International Journal of Plasticity 55 (2014) 198–218

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Multiaxial constitutive model of discontinuous plastic flow at cryogenic temperatures

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A R T I C L E I N F O

Article history:
Received 29 December 2012
Received in final revised form 29 August 2013
Available online 21 September 2013

Keywords:
Multiscale constitutive model
Discontinuous plastic flow
Cryogenic temperatures
Multiaxial loads

A B S T R A C T

FCC metals and alloys are massively used in cryogenic applications down to the temperature of absolute zero, because of suitable physical and mechanical properties including high level ductility. Many of these materials undergo at low temperatures a process similar to dynamic strain ageing, reflected by the so-called discontinuous plastic flow (DPF, serrated yielding). The physically based multiaxial constitutive model presented in the paper constitutes a generalization of the previous uniaxial model that proved efficient in describing the plastic flow instabilities occurring at extremely low temperatures. The model takes into account thermodynamic background, including the phonon mechanism of heat transport and thermodynamic instability caused by specific heat vanishing with the temperature approaching absolute zero. The DPF is described by the mechanism of local catastrophic failure of lattice barriers (for instance Lomer-Cottrell 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 step-wise increase of the strain rate (macroscopic slip). In the present paper the plastic flow discontinuity associated with the proportional loading paths is studied. Identification of parameters of the constitutive model is based on the experimental data collected during several campaigns of tensile tests carried out on copper and stainless steel samples immersed in liquid helium (4.2 K).

1. Introduction

FCC metals and alloys (such as copper, copper alloys or stainless steel) are often applied in cryogenic conditions, down to the temperatures close to absolute zero, because of their remarkable properties including ductility. Many of these materials undergo at low temperatures a process similar to dynamic strain ageing, reflected by the so-called discontinuous plastic flow (DPF, serrated yielding). Thermodynamic conditions of DPF are strictly linked to the so-called thermodynamic instability, related to vanishing specific heat when the temperature approaches absolute zero. The DPF manifests itself at the macroscopic level by the instability of plastic flow often termed serrated yielding. It occurs in the range of temperatures between absolute zero and the temperature that characterizes a transition from the screw dislocations to the edge dislocations mode. Vanishing specific heat substantially helps to explain the instability (which becomes visible in the form of serrated flow), specifically at extremely low temperatures. Instabilities occurring at higher temperatures, e.g., in Al–Mg or Fe–Mn etc., are of different nature and are not addressed in the paper.

The present paper is focused on new multiaxial and thermodynamically coupled constitutive description of discontinuous plastic flow in FCC materials strained at very low temperatures. As an example of typical cryogenic application, Fe–Cr–Ni austenitic stainless steels are used to manufacture components of superconducting magnets and cryogenic transfer lines

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http://dx.doi.org/10.1016/j.ijplas.2013.09.004

since they preserve ductility practically down to near-0 K. However, the model presented in the paper is applied to a wide range of materials used at cryogenic temperatures like stainless steels, copper, copper and aluminium alloys etc.

As a good illustration of complexity of the plastic strain induced phenomena that occur at extremely low temperatures the response of 316 LN stainless steel (DIN : X2CrNiMo17-13-3), one of the most frequently applied materials, is shown. Three distinct domains of response of this low stacking fault energy (LSFE) material are indicated in Fig. 1. *Domain I* corresponds to the temperature range below T_1 where the plastic flow instability called discontinuous or serrated yielding takes place. *Domain II* stretches between T_1 and M_d, the latter being the temperature above which the process of plastic strain induced $\gamma \rightarrow \alpha'$ phase transformation does not take place. Inside this domain the plastic flow is smooth and accompanied by the transformation from parent γ phase to the secondary α' phase. Finally, *domain III* above the temperature M_d is characterized by smooth plastic flow and stable behavior with respect to the phase transformation. The area of application of the present constitutive model stretches between 0 and T_1, where the instability of plastic flow is observed for a wide range of strain rates.

It is worth pointing out that the serrated yielding is characteristic both of low (LSFE) and high stacking fault energy (HSFE) materials strained at very low temperatures (Obst and Nyilas, 1991). Essentially, it represents oscillatory mode of plastic deformation and manifests itself by the plastic flow discontinuous in terms of $d\sigma/d\varepsilon$. As already indicated, the serrated yielding occurs below a specific temperature: T_1 for LSFE materials and T_0 for HSFE materials. Each of these temperatures represents a transition from screw to edge dislocations mode (Obst and Nyilas, 1991). According to Seeger (1957), 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. The excitation of lattice is very low and the edge dislocations move at lower stress than the screw dislocations. Both transition temperatures (T_0 and T_1) are material dependent and can reach some 35 K (the highest values found to date). Each of them can be found by plotting the yield strength against temperature at various pre-specified plastic strain levels. It is worth indicating, that DPF occurs for a wide range of strain rates exceeding a specific – material dependent – lower critical value $\dot{\varepsilon}_1^p$ (Komnik and Demirski, 1984; Reed and Walsh, 1988; Reed and Simon, 1988; Pustovalov, 2008). On the other hand, for the strain rates in excess of the upper critical value $\dot{\varepsilon}_2^p$, the accumulation of heat under nearly adiabatic conditions causes increase of temperature of the sample beyond T_0 or T_1, which leads in consequence to a transition to *Domain II* and restoration of the classical smooth plastic flow.

Serrated yielding has been investigated by several authors, among them Basinski (1957), Schwarz and Mitchell (1974), Estrin and Tangri (1981), Reed and Simon (1988), Reed and Walsh (1988), Burns (1994), Hähner and Zaiser (1997), Zaiser and Hähner (1997), Benallal et al. (2006, 2008). Some other authors like Wessel (1957) or Tabachnikova et al. (1984), suggested that "high flow stresses at low temperatures can promote avalanche multiplication of mobile dislocations". However, they did not develop mathematical models to explain the dislocation nature of flow instabilities.

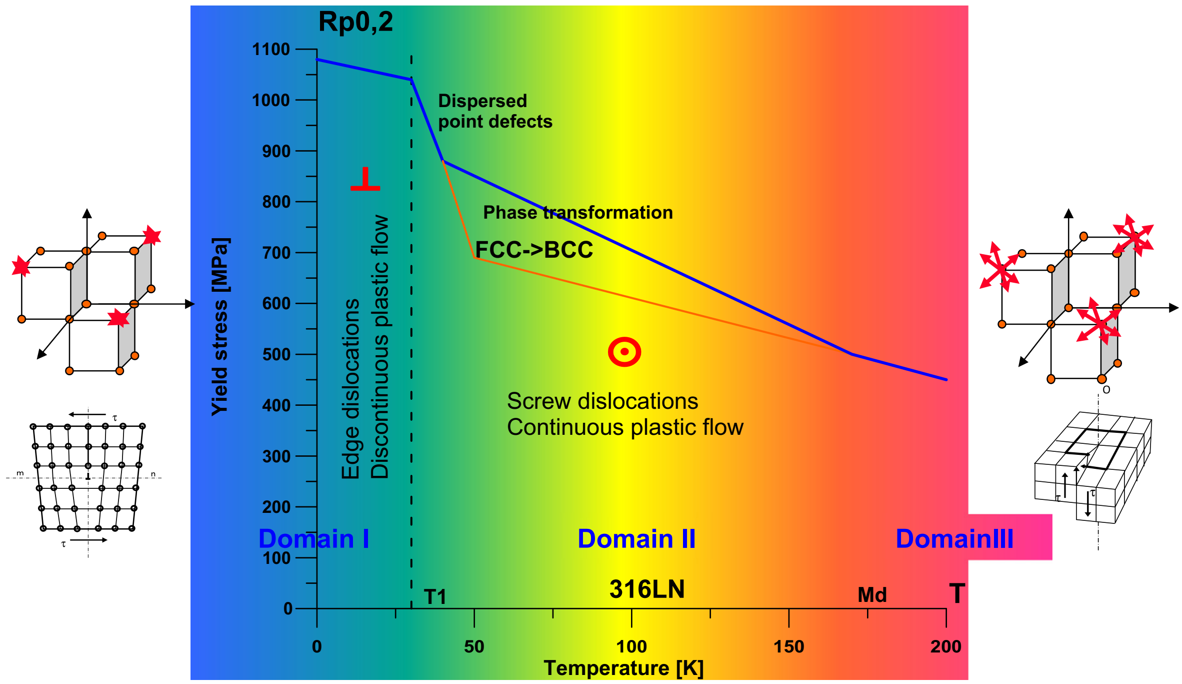

Fig. 1. The mechanisms of plastic flow at extremely low temperatures illustrated by means of the plot of yield stress (R_{p02}) against temperature (T) for 316LN stainless steel.