Shakedown of Structures Undergoing Plastic Strain Induced Phase Transformation

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Selected stainless steel grades are widely used in cryogenic installations, including superconducting particle accelerators cooled with liquid or superfluid helium. Grades such as 304L, 316L, and 316LN are preferred for their favourable mechanical properties and moderate cost. Despite their high ductility, these steels exhibit metastable behaviour due to a plastic strain–induced phase transformation from an fcc to bcc lattice. The primary phase (austenite) is ductile, while the secondary phase (martensite) is relatively brittle and deforms elastically. At extremely low temperatures, the phase transformation progressively replaces the ductile, energy-dissipating phase with a more elastic one, thereby promoting accelerated shakedown. Cyclic torsion tests were conducted at 77 K under torque control to investigate shakedown behaviour in metastable austenitic stainless steels 304, 304L, 316L, and 316LN (Fig. 1). The martensite content was measured on the surface of round-bar specimens during testing to monitor the progression of the phase transformation. The dissipated energy per cycle was analysed, showing that 316LN steel dissipates more energy compared to 304, 304L, and 316L, as its hysteresis loops exhibit only minor narrowing. This fact supports the hypothesis that phase transformation accelerates shakedown. Consequently, more stable steels, such as 316LN, are more resistant to shakedown.

(a) (b) (c)

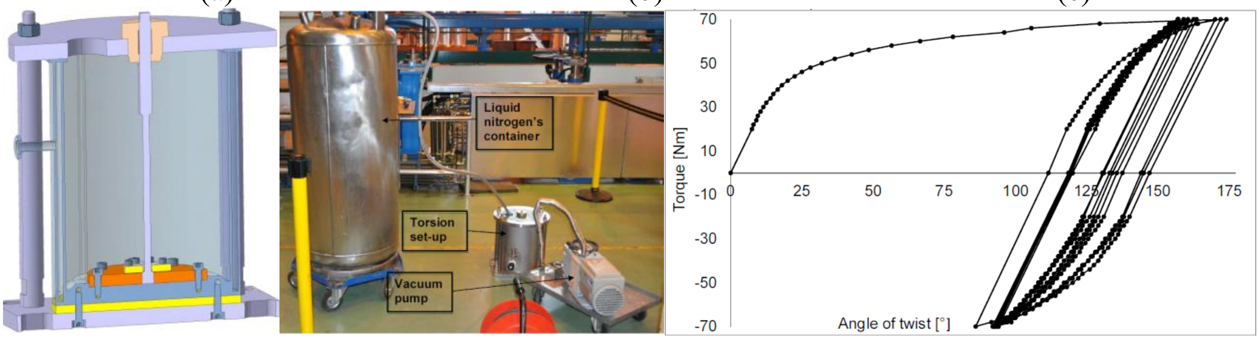

Figure 1. a) Cryostat for torsion tests (bar dimensions: 8 mm diameter, 200 mm length; elastic shear modulus G_{77K}=75 GPa); b) Experimental set-up; c) Torque vs angle of twist [1, 2]

To support the experimental findings, a physics-based multiscale constitutive model [1], [2] was developed and implemented in the AceGen/AceFEM tool. The model incorporates hardening mechanisms coupled with plastic strain induced fcc-bcc phase transformation. Cyclic torsion was simulated in 3D for various phase transformation kinetics to assess their impact on cyclic response (shakedown) and martensite content.

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