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Ductile fracture of an ultra-high strength steel under low to moderate stress triaxiality

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ABSTRACT

Aeronautical structures such as landing gears, wheels or turbine shaft are designed to withstand predefined loadings corresponding to critical scenarios. This work addresses the definition of a ductile failure initiation criterion under multiaxial loading for ML340©™ ultra high strength steel employed in such structures. The experimental testing campaign includes tension–torsion tests under proportional loading, standard tensile tests, tensile tests on notched round and flat specimens and plane strain tests. The experimental database covers a stress triaxiality range from 0 to 1.3 and various positive Lode parameter stress states. A von Mises quadratic yield criterion with a combined Voce/linear hardening function is employed to describe plastic behavior. The hardening function is identified using an inverse method to fit cross section reduction in order to take into account large strains. A simple non-linear damage cumulation rule based on Rice and Tracey/Johnson Cook formulation with a Lode-dependent term is proposed. Good agreement was found between predicted and observed failure initiation load steps and failure locations.

1. Introduction

Aeronautical structures such as landing gears, wheels or turbine shaft are designed to withstand predefined loadings corresponding to critical scenarios. Under such severe conditions, failure can occur either by buckling, which corresponds to a geometrical instability, or by ductile failure, corresponding to material failure due to the development of damage. This work addresses the second failure mode. Parts often having complex geometries are subjected to high stresses under multiaxial loading combining tension and shear. Conventional aeronautical limit load design methods are critical stress approaches based on analytical models dealing with failure of simple structures [1,2]. Those methods are known to be robust but lead to very conservative safety margins. Fast growing developments in aeronautical field is challenging the relevance of such safety margins. To overcome the obvious limitations of analytical models, finite element (FE) simulations of entire structures can nowadays be used to determine local stresses and strains. When analyzing critical scenarios, it becomes necessary to account for the development of plasticity. Failure can then be assessed using macroscopic models describing the development of damage up to failure. In addition a wide range of failure scenarios can be investigated at a relatively low cost. Although still facing difficulties (reliability, robustness, identification, etc.), these methods appear as attractive for advance design strategies and were evaluated during two round robins organized by the Sandia National Laboratories [3,4].

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Nomenclature

a, b, c, d material parameters for the damage function
D, D^{max} damage, maximum value of damage over a given specimen
d_i, d_o inner and outer diameters of the tension–torsion specimens
e, h thickness and height of the central part of tension–torsion specimens
F force
$L_0, \Delta L$ initial gage length, elongation
L Lode parameter
M torque
p, p_F cumulated plastic strain, cumulated plastic strain at failure
$\dot{p}_1 \geqslant \dot{p}_2 \geqslant \dot{p}_3$ eigenvalues of the plastic strain rate tensor
R flow stress
$R_0, Q_1, b_1, Q_2, b_2, H$ material parameters describing the flow stress
$s_1 \geqslant s_2 \geqslant s_3$ eigenvalues of the stress deviator
S_0 initial cross section
t time
T stress triaxiality
W damage function
κ tensile to shear stress ratio
$\phi_0, \Delta\phi$ initial diameter, diameter variation
ρ_0 initial notch radius
σ_{eq}, σ_{kk} von Mises stress, trace of the stress tensor
θ, θ_F rotation angle, rotation angle at failure

Table 1
Chemical composition of ML340 steel provided by the steel manufacturer and quantified by electron microprobe analysis. Measured carbon content could not be measured using this technique.

	C	Ni	Cr	Mo	Al	Co	V bal.
Nominal	0.23	13.0	3.30	1.50	1.50	5.80	0.25
Measured	–	12.77	3.33	1.56	1.40	5.96	0.26

Aeronautical structures mentioned above are subjected to loading conditions corresponding to low to moderate stress triaxiality with combined tension/shear loading. Under these stress conditions, ductile failure models only using stress triaxiality as the driving force for damage growth [5–7] have been reported not to be able to represent failure. In particular it was shown that stress states leading to shear or plane strain deformation result in lower ductilities than stress states corresponding to axisymmetric deformation states. To account for this effect, models incorporating the Lode angle [8] of the stress tensor have been proposed in the literature [9–13].

In this study, plastic and failure behavior of an ultra high-strength steel used to manufacture turbine shafts is investigated (Section 2). Test specimens were selected so as to be representative of loading conditions. They therefore consist in axisymmetric smooth and notched bars, flat notched bars, plane strain specimens and tension–torsion specimens tested for various tensile stress to shear stress ratios (Section 3). The elastoplastic behavior of the material is identified using an inverse method by comparing simulated and experimental load—elongation curves up to necking and non contact measurements of the diameter variation in the necking area (Section 4). A fracture initiation model (Section 5) is finally developed to represent failure for the entire database by post-processing elastoplastic finite element simulations. The model describes the combined effects of stress triaxiality and Lode parameter on rupture. It is validated against macroscopic failure and fracture initiation points identified by fractographic examination.

2. Material

The investigated material is a ML340©™[1] ultra-high strength highly alloyed steel develop by Safran Aicraft Engines and Aubert & Duval [14] to manufacture aircraft turbine shafts. Nominal and measured compositions are given in Table 1. Raw material is poured as a rod using vacuum induced melting followed by double vacuum arc remelting. The material is then solution heat treated above 900 °C and directly air-quenched in order to transform the high temperature austenitic structure into a martensitic structure. An additional extended quench is performed bellow 0 °C in order to transform remaining residual austen-

[1] (©Safran and Aubert&Duval, ™Aubert&Duval).

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