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Centre des Matériaux – Évry

Méthodes pour la détermination de la durée de vie des structures sous chargements complexes

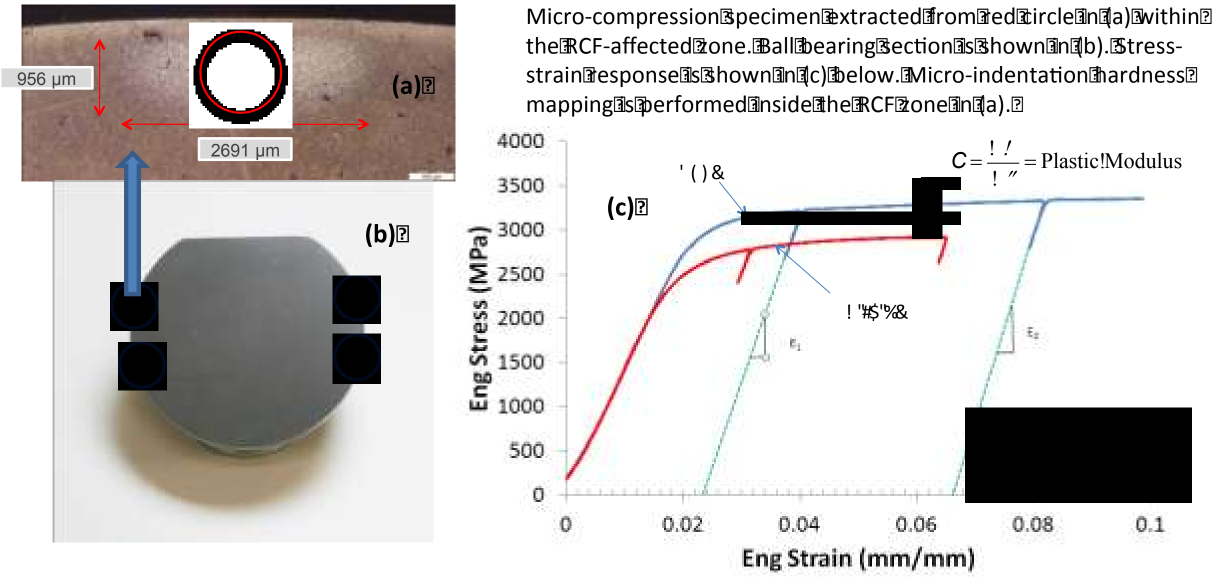
Determination of service life in structures subject to complex loading environments

N. K. Arakere, J. Cormier, P. Sabnis

Rolling contact fatigue life prediction: An experimental and numerical approach

Nagaraj K. Arakere
Professor, Mechanical & Aerospace Engineering
University of Florida
Gainesville, Florida, USA

Rolling-element bearings are key precision components used in nearly all machinery. The annual revenue associated with bearings is a substantial $50 billion worldwide. Future demands for high performance rotor support used in turbine engines, wind turbines and high-speed rail require bearings to survive hundreds of billions of revolutions under severe operating conditions. Rolling contact fatigue (RCF) subjects ball and roller bearing subsurface material to a large number of stress cycles ($\sim 10^{11}$) with complex triaxial stress state, non-proportional loading, high hydrostatic stress component, and changing planes of maximum shear stress during a loading cycle. The confined volume of micro-plastically stressed material in RCF is only a few mm^3 and highly localized. These conditions are very different from traditional bulk material fatigue testing with tensile, shear or rotating beam specimens at higher strain amplitudes and lower cycles ($\sim 10^7$), and the average cyclic fatigue response obtained from such testing does not mimic the complex triaxial stress state in ball bearings. Current life prediction models are extensions to the crack-initiation-based probabilistic life model by Lundberg and Palmgren (LP) using elastic Hertzian contact stresses, proposed in 1947. This approach worked reasonably for older technology “dirty” bearing steels with expected L_{10} life of about 2,000 hours. Because the current LP approach is not based on rigorous mechanistic principles that explicitly considers the material microstructure and the evolution of localized constitutive behavior under contact loading, the approach grossly underestimates RCF life of modern case hardened plastically graded ultra clean VIM-VAR bearing steels. This talk will present a material-specific RCF life prediction approach based on measuring the subsurface microstructural evolution via micro-indentation mapping and extraction of micro-compression pillars within the RCF-affected zone and modeling the cyclic elastic-plastic subsurface fields. Enhancements to the LP approach are proposed based on computed subsurface stress fields. This research project is sponsored by Pratt & Whitney and the National Science Foundation.



Micro-compression specimen extracted from red circle in (a) within the RCF-affected zone. Ball bearing section is shown in (b). Stress-strain response is shown in (c) below. Micro-indentation hardness mapping is performed inside the RCF zone in (a).

A microstructure sensitive model to account for the non-isothermal creep behaviour of Ni-based single crystal superalloys

Jonathan CORMIER,
Institute Pprime,
ENSMA-Université de Poitiers, France

Nickel-based single crystal superalloys are widely used for the design of aeronautic and industrial gas turbine blades and vanes due to their superior mechanical properties especially in creep up to 1,100°C. A reliable design of these components against creep deformation for regular operating conditions should take into account all creep stages (i.e. primary, secondary and tertiary), creep anisotropy and microstructure degradation (i.e. rafting). However, the successful design of these components also requires a finer description of all the microstructure evolutions occurring during the complex thermomechanical loading encountered during the certification procedures. Indeed, several engine certification tests require the use of repeated close γ'-solvus overheatings which leads to fast microstructure evolutions and consequently, transient mechanical behaviors.

The Polystar model was recently developed to capture the impact of such fast microstructure evolutions and their consequences on the mechanical behavior [1, 2]. New internal variables were introduced in a crystal plasticity framework to take into account microstructure evolutions such as γ' dissolution/precipitation and dislocation recovery processes. This model, calibrated on [001] oriented single crystals, provides a suitable framework to successfully model creep under complex loading. The impact of overheating or thermal cycling close to the γ' solvus on the creep behaviour is well captured, as well as the effects of as-received (i.e. after full heat treatments) microstructure variations such as lower γ' volume fraction.

In addition to a presentation of the model anatomy, the following issues will be detailed in this presentation:

1. The influence of the accumulated creep strain on the γ' dissolution kinetics [3].
2. The use of *in situ* non-isothermal creep experiments under synchrotron radiation for a better identification of the microstructure evolution kinetics [4].
3. The calibration of the model against LCF and dwell-fatigue mechanical behavior.
4. The Polystar microstructure predictions vs. experimental measurements under complex thermomechanical histories and multiaxial stress state [5].
5. The predictability of the model compared to "close-to-reality" experiments using the newly developed MAATRE test bench.

References

1. Cormier, J. and G. Cailletaud, *Constitutive modeling of the creep behavior of single crystal superalloys under non-isothermal conditions inducing phase transformations.* Materials Science and Engineering, 2010. A527(23): p. 6300-6312.
2. Ghighi, J., J. Cormier, E. Ostoja-Kuczynski, J. Mendez, G. Cailletaud, and F. Azzouz, *A Microstructure Sensitive Approach for the Prediction of the Creep Behaviour and Life under Complex Loading Paths.* Technische Mechanik, 2012. 32(2-5): p. 205-220.
3. Giraud, R., Z. Hervier, J. Cormier, G. Saint Martin, F. Hamon, X. Milhet, and J. Mendez, *Strain effect on the γ' dissolution at very high temperatures of a nickel based single crystal superalloy.* Metallurgical and Materials Transactions A, 2012. In press.
4. Le Graverend, J.-B., L. Dirand, A. Jacques, J. Cormier, O. Ferry, T. Schenk, F. Gallerneau, S. Kruch, and J. Mendez, *In situ measurement of the γ/γ' lattice mismatch evolution of a nickel-based single crystal superalloy during nonisothermal very high temperature creep experiments.* Metallurgical and Materials Transactions A, 2012. 43A: p. 3946-3951.
5. Le Graverend, J.-B., *Etude et modélisation des effets d'incursions à très haute température sur le comportement mécanique d'un superalliage monocristallin pour aube de turbine*, PhD Thesis, ISAE-ENSMA, 2013.

Numerical simulation of coupled phenomena: Application to crystal plasticity and regularised damage

Prajwal SABNIS,
Centre des Matériaux, France

Numerical simulations are seeing an ever increasing interest at every stage of an industrial process. In particular, aerospace and energy industries rely rather heavily on simulations for validation of designs and for the determination of safe operating lifetimes. Within the latter context, fracture simulations are of particular interest. Most models in use today have been developed from a correlation of empirical data and decoupled numerical models which were originally developed for special simple cases. As is increasingly evident in literature, an earnest consideration of the coupled nature of various phenomena is necessary for a realistic simulation of material response. In this sense, numerical models based on energetic approaches offer interesting possibilities for the development of generalised models.

One such coupled model, the XMD model, is introduced in the presentation. The model includes a strong coupling between the traditional crystal plasticity model and a regularised damage model. Crack -paths predicted by the XMD model in real and fictional test specimens subject to various loading conditions are presented in order to exhibit the wide applicability of generalised models. Some future avenues are also identified for further development.