THE CHARACTERISTIC OF DEFORMABILITY OF Fe-Ni SUPERALLOY DURING HIGH-TEMPERATURE DEFORMATION

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Abstract

The influence of two variants of initial soaking at 1100 °C / 2 h and 1150 °C / 2 h and parameters of hot plastic deformation on the deformability of an A-286 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 power function. Activation energy for hot working (Q) was assessed for the alloy after two variants of initial soaking, i.e. 1100 °C / 2h and 1150 °C / 2h and amounted - respectively - 442 kJ/mol and 519 kJ/mol.

Keywords: A-286 superalloy, hot deformation, plastic properties, Zener-Hollomon parameter, activation energy for hot working

1. INTRODUCTION

The behavior of metals and alloys in the hot working process is complex and it varies with the changing of process parameters [1-5], such as the deformation, strain rate and temperature. The high-temperature plastic deformation is connected with dynamic recovery and recrystallization processes which have an effect on the structure and properties of alloys. An important issue with respect to steels and nickel alloys is to find the relationship between the hot working parameters, the microstructure and their properties.

The Fe-Ni superalloys, precipitation hardened with γ'- $Ni_3(Al,Ti)$ intermetallic phases, are difficult to deform and are characterized by high values of flow stress at high temperatures. The high flow stress of these alloys results from their complex phase compositions, high activation energy for hot working and a low dynamic recrystallization rate. The selection of hot working conditions for Fe-Ni alloys should take into account the following factors [6-10]: the austenite grain size, hot working parameters and the course of recrystallization process. The grain size is of special importance, for grain refining contributes to accelerating the recovery and dynamic recrystallization, and obtaining smaller diameters of recrystallized grains. The refinement of grain in creep resisting Fe-Ni superalloys considerably improves 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 Fe-Ni superalloy.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

The examinations were performed on rolled bars, 16 mm in diameter, of an austenitic A-286 type superalloy. The chemical composition is given in **Table 1**.

The samples for investigations were made from rolled bars sections which were subjected to preheating, i.e. 1100 °C / 2 h and 1150 °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].

Table 1 Chemical composition of the investigated Fe-Ni superalloy

Content of an element (wt. %)														
C	Si	Mn	P	S	Cr	Ni	Mo	V	W	Ti	Al	B	N	Fe
0.05	0.56	1.25	0.026	0.016	14.3	24.5	1.35	0.32	0.10	1.88	0.16	0.007	0.0062	55.3

The alloy deformability was examined through hot torsion testing with a Setaram 7 MNG torsion plastometer. Plastometric tests were carried out every 50 °C in the range of temperatures of 900-1150 °C, with a constant soaking time of 10 min at a given temperature. Solid cylindrical samples (Ø 6.0 × 50 mm) were subjected to torsion at rotational speeds of 50 and 500 min^{-1}, corresponding to strain rates of 0.1 s^{-1} and 1.0 s^{-1}, respectively. The samples after deformation until failure were cooled in water in order to freeze the structure.

From the recorded data, 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} (MPa) - maximum flow stress on the flow curve;
- ε_p (-) - deformation corresponding to the maximum flow stress;
- σ_f (MPa) - 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 (J·mol^{-1}) - activation energy for hot working, R (J·K^{-1}·mol^{-1}) - molar gas constant, T (K) - temperature, and A (s^{-1}), α (MPa^{-1}), 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 of 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 of Eq. (2) by a graphic method with using the regression analysis.

3. RESULTS AND DISCUSSION

After solution heat treatment at 1100 °C / 2 h / w. the presence of twinned austenite with medium-size grain ($\bar{A}$ = 2120 μm^2) and a small amount of insoluble particles was revealed in the alloy structure (**Figure 1a**). The increasing parameters of the solution heat treatment to 1150 °C / 2 h / w. resulted in an increase of the matrix grain ($\bar{A}$ = 6296 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 variant of initial soaking at 1100 °C / 2 h and a strain rate of 0.1 s^{-1} show a single peak in the flow stress-strain curves, and indicate that the recovery and dynamic recrystallization proceeded during the hot working process (**Figure 2**). High deformability values were obtained for the alloy in a wide range of torsion temperatures, i.e. 950-1100 °C. An increase of strain rate to 1.0 s^{-1} caused a significant increase of flow stress and a decrease in deformability of the alloy at all tested temperatures. This phenomenon could be explained by a higher alloy strengthening rate and a too slow removal of work hardening as a result of dynamic recovery and recrystallization.

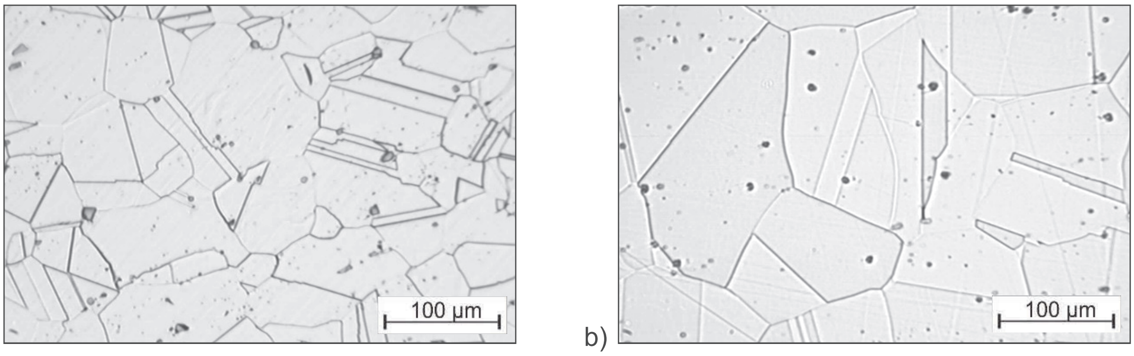
a) b)


Figure 1 Diversified microstructure of the Fe-Ni alloy after initial solution heat treatment at: a) 1100 °C / 2 h / w. ($\bar{A}$ = 2120 µm^2); b) 1150 °C / 2 h / w. ($\bar{A}$ = 6296 µm^2)

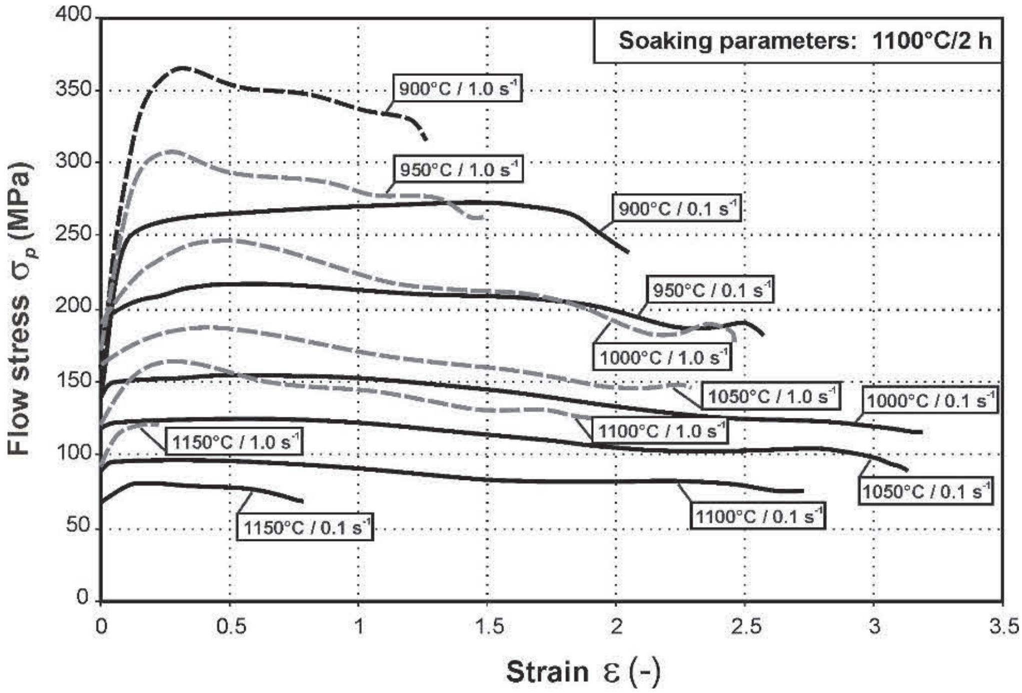


Figure 2 The effect of torsion temperature on the flow stress and deformability of the Fe-Ni alloy after initial soaking at 1100 °C / 2 h. Strain rate: 0.1 s^{-1} and 1.0 s^{-1}

An increase of the initial soaking temperature to 1150 °C / 2 h significantly reduces the alloy deformability for the two strain rates, both at low and high deformation temperatures (**Figure 3**). High values of alloy deformability were obtained in a narrow range of torsion temperatures, i.e. 1000-1050 °C. This behaviour of the alloy can be explained by a larger austenite grain size at the above-mentioned soaking temperature and the resultant lower rates of recovery and dynamic recrystallization.

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**. In the case of the initial soaking variant at 1100 °C / 2 h and the strain rate of 0.1 s^{-1}, the examined alloy showed a continuous decrease in σ_{pp}, from the value of 277 MPa at 900 °C to the 81 MPa at 1150 °C (**Figure 4a**). Initially, the strain limit ε_f increased with the torsion temperature and reached its maximum value of 3.19 / 3.14 at 1000-1050 °C, after which it started falling (**Figure 5a**). An increase in the strain rate to 1.0 s^{-1} caused an increase of σ_{pp} to a maximum value of 367 MPa at 900 °C (**Figure 4a**), and a reduction of the strain limit to its maximum value of 2.47 / 2.34 at a temperature of 1000-1050 °C (**Figure 5a**).

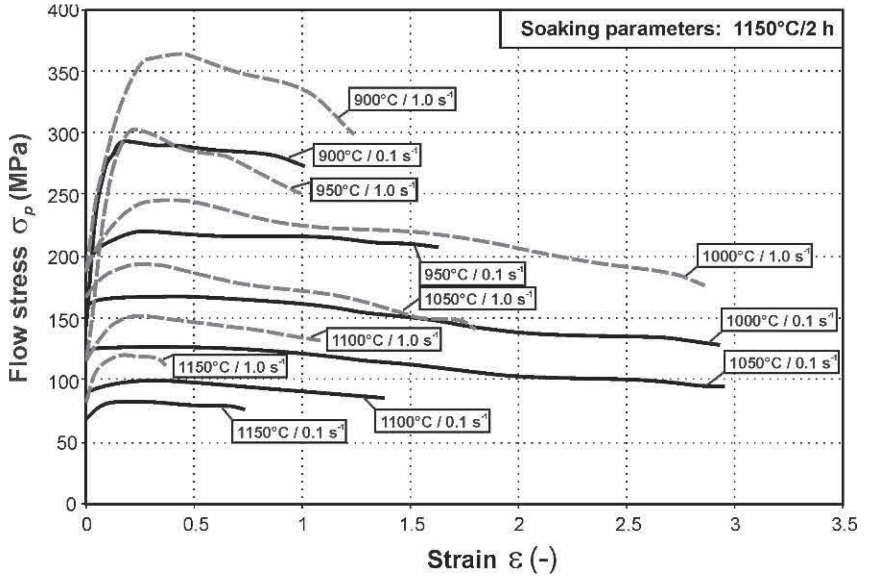


Figure 3 The effect of torsion temperature on the flow stress and deformability of the Fe-Ni alloy after initial soaking at 1150 °C / 2 h. Strain rate: 0.1 s^{-1} and 1.0 s^{-1}

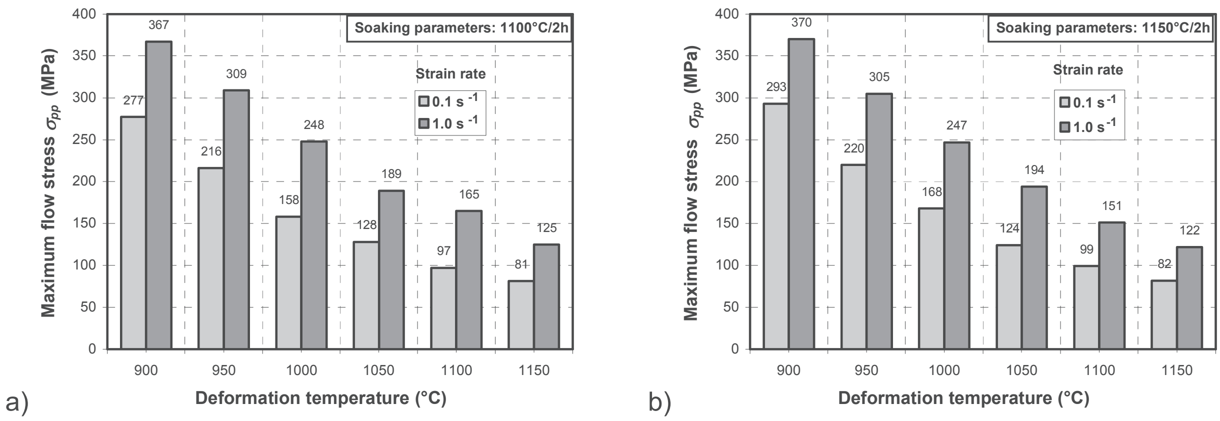


Figure 4 The effect of deformation conditions on maximum flow stress of the Fe-Ni alloy. Initial alloy soaking: a) 1100 °C / 2 h, b) 1150 °C / 2 h

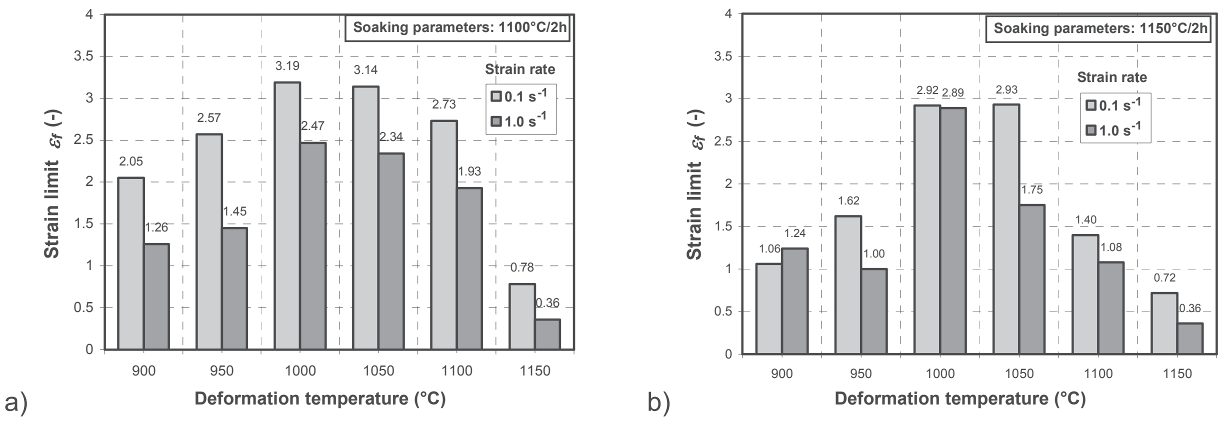


Figure 5 The effect of deformation conditions on strain limit of the Fe-Ni alloy. Initial alloy soaking: a) 1100 °C / 2 h, b) 1150 °C / 2 h

An increase in the initial soaking temperature of the alloy to 1150 °C / 2 h at the strain rate of 0.1 s^{-1} resulted in a growth of σ_{pp} maximally to 293 MPa at 900 °C (**Figure 4b**) and a reduction of ε_f maximally to 2.92 / 2.93 in the temperature range of 1000-1050 °C (**Figure 5b**). An increase in the torsion rate to 1.0 s^{-1} resulted in a further increase of the σ_{pp} value to maximally 370 MPa at 900 °C (**Figure 4b**), and a decrease of ε_f to maximally 2.89 / 1.75 in the temperature range of 1000-1050 °C (**Figure 5b**).

The hot working activation energy, *Q*, was calculated using a computer programme Energy 3.0 [16]. It was found that the hot working activation energy of alloy Fe-Ni depends on the temperature of initial soaking and amounts to: *Q* = 441.8 kJ/mol - for initial alloy soaking at 1100 °C / 2 h; *Q* = 518.7 kJ/mol - for initial alloy soaking at 1150 °C / 2 h. The higher value of the hot working activation energy *Q* for the alloy after initial soaking at 1150 °C / 2 h can be explained by a larger austenite grain size and a higher degree of matrix saturation with alloying elements in its initial state.

The dependencies between the maximum flow stress σ_{pp} and the Zener-Hollomon parameter *Z* are presented in **Figure 6**. For both variants of initial soaking, a power dependence (R^2 = 0.98) was obtained for the alloy flow stress as a function of the *Z* parameter. It was shown that the determined dependencies between the maximum flow stress σ_{pp} and the *Z* parameter had the form of power functions (Eq. (3) and (4)):

- for the alloy after initial soaking at 1100 °C / 2 h:
  $\sigma_{pp} = 0.43 \cdot Z^{0.151}$ MPa, (3)
- for the alloy after initial soaking at 1150 °C / 2 h:
  $\sigma_{pp} = 0.34 \cdot Z^{0.133}$ MPa. (4)

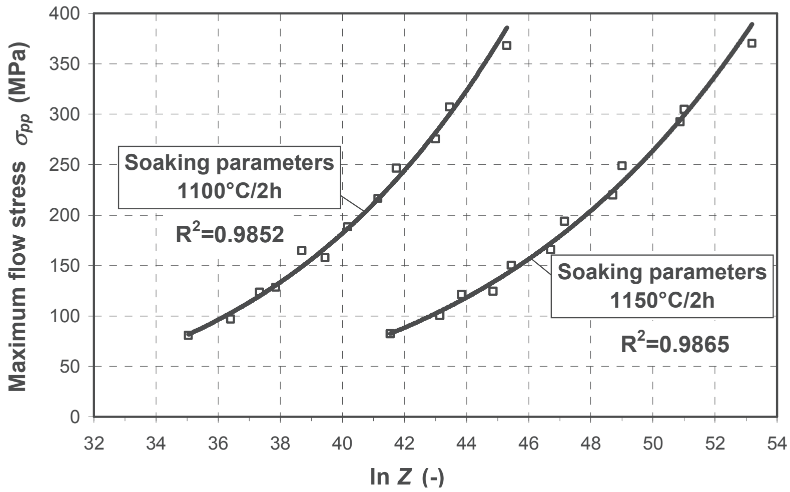


Figure 6 Dependence of the maximum flow stress on the Zener-Hollomon parameter *Z*.
Initial alloy soaking: 1100 °C / 2 h and 1150 °C / 2 h

4. CONCLUSION

In the temperature range of 900-1150 °C at a strain rate of 0.1 s^{-1} and 1.0 s^{-1}, the flow curves of the examined Fe-Ni superalloy have a shape typical for a material where dynamic recovery and recrystallization have taken place. The indexes of the 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 1100 °C / 2 h, at a strain rate of 0.1 s^{-1} in the temperature range of 1050-950 °C. The use of a higher initial soaking temperature 1150 °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 high activation energy for hot working Q. Its value depends significantly on the conditions of initial soaking. For the alloy after initial soaking at 1100 °C / 2 h, the estimated activation energy in the range of the used deformation parameters was Q = 442 kJ/mol. In the case of hot working of the alloy after initial soaking at 1150 °C / 2 h, the activation energy was higher and amounted to Q = 519 kJ/mol.

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