Selected issues of constitutive model of discontinuous plastic flow (DPF) in 304 austenitic stainless steels at cryogenic temperatures

MSc J.Tabin, PhD student

Supervisor: Prof. Błażej Skoczeń

Abstract

FCC metals, alloys or composite materials such as: austenitic stainless steel (304, 316, 316LN, 321, etc.), Cu-OFE (C10100, C10200, C11000) or superconductor composite materials (Cu-Nb/Ti, Cu-Nb, Al.-Zr-Nb) are frequently used in cryogenic applications at temperature near to absolute zero, because of their excellent physical and mechanical properties, including ductility. As example, austenitic stainless steels are commonly used to manufacture components of superconducting magnets and cryogenic transfer lines. In such extreme temperature, these materials undergo discontinuous plastic flow phenomenon (DPF). Macroscopic character of DPF is related with stress oscillations and energy dissipation during deformation of sample.

The DPF has been investigated by many authors, among them: Basiński [1], Zeiser and Hahner [2], Obs and Nyilas [3], but previous investigations did not develop models which explain nature of DPF. A new uniaxial model of DPF, which include the mechanical nature of this phenomenon and the thermodynamic background has been developed at Cracow University of Technology by Skoczeń et al. [4]. Previous experiments allow to validate model and identify new phenomena, such as evolution of slip bands during uniaxial tensile test at liquid helium temperature, which has not enough recognized .

The present paper is dedicated not only validation of constitutive model but also to identify the parameters of traveling slip bands which are fundamental in development of temperature model related with DPF phenomenon

Keywords:

discontinuous plastic flow phenomenon, DPF, tensile test at cryogenic temperatures

1. The “mods” of plastic flow

The range and character of plastic flow in FCC materials are determined by many external and structural factors, among them are: crystal system, rates of deformation, chemical composition, heat treatment and temperature in which plastic flow occurs.

It turns out, that below specific temperature T1 (strongly material dependent) instability of plasticity occurs. This effect for austenitic stainless steel is presented in Fig.1a. The Stress-strain curves for uniaxial tensile test for identical sample loaded at different temperature (4,2K- blue, room temperature- red) are compared. In Fig.1b influence of temperature on plastic flow is presented.

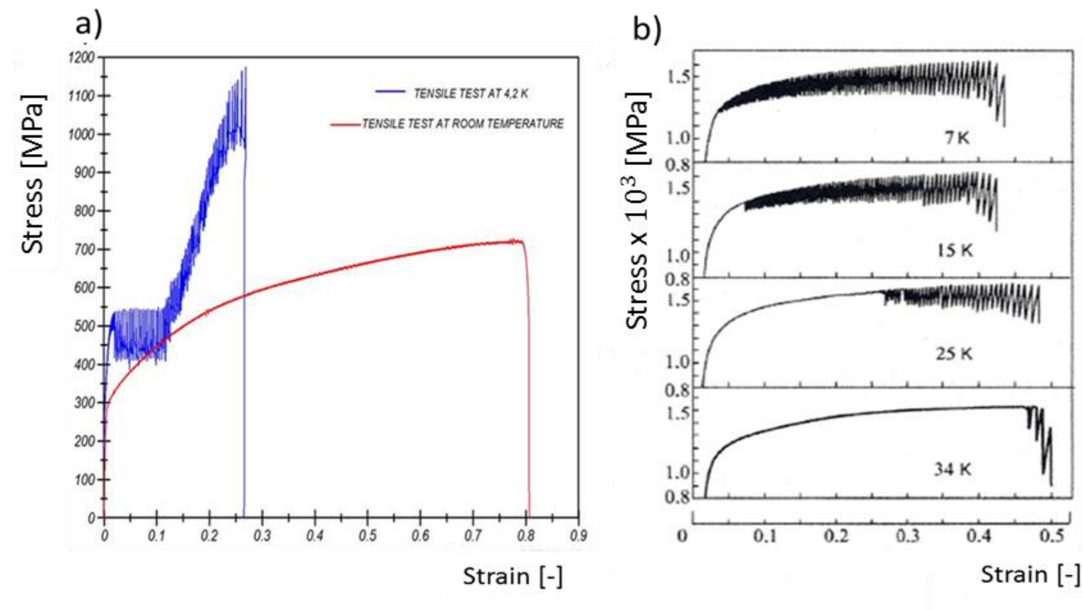

Fig. 1. *Stress-strain curves: a) for 304 austenitic steel specimen uniaxial tensile tested at room temperature (red) and liquid helium temperature (blue). b) Effect of temperature on plastic flow (316LN),* $\dot{\varepsilon} = 2{,}4 \cdot 10^{-4}\ [1/s]$ *[3].*

It is worth pointing out that DPF is similar in many aspects to Portevin-Le Chatelier effect (PLC) which occurs, in contrast to DPF, at high temperature (for carbon steel at 85 °C). The PLC effect occurs in alloys of aluminium, copper, zirconium, and austenitic, mild and low-carbon steels. The most distinct feature of the PLC effect is the localization of strain in a section of the stressed specimen and the motion of the localized strain along the specimen with increasing stress [5]. It is necessary to emphasize, that origin of DPF and PLC are quite different and are related with type of barriers which occur during evolution of slip bands [3] (PLC effect is comprehensively described by P. Hähner, M. Zaiser [2] and by Yilmaz [5]).
Thus, the mechanism of DPF is related with formation of dislocation pile-ups at strong obstacles such as the Lomer-Cottrell barriers. The back stresses of the piled-up groups block motion of newly created dislocations. The local shear stress at the head of dislocation pile-up, proportional to the number of dislocations in the pile-up, may reach the level of cohesive strength and the Lomer-Cottrell lock may collapse by becoming a dislocation. Such a local catastrophic event can trigger similar effects in other groups of dislocations. Thus, the final result is massive, has a collective character and leads to load drops observed in the stress-strain curve [4].

2. Experimental results

Identification of parameters of the constitutive model of DPF implies a significant experimental effort. This section provides results of uniaxial tensile tests at liquid helium temperature for 304 austenitic stainless steel (DIN: X5CrNi1810), tests were carried out at Cracow University of Technology – experimental set-up is presented in Fig. 2.

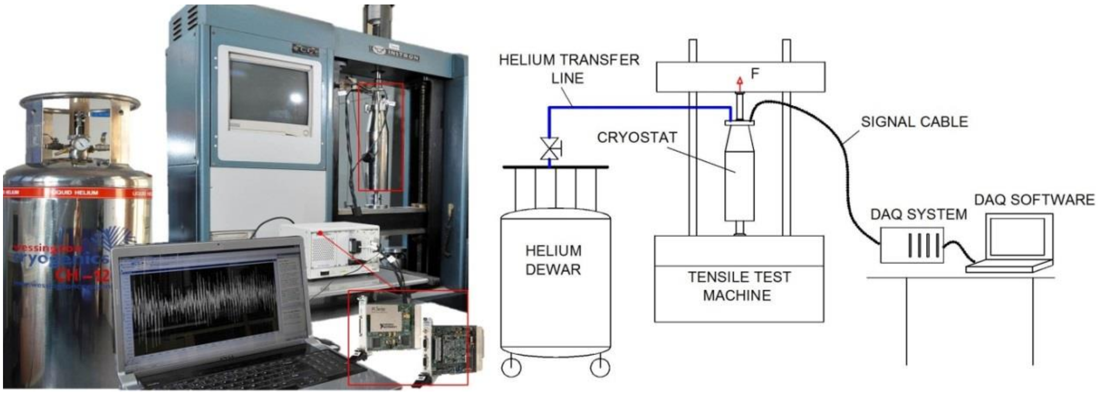

Fig. 2. Experimental set-up for tensile test at cryogenic temperature

The gage length of the specimen was equal to 20 *mm* and the cross-section was equal to 1,5 mm^2. The elongation was measured by using clip-on extensometers mounted on the specimen. Internal piezoelectric sensor, aligned with the specimen, was used. The temperature of specimen was constantly monitored during the test (Fig.3). All tests were kinematically controlled. The stroke speed of crosshead was equal to 0.5 *mm/min*. The sampling frequency was equal 1 *kHz*.

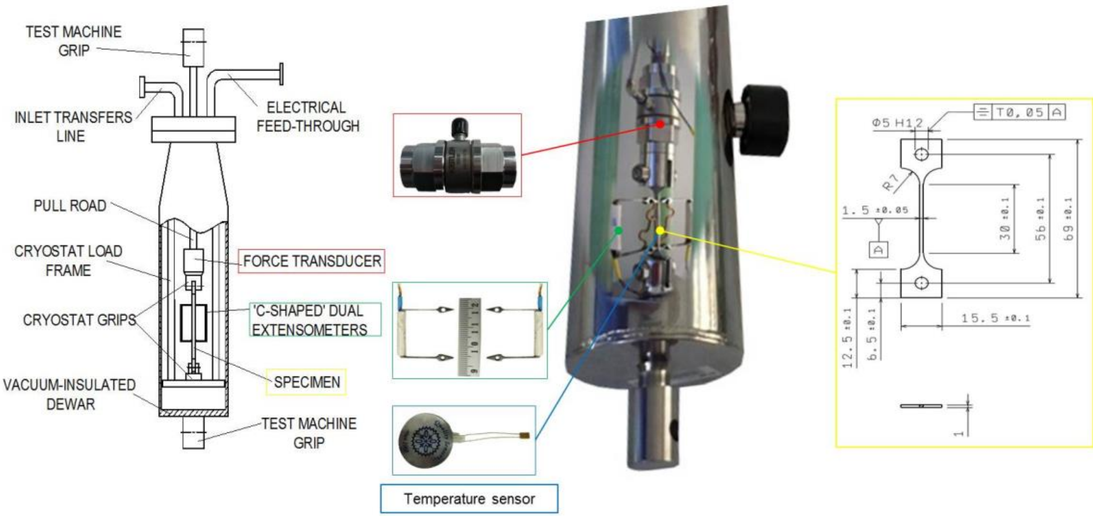

Fig. 3. *Measurement paths for tensile testing at cryogenic temperature. The force is measured by means of piezoelectric sensor, the elongation by means of clip-on extensometers and special temperature sensor is used for monitoring of specimen temperature*

The stress-strain curve for 304 austenitic steel specimen obtained during uniaxial tensile test is shown in Fig. 4.

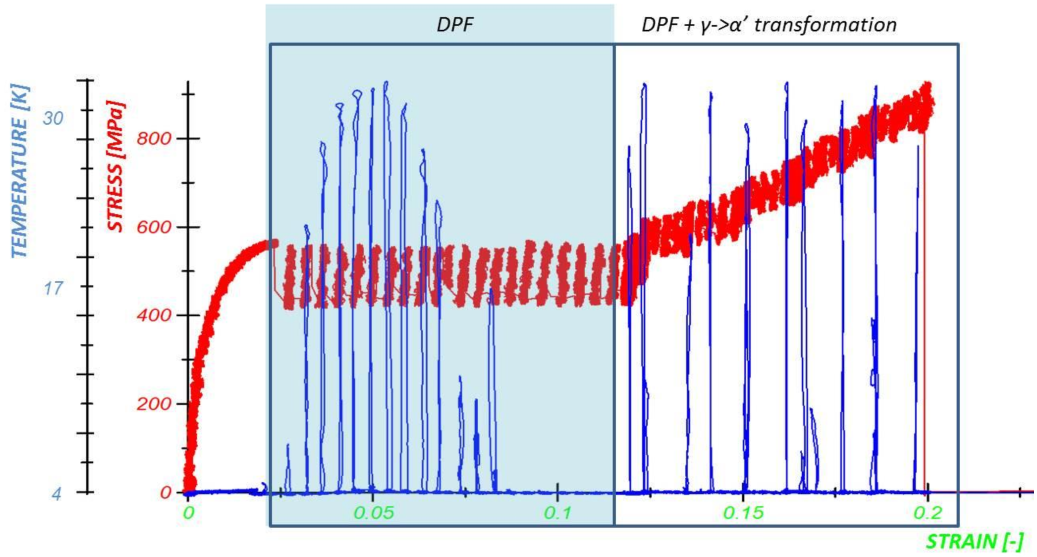

Fig. 4. *Stress-strain curve (red) and temperature-strain curve (blue) for 304 specimen loaded at liquid helium temperature (4,2K). The range of discontinuous plastic flow phenomenon (DPF)*

Each serration during DPF is accompanied by considerable increase of temperature, related to dissipation of plastic power and thermodynamic instability. Single serration in the stress-strain diagram (Fig.5) shows similar pattern: after the initial elastic process (stage 1), smooth plastic flow occurs (stage 2) until the abrupt drop of stress (stage 3), than relaxation is observed (stage 4). After abrupt drop of stress, the beginning of elastic stage immediately occurs [4].

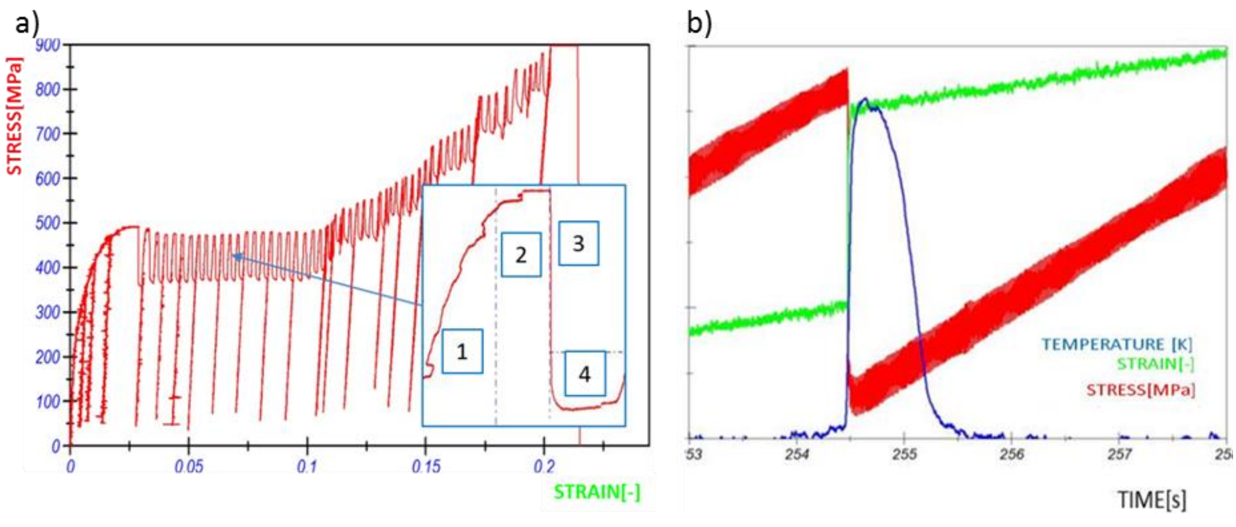

Fig. 5. *Illustration of DPF with four stages of the process: elastic (1), plastic flow (2), drop of stress (3), and relaxation (4). (b) time response of stress (red), strain (green) and temperature (blue) for one serration*

The numerical results obtained for Skoczeń model, calibrated for 304 austenitic steel are presented in Fig. 6.

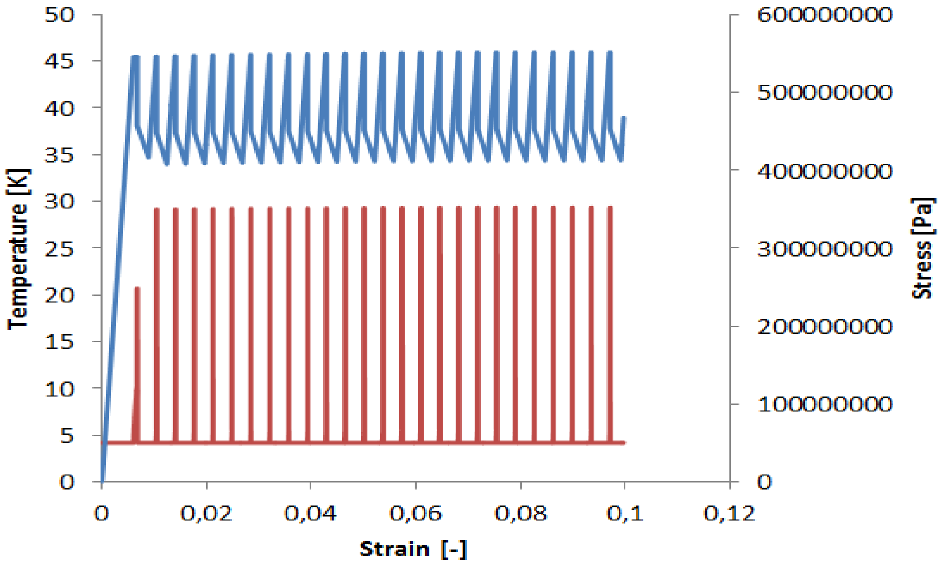

Fig. 6. *The numerical results obtained for 304 austenitic stainless steel. Stress against strain (blue) and temperature- strain curve (red)*

The numerical distribution of temperature has explicitly different shape than experimental results. The reason lies in the assumptions of Skoczeń model. RVE (representative volume element) travel with slip band. During experiment, temperature sensor is fixed spatially, therefore tracking of slip band evolution is possible (Fig.7).

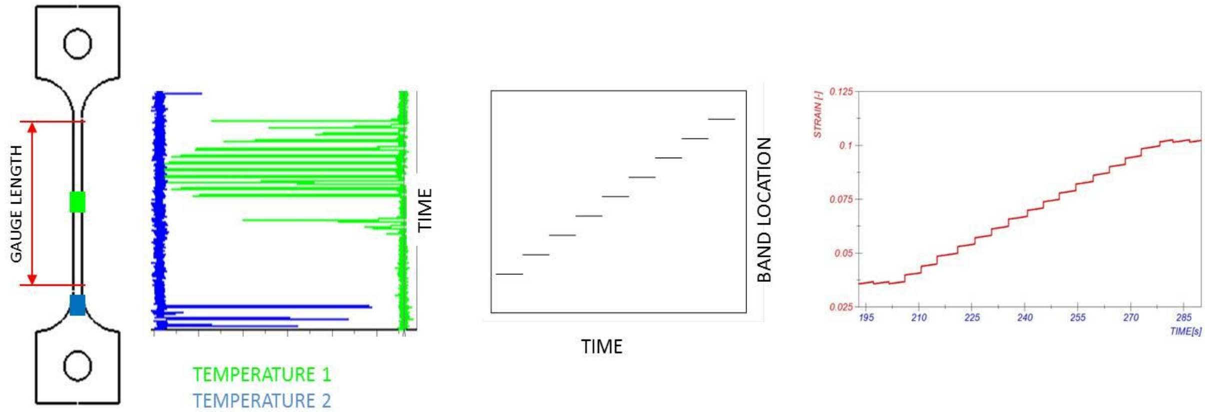

Fig. 7. *Schematic of slip band motion and orientation in 304 steel specimen during strain-controlled tensile test at 4.2K*

The continuous evolution of slip bands is typical for 304 steel because $\gamma \rightarrow \alpha'$ martensitic transformation begins relatively late than in 316 or 304 LN. It seem, that reason lies in content of carbon in each materials.

First plastic slip for tested specimen occurs in place where share stress is the greatest. For presented experimental , the greatest share stress in specimen occurs in grip (stress concentration). Then slip band travel through gauge length to opposite grip and process is repeated until martensitic transformations occurs.

Such evolution of slip bands is characteristic for steel specimens loaded at room temperature. Special experiments were carried out by Jodłowski [6] . Interferometry phenomenon allowed him track evolution of slip bands for different geometry of specimens. Experimental results confirmed that first slip band occurs in grips.

In summary, it is possible to obtain a correlation between the drops of stress and the temperature oscillations, given fixed spatial position of the temperature sensor and travelling RVE associated with the slip band. In order to determine appropriate distribution of temperature in model, identification of slip band parameters are required. First of all, based on experimental results, it is possible to determine the temperature generated in slip band ($T_p = 36\ K$). The temperature of liquid helium is $T_H = 4{,}2\ K$.

Elongation in time domain is stepwise function for which were determined two specific velocity of slip bands (Fig 8). The V_A is related with abrupt drop of stress (stage3), and $V_B$with stage 1 and stage 2 (elastic and plastic range) .

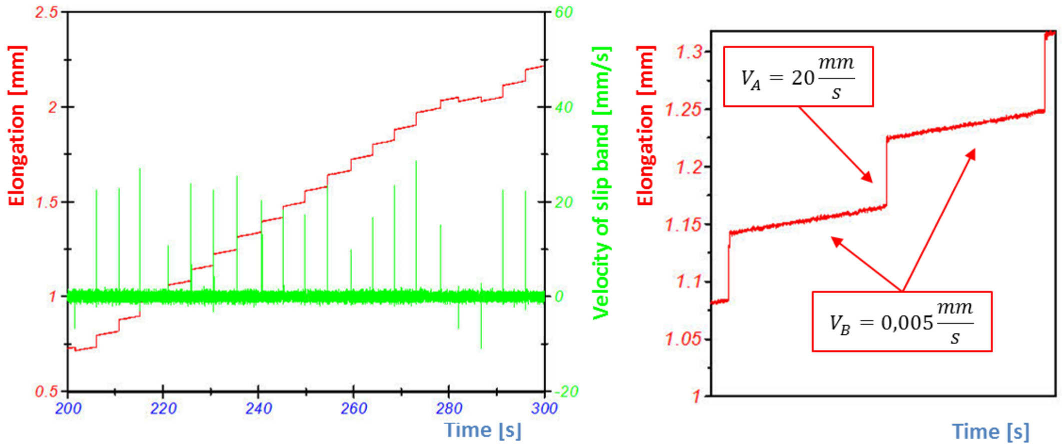

Fig. 7. *Stepped curve of elongation in time domain (red) and average velocity of slip bands*

The presented problem can be described by special differential equation (advection-diffusion differential equation). In the next step, based on advection-diffusion nature of presented phenomenon, author intends to develop the temperature model.

3. Conclusion

The oscillations of temperature associated with serrations can be predicted by knowing the plastic power dissipated during the DPF and the thermodynamic properties of materials in the range of temperatures between absolute zero and T1(material dependent). Thus, it is possible to obtain a correlation between the drops of stress and the temperature oscillations, given fixed spatial position of the temperature sensor and travelling RVE associated with the slip band. These conclusions have rather fundamental meaning for thin-walled structures operating at extremely low temperatures like heat exchangers, corrugated expansion bellows or vacuum chambers.

References

[1] Z. Basiński, Proc. Phys. Soc.,London, Sect. A 240, 229 (1957).

[2] P. Hähner, M. Zaiser. Oscillatory modes of plastic deformation: theoretical concepts. Physica Status Solidi B 199, 267–330, (1997).

[3] B. Obst, A. Nyilas. Experimental evidence on the dislocation mechanism of serrated yielding in f.c.c. metals and alloys at low temperatures. Materials Science and Engineering, A137, 141-150, (1991).

[4] B. Skoczeń, J. Bielski, J. Tabin. Multiaxial constitutive model of discontinuous plastic flow at cryogenic temperatures, International Journal of Plasticity 55 198–218, (2014).

[5] Ahmet Yilmaz. The Portevin–Le Chatelier effect: a review of experimental findings. Science and technology of advanced materials. (2010).

[6] H. Jodłowski. The experimental determination of plastic zones in steels with physical yield point. Praca Doktorska. Cracow University of Technology.(2007).