Investigation of multiaxial fatigue in the prospect of turbine disc applications: Part I – Experimental setups and results

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ABSTRACT. *An experimental study is presented for two alloys commonly used for compressor and turbine discs in the context of fatigue crack initiation. It includes classical uniaxial tests together with multiaxial ones, both in tension-compression torsion, in tension-internal pressure and in biaxial loads applied on a specially designed cruciform specimen. The experimental devices including heating system are presented. The specimens design and the associated specific testing procedures are also described. Some results with crack observations are discussed here within a thermo-elastic approach. Nevertheless multiaxial fatigue criteria based on results of cylic viscoplastic calculations are analyzed in Part II.*

INTRODUCTION

Fatigue is recognized to be the main cause of mechanical failures. Complex geometrical structures are often involved and complex multiaxial loadings are occurring. Rotating parts in turboengines, like turbine or compressor discs, that are subjected to severe and complex cyclic loads, are typical examples. They involve the interaction of Low Cycle Fatigue (ground-to-ground cycles) and High Cycle Fatigue (vibratory) in regions with high biaxialities and high mean-stresses. With the objective to assess current design methodologies for turboengine discs, an important research program involved four main partners: Snecma, Turbomeca, Onera and CEAT. A significant experimental part of this study has been conducted on a titanium alloy (TA6V) and nickel-based alloy (INCO718DA), at respectively 200°C and 550°C. In addition to standard LCF fatigue test under strain control with various strain ratio, and HCF tests under stress control, the experimental program includes a significant number of complex multiaxial tests that we discussed in this paper focusing of fatigue crack initiation problems under multiaxial considerations. Typical examples of multiaxial fatigue facilities are evoked in [1].

EXPERIMENTAL DEVICES FOR A STUDY OF MULTIAXIALITY EFFECTS

An extensive test program has been conducted on the facilities of multiaxial fatigue from ONERA and CEAT with two kinds of geometries: tubular specimens and cross-like specimens. Table 1 gathers the different testing facilities of both partners and their mechanical and thermal possibilities. Figure 1 shows the stress domain explored by experimental devices. We can observe the good complementarity of tests that allow us to investigate a large domain, almost complete except near the bi-compression region, but this loading is not encountered on industrial parts involved.

Multiaxial testing devices		Mechanical Parameters			Thermal Parameters		Present ivestigation	
Partner	Kind of loading	loading range (per axis)		Freq. max.	Kind of heating system	Temp. max	Temp.	material
ONERA	*Tension-Tension*	±200 kN	±200 kN	*Induction with concentrator*	*Induction with concentrator*	600°C	200°C	TA6V
	Tension-Torsion	±63 kN	±500 N.m	*Induction*	*Induction*	1200°C	550°C	INCO718
	Tension-Internal pressure	±63 kN	80/1500 bars	*Induction*	*Induction*	1200°C	550°C	INCO718
CEAT	*Tension-Torsion*	±250 kN	±2000 N.m	*Induction and Joule effect (or furnace)*	*Induction and Joule effect (or furnace)*	1200°C	550°C	INCO718
	Tension-Internal pressure	±250 kN	300/1200 bars	*Induction and Joule effect (or furnace)*	*Induction and Joule effect (or furnace)*	600°C	200°C 55°C	TA6V INCO718

Table I: Multiaxial fatigue testing devices.

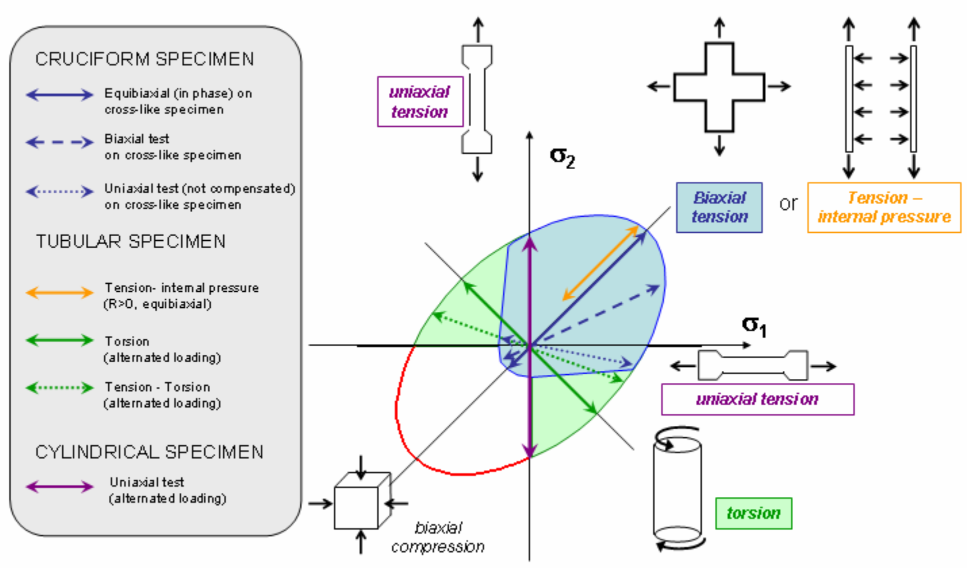


Figure 1: Possible stress domain and corresponding experiments.

TUBULAR SPECIMENS

Tension-torsion tests

The axial/torsional tests allow combining tension-compression and shear stresses. Axial-torsional tests are used relatively extensively for multiaxial fatigue problems, particularly for reasons of simplicity of implementation. The tests were performed on tubular specimens conventionally employed in the laboratory with a thickness of 1 mm. This puts us in Volume Element configuration so that shear stresses are relatively uniform in the wall. In addition, FEM simulations have shown that the rules of "Strength of Materials" analysis gave results very realistic in this thin-walled geometry. Tests are performed at 2Hz under force and torque control. To better understand the effects of multiaxiality, samples were tested in various configurations: traction, torsion and combined tension-torsion (in-phase and out-of-phase).

Tension-internal pressure tests

Internal pressure tests [2] allow us to apply positive stress. One can precise that external pressure is required for alternated loading. The biaxial present devices were developed specially for high temperature tests.

Specimen design

The specimen geometry is highly similar to the previous one except two points:

- Flat zones located at specimen heads for the torque application were removed, which aims to facilitate tightness seal through a bigger contact area in the case of application of internal pressure.
- Outer radius of the cylindrical part has been reduced in order to obtain a thickness of 0.8mm. This significance of this diameter decreasing is to obtain a stress field of interest regarding the lifetime range considered, especially for INCO718.

One difficulty, specific to internal pressure tests, is the problem known as bulging, corresponding to an outward bend produced by pressure. Figure 2 shows a simulated example of such phenomenon where we observe a significative curvature in the cylindrical area. This instability has been studied qualitatively by F.E. simulations in large strain formalism. The bulging is linked to the non-linear behavior and could occur in two ways: either because of monotonic loading with a very significant plasticity in the center of the specimen, either because of mechanical cycling. In this instance, it appears that plastic strain is more localized near the top fillet, where stress concentration takes place. Cycling induces significant cumulative plasticity, that leads to the geometrical instability called bulge. Thus, it was shown that the specimen was correctly designed for monotonic loading. For cyclic loading, the chosen solution was to create deliberately a slight longitudinal temperature gradient near the fillet, limiting plasticity and so resulting bulging, which has been validated experimentally.

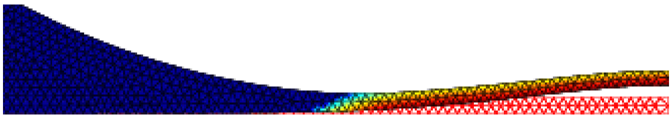


Figure 2: Isovalues of cumulated plastic strain at 5000 cycles (1100bars-90bars). Distorted geometry with an amplification factor (2) on displacements.

Testing methodology

The gas used for the pressure is argon in order to reduce oxidation inside the tube, favouring thereby the crack initiation at the exterior radius where the surface roughness is closer to those encountered in the industrial pieces. One can precise that only lapping is done for the machining inside the tube. A particularity of internal pressure test consists in control method. The objective is to obtain in the case of a single pressure, a uniaxial stress state ($\sigma_{\theta\theta}$). Nevertheless, the application of pressure inside is a problem of closed tube (cap-end effects), i.e. the pressure is also applied at the axial load cell. Therefore to overcome this effect in order to obtain purely uniaxial stress on outer surface, it is necessary to compensate precisely the force induced by the pressure. The test analysis could be performed by the rules of « Strength of Materials ». In the thin-walled approximation (thickness <<radius), one can show that the stress is given by:

$$\sigma_{\theta\theta} = \frac{PR}{e} \qquad (1)$$

where P, R and e represents respectively the pressure, the radius and the thickness. Once again, F.E. analysis allows us to obtain similar result with the previous equation.

Some results of multiaxial tests on tubular specimen

Figure 3 presents obtained results on INCO718DA at 550°C using the equivalent stress amplitude criterion defined as:

$$\sigma_{a_{eq}} = \frac{1}{2}\max_t\left(\max_{t_0}\left(\sqrt{\frac{3}{2}\left(\sigma'(t)-\sigma'(t_0)\right):\left(\sigma(t)-\sigma(t_0)\right)}\right)\right) \qquad (2)$$

Obviously this kind of representation shows clearly the effect of loading ratio. Several points are noteworthy:

- There is a good consistency in all axial and/or torsional (in-phase combination) with a criterion based on the equivalent stress amplitude.
- Out-of-phase axial-torsional tests give lifetimes significantly lower than in the in-phase configuration.
- There is a significant difference between tension and internal pressure tests (corresponding to a circumferential tension). This could be presupposing an effect of anisotropy. A possible way to explain this is the fibre of the material through the orientation of carbide clusters [3].

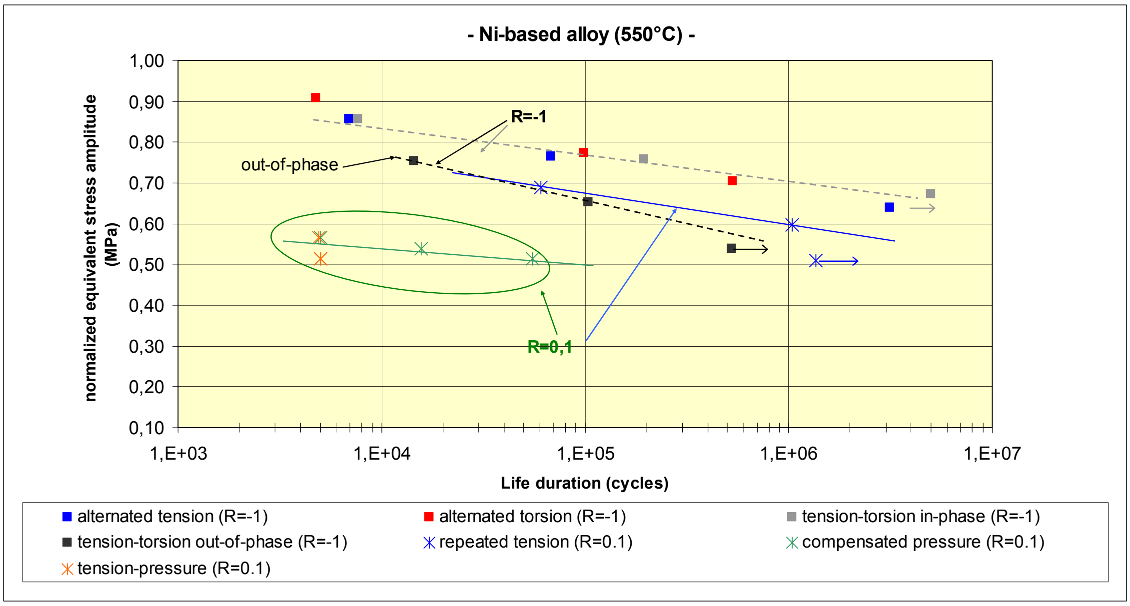


Figure 3: Curve of equivalent stress amplitude based on the life duration

For example, figure 4 shows a typical view of a broken specimen under equibiaxial loading. The observed cracks are always longitudinal when an internal pressure is applied.

Figure 4: Specimen broken in tension-internal pressure equibiaxial regime (CEAT, TA6V)

CRUCIFORM SPECIMENS

The biaxial fatigue tests on cross-like specimens were performed on an experimental device specially designed and manufactured at Onera, with a capacity of 200kN per axis [4-6]. The heating system is a single-coil inductor using a concentrator in the center.

Specimen design

For cruciform specimen, design is an essential step of the experimental part [7]. The aim was to have a central area not flat but thinner in the middle to favour crack initiation in the middle. The principal difficulty is to avoid crack close to the attachment zones that represent stress concentrations. Therefore the specimen has been designed by optimization with an equibiaxial loading under elastic hypothesis and verified in cyclic viscoplasticity. Two optimization criteria were used: to maximize the stress in the middle of the specimen and to minimize the gap (> 10%) between this stress and those obtained close to the fillet. The geometry has been made entirely variable with the choice of 7 parameters shown in red in Figure 5a.

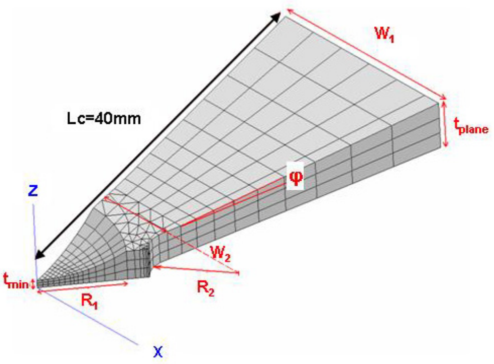
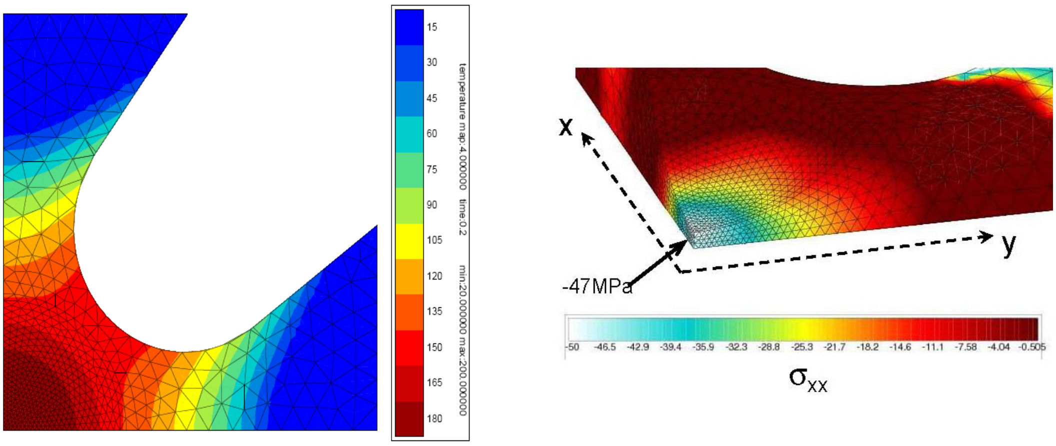


Figure 5a: Parameters optimization of the cross-like specimen

Figure 5b: Specimen mounted on the biaxial device

Testing methodology

Special attention was carried out to evaluate stresses in the gage area from the external loading. Fatigue testing on cruciform specimen has two characteristics: a thermal effect due to our heating system and an effect that we called “ring effect”. The first one is located in the middle of the specimen. This generates thermal stresses that it is necessary to estimate. To do that, a temperature calibration was carried out to construct the temperature map. It is then injected into a Finite Element calculation in order to assess the compressive stresses caused by the local heat and the external more massive ring, with a lower temperature. Taking into account the local thermal gradients with our geometry generates compressive stress of -47MPa (Figure 6).



a. Temperature (°C)

b. Compressive stresses thermally induced (MPa)

Figure 6: Influence of the thermal gradient on cruciform specimen.

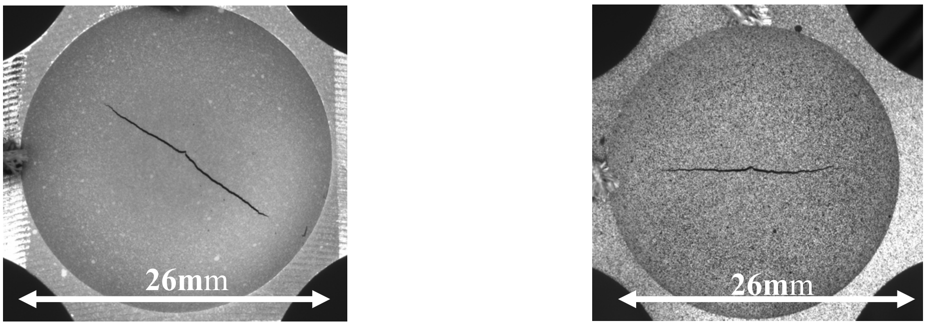
The second effect, referred to the "ring effect" takes place even at room temperature. It is interpreted as a structural version of Poisson’s effect. For this type of geometry, Poisson’s effect makes the coupling between the two perpendicular forces when evaluating the local central stresses, as:

$$\begin{cases} \sigma_1 = aF_1 - bF_2 \\ \sigma_2 = -bF_1 + aF_2 \end{cases} \tag{3}$$

Finally these two effects must be taken into account in a preliminary procedure for the determination of the overall forces to be applied. It consists first to identify precisely the thermal stresses, which affects the local stress ratio, then to correctly identify the mechanical compensation required between each axis. In addition, for an out-of phase configuration, we can show that the phase difference in force is not equal to the phase difference locally in terms of stress. In our case, under elastic considerations, we had to impose 56.65° on force axes to obtain locally an out-of-phase equibiaxial test (90°).

Results and remarks

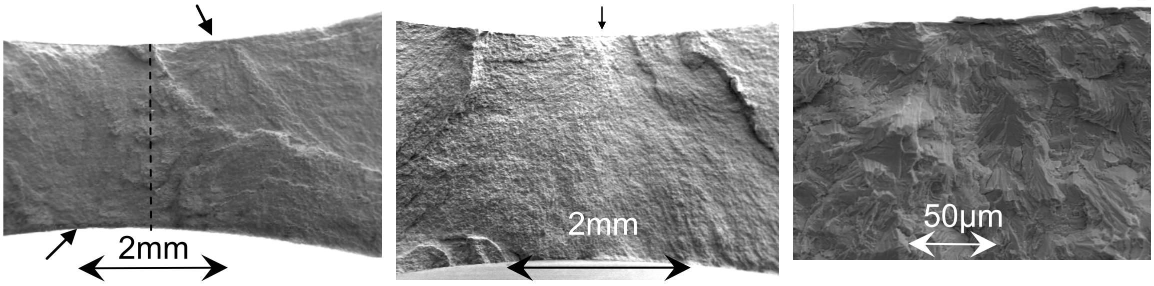
All tested specimens are subjected to fractographic investigation by light microscope (figure 7) and SEM. Images shown in figure 8 are characteristic of post-mortem observations obtained by SEM, that all the cracks appear at the free surface. Their location exhibits a classification: the crack initiates in the middle of the specimen for equibiaxial loading (in or out-of-phase) while we can observe a slight offset in the case of local uniaxial loading or with a low biaxiality ratio. Figure 9 collects the results in terms of lifetime for various configurations. We may mention here that these results are from the thermo- elastic analysis. Obviously, this required geometry could not be considered as a Volume Element. In particular, we can expect a localization of plastic deformation near the free surface. It is therefore essential for a detailed analysis of life duration to use full cyclic inelastic F.E. analysis. For compact cruciform specimens, it allows us to obtain the local multiaxial cyclic stress-strain responses and their stabilized mean-stress level in critical regions, as explained in Part II.



a. Equibiaxial test (F1=F2)

b. Compensated unixial test (F1/F2=2.197)

Figure 7: Typical examples of observed cracks on Titanium alloy.



Uniaxial compensated

Equibiaxial (in phase)

Quasicleavage facies (uniaxial compensated)

Figure 8: Location of crack initiations on cruciform specimen and facies example.

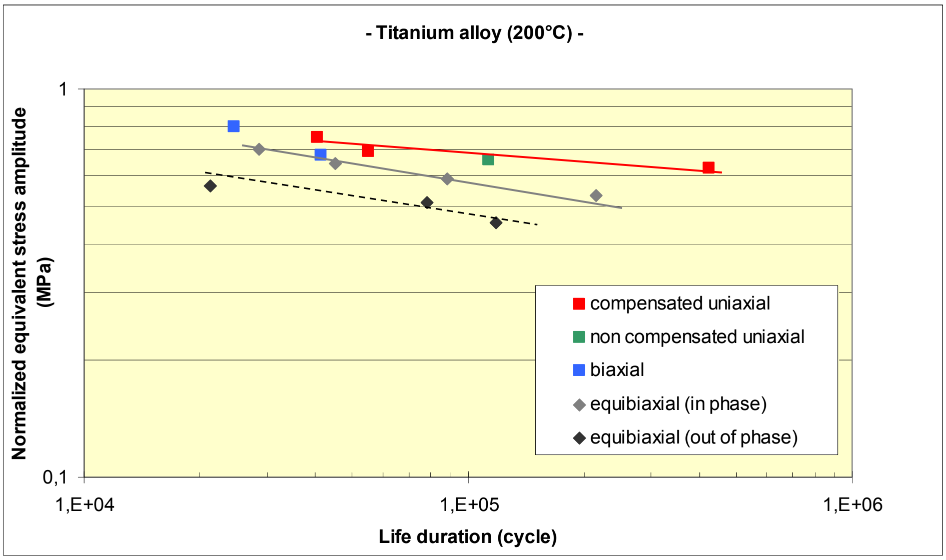


Figure 9: Amplitude curve of equivalent stress based on the life (TA6V on cruciform specimen at 200 ° C)

CONCLUSION AND OUTLOOK

Various multiaxial fatigue test facilities have been presented here, involving the characterization and the identification of multiaxiality effects for fatigue crack initiation in the prospect of turbine disc applications. Associated experimental procedures are also described, taking into account thermal effects. All these multiaxial test conditions have been evaluated by strength of materials rules and thermo-elastic Finite Element analysis. Obviously the full cyclic inelastic Finite Element analysis was also performed for the obtained database. It is presented in the next paper subtitled "PART II: Fatigue criteria analysis and formulation of a new combined one". This kind of complex testing due to the multiaxiality is essential if one seeks to be predictive in conditions close to those for motorists, where uniaxial loading very often studied in the laboratory is far from the stresses encountered on industrial parts.

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