

# THERMAL STABILITY AND MECHANICAL PROPERTIES OF NANOSTRUCTURED NICKEL BASED ALLOY INCONEL 718

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**Abstract.** Thermal stability of nanostructured (NS) nickel based alloy Inconel 718 has been investigated. This structure was formed by severe plastic deformation (SPD) via high pressure torsion (HPT) and multiple isothermal forging (MIF) of the alloy with an initial coarse-grained (CG) structure. The produced microstructures were analyzed. Such NS conditions are characterized by the nonequilibrium grain boundaries and a high hardness value that is twice larger than that of a CG alloy. Tensile tests of NS alloy after MIF have shown very high room-temperature strength. Thermal stability of the studied structural conditions of the alloy depends on the presence and stability of the precipitates of  $\delta$ - and  $\gamma''$ -phases, each of which, in accordance with its quantity, sizes, coherence with matrix, prevents the grain growth.

## 1. INTRODUCTION

INCONEL<sup>®</sup> alloy 718 is a high-strength, corrosion-resistant nickel chromium material used at -253 to 760 °C [1]. The phases normally presented in the alloy are: the austenitic matrix based on Ni, Fe, Cr with an FCC structure; the major strengthening metastable  $\gamma''$ - phase ( $\text{Ni}_3\text{Nb}$ , BCT); about 4% volume fraction of the incidental strengthening  $\gamma'$ -phase ( $\text{Ni}_3\text{Al}(\text{Ti})$ , FCC); carbides; incoherent  $\delta$ -phase ( $\text{Ni}_3\text{Nb}$ , orthorhombic) [2]. This superalloy widely used in aircraft engine building is applied for superplastic forging and forming [3]. The average grain size less than 10  $\mu\text{m}$  is usually required for superplasticity [4]. It is well known [5] that grain

refinement up to NS condition can be achieved by using severe plastic deformation. In papers [6-8] the possibility of such structure formation for alloy 718 was described that provided low temperature superplasticity. The important structure characteristic such as thermal stability of fine grain during superplastic deformation has been insufficiently investigated. Thermal stability depends on condition of grain boundary and existing of second phase and its quantity, sizes and distribution. Also poor attention was given to mechanical properties of NS alloy in spite of its great practical importance. Therefore, the aim of the present work is to investigate thermal stability and mechanical properties of NS nickel-based alloy.

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**Table 1.** Composition of the Inconel 718 that was studied (wt.%).

Cr	Al	Ti	Fe	Nb	Mo	Co	B	C	Ni
19	0.5	0.9	18.5	5.1	3.0	0.1	0.025	0.04	Bal.

## 2. MATERIAL AND EXPERIMENTAL METHODS

Material selected for this study was hot-deformed nickel based alloy Inconel 718. The chemical composition of the alloy used in this work is shown in Table 1. Samples with sizes 40 mm in diameter and 60 mm long of alloy were machined from 200 mm diameter billet. Bulk samples with NS condition were generated using SPD via HPT and MIF. HPT was carried out on 5 revolutions at room temperature. The dimensions of an initial sample were 4 mm in diameter and 0.7 mm thick. The true strain value for  $e$  points of a sample located on the radius  $r$  is determined as shear strain:

$$e = \ln \left( \frac{2\pi r N}{\sqrt{3} L} \right), \quad (1)$$

where  $N$  – the number of revolutions,  $L$  – sample thickness, mm.

MIF was produced by 100 and 630 ton-force presses on flat dies with decreasing the deformation temperature from 950 to 575 °C. Sample dimensions were 40-80 mm in diameter and 10-12 mm long [6-8].

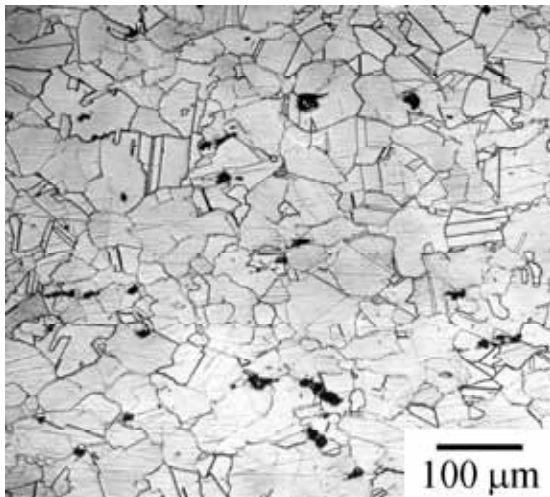
Annealings at 600 °C during 2, 5, 10 hours of thin samples were carried out using closed container with small volume of air. Microhardness and hardness measurements were carried out by standard methods. Loading of 50 g was used. Mechanical tests at room temperature were carried out on sheet samples, with a gauge dimension of 12 mm × 5 mm × 2 mm by using the Instron testing machine.

The microstructure of the specimens was characterized by using a JEOL JEM-2000EX and JEM-2100 transmission electron microscopes (TEM), JXA-6400 scanning electron microscope (SEM) and Axiovert-100A optical microscope (OM).

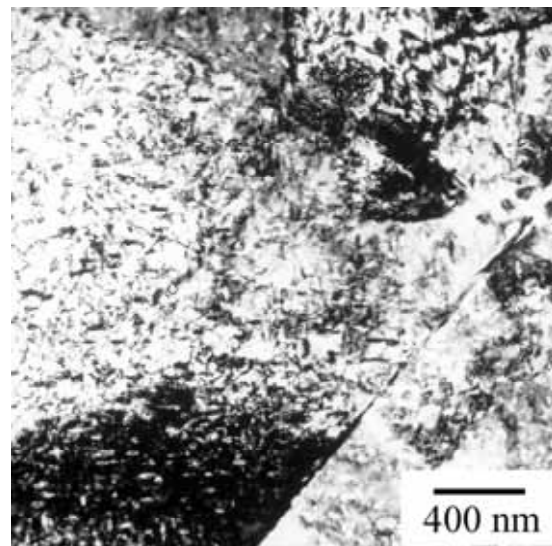
## 3. EXPERIMENTAL RESULTS AND DISCUSSION

### 3.1. Initial state

The microstructure of investigated alloy was fully recrystallized CG with a mean grain size of 40 μm. TEM studies have shown that coherent disk-type  $\gamma''$ -precipitates are uniformly distributed within grains (Fig. 1). The diameter of  $\gamma''$ -phase disks is about 60 nm, and their thickness is 20 nm. Carbides with a mean grain size of about 5 μm are presented.

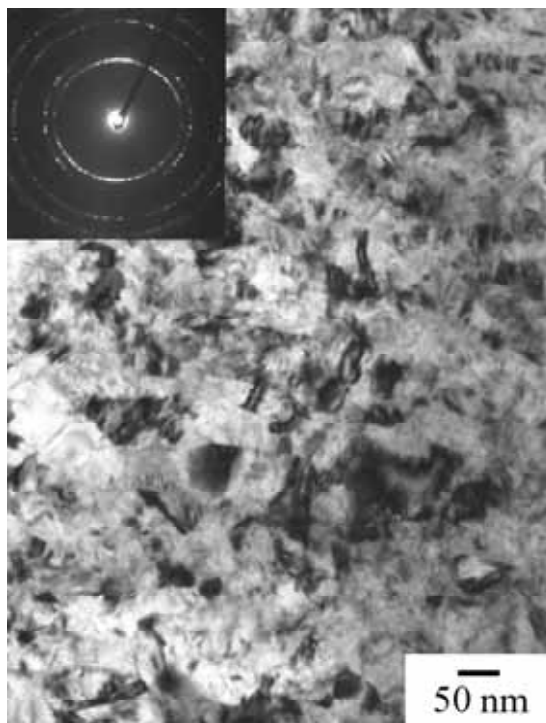


a)



b)

**Fig. 1.** As-received microstructure of Inconel 718: a- OM; b- TEM.



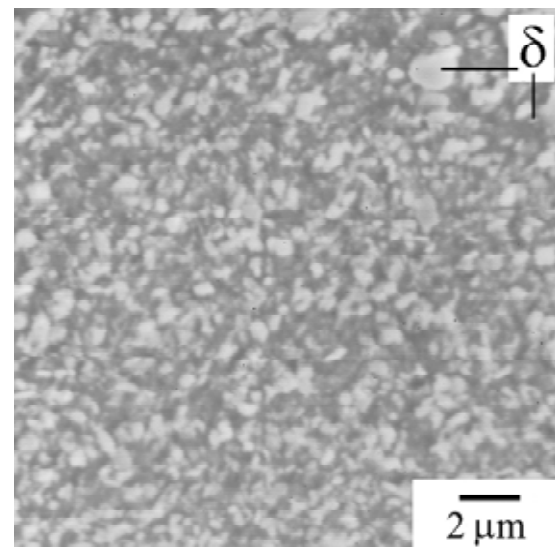
**Fig. 2.** Microstructure and electron-diffraction pattern of Inconel 718 subjected to HPT.

### 3.2. Microstructure of Inconel 718 after HPT

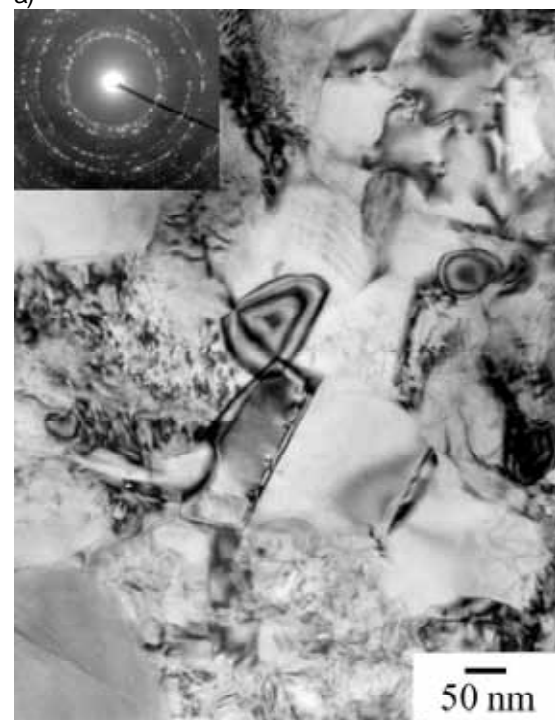
The microstructure investigation of Inconel 718 alloy after shear deformation under high pressure on the Bridgeman anvil showed that average grain size was about 30 nm (Fig. 2). This NS condition is characterized by the significant elastic stresses and non-equilibrium grain boundaries [5].

### 3.3. The microstructure of Inconel 718 after MIF

In bulk samples of Inconel 718 alloy subjected to MIF with decreasing deformation temperature to 575 °C the uniform NS condition with grain size of about 80 nm was formed (Fig. 3). Grains of  $\delta$ -phase with non-coherent boundaries are distributed uniformly (Fig. 3a). TEM studies have shown that the duplex structure consists of  $\gamma$ + $\delta$ -phases. A lot of high angular grain boundaries and zones of non-equilibrium boundaries and grains with high dislocation density can be observed (Fig. 3b) [5,8].



a)

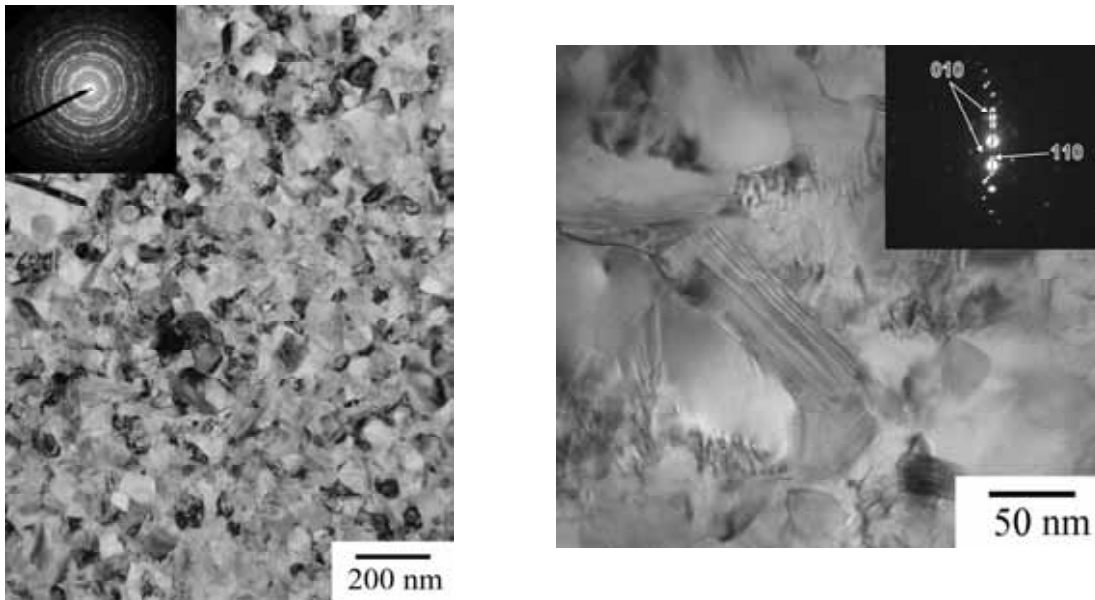


b)

**Fig. 3.** Microstructure of Inconel 718 subjected to MIF: a – SEM image; b – TEM image and electron-diffraction pattern.

### 3.4. Influence of annealing on microstructure

The microstructure of alloy after HPT ( $e=5.8$ ) and annealing at 500 °C during 2 hours is characterized by an insignificant relaxation of stresses and the formation of a more equilibrium state. This is evi-



**Fig. 4.** Microstructure of Inconel 718 subjected to HPT ( $\epsilon=5.8$ ) and annealing at 600 °C during 10 hours.

denced by some reduced level of the microhardness caused probably by the decreased dislocation density both within the interior of cells and along boundaries, as well as the formation of separate grains with high-angle boundaries and typical contrast. Grain growth was not observed under this annealing condition.

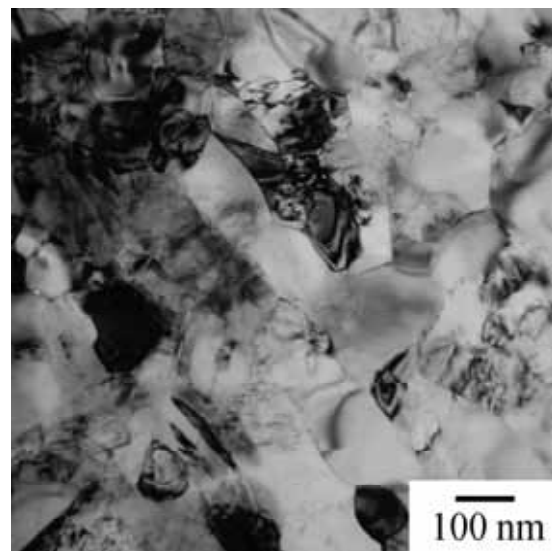
The investigation of alloy subjected to HPT ( $\epsilon=5.8$ ) and annealing at 600 °C shows that with increasing the duration from 2 to 10 hours the quantity of high-angular boundaries increases while the quantity of non-equilibrium boundaries decreases. The grain size after 10 hours annealing increased but it does not exceed 100 nm.  $\gamma''$ -precipitates were not observed by morphological character on TEM images (Fig. 4). Scattering spots from  $\gamma$  phase and spots from superlattice structure of  $\delta$  phase were found on electron-diffraction pattern of alloy after annealing during 10 hours. Scattering spots on planes (010) and (110) of  $\delta$ -phase on electron-diffraction pattern were revealed in Fig. 4b.

The microstructure investigations of alloy after MIF and annealing at 600 °C during 2 (Fig. 5), 5, 10 hours were carried out. The quantity of high-angular boundaries increased while the quantity of non-equilibrium boundaries decreased with increasing the duration of annealing. Some grain boundaries are characterized by a banded contrast, which is apt to equilibrium high angle grain boundaries. The aver-

age grain size increased from 80 nm to 170 nm after 10 hours annealing.

### 3.5. Effect of annealing duration at 600 °C on hardness of NS alloy

From graphs in Fig. 6 it is clear that hardness of alloy increases after severe plastic deformation.



**Fig. 5.** Microstructure of Inconel 718 subjected to MIF and annealing at 600 °C during 2 hours.

**Table 2.** Tensile properties of NS alloy ( $\gamma+\delta$ ) at room temperature.

Grain size, [ $\mu\text{m}$ ]	Ultimate Strength, [MPa]	Yield Strength, [MPa]	EI, [%]	RA, [%]	Information
-	1276	1034	10	15	AMS5662 [10]
0.5	1699/1583*	1438/1298	5.4/3.2	6.4/3.3	[7]
0.3	1560	1300	5.1	11.0	[11]
0.08	1920	1845	4.8	6.1	[11]

\* Longitudinal / transverse sheet direction

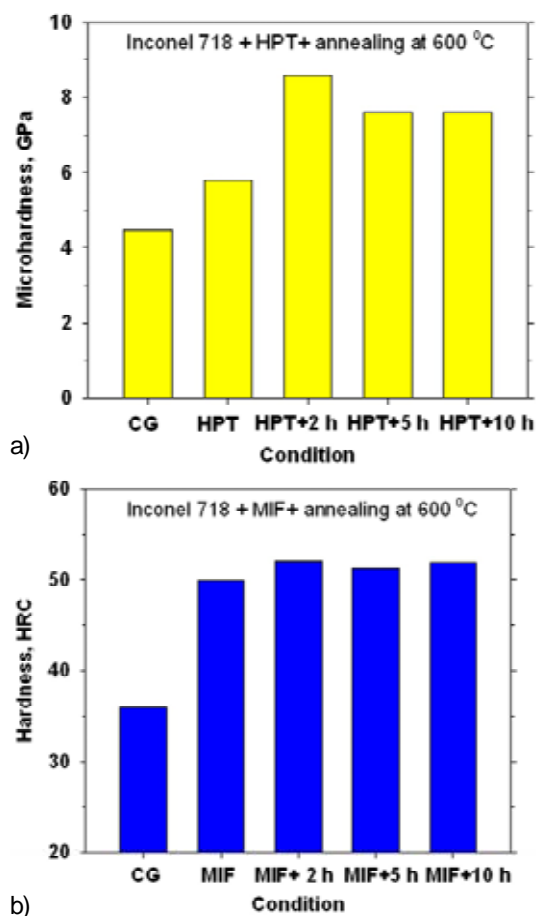
Annealing during 2 hours results in more additional increasing of alloy subjected to HTP (Fig. 6a) than that subjected to MIF (Fig. 6b). The hardness reduced slightly if duration of annealing was more than 2 hours. The increase of hardness is probably connected with polygonization occurring during pre-recrystallization annealing, at which the pinning of mobile dislocations by the atoms of dissolved and alloying elements takes place in the initial deformed material and in dislocation walls. The generation of short-range order regions is perhaps another reason for strengthening [9].

### 3.6. Room temperature tensile properties of duplex ( $\gamma+\delta$ ) NS alloy

The comparison of mechanical properties of alloy 718 with different grain size [7,10,11] is shown in Table 2. Thus, it is concluded that with reducing the average grain size of alloy the strength properties increase. NS alloy with grain size of about 80 nm has 47% higher ultimate strength and 75% higher yield strength than CG alloy. A 52-59% reduction in ductility of the NS alloy is revealed.

## 4. CONCLUSIONS

1. The NS condition of Inconel 718 formed by HPT is thermally stable during annealing at 600 °C (10 h) and grain size is not higher than 100 nm.
2.  $\gamma''$  precipitates were not observed by TEM in alloy subjected to HPT and annealing at 600 °C during 10 hours.
3. The NS Inconel 718 formed by MIF with duplex ( $\gamma+\delta$ ) structure with a grain size of 80 nm is thermally stable at less than 600 °C ( $0.56 T_m$ ).
4. The reduction in a grain size of Inconel 718 to 80 nm leads to the enhancement of strength up to 1920 MPa at room temperature and the decrease of ductility.



**Fig. 6.** Effect of annealing duration at 600 °C on hardness of NS alloy: a – after HPT; b – after MIF.

## ACKNOWLEDGEMENTS

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