BIAXIAL FATIGUE FRACTURES OF CASE-HARDENED AND HIGH-TEMPERATURE COATINGS-PROTECTED SPECIMENS

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Abstract

In the contribution, the effect of various surface treatments on appearance of fracture surfaces and micromechanisms involved in the fracture process under bending, torsion and combined bending-torsion fatigue loading is discussed based on microscopical and 3D topographical observations and measurements. The studied materials include nitrided steel specimens featuring an inner fish-eye type of fracture and nickel-base superalloy specimens with protective diffusion and thermal barrier high-temperature coatings, for which the room-temperature failures approximate those following the shutdown of the engine.

Keywords: Biaxial fatigue; bending; torsion; case-hardening; nitriding; high-temperature coatings; diffusion coatings; thermal barrier coatings; fractography.

INTRODUCTION

Combined tension-torsion or bending-torsion loading is frequently employed to simulate operational conditions of rotational structural parts that often fail under such loading regimes because of functional requirements, possible axial misalignments and thermal expansion or contraction. In order to assess fatigue performance, one needs to estimate the relative importance of axial and torsional components which depends on microstructure and on component design. If such a component is made with a case-hardened surface layer produced, for instance, via shot-peening, induction hardening, carburization or nitriding, or if it is prepared with a protective coating, its failure could be a quite complex event due to gradients/interfaces in material properties.

As the fracture surface represents a failure process gauge, fractography became a vital tool in designing new materials as well as for post-mortem analyses of in-service failures. Despite a great progress achieved so far, starting from an early observation of fractures in ancient tools and weapons [1], down to modern approaches such as 3D surface measurements [2] or studies of surface textures at mesoscale [3], there still seems to be very limited information on combined axial-torsional fatigue fractures in general and, in particular, axial-torsional fractures of gradient/layered materials. In this paper, appearance of fatigue fracture surfaces and micromechanisms involved in the fracture process of case-hardened and high-temperature-coatings-protected specimens are discussed based on microscopical observations and 3D topographical measurements of such fractures.

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EXPERIMENTAL

Biaxial bending-torsion fatigue experiments

All experiments were conducted on smooth cylindrical specimens by means of the biaxial fatigue testing stand MZGS-200 constructed at the Opole University of Technology, Opole, Poland [4]. Symmetric bending, symmetric torsion and their synchronous in-phase combinations were applied with the frequency $f \approx$ 30Hz at room temperature until macroscopic failure of a specimen. The external nominal stresses were highest at the free surface and linearly decreased towards the centre for all loading regimes. Bending stresses were highest at the two opposite sides of a specimen. Torsion, on the other hand, imposed equal stresses along any set of points equally distant from the centre.

Studied materials

Case-hardened specimens

As an example of case-hardening, results obtained on nitrided specimens are reported here. The substrate material was a high-strength low-alloy Cr-Al-Mo nitriding steel. Specimens were annealed (920 °C, 25 min, air), quenched (930 °C, 25 min, oil) and tempered (650 °C, 25 min, air) prior to nitriding (cleaning: 510 °C, 30 min; nitriding: 515 °C, 8 h), which resulted in the formation of the nitride (microstructurally distinguishable) layer of thickness of about 0.2 mm. High residual compressive stresses that were present near the surface (approximately -800 MPa in maximum) gradually decreased, reached a zero value at the depth of ~ 0.7 mm and were followed by small balancing tensile stresses.

High-temperature coatings-protected specimens

High-temperature protective coatings included: 1) aluminide and Cr-modified aluminide diffusion coatings (DCs) and 2) plasma-sprayed thermal barrier coatings (TBCs). In both cases, the substrate material was cast Inconel 713LC nickel-based superalloy with the average grain size of about 2.3 mm (DCs) and 1 mm (TBCs). Diffusion coatings of the thickness of about 80 μm were deposited by the out-of-pack method (1050 °C, 5 h) followed by annealing (950 °C, 5 h), which resulted in the two distinct sublayers with a more or less gradual interface between them and a sharp interface between the inner diffusion zone and the substrate. Thermal barriers consisted of a metallic CoNiCrAlY bond coat and a ceramic yttria partially stabilized zirconia (YSZ) top coat of the thicknesses of 0.21 mm and 0.18 mm respectively. Although both of these coatings are designed to provide protection against high-temperature oxidation and hot corrosion, the failure frequently occurs via thermal or thermo-mechanical fatigue at the end of the heating-holding-cooling cycle, following the shutdown of the engine.

Fractography

Upon failure (i.e. the fracture of the specimen after N_f loading cycles), fracture surfaces were examined by optical and scanning electron microscope (SEM). In some cases 3D topographical data of selected surface regions were extracted either by means of SEM-stereophotogrammetry (e.g. [2]) or via optical profilometry.

RESULTS AND DISCUSSION

Nitrided specimens

All nitrided specimens were fatigued in the high cycle fatigue domain (N_f of 2.0×10^5 to 6.1×10^6 cycles) and failed by an internal "fish-eye" type of fracture. The initiation occurred at a non-metallic inclusions located in the core material at the depths of 0.4-1.0 mm. This was due to the fact that, for this fatigue region, the applied stresses were too low to damage the nitride layer and because of high compressive residual stresses in the diffusion zone [5]. The failure comprises (Fig.1): 1) decohesion of the inclusion-matrix interface which, most likely, constitutes a major part of the total life [6], 2) internal nearly semi-elliptical fish-eye crack growth, 3) breakage through the nitride layer, 4) fast atmosphere-assisted crack growth, and 5) final fracture. Regardless of the loading mode, a general tendency of fish-eye cracks was to grow in an opening mode I. This is evidenced by changing of the orientation of the fish-eye plane from being perpendicular to the specimen's axis for bending to being inclined in the radial direction by ~ 45º for torsion, and also by observed striations. An example of the fish eye-crack in the specimen subjected to combined bending-torsion loading is shown in Fig.1. In this case, inclination angles in radial and tangential directions were approximately 6º and 29º respectively. The crack initiated in the depth of 0.68 mm at an inclusion with the effective diameter of ~ 20 μm.

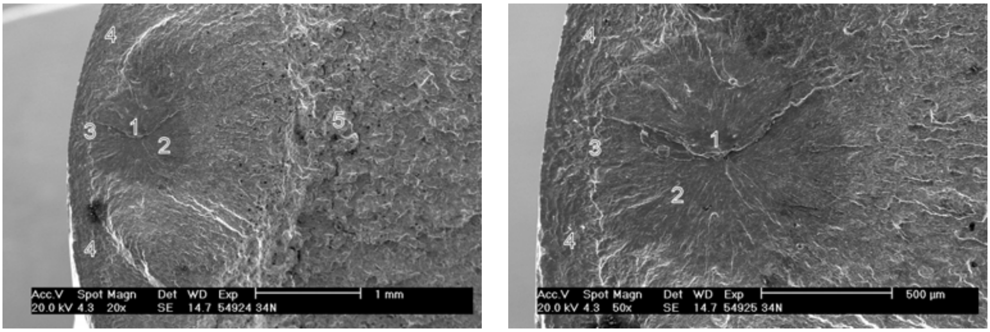

Fig.1. Fish-eye type failure in nitrided steel specimen subjected to combined bending-torsion loading (σ_a = 510 MPa, τ_a = 510 MPa, $N_f = 2.0\times10^5$ cycles).

Diffusion coatings

In this case, the cracks initiated either at the free surface, or both at the surface and at secondary-phase particles within the upper part of the diffusion zone, if there were sufficiently high normal stresses at the particle/matrix interface. This resulted in the fatigue performance being sensitive to the loading mode and the applied stress level (uncoated specimens outperformed the coated ones in the low cycle fatigue region when subjected to bending and combined bending-torsion loading) [7,8]. In the latter case, cracks initiated on secondary-phase particles gradually interconnected and propagated towards the free surface as well as into the specimen bulk until reaching the substrate material. At this point, a change to the crystallographic crack growth was observed along dendrites of Inconel 713LC alloy, Fig.2.

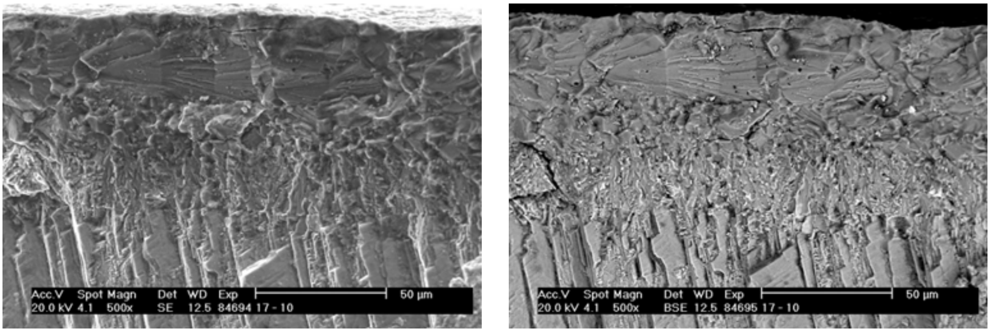

Fig.2. Detail of an initiation site within aluminide diffusion coating in Inconel 713LC specimen subjected to combined bending-torsion loading (σ_a = 289 MPa, τ_a = 233 MPa, N_f = 6.0×10^4 cycles).

Thermal barrier coatings

In thermal barrier coatings, cracks likely always initiated on the pre-existing defects within the ceramic top coat at or very near the surface. Torsion loading component was found to promote growth of surface cracks inclined with respect to the specimen longitudinal axis (by ~ 45º in the case of pure torsion) resulting in an extensive coating delamination (Fig.3) making it quite difficult to find an intact section of coating still attached to the substrate at the level of the fracture plane. The TBC/substrate interface was the weakest part of the system also under the pure bending mode, even when the thermally grown oxides (mostly alumina) scale of the thickness of about 5 μm was introduced at this interface via prolonged high-temperature exposures [9].

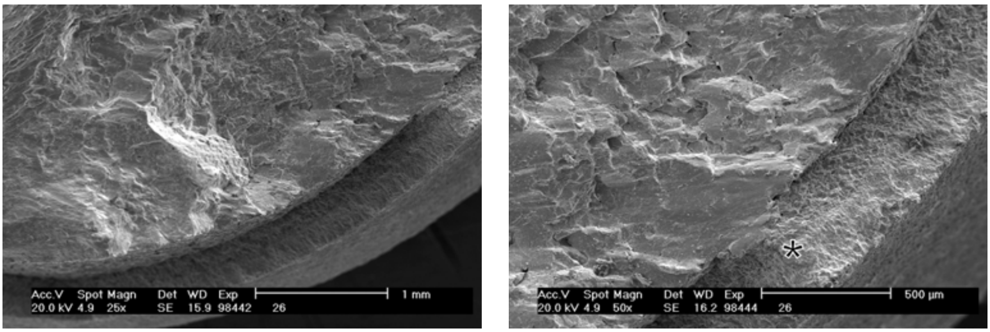

Fig.3. Detail of an initiation site (indicated by a star) within thermal barrier coating in Inconel 713LC specimen subjected to combined bending-torsion loading (σ_a = 264 MPa, τ_a = 272 MPa, N_f = 4.2×10^4 cycles).

CONCLUSIONS

Mechanical/thermochemical surface treatments and surface coatings that are often applied to improve life of engineering components result in gradients in material properties or generation of sharp interfaces that in general add to the complexity of the failure process. This is particularly true for complex loading regimes such as combined axial-torsion loading, which is a typical operation mode of rotational structural parts. Fractography, as a method of description of fracture surfaces, is in such cases the vital tool that provides an important insight into the failure process and allows optimizing the performance and operational lifetimes.

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