MULTISCALE CONSTITUTIVE MODEL OF PLASTIC FLOW DISCONTINUITIES AT EXTREMELY LOW TEMPERATURES

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Summary 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. Most of these materials undergo at low temperatures dynamic strain ageing reflected by discontinuous plastic flow (DPF, serrated yielding). The physically based constitutive model presented in the paper takes into account the relevant thermodynamic background. The DPF effect is described by the mechanism of local catastrophic failure of Lomer–Cottrell (LC) locks under the stress fields related to the accumulating edge dislocations. The failure of LC locks leads to massive motion of released dislocations accompanied by the step-wise increase of the strain rate. In the present paper the plastic flow discontinuities associated with the proportional and the non-proportional loading paths are studied.

DISCONTINUOUS PLASTIC FLOW (DPF)

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 (Fig. 1) and reflects discontinuous nature of plastic flow (discontinuous in terms of $d\sigma / d\varepsilon$). Serrated yielding occurs below a specific temperature: T_1 for LSFE materials and T_0 for HSFE materials. Each of them represents transition from screw to edge dislocations. 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 will collapse by becoming a glissile dislocation. This process takes place below the temperature T_0 or T_1 where the dislocations have predominant edge character and cannot leave the pile-ups 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. Each serration is accompanied by a considerable local increase of temperature, related to the dissipation of plastic power and the so called thermodynamic instability.

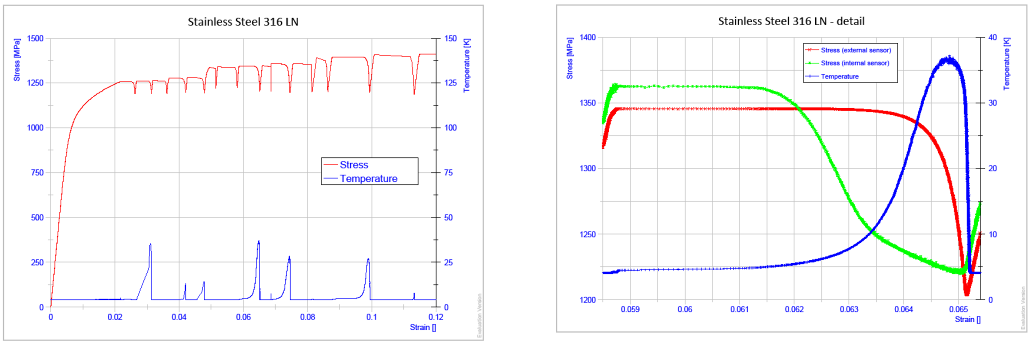

Fig. 1 (a) DPF in FCC metals (316L at 4.2 K). (b) Single serration: stress/strain and temperature experimental curves

RVE BASED CONSTITUTIVE MODEL

The main function that reflects the readiness of lattice with respect to discontinuous plastic flow is the density B of the dislocation groups (located at the Lomer–Cottrell locks). It is assumed that the increment of B is strictly related to the increment of the accumulated plastic strain (Odqvist parameter). The 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 postulated [4]:

$$\dot{B} = F_{LC}\left(T, \underline{\sigma}\right)\dot{p}H\left(p - p_{LC}\right) \tag{1}$$

Evolution of dislocations density as a function of deformation at the temperature T is described by an equation containing the creation and the annihilation terms. The average shear stress in the lattice and the shear stress at the head of dislocation pile-up (τ_e) are computed. The initial stages of the process reflect the elastic-plastic loading under nearly

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isothermal conditions, corresponding to low excitation of the lattice. Under these circumstances (no thermal activation) the rate-independent plasticity can be applied. Thus, the yield surface has the standard form expressed by the stress intensity with mixed kinematic/isotropic hardening included. Furthermore, it is assumed that the continuum containing LC locks obeys the associated flow rule. It is postulated in the present model that in every serration cycle the parameter B is accumulated *de novo* from 0, as soon as the discontinuous plastic flow is triggered after intersection of the current loading path with the interaction curve in the (B- τ_e) space (serration criterion, [4]):

$$\begin{aligned} &\tau \le \tau_{\min} && \Rightarrow && B = B_{cr} \\ &B \le B_{\min} && \Rightarrow && \tau_e = \tau_{cr} \\ &\tau > \tau_{\min} \wedge B > B_{\min} && \Rightarrow && \left(1-\frac{B_{\min}}{B_{cr}}\right)\frac{\tau_e}{\tau_{cr}} + \left(1-\frac{\tau_{\min}}{\tau_{cr}}\right)\frac{B}{B_{cr}} - \left(1-\frac{B_{\min}}{B_{cr}}\right) - \left(1-\frac{\tau_{\min}}{\tau_{cr}}\right)\frac{B_{\min}}{B_{cr}} = 0 \end{aligned} \tag{2}$$

PROPORTIONAL AND NON-PROPORTIONAL LOADING PATHS

In order to perform a numerical analysis and to calibrate the model (i.e. identify the parameters) an incremental algorithm has been developed and validated w.r.t. the uniaxial stress state. The numerical algorithm consists of five blocks (initial state, elastic deformation, plastic deformation, serration - drop of stress, relaxation), that are activated along with the recognized phase of the deformation process. The process is strain-controlled, i.e. for a set of internal functions and state parameters given at the step k, new values are determined at the step $k + 1$ following given increment of the total strain. The algorithm begins with the state of no strain and stress in the sample and with the initial values of the state functions and parameters. The density of the LC locks is set to zero and the initial values are set for the density of dislocations as well as for the yield stress. The accumulated plastic strain is equal to zero and the threshold of the plastic strain for the onset of LC locks evolution is assumed. Several proportional and non-proportional loading paths were analysed for a 2-D plane-stress case of a thin-walled plate subjected to bi-axial traction (Fig. 2).

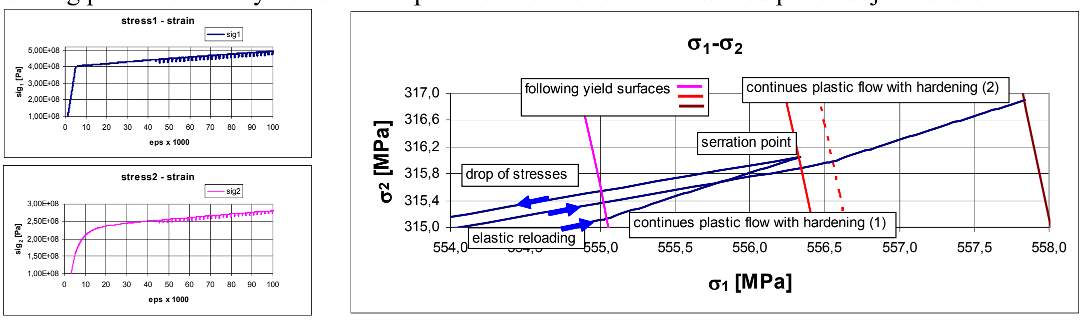

Fig. 2 (a) Stress-strain response for a bi-axial case (b) Evolution of yield surface and stress path for single serration

The 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. The so-called thermodynamic instability has been derived from the quantum representation of the energy of lattice associated with the phonon heat transport mechanism. Based on this description the relevant oscillations of temperature were computed. They are strongly coupled to the plastic flow discontinuities via the dissipation of plastic power and its conversion to heat.

CONCLUSIONS

DPF has been described by the mechanism of local catastrophic failure of LC locks under the stress fields produced by the accumulation of edge dislocations. 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 the discontinuous plastic flow is the density of dislocation groups (located at the LC locks). Kinetics of evolution of this function has been postulated at the mesoscopic level and the relevant production rate of dislocation groups has been identified by means of the experimental basis. The model has been applied to prove that the DPF is a multiaxial phenomenon which until now has not been described in the literature.

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References

[1] Obst, B., Nyilas, A.: Experimental evidence on the dislocation mechanism of serrated yielding in ... Mat. Sci. Eng. A137: 141-150, 1991.
[2] Obst, B., Nyilas, A.: Time-resolved flow stress behavior of structural materials at low temperatures. Advances in Cryogenic Engineering (Materials), Vol. 44, Plenum Press, New York, 331-338, 1998.
[3] Zaiser, M., Haehner, P.: Oscillatory modes of plastic deformation: theoretical concepts. Phys. Stat. Sol. (b), 199, 267-330, 1997.
[4] Skoczeń, B. et al., Constitutive model of discontinuous plastic flow at cryogenic temperatures, Int. Journal of Plasticity, 26: 1659-1679, 2010.