DISCONTINUOUS PLASTIC FLOW IN THE LOW-TEMPERATURE SUPERCONDUCTORS

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1. General

Low-temperature (LT) superconductors consisting of superconducting filaments embedded in the copper matrix are used in the applications where high current density can generate strong magnetic field. Primary applications of LT superconductors (e.g. Cu/NbTi, Cu/Nb3Sn) include: magnets for MRI, nuclear magnetic resonance (NMR), laboratory apparatus, particle accelerators, electric power conditioning, levitating trains and superconducting magnetic energy storage (SMES). The applied magnetic field, the temperature and the current density in such devices must be maintained below a critical surface in order to retain superconductivity. Therefore, any heat dissipation effects, such as energy dissipation during the discontinuous plastic flow (DPF), are undesired. Such effects may occur independently in the matrix and in the filaments during the plastic deformation at near 0K temperature. 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 a drastic drop of stress. Moreover, the plastic power dissipated in the slip band is partially converted to heat, which results in a drastic increase of temperature promoted by the thermodynamic instability (nearly adiabatic process). Thus, DPF is a potential factor leading to the loss of superconductivity in the magnet. Therefore, the experimental investigations and the constitutive modelling of DPF in the LT superconductors seem to be essential.

2. Tensile test results of LT superconductors at 4.2 K

In order to investigate the behaviour of LT superconductors at cryogenic temperatures, a custom built experimental set-up was used (Tabin et al., 2017). A cryostat equipped with tested specimen and the relevant transducers was mounted between traction machine grips. The cryogen (liquid helium, 4.2 K) was fed into the cryostat by means of a transfer line, until the specimen with the transducers was immersed in the bath. The level of the cryogen inside the cryostat was indicated by a dedicated thermistor.

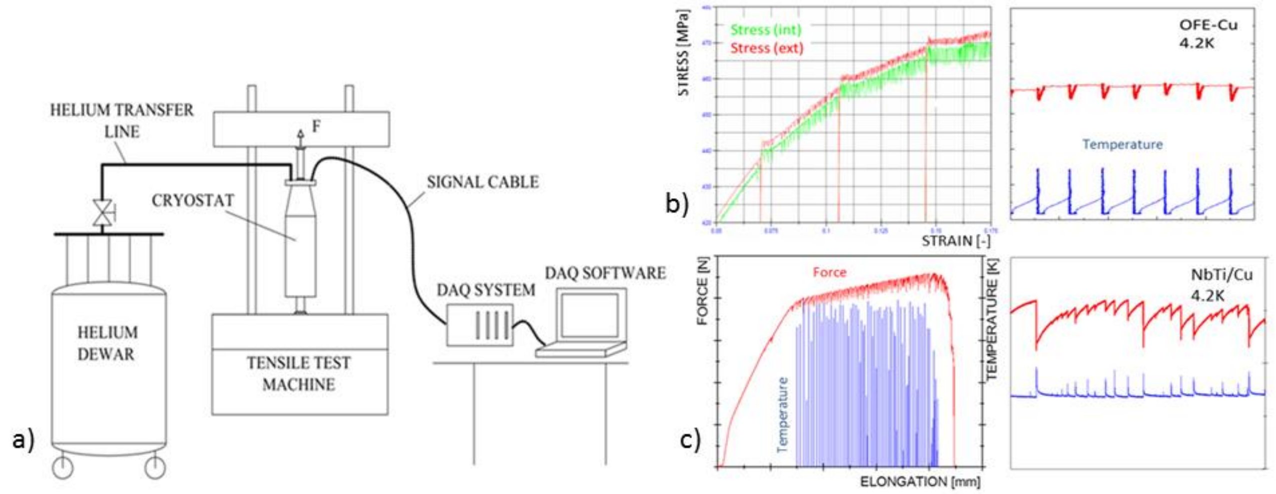

Fig. 1 a) The experimental set-up for uniaxial tests at 4.2K; b) the stress-strain curve (red and green) and the temperature-strain curve (blue) for OFE-Cu; c) the force-elongation curve (red) and the temperature-elongation curve (blue) for NbTi/Cu composite

The kinematically controlled tests were carried out. During each test, the elongation of the specimen was measured by means of the clip-on extensometers, whereas the applied force was measured by means of the piezoelectric transducer mounted above the specimen. The temperature of the specimen during plastic deformation was measured by means of the thermistor mounted in the middle of the gauge length. General scheme of the experimental set-up, as well as uniaxial tensile test results, are presented in Fig. 1.

3. Multiscale constitutive model of DPF

During the uniaxial tensile tests at 4.2K, the plastic flow instability (serrations) is observed independently in the Cu matrix and in the NbTi filaments (Fig. 1c). The DPF consists in the massive failure of lattice barriers associated with the increase of the resolved shear stress at the heads of the dislocations pile-ups, until the stresses reach the level of cohesive strength of the material (Skoczeń et al., 2010). The main function that reflects the number of internal lattice barriers per unit surface is the density B. The rate of production of dislocation pile-ups at the internal lattice barriers $\dot{B}$ is strictly related to the rate of the accumulated plastic strain $\dot{p}$. In general, the kinetics of DPF is expressed by:

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

where F^{+}_{LC} is function of dislocations density ρ, temperature T, and stress σ, whereas p_{LC} represents the threshold above which the lattice barriers massively develop. $H(\ldots)$ denotes the Heaviside function. The criterion of avalanche-like failure of lattice barriers is based on the interaction between B (the density of lattice barriers) and τ_e (the average shear stress at the head of dislocation pile-up). A combination of both parameters triggers the serration (drop of stress) (Skoczeń et al., 2008). A numerical model of DPF is provided for the transversely isotropic composite, consisting of the filaments in the copper matrix (Fig. 2).

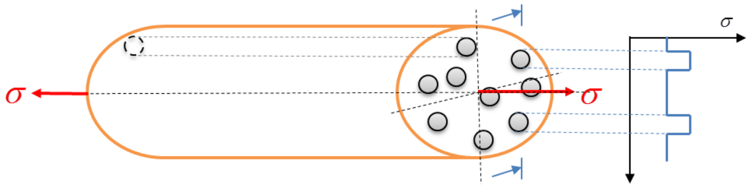

Fig. 2 Transversely isotropic composite consisting of filaments embedded in the copper matrix

It is assumed that during the kinematically controlled tensile test, the total strain is the same for the matrix and the filaments. Thus, the effective stress has following form:

(1) $$\bar{\sigma} = \beta_m \sigma_1 + \beta_f \sigma_2$$

where β_m, β_f denote the surface fraction of the matrix (OFE-Cu) and the filaments (NbTi), and σ_1, σ_2 denote the stress in the matrix and in the filaments, respectively. The above discussed constitutive model is physically based, and reflects all the important features of the DPF. Moreover, the model allows us to reproduce the observed serrations, which is crucial for its application in the design of components operating at extremely low temperatures.

Acknowledgments This work has been supported by the National Science Centre through the Grant No UMO-2016/21/N/ST8/02368.

References

[1] Skoczeń, B., 2008. Constitutive model of plastic strain induced phenomena at cryogenic temperatures. Journal of Theoretical and Applied Mechanics, 46, 4, pp. 949-971,

[2] Skoczeń, B., Bielski, J., Sgobba, S., Marcinek, D., 2010. Constitutive model of discontinuous plastic flow at cryogenic temperatures. International Journal of Plasticity 26, pp. 1659-1679.

[3] Tabin, J., Skoczen, B., Bielski, J., 2017. Damage affected discontinuous plastic flow (DPF). Mechanics of Materials 110, pp. 44-58.