THE CHARACTERISTIC OF DEFORMABILITY OF NI-FE SUPERALLOY DURING HIGH-TEMPERATURE DEFORMATION

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Abstract

The influence of two variants of initial soaking at 1120 °C / 2 h and 1180 °C / 2 h and parameters of hot plastic working on the deformability of an IN 718 type superalloy have been presented. The hot deformation characteristics of alloy were investigated by hot torsion tests. The tests were executed at constant strain rates of 0.1 s^{-1} and 1.0 s^{-1}, and testing temperature in the range of 900 °C to 1150 °C. Plastic properties of the alloy were characterized by worked out flow curves and the temperature relationships of maximum flow stress (σ_{pp}) and strain limit (ε_f). The relationship between the maximum flow stress and the Zener-Hollomon parameter (Z) was described by $\sigma_{pp} = A \cdot Z^n$ power function. Activation energy for hot working (Q) was assessed for the alloy after two variants of initial soaking, i.e. 1120 °C / 2 h and 1180 °C / 2 h and amounted - respectively - 478 kJ/mol and 628 kJ/mol.

Keywords: IN 718 superalloy, hot deformation, plastic properties, Zener-Holomon parameter, activation energy for hot working

1. INTRODUCTION

The behaviour of metals and alloys during hot plastic working has a complex nature and it varies with the changing of such process parameters as [1-5]: deformation, strain rate and temperature. The high-temperature plastic deformation is coupled with dynamic recovery and recrystallization processes which influencing the structure and properties of alloys. One of crucial issues is finding the relationship between the hot plastic deformation process parameters, microstructure and properties for steels and nickel alloys.

The Ni-Fe superalloys precipitation hardened by intermetallic phases of γ'-$Ni_3(Al,Ti)$ and γ'' (Ni_3Nb) types are difficult to deform and are characterized by high values of flow stress at a high temperature. High deformation resistance of Ni-Fe alloys is caused by a complex phase composition, high activation energy for hot working and a low rate of dynamic recrystallization. When choosing the conditions for hot plastic working of Ni-Fe alloys, the following factors should be considered [6-10]: the matrix grain size, plastic deformation parameters and the course of the recrystallization process. The grain size is particular importance. Grain refining leads to an increased rate of recovery and dynamic recrystallization and to a smaller diameter of recrystallized grains. This is important, for the grain refinement in a Ni-Fe superalloys has an advantageous influence on increasing their yield point and fatigue strength [11, 12].

In the presented study, research has been undertaken on the influence of two variants of initial soaking and the parameters of hot plastic working on the characteristics of deformability in a Ni-Fe superalloy.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

The examinations were performed on rolled bars, 16 mm in diameter, of an IN 718 type superalloy. The chemical composition is given in **Table 1**.

Table 1 Chemical composition of the investigated Ni-Fe superalloy

Content of an element (wt. %)														
C	Si	Mn	P	S	Cr	Ni	Mo	Co	Al	Cu	Nb	Ti	B	Fe
0.04	0.16	0.08	0.007	0.002	18.5	52.1	3.05	0.24	0.54	0.03	4.89	0.91	0.001	19.45

The samples for investigations were made from rolled bars sections which were subjected to preheating, i.e. 1120 °C / 2 h and 1180 °C / 2 h with subsequent cooling in water. Heat treatment of this type corresponds to the soaking parameters of the investigated superalloy before hot plastic processing [13-15].

The research on the alloy deformability was performed in a hot torsion test on a Setaram torsion plastometer 7 MNG. The plastometric tests were performed every 50 °C in a temperature range of 900-1150 °C, with a constant holding time of 10 min at the defined temperature. Solid cylindrical specimens (Ø 6.0 × 50 mm) were twisted at a rotational speed of 50 and 500 rpm, which corresponds to the strain rate of 0.1 and 1.0 s^{-1}, respectively. To freeze the structure, the specimens after deformation until failure were cooled in water.

From the data recorded, dependencies were determined of the flow stress (σ_p) as a function of substitute strain (ε), according to the methodology presented in papers [16-18]. On the flow curves determined, the following parameters characterizing plastic properties of the alloy in the torsion test were defined:

- σ_{pp} - maximum flow stress on the flow curve;
- ε_p - deformation corresponding to the maximum flow stress;
- σ_f - stress at which the sample is subject to failure;
- ε_f - deformation at which the sample is subject to failure, the so-called strain limit.

Relations between the flow stress and alloy deformation, and the deformation conditions were described using the Zener-Hollomon parameter Z [19, 20]:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{R \cdot T}\right) = A \cdot \left[\sinh\left(\alpha \cdot \sigma_{pp}\right)\right]^n \quad (1)$$

where: $\dot{\varepsilon}$ - strain rate, Q - activation energy for hot working, R - molar gas constant, T - temperature, and A, α, n - constants depending on grade of the investigated material.

The activation energy for hot working Q was determined in accordance with the procedure specified in the work by Schindler and Bořuta [16]. The solution algorithm consisted in transforming Eq. (1) to the form:

$$\dot{\varepsilon} = A \exp\left(\frac{-Q}{RT}\right) \cdot \left[\sinh(\alpha \cdot \sigma_{pp})\right]^n \quad (2)$$

Further procedure was based on solving Eq. (2) by a graphic method with using the regression analysis.

3. RESULTS AND DISCUSSION

After solution heat treatment at 1120 °C / 2 h / w., in the alloy microstructure presence was found of twinned gamma matrix with medium-size grain ($\bar{A}$ = 6920 μm^2) with a small amount of insoluble particles (**Figure 1a**). The increasing parameters of the solution heat treatment to 1180 °C / 2 h / w. resulted in an increase of the matrix grain ($\bar{A}$ = 15830 μm^2) and a reduction in the quantity of undissolved primary particles (**Figure 1b**).

The plastometric investigations, in the form of the calculated alloy flow curves at temperatures of 900-1150 °C for two options of initial soaking are shown in **Figure 2** and **Figure 3**. The results obtained for the option of initial soaking at 1100 °C / 2 h and strain rate 0.1 s^{-1} showed a single peak in the flow stress-strain curves, and indicated that a recovery and dynamic recrystallization took place during the hot deformation (**Figure 2**). High deformability values were obtained for the alloy in a wide range of torsion temperatures, i.e.

1000-1100°C. An increase of strain rate to 1.0 s^{-1} results in a significant increase of flow stress values and a distinct decrease of the alloy deformability at all temperatures analysed. This phenomenon can be explained by a higher speed of the alloy strengthening and too slow removal of the strengthening as a result of dynamic recovery and recrystallization.

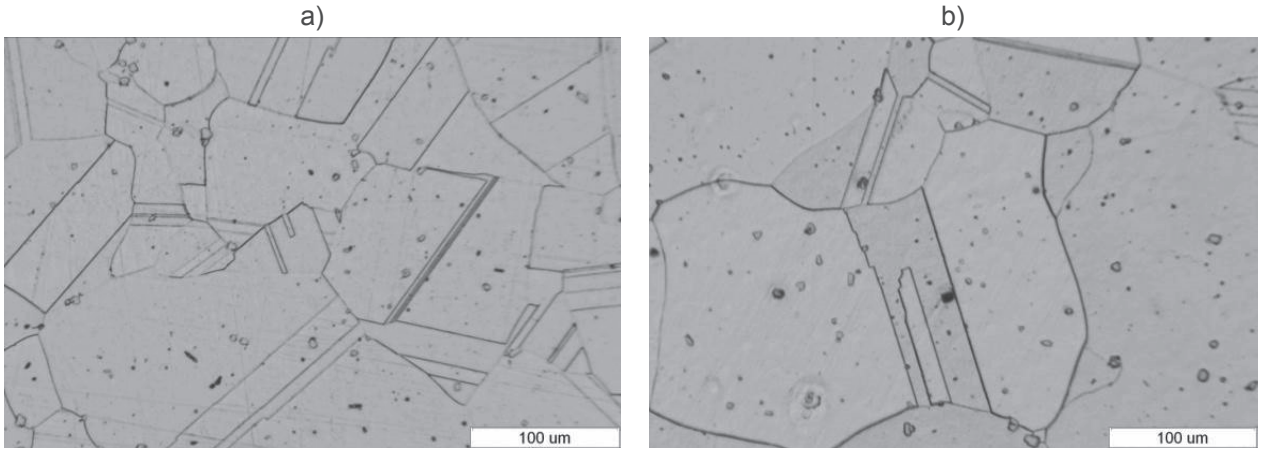

Figure 1 Diversified microstructure of the Ni-Fe alloy after initial solution heat treatment at: a) 1120°C /2h /w. ($\bar{A}$ = 6920 μm^2); b) 1180 °C / 2 h / w. ($\bar{A}$ = 15830 μm^2)

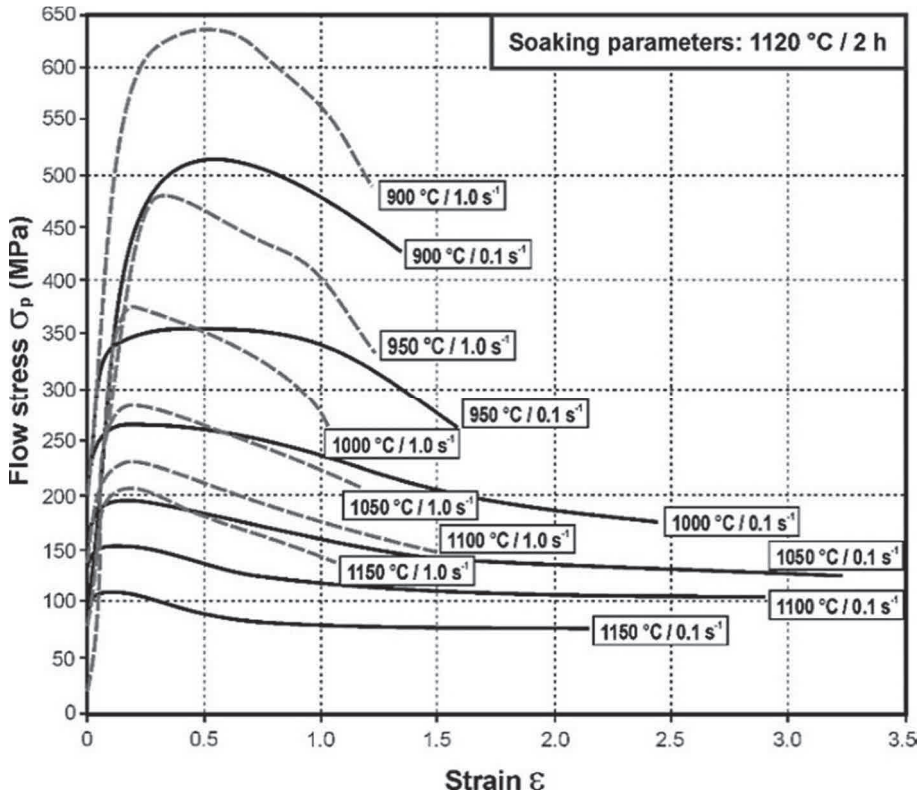

Figure 2 The effect of torsion temperature on the flow stress and deformability of the Ni-Fe alloy after initial soaking at 1120 °C / 2 h. Strain rate: 0.1 s^{-1} and 1.0 s^{-1}

An increase of the initial soaking temperature to 1180 °C / 2 h significantly reduces the alloy deformability for the two strain rates, both at low and high deformation temperatures (**Figure 3**). In this case, fairly high deformability values were obtained for the alloy in a higher range of torsion temperatures, i.e. 1050-1150 °C.

Such behaviour of the alloy may be explained by a larger growth of matrix grains at this soaking temperature and, consequently, lower recovery and dynamic recrystallization rates.

The values determined for the maximum flow stress σ_{pp} and strain limit ε_f depending on the temperature and strain rate are presented in **Figure 4** and **Figure 5.**

For the option of initial soaking at 1120 °C /2 h and strain rate of 0.1 s^{-1}, the alloy under discussion shows a continuous drop of σ_{pp} from values 514 MPa at a temperature of 900 °C to the value of 113 MPa at 1150 °C (**Figure 4a**). The strain limit ε_f rises initially together with the torsion temperature, reaching the maximum of 3.25 / 2.91 at 1050-1100 °C, and then falls (**Figure 5a**). An increase of the strain rate to 1.0 s^{-1} results in an increase of σ_{pp} to maximum values of 636 MPa at the temperature of 900 °C (**Figure 4a**) and a decrease of the strain limit to the maximum of 1.23 / 1.43 at 1050-1100 °C (**Figure 5a**).

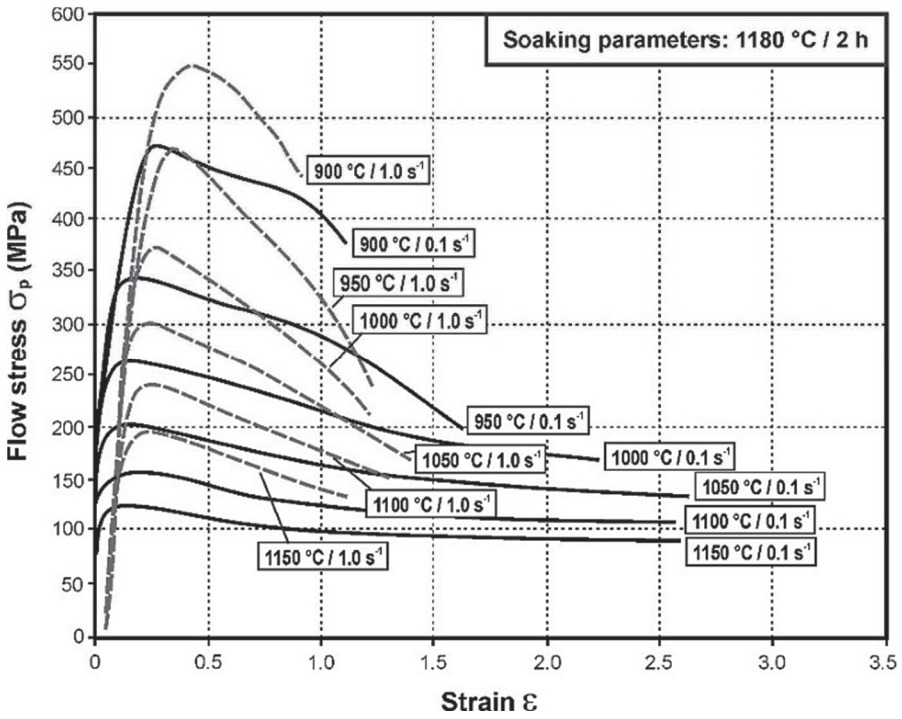

Figure 3 The effect of torsion temperature on the flow stress and deformability of the Ni-Fe alloy after initial soaking at 1180 °C / 2 h. Strain rate: 0.1 s^{-1} and 1.0 s^{-1}

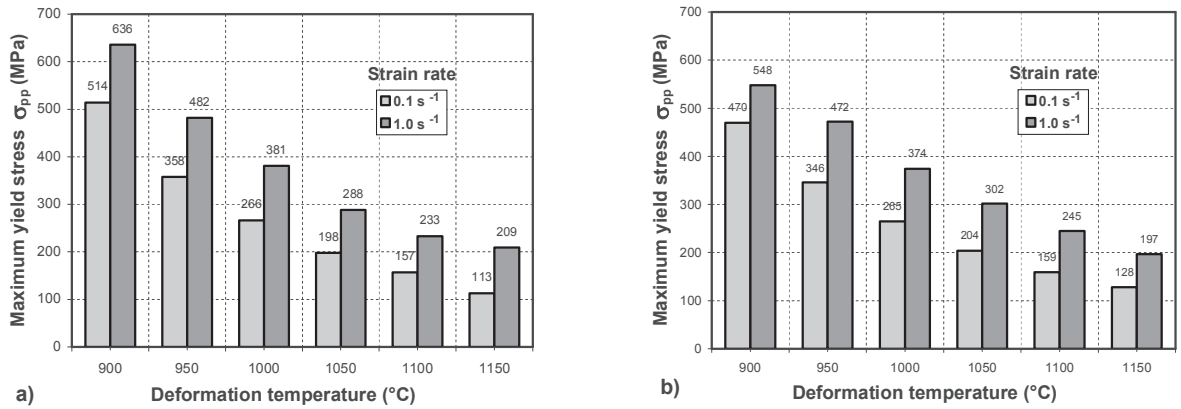

Figure 4 The effect of deformation conditions on maximum flow stress of the Ni-Fe alloy. Initial alloy soaking: a) 1120 °C / 2 h, b) 1180 °C / 2 h

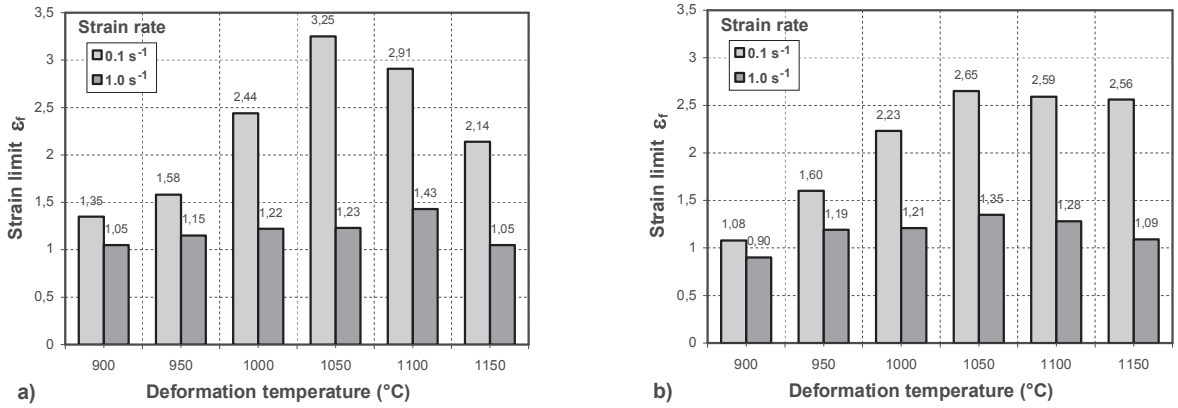

Figure 5 The effect of deformation conditions on strain limit of the Ni-Fe alloy. Initial alloy soaking: a) 1120 °C / 2 h, b) 1180 °C / 2 h

An increase of the alloy initial soaking temperature to 1180 °C / 2 h at a strain rate of 0.1 s^{-1} results in a small decrease of σ_{pp} to maximum values of 470 MPa at 900 °C (**Figure 4b**) and slight decrease of ε_f to the maximum of 2.65 / 2.59 in the range of 1050-1100 °C (**Figure 5b**). An increase of the torsion speed to 1.0 s^{-1} results in further increase of the σ_{pp} value to maximum values of 548 MPa at 900 °C (**Figure 4b**), and decrease of ε_f to the maximum values of 1.35 / 1.28 at the temperature of 1050-1100 °C (**Figure 5b**).

The activation energy for hot working Q was calculated by the means of a computer programme Energy 3.0 [16]. The activation energy, Q, for hot working of the Ni-Fe alloy depends on the temperature of initial soaking and equals as follows:

- Q = 478.6 kJ/mol - for initial alloy soaking 1120 °C / 2 h;
- Q = 628.0 kJ/mol - for initial alloy soaking 1180 °C / 2 h.

The higher value of the activation energy Q for hot working of the alloy after initial soaking at 1180 °C / 2 h can be justified by larger growth of the initial matrix grain and higher degree of matrix saturation with alloying elements.

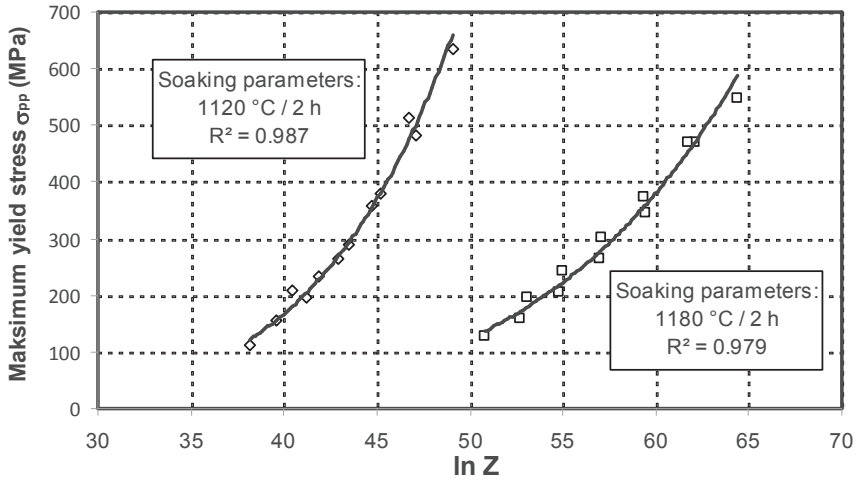

Figure 6 Dependence of the maximum flow stress on the Zener-Hollomon parameter Z. Initial alloy soaking: 1120 °C / 2 h and 1180 °C / 2 h

The dependencies between maximum flow stress σ_{pp} and Zener-Hollomon Z parameter are presented in **Figure 6**. For both options of initial soaking, a power dependence (R^2 = 0.98) of the alloy flow stress was

obtained as a function of the Z parameter. So determined function dependencies between the maximum flow stress σ_{pp} and the Z parameter had a form of power function (Eq. (3) and (4)):

- for the alloy after initial soaking 1120 °C / 2 h:
  $\sigma_{pp} = 0.35 \cdot Z^{0.155}$ MPa, (3)
- for the alloy after initial soaking 1180 °C / 2 h:
  $\sigma_{pp} = 0.61 \cdot Z^{0.107}$ MPa. (4)

4. CONCLUSION

The flow curves of the investigated Ni-Fe superalloy in the temperature range of 900-1150 °C at a strain rate of 0.1 s^{-1} and 1.0 s^{-1} have a shape characteristic of a material in which dynamic recovery and recrystallization processes took place. Indexes of plastic properties of the alloy during hot plastic deformation depend significantly on the temperature of initial soaking and torsion parameters.

The best combination of the maximum flow stress (σ_{pp}) and strain limit (ε_f) was obtained for an alloy after initial soaking at 1120 °C / 2 h and a strain rate of 0.1 s^{-1} in the temperature range of 1050-1100 °C. The use of a higher initial soaking temperature 1180 °C / 2 h, and strain rate of 1.0 s^{-1} is not recommended due to problems in the recovery and dynamic recrystallization processes, and decrease of the alloy plasticity.

For both variants of initial soaking was found a significant influence of the deformation parameters on the maximum flow stress of the alloy. The dependence between the maximum flow stress (σ_{pp}) and the Zener-Hollomon parameter (Z) was described with a power function in the following form: $\sigma_{pp} = A \cdot Z^n$.

The tested superalloy has a high activation energy of the hot working Q, with the energy value depending on the conditions of initial soaking. For the alloy after initial soaking at 1120 °C / 2 h, the estimated activation energy in the range of applied deformation parameters was Q = 478 kJ/mol. In the case of alloy deformation after initial soaking at 1180 °C / 2 h, the activation energy was higher and equal Q = 628 kJ/mol.

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