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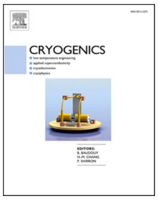

Strain measurement by means of clip-on extensometers during discontinuous plastic flow at 4 K

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ABSTRACT

The clip-on extensometers are recommended by international standards (ASTM E 1450-16 or ISO 6892-4:2015) for tension testing of structural alloys at 4 K. They are also frequently used to identify mechanical and electromechanical properties of superconducting wires or cables at cryogenic temperatures. In this study, the time responses of clip-on extensometers during uniaxial tensile tests of the engineering materials at liquid helium temperature are analysed. It turns out, that strong strain localization and self-excited vibrations of extensometers related to the plastic flow instability disturb the strain measurement. These measurement artefacts may affect the identification of the mechanical parameters, such as the 0.2% proof stress or the total elongation.

1. Introduction

Until the 1980s, strain measurements in liquid helium (4 K) were complicated but tensometers for cryogenic temperatures were developed and reliable clip-on extensometers were fortunately introduced [1]. Such transducers can work with high resolution, and reproducible signals for a variety of engineering measurement tasks such as tensile, fracture, compression, fatigue, flexural, and component tests at cryogenic environments. The correct measurement of strains is the key factor in the materials investigation and engineering design of complex structures. Properly designed and attached clip-on extensometers can transfer the strain information for further computation of mechanical parameters (Fig. 1). Although different techniques are available at cryogenic temperatures, the strain gauge technology is still mostly used [2–6]. Moreover, the clip-on extensometers based on strain gauges (Fig. 1) are recommended by the international standards [7, 8] for tensile testing of metals at liquid helium [3, 9–12]. These transducers are often selected for strain measurement during cryogenic tensile tests of polycrystalline materials [13], composites [2, 5] or high-entropy alloys [4, 14, 15]. Moreover, the International Electrotechnical Commission (IEC) supports the efforts to establish the international standards of the testing methods for superconducting technical wires at cryogenic temperatures, and the clip-on extensometers are considered as strain transducers to identify the tensile properties [16–18].

The most advanced material test laboratories, such as CryoMaK in Karlsruhe Institute of Technology in Germany, National Institute for Materials Science, or High Energy Accelerator Research Organization (KEK) in Japan, CERN in Switzerland, or NASA in the USA, use clip-on extensometers to measure the elongation and to identify the mechanical parameters at cryogenic temperatures [15, 18–24].

During tensile tests of the engineering materials at cryogenic temperatures, unusual behaviour is observed. When temperature tends to the absolute zero, below a transition temperature the discontinuous plastic flow (DPF) occurs [25]. This effect, also called a serrated yielding or an intermittent plastic flow, is reflected by stress oscillations. Moreover, during the tension of austenitic stainless steels (widely used for cryogenic industrial applications), when a yield point is reached, a long stress plateau may occur [11]. It reflects a Lüders-like deformation (Fig. 2), normally observed at room temperatures in carbon steels [26, 27] or in ultra-fine grained austenitic stainless steels [28]. Overall, strong strain localization is observed during the uniaxial tensile test at 4 K in the engineering materials. Bearing in mind that extensometers integrate the axial strain along the gauge length the following question arises: how do the plastic flow instability and the strong strain localization related to it, impact the strain measurement (carried out by means of clip-on extensometers) and hence the identification of mechanical parameters?

Until now, the DPF was successfully investigated by many prominent researchers [25, 29, 30]. Nevertheless, they did not present the complex analysis of measurement artefacts during strain measurement at 4 K performed by the clip-on extensometers. In this study, the time responses of clip-on extensometers during the uniaxial tensile tests of the engineering materials at 4 K are analysed. It turns out, that the strong strain localization and the self-excited vibrations of extensometers, related to the plastic flow instability (DPF) disturb the strain measurement. These measurement artefacts affect the identification of mechanical parameters, such as the proof stress $R_{0.2\%}$ or the total elongation [7, 8].

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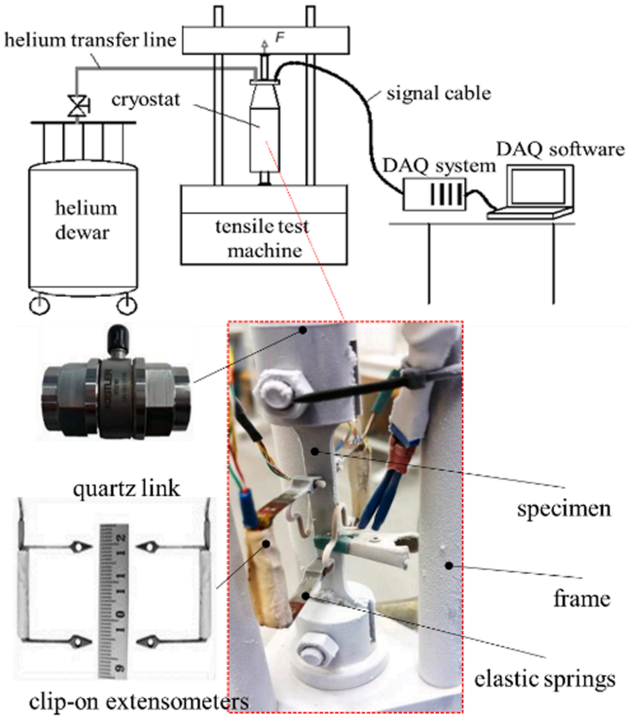

Fig. 1. Experimental set-up for uniaxial tensile test at cryogenic temperatures equipped with clip-on extensometers.

2. Materials and methods

The typical experimental set-up for a tensile test at cryogenic temperatures is presented in Fig. 1. The main part of the system is the cryostat (vacuum insulated enclosure around the sample), connected to the liquid helium dewar by means of the helium transfer line. Before the test start, the liquid helium flows from the dewar to the cryostat, until the specimen equipped with the sensors is immersed in the cryogenic medium. The cryostat is mounted between the grips of the tensile test machine, which performs the tension. The clip-on extensometers are attached directly to the specimen. To hold the extensometers, two elastic springs can be used. The insufficient magnitude of the operating force may cause the slip of the extensometer blades during the tensile test, resulting in an abrupt drop of the strain signal. To avoid this effect, the grooves (0.02 mm deep) are cut into the specimen surface. No effect of grooves was noticed on spatio-temporal characteristics of the shear band and failure mod. The grooves can be the stress concentrator during the initial stages of tension, but due to the strain-induced phase transformation the hardening effect is observed, and the plastic strain relocates out of the grooves [31].

In the present study, the metastable austenitic stainless steel (304, 316L), the high manganese austenitic stainless steel (JK2LB), the Ti-alloy (ATI 7-6™), and the superconducting multifilament composite (Cu-NbTi) are examined. Two types of uniaxial tensile tests are performed, namely, displacement and stress-controlled (Table 1). The tests are carried out at the liquid helium temperature (4 K).

3. Results and discussion

Based on the time responses of the force transducer and the clip-on extensometers (Fig. 3 a, f, j, Fig. 3 a and Fig. 4 b), the stress–strain characteristics (Fig. 1 b and Fig. 3 e, i) and the mechanical properties for different materials are identified. The results present strong strain localization under the tensile test. For instance, during the serrations

Table 1
Projection of macroscopic shearing strain Δx during DPF. Specimen parameters and test conditions.

Material	Cross section [mm^2]	Gauge length [mm]	Parallel length [mm]	Displacement (d) orstress (f) controlled test [mm/s]or[MPa/s]	Shearing strain projection Δx[mm]
304	1.50	20.01	30.02	1.0 (d)	0.09
JK2LB	9.06	25.30	25.00	0.008 (d)	0.42
ATI 7-6™	8.58	25.00	25.00	0.5 and 5.0 (f)	0.34
OFE Cu	9.01	25.10	25.03	1.0 (d)	0.02
Cu-NbTi	9.06	25.00	50.1	1.0 (d)	0.04

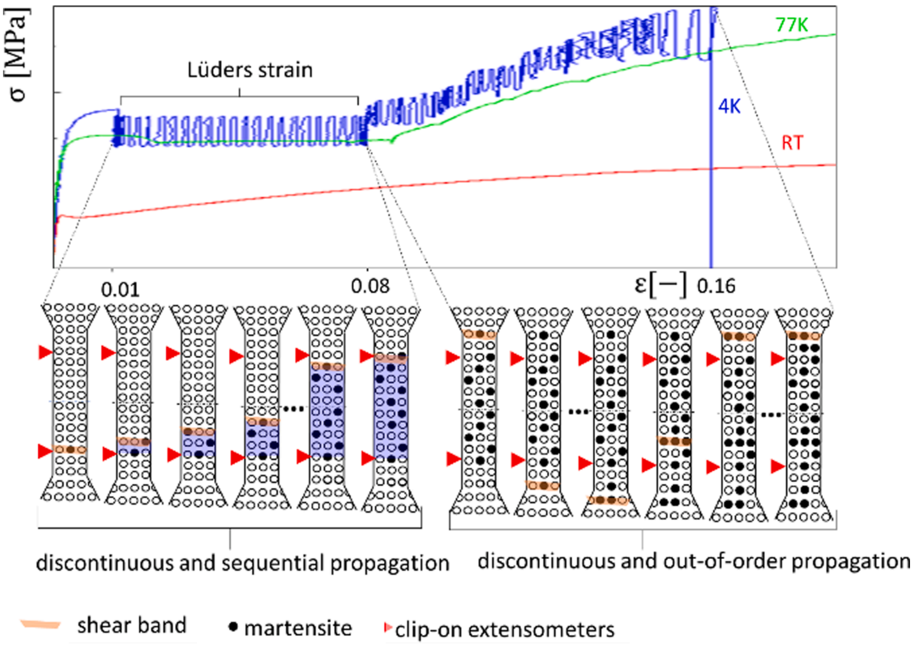

Fig. 2. Engineering stress (σ) vs. engineering strain (ε) for uniaxial tensile tests of 316L at a wide range of temperatures (4 K, 77 K and room temperature). Schematic illustration of strain localization during tensile test of 316L dog bone specimen at 4 K temperature.

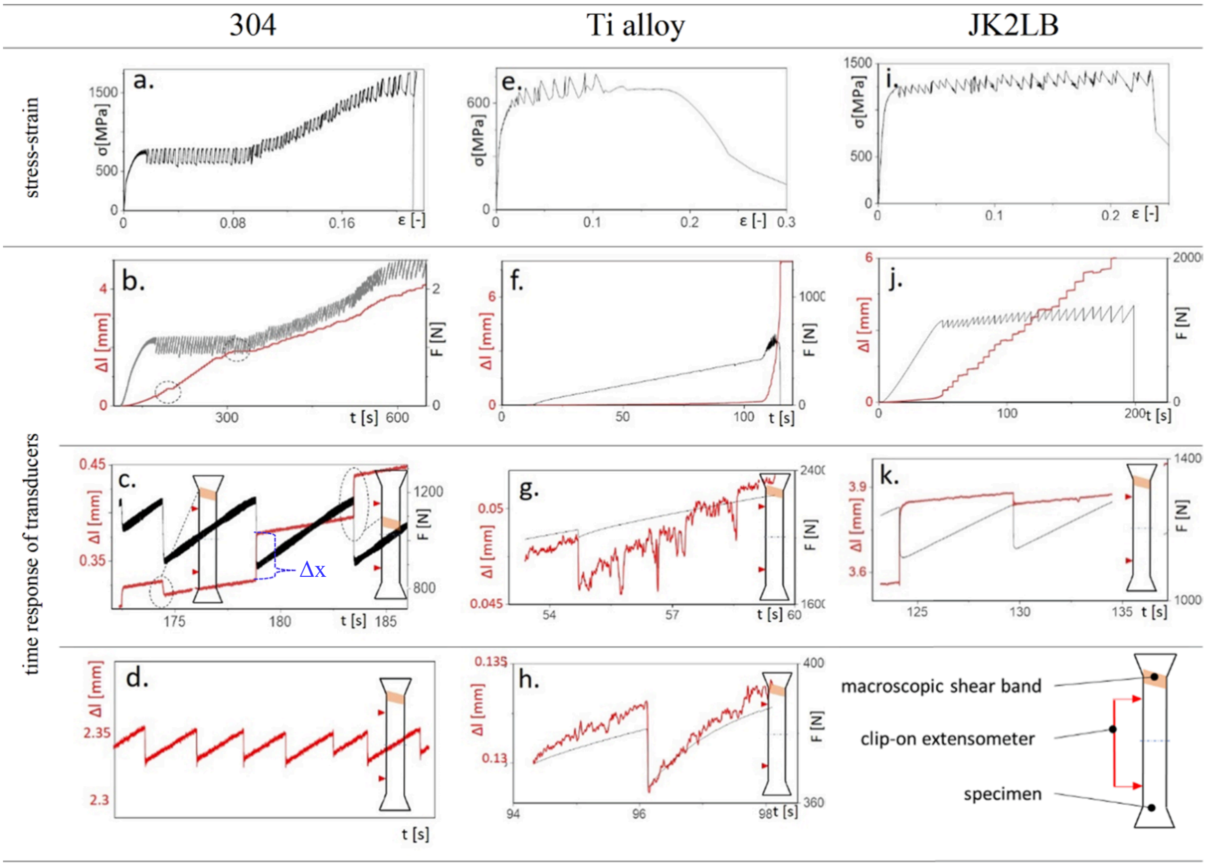

Fig. 3. Tensile tests results (single tests) for 304 (a, b, c, d), ATI 7-6™ (e, f, g, h) and JK2LB (i, j, k) at 4 K. Time responses of transducers: quartz force link (F[kN], black curves) and extensometers (Δl[mm], red curves). Identification of the macroscopic shearing strain projection (Δx) on tension direction. Scheme of experimental setup and macroscopic shear band localization during test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

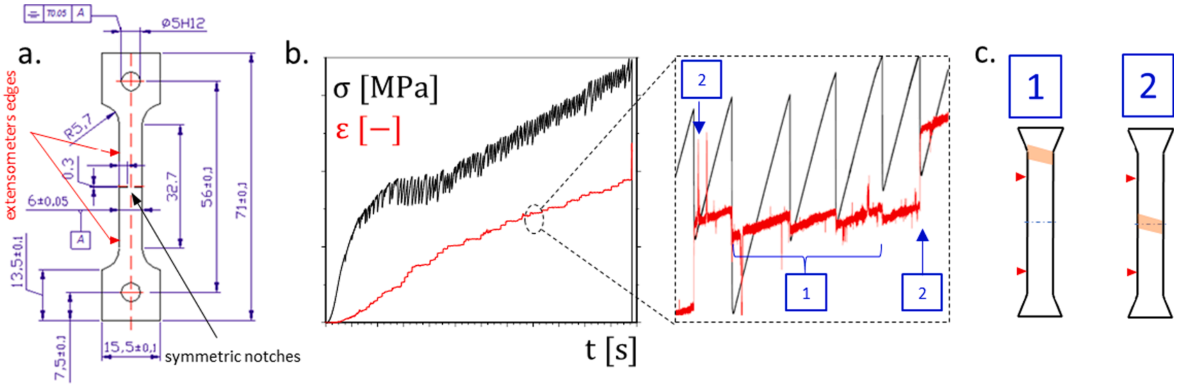

Fig. 4. a) 304 specimen with symmetrical notches; b) time responses of force transducer (black curve) and extensometers (red curve) during tensile test at 4 K; c) the shear band occurs out of notches as well as out of the extensometers' gauge length. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

plateau of displacement-controlled test of the austenitic stainless steel (Fig. 2), the shear band propagates discontinuously from one end of the specimen to the other (cf. [31–33]), just as during Lüders strain in low-carbon steels at room temperature [27]. Then, due to the advanced strain-induced phase transformation, the shear band starts to propagate in a random way. The schematic illustration of strain localization during the test at 4 K is presented in Fig. 2.

Generally, the stepwise increase of the elongation signal is expected during discontinues plastic flow (DPF). Meanwhile, the drop of the elongation signal is observed. It means that the macroscopic shear band is localized out of the extensometers' gauge length and the squeezing of extensometers' arms takes place (Fig. 3c, d, g, k).

It is worth pointing out that the DPF occurs in austenitic stainless steels or JK2B at 4 K when the strain threshold is achieved (Fig. 2, Fig. 3). The DPF strain threshold effect is clearly presented by Han et al. [34]. Walsh et al. [35], in turn, present the stress–strain curve for JK2LB without the serrations because the strain threshold is not achieved. Therefore, international standards present two cases how to identify the proof strength $R_{0.2\%}$, namely, when serrations occur before and after 0.2% strain. Nevertheless, in the first case, when strain localization occurs out of the extensometers' gauge length, the identification of $R_{0.2\%}$ is problematic. Unfortunately, international standards do not consider such a circumstance. The same problem may occur during the identification of final gauge length after fracture based on the time response of extensometers. Obviously, the final gauge length after fracture can be confirmed using the fractured specimen but, at 4 K the thermal expansion has to be taken into account.

Based on the time response of extensometers, it is possible to determine the underestimation of total strain when the shear band occurs out of extensometers' gauge length. During the tensile test of fcc materials at 4 K, the massive and collective failure of lattice barriers is reflected by the macroscopic shear band [36]. The magnitude of the macroscopic shearing strain projection on tension direction (Δx) can be identified (e.g. Fig. 3c). In Table 1 the maximum macroscopic shearing strain projection recorded during tests are presented.

It is obvious that when the extensometer gauge length is long enough the shear bands occur between the knife-edge of the extensometers. However, for the austenitic stainless steels the strong hardening effect due to the phase transformation may take place and the shear band still may occur out of the extensometers' gauge length [11, 37]. It is worth pointing out that during the tensile test of 304 specimen with symmetrical notches at 4 K, the shear band also occurs out of the notches and the extensometers' gauge length (Fig. 4).

The plastic flow instability and the strong strain localization are also observed in superconducting wires or cables [5]. The low and high temperature superconductors (LTS or HTS) are composite conductors applied in the large magnet applications, such as the central solenoid and toroidal field superconducting magnets (International Thermonuclear Experimental Reactor, ITER), the modern nuclear magnetic resonance (NMR), or the Large Hadron Collider luminosity upgrade (CERN). The correct measurement of strains during the loading of wires or cables is the key factor in the materials investigation and engineering design of complex superconducting structures working in cryogenic environments [5, 16, 38–40]. For instance, it is important to investigate correctly the strain effect on the critical current (Ic) and to determine the irreversible limits for Ic degradation in cables. The experimental setups for investigation of such electromechanical properties are often equipped with clip-on extensometers [16, 17, 41–43]. In RE-123 coated conductors with Hastelloy C-276 substrates it was found that the quenching is attributable to the discontinuous yielding and related to the strain localization in the Hastelloy substrate. In the conclusions, the Authors affirmed that in their case the extensometer calibration procedure should be re-examined to provide more precise specification in the guideline [16].

In order to show how DPF in superconducting composite influences strain measurement, the displacement-controlled uniaxial tensile tests of Cu-NbTi specimen at 4 K are carried out. The composite specimen for the tensile test at cryogenic temperatures is severed from superconducting auxiliary busbars which are used to feed the "spoolpieces" – superconducting corrector magnets located in the main dipole in the Large Hadron Collider at CERN [44]. These busbars consist of a rectangular shape copper conductor and NbTi filaments. The cross-section of the tested specimen and the specimen grip system is presented in Fig. 5 b.

The time response of clip-on extensometers shows clearly that during DPF the shear bands occur out of extensometers' gauge length just as the localized neck, therefore the time responses of extensometers decreases. The fracture occurs near the bottom grip.

Except for the strong strain localization which occurs out of the extensometers' gauge length, the time response of clip-one extensometers during loading at 4 K may be distorted by other factors. The vibration of a tensile test machine [45], the extensometers blade slipping [2] or the plastic flow instability of testing specimen (Fig. 6c), each of them generates the self-excited vibrations of extensometers. It results in the measurement artefacts represented by the "hanks" on the stress–strain curve (Fig. 6 a). It is worth pointing out that for this stress–strain curve, the measurement artefact resulting from the shear banding out of extensometers' gauge length, are also observed (Fig. 6 b).

The post-factum analysis of the time response of the clip-on extensometers is an easy method to identify the artefacts of the strain measurement performed by the clip-on extensometers. Properly identified mechanical parameters are crucial, especially when one designs and develops the materials for the cryogenic infrastructure, the spaceship, or the superconducting magnets. These sophisticated technologies operate at temperatures near absolute zero where the plastic flow instability and the strain localization appear frequently.

4. Conclusions

- The strong strain localization out of the extensometers' gauge length and self-excited vibrations of extensometers related to the plastic flow instability (DPF) may disturb the strain measurement performed by clip-on extensometers.
- The clip-on extensometers can be used during the tensile test at helium temperature, nevertheless, the gauge length should be close to the parallel length of the specimen. However, for austenitic stainless steels, the strong hardening effect due to the phase transformation may take place and the shear band still may occur out of the extensometers' gauge length. Therefore, the time response of extensometers should be verified in terms of the drop of the signal during the tension at cryogenic temperatures.
- The international standards of identifying the mechanical and the electromechanical parameters of engineering materials and superconducting wire at cryogenic temperatures should be reconsidered according to the strain measurement procedure [2, 16, 41].

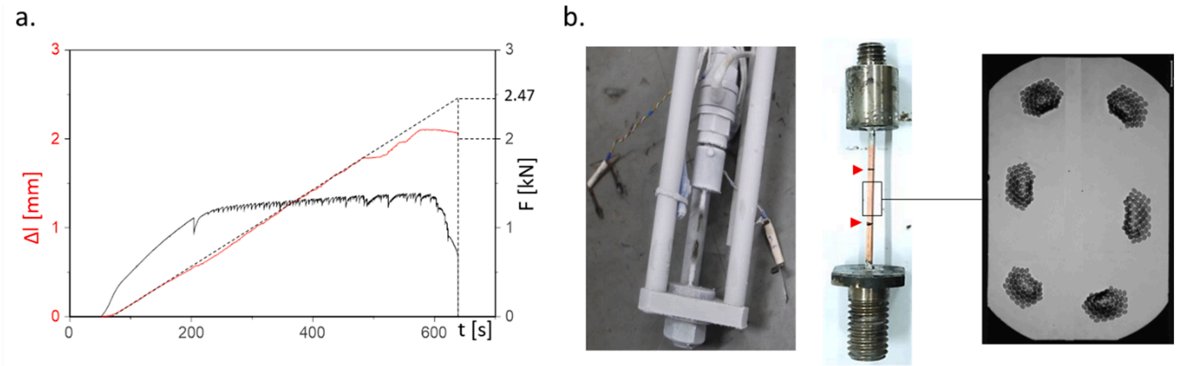

Fig. 5. DPF in superconducting multifilament composite Cu-NbTi during displacement-controlled tensile test at 4 K, time responses of clip-on extensometers (red) and force transducer (black) b) cross-section of specimen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

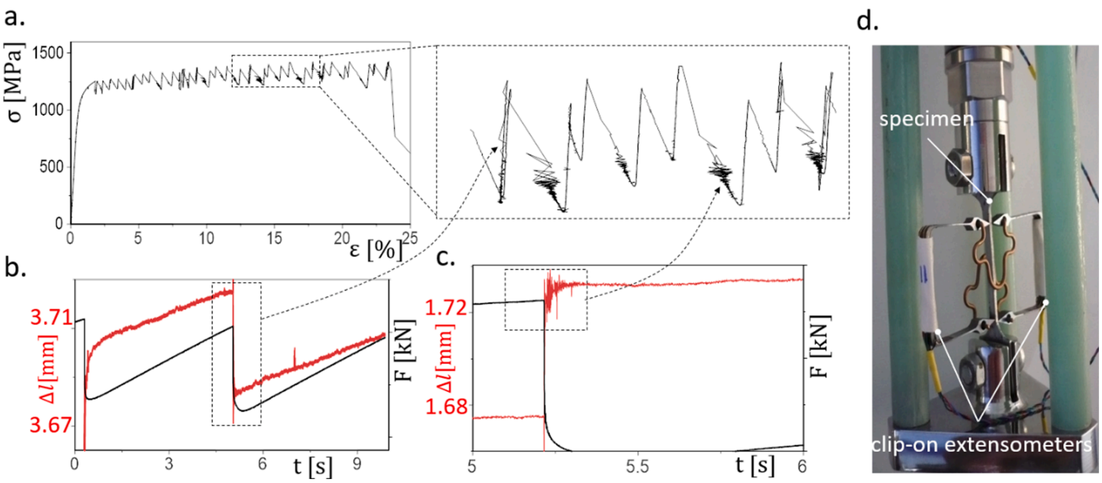

Fig. 6. a) Artefacts on stress–strain curve of JK2LB during uniaxial tensile test at 4 K; b) time response of clip-on extensometers (red) and force transducer (black) when shear band occurs out of extensometers' gauge length; c) self-excited vibrations of extensometers induced by the plastic flow instability; d) strain measurement set-up. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The raw/processed data required to reproduce these findings can be shared with interested researchers upon request.

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