm) | Fatigue strength (MPa) | Cycles |
|-----------|-------------------------|----------------------|--------|--------|------------------|------------------------|--------|
| AMS 5662\(^a\) | ≥1276/1000\(^b\)       | ≥1034/862            | ≥12/12 | ≥15/15 | -                | -                      | -      |
| CG+HT\(^a\)   | 1428/1176               | 1180/976             | 19/18  | 20/32  | 11-22            | 910                    | >1.6×10\(^5\) |
| MC+HT         | 1488/1169               | 1234/995             | 17/23  | 23/45  | 4.6              | 910                    | >1.6×10\(^5\) |
| NS+HT         | 1520/1164               | 1252/993             | 19/21  | 35/42  | 3.9              | 910                    | >1.6×10\(^5\) |

\(^a\) [6], coarse-grained (CG).

\(^b\) At room temperature.

\(^c\) At grain size 19.6 µm [7].

Comparative fatigue tests of the samples at room temperature have shown that the properties of NS alloy on the scale of 10\(^5\) cycles are higher by the factor of 1.6 than those stipulated elsewhere [7].
Stress rupture data shown in table 3 indicate that with decreasing a mean grain size of γ-phase one observes the tendency towards decrease of stress rupture and increase of ductility. All presented conditions meet the material specification requirements.

**Table 3. Stress rupture data at 650°C of Inconel 718 after MIF and heat treatment.**

| State     | Stress (MPa) | Time (hrs) | El (%) | RA (%) |
|-----------|--------------|------------|--------|--------|
| AMS 5662  | 689          | ≥23        | ≥4     | -      |
| MC+HT     | 710          | 29.8       | 20.2   | 61.0   |
| NS+HT     | 27.0         | 25.3       | 73.5   | -      |

The investigation results show that for increasing alloy’s strength properties at operating temperatures it is appropriate to have δ-phase totally dissolved in order to increase the quantity of strengthening γ”-phase precipitates during aging.

4. Summary
With decreasing grain size to NS state of alloy 718 occurs a significant increase of strength properties at room temperature, in particular ultimate strength increased up to 1920 MPa.

It is highly appropriate to employ NS Inconel 718 after heat treatment when it possesses high strength and sufficient ductility.

For increasing service life of NS Inconel 718 components it is reasonable to develop a special heat treatment.

Acknowledgements
This study was carried out with the financial support of the Russian Foundation for Basic Research, Projects # 07-08-00287a, 09-08-08126z.

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