Journal of Materials Processing Tech. 258 (2018) 116–127

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

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

Micro-voids quantification for damage prediction in warm forging of biocompatible alloys using 3D X-ray CT and RVE approach

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ARTICLE INFO

Keywords:
Micro-voids
Damage prediction
Warm forging
Biocompatible alloys
X-ray computed tomography
Representative volume element

ABSTRACT

This study aims to quantify the three-dimensional (3D) micro-voids for damage prediction in warm forging through non-destructive X-ray computed tomography (CT) and RVE approach. Typical biocompatible alloys, i.e., stainless steel 316 L (SS316L) and titanium alloy Ti-6Al-4V, were used as specimen materials in warm-forging a medical implant, i.e., a basal thumb implant. X-ray CT scanning was performed for both the preforms and forged components. Volumetric CT images were then reconstructed and the 3D micro-void distribution and evolution inside the materials were detected and analysed quantitatively. Furthermore, three typical local strain regions, i.e., the small tensile strain region (STSR), small compressive strain region (SCSR) and large compressive strain region (LCSR), were established as the 3D representative volume element (RVE) models for both SS316L and Ti-6Al-4V preforms. The spatial location, size and volume of each micro-void were obtained from defect analysis of the 3D CT images and considered explicitly for subsequent damage prediction. An improved thermo-mechanical coupled micromechanics-based damage (micro-damage) model, which considered the variation of volume fraction of micro-voids (VFMVs), was implemented into finite element (FE) package ABAQUS for localized damage prediction of the RVE models. The damage distributions of the RVE models at different strain levels were visualized and identified. Finally, the localized damage evolutions at both compressive and tensile deformations were predicted and found to match quite well with the findings acquired from CT scanning. Thus, the application of non-destructive X-ray CT measurement of micro-voids, incorporating the RVE approach, was able to play a significant role leading to a more reliable damage prediction in the warm forging process.

1. Introduction

Due to the continual growth of the world's population, particularly the aging population, along with the maturation of medical technology, the demand for medical implants is ever-increasing. However, mechanical failures of metallic implants have been found, with an estimation of about 20% (Marshall et al., 2008). The main reason for this undesirable result arises from the manufacturing limitations of the fabrication processes, such as investment casting and metal injection molding, which inevitably leave voids and porosity inside the components (Boljanovic, 2009). In order to enhance the strength, and avoid sudden failure during the implantation of these critical metallic implants, warm forging is believed to be a viable alternative process (Sheljaskov, 1994). The forged component not only shows a more densified structure, less internal defects, and desirable grain flow strengthening, it also exhibits a better dimensional accuracy and surface quality over cast parts.

During the warm forging process, the inherent micro-defects (e.g., micro-voids/cracks, inclusions, etc.) can be reduced or healed under strong plastic compressive stress. However, some of the adjacent micro-defects may be aggregated and coalesced, which can lead eventually to damage accumulation and aggravation inside the component. Ishikawa et al. (2005) studied the causes of micro-defects initiation and found that it may not be possible to achieve defect-free components in general practice. Lee et al. (2011) predicted void deformation in forging large ingots and proposed a criterion for void closure. Chen and Lin (2013) investigated void evolution by FE simulations and experiments for large forgings during hot working. Feng et al. (2016) conducted FE simulations of a 3D void growth model to investigate the internal void closure in the cogging process by considering the void shape, stress and strain state. It can be seen that the quantification of micro-voids to improve the constitutive models that account better for damage prediction is of great importance in the metal forming process.

Nowadays, the micromechanics-based damage (micro-damage) model is used widely for damage prediction due to the sound physical understanding of damage caused fundamentally by micro-void

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https://doi.org/10.1016/j.jmatprotec.2018.03.020
Received 9 January 2018; Received in revised form 23 March 2018; Accepted 24 March 2018
Available online 28 March 2018

evolution in metallic material. Gurson (1977) originally proposed the void growth model based on the framework of micromechanics for porous materials. Tvergaard and Needleman (1984) extended Gurson's model for the FE analysis of cup-cone fracture through the initiation and evolution of voids, which is known as the GTN model. Pardoen and Hutchinson (2000) improved the GTN model to establish the criterion for the onset of coalescence by considering the void shape and location, strain hardening and stress triaxiality. By introducing two damage parameters, i.e., void volume fraction and shear growth parameter, Malcher et al. (2014) further extended the GTN model for ductile fracture prediction under different stress triaxiality conditions. Soyarslan et al. (2016) proposed a thermomechanical constitutive model which incorporated both micro-void and micro-crack for damage prediction at finite strains. Zhao et al. (2016a,b) studied the damage mechanism of tearing failure in the fine-blanking process by combining the damage mechanics and the porous micromechanics model with consideration of the shear loading condition.

The above-mentioned damage models are always implemented in FE code for damage prediction. Since the micro-voids inside the metallic materials generally have irregular shapes and are distributed randomly, it is very difficult to describe all the microstructure details of the material at the macroscopic level and to carry out the FE simulation within reasonable computational time. Thus, multiscale analysis is booming as an effective method for investigating the material behaviour at different length scales (Geers et al., 2010). One of the most promising approaches for multiscale homogenization analysis is based on the concept of the representative volume element (RVE). By combining statistical analysis and numerical simulations, Gitman et al. (2007) determined the size of 2D RVE based on the Chi-square criterion for random heterogeneous material. Shen et al. (2009) investigated the influence of different shapes (sphere, triangular, rectangular, etc.) of defects on the effective Young's modulus of RVE. Lian et al. (2014) studied the damage initiation of DP steels on the microscopic level based on RVE simulations under different stress states. Chan et al. (2015) proposed a RVE-based multiscale approach for stress-strain behaviour prediction of void-considered metal alloy.

Although numerous studies of multiscale analysis have been done on various materials, the modelling of micro-voids in RVE is generally based on assumption or statistical analysis (Matouš et al., 2017), and the acquisition of damage parameters in FE simulations is obtained mostly through 2D destructive measurements (Zhao et al., 2016a,b). This study, thus, aimed to incorporate the non-destructive X-ray CT with a 3D RVE approach for damage prediction in warm-forging biocompatible alloys. The high-resolution X-ray CT detection enables the all-round visualization and quantification of the inherent micro-voids in three dimensions (Hsieh, 2009). For the CT scanning of material deformation at high temperatures, Kaye et al. (2013) viewed that the *in situ* measurement would result in the recrystallization of material during the interruption periods for CT image capturing. Therefore, *ex situ* X-ray CT scanning with a quenching process was adopted in this study to freeze the microstructure for better statistical analysis of the micro-void evolution during straining. Typical biocompatible alloys, stainless steel 316 L (SS316L) and Ti alloy Ti-6Al-4V, were used in this study. The hot/warm forging temperature of austenitic SS316L had been carefully controlled and monitored within a very narrow range in order to avoid excessive grain growth or intergranular corrosion/cracking due to the hot cracking susceptibility (Matula et al., 2001). Whereas, hot/warm forging temperature range of titanium alloys is relatively wide, such as that Ti-6Al-4V alloy, which can be forged readily from 540 °C to near β phase transition temperature (Park et al., 2002; Beal et al., 2006). Obviously, this is exactly the factual difference between that no phase change of mono-phase austenitic SS316L during hot/warm forging and that of hot-working on the two-phase (α + β) Ti-6Al-4V alloy (Momeni and Abbasi, 2010). A specific forging tooling was designed for warm-forging a basal thumb implant. Both the preforms and forged components were scanned and their volumetric CT images were reconstructed for quantitative analysis of the micro-void distribution. 3D RVE models representing different local strain conditions were then established and their damage evolutions were predicted numerically with an improved thermo-mechanical coupled micro-damage model and further verified experimentally.

Table 1
Chemical composition (% in mass) of SS316L in this study.

C	Mn	S	Si	Cr	Ni	Mo	Fe
0.024	1.68	0.003	0.03	16.73	11.55	1.52	balance

Table 2
Chemical composition (% in mass) of Ti-6Al-4V in this study.

C	O	Fe	Al	V	Ti
0.03	0.03	0.25	6.22	4.15	balance

2. Experimental methods

2.1. Material and specimen preparation

The biocompatible alloys used in this study were cast SS316L and Ti-6Al-4V; their chemical compositions are shown in Tables 1 and 2 respectively. The cast process leaves a variation in size of micro-voids and inclusions, which is conducive to subsequent micro-void measurement and analysis. Since the forging process involves applying compressive loading to a work piece, compression tests were carried out in this study to obtain the mechanical properties of the materials. The specimens for compression tests were cut to cylindrical shapes of Ø8.0 mm × 12.0 mm. The configuration and dimensions of the basal thumb implant (Swanson, 2016) for warm forging experiments is shown in Fig. 1. Such a small component was conducive to the full penetration of an X-ray for the detection of the internal micro-voids, and it could be produced by the open-die forging process in one stroke. Since the spherical part of the implant was much bigger than the rod part, the preform was designed as a stepped cylinder, as shown in Fig. 2. The parting lines of the die were set at the maximum cross section area; flashes were formed at the parting lines after the die cavity was filled fully, and the external flash thickness was set as 0.8 m m. It should be noted that the specimens used for compression tests and warm forging experiments were segmented from the same raw material to ensure the consistency of the material properties.

2.2. X-ray CT scanning

A high-resolution micro-focus X-ray CT system YXLON FF35 CT was employed to detect the internal micro-void distributions of both the preforms and forged components. As an example, Fig. 3 shows the X-ray CT scanning of the forged basal thumb component. The X-ray tube source was operated at 160 kV voltage and 120 μA current for SS316L specimens as well as 140 kV voltage and 110 μA current for Ti-6Al-4V specimens. A tin sheet with a thickness of 1.0 mm was used as a pre-filter to reduce the beam hardening effect. 1440 projections were generated in one full rotation with a 400 ms integration time, and the 3D volumetric CT data were generated using the in-house CERA reconstruction spooler. Then the 2D and 3D CT images were visualized with VGStudio MAX 2.2. The comparison of relative pixel intensity values was adopted to separate the background and material in the CT images. An advanced segmentation algorithm was used for defect detection inside the specimen, which allowed for grey value variations, including noise reduction for seed point location and surrounding air connection. Hence, information like size, number, spatial location, compactness, and sphericity of micro-voids could be obtained. An