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BŁAŻEJ SKOCZEŃ*

# DISCONTINUOUS PLASTICITY AT EXTREMELY LOW TEMPERATURES

# NIECIĄGŁE PŁYNIĘCIE PLASTYCZNE W EKSTREMALNIE NISKICH TEMPERATURACH

Abstract

Evolution of scientific instruments based on the principle of superconductivity generates ever increasing interest in development and mathematical description of materials suitable for extremely low temperatures. Fcc metals and alloys are frequently used in cryogenic applications, nearly down to the temperature of absolute zero, because of their excellent physical and mechanical properties including ductility. Many of these materials undergo at low temperatures three essentially different dissipative phenomena: discontinuous plastic flow (serrated yielding), plastic strain induced transformation from the parent phase (γ) to the secondary phase (α') as well as evolution of micro-damage. All three phenomena lead to irreversible degradation of lattice and accelerate the process of material failure. Discontinuous yielding belongs to the class of dissipative phenomena often termed plastic flow instabilities. It is characteristic both of low and high stacking fault energy materials loaded beyond the yield point at very low temperatures. Serrated yielding represents oscillatory mode of deformation and reflects discontinuous (in terms of $d\sigma/d\varepsilon$) nature of plastic flow. It occurs below threshold temperature ($T_1$ or $T_0$) that represents transition from screw to edge dislocations mode. In the present paper a physically based constitutive model of discontinuous plastic flow is presented and its most important features when compared to classical plasticity are highlighted. The results of low temperature experiments are illustrated and discussed.

*Keywords: constitutive model, yield condition, discontinuous plastic flow, cryogenic temperature*

Streszczenie

Ewolucja instrumentów naukowych wykorzystujących zjawisko nadprzewodnictwa wywołuje wzrastajace zainteresowanie rozwijaniem i opisem matematycznym materiałów zdolnych do pracy w ekstremalnie niskich temperaturach. Materiały i stopy o strukturze RSC są często stosowane w temperaturach kriogenicznych, sięgajacych niemal absolutnego zera, ze względu na ich doskonałe własności fizyczne i mechaniczne, a szczególnie zachowanie cech plastycznych. Wiele spośród nich podlega w niskich temperaturach trzem zasadniczo róznym zjawiskom: nieciągłemu płynięciu plastycznemu, indukowanej odkształceniem plastycznym przemianie fazowej od struktury pierwotnej (γ) do struktury wtórnej (α'), jak również ewolucji mikrouszkodzeń. Wszystkie trzy zjawiska prowadzą do nieodwracalnej degradacji sieci krystalicznej i znacznie przyspieszają proces zniszczenia materiału. Nieciągłe płynięcie plastyczne należy do takiej klasy zjawisk związanych z rozpraszaniem energii, która nosi nazwę niestateczności płynięcia plastycznego. Zjawisko to jest charakterystyczne zarówno dla materałów o niskiej, jak i wysokiej energii błędu ułożenia, obciążanych powyżej granicy plastyczności w bardzo niskich temperaturach. Nieciągłe płynięcie plastyczne reprezentuje tzw. oscylacyjną formę deformacji i odzwierciedla nieciągłą (w sensie $d\sigma/d\varepsilon$) naturę procesu odkształcenia plastycznego. Opisywane zjawisko występuje poniżej tzw. temperatury progowej ($T_1$ lub $T_0$), która reprezentuje przejście od dyslokacji typu śrubowego do dyslokacji typu krawędziowego. W artykule zaprezentowano fizycznie uzasadniony model konstytutywny nieciągłego płynięcia plastycznego, a także jego najważniejsze cechy w zestawieniu z klasycznym opisem płynięcia plastycznego. Zilustrowano również i przedyskutowano wyniki badań doświadczalnych przeprowadzonych w niskich temperaturach (4,2 K).

*Słowa kluczowe: model konstytutywny, warunek plastyczności, nieciągłe płynięcie plastyczne, temperatury kriogeniczne*

* Prof. dr hab. inż. Błażej Skoczeń, Instytut Mechaniki Stosowanej, Wydział Mechaniczny, Politechnika Krakowska.

## 1. Introduction

The present paper is focused on experiments and constitutive description of discontinuous plastic flow in FCC materials strained at very low temperatures. The model presented in the course of the paper can easily be adopted to describe various materials used at cryogenic temperatures (like stainless steel, copper, copper and aluminium alloys etc.). Discontinuous (serrated) yielding is characteristic both of low (LSFE) and high stacking fault energy (HSFE) materials strained at very low temperatures. It represents oscillatory mode of plastic deformation and reflects discontinuous nature of plastic flow (discontinuous in terms of $d\sigma/d\varepsilon$ ). Serrated yielding occurs below a specific threshold temperature: $T_1$ for LSFE materials and $T_0$ for HSFE materials. Each of them represents transition from screw to edge dislocations [8]. Seeger [13], pointed out that type of dislocations may change at very low temperatures because of lack of thermal energy necessary for generation and motion of dislocations of predominantly screw character. As the excitation of lattice is very low the edge dislocations move at lower stress than the screw dislocations. The transition temperatures ($T_0$ or $T_1$) are strongly material dependent and can reach some 35 K (the highest values found to date). Both transition temperatures can be found by plotting the yield strength against temperature at various specified plastic strain levels. The temperature $T_1$ is indicated in Fig. 1a for a LSFE alloy. Also, serrated yielding turns out to be a strain rate sensitive phenomenon and occurs for plastic strain rate exceeding a critical (material dependent) value [6, 10, 11].

Serrated yielding has been investigated, mostly experimentally, by many authors, among them: Basinski [1]; Schwarz and Mitchell [14]; Reed and Simon [11]; Reed and Walsh [10]; Hähner and Zeiser [5]; Zeiser and Hähner [19]; Benallal et al. [2, 3]. A discussion of serrated yielding in terms of dislocation motion has been given by Obst and Nyilas [8, 9]. Other authors Tabachnikova et al. [18] suggested earlier that "high flow stresses at low temperatures can promote avalanche multiplication of mobile dislocations", but did not develop models to explain the dislocation nature of instabilities. In their attempt to explain the phenomenon of discontinuous yielding the authors make reference to the work by Seeger [13]. They point out that the pile-ups of dislocations on the internal barriers in the lattice give rise to stress concentrations of the order of magnitude of theoretical shear strength. The load drops observed in the stress-strain curves are due to some catastrophic process consisting in the spontaneous generation of dislocations as soon as the internal barriers are broken. Thus, the plastic flow instability is of mechanical nature. A different point of view has been developed by Basinski, 1957, who attributed the load drops to thermodynamic properties of materials at very low temperatures represented by the specific heat and thermal conductivity tending to 0 with temperature. Adiabatic heating hypothesis, developed by Basinski, was based on the assumption that any sufficiently fast dissipative process at very low temperature, where the plastic work is converted to heat, leads to increase of local temperature and to drastic decrease of flow stress (negative slope of flow stress against temperature). Different approach to explanation of serrated yielding has been presented by Zaiser and Hähner, 1997, in their survey of oscillatory modes of plastic deformation. The authors attribute discontinuous nature of plastic flow at low temperatures to strain rate softening instabilities and point out similarities between the low temperature phenomena and the Portevin – Le Chatelier (PLC) effect that occurs at room temperature. The mechanism of strain rate sensitivity consists of positive instantaneous response of the flow stress to a sudden increase in the strain rate followed by its relaxation to a quasi steady state asymptotic value after the transients have died out. Such behaviour is characteristic of the strain ageing materials. The parameter that governs asymptotic behaviour of the flow stress in the low temperature plasticity is the specimen temperature. It is worth pointing out that both the mechanical approach developed by Obst and Nyilas [8], and the thermodynamically justified theory developed by Zaiser and Hähner [19], reflect complex nature of the flow instabilities that occur at very low temperatures (below $T_1$ or $T_0$).

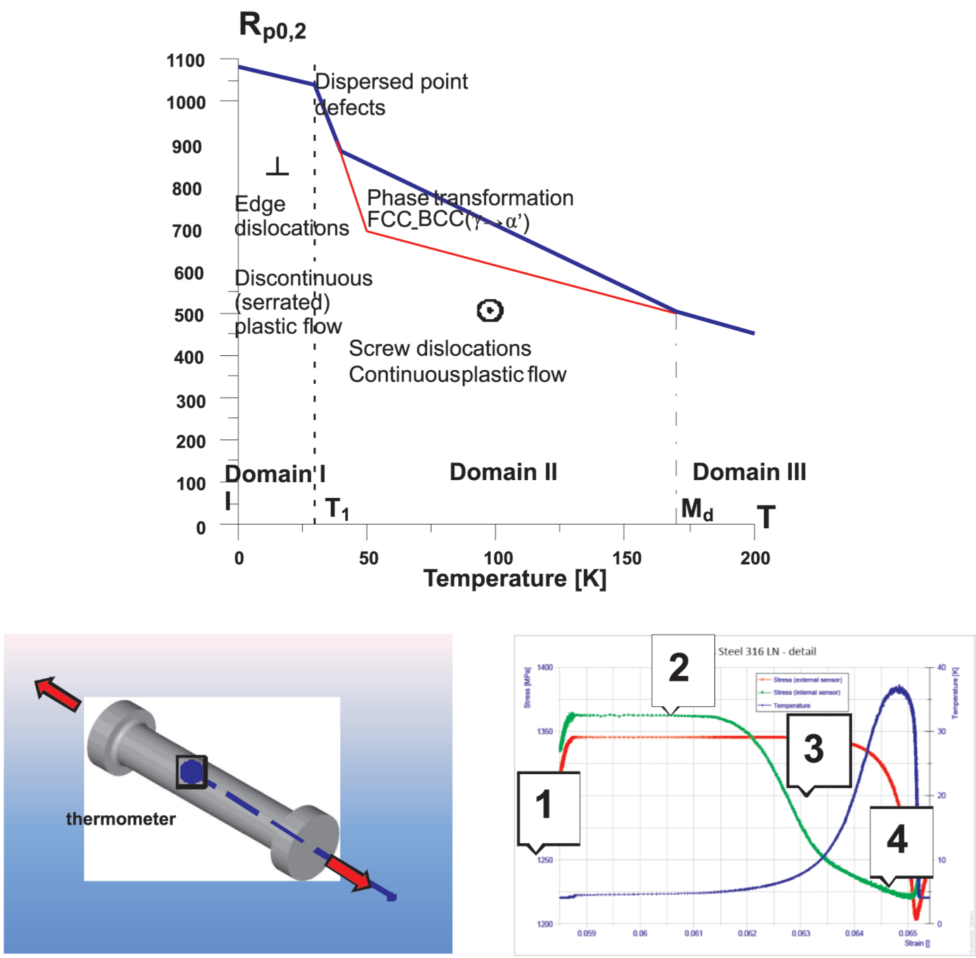



Fig. 1a) Yield point ($R_{p02}$) against temperature ($T$) for LSFE materials deformed at low temperatures (here: 316LN). b) Illustration of discontinuous plastic flow with four stages of the process: elastic (1), plastic flow (2), drop of stress (3), relaxation (4)

Rys. 1a) Granica plastyczności ($R_{p02}$) w funkcji temperatury ($T$) dla materiałów o niskiej energii błędu ułożenia odkształcanych w niskich temperaturach (stal: 316LN). b) Ilustracja czterech etapów nieciągłego płynięcia plastycznego: sprężystego (1), plastycznego (2), spadku naprężenia (3), relaksacji (4)

## 2. Kinetics of discontinuous plastic flow

The apparent feature of serrated yielding (observed in the course of low temperature testing) consists in frequent abrupt drops of stress as a function of strain during monotonic loading. The mechanism of discontinuous yielding is related to formation of dislocation pile-ups at strong obstacles such as the Lomer-Cottrell locks during the strain hardening process. The back stresses of the piled-up groups block the 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 glissile dislocation. This process takes place below the temperature $T_0$ or $T_I$ where the dislocations have predominant edge character and cannot leave the pile-up by cross-slip. Such a local catastrophic event can trigger similar effects in the other groups of dislocations. Thus, the final result is massive and has a collective character. At low temperatures, where very high stresses are expected this avalanche-like process is followed by a spontaneous generation of dislocations by rapidly increasing number of sources. This – in turn – leads to a rapid local deformation and the load drops observed in the stress-strain curve. During tensile test at low temperatures the avalanche-like barrier crossing by dislocation pile-ups is manifested by acoustic effects of dry sounds emitted by the specimen.

Each serration is accompanied by a considerable local increase of temperature, related to the dissipation of plastic power and vanishing specific heat when the temperature tends to 0 K. Typical stress-strain curves for materials (OFE Cu, AISI 316L) that exhibit discontinuous yielding are illustrated in Fig. 2.

Every spike in the stress-strain diagram shows similar pattern (Fig. 1b): after initial elastic process (1) smooth plastic flow occurs (2) until the abrupt drop of stress (3) and further relaxation (4). No significant increase of temperature is observed during the smooth plastic flow. It seems that the temperature increases dramatically when the abrupt relaxation of stress begins. However, as the temperature of sample is usually measured at the surface, it might be delayed by thermal diffusivity (if the phenomenon does not occur in the proximity of the surface) and by the time response of the thermometer.

The main function that reflects the readiness of lattice with respect to discontinuous plastic flow is the density $B$ of the dislocation groups (concentrated at the Lomer-Cottrell locks). The RVE containing the dislocation groups is shown in Fig. 3a. It is assumed that the increment of $B$ is strictly related to the increment of accumulated plastic strain

$$dp = \sqrt{\frac{2}{3} d\underline{\underline{\varepsilon}}^{p} : d\underline{\underline{\varepsilon}}^{p}} \tag{1}$$

Increasing intensity of plastic flow generates more barriers for the motion of dislocations. Therefore, the following kinetic law of evolution for the density of the Lomer-Cottrell locks is applied [17]

$$\dot{B} = F_{\mathrm{LC}}^{+}\left(\rho, T, \underline{\underline{\sigma}}\right) \dot{p} H\left(p - p_{\mathrm{LC}}\right) \tag{2}$$

where $F_{\mathrm{LC}}^{+}$ is a function of density of dislocations $\rho$, temperature $T$ and the level of stress $\sigma$, whereas $p_{\mathrm{LC}}$ represents a threshold above which the Lomer-Cottrell barriers massively develop. Here, $H$ denotes the Heaviside function:

$$H(x) = 0 \quad \text{for} \quad x < 0; \quad H(x) = 1 \quad \text{for} \quad x \geq 0 \tag{3}$$

For an isothermal process and small variation of the flow stress a simple linear representation can be easily obtained

$$dB = F_{\mathrm{LC}}^{+} dp; \quad p \geq p_{\mathrm{LC}} \tag{4}$$

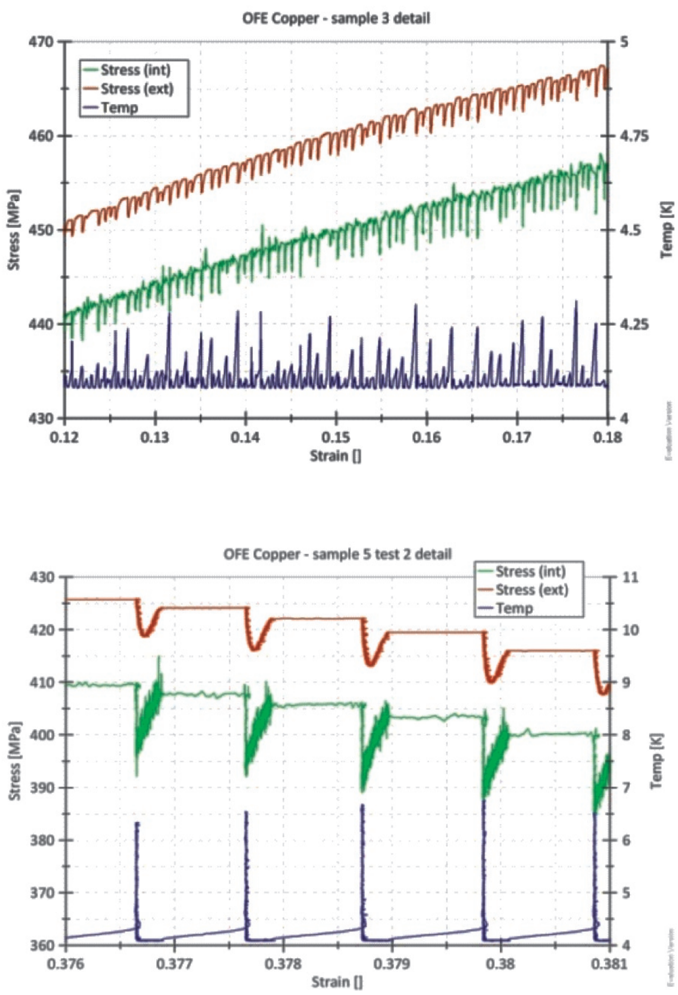
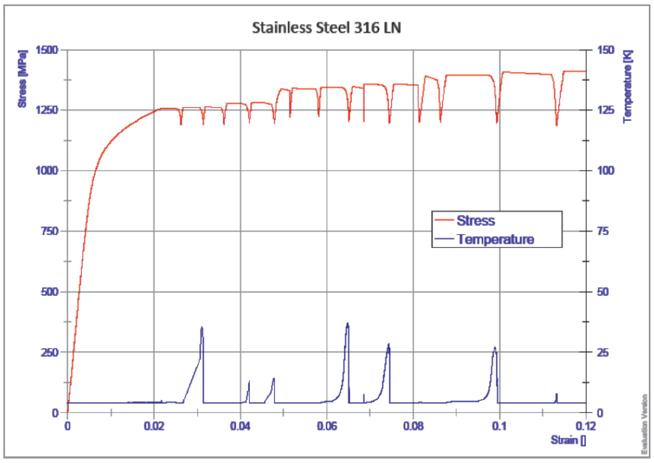



Fig. 2a. Serrated yielding in FCC metals: OFE Copper at 4.2 K

Rys. 2a. Nieciągłe płynięcie plastyczne w materiałach o strukturze RSC: Miedź OFE Cu w temperaturze 4.2 K



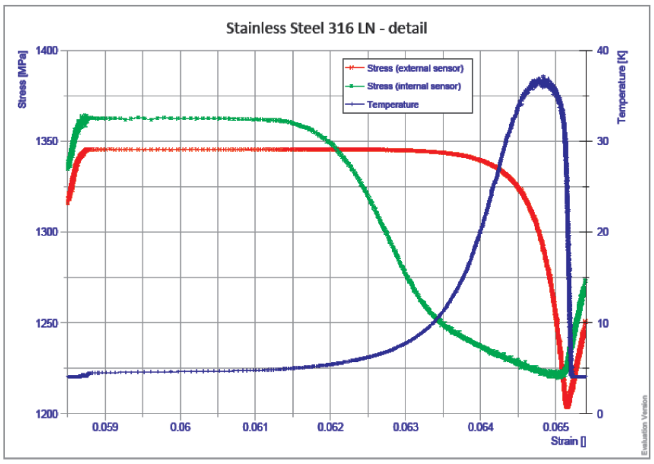




Fig. 2b. Serrated yielding in FCC metals: 316L stainless steel at 4.2 K

Rys. 2b. Nieciągłe płynięcie plastyczne w materiałach o strukturze RSC: stal 316L w temperaturze 4.2 K

### 3. RVE based constitutive description of discontinuous plastic flow

Failure of LC locks leads to massive motion of released dislocations as well as spontaneous generation of dislocations by new sources, accompanied by the step-wise increase of the strain rate. The initially microscopic process becomes macroscopic and leads to load drops observed in the stress-strain curve. Local shear stress $\tau$ is accompanied by the amount of crystallographic slip, denoted by $\gamma$. The evolution of dislocation density $\rho$ as a function of strain is described by the following equation

$$\frac{d\rho}{d\gamma} = \left.\frac{d\rho}{d\gamma}\right|_{+} + \left.\frac{d\rho}{d\gamma}\right|_{-} \tag{5}$$

where the component denoted by "+" represents the rate of production of dislocations and the component denoted by "–" stands for the rate of annihilation of dislocations [4]. The production part is expressed by the formula

$$\left.\frac{d\rho}{d\gamma}\right|_{+} = \frac{1}{\lambda b} \tag{6}$$

where $\lambda$ is the mean free path of dislocation and $b$ denotes length of the Burgers vector. The annihilation part is given by the following relation

$$\left.\frac{d\rho}{d\gamma}\right|_{-} = -k_a \rho \tag{7}$$

where $k_a$ represents the dislocation annihilation constant. The mean free path of dislocation obeys the following rule

$$\lambda = \frac{1}{\sum_i \lambda_i^{-1}} \tag{8}$$

with $\lambda_i$ denoting the mean free path related to a specific type of obstacle. In the simplest case

$$\frac{1}{\lambda} = \frac{1}{d} + k_1\sqrt{\rho} \tag{9}$$

where $d$ is the average grain size and $k_1$ is a constant. Combining eqs (5) through (9) one obtains

$$\frac{d\rho}{d\gamma} = \frac{1}{db} + \frac{k_1}{b}\sqrt{\rho} - k_a \rho \tag{10}$$

Assuming the following relations for the macroscopic stress and strain

$$\sigma = M\tau; \quad \gamma = M\varepsilon \tag{11}$$

where $M$ is the Taylor factor, and accepting that the plastic strain dominates

$$\varepsilon \approx \varepsilon^p \tag{12}$$

the following formula can be derived

$$\frac{d\rho}{d\varepsilon^p} = M\left[\frac{1}{db} + \frac{k_1}{b}\sqrt{\rho} - k_a \rho\right] \tag{13}$$

Making reference to eq. (2) and assuming that

$$\varepsilon^p \geq \varepsilon^p_{\mathrm{LC}} \tag{14}$$

the increment of density of the LC barriers reads

$$\dot{B} = F^{+}_{\mathrm{LC}}\dot{\varepsilon}^{p} \tag{15}$$

The average shear stress in the lattice is composed of lattice friction and interaction between the dislocations (Madec et al. [7])

$$\tau = \tau_0 + \mu\alpha b\sqrt{\rho} \tag{16}$$

where $\mu$ is the shear modulus and $\alpha$ is the coefficient of dislocations interaction. The shear stress at the head of dislocation pile-up amounts to

$$\tau_e = \frac{\pi(1-\nu)}{\mu b}\bar{\lambda}\tau^2 \tag{17}$$

and is a quadratic function of the average shear stress in the lattice. Here, the mean free path of dislocation $\bar{\lambda}$ is interpreted as distance between the source and the barrier with three types of obstacles taken into account: the grain boundaries, the dislocations and the LC locks

$$\frac{1}{\bar{\lambda}} = \frac{1}{\lambda} + k_2\sqrt{B} \tag{18}$$

The following criterion of avalanche-like failure of LC locks is applied [17]

$$\begin{cases} \tau \le \tau_{\min} & \Rightarrow \quad B = B_{cr} \\ B \le B_{\min} & \Rightarrow \quad \tau_e = \tau_{cr} \\ \tau > \tau_{\min} \wedge B > B_{\min} & \Rightarrow \quad \left(1-\dfrac{B_{\min}}{B_{cr}}\right)\dfrac{\tau_e}{\tau_{cr}} + \left(1-\dfrac{\tau_{\min}}{\tau_{cr}}\right)\dfrac{B}{B_{cr}} - \left(1-\dfrac{B_{\min}}{B_{cr}}\right) - \left(1-\dfrac{\tau_{\min}}{\tau_{cr}}\right)\dfrac{B_{\min}}{B_{cr}} = 0 \end{cases} \tag{19}$$

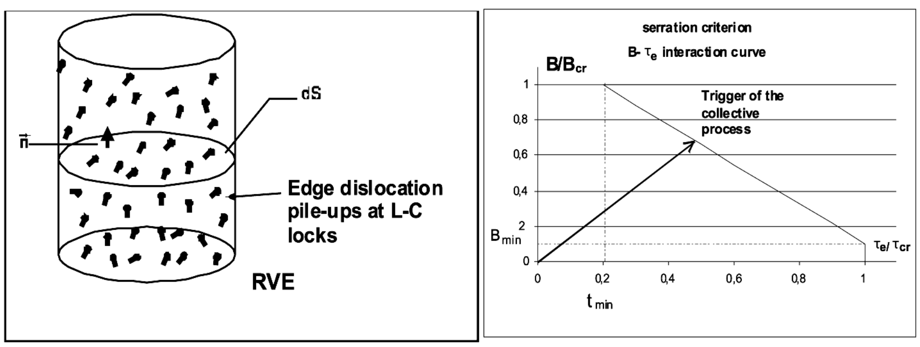



Fig. 3a) RVE; (b) the interaction curve ($B$, $\tau_e$): normalized density of LC locks ($B$) against normalized shear stress at the head of dislocation pile-up ($\tau_e$)

Rys. 3a) Reprezentatywny element objętościowy (REO); (b) krzywa graniczna ($B$, $\tau_e$): znormalizowana gęstość barier LC locks ($B$) w funkcji znormalizowanego naprężenia stycznego w czole spiętrzenia dyslokacji ($\tau_e$)

Generally, it is assumed that the interaction between $B$ and $\tau_e$ acts as a trigger for the serration (Fig. 3b), but for sufficiently large value of one of them the other is insignificant for the phenomenon to occur. The values $B_{\min}, \tau_{\min}$ should be regarded as auxiliary only, as long as the precise profile of interaction curve for a given material is not known. Thus, as soon as the density of dislocation groups combined with the shear stress at the head of dislocation pile-up reaches the interaction curve, the avalanche-like process is triggered and all the LC barriers are broken. The process of massive failure of LC locks results in an instantaneous increase of plastic strain (Fig. 4)

$$\Delta\varepsilon_s = \frac{B}{F_{LC}^-} \tag{20}$$

where $F_{\mathrm{LC}}^-$ is another function of density of dislocations $\rho$, temperature $T$ and the level of stress $\sigma$ and $\Delta\varepsilon_s$ is interpreted as the amount of slip during the catastrophic failure of LC barriers. Assuming that the process is kinematically controlled and takes place at the constant value of the total strain, strain redistribution results in the proportional elastic drop of stress

$$\Delta\sigma = E\Delta\varepsilon_s \tag{21}$$

During the massive failure of LC locks followed by fast motion of glissile dislocations in the lattice a quantity of heat is produced. The amount of heat is a function of plastic work and internal friction in the lattice when abrupt slip occurs

$$\Delta Q = \eta(\Delta W^p + \Delta W^f) \tag{22}$$

Here, $\eta$ denotes the relevant conversion factor. Following the curve of specific heat under constant volume the following temperature increment occurs

$$\Delta T = \frac{\Delta Q}{mC_V(T)} \tag{23}$$

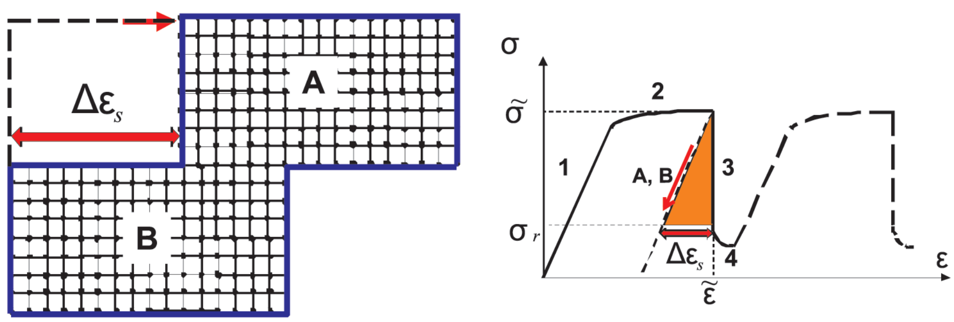



Fig. 4. The mechanism of plastic slip ( $\Delta\varepsilon_s$ ) during the plastic flow discontinuity

Rys. 4. Mechanizm plastycznego poślizgu ( $\Delta\varepsilon_s$ ) towarzyszący nieciągłemu płynięciu plastycznemu

The increase of temperature, illustrated in Fig. 1b, may even be of the order of 40–50 K. Thus, temperature variation becomes a driving force in the process of stress relaxation, represented by stage 4 in Fig. 1b (Zaiser, Hähner [19]). The stress relaxation is described by the following set of equations

$$\begin{aligned} &\sigma = \sigma_r + \Delta\sigma_T \\ &\frac{d}{dt}(\Delta\sigma_T) = \frac{1}{t_T}[(\sigma_\infty - \sigma_r) - \Delta\sigma_T] \end{aligned} \tag{24}$$

where $\sigma_r, \sigma_\infty$ are the stress levels after the catastrophic slip and after the transients have died out, respectively. Here, $t_T$ denotes the characteristic time. Temperature relaxes to a new steady state value inducing an additional evolution of stress $\Delta\sigma_T$.

The first two stages of single serration (1 and 2) reflect elastic-plastic loading under nearly isothermal conditions [19], corresponding to low excitation of the lattice. Under these circumstances (no thermal activation) the rate-independent plasticity can be applied, at least until the catastrophic failure of LC locks. Thus, the yield surface takes the form (Fig. 5)

$$f_y(\underline{\underline{\sigma}}, \underline{\underline{X}}, R) = J_2(\underline{\underline{\sigma}} - \underline{\underline{X}}) - \sigma_y - R \tag{25}$$

where

$$J_2(\underline{\underline{\sigma}} - \underline{\underline{X}}) = \sqrt{\frac{3}{2}(\underline{\underline{s}} - \underline{\underline{X}}) : (\underline{\underline{s}} - \underline{\underline{X}})} \tag{26}$$

is the second invariant of the stress tensor. Here, $\underline{\underline{s}}, \underline{\underline{X}}$ denote the deviatoric stress and the back stress tensors, whereas $\sigma_y, R$ are the yield stress and the isotropic hardening variable, respectively. Furthermore, it is assumed that the continuum containing LC locks obeys the associated flow rule

$$d\underline{\underline{\varepsilon}}^p = \frac{\partial f_y}{\partial \underline{\underline{\sigma}}} d\Lambda \tag{27}$$

with the yield function postulated as the potential of plasticity. The hardening model is represented by the following equations

$$d\underline{\underline{X}} = \frac{2}{3} C_X d\underline{\underline{\varepsilon}}^p; \quad dR = C_R dp \tag{28}$$

where $C_X; C_R$ denote the kinematic and the isotropic hardening moduli, respectively. The evolution of parameter $B$ can be computed from eq. (2)

$$dB = F_{LC}^{+}(\rho, T, \underline{\underline{\sigma}}) dp \tag{29}$$

It is assumed that in every loading/unloading "cycle" (single tooth in the stress-strain curve) the parameter $B$ is accumulated from 0 and as soon as the condition (19) is fulfilled the plastic flow instability (drop of stress) takes place.

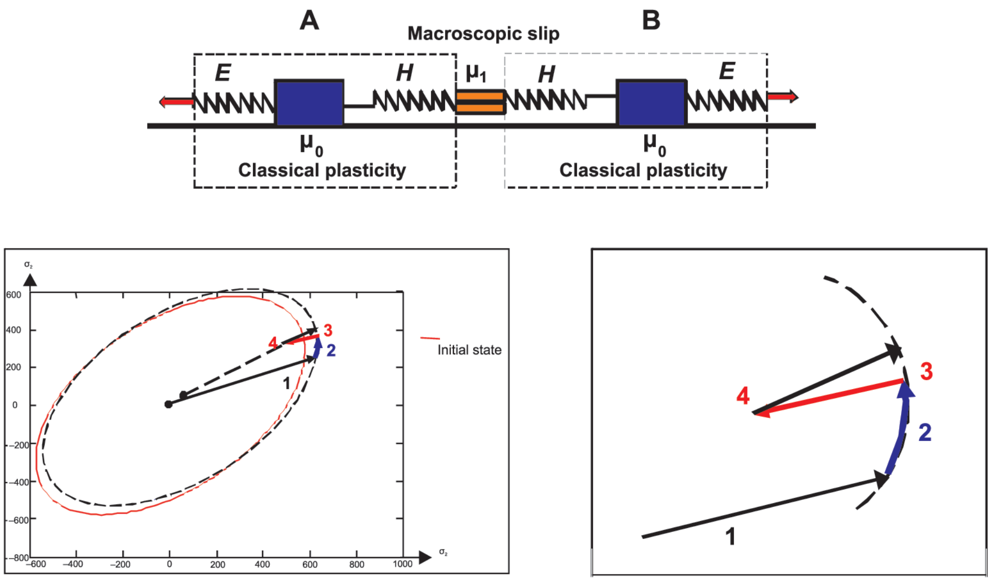



Fig. 5. Illustration of discontinuous plastic flow in multi-axial conditions

Rys. 5. Ilustracja nieciągłego płynięcia plastycznego w warunkach obciążeń wieloosiowych

### 4. Experiments at cryogenic temperatures

The measurements carried out at very low temperatures are usually laborious, time consuming and require rather sophisticated equipment in order to obtain the correct experimental conditions. Typical examples of stress-strain curves are shown in Fig. 6, where discontinuous plastic flow is reflected by quantifiable serrations. However, in order to calibrate precisely the constitutive model many dedicated tests are necessary. Extremely low temperatures make the task more challenging, since the cryostat excludes some known methods as e.g. digital image correlation used often at room temperature, where direct measurement of strain fields during all stages of the test is possible.

A method of high precision tensile testing down to 4.2 K has been developed at CERN [15]. Specimens of 1 $mm^2$ to 9 $mm^2$ square cross section with a calibrated length of 25 mm were tested in a liquid He cryostat. LVDT sensors and a carbon potentiometer fixed on the calibrated length of the specimen allowed high precision measurements of strain in the early stage of deformation (up to 10%) and in the plastic regime. High resolution in displacement (about 0.5 μm), achievable after conversion of the LVDT signals, permits precise evaluation of the elastic modulus and the yield stress at 4.2 K and allows transient phenomena of serrated yielding to be precisely recorded. A CX-SD Cernox™ thin film resistance cryogenic temperature sensor by Lake Shore Cryotronics, Inc. with fast thermal response time at 4.2 K (1.5 ms), directly glued on the calibrated length of the sample, allows the temperature of the sample to be recorded during the whole test and particularly during serrated yielding transients accompanied by temperature instabilities. In order to record the rapid transient phenomena occurring during serrated yielding, sampling frequency can be set from 20 Hz to 20 kHz and can be modified during the test. Higher frequencies are applied during a limited time in order to record single serrated yielding cycle. An internal load cell, equipped with calibrated strain gauges and immersed in the liquid He bath, measures the stress in the proximity of the specimen. Compared to a conventional load cell located externally with respect to the cryostat, measuring the stress close to the specimen allows more reliable stress-time dependence to be recorded during serrated yielding. The experiments reported in the present paper were carried out at sufficiently small strain rate to avoid oscillation of temperature around $T_1$ [17].

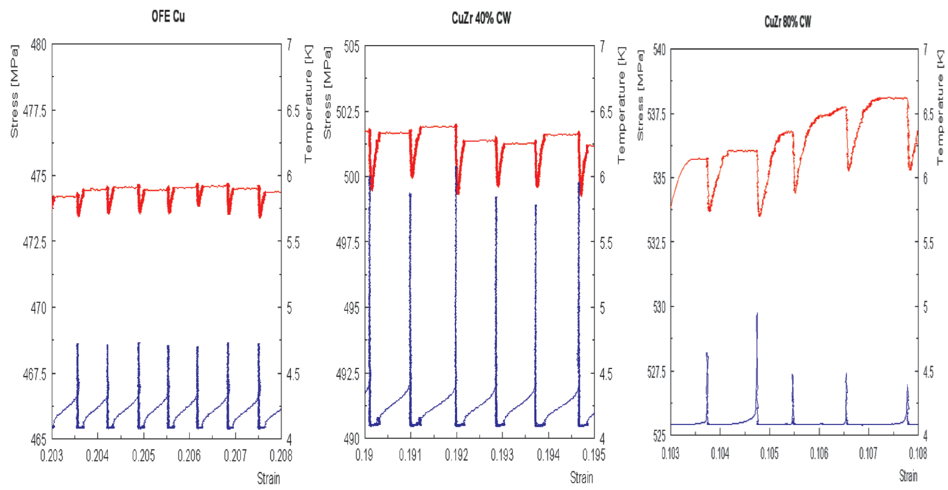



Fig. 6. Examples of serrations in the stress-strain response (OFE Cu, Cu-Zr)

Rys. 6. Przykłady nieciagłego płynięcia plastycznego w relacji naprężenie–odkształcenie

### 5. Mechanical origin versus thermal activation of plastic flow instability

In the course of research dedicated to this particular problem of plastic flow instability two explanations were competing with each other: thermal activation of serrations and mechanical origin of the phenomenon. Thermal activation theory has been promoted – among others – by Basinski [1]. He attributed the load drops to the thermodynamic properties of materials at very low temperatures, represented in particular by the specific heat and the thermal conductivity tending to 0 with temperature. The adiabatic heating hypothesis was based on the assumption that any sufficiently fast dissipative process at very low temperatures (where the plastic work is converted to heat) leads to increase of local temperature and to drastic decrease of flow stress (negative slope of flow stress against temperature).

The mechanical origin of discontinuous yielding was highlighted by Obst and Nyilas [8]. In their attempt to explain this phenomenon the authors made reference to the work by Seeger [13]. They strongly pointed out that the pile-ups of dislocations on the internal barriers in the lattice give rise to stress concentrations of the order of magnitude of theoretical shear strength. Thus, the load drops observed in the stress-strain curves were attributed to a catastrophic process consisting in the spontaneous generation of dislocations as soon as the internal barriers were broken. This observation led to the conclusion that the plastic flow instability was of mechanical nature and all the associated thermodynamic phenomena were of rather secondary meaning.

Still another explanation of serrated yielding was developed by Zaiser and Hähner, 1997. The authors attributed discontinuous nature of plastic flow at low temperatures to strain rate softening instabilities. Moreover, they pointed out similarities between the low temperature phenomena and the so-called Portevin – Le Chatelier (PLC) effect that occurs at room temperature. According to Zaiser and Hähner the mechanism of strain rate sensitivity consists of two basic steps:

– positive instantaneous response of the flow stress to a sudden increase of strain rate,
– relaxation of the flow stress to a quasi steady state asymptotic value.

Such behaviour is often classified as the oscillatory mode of plastic flow and is related to interpretation of serrated yielding in terms of dynamic strain ageing (DSA). The basic parameter that governs asymptotic behaviour of the flow stress in the low temperature plasticity is temperature.

Given at least three different theories developed to explain serrated yielding there was a need to carry out an additional experimental effort and to perform more precise tests in order to detect the real nature of this phenomenon. A crucial step has been achieved by mounting high sensitivity internal load cell in the proximity of the sample (inside the cryostat) and performing the measurements with the sampling frequency of 20 kHz. A comparison (Fig. 1) of the records obtained by means of the internal load cell (green curve) with the values recorded by using the external load cell (red curve) clearly shows that the drop of stress in reality precedes the increase of temperature (blue curve) and the thermodynamic response is secondary with respect to the mechanical effect. On the other hand, the measurements carried out in the past by means of the external load cell were misleading and led to a false interpretation that the temperature rise was at the origin of flow instability (drop of stress). Thus, the measurements reported explain the correct sequence of events when plastic flow instability occurs. As a consequence, the mechanical theory with thermally activated relaxation has been adopted as the basis of constitutive model presented in the paper.

## 6. Conclusions

The constitutive model discussed in the present paper addresses plastic flow instabilities that occur at extremely low temperatures in the materials characterized by the low stacking fault energy. As the serrated yielding leads to irreversible degradation of lattice and may accelerate the process of material failure the constitutive description turns out to be crucial for the correct dimensioning of structures applied at very low temperatures (superconducting magnets, cryogenic distribution systems, low temperature thermo-mechanical compensation systems etc.). For instance, temperature instabilities caused by a sudden energy release associated to serrated yielding may be critical for such components like superconducting wires (onset of resistive transition if local plastic deformation occurs). The new coupled constitutive model takes into account the relevant thermodynamic background related to the mechanisms of heat transport in the weakly excited lattice at very low temperatures.

Discontinuous plastic flow has been described by the mechanism of local catastrophic failure of Lomer-Cottrell locks under the stress fields produced by the accumulation of edge dislocations (below the characteristic temperature $T_1$). Failure of LC locks leads to massive and spontaneous motion of released dislocations accompanied by rapid load drop and subsequent stress relaxation. The process has been subdivided into four stages. The main function that reflects the readiness of lattice to trigger discontinuous plastic flow is the surface density of dislocation groups located at the Lomer-Cottrell locks. Kinetics of evolution of LC locks has been postulated at the mesoscopic level and the relevant production rate of dislocation groups has been identified. It is worth pointing out, that the model is attractive in view of its simplicity and relatively small number of parameters to be identified at cryogenic temperatures.

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