Magnetoelastic effect for 316LN-IG stainless steel at low temperatures

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Background

316LN-IG stainless steel is austenitic and used widely in devices operating at liquid helium temperatures, in particular, in TF-coils of the ITER magnet system. Non-magnetic under normal conditions, it becomes magnetic under low-temperature plastic strain as a result of the γ → α martensitic transformation. As is known, appearance of magnetization is a sign of embrittlement of austenitic stainless steels, which results in development of cracks and is highly undesirable in exploiting apparatus under extreme conditions, such as nuclear reactors. This is a problem also for devices operating at liquid helium temperatures, the more that a strain at these temperatures is uneven and can result in dynamic forces.

Objectives

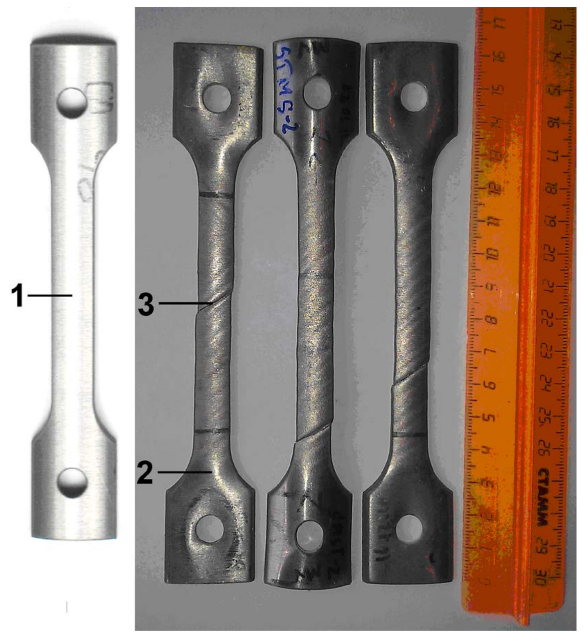
- Uniaxial tensile testing the steel 316LN-IG (0.013% C; 11.5% Ni; 16.5 Cr; 2.0% Mn) in liquid and gaseous helium below 7 K.
- Measuring time dependences of strain, strain induced magnetization and temperature of stressed samples.
- Interrelating elastic, magnetic and thermal effects arising in the steel strained at the helium temperatures.

Conclusion

- In the range of the jumping plastic strain a complicated behavior of local deformation near slip bands is observed. Regions adjacent to slip bands are unloaded and shrink at the moment of strain jump.
- In the elastic and plastic ranges the magnetoelastic effect indicating a negative longitudinal magnetostriction for the initial γ phase and the strain-induced α phase is found.
- Taking into account the magnetoelastic effect, a lack of local heating at strain jumps found in the previous work [Krivykh AV, Anashkin OP, Keilin VE, Diev DN, Poliakov AV, Shcherbakov VI. *Proc. Int. Sci.-Tech. Conf. Nanotechnologies of Functional Materials (NFM'12), St. Petersburg, Russia, 2012, pp. 235-240 (in Russian)*] can be explained by the magnetocaloric effect in regions unloaded at the jumps. Such situation is possible if energy needed for adiabatic reorientation of magnetic moments when stress drops is comparable with heat release in slip bands.

Samples

Preparation and appearance



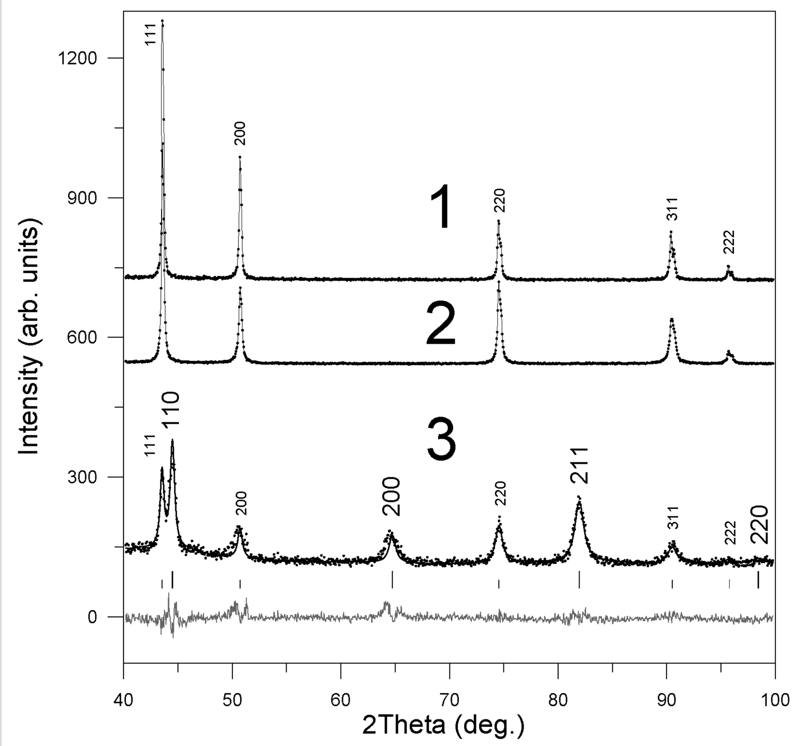
Samples were made from tubes «as received» as well as after complete simulation of the production cycle in manufacturing of conductors for ITER magnet system,

in accordance with the requirements of ASTM E8M:

- cut out from tubes along their axis by waterjet cutting,
- base length is 50 mm, total length is 140 mm, width is 12.5 mm.

Tube segments «as received» (on the left) and after tensile tests. Numerals mark regions where X-ray diffraction analysis was performed (see next Figure).

X-ray phase analysis



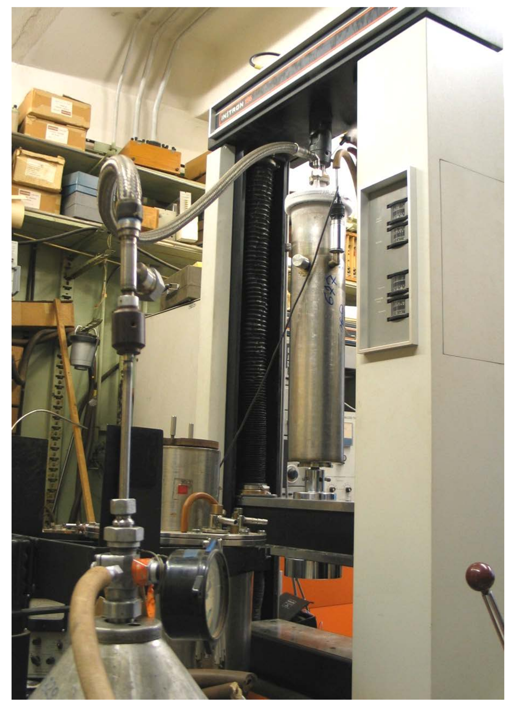
Typical X-ray diffraction patterns (T=300 K, CuK_α) for samples before (1) and after (2, 3) tensile tests below 7 K. The regions 1, 2 and 3 see in previous Figure.

In non-deformed (1) and low-deformed (2) regions only the γ phase with f.c.c. structure is present, a=3.602 Å. Numerals are indices of diffraction reflections, solid line connecting experimental points guides for the eye.

In strongly deformed regions near slip bands (3) percentage of the γ phase, a=3.60 Å, is reduced to 20%, and 80% is the α phase with b.c.c. structure, a=2.88 Å. Points correspond to experimental curve, black solid line is calculated profile, below is the difference curve (grey line); positions and indices of diffraction reflections are marked by large symbols for the α phase and small ones for the γ phase.

Methods

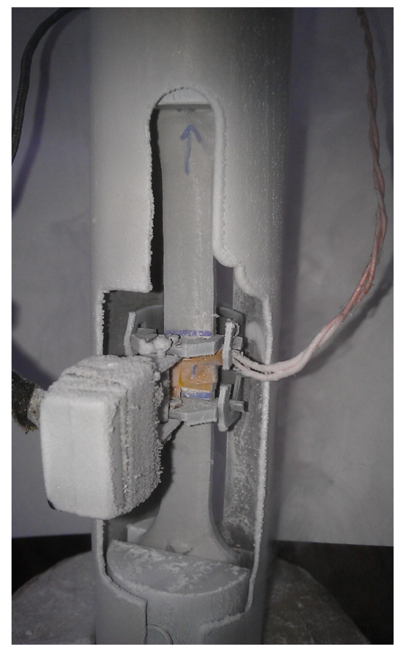
Tensile tests were performed in accordance with the requirements of ASME E1450 in liquid and gaseous helium below 7 K on the universal machine «Instron-1195»



To create low temperatures the load-carrying cryostat of submersible type with allowable force to 40 kN was used.

Mechanical rigidity of the machine with cryostat was $7.5 \cdot 10^{-2}$ μm/N, and normal strain rate was $3 \cdot 10^{-4}$ s^{-1}.

During the tests an applied stress and followed strain, temperature and strain-induced magnetization of samples tested were measured depending on time



Stress was measured by a sensor located on the machine frame.

Strain was measured by an extensometer with base of 10 mm and an accuracy of 0.2% mounted directly on a sample to locate simultaneously strain jump.

Temperature was taken on sample surface by carbon or germanium thermometer with an accuracy of 0.4%. A quick-response germanium thermometer can register fast temperature changes inaccessible to carbon one, but was limited in working range, up to 30 K.

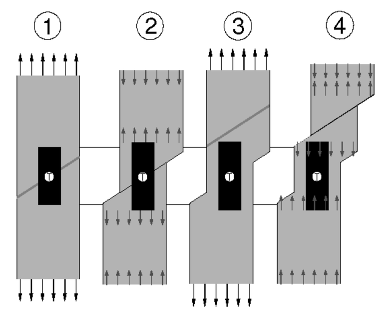
Magnetization was measured by Hall probe (2.5x2.5 mm^2) fixed on sample surface. It registered the normal component of induced magnetic field.

The X-ray phase analysis of samples was carried out at room temperature before and after their low-temperature tensile tests, on the Bruker diffractometer (CuK_α radiation) using the FullProf suite.

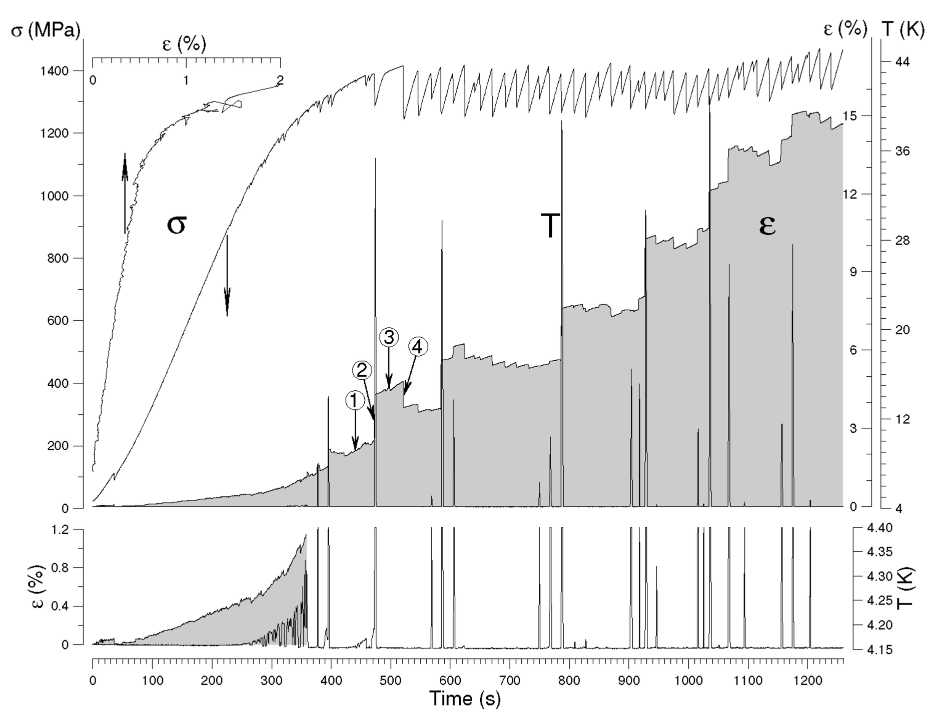
Results

Fragments of tensile stress-strain diagrams and time dependences of stress, strain and temperature

for tube segment under test in liquid helium



Schemes of deformation for the region under test corresponding to points 1, 2, 3 and 4 in the ε curve. Black rectangle is region where strain is measured, and white circle marked by T is area where temperature is measured. Arrows show stress (in schemes 1 and 3, grey lines correspond to subsequent slips) and an elastic force when stress drops as slip happens (in schemes 2 and 4).



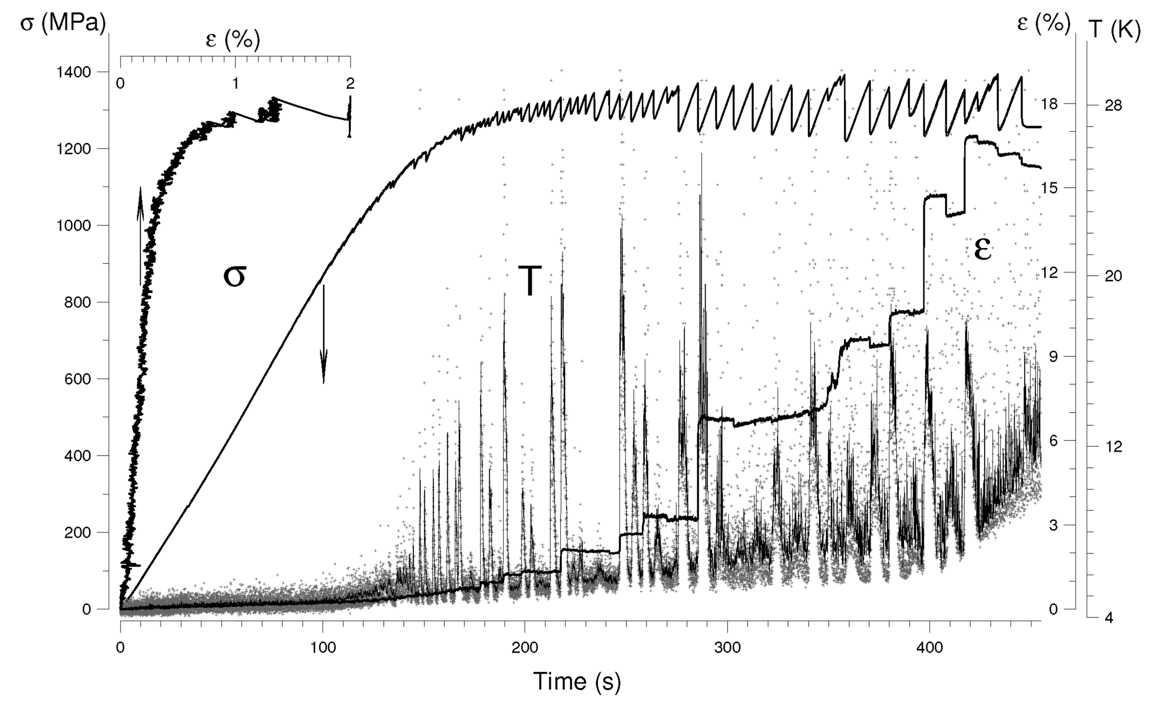
(σ) stress, arrows point to horizontal axes corresponding to curves;

(ε) unit strain for 10 mm region in the middle of the sample, below is the strain on a large scale for elastic and transitional to plastic ranges;

(T) temperature taken by carbon thermometer on sample surface in the strain region, below is temperature near 4 K on a large scale;

horizontal axis is test time with step of 0.93 s.

for tube segment under test in gaseous helium



(σ) stress, arrows point to horizontal axes corresponding to curves;

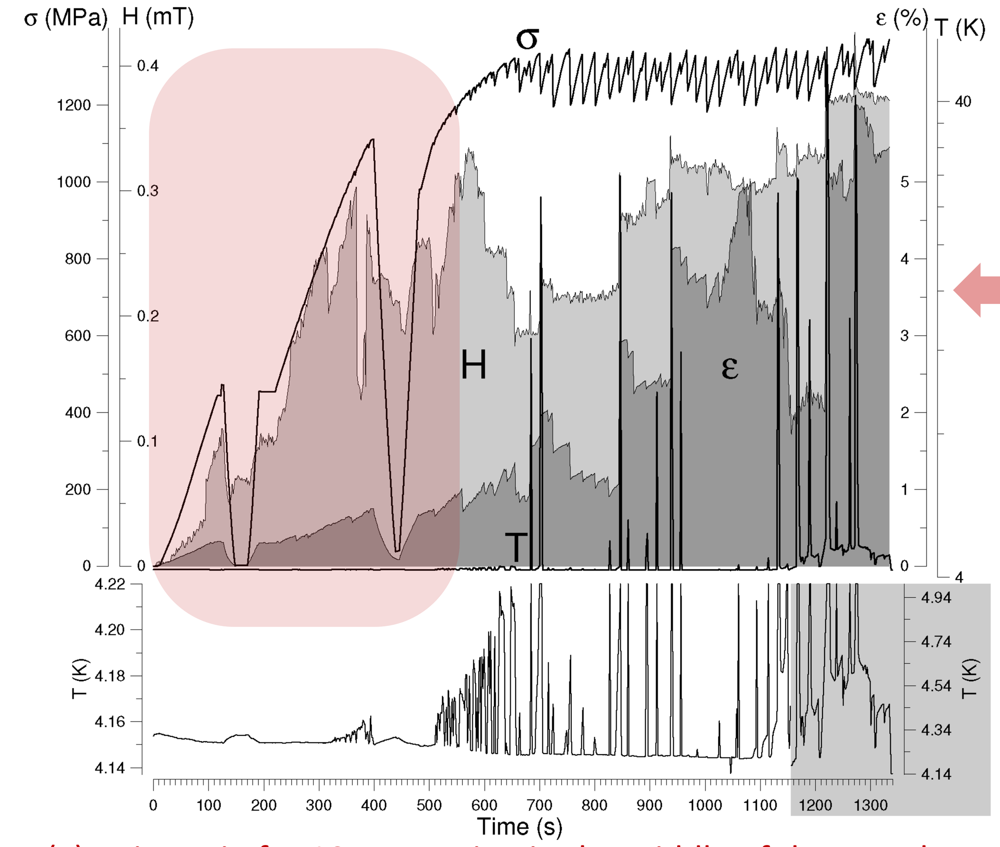
(ε) unit strain for 10 mm region in the middle of the sample;

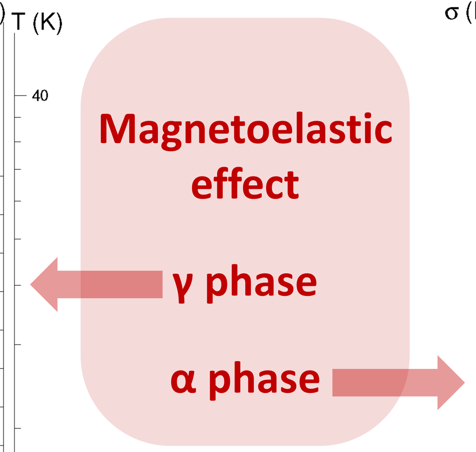
(T) temperature taken by quick-response germanium thermometer on sample surface in the strain region, points correspond to measured quantities, solid line is curve smoothed by three points, in plastic range the data are doubtful because of large heat release;

horizontal axis is test time with step of 0.02 s. Strain rate is $6 \cdot 10^{-4}$ s^{-1}.

Time dependences of stress, strain, temperature and strain induced magnetization

for tube segment under test in liquid helium





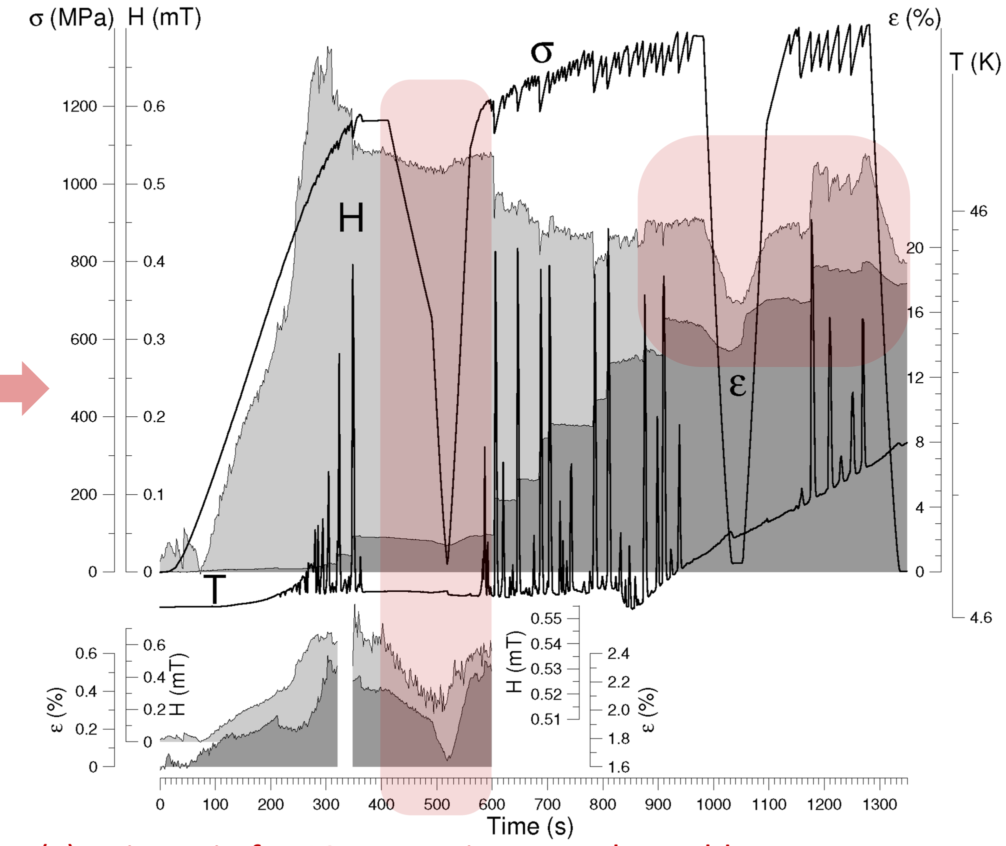
(σ) stress; (ε) unit strain for 10 mm region in the middle of the sample;

(T) temperature on sample surface in the strain region (logarithmic scale), below is the temperature near 4 K on a large scale for the test time up to 1150 s (left axis) and after 1150 s (right axis, grey field);

(H) magnetic field normal to sample surface in the strain region;

horizontal axis is test time with step of 1.74 s.

for tube segment with weld under test in gaseous helium



(σ) stress; (ε) unit strain for 10 mm region near the weld;

(T) temperature on sample surface in the strain region (logarithmic scale);

(H) magnetic field normal to sample surface in the strain region; below is the strain and the magnetic field on large scales for elastic range (left axes) and unloading region (right axes);

horizontal axis is test time with step of 1.74 s.

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