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Strain localization during discontinuous plastic flow at extremely low temperatures

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ABSTRACT

The phenomenon of strain localization in the course of discontinuous plastic flow (DPF) at extremely low temperatures is investigated. DPF is observed mainly in fcc metals and alloys strained in cryogenic conditions, practically down to absolute zero. These materials undergo at low temperatures a process similar to dynamic strain ageing, manifested by the so called serrated yielding (DPF). DPF is attributed to the mechanism of local catastrophic failure of lattice barriers (including Lomer–Cottrell locks), under the stress fields related to the accumulating edge dislocations. Failure of LC locks leads to massive motion of released dislocations, accompanied by step-wise increase of the strain rate (macroscopic slip) and drastic drop of stress. Recent experiments indicate strong strain localization in the form of shear bands propagating along the sample. The plastic power dissipated in the shear band is partially converted to heat, which results in a local drastic increase of temperature promoted by the so-called thermodynamic instability (nearly adiabatic process). The Dirac-like temperature function is measured by two thermometers located in the gage length of the sample. Spatio-temporal correlation indicates smooth shear band propagation, as long as the process of phase transformation remains on hold. A physically based multiaxial constitutive model presented in the paper describes both DPF and strain localization, accompanied by temperature distribution represented by Green-like solution of heat diffusion equation. The model accounts for the thermodynamic background, including phonon mechanism of heat transport, accompanied by specific heat vanishing with the temperature approaching absolute zero. Experimental identification of parameters of the constitutive model is carried out. A projection of the model to the range where the phase transformation takes place is discussed.

1. Introduction

The phenomenon of strain localization in the course of DPF at extremely low temperatures has not been addressed in the literature. On the other hand, a significant effort has been focused on the mechanism of shear bands initiation and propagation during the so-called PLC (Portevin-Le Chatelier) effect, observed in certain materials at room temperature. The reason for such a dramatic lack of information on the behaviour of materials at extremely low temperatures is related to testing conditions. The experiments are carried out inside a double-wall cryostat, which is not transparent and usually tightly equipped with necessary instruments. Thus, there is practically no possibility to scan the surface of the sample by means of such instruments like thermographic camera, in order to detect possible effects of strain localization. In order to do so, specific deduction methods have to be used, which will be explained in the course of the present paper.

1.1. DPF at extremely low temperatures

Fcc metals and alloys are applied in modern cryogenic installations (including superconducting magnets or cryogenic transfer and storage systems) within the whole range of temperatures, from near-0 K to ambient temperature. Such materials like copper and its alloys, aluminum alloys or different grades of stainless steel show truly remarkable properties at extremely low temperatures, including high ductility (cf. Sgobba and Hochoertler, 1999). To give an example of typical cryogenic application, Fe-Cr-Ni austenitic stainless steels are used to manufacture components of superconducting magnets and cryogenic transfer lines, since they preserve ductility down to absolute zero. Many of these materials undergo at near-0 K temperatures (for instance in superfluid helium, 1.9 K, or in liquid helium, 4.2 K) some sort of dynamic strain ageing, called DPF. DPF manifests itself at the macroscopic level by oscillatory mode of plastic flow, consisting in abrupt drops of stress

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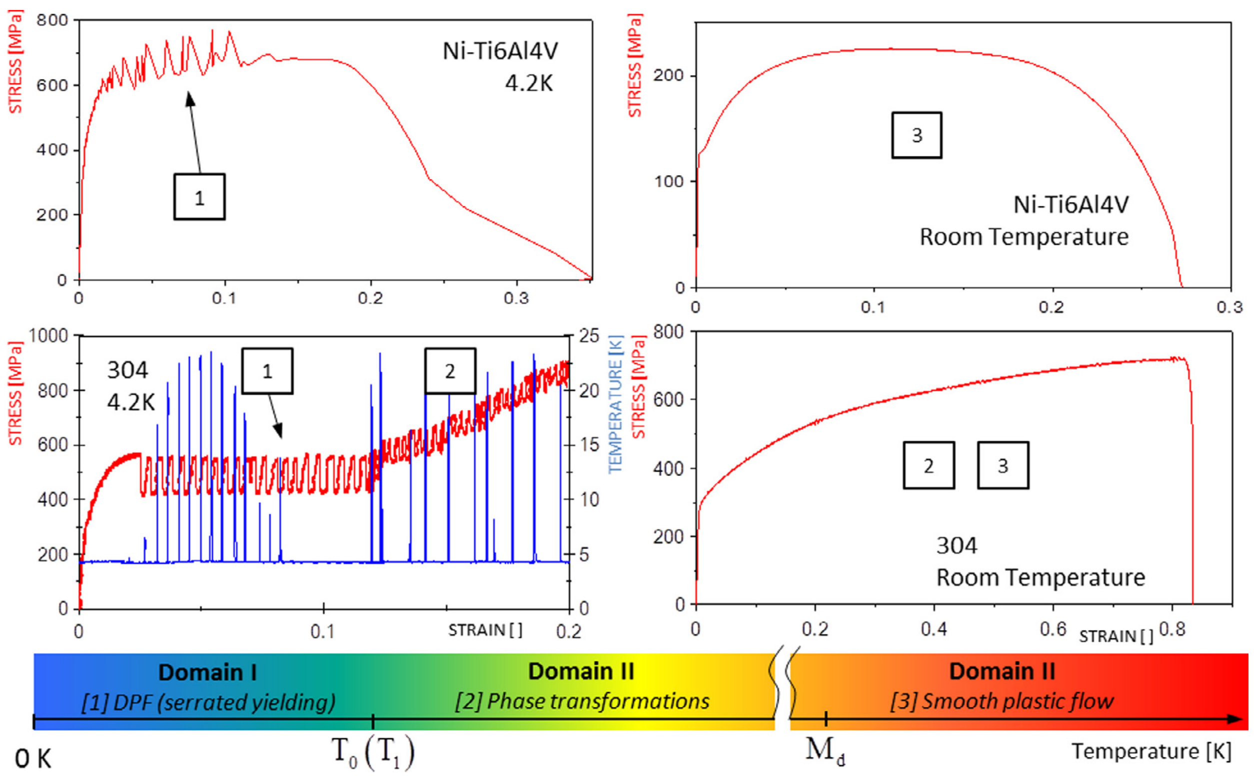

Fig. 1. Types of plastic flow (serrated versus smooth yielding) as a function of temperature (engineering stress - strain curves).

against strain. Another important feature of DPF consists in the fact, that it occurs in the temperature range between 0 K and a material dependent temperature (T_0 or T_1), associated with the transition from screw to edge dislocations mode. General thermo-mechanical aspects of DPF are strictly linked to the so-called thermodynamic instability, which consists in strong oscillations of temperature due to heat accumulation in near adiabatic conditions, resulting from vanishing specific heat when the temperature approaches absolute zero. This effect is accompanied by vanishing thermal conductivity and vanishing thermal contraction coefficient. Instabilities occurring at higher temperatures, like the PLC effect, are usually of different nature and are not addressed in the present paper.

In order to illustrate the plastic strain induced phenomena that occur at extremely low temperatures, typical response of selected alloys (Ni-Ti6Al4V, grade 304 stainless steel), used for structural applications at cryogenic temperatures, is shown in Fig. 1. In particular, three domains of response are distinguished: below T_1 where the DPF (serrated yielding) takes place, between T_1 and M_d where the diffusionless plastic strain induced $\gamma \rightarrow \alpha$' phase transformation occurs, and above M_d where the smooth plastic flow is observed.

Generally, DPF represents the so-called oscillatory mode of plastic deformation and is detected in many low (LSFE) and high stacking fault energy (HSFE) materials strained at extremely low temperatures (Obst, Nyilas, 1991). As soon as the serrated yielding occurs, the plastic flow becomes discontinuous in terms of $d\sigma/d\varepsilon$. The DPF takes place below a thermal threshold, characteristic of given material: T_1 for LSFE materials and T_0 for HSFE materials (both transition temperatures are material dependent and can reach some 35 K).

Serrated yielding occurs for a wide range of strain rates (Komnik and Demirski, 1984; Reed and Walsh, 1988; Reed and Simon, 1988; Pustovalov, 2008). When the strain rate exceeds a critical value, nearly adiabatic accumulation of heat takes place and causes fast increase of temperature of the sample to the level above T_0 or T_1. This leads to restoration of the classical smooth plastic flow (Fig. 2).

Thus, the DPF is usually bound by the lower and the upper limits of the strain rate. Lower limit does not play a substantial role and is often close to zero, whereas, the upper limit has an important meaning for the way the serrated yielding develops. Typically, heat transport conditions at the temperature of liquid helium are close to adiabatic, and enhanced strain rate causes subsequent heat accumulation and strong temperature rise. For higher strain rates, the adiabatic overheating leads to gradual increase of temperature until it reaches the critical level T_0or T_1. As soon as the critical temperature level is reached, transition from serrated to smooth plastic flow is observed and DPF temporarily disappears. It is a renewed cool down below T_0 or T_1 that brings the material back to the oscillatory mode of plastic flow.

1.2. The mechanism of DPF

Recent history of low temperature serrated yielding started already in the fifties of 20th century. The mechanism of DPF was analyzed by several authors, among them Basinski, 1957, Schwarz and Mitchell, 1974, Reed and Simon, 1988, Reed and Walsh, 1988, Hähner and Zaiser, 1997, Zaiser and Hähner, 1997, Benallal et al., 2006. Some investigators (cf. Wessel, 1957; Tabachnikova et al., 1984) postulated that sufficiently high flow stress at extremely low temperature can induce avalanche-like process of multiplication of mobile dislocations, which leads to plastic flow instability. Other authors, among them Estrin and Tangri, 1981, Dolgin and Natsik, 1991, as well as Burns, 1994, developed rather simple models of DPF. An extensive study of DPF was carried out by Basinski, already in 1957. Basinski developed a thermodynamic approach, including the fact that the specific heat and the thermal conductivity tend to zero with temperature. He based his approach on the adiabatic heating hypothesis, claiming that any fast dissipative process that