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Micromechanical investigation into the effect of texture on the fatigue behaviour of superelastic nitinol

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ABSTRACT

One material that has found particular favour for use in the manufacture of biomedical endovascular stents is the near equiatomic NiTi alloy, Nitinol. Stents are typically laser-cut from textured micro-tubing; texture is the distribution of crystallographic grain orientations in a polycrystalline material. Despite the well documented dependence of mechanical behaviour on crystallographic texture, the standard computational design practice for such stents simply calls for the use of uniaxial homogenous material properties which assumes continuum material behaviour. This study offers a computational examination into the effect of crystallographic texture on NiTi's fatigue behaviour in order to highlight concerns with this current design practice. The computational methodology first developed by Bruzzi and McHugh (2002), and modified for use with superelastic NiTi by Weafer and Bruzzi (2016), is adapted to include crystallographic texture. This defect tolerant approach correlates local crack-tip driving force conditions of an initial small crack with an experimental long crack growth rate curve, using crack closure. Computationally derived predictions of fatigue life are compared for superelastic NiTi specimens considering the material as (1) a continuum material with homogenous behaviour, and (2) a textured material with anisotropic granular behaviour, presented using both realistic and idealised microstructural features. In this manner, further insight is achieved into the effect of crystallographic texture on the fatigue behaviour of superelastic NiTi and offers a quantitative explanation towards the observed scatter in experimental fatigue data.

1. Introduction

1.1. Superelasticity

Superelasticity is the term given to the stress-induced phase transformation, from an austenite to martensite phase, which underpins NiTi's remarkable trait of improved fatigue performance with increasing mean strain [1,2]. Superelastic NiTi has therefore proven particularly appealing in the biomedical industry for use in self-expanding endovascular stents [3]. Such devices have proven effective in the treatment of atherosclerosis in a variety of vessels and arteries. However, fracture rates of up to 65.4% in such stents have been reported in clinical studies [4]; such failures have been attributed to cumulative fatigue damage. Accurate characterisation of NiTi's fundamental fatigue behaviour, in particular local microstructural effects on global mechanical response, is therefore essential for their prolonged safe use in human arteries.

NiTi's phase transformation can be induced by changes in temperature or stress; via an application of load, or upon cooling below the martensite-start temperature (M_s). Austenitic NiTi (ordered cubic B2 structure) is a hard, stiff material whereas martensitic NiTi (complex-twinned monoclinic B19′ structure) is a softer, more ductile material with a lower yield stress [5]. In a crystallographic context, the stress-induced martensite transformation (SIMT) occurs by rearrangement of atomic planes via Bain strain and lattice invariant shear [6]. By this microstructural process, NiTi can withstand approximately 6–8% strain without permanent deformation. This ability to accommodate such significant strains is highly desirable in stent device design for stent deliverability, durability, and conformance. Upon removal of the stress, the superelastic strain recovers at a lower stress level than at which it is induced, i.e. along a hysteresis curve [7], as shown in Fig. 1.

1.2. Microstructural texture

As described above, NiTi derives its unique mechanical behaviour from the coordinated atomic movements manifesting in a phase transformation from cubic austenite to monoclinic

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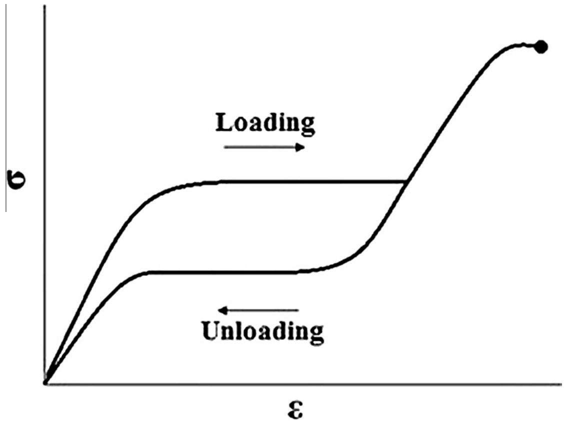

Fig. 1. Schematic representation of the superelastic stress-strain behaviour of NiTi. Adapted from [7].

martensite. Therefore, any significant alignment of the atomic planes resulting from crystallographic texture can have a marked influence on mechanical response. It has been experimentally shown that texture has an effect on crack trajectories in NiTi tube specimens subjected to uniaxial cyclic loading [8]. In addition, substantial variations in mechanical behaviour have been observed between rolled and transverse directions of cold-drawn NiTi sheets [9]; this can be attributed to the hindrance of deformed martensite structures and defects in the specimen leading to differing dominant de-twinning and reorientation modes and dislocation densities.

Despite the clear dependence of mechanical properties on crystallographic texture, standard practice implemented in the computational design of a biomedical stent device assumes the material behaves as a continuum. As a result, homogenous material properties, extracted from experimental uniaxial tensile testing of suitable specimens, are simply used to describe material behaviour. However in small engineering components, such as stent struts, individual grain behaviour becomes significant due to the grain to strut width ratio. This study, therefore, aims to highlight the importance of incorporating crystallographic textural effects into the micromechanical modelling procedures through the comparison of predicted fatigue behaviour of superelastic NiTi with and without the incorporation of crystallographic textural effects. Ultimately, this work aims to contribute to the development of design rules for maximising the performance of NiTi medical devices.

2. Material characterization

2.1. Microstructural imaging

For the incorporation of crystallographic textural features into the fatigue modelling methodology, a sequence of mechanical polishing and chemical etching was carried out on a custom manufactured superelastic NiTi specimen to reveal the grain structure (Fig. 2). Polishing was completed to a 0.06 μm roughness and etching was performed using a HF:HNO_3:H_20 solution. Scanning Electron Microscopy (SEM) imaging was subsequently carried out to visualise the grain structure. A total of 40 grains were identified in a selected test area; a 200 μm × 290 μm rectangle at the centre of the specimen. The average grain size in the test area was found to be 29.8 ± 4 μm having an aspect ratio close to one. Furthermore, a number of inclusions averaging in the size of 8.2 ± 1 μm were also identified in the SEM images; as seen as the dark regions of Fig. 2. Utilising Energy Dispersive X-ray Analysis (EDXA) techniques, these inclusions were positively identified as TiC precipitates.

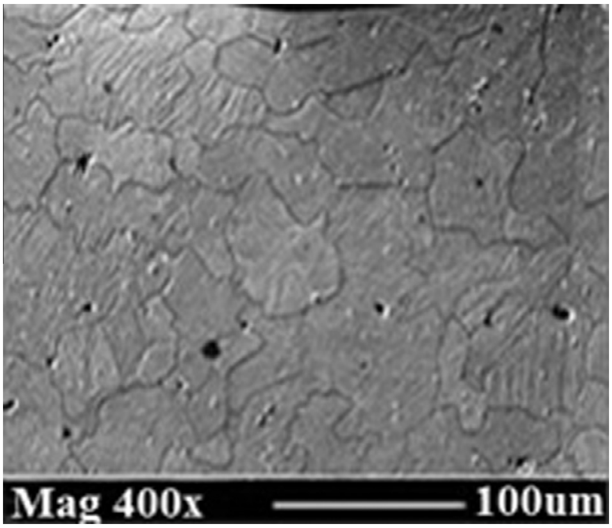

Fig. 2. SEM micrograph of the microstructure present in the NiTi specimen used in this study.

2.2. Texture characterisation

Employing Electron Back-Scatter Diffraction (EBSD) analysis techniques, characterisation of the crystallographic texture in the NiTi specimen was achieved. Kikuchi patterns are characteristic of the crystal structure and orientation of the sample region from which they are generated; results from a (1 1 1) orientated grain located in the test area of the specimen can be seen in Fig. 3. Using these Kikuchi patterns, the grain orientation of each grain in the 200 μm × 290 μm test site of the specimen was identified and a grain orientation distribution map was successfully generated. For the incorporation of texture into the fatigue modelling methodology used in this study, a Finite Element Analysis (FEA) model was constructed using the experimentally determined microstructure of the specimen; this will be described further in Section 3.2 of this paper.

The texture of the experimental specimen was found to comprise mostly of (1 0 0), (1 1 0) and (1 1 1) orientated grains; the highest proportion being of the (1 1 1) grain orientation. When the grain orientation distribution of the specimen used in this study is compared against an experimentally established texture of a flattened NiTi tube stent specimen [10], very similar results are seen. The average grain size in the NiTi tubing was reported as 25 ± 3 μm, as compared to 29 ± 4 μm in the NiTi specimen used in this study and, similarly, the majority of grains present in the tubing had (1 0 0), (1 1 0) and (1 1 1) crystallographic orientations with the highest proportion identified as the (1 1 1) orientation. Thus confirming the texture of the NiTi specimen used in this study was similar to that reported in micro-tubing used in stent production.

3. Fatigue model methodology

3.1. Crack closure model concept

The work presented in this paper is based upon the methodology for modelling small crack fatigue behaviour of metallic materials first developed by Bruzzi and McHugh [11]. This methodology was subsequently modified to capture the complex transformational behaviour of superelastic NiTi by Weafer and Bruzzi [12]. This modelling approach focuses on computationally correlating local crack-tip driving force conditions of an initial