Deformation behavior of stainless steel under uniaxial tension

A M Nikonova¹, Y V Li¹ and S A Barannikova¹,²,³

¹Institute of Strength Physics and Materials Science SB RAS, Tomsk, Russia
²National Research Tomsk State University, Tomsk, Russia
³Tomsk State University of Architecture and Building, Tomsk, Russia

E-mail: zharmukhambetova@gmail.com

Abstract. The present work is devoted to the study of the laws of macroscopic localization of plastic deformation of austenitic stainless steel AISI 321 at low and high temperatures. The studies of AISI 321 steel found that at the stages of linear strain hardening, the propagation velocity of the localized plastic deformation centers and the spatial period of local elongation change when test temperature increases by the exponential law. Patterns of plastic strain localization as single bands are due to the Portevin – Le Chatelier effect on jerky flow.

1. Introduce

As requirements to the reliability and strength of machines and structures grow, studies of the physical nature of the elasto-plastic transition, microplasticity, yield stress and ultimate strength have become even more important [1]. That was a subject of particular relevance to the large deformations when the laws of strain hardening change. The problem is particularly acute from the use of large plastic deformations in the technological processes of rolling, swaging, stamping and drawing. Since these methods are used to obtain ultrafine-grained and nanocrystalline states of metals and alloys, it is becoming clear why problems of insufficient plasticity and transition of the material to an unacceptable fracture mode are so severe. In the physical description of the plastic flow process, the issue of the causes and the nature of macroscopic localization and strain hardening during the transition from one stage of the process to another remains open [2, 3]. In addition, the question of whether there is a link between microscopic and macroscopic mechanisms of localized plastic deformation has not yet been studied. Thus, there are gaps in both the microscopic and macroscopic descriptions of the plasticity phenomenon [4, 5]. It is known that austenitic stainless steels have a deformation-unstable structure in which phase transformations with the formation of particles of the α'-phase can occur under force action [6]. Austenitic stainless steels are used for the production of welded construction and vessels operating in aggressive environments, as well as for low-temperature technology. During the operation of equipment at low temperatures, the impact of both static and dynamic loads is possible. In metastable austenitic steels the martensitic transformations can lead to hardening of the material on the one hand and can cause embrittlement of the parts of low-temperature equipment on the other. During tension of metastable austenitic, the features of the Portevin – Le Chatelier effect (PLC) at various strain rates and at elevated temperatures were considered in [6]. The present work is devoted to the study of the laws of macroscopic localization of plastic deformation of austenitic stainless steel AISI 321 at low and high temperatures. It should be noted that at low temperatures the localization of plastic deformation of stainless steels have not been previously studied using the digital image correlation method (DIC).
2. Materials and research methods

AISI 321 steel samples were prepared in the form of a dog bones with dimensions of the working part 50 × 10 × 2 mm. These were tested in tension on a test machine LFM-125 at a speed of 6.67×10^{-5} s^{-1} and in the temperature range of 123 K to 373 K. The microstructure of the material was a uniformly distributed austenitic grain, elongated in the rolling direction with an average grain size of 12 ± 5.5 μm. Visualization and evolution of macroscopic localized plastic deformation bands at different load stages was carried out by digital speckle correlation method and speckle photographs [7, 8] when the samples were in clear bulb and the temperature was constant by using continuous feeding of nitrogen vapor from Dewar. The temperature was measured using a thermocouple located inside the flask near the sample. The nitrogen vapor rate was set using a heating element located inside the Dewar vessel. The sample was illuminated with a coherent beam of a semiconductor laser with a wavelength of 635 nm and a power of 15 W. Images of the speckle structures were recorded using a pixellink PL-B781 digital video camera with a frequency of 10 Hz, digitized and saved as files [9]. Using the method of digital image correlation, displacement fields can be measured at very high accuracy by tracking changes on the surface of the studied material and the subsequent comparison of digital photographs. The brightness of transmitted light was recorded for an arbitrary point of the speckle pattern. The dispersion and mathematical expectation were calculated, the ratio of which was used to display the localized zones of plastic deformation [9].

3. Results and discussions

The results of these experiments are shown in Figure 1. As test temperature lowers, the strength increases and the ductility decreases due to martensitic transformation.

The stress-strain diagrams σ (ε) of AISI 321 steel in the temperature range 123 ... 373 K contains three regions: elastic region, plastic deformation and fracture. After a certain level of plastic deformation, voltage fluctuations on jerky flow are noticeable on the load curve. The voltage drops reach 1–2 MPa with increased total deformation, their nature is due to the γ-α' phase transformation [6] and the Portevin – Le Chatelier (PLC) effect [10, 11].

An analysis of the staging of the load curves of the AISI 321 austenitic stainless steel in all temperature range made it possible to identify two sections with different lengths in the logarithmic coordinates of \( \ln(s - s_0) = f(\ln e) \): the stages of linear strain hardening (I) and the jerky flow (II). The stage of parabolic strain hardening and the prefraction stage were not identified on the loading curves.

It is known that microdamage accumulates in the sample during deformation [12, 13]. Therefore, a comparison between staging of the deformation curves and patterns of plastic deformation localization can be made. Using the experimental method described in [14], the damage parameter D was calculated according to the secant modulus, determined by the slope of the linear portion of the load curves. The uniaxial tensile tests were performed with a constant speed of 0.2 mm/min on a LFM-125 testing machine in load-unload mode at the same interval of total deformation.

The dependences of the damage parameter on the total deformation (D (ε)) show the process of damage accumulation during tensile strength of AISI 321 steel in the temperature range of 123 – 373 K, i.e. according to [12, 13], the damage parameter is equal to zero in the initial state and reaches unity at the time of destruction of the sample. The obtained data allowed us to establish that there is an exponential dependence between the damage parameter and the total deformation during tension of the samples, which is described by the equation

\[
D = 1 - \alpha \cdot \exp(-\lambda \cdot \varepsilon),
\]

where α and λ are constants different for the corresponding test temperature.
Temperature dependences of the mechanical characteristics of AISI 321 under tension at a speed of $6.67 \times 10^{-5}$ s$^{-1}$: yield point (a), tensile strength (b), elongation at break (c), time to failure (d).

Taking logarithm of the $D(\varepsilon)$ curves will allow us to identify several linear sections that are associated with damage accumulation at the corresponding stages of the plastic flow of these materials. Let us consider the pictures of macroscopic localization of plastic deformation.

An analysis of the local elongation distributions showed that at the stage of linear strain hardening the strain is distributed nonuniformly at specified intervals.

The process of macroscopic localization of plastic deformation has spatial and temporal ordering as in the previously studied fcc single crystals of stainless steel and pure metals Cu, Ni, as well as Al polycrystal [2, 3]. In the patterns of local elongation distributions (Figure 2), four high-amplitude equidistantly located centers of plastic strain localization are observed. In the AISI 301L steel, the synchronized movement of the centers of plastic deformation along the tensile axis with the same speed, which was determined by the slope of the lines in the kinetic diagram (Figure 3), is recorded. This figure shows the positions of the deformation localization maxima on the tensile axis depending on the time. It has been established that the propagation velocity of plastic strain localization centers and the spatial period of local elongations change when test temperature increases by the exponential law.

At the stage of jerky flow, as opposed to the stage of linear strain hardening, four single fronts of localization of plastic deformation propagate sequentially one after the other through the sample at specified interval of total deformation. The first front of localized plastic deformation arises when total deformation corresponds to a voltage jump on the stress-strain curve. This front of plastic strain localization moves along the sample at a constant speed towards the fixed grip of the testing machine.
Figure 2. Distribution of the local elongation components $\varepsilon_{xx}$ for the midline of a sample of AISI 321 steel at $T = 297$ K at different stages: $\varepsilon_{tot} = 0.094$ (a); $\varepsilon_{tot} = 0.097$ (b); $\varepsilon_{tot} = 0.106$ (c).

Figure 3. Kinetic diagram of the spatio-temporal evolution of plastic deformation centers in AISI 321 at the stage of linear strain hardening at $T = 173$ K.

A second, third, and fourth fronts arise sequentially with the growth of total strain $\varepsilon_{tot}$. Each front of plastic strain localization occurs immediately after previous front passed through the whole working length of the sample. The occurrence of the above centers of plastic strain localization also corresponds to stress jumps on the stress-strain curve. The motion of fronts of plastic strain localization is similar to the cruciform pattern observed previously for Al-Mg alloys in [11] and corresponds to the “turning points” of the angular oscillator. At the stage of rotation of the band, its borders take the form of a broken line.

It should be noted the formed fourth localization front, as opposed to previous three fronts, does not disappear after passing through the sample, but oscillates relative to the load axis and continues to move at a different speed towards the movable grip of the testing machine. Then the last center of localized deformation stops and the sample is destroyed due to the formation of a main crack. Apparently, in this region of the sample (near the breakpoint of the boundary of the last band of plastic strain localization), a stress concentration sufficient to form microcracks is created.
The deformation bands have a strong influence on the destruction of alloys exhibiting discontinuous deformation: under the conditions of the PLC effect the main crack always passes along one of the deformation bands that accumulate in the deformable material, despite pore formation [5, 11]. Thus, the development of the main crack was preceded by an intense spatially inhomogeneous plastic deformation occurring at the last deformation front.

4. Conclusions
The studies of AISI 321 steel found that at the stages of linear strain hardening the propagation velocity of the localized plastic deformation centers and the spatial period of local elongation change when test temperature increases by the exponential law. Patterns of plastic strain localization as single bands are due to the Portevin – Le Chatelier effect on jerky flow. On jerky flow, which is the final stage before the fracture of the specimen, there were no fusion of center of deformation localization, leading to the formation of a neck, as was observed for previously studied materials [15]. Therefore, the deformation processes at the last front of plastic strain localization should be considered as the stage of prefracture of the alloy, which demonstrates jerky flow.

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References
[1] Pelleg J 2013 Mechanical Properties of Materials (Dordrecht: Springer Netherlands)
[2] Zuev L B, Barannikova S A and Maslova O A 2019 The Features of Localized Plasticity Autowaves in Solids Mater. Res. 22
[3] Zuev L B and Barannikova S A 2019 Autowave Physics of Material Plasticity Crystals 9 458
[4] Mao B and Liao Y 2019 Modeling of lüders elongation and work hardening behaviors of ferrite-pearlite dual phase steels under tension Mech. Mater. 129 222–9
[5] Lebyodkin M A, Kobelev N P, Bougherira Y, Entemeyer D, Fressengeas C, Lebedkina T A and Shashkov I V 2012 On the similarity of plastic flow processes during smooth and jerky flow in dilute alloys Acta Mater. 60 844–50
[6] Müller A, Segel C, Lindero M, Vinogradov A, Weidner A and Biermann H 2016 The Portevin–Le Chatelier Effect in a Metastable Austenitic Stainless Steel Metall. Mater. Trans. A 47 59–74
[7] Rastogi P K 1997 An electronic pattern speckle shearing interferometer for the measurement of surface slope variations of three-dimensional objects Opt. Lasers Eng. 26 93–100
[8] Kumar A, Dutta A, Makineni S K, Herbig M, Petrov R H and Sietsma J 2019 In-situ observation of strain partitioning and damage development in continuously cooled carbide-free bainitic steels using micro digital image correlation Mater. Sci. Eng. A 757 107–16
[9] Zuev L B, Gorbatenko V V and Pavlichev K V 2010 Elaboration of speckle photography techniques for plastic flow analyses Meas. Sci. Technol. 21 054014
[10] Halim H, Wilkinson D and Niewczas M 2007 The Portevin–Le Chatelier (PLC) effect and shear band formation in an AA5754 alloy Acta Mater. 55 4151–60
[11] Spencer K, Corbin S. and Lloyd D. 2002 The influence of iron content on the plane strain fracture behaviour of AA 5754 Al–Mg sheet alloys Mater. Sci. Eng. A 325 394–404
[12] Lemaitre J 1986 Local approach of fracture Eng. Fract. Mech. 25 523–37
[13] Castagne S, Habraken A M and Cescotto S 2003 Application of a Damage Model to an Aluminum Alloy Int. J. Damage Mech. 12 5–30
[14] Luo A C J, Mou Y and Han R P S 1995 A large anisotropic damage theory based on an incremental complementary energy equivalence model Int. J. Fract. 70 19–34
[15] Orlova D V., Barannikova S A and Zuev L B 2016 On the kinetics of localized plasticity domains emergent at the pre-failure stage of deformation process AIP Conf. Proc. 1783 020168