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Multiscale approach with RSM for stress–strain behaviour prediction of micro-void-considered metal alloy

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ABSTRACT

This paper presents the concept of using a representative volume element (RVE) in a multiscale approach to predict the macroscopic stress–strain behaviour of a cast SS316L specimen under tension up to the point prior to necking. RVE models with various micro-void spatial configurations were built, and the effects of micro-voids and strain rate on the material properties (e.g., yield strength, ultimate tensile strength (UTS), ultimate tensile strain and strain hardening coefficient) were analysed. The spatial configuration of the micro-voids inside the cast SS316L specimen was acquired by the X-ray CT scanning system and each micro-void in the gauge length part was converted into a matching RVE model in the finite element (FE) analysis. Response surface methodology (RSM) was employed to investigate the effect of RVE configurations, i.e., the size of the RVE and the shape and spatial location of the micro-voids, on the material properties (yield strength and UTS) of the cast SS316L specimen at the macroscopic level, and then the optimal levels of the RVE configuration were determined. The stress–strain curve from the simulation did show a good agreement with the experimental results and hence the proposed concept was verified.

1. Introduction

Stainless steel (SS) is one of the most commonly used metal alloys, due to its high tensile strength at elevated temperatures and corrosion resistance [1,2]. The components made by this kind of metal alloy can be manufactured by various conventional metal forming technologies. Hot forming technologies such as hot forging is one of the most widely adopted processes in the manufacture of SS products [3,4] due to it has the advantage of an increased ductility and reduced strength of the work material. However, some SS components for certain special uses such as precision components [5,6] and metallic implants [7], cold forming is more suitable for the manufacturing as it can improve mechanical properties and corrosion fatigue resistance of the product, and provide a good surface finish and dimensional accuracy [8].

For the minimization of production time and cost, metal forming simulations are usually performed in order to study the deformation mechanics and the limiting factors in the design and manufacturing processes. The most promising technique for simulating the metal flow during forming is the finite element method (FEM) [9]. The prediction of the ultimate deformed component shape by the simulation requires its mechanical properties and these properties to be highly correlated with the metal alloy's intrinsic microstructure. When there are inherent micro-voids, they may affect the mechanical properties of the material adversely [10]. As the loading increases, nucleation and growth of these micro-voids occur; micro-cracks are formed and propagated until eventual rupture. Therefore, inherent micro-voids in the material should be considered for accurate simulation in FE analysis. However, such detailed modelling will consume tremendous computational resources, and this makes the design process not competitive.

Micro-to-macro modelling has become one of the most popular methods to solve this problem. Different mechanical behaviours have been modelled and evaluated from a variety of physical formulations at different length scales. Presently, the common linkage between the microscopic and macroscopic scales is established by homogenisation method. The main idea is to evaluate the effective and homogenised constitutive parameters for a material with a heterogeneous microstructure [11,12]. These constitutive parameters are determined only from the representative volume element (RVE), which is the smallest repetitive element of the heterogeneous material [13], by carrying out numerical methods such as the FE analysis. The definition of RVE has been investigated by many scholars: Kouznetsova et al. [14] assumed that the appropriate size of 2D RVE had already been selected, and then the heterogeneous microstructures with different volume fraction of

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Nomenclature

A	the initial yield strength of the material
B	the hardening modulus
C	the strain rate dependency coefficient
n	strain-hardening coefficient
m	the thermal softening effect
σ	the equivalent plastic stress
ε	the equivalent plastic strain
$\dot{\varepsilon}$	the equivalent plastic strain rate
$\dot{\varepsilon}_0$	the reference strain rate, which is equal to $1.0\ \mathrm{s}^{-1}$
$\varepsilon_{\mathrm{UTS}}$	ultimate tensile strain
T	working temperature
T_r	room temperature
T_m	the melting temperature of the material
VFMV	the ratio of the micro-defects volume to the whole RVE volume
X_1, X_2, X_3	the independent variables of Box–Behnken design: the size of the RVE, the shape of the micro-voids and the spatial location of the micro-voids
y_1, y_2	the measured responses: yield strength and UTS

micro-voids were studied. Kanit et al. [15] proposed a two-phase 3D voronoï mosaic model for a specific random microstructure. Volumes of different sizes were analysed using FE simulations in the cases of linear elasticity and thermal conductivity. Gitman et al. [16] studied the determination of size of 2D RVE based on the combination of statistical analysis and the numerical modelled material response. However, the construction of RVE, which contains micro-void with different spatial arrangements (e.g., different volume fractions, shapes and spatial locations of micro-void) in the multiscale approach, has been found to be very limited.

Although much of the research related to the micro-to-macro approach has been done on materials with various phases [12,17,18], the existence of micro-voids and the subsequent degradation of mechanical properties are usually neglected. This study, thus, attempted to tackle the shortcoming by incorporating the stress–strain behaviour of some micro-scaled RVE models with micro-voids into the stress analysis of a macro-scaled component by using the multiscale approach. Micro-voids with different spatial arrangements were built inside the RVE models. The influence of volume fraction, shape and spatial location of the micro-void on the stress–strain behaviour was simulated and analysed at the microscopic level. In this study, a cast SS316L designated for medical implant was used. Generally, cold forming is performed in order to meet the rigorous requirements regarding the strength, corrosion resistance and dimensional accuracy of the medical implant [7]. Therefore, the study on the stress–strain behaviour of the cast SS316L specimens for tensile tests was carried out at room temperature. The internal micro-voids of the specimen were scanned by an industrial X-ray computed tomographic (CT) scanning system. Based on the spatial information of the micro-voids, each of them was replaced by the corresponding RVE model and the deformation of the entire macroscopic model was obtained by the FE analysis. RSM [19] was employed to investigate the effect of RVE configurations, i.e., the size of the RVE and the shape and spatial location of the micro-voids, on the material properties (yield strength and UTS) of the cast SS316L specimen at the macroscopic level. The numerical simulation results were compared using the experimental stress–strain data of the specimens and the proposed methodology was verified.

2. FE models of RVE with different spatial configurations of micro-voids

When a metal alloy is fabricated, a sequence of metallurgical changes is involved and micro-voids are inevitably formed. In the current proposed methodology, the micro-voids in the cast SS316L specimen were regarded as inclusions with null property values. Since the size and spatial distribution of the micro-voids might not be regular and consistent within the material, the effect of the spatial configurations of the micro-voids on the stress–strain behaviours of the RVE models have to be investigated [20,21]. At the microscopic level, all RVE models were built in cubic shape with a side length of 0.15 mm and various spatial arrangements include (i) 1%, 2.5%, 5% and 7.5% volume fractions of the micro-void (VFMV) (Fig. 1), i.e. the volume of the micro-void divided by that of the RVE model, (ii) micro-voids in shapes of a sphere, tetrahedron, cube and ellipsoid (Fig. 2), to confirm that the different micro-void shapes of RVE models had the same VFMV, Table 1 illustrates the parameters of different micro-voids in Fig. 2, and (iii) five different spatial locations (SLs), as shown in Fig. 3. The SLs were defined by including an array of five micro-voids in the size of 2.5% VFMV at the middle of the RVE model with even distribution, namely SL1–SL5. Hence, five RVE models with a single micro-void at different SLs were built, as shown in Fig. 4. All of these RVE geometrical models were built using the commercial FE package ABAQUS/CAE 6.13.1 and the 10-node modified quadratic tetrahedral element, C3D10M, was used to mesh the models. For each RVE model in the FE analysis, displacement loading was applied on the top surface, as shown in Fig. 5. And the nodes on the bottom surface were constrained in the z direction. The flowchart of the FE simulation process is shown in Fig. 6.

The Johnson–Cook (J–C) model [22] was employed as the material constitutive model to describe the stress–strain relationship of

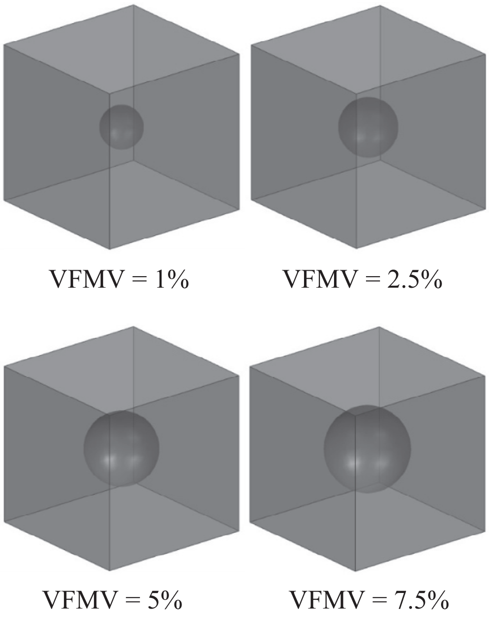

Fig. 1. RVE models with different VFMV.