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PLASTICITY OF NICKEL-BASED SUPERALLOY 625 AT ELEVATED TEMPERATURE

Waldemar Ziaja, Maciej Motyka
Marek Poręba

Summary

Structural elements made of nickel-based superalloys are often plastically formed at elevated temperature (e.g. by stamping) so detailed characterization of their deformation behaviour is crucial. Some alloys exhibit unstable plastic flow at elevated temperature characterized by serrated yielding, known as Portevin-Le Chatelier (PLC) effect. This phenomenon is usually attributed to dynamic strain ageing (DSA). The PLC effect is observed in many nickel-based superalloys within a certain range of deformation temperature and strain rate. The aim of presented research was to investigate deformation behaviour of 625 nickel-based superalloy in tensile tests in the temperature range of 200-1100°C and for strain rates of $5\cdot10^{-4}$ and $5\cdot10^{-2}$ s^{-1}. The effect of temperature and strain rate on the mechanical properties of the 625 alloy and character of serrations on the stress-strain curves was analysed. Strain rate sensitivity parameter dependence on deformation temperature was determined.

Keywords: nickel-base superalloys, alloy 625, plasticity at elevated temperature, dynamic strain ageing (DSA), Portevin-Le Chatelier (PLC) effect

Plastyczność nadstopu niklu 625 w podwyższonej temperaturze

Streszczenie

Elementy konstrukcji z nadstopów niklu wytwarzane są często w procesach przeróbki plastycznej blach w temperaturze podwyższonej. Konieczność opracowania szczegółowej charakterystyki odkształcania plastycznego materiałów kształtowanych blach. Niektóre stopy, w tym nadstopy na osnowie niklu, cechują się niestabilnością płynięcia plastycznego podczas odkształcania w temperaturze podwyższonej. Spowodowana jest dynamicznym starzeniem odkształceniowym. Przejawia się cyklicznymi zmianami naprężenia na krzywej rozciągania (tzw. „ząbkowaniem”) – efekt Portevina-Le Chateliera (PLC). Efekt PLC stwierdzono w wielu gatunkach nadstopów niklu, w określonym zakresie temperatury i prędkości odkształcania. W pracy prowadzono ocenę procesu odkształcania plastycznego nadstopu niklu 625 w próbie statycznej rozciągania w zakresie temperatury 200-1100°C, z prędkością odkształcania – $5\cdot10^{-4}$ i $5\cdot10^{-2}$ s^{-1}. W prowadzonej analizie wyników ustalono wpływ warunków odkształcania plastycznego stopu 625 na charakter zjawiska „ząbkowania” oraz właściwości mechaniczne. Określono również zależność współczynnika czułości naprężenia płynięcia plastycznego na prędkość odkształcania od temperatury odkształcania.

Słowa kluczowe: nadstopy niklu, stop 625, plastyczność, dynamiczne starzenie odkształceniowe, efekt Portevina-Le Chateliera (PLC)

Address: Waldemar ZIAJA PhD. Eng., Maciej MOTYKA DSc. Eng., Marek PORĘBA PhD. Eng., Faculty of Mechanical Engineering and Aeronautics, Department of Materials Science, Rzeszow University of Technology, Powstancow Warszawy 12, 35-959 Rzeszow, e-mail: wziaja@prz.edu.pl

1. Introduction

Nickel-based superalloys are important materials for structural elements of gas turbines. A lot of them are produced by casting methods (e.g. blades) but some subassemblies are made also of thin sheets. In that case structural elements are manufactured by plastic working therefore the plasticity and formability are the important criteria for material selection. It is generally known that nickel-based superalloys are characterized by low plasticity at room temperature so plastic working operations are conducted usually at elevated temperature. Selection of working conditions should be based on hot deformation characteristics of material [1-3]. For this purpose deformation mechanism maps (processing maps) are very useful as they show the ranges of temperature and strain rate appropriate for plastic working [4]. Their also enable prediction of the range of processing parameters for shear bands formation and intergranular cracking in deformed products. The results of forming operations are strongly dependent on chemical composition and initial microstructure of examined material – especially grain size [5]. For example the processing maps for Inconel 718 alloy with grain size of 90 μm, deformed to the strains of 0.1, 0.3, 0.5 and 0.7, show three regions of unstable deformation: shear bands formation – $\varepsilon \geq 0.3$, T = 950-960ºC, $\dot{\varepsilon}$ = = 1–100 $s^{-1}$and two regions of intergranular cracking located at 1125–1150ºC ($\dot{\varepsilon}$ = 30-100 s^{-1}) and 1140-1150ºC ($\dot{\varepsilon}$ = 0.001-0.01 s^{-1}) [4]. Processing maps also indicate the condition ranges of dynamic recrystallization which should be considered in the plastic working condition selection – e.g. hot continuous rolling or forging [4, 6].

It is worth to notice that the most often processing maps are elaborated based on experimental results obtained from compression tests on bulk samples (on Gleeble simulators). Hence their application for thin sheets deformed in tension is limited [7].

Alloy 625 is a solution strengthened, nickel-based superalloy with chromium, molybdenum and niobium as the main alloying elements. Thanks to its unique properties – good mechanical properties at high temperature and corrosion resistance as well as excellent fabrication characteristics – it is used in a wide range of applications in aerospace industry, chemical processing, marine engineering and nuclear reactors [8]. Alloy 625 exhibits the Portevin-Le Chatelier (PLC) effect during plastic deformation within a certain range of temperature and strain rate. The PLC effect is related to inhomogeneous plastic deformation, most often explained by Dynamic Strain Ageing (DSA). This phenomenon is often accompanied by the negative strain rate sensitivity, characteristic for some nickel-based alloy, which cannot be explained only by the influence of DSA [9, 10].

The strain rate sensitivity coefficient (m) is a measure of the dependence of the flow stress (σ_{pf}) of the material on external testing conditions such as the applied strain rate ($\dot{\varepsilon}$) and the temperature (T). Generally its value may vary between 0 and 1. When a material's behaviour is strain rate sensitive, a considerable delay in necking may occur. Superplastic materials, with m values higher than 0.3, are able to withstand elongations of several hundred percent before failure and, thus, constitute a very evident case of the influence of m on ductility. The strain rate sensitivity coefficient *m* can be defined as [4]:

$$m = \frac{\mathrm{d}\log\sigma_{pf}}{\mathrm{d}\log\dot{\varepsilon}} \tag{1}$$

where: σ_{pf} – plastic flow stress, $\dot{\varepsilon}$ – strain rate.

In the paper plasticity of the alloy 625 in the temperature range of 200-1100°C was examined on the basis of the results of tensile tests carried out at the strain rates of $5\cdot10^{-4}$ and $5\cdot10^{-2}$ s^{-1}. Character of the stress-strain curves was analysed and conditions for which PLC effect took place were identified. Dependence of strain rate sensitivity coefficient on the temperature was also calculated for the 625 alloy.

2. Experimental procedure

Material tested was ATI 625HP alloy (AMS5599G) in the form of the sheet 1.0 mm in thickness, cold rolled, annealed at minimum 871°C and air cooled (Table 1).

Table 1. Chemical composition of the alloy 625 tested

Elements content, wt.%											
Ni	Cr	Fe	Mo	Nb+Ta	C	Mn	Si	Al	Ti	S	P
Bal.	20.84	4.66	8.51	3.37	0.03	0.03	0.10	0.16	0.20	0.0001	0.006

The microstructure of the alloy consisted of equiaxed grains with significant number of annealing twins (Fig. 1).

Tensile tests at elevated temperature were carried out using Instron 5982 testing machine. Flat specimens (gauge width b_0 = 12.5 mm, gauge length l_0 = = 25 mm) were deformed without protective atmosphere at the temperature range of 200-1100ºC and strain rates $5\cdot10^{-4}$ and $5\cdot10^{-2}$ s^{-1}. Based on tensile test results the values of yield strength (YS), ultimate tensile strength (UTS) as well as total and uniform elongation (EL and EL_u respectively) were determined. Yield strength was calculated by 0.2% offset method.

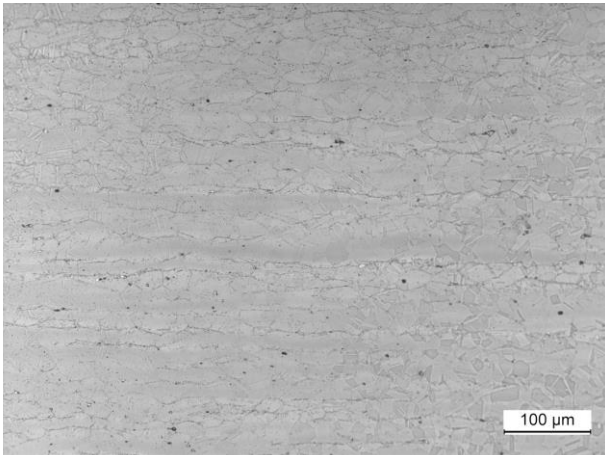

Fig. 1. Microstructure of the alloy 625 in as-received state

3. Results and discussion

Alloy 625 exhibits diverse behaviour during tensile test depending on the test temperature and strain rate applied (Fig. 2). At the strain rate of $5 \cdot 10^{-4}$ s^{-1} the stress-strain curves showed similar character for the test temperature up to 600°C. It is characterized by intensive strain hardening and high uniform elongation – over 40%. Characteristic feature of the stress-strain curves of the 625 alloy deformed in that range of temperature are serration resulting from stress instability in the strain hardening stage of the test that are manifestation of Portevin-Le Chaterlier (PLC) effect.

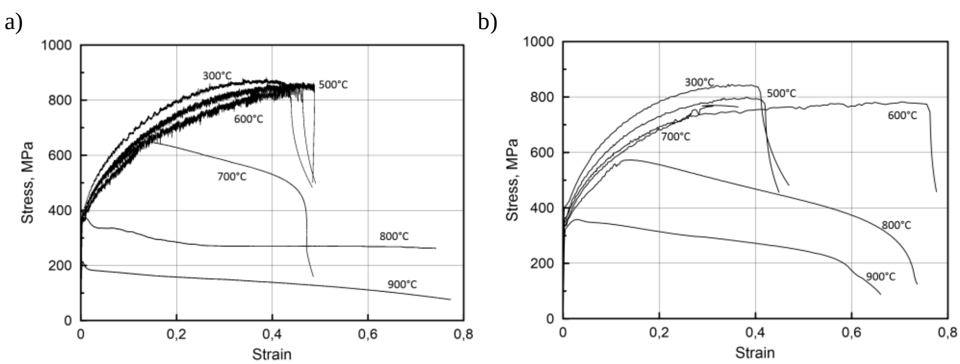

Fig. 2. Tensile stress-strain curves of 625 alloy at various temperature and the strain rate of: a) $5 \cdot 10^{-4}$ s^{-1} and b) $5 \cdot 10^{-2}$ s^{-1}

Inhomogeneous plastic deformation is a result of interactions between diffusing solute atoms and mobile dislocations. Dislocations are blocked by the solute atoms causing strengthening of the material. At certain stress value mobile dislocations are released resulting in reduction of force required for deformation. This phenomenon is responsible for rapid fluctuations of force during tensile deformation [10]. The character of the serrations is dependent on the test temperature and strain rate applied. For 625 alloy deformed at the strain rate of $5 \cdot 10^{-4}$ s^{-1} type B serrations were observed at the temperature range of 300-400°C. At higher temperature (500-700°C) they became more regular (C type) which is usually typical for low strain rates and high temperature (Fig. 3) [11].

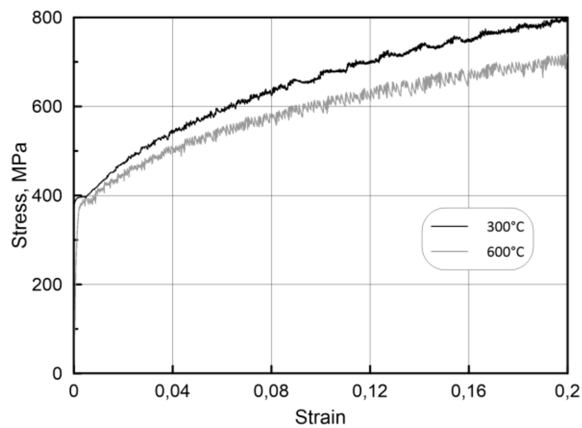

Fig. 3. Serrated tensile stress-strain curves of 625 alloy at various temperature and strain rate $5 \cdot 10^{-4}$ s^{-1}

At the test temperature of 700°C the character of stress-strain curve changed significantly. There was still distinct strain hardening stage with serrations observed on the curve but both uniform elongation and ultimate tensile strength values were substantially reduced compared to the tests at lower temperature and strain developing during the neck formation stage was larger (Fig. 2a).

Further change of the deformation behaviour of the alloy was observed at the test temperature of 800°C. Although yield strength was not decreased significantly the alloy did not show strain hardening and total elongation was significantly increased. Increase of test temperature above 800°C caused drastic reduction of both yield and tensile strength. This phenomenon can be attributed to the increasing intensity of the processes of dynamic recovery and recrystallization and change of the dominant deformation mechanisms (Fig. 5).

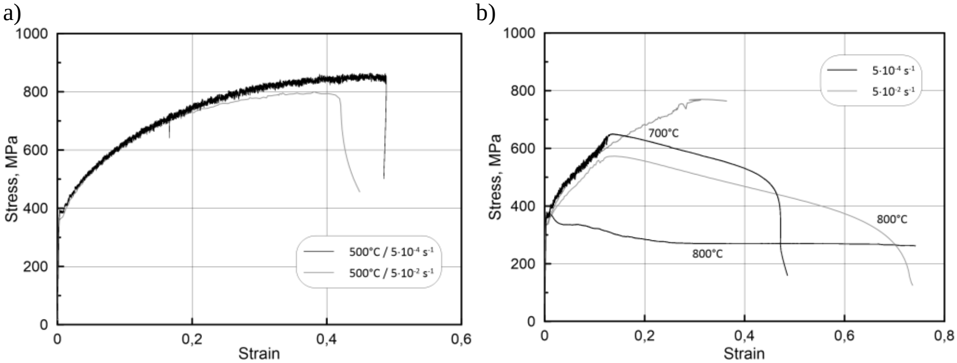

Fig. 4. Stress-strain curves of 625 alloy at various temperature and strain rates

The effect of higher strain rate ($5\cdot10^{-2}$ s^{-1}) on mechanical properties depends strongly on the test temperature. It caused almost complete suppression of serrations on the stress-strain curves (Fig. 1b). At the temperature range of 200-800°C the yield strength showed low sensitivity to the strain rate (Fig. 5). In the range of 400-800°C its values were slightly reduced comparing to the test at low strain rate, resulting in negative value of strain rate sensitivity parameter (Fig. 6). Also tensile strength was lower at higher strain rate but only up to the temperature of 600°C. For higher test temperature increase of the strain rate resulted in extension of the strain limits of strain hardening effect, even at 800°C, and significantly higher values of ultimate tensile strength (Fig. 4b). In that temperature range the strain rate sensitivity of the alloy was considerably higher which can be attributed to operation of thermally activated deformation mechanisms (Fig. 5a).

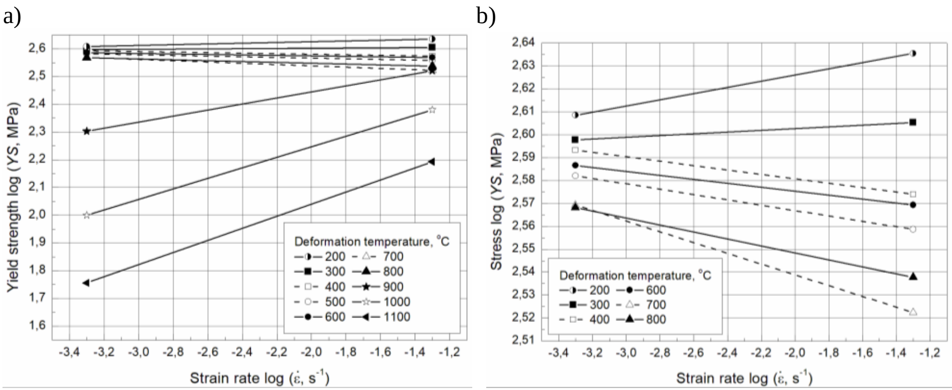

Fig. 5. Yield strength–strain rate relationship for all applied deformation temperatures (a) and for DSA temperature range (b)

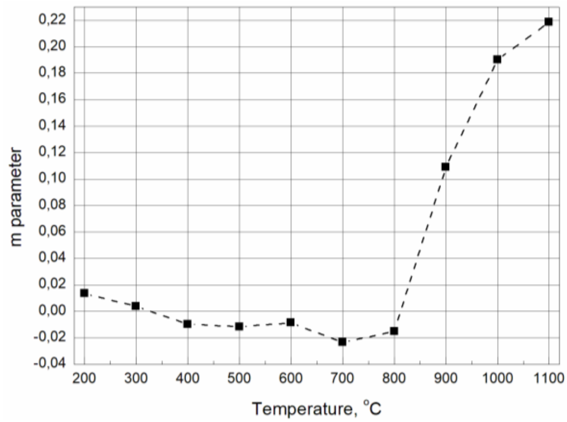

Fig. 6. Dependence of *m* parameter on deformation temperature

The yield strength dependence on the test temperature (Fig. 7) is usually the basis for determination of activation energy of plastic deformation [12]. For the 625 alloy examined two temperature ranges were identified with different slope of the lines on Arrhenius plot, suggesting domination of different plastic deformation mechanism. It is related to the strong influence of the processes of dynamic recovery and recrystallization on the plasticity, deformation characteristic at elevated temperature and microstructure of the hot formed alloy 625 [13-15].

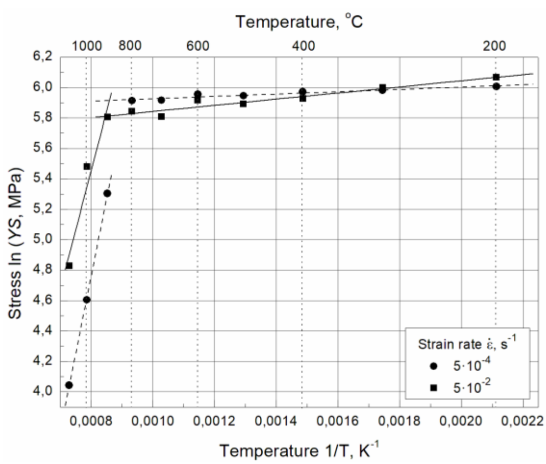

Fig. 7. Dependence of YS on deformation temperature (Arrhenius plot)

4. Conclusions

Based on the analysis of the results of elevated temperature tensile tests carried out at various strain rates following observations and conclusions were formulated:

1. Stress-strain curves obtained for 625 alloy at the strain rate of $5\cdot10^{-4}$ s^{-1} and test temperature up to 700°C showed characteristic serration resulting from tensile stress instability (Portevin-Le Chaterlier effect) caused by dynamic strain ageing. The character of the serrations was dependent on the test temperature. Type B serrations were observed at the temperature range of 300-400°C which gradually switched to type C at higher temperature (500-700°C). Application of high strain rate ($5\cdot10^{-2}$ s^{-1}) resulted in almost complete suppression of serrations on the stress-strain curves.

2. Negative strain rate sensitivity was observed for 625 alloy at the temperature range of 400-800°C, but this phenomenon cannot be attributed solely to the dynamic strain aging.

3. Up to the temperature of 600°C tensile strength decreased with increasing strain rate. For the test temperature of 700°C and higher reverse dependence was observed which was attributed to increasing contribution of high temperature deformation mechanisms and reduced effect of dynamic strain aging.

4. Strain hardening was not observed in the alloy deformed at low strain rate ($5\cdot10^{-4}$ s^{-1}) at the temperature of 800°C and above, while for the high strain rate ($5\cdot10^{-2}$ s^{-1}) it was true for the tests carried out at 900°C and above. Recommended temperature for plastic forming would be dependent on the required strain rate.

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