DEFORMABILITY AND QUANTITATIVE DESCRIPTION OF THE MICROSTRUCTURE OF HOT-DEFORMED A-286 SUPERALLOY

[1]Kazimierz DUCKI, [1]Jacek MENDALA, [2]Lilianna WOJTYNEK

[1]*Silesian University of Technology, Katowice, Poland, EU,*
kazimierz.ducki@polsl.pl, jacek.mendala@polsl.pl

[2]*Opole University of Technology, Opole, Poland, EU, l.wojtynek@po.edu.pl*

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Abstract

The influence of initial soaking and parameters of hot plastic working on the deformability and microstructure of the A-286 superalloy have been presented. The research was performed on a torsion plastometer in the range of temperatures of 900 - 1150 °C, at a strain rates of 0.1 s^{-1} and 1.0 s^{-1}. Plastic properties of the alloy were characterized by the worked out flow curves and the temperature relationships of flow stress and strain limit. The structural inspections were performed on microsections taken from plastometric samples after so-called "freezing". The stereological parameters as the recrystallized grain size, inhomogenity and grain shape have been determined. Functional relation between the average grain area and the Zener-Hollomon parameter has been developed and the activation energy for hot working has been estimated.

Keywords: A-286 superalloy, hot deformation, plastic properties, recrystallization, quantitative metallography

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: deformation, strain rate and temperature [1,2]. The high-temperature plastic deformation is coupled with dynamic recovery and recrystallization processes which influencing the microstructure and properties of steels and alloys.

The Fe-Ni superalloys are difficult to deform and are characterized by high values of flow stress at a high temperature. High deformation resistance of superalloys 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 Fe-Ni superalloys, the following factors should be considered [3,4]: 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 Fe-Ni superalloys has an advantageous influence on increasing their yield point and fatigue strength [5,6].

The aim of the work was to investigate the influence of initial soaking and hot plastic working parameters on the deformability and microstructure of the A-286 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**.

Table 1 Chemical composition of the investigated A-286 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 samples for investigations were made from rolled bars sections which were subjected to preheating, i.e. 1100 °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 [7,8]. 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 s^{-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 [9,10]. 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 (MPa),
- ε_p – deformation corresponding to the maximum flow stress (-),
- σ_f – stress at which the sample is subject to failure (MPa),
- 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 by using the Zener-Hollomon parameter Z (s^{-1}) [11,12]:

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

where: $\dot{\varepsilon}$ – strain rate (s^{-1}), Q – activation energy for hot working ($J \cdot mol^{-1}$), R – molar gas constant (8,314 $J \cdot mol^{-1} \cdot K^{-1}$), T – temperature of deformation (K), 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 [13]. The solution algorithm consisted in transforming Eq. (1) to the form:

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

Further procedure was based on solving Eq. (2) by a graphic method with using the regression analysis. Structural inspections were performed on longitudinal microsections taken from the plastically deformed samples until failure after so-called "freezing". Due to the deformation inhomogeneity, microscopic observation was conducted in a representative region located at a distance of ca. 0.65 - 0.75 of the specimen radius. A quantitative analysis of the investigated microstructures was carried out by means of a computer program MET-ILO v. 3.0 [14]. For the analyzed microstructures, in accordance with the methodology presented in paper [15], the following stereological parameters were determined:

- average area of grain plane section ($\bar{A}$),
- variability coefficient of the grain plane section area $v(\bar{A})$,
- volume fraction of dynamically recrystallized grains in the structure V_V,
- grain elongation coefficient δ (Feret coefficient),
- classical dimensionless shape coefficient ξ.

3. RESULTS AND DISCUSSION

The results of the plastometric investigations, in the form of the calculated alloy flow curves at temparatures of 900 – 1150 °C along with corresponding specimen microstructures for two strain rates, are shown in **Figure 1** and **Figure 2**.

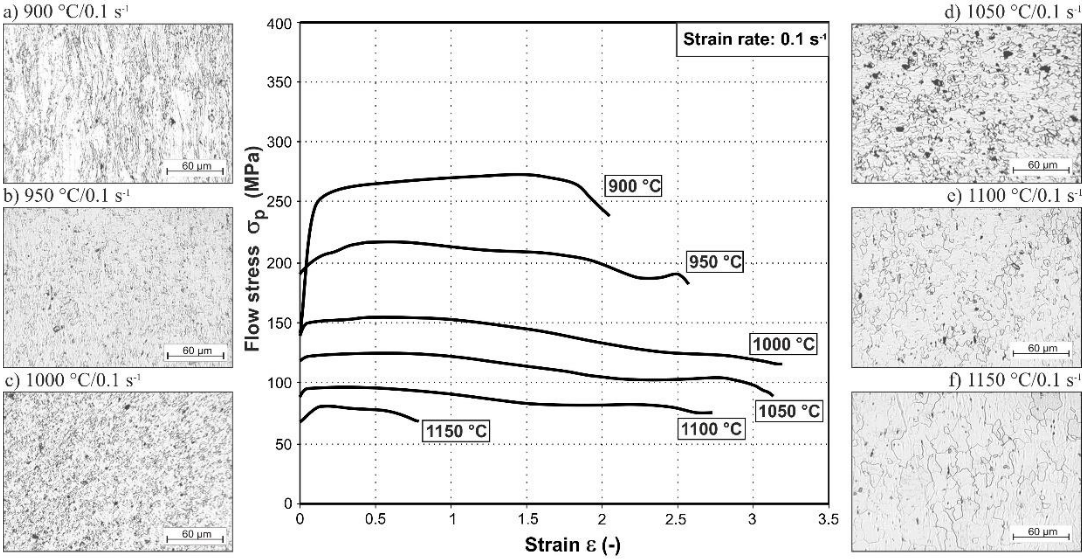

Figure 1 The effect of deformation temperature on the flow stress and microstructure of the A-286 superalloy after initial soaking at 1100 °C / 2 h. Strain rate: 0.1 s^{-1}

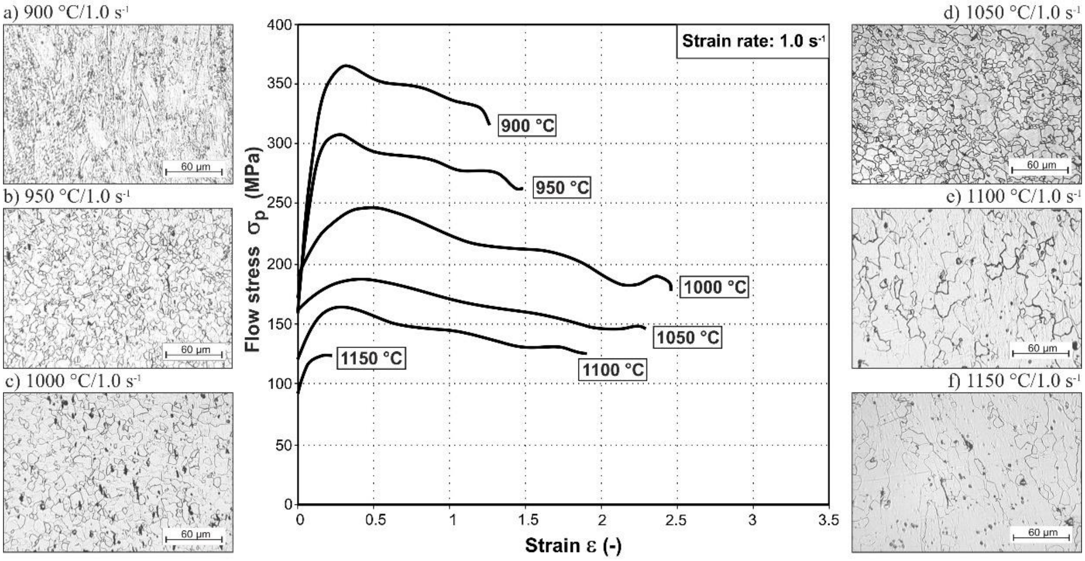

Figure 2 The effect of deformation temperature on the flow stress and microstructure of the A-286 superalloy after initial soaking at 1100 °C / 2 h. Strain rate: 1.0 s^{-1}

The curves obtained for the strain rate of 0.1 s^{-1} have a shape characteristic of a material in which dynamic recovery and recrystallization took place (see **Figure 1**). High deformability values (ε_f = 3.1 - 3.3) were obtained for the alloy in a torsion temperature range of 1000 – 1050 °C. After deformation at 900 °C, considerably elongated grains of deformed austenite as well as formation of fine recrystallized grains were observed in the specimen microstructure (see **Figure 1a**). In a torsion temperature range of 950 - 1100°C, the alloy microstructure consisted of dynamically recrystallized grains (see **Figure 1b-e**). With an increasing deformation temperature, a gradual growth of the recrystallized grains was observed. The recrystallized grains are characterized by a deformed grain boundary line, which indicates an extensive cumulated deformation in the specimens. At the highest torsion temperature (1150 °C), some elongated grains of dynamically recrystallized austenite were observed in the alloy microstructure (see **Figure 1f**).

An increase of strain rate to 1.0 s^{-1} significantly increases the flow stress values and clearly decreases the alloy deformability at all the temperatures examined (see **Figure 2**). This phenomenon can be explained by a higher alloy consolidation rate as well as too slow removal of the strengthening as a result of dynamic recovery and recrystallization. The highest values of strain limit were lower (ε_f = 2.3 - 2.5) and they were obtained for the alloy at torsion temperatures in the range of 1000 - 1050°C. After deformation at 900 °C, the alloy microstructure is not completely recrystallized, which is indicated by the presence of primary austenite grains and fine recrystallized grains (see **Figure 2a**). At a torsion temperatures range of 950 – 1100 °C, the alloy microstructure consisted of dynamically recrystallized grains (see **Figure 2b-e**). With an increasing deformation temperature, a gradual growth of the recrystallized grains was observed. The boundaries of recrystallized grains are less deformed compared to the specimens deformed at a lower rate, which can be explained by a lower cumulated deformation in the specimens. At the highest torsion temperature (1150 °C), the alloy microstructure contain a small amount of dynamically recrystallized grains, which is probably related to the failure of the sample at low strain (see **Figure 2f**).

The results of a quantitative evaluation of the investigated A-286 superalloy microstructure after deformation until failure in a temperature range of 900 – 1150 °C and a strain rates of 0.1 s^{-1} and 1.0 s^{-1} are presented in **Table 2** and in **Figure 3** and **Figure 4**.

Table 2 Stereological parameters of the A-286 superalloy microstructure after deformation in a temperature range of 900 – 1150 °C at a strain rates of 0.1 s^{-1} and 1.0 s^{-1}

Deformation parameters		**Volume fraction of recrystallized grains**	**Grain average area**		**Grain elongation coefficient**		**Dimensionless shape coefficient**	
T (°C)	**$\dot{\varepsilon}$ (s^{-1})**	**V_V (%)**	**$\bar{A}$ (μm^2)**	**$v(\bar{A})$ (%)**	**δ**	**$v(\delta)$ (%)**	**ξ**	**$v(\xi)$ (%)**
900	0.1	41.3	16*	93	1.02	48	1.18	51
950	0.1	100	25	55	1.04	38	0.48	48
1000	0.1	100	40	130	1.09	43	0.51	53
1050	0.1	100	52	240	1.12	66	0.52	51
1100	0.1	100	103	232	0.99	43	0.64	48
1150	0.1	100	198	242	1.31	47	0.62	58
900	1.0	68.0	12*	135	1.09	45	0.53	49
950	1.0	100	23	140	1.00	53	0.53	56
1000	1.0	100	39	183	1.07	43	0.65	51
1050	1.0	100	49	204	1.00	56	0.71	51
1100	1.0	100	87	190	1.03	52	0.61	55
* recrystallized grains without fraction of primary grains								

In the microstructure of the alloy after deformation in the investigated temperature range at a rate equal 0.1 s^{-1}, monotonous growth of the grain average area ($\bar{A}$) is observed from a value 16 μm^2 at 900 °C to 198 μm^2 at 1150 °C (see **Figure 3**). Up to the deformation temperature of 1100 °C, the dynamically recrystallized grains are approximately equiaxial (δ = 0.99 - 1.12), whereas at the highest torsion temperature, 1150 °C, they are elongated (δ = 1.31) (see **Figure 4**). An increase of the torsion rate up to 1.0 s^{-1} induces a certain reduction of the recrystallized grain size. Also, in this case, in the investigated range of deformation temperatures, a monotonous growth of the grain average area ($\bar{A}$) was observed, from 12 μm² at 900 °C to 87 μm² at 1100 °C (see **Figure 3**). In the analyzed range of torsion temperatures of 900 – 1100 °C, the dynamically recrystallized grains are approximately equiaxial (δ = 1.00 - 1.09) (**Figure 4**).

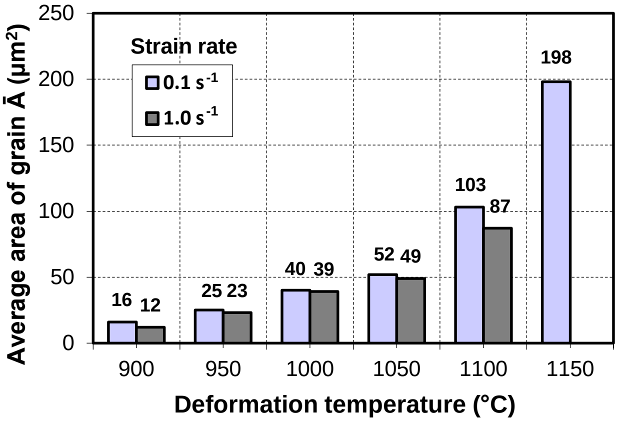

Figure 3 The effect of deformation temperature on the average area of recrystallized grains after torsion at a rate of 0.1 s^{-1} and 1.0 s^{-1}

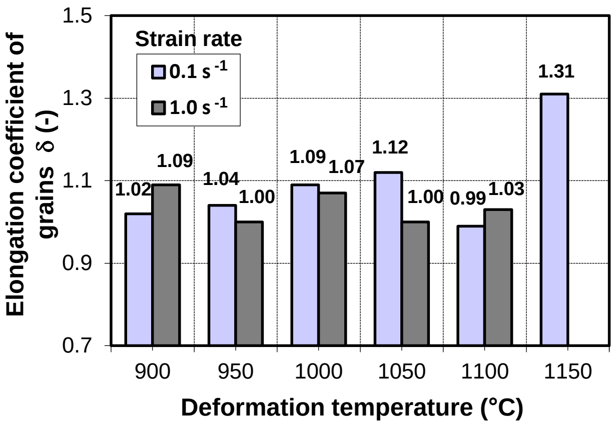

Figure 4 The effect of deformation temperature on the elongation coefficient of recrystallized grains after torsion at a rate of 0.1 s^{-1} and 1.0 s^{-1}

The dependencies between the alloy deformation parameters and the average area of the recrystallized grains are shown in **Figure 5**. For both of the torsion rates applied, mathematical dependencies of an exponential nature were obtained.

The functional dependence between the average grain area and the Zener-Hollomon parameter *Z* are presented in **Figure 6**. For the analyzed alloy deformation parameters, a mathematical dependence of an involutory nature was determined:

$$\bar{A} = 9.3 \cdot 10^{5} \cdot Z^{-0.250} \quad (3)$$

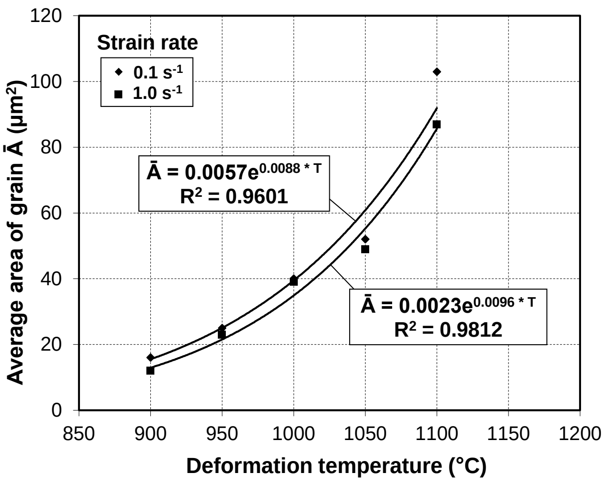

Figure 5 Relationship between the average grain area after recrystallization versus deformation temperature and strain rate

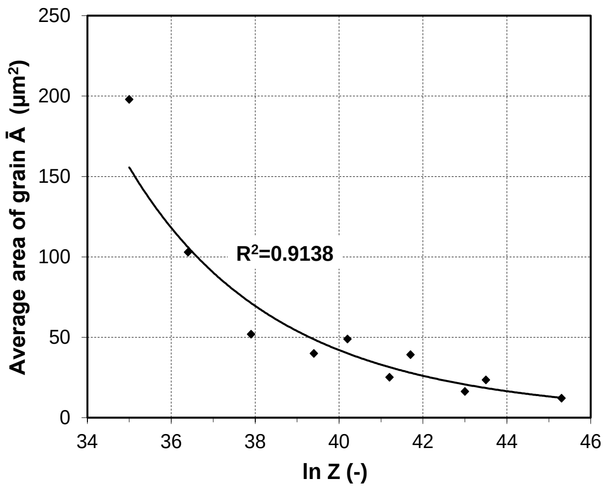

Figure 6 Relationship between the average grain area after recrystallization and the Zener-Hollomon parameter *Z*

The activation energy for hot working *Q* was calculated by the means of a computer programme Energy 3.0 [13]. The estimated activation energy for hot working in the range of the applied deformation temperatures of 900 – 1150 °C and strain limits 0.1 s^{-1} and 1.0 s^{-1}, was high and amounted Q = 441.8 kJ·mol^{-1}.

4. CONCLUSION

The performed examinations on a torsion plastometer in the range temperature of 900 – 1150 °C and strain rates 0.1 s^{-1} and 1.0 s^{-1}, indicated that the deformability and microstructure of the A-286 superalloy depend considerably on parameters of the hot plastic working.

Optimum values of maximum flow stress and strain limit were obtained for the superalloy after the initial soaking at 1100 °C / 2 h and deformation in the temperature range of 1000 – 1050 °C at strain rate 0.1 s^{-1}. The use of higher deformation temperature and strain rate 1.0 s^{-1} is not recommended due to a growth of matrix grains, difficulties in the course of the recrystallization process as well as a decrease of the alloy plasticity.

A considerable influence has been found of the deformation temperature and strain rate on grain size and inhomogenity of the grain size after dynamic recrystallization. However, no explicit influence of the alloy deformation parameters on the shape of recrystallized grains has been observed.

The functional dependence between the average grain area ($\bar{A}$) and the Zener-Hollomon parameter (*Z)* has been described by a simply equation.

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