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Low cycle fatigue behaviour and anisotropy of two steels for turbogenerator coil retaining rings and rotors

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ABSTRACT. Turbogenerator rotors and coil retaining rings (CRR) are typically subjected to low cycle fatigue (LCF). The rotor contains uniformly spaced longitudinal slots, where copper conductors are packed: at the nominal speed of 3000 rpm a great centrifugal force acts on the copper conductors that must be restrained by CRRs, shrunk fitted onto the body over the coils. Thus, at each on-off transitory (10,000 – 15,000 in the whole machine life) both the rotor and the CRR are subjected to a cyclic load. Several contributions report the mechanical properties of the typically used steels for rotor and CRR manufacturing, but none deals with their characterization under LCF in strain controlled conditions, while investigations on the anisotropy were performed just on CRR steels in load controlled conditions. This research aims at determining the main parameters describing the LCF performance of two widely applied steels for rotors and CRRs, investigating also the anisotropy in the dynamic behaviour: for this purpose an extensive experimental campaign was carried out on specimens machined (in the tangential and radial directions) from prolongations of trial rotors and CRRs. An original approach was used for misalignment compensation, strain control and data recording, sensitivity analyses were finally performed on results.

KEYWORDS. Turbogenerator; Rotor; Coil Retaining Ring; Low Cycle Fatigue; Anisotropy.

INTRODUCTION

A turbogenerator rotor contains uniformly spaced slots, lodging copper conductors and insulation materials, here held in place by non magnetic metal wedges. The copper conductors emerge at the slot ends to form a coil, wound around the rotor. As the rotor spins (at the nominal speed of 3,000 rpm), the copper conductors, together with the insulation material are pushed outside due to centrifugal forces and must be restrained. Along most of the rotor length, this resistant is provided by the slot wedges, while, at the two ends coil retaining rings (CRRs) are shrunk fitted onto the rotor body over the conductor coils. Both the rotor and the CRRs are typical examples of components being subjected to low cycle fatigue (LCF). Acting loads are static in the nominal conditions, i.e. at the constant rotational speed of 3000 rpm, while a cycle is completed at any machine switch on and switch off. During the switch on transitory, the centrifugal forces are increased, as the rotational speed is increased from zero to its nominal value, meanwhile the friction stresses at the shrink-fit are reduced. An opposite effect occurs, as the machine is switched off. Recent studies showed that in the whole life of a turbogenerator (approximately 50 years) from 10,000 to 15,000 transitories may take place.

Some papers deal with the main features of materials for CRR manufacturing: they are non magnetic, with high thermal and electrical conductivity and a high coefficient of thermal expansion. From the mechanical point of view, these materials, such as 18Mn18Cr, have high static and fatigue resistances, high corrosion resistance and a great fracture toughness [1-2]. Other studies [3] regarded the mechanical properties of the steels used in rotor manufacturing, such as, 26 NiCrMoV 14 5 (ASTM A470). However, despite the typical LCF load, none of these studies applied the typical LCF models, such as the Manson-Coffin model, for design purposes or structural analysis. A possible reason is that no data are often available, concerning LCF curves and related coefficients for their analytical description. Another question to be investigated involves the behaviour of these materials along different forming directions, i.e. the anisotropy. Just few contributions [4-5] deal with experimentations on this item, but only with reference to 18Mn18Cr. Fatigue tests were conducted with specimens machined from trial components in the tangential and radial directions. However, the experiments were conducted in load controlled conditions, in stead of the usual strain controlled conditions for LCF applications.

The object of this paper is to experimentally investigate the LCF performance of two commonly used steels for rotor and CRR manufacturing, also discussing the anisotropic behaviour in two different forming directions and the sensitivity of the applied regression models.

MATERIALS AND METHODS

The experimental campaign was arranged in a two-factor (the material and the forming direction) plan (Tab. 1). Two materials, 18Mn18Cr for the CRR and 26 NiCrMoV 14 5 for the rotor, were considered: specimens were machined from trial components along the radial and tangential directions, in agreement with [4-5]. For each of the four cases a quantity of 40 specimens appeared to be adequate for LCF characterization with good percent replication (about 65%) and data reliability [6-7]. The specimens to be manufactured along the tangential direction were designed according to [8]: they have uniform gage test section and are shown in Fig. 1a. The remaining specimens (Fig. 1b), machined in the radial direction, have an hourglass shape and a shorter length, due to the reduced CRR thickness (80 mm).

		Material	
		26 NiCrMoV 14 5 (rotor)	18Mn18Cr (CRR)
Direction	tangential	40 specimens	40 specimens
	radial	40 specimens	40 specimens

Table 1: Two-factor plan of the experimental campaign.

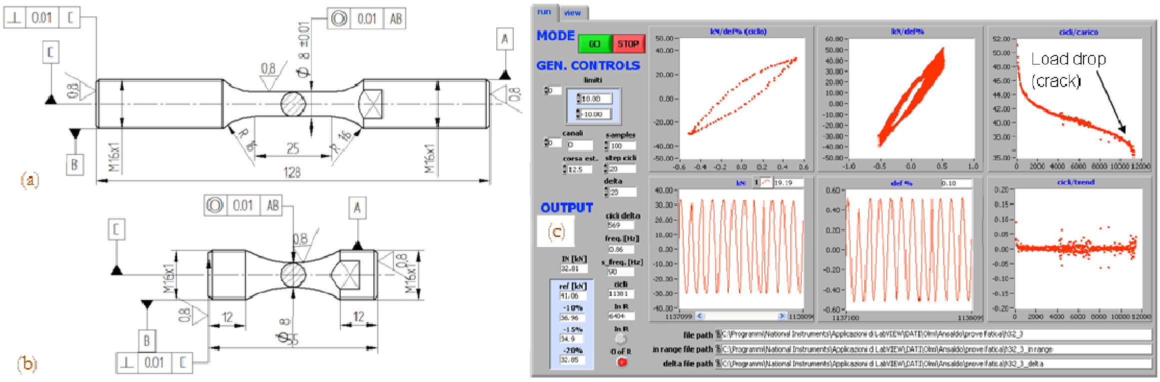

Figure 1: Specimen drawings (a, b) and Front Panel of one of the LabView programs for hysteresis cycle monitoring (c).

The specimens in the rotor material were produced according to the following procedure [9-10]: bottom poured oxygen furnace melts were vacuum-degassed (vacuum oxigen decarburization) by the lift-gas method. Afterwards, a two step forging process was applied for closing pores at the centre and a lengthy cycled heat treatment in the annealing range was used to reduce residual hydrogen. Before cutting a rotor prolongation for specimen machining, the following treatments were applied: 840°C austenitization, salt bath quench and 600°C temper [11]. The trial CRR was initially forged hot at 1100-1200°C with a following heat treatment at 1050°C ± 5°C for 8 hours and with water cooling. The forged ring was then machined, examined by non destructive tests and cold expanded (by the wedge method). Finally, before prolongation cut, a stress relief was applied at 350°C for ten hours with cooling in calm air [4,12].

The fatigue tests were preceded by static tests, in order to compare the static to the cyclic behaviours. All the tests were performed by an INSTRON 8032 testing machine, equipped with an original specimen loading-constraining device, for lateral and angular misalignment automatic compensation [13]. The static tests were performed in displacement controlled condition at the constant actuator speed of 5 μm/s, all the fatigue tests were conducted by controlling the strain at the central minimum section of each specimen. For this purpose, a longitudinal extensometer was used, and an original methodology was developed, validated and applied for the tests on hourglass specimens [14]. Specimens heads were adequately pre-compressed, in order to avoid clearance run at fatigue load inversion. The data acquisition was performed on three channels, related to the actuator displacement, to the load intensity and to the extensometer strain reading. The measuring chain was composed by the analogical output of the INSTRON machine, by an SCB-68 platform and a DAQ Card NI 6062E (National Instruments, Mopac, Expwy, Austin, TX, USA). Data acquisition monitoring and recording were performed by specifically developed LabView programs: they had an essential role in detecting hysteresis cycle stability and in the diagnosis of crack initiation, by on-line monitoring of the maximum load value of each cycle, whose abrupt drop was related to crack nucleation. Tests were conducted up to initiation or stopped after the run-out value of 50,000 cycles.

EXPERIMENTAL RESULTS AND DISCUSSION

Both the materials have very good static properties: 26 NiCrMoV 14 5 (rotor material) has a ultimate resistance of about 900 MPa and a yield strength a bit lower than 800 MPa, while 18Mn18Cr (CRR material) has both ultimate and yield strength higher than 1200 MPa. Cyclic curves were determined by interpolating the terminal points of stabilized cycles: from 20 to 30 points were involved in each interpolation to increase result reliability (Fig. 2a); cycling implies a softening effect, clearly visible in Fig. 2b. Considering the behaviour of the CRR material in the two directions (Fig. 2b), it can be observed that the static curves are very close each other, while a slight gap (5%) between the cyclic curves can be noticed at the highest strain values. No significant differences occur in the case of the rotor material.

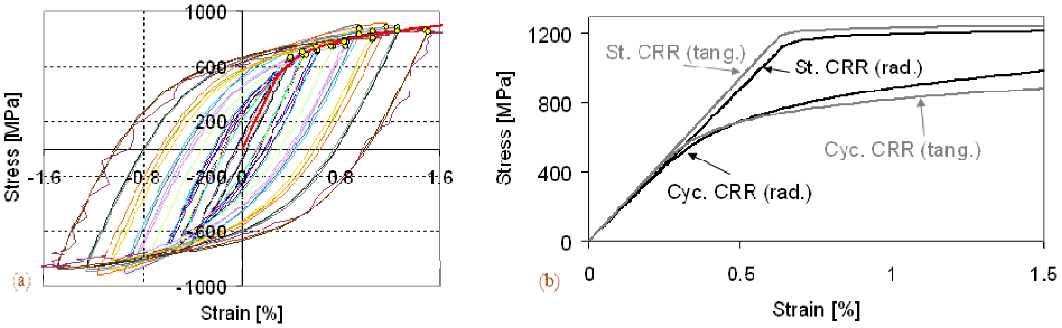

Figure 2: Experimental determination of the cyclic curve in the tangential direction (a) and CRR material static and cyclic curves (b).

The Manson-Coffin curves were then determined by decomposing the total strain amplitude ($\Delta\varepsilon/2$) at each level into its elastic ($\Delta\varepsilon_{el.}/2$) and plastic ($\Delta\varepsilon_{pl.}/2$) parts and by conducting a linear interpolation in the logarithmic scale, which led to the calculation of the nominal values of the fatigue strength and ductility coefficients and of the fatigue exponents. The study was then completed by a sensitivity analysis of the performed regressions, aimed at the determination of tolerance bands to be applied to the determined curves and related coefficients. This study was initially approached, according to the methodology proposed in [15]: the variance of the slope and of the constant term were firstly evaluated, which led to the estimation of linear tolerance bands. The regression task and the estimation of hyperbolic tolerance bands was then conducted according to [7]. By reworking the equations in [7], an original closed-form equation was made available, to apply the hyperbolic bands not only to the elastic or plastic curves only, but also to the total Manson-Coffin distribution. Fig. 3 compares the LCF curves (for the CRR material in the tangential direction) with tolerance bands, determined according to the two methodologies (at the same 95% confidence level). Some differences can be noticed with reference to the tolerance bands: while the linear ones (Fig. 3a, [15]) are sufficiently wide and able to contain all the experimental points, the hyperbolic ones (Fig. 3b, [7]) are very thin: consequently some points cannot be enclosed in the internal area. It seems to be a common problem, observable even in the example proposed in the Standard [7] itself, again referred to a LCF experimental campaign. From this point of view it seems that the linear model in agreement with [15] is more reliable than the hyperbolic one suggested in [7]. Similar results were determined in all the other investigated cases.

The last item to be considered was the anisotropy on the fatigue distribution. The comparison of the nominal curves (Fig. 4) shows the fatigue response is a bit better in the radial direction for high strain values, while the two curves are almost coincident at lower strain amplitudes in the typical life range of turbogenerator applications. The same effect (more remarkable for the rotor material) was observed for both materials.

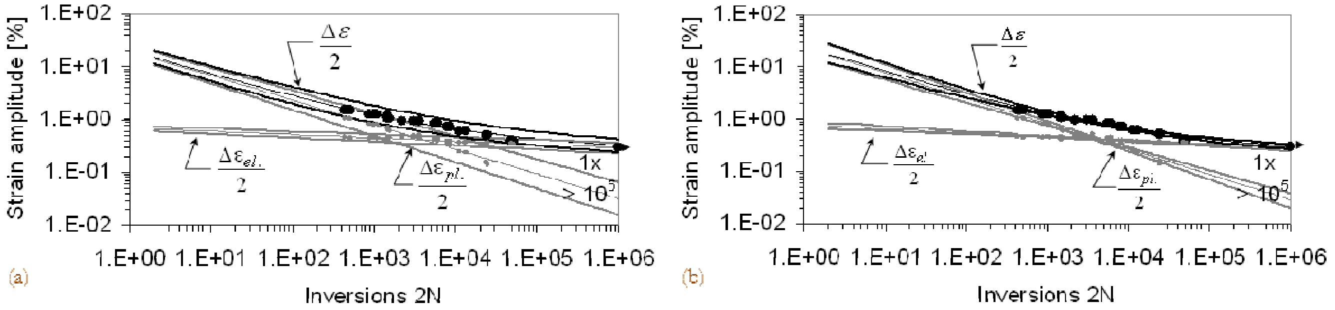

Figure 3: LCF curves for the CRR material in the tangential direction, with linear (a) and hyperbolic (b) tolerance bands.

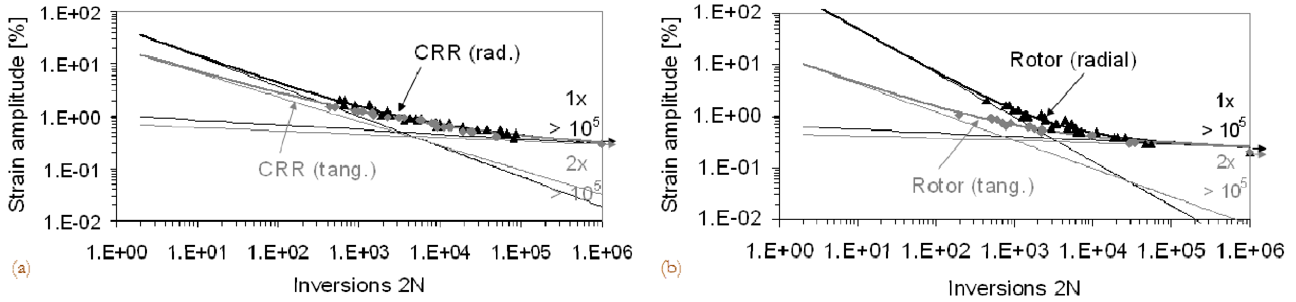

Figure 4: LCF curves for the CRR (a) and for the rotor (b) materials in the two forming directions.

FINAL REMARKS AND CONCLUSIONS

The most impressive results can be so summarized:

- ✓ An extensive experimental campaign was planned, according to a two-factor (material and forming direction) table. Static, cyclic and fatigue curves and related coefficients were determined for all the investigated cases.
- ✓ Sensitivity analyses were conducted on the regressions for LCF curves. Two different models, leading to linear [15] and hyperbolic bands [7] were applied and completed with the proposal of an original equation. The linear model appeared to be more reliable and conservative for the best fitting to the experimental results.
- ✓ Non significant anisotropy effects were observed. Slight differences were noticed between the fatigue curves, but only at very high strain values, while the curves are almost coincident in the typical life range for turbogenerator applications.

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