THE HIGH-TEMPERATURE STRENGTH AND PLASTIC PROPERTIES OF INCOLOY 800HT AND INVAR 36 ALLOYS

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Abstract

By using of hot tensile tests, which were realized on the simulator HDS-20, the strength and plastic properties of two progressive alloys, based on Fe-Ni-Cr (Incoloy 800HT) and Fe-Ni (Invar 36), were experimentally determined. By a special type of a tensile test, involving a continuous control heating of the tested specimens at their simultaneous load by a constant tensile force of 80 N, a nil-strength temperature of both investigated alloys was determined. In comparison to the Invar 36 alloy, the Incoloy 800HT alloy showed a 71 °C lower nil-strength temperature. By continuous uniaxial tensile tests to rupture, which were performed in a range of deformation temperatures of 800 – 1,390 °C at a constant tensile rate of 1 $mm \cdot s^{-1}$, the strength and plastic properties of both investigated alloys were examined. In comparison to the Invar 36 alloy, the Incoloy 800HT alloy showed in the whole range of deformation temperatures a higher strength. A nil-ductility temperature of the Incoloy 800HT and Invar 36 alloys was 1310 °C and 1390 °C, respectively. A difference between the nil-strength temperature and the nil-ductility temperature was in the case of the Incoloy 800HT and Invar 36 alloy established as 38 °C and 29 °C, respectively.

Keywords: Incoloy 800HT, Invar 36, nil-strength temperature, nil-ductility temperature

1. INTRODUCTION

The main aim of the presented work is a research of the high temperature strength and plastic properties of two selected alloys, based on Fe-Ni-Cr (Incoloy 800HT) and Fe-Ni (Invar 36). The secondary aim is a determination of the nil-strength temperature and nil-ductility temperature of both investigated alloys.

For an experimental examination of the strength and plastic properties at high temperatures it is suitable to use uniaxial tensile tests or torsion tests to a rupture of a tested specimen [1-3]. By using of universal plastometers of the Gleeble type it is possible to determine (among other things) the nil-strength temperature and nil-ductility temperature of the investigated metal material [4-9]. The nil-strength temperature *NST* (°C) is defined as a temperature associated with a loss of all strength of metal due to the melting of grain boundaries. After reaching of this temperature materials cannot withstand any load. The nil-strength temperature is very important for the study of brittleness of metal materials at high temperatures [6-9]. The nil-ductility temperature *NDT* (°C) corresponds to a temperature at which the ductility of the material is equal to zero (achieving of 100 % brittleness). The value of the nil-ductility temperature *NDT* (°C) can be determined by using of tensile tests with a direct heating to the deformation temperatures [4,7-9].

The Incoloy 800HT alloy is characterized by high strength and corrosion resistance at high temperatures. Thanks to these properties, the Incoloy 800HT alloy is used in the aerospace industry, at a construction of rocket engines or turbines and in the chemical or petrochemical industry. In addition, this alloy is used at a construction of catalytic and convection pipelines and for high-temperature heat exchangers in gas-cooled nuclear reactors [10-12]. The Invar 36 alloy is widely known for its very low thermal expansion which is close to zero. This fact makes this alloy one of the most effective for use in precision instruments, magnetic rectifiers, relays, transformer sheets, dynamo sheets, radio and electronic equipment, aircraft equipment, optical and laser systems. In addition, this alloy can be used for storage and transport of cryogenic liquids [13-15].

2. EXPERIMENT DESCRIPTION

For the purposes of the presented work, two progressive alloys, based on Fe-Ni-Cr (Incoloy 800HT) and Fe-Ni (Invar 36), were selected. The chemical composition of the investigated alloys, which were delivered in the initial state after cold drawing and annealing, is shown in **Table 1**.

Table 1 Chemical composition of the investigated alloys in wt. %

Alloy	C	Si	Mn	Cr	Cu	Co	Ni	Ti	Al	P	S	Fe
Incoloy 800HT	0.071	0.46	0.87	19.57	0.32	-	30.67	0.60	0.42	0.025	0.001	46.62
Invar 36	0.043	0.15	0.40	-	-	0.013	36.01	-	-	-	-	63.38

By using of hot tensile tests, which were realized on the simulator HDS-20, the strength and plastic properties of both investigated alloys were experimentally determined.

By using a special type of a hot tensile test, the nil-strength temperature of the investigated alloys was determined. For these purposes the cylindrical specimens with a diameter of 6 mm and length of 81 mm were prepared from both investigated alloys. These specimens were then heated up in two stages by electrical resistant heating, and there was applied a small constant tensile force of 80 N to the specimens during the whole test. The specimens were heated up at a rate of 20 $°C \cdot s^{-1}$ to the temperature of 1,100 °C, and then slowly heated at a rate of 2 $°C \cdot s^{-1}$ from this temperature to the moment of their rupture. In order to eliminate possible inhomogeneities in the investigated alloys and make a statistical evaluation, this test was performed 3 times in the same conditions.

By using of the continuous uniaxial tensile tests to rupture, the strength and plastic properties of the investigated alloys at high temperatures were examined. For these purposes, the cylindrical specimens with a diameter of 10 mm and length of 116.5 mm, which were threaded at the ends, were prepared from the investigated alloys. These specimens were then attached into stainless steel jaws with a partial contact area and electrical resistance heated with a rate of 10 $°C \cdot s^{-1}$ directly to the deformation temperatures which were selected in a range of 800 °C – 1,390 °C. After a uniform 4-minute dwell time at the deformation temperature, the specimens were deformed at a constant tensile rate of 1 $mm \cdot s^{-1}$, which corresponds to the mean strain rate at the beginning of the test – ca. 0.1 s^{-1}, until their rupture.

3. PROCESSING OF MEASURED DATA AND DISCUSSION OF RESULTS

The experimentally determined nil-strength temperature corresponds to the highest value of the registered temperature at a moment of rupture of the tested specimen (due to the combination of melting of grain boundaries and the effect of a very small tensile force). This phenomenon is easily identifiable because it is accompanied by a steep decrease of the measured temperature (see **Figure 1** and **Figure 2**). The mean values $NST_{(mean)}$ (°C) and standard deviations of the measured nil-strength temperatures of the investigated alloys were subsequently determined. For the Inconel 800HT alloy was $NST_{(mean)}$ = 1,348 °C (standard deviation of 4.8 °C) and for the Invar 36 alloy was $NST_{(mean)}$ = 1,419 °C (standard deviation of 5.9 °C). The determined nil-strength temperatures of both investigated alloys correspond to solidus temperatures which were calculated by simulations in the JMatPro software. The solidus temperatures of 1,358 °C and 1,439 °C were determined for the Incoloy 800HT and Invar 36 alloys, respectively. The determined nil-strength temperatures are lower than the solidus temperatures of both investigated alloys, which corresponds to the results of the works [4,6].

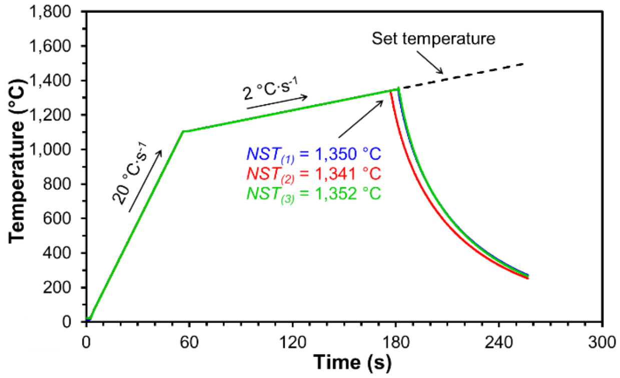


Figure 1 The measured nil-strength temperature of the Incoloy 800HT alloy

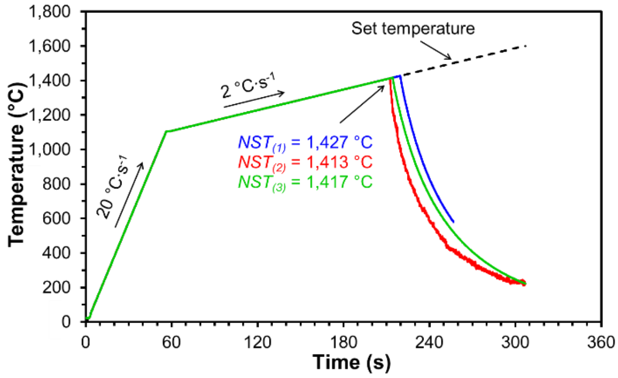


Figure 2 The measured nil-strength temperature of the Invar 36 alloy

From the data registered during the continuous uniaxial tensile tests, tensile diagrams documenting the relationships between the measured force and the total elongation were prepared – see examples in **Figure 3**. From these diagrams it was possible to determine the maximum force values $F_{max.}$ (kN) and total elongation to the rupture ΔL (mm). These values were then used for the calculation of the contractual hot ultimate tensile strength UTS_H (MPa) and hot ductility A_H (%) of all ruptured specimens:

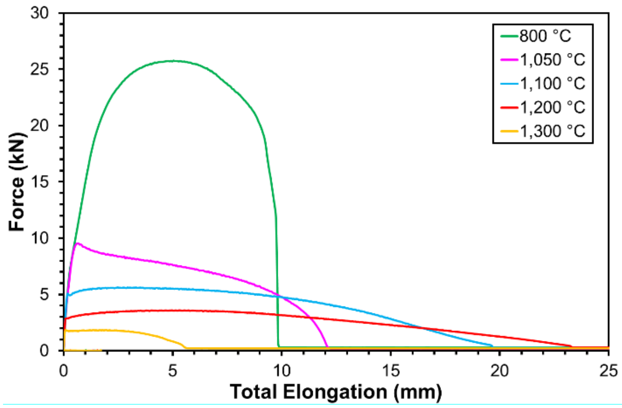


Figure 3 Selected tensile diagrams of Incoloy 800HT alloy

$$UTS_H = \frac{F_{max.} \cdot 1000}{S_0} \tag{1}$$

$$A_H = \frac{\Delta L}{L_0} \cdot 100 \tag{2}$$

where S_0 (mm) is the initial cross-sectional area of the tested specimens and L_0 (mm) is the measured length which was equal to 20 mm (in the case of the used jaws from stainless steel and the dimensions of the tested specimens). The hot reduction of area RA_H was expressed by cross-sectional areas of tested specimens after rupture S_1 (mm^2) and initial cross-section S_0 = 78.5 mm^2:

$$RA_H = \frac{S_0 - S_1}{S_0} \cdot 100 \tag{3}$$

With an increase of deformation temperature, the deformation resistance and related contractual hot ultimate tensile strength decreased (see **Figure 4**). In comparison to the Invar 36 alloy, the Incoloy 800HT alloy showed in the whole range of deformation temperatures a higher strength. The higher hot ultimate contractual tensile strength of Incoloy 800HT alloy, which manifested itself significantly especially at temperatures of 800 – 1,100 °C, can be explained by the high chromium content and the alloying of this alloy also with aluminum and titanium (compared to the Invar 36 alloy). In nickel alloys, chromium is partially dissolved in the basic matrix and the rest is involved in the formation of complex carbides which main function is to increase the heat resistance of these alloys. Chromium, generally in the solid solution, strengthens the basic matrix and, in the case of austenitic-type alloys, also reduces the recrystallization capabilities, which results in an increase of deformation resistance of the alloy. Aluminum and titanium enable a higher hardness of nickel-based superalloys because they form intermetallic precipitates with nickel $Ni_3(Al,Ti)$, which reach high creep limits [16-18].

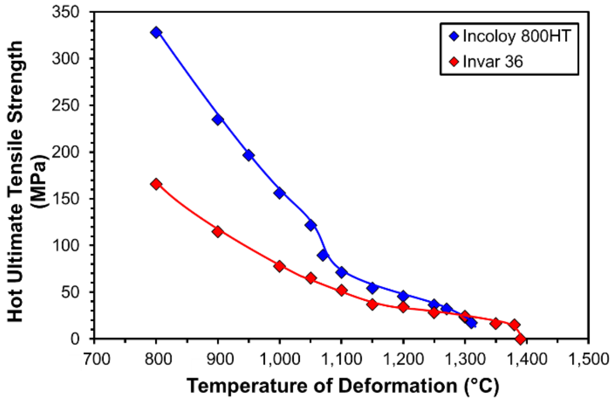
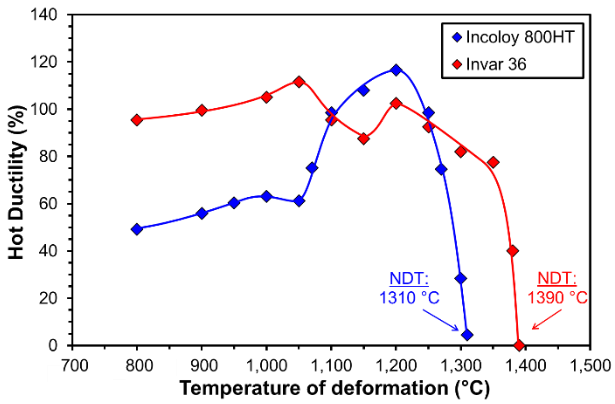
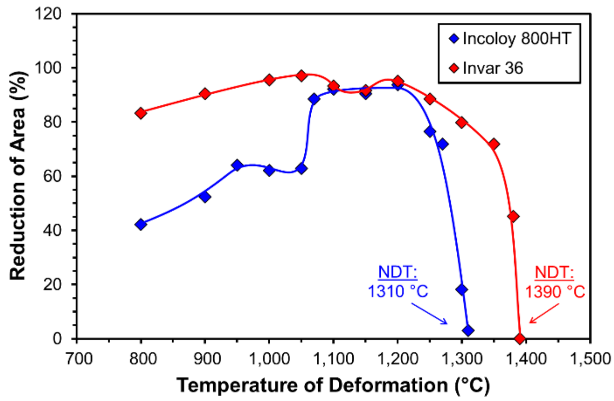


Figure 4 The contractual hot ultimate tensile strength of the investigated alloys

The hot plastic properties, expressed by hot ductility and reduction of area, of both investigated alloys can be seen in **Figure 5**. The Incoloy 800HT alloy shoved, especially in the temperature range 800 – 1,070 °C, lower plastic properties than Invar 36 alloy, which can be explained by the high chromium content (approx. 20 wt. %) in the Incoloy 800HT alloy. In comparison to the Invar 36 alloy, the Incoloy 800HT alloy showed at deformation temperatures above 1,200 °C earlier and rapid decrease of plastic properties (hot ductility and reduction of area of tested specimens). This decrease of plastic properties of both investigated alloys at high temperatures was probably caused due to their overheating and burning.



a) Hot Ductility



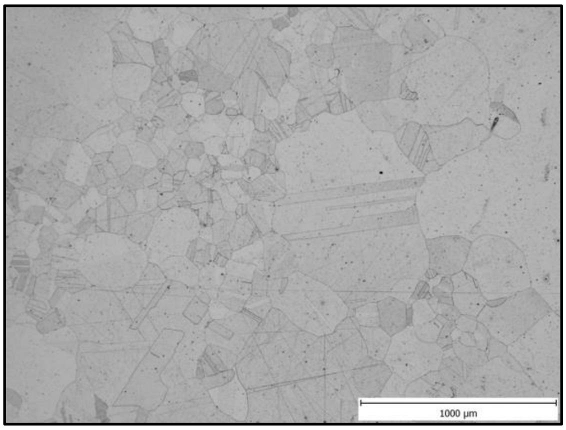
b) Reduction of Area

Figure 5 The plastic properties of the investigated alloys

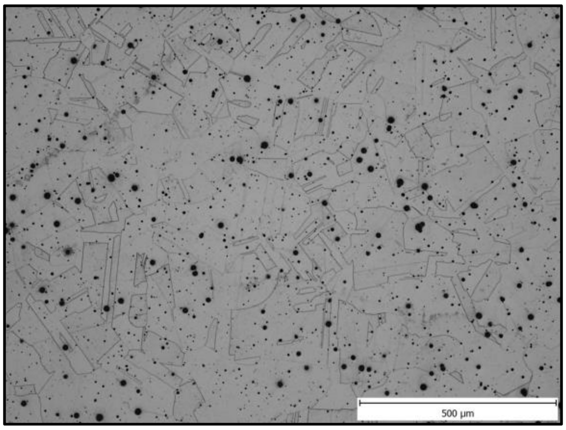
The Incoloy 800HT alloy showed the maximal plastic properties at the temperature range of 1,100 – 1,250 °C (with a local maximum at 1,200 °C). The Invar 36 alloy showed the maximal plastic properties around the temperature of 1,050 °C. Based on the results of the uniaxial tensile tests, the nil-ductility temperature of 1,310 °C for the Incoloy 800HT alloy and 1,390 °C for the Invar 36 alloy was determined (see **Figure 5**). The Invar 36 alloy therefore showed an 80 °C higher nil-ductility temperature than Incoloy 800HT alloy. The difference between the nil-strength temperature and the nil-ductility temperature was in the case of the Incoloy 800HT alloy 38 °C, and 29 °C in the case of the Invar 36 alloy. Determined differences between the nil-strength temperature and nil-ductility temperature of both investigated alloys corresponds to the results in the works [5,7,8] in which the difference between the nil-strength temperature and the nil-ductility temperature of the investigated steels was on average 31 °C with a deviation of ± 8 °C.

From the point of view of formability, it is interesting a local decrease of plastic properties of the Invar 36 alloy in the temperature range of 1,050 – 1,200 °C, which was determined also in the work [13]. In the case of the

Incoloy 800HT alloy around the temperature 1,050 °C, a similar anomaly deviating from the dependence of plastic properties on the deformation temperature was found. For the reason of finding the causes of these declines, or changes in the trend, metallographic analyses were additionally performed. The aim of these analyses was to characterize the initial structural state of both investigated alloys at selected temperatures. Both investigated alloys showed an initial austenitic structure after heating to the selected temperatures (see examples in **Figure 6**), which was also confirmed by simulations of heating of the investigated alloys in the JMatPro software. The structure of the Invar 36 alloy in all cases contained a relatively large amount of black formations which are probably carbides. SEM and EDS analysis of these samples would be necessary to accurately identify these formations. However, the metallographic analyses and simulations in the JMatPro software did not provide the necessary explanation for the decrease of plastic properties in the given range of deformation temperatures.



a) Incoloy 800HT alloy – temperature of 1,050 °C



b) Invar 36 alloy – temperature of 1,150 °C

Figure 6 Example of photo documentation of initial structure after heating of investigated alloys

4. CONCLUSIONS

The high temperature strength and plastic properties of Incoloy 800HT and Invar 36 alloys were investigated by using of the simulator HDS-20.

The nil-strength temperature of 1,348 °C for the Incoloy 800HT alloy and 1,419 °C for the Invar 36 alloy was determined. In comparison to the Invar 36 alloy, the Incoloy 800HT alloy showed in the whole range of deformation temperatures a higher contractual ultimate tensile strength. The Incoloy 800HT alloy showed the max. plastic properties at a temperature range of 1,100 – 1,250 °C (with a local maximum at 1,200 °C). The Invar 36 alloy showed the maximal plastic properties around the temperature 1,050 °C. The nil-ductility temperature of 1,310 °C for the Incoloy 800HT alloy and 1,390 °C for the Invar 36 alloy was determined. From the point of view of formability, an interesting local decrease of plastic properties of the Invar 36 and Incoloy 800HT alloys was found in the temperature range of 1,050 – 1,200 °C and around the temperature of 1,050 °C, respectively.

The achieved results can be used for an optimization of heating and forming temperatures, or for processes associated with a welding of both investigated nickel alloys.

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