COMPARISON OF HOT DEFORMATION BEHAVIOR OF SUPERALLOYS INCONEL 600 AND INCOLOY 825

Horymír NAVRÁTIL, Vojtěch ŠEVČÁK, Ivo SCHINDLER, Roman COUFAL, Rostislav KAWULOK

VSB - Technical University of Ostrava, Faculty of Materials Science and Technology, Ostrava, Czech Republic, EU, horymir.navratil@vsb.cz, vojtech.sevcak@vsb.cz, ivo.schindler@vsb.cz, roman.coufal.st@vsb.cz, rostislav.kawulok@vsb.cz

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Abstract

On the hot deformation simulator HDS-20 uniaxial compression tests of two nickel superalloys supplied in the molded state were performed. The cylindrical specimens were heated at rate of 10 °C·s^{-1} directly to the deformation temperature (i.e. from 880 °C to 1,240 °C with dwell time of 180 s after heating) and then were compressed at a constant strain rate of 0.1 s^{-1}, 2 s^{-1} or 30 s^{-1} to a true strain of 1.0. Both materials exhibit a similar true stress-true strain curve with a relatively strong peak signalling the initiation of dynamic recrystallization. From the peak stress, the values of hot deformation activation energy were calculated, namely 483 kJ mol^{-1} for Inconel 600 and 601 kJ mol^{-1} for Incoloy 825. With the knowledge of these variables, equations describing peak stress could be derived for both superalloys (known sinus hyperbolic relation) with good accuracy. It corresponds to the peak strain (power dependence) depending on the Zener-Hollomon parameter, which represents the temperature-compensated strain rate. These dependencies and experimental data were mathematically and graphically compared for both materials. Peak stress is the amount appropriate for simple and fast prediction of the maximum flow stress due to the deformation parameters, excluding the effect of strain.

Keywords: Nickel superalloys, activation energy during hot deformation, true strain, true stress

1. INTRODUCTION

The aim of the work was to compare the deformation behavior of two nickel superalloys. The comparison will be based on the graphical comparison of measured and predicted values of peak stress and strain corresponding to the peak stress of both investigated alloys.

Nickel based superalloys are an atypical category of metallurgic materials with an unique combination high-temperature strength, toughness and resistance to degradation in corrosive or oxidizing environments. These alloys are extensively used in aircraft and power-generation turbines, rocket engines, and other challenging environments, including chemical processing and nuclear power plants. Accelerated alloy and process development activities during the past few decades have resulted in materials that can tolerate average temperatures of 1,050 °C occasional excursions (or local hot spots near airfoil tips) to temperatures as high as 1,200 °C, which approximately 90 % of the melting point of the alloy [1].

Nickel based superalloys generally constitute 40 - 50 % of total weight of an aircraft engine and are used most extensively in the combustor and turbine sections where elevated temperatures are maintained during operation. Such components may contain equiaxed grains or columnar grains, or may be cast as single crystals completely eliminating grain boundaries, because grain boundaries are locations for damage accumulation at high temperatures [1].

Nickel based superalloys are based on the nickel-aluminum system. The system is the binary basic for superalloy compositions. Microstructure nickel based superalloys are composed of matrix γ, curing phase γ´ (Ni_3Al), carbids and intermetallic phases [1].

Incoloy 825 and Inconel 600 are typical Ni-Cr alloys. Corrosion resistance of Inconel 600 and Incoloy 825 are smaller than corrosion resistance of Ni-Cr-Mo alloys, such as alloys 625 and 276. However, production Inconel 600 and Incoloy 825 are economic more advantageous [2,3].

In order to describe deformation behavior of not only nickel superalloys, it is important to know the value of activation energy Q ($J \cdot mol^{-1}$). The value of the activation energy is particularly affected by the given chemical composition and material microstructure. The seeming value of the activation energy during hot forming processes can be affected by the methodology of the mathematical processing of the relevant experimental data. The value of the activation energy represents a very important material constant. For example, it is needed for calculating the Zener-Hollomon parameter Z (s^{-1}). When we know the value of Z, we can predict the corresponding strain value that is necessary for initiating dynamic recrystallization at a given temperature T (K) and strain rate $\dot{e}$ (s^{-1}). There are various methods for determining the value of Q during hot forming processes [4-10].

A conventional procedure for determining the activation energy value is its derivation from the Arrhenius equation (1) when we know all of the other parameters [5].

$$\dot{e} = C \cdot \exp\left(\frac{-Q}{R \cdot T}\right) \cdot [\sinh(\alpha \cdot \sigma_{max}]^n \quad (1)$$

where C (s^{-1}), n (-), α (MPa^{-1}) are material constants, R ($J \cdot mol^{-1} \cdot K^{-1}$) is molar gas constant, T (K) is thermodynamic temperature of deformation and σ_{max} (MPa) is flow stress that corresponds to the peak stress on the certain stress-strain curve.

This equation is often solved using a simple graphic method that utilizes repeated linear regression. Such method significantly simplifies the equation for low stress values. Equation (1) then looks like this [4]:

$$\dot{e} = C_1 \cdot \exp\left(\frac{-Q}{R \cdot T}\right) \cdot {\sigma_{max}}^n \quad (2)$$

where C_1 (s^{-1}) is material constant.

For high stress values, equation (1) looks like this [4]:

$$\dot{e} = C_2 \cdot \exp\left(\frac{-Q}{R \cdot T}\right) \cdot \exp(\beta \cdot \sigma_{max}) \quad (3)$$

where C_2 (s^{-1}) and β (-) are material constants.

The constant α can be calculated from the following equation [4]:

$$\alpha = \frac{\beta}{n} \quad (4)$$

Zener-Hollomon parameter can be obtained from equation (5), which can be used to predict the stress peak [6]:

$$Z = \dot{e} \cdot exp\left(\frac{Q}{R \cdot T}\right) \quad (5)$$

Peak strain can be calculated from the following equation [7]:

$$e_p = U \cdot Z^W \quad (6)$$

where U (-), W (-) are material constants.

Peak stress can be obtained from equation (7) [4]:

$$\sigma_{max} = \frac{1}{\alpha} \cdot arc\ sinh \sqrt[n]{\frac{Z}{C}} \quad (7)$$

2. DESCRIPTION OF THE EXPERIMENT

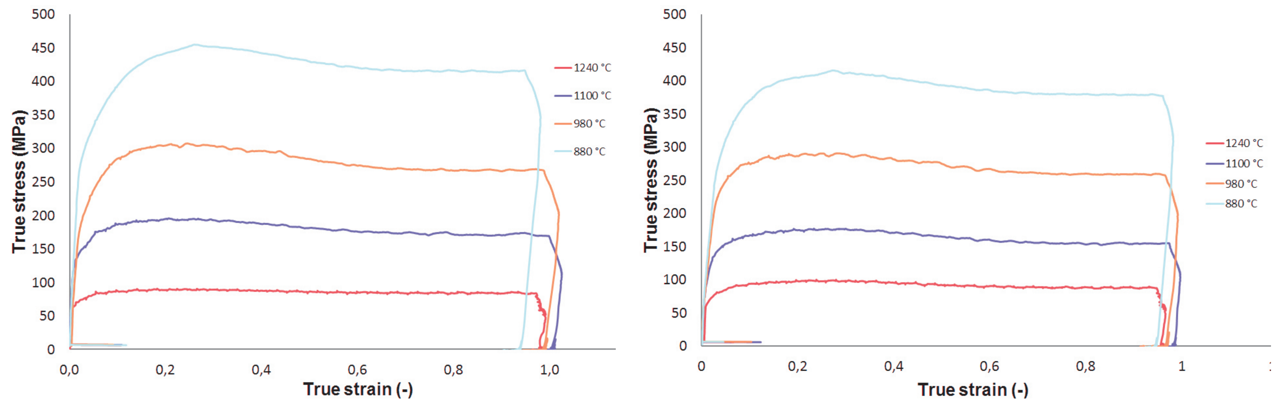
Experimental data were obtained by the means of a uniaxial compression tests. The tested samples were heated directly to the given deformation temperatures by using of the electric resistance heating. The tests were conducted using simulator HDS-20.

Chemical composition of the above-mentioned nickel superalloys is as follows: Inconel 600 contains 16.0 Cr - 9.2 Fe - 0.21 Ti, and nickel the nickel residue. Incoloy 825 contains 30.0 Fe - 22.5 Cr - 3.4 Mo - 1.7 Cu - 1.2 Ti and nickel the nickel residue. The stated chemical contents are stated in weight %.

Individual samples were installed between the anvils. The diameter of the used samples was 10 mm and their length 15 mm. They were next heated using the electric resistance heating with a heating rate of 10 °C·s^{-1} to the following temperatures: 880 °C, 980 °C, 1,100 °C and 1,240 °C. All samples were kept at the given temperature for 180 s. The samples were then deformed by uniaxial compression at strain rates of 0.1 s^{-1}, 2 s^{-1} and 30 s^{-1}. Thanks to this fact, stress-strain curves are obtained for the given strain rate for all deformation temperatures. The samples are subsequently freely cooled down.

3. ASSESSMENT OF THE DEFORMATION STRAIN CURVES OBTAINED FROM EXPERIMENTAL DATA

Stress and strain values were recorded at certain times during the tests. The acquired results were used in the excel program environment for creating the corresponding stress-strain curves for both examined materials at a strain rate of 2 s^{-1} (see **Figure 1**). Each individual curve represents a given temperature during the deformation process. The values of peak stress σ_{max} and corresponding peak strain values e_p were obtained for both superalloys for each temperature based on these diagrams. Moreover, it is clear from these diagrams that the material went through a healing process, resulting into a stabilized plastic flow of the material.



a) Incoloy 825 b) Inconel 600

Figure 1 Stress and strain relation for the investigated alloys for a strain rate of 2 s^{-1}

Figure 1 (a) shows stress-strain curves for the Incoloy 825. At a temperature of 880 ° C, there is significant effect of hardening in the initial phase. This process continues until the peak strain value e_p is reached. This moment corresponds to the beginning of dynamic recrystallization. Then dynamic recrystallization prevails in the material, due to which tension is reduced and material plastic flow stabilizes. For deformation at 980 °C, the true stress drops due to a decrease deformation resistance. Even at this deformation temperature, dynamic recrystallization with a subsequent stabilized flow occurred upon exceeding the peak strain value e_p. When increasing the nominal temperature even more, particularly to 1,100 °C a and 1,240 °C, the deformation resistance further decreases, which means that the maximal stress σ_{max} decreases as well. At 1,240 °C, the stress-strain curve becomes almost constant. As a result, finding the stress peak, which corresponds to peak strain e_p and maximal stress σ_{max}, is more complicated.

Figure 2 (b) shows stress-strain curves for the Inconel 600. The relation is analogous to the Incoloy 825 alloy, which means that increasing temperature causes the deformation resistances to decrease and the stress-strain curves to move to lower stress. As a result of this phenomenon, the peak strain e_p and peak stress σ_{max} values also decrease. The stress curve for the Inconel 600 alloy at the temperature of 1,240 ℃ is almost constant. As a result, finding the corresponding stress peak is more complicated here as well.

4. CALCULATION OF THE VALUE OF ACTIVATION ENERGY DURING HOT DEFORMATION AND DISCUSION OF RESULTS

The equations for activation energy calculations stated in the previous chapter can be solved graphically using multiple regression analyses. The ENERGY 4.0 software is used for this purpose. For a selected high temperature (for low stress values), the constant *n* is obtained using linear regression of the experimental data along coordinates $\ln \sigma_{max} \sim \ln \dot{e}$. For a selected low temperature (for high stress values) the constant β is determined by regression of the experimental data along coordinates $\sigma_{max} \sim \ln \dot{e}$. The value of constant α is subsequently calculated from relation (4). When these values are known, we can use relation (1) for calculating constants *C* and *Q* based on a final linear regression off all the acquired data recorded in the coordinate system $T^{-1} \sim (\ln \gamma - n. \ln(\sinh(\alpha. \sigma_{max})))$ [4].

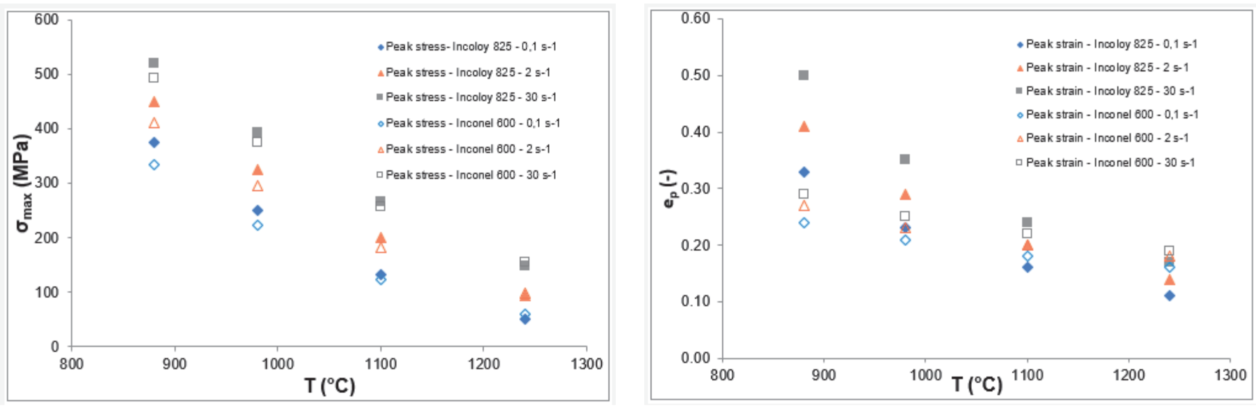
This estimation method for estimating constants *n* and β is inaccurate. It can be quite significantly influenced by the dispersion of the experimentally obtained data and by the selection of the corresponding temperature. This inaccuracy can be significantly reduced by using the ENERGY 4.0 software. This software allows for interactive removal of the points that significantly deviate from the trends determined by the graphic method. In this software, the values of the *n* and β constants, determined by linear regression, are used as the initial estimation of the parameters for making all data that correspond to equation (1) more accurate. When an estimate of the selected material constants is not initially conducted, the multiple regression for improving the accuracy is very unreliable [4].

Particular results from the experiments conducted with the given nickel superalloys are showed in **Table 1**. **Table 1** showes values of the material constants and activation energy during hot deformation for the Incoloy 825 and Inconel 600 alloys.

Table 1 Values acquired from ENERGY 4.0 for the Incoloy 825 and Inconel 600 alloys

Quantity	Inconel 600	Incoloy 825
Q (kJ·mol^{-1})	**482.9**	**601.5**
n (-)	4.68	4.15
α (MPa^{-1})	0.0072	0.0095
C (s^{-1})	$3.38 \cdot 10^{17}$	$1.08 \cdot 10^{21}$
U (-)	0.048	0.0043
W (-)	0.033	0.072

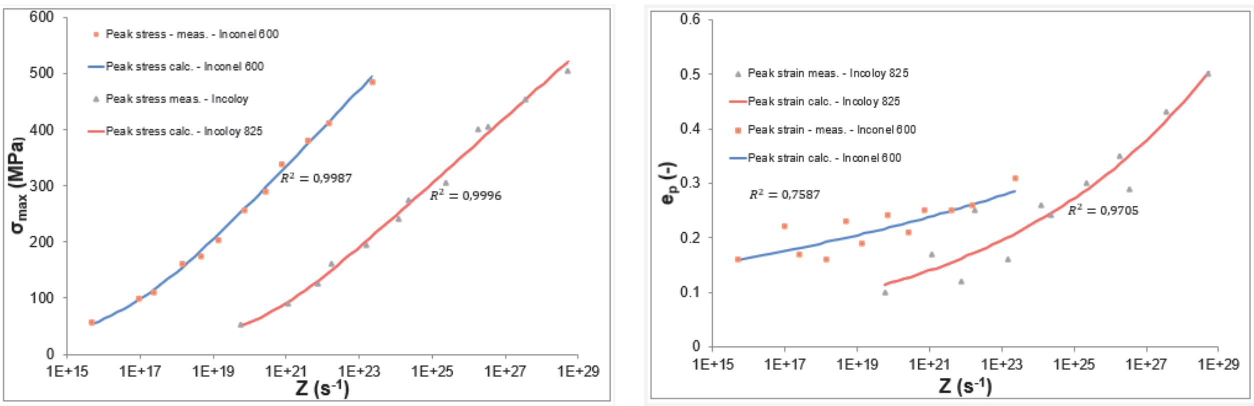
Figure 2 is a graphical comparison of the peak stress and peak strain of the two compared alloys. The comparison shows which of the alloys have higher or lower peak stress and peak strain under given conditions. As temperature increases, the peak stress and peak strain values for both materials decrease.



a) peak stress b) peak strain

Figure 2 Comparison of peak stress and peak strain for Incoloy 825 and Inconel 600 alloys

Figure 3 graphically depicts the dependence of peak stress and peak strain on the Zener-Hollomon parameter. As Zener-Hollomon parameter increases, the peak stress and peak strain values for both materials increase. The Incoloy 825 alloy has a higher activation energy value during hot forming and therefore exhibits higher Zener-Hollomon parameter values under the same conditions. There is also a comparison of measured and predicted values of peak stress and peak strain and evaluation of accuracy.



a) peak stress b) peak strain

Figure 3 Dependence of peak stress and peak strain on Zener-Hollomon parameter (points - measured values, line - calculated values)

5. CONCLUSION

During the plastometric tests, conducted with the help of a uniaxial compression tests, a series of data was obtained for subsequent calculations in the ENEGY 4.0 program. The nickel superalloys were tested at various temperatures and for various deformation rates. The values of the activation energy of hot forming processes and graphic relations between the stress and strain for both alloys were acquired.

The values of the activation energy of hot forming process for both nickel superalloys were calculated from the obtained experimental data and subsequent calculations. The activation energy of hot forming of the Incoloy 825 alloy was calculated to 601.5 kJ·mol^{-1}. Activation energy in hot forming of the Inconel 600 was calculated to be 482.9 kJ·mol^{-1}. It is clear that when deformation temperature reaches 880 °C, the stress-strain curve of the Incoloy 825 alloy moves towards significantly higher stress than it does the stress-strain curve of the

Inconel 600 alloy. This tendency is same even for temperatures of 980 °C and 1,100 °C, however, the differences are not pronounced as much anymore. The difference become negligent when the temperature reaches 1,240 °C. A higher activation energy value during the forming process was obtained for the Incoloy 825 alloy and its stress-strain curves move towards higher stress than in the case of the Inconel 600 alloy.

The graphical comparison of peak stress and peak strain of both alloys shows that at 1,240 °C the maximum stress and strain are slightly higher for the Inconel 600. For other temperatures, the peak stress values are slightly higher for the Incoloy 825. A similar trend is evident for peak strain, but here the differences increase with decreasing temperature. Obviously, at 1,240 °C, the deformation resistance is higher for the Inconel 600 alloy, at lower temperatures the Inconel 825 had higher. The reason may be a more complex chemical composition with a higher content of alloying elements Incoloy 825.

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