Tribology International ▪ (▪▪▪▪) ▪▪▪–▪▪▪

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

The influence of contacting Ni-based single-crystal superalloys on fretting fatigue of Ni-based polycrystalline superalloys at high temperature

R.M.N. Fleury *, R.J.H. Paynter *, D. Nowell

Department of Engineering Science, University of Oxford, Parks Road, OX1 3PJ Oxford, UK

ARTICLE INFO

Article history:
Received 23 June 2013
Received in revised form
9 January 2014
Accepted 10 January 2014

Keywords:
Fretting fatigue
Single-crystal
Ni-based superalloys
Contact mechanics

ABSTRACT

Fretting fatigue tests at high temperature were carried out with single-crystal and polycrystalline alloys. The influence of the crystallographic orientation of contacting single-crystal pads on the lives of polycrystalline specimens is investigated. An analytical formulation of the contact problem between two anisotropic cylinders is used to study the changes in peak stress and contact width due to the orientation of the single-crystal. Finite element analysis is also used to study the variation of stress near the contact edge due to crystallographic orientation. An area averaging method is suggested to correlate fretting fatigue and plain fatigue curves. Using finite element analysis combined with the area averaging method, a better correlation was found between fretting fatigue results and plain fatigue.

1. Introduction

Fretting fatigue has been one of the main issues in the design of the blade/disk assembly in gas turbines. This phenomenon occurs whenever two contacting surfaces have a small oscillating relative displacement and, at the same time, are subjected to fatigue loads. Fretting accelerates crack nucleation and it can reduce fatigue lives up to 10 times [1]. Much research has been carried out in fretting fatigue in the past two decades and a large amount of data is available for commonly used alloys such as titanium and aluminium alloys [2–4]. However, fretting data for nickel based alloys are not as easily found and only recently has work with those alloys been carried out [5]. There is a constant search in the aerospace industry for new alloys that can hold on to their strength and properties at high temperatures. Nickel superalloys currently represent the best results and are widely used in the hot stages of aeroengines. In addition to polycrystalline Ni-based alloys, single-crystal Ni-based alloys are used in the manufacturing of turbine blades due to their higher tolerance to creep. However, they also introduce extra variables to the problem that need better understanding.

It is well known that the characteristics of partial slip contacts (i.e., peak stress, contact width, slip zones, etc.) depend widely on the elastic properties and the compliance of the bodies in contact. Furthermore, the properties of metallic crystals are not isotropic and depend on their crystallographic structure and orientation. Nickel crystals, for example, have face centred cubic (FCC) structure and orthotropic elastic properties, which means that some properties, i.e. elastic stiffness, are similar in three orthogonal principal directions, but may be different in other orientations. The use of single-crystals in components subjected to fretting can lead one to wonder what influence the crystallographic orientation will have on the contact tractions and fatigue lives of components. It has been reported in [6–8] that the stresses in the single-crystal body change significantly as a function of the orientation. This effect can be expected since the elastic matrix of an orthotropic material changes with respect to the orientation.

No work on the effect of single-crystal orientation on the fretting behaviour of a contacting polycrystalline alloy has been reported. A particular motivation for the current study is that recent fretting fatigue tests carried out at the University of Oxford and at Rolls-Royce plc on polycrystalline specimens in contact with single-crystal pads, both Ni-based alloys, have shown unusual scattered behaviour in the results. The difficulty of fully controlling the crystallographic orientation of the fretting pads has been suggested as one possible reason for the observed variation in lives. Physically, there is only one way in which the effect of the crystallographic orientation of single-crystal pad can affect the fatigue life of a polycrystalline fretting fatigue specimen: through the contact tractions. The change in contact tractions due to the crystallographic orientation can be split into the change

* Corresponding authors. Tel.: +44 1865 273811; fax: +44 1865 273906.
E-mail addresses: rodolfo.fleury@eng.ox.ac.uk (R.M.N. Fleury), robert.paynter@eng.ox.ac.uk (R.J.H. Paynter).

0301-679X/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.triboint.2014.01.011

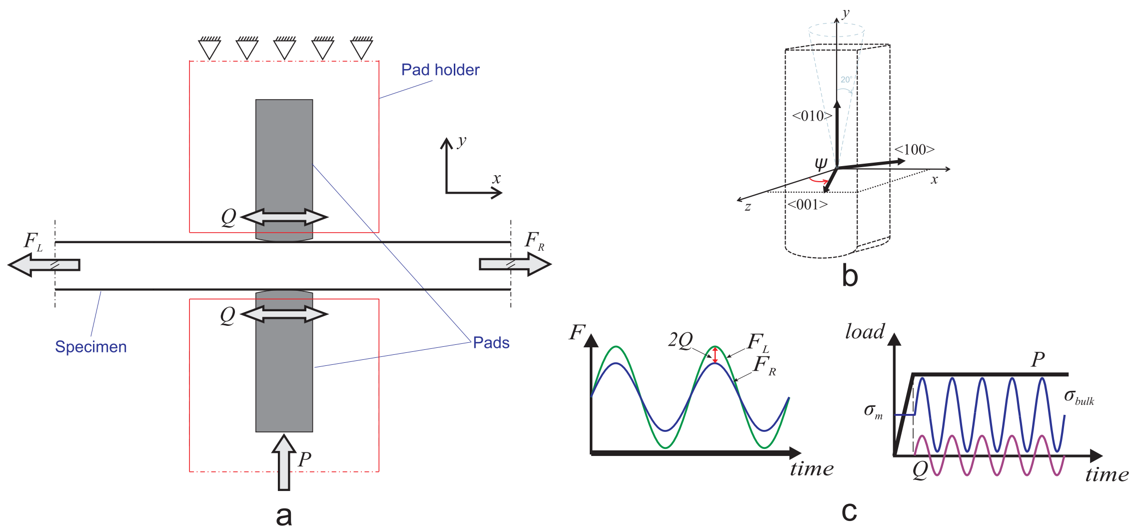

Fig. 1. (a) Schematic representation of the fretting fatigue hot rig. (b) Schematic representation of the single-crystal pads' crystallographic orientation. (c) Fretting fatigue load history and definition of shear load by the difference of applied force amplitude.

in the contact characteristics, peak pressure and contact size, and the change in coefficient of friction (CoF). In this paper we will focus on the first issue, but indications of the dependency of the CoF due to the crystallographic orientation have been reported in [9].

Fretting fatigue experiments at high temperature were conducted and the impact of crystallographic orientation of single-crystal pads was evaluated. The orientation of the principal directions in the plane of contact were measured beforehand and it was assured that the pads had controlled orientation in each test. A non-destructive indentation technique was used in the measurement of crystallographic directions.[1] The experimental procedure and set-up is described in Section 2. A brief description of the elastic properties of single-crystal Ni alloys will be presented in this paper. Then, an anisotropic contact solution is formulated using the Stroh formalism for anisotropic elasticity. The solution presented here is a reformulation of the solutions given in [10,11]. The analytical solution for contacting anisotropic cylinders will be used to study the influence of the crystallographic orientation of single-crystal elastic bodies on the normal contact tractions. A simplified frictionless contact problem between two half planes will be used in this analysis. With the help of finite element analysis (FEA), friction will be included in the problem and the partial slip problem for single-crystals will be analysed. The results of the contact stress analysis will also be compared with the fretting fatigue experiments mentioned above.

2. Experimental work

2.1. Experimental method

High temperature fretting rigs have been developed in the past two decades to reproduce the fretting conditions in the blade/disk assembly of gas turbines. Although not as high as the combustion temperatures, the temperature at the root of the blades, where multiple contact points between blades and the disk occur, is still very high for metallic alloys. Their properties show significant change compared to room temperature and hence it is important to conduct tests at similar temperatures. The experimental work was carried out on a rig at the University of Oxford custom built for high temperature fretting fatigue tests. A schematic of the specimen and pads used is given in Fig. 1a. The rig is equipped with three hydraulic actuators (each 100 kN in capacity): two that pull on each end of the fatigue specimen and a third that applies force to clamp the pads to the specimen. The furnace of a compact design has PID control and can be operated up to 900 °C. The temperature feedback is via a thermocouple embedded in the pad holder; this has been calibrated against measurements where thermocouples were embedded in a lightly loaded fatigue specimen and at the contact face of the pads.

The fatigue specimens are made up of a polycrystalline Ni-based alloy, alloy A, representing the hub of the turbine disk, and the pads are made up of a single-crystal alloy, alloy B, representing the blade roots.[2] Tests with pads made up of the same polycrystalline alloy were also conducted for comparison with the single-crystal results. The polycrystalline specimen has 10×10 mm cross-section in the centre and it is long enough so that it can be attached to hydraulic actuator outside the furnace. The pads have a 12 mm width in the z direction and a radius $R = 100$ mm. The pad is wider in the z-axis to avoid alignment issues in that direction and the most severe edge effects on the specimen, which would happen if the edge of the pad was contacting the surface of the specimen. The pad protrudes 2 mm out of the pad holder. The protrusion was reduced as much as possible to avoid rotation of the pad when applying the shear load. The single-crystal pads have been manufactured such that one of its principal crystallographic direction, ⟨010⟩, lies along the y direction within a tolerance of 20° (Fig. 1b). However, the other two principal directions can be in any direction on the x–z plane. The secondary crystallographic orientation is defined here by the angle ψ between the lattice direction ⟨100⟩ and the x-axis, or equivalently between ⟨001⟩ and the z-axis. The secondary crystal orientation was measured by an indentation technique described in Section 2.2.

The normal contact force P was applied by the bottom actuator and kept constant throughout the test and for all tests. Special care was taken to assure the specimen was not bent after applying the normal force. The fatigue load was obtained by in-phase tension applied to the two ends of the specimen by the left and right actuators. However, the amplitudes of the left and right loads are different, such that, the difference in amplitude induces shear tractions at the contact interface. All partial slip tests were

[1] By non-destructive it is meant that the pads can still be used afterwards, since the indentation is made far from the contacting face. Indentation methods generally cause damage, but are not necessarily destructive.

[2] Due to the confidentially agreement between the University of Oxford and Rolls-Royce plc we are unable to provide the names and properties of the alloys.

Please cite this article as: Fleury RMN, et al. The influence of contacting Ni-based single-crystal superalloys on fretting fatigue of Ni-based polycrystalline superalloys at high temperature. Tribology International (2014), http://dx.doi.org/10.1016/j.triboint.2014.01.011