International Journal of Pressure Vessels and Piping 88 (2011) 356–364

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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

An anisotropic tertiary creep damage constitutive model for anisotropic materials

Calvin M. Stewart [a,*], Ali P. Gordon [a], Young Wha Ma [b], Richard W. Neu [c]

[a] Department of Mechanical, Materials, & Aerospace Engineering, University of Central Florida, USA
[b] Department of Mechanical Engineering, Chung Ang University, 221 Huksuk Dongjak, Seoul 156-756, Republic of Korea
[c] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, USA

ARTICLE INFO

Article history:
Received 20 April 2010
Received in revised form
30 June 2011
Accepted 30 June 2011

Keywords:
Transversely-isotropic
Continuum damage mechanics (CDM)
Directionally-solidified
Ni-base superalloy
Void induced anisotropy
Multiaxial

ABSTRACT

When an anisotropic material is subject to creep conditions and a complex state of stress, an anisotropic creep damage behavior is observed. Previous research has focused on the anisotropic creep damage behavior of isotropic materials but few constitutive models have been developed for anisotropic creeping solids. This paper describes the development of a new anisotropic tertiary creep damage constitutive model for anisotropic materials. An advanced tensorial damage formulation is implemented which includes both material orientation relative to loading and the degree of creep damage anisotropy in the model. A variation of the Norton-power law for secondary creep is implemented which includes the Hill's anisotropic analogy. Experiments are conducted on the directionally-solidified bucket material DS GTD-111. The constitutive model is implemented in a user programmable feature (UPF) in ANSYS FEA software. The ability of the constitutive model to regress to the Kachanov-Rabotnov isotropic tertiary creep damage model is demonstrated through comparison with uniaxial experiments. A parametric study of both material orientation and stress rotation are conducted. Results indicate that creep deformation is modeled accurately; however an improved damage evolution law may be necessary.

1. Introduction

In the power generation and aerospace industries, components such as pressure vessels, pipes, gas turbine disks and vanes, and turbine blades experience high temperatures such that creep deformation will occur. In the case of industrial gas turbines where the cycle duration and maintenance intervals can be in the thousands of hours, and there are drives to increases temperature and pressure, careful selection and accurate prediction of material behavior is paramount; therefore, directionally-solidified (DS) materials have been implemented to minimize intergranular (brittle) creep cracking by alignment of long grains with the first principal stress direction [1]. Typically DS gas turbine blade materials are transversely-isotropic, consisting of a columnar microstructure where there is a plane of "transverse grain (T)" isotropy and an enhanced "longitudinal grain (L)" orientation. Creep and stress-rupture properties are one of the more important variables in the overall life of turbine blades [2].

In the case of welded pressure vessels, welding is a directional solidification process. A single weld bead consists of a single columnar solidification microstructure. Multi-pass welding (used on pressure vessels) will produce a transversely-isotropic microstructure [3].

In the case of thin-walled pipes used in power plants, considerable work has been focused around isotropic creep damage modeling [4,5]. Literature has demonstrated that strength anisotropy in thin-walled tubular elements is common [6].

Accurate, modeling of the creep deformation and damage behavior of transversely-isotropic materials is important. A novel anisotropic creep damage model for transversely-isotropic materials is developed based on the Kachanov-Rabotnov isotropic formulation [7,8]. Experiments are conducted on uniaxial specimen of the bucket material DS GTD-111. The constitutive model is implemented in Finite Element Analysis (FEA) software. A comparison between the experiments, Kachanov-Rabotnov model, and novel constitutive model is conducted. An examination of the strain tensor is provided. A parametric exercise of the constitutive model for various material orientations and states of stress demonstrates functionality.

2. Continuum damage mechanics

A damage mechanism is a manifestation of the degradation of the microstructure of a material and can occur in two forms: transgranular (ductile) damage and intergranular (brittle) damage. Transgranular (ductile) damage arises where slip bands of plasticity

* Corresponding author. 4000 Central Florida Blvd., Bldg. 40 Room 358, Orlando, FL 32816-2450, USA. Tel.: +1 (407) 435 0047.
E-mail address: calvin.stewart@knights.ucf.edu (C.M. Stewart).

0308-0161/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijpvp.2011.06.010