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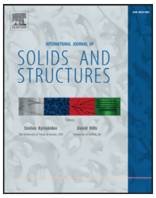

On the effect of deformation twinning and microstructure to strain hardening of high manganese austenitic steel 3D microstructure aggregates at large strains

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ABSTRACT

The hardening and deformation characteristics of Hadfield microstructure are studied to investigate the effect of microstucture to the material behavior. A crystal plasticity model including dislocation slip and deformation twinning is employed. The role of deformation twinning to the overall strain hardening of the material is evaluated for two different grain structures. Large compressive strains are applied on 3D microstructural aggregates representing the uniform and non-uniform grain structures of Hadfield steels. The grain structure has an effect on the strain hardening rate as well as on the overall hardening capability of the microstructure. A major reason causing the difference in strain hardening arises from the different twin volume fraction evolution influenced by intra-grain and inter-grain interactions. A mixture of large and small grains was found to be more favorable for twinning and thus resulting in a greater hardening capability than uniform grain size.

1. Introduction

The high manganese austenitic steels in various compositions are extensively used by industry due to their remarkable strain hardening capability, good ductility, and reasonable formability. These properties also facilitate excellent wear resistance against indenting hard particles in many applications. One of the most frequently used high manganese austenitic steel grade in wear related applications is commonly known as the Hadfield steel.

The Hadfield steel offers a desired set of properties that are generated by several hardening mechanisms including the high concentration of interstitial atoms interacting with dislocations, slip-twin interactions, and interactions between twin systems. Also martensitic transformation may take place depending on the composition, contributing also to the strengthening of the microstructure (Karaman et al., 2000b; Efstathiou and Sehitoglu, 2010; Shtremel and Kovalenko, 1987; Canadinc et al., 2005; 2007; Hutchinson and Ridley, 2006; Dastur and Leslie, 1981; Owen and Grujicic, 1999). It is difficult to experimentally separate all the different contributions to the hardening and understand their origin in the anisotropic polycrystalline microstructure. Computational approach can offer an additional view to the deformation and hardening behavior of the material. Meso-scale simulations focusing on the intra-grain and inter-grain behavior, above the length scale of individual dislocations or twins but much below the macroscopic scale, increase the understanding how the strong strain hardening of the Hadfield occurs. The key for effective failure and wear prediction is to establish the relationships between the microstructure, hardening mechanisms, and stress concentrations.

Despite reasonable agreement between the macroscopic behavior and experiments, many of the previous modeling efforts (Karaman et al., 2000a; Onal et al., 2014; Bal et al., 2016; Canadinc et al., 2003) for the Hadfield steel operate with the self-consistent schemes to produce the macroscopic material response informed by the microstructure level deformation behavior. The nature of the polycrystal averaging schemes have a tendency to mask the individual characteristics of the local hardening, as the grain structures are not explicitly included in the computations, and therefore neither the involving grain boundaries and stress concentrations. With the self-consistent schemes, it is a very expected result that no distinctive difference can be observed when relatively similar grain size distributions are examined because the models often only include a hardening term related to the absolute grain size. Hence, no direct information can be extracted from the individual intra-grain hardening or their expanding effect on the inter-

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grain behavior. For example, Cheng and Ghosh (2015) noted in their simulations that the grain structure has a significant effect on the propensity of micro-twins in magnesium. Gutierrez-Urrutia et al. (2010) observed with experiments that also the grains with non-favorable Schmid factors can exhibit twinning facilitated by the interaction with the neighbouring grains in TWIP steels. They also observed that the grain size affects the overall hardening of the TWIP steels, partially through the effect of grain size to the propensity of twinning.

In this work we study the deformation and hardening behavior of the Hadfield steel with two 3D microstructure aggregates representing the microstructure. A crystal plasticity model including a contribution from deformation twinning is utilized. The effect of deformation twinning on the material behavior is analyzed. The grain structures of the two aggregates are dissimilar, but only with a relatively small variation, in order to investigate the effect of variations on the grain structure to the macroscopic and microscopic level material behavior. The feasibility of the direct microstructure aggregate based method is also evaluated. Understanding the effect of the grain structure on the strain hardening of steels exhibiting deformation twinning is in a relevant role when designing new alloys.

2. Materials and methods

2.1. Material

The investigated material is 12.34Mn-1.03C (wt-%) Hadfield steel, the composition of which is in the range of the conventional Hadfield grades. This Hadfield grade has been widely studied in refs. Karaman et al. (2000b); 2000a), providing necessary the details of the material behavior and on prevailing deformation micro-mechanisms. The crystal plasticity model parameters have been previously identified and verified by Lindroos (2016) for chosen single crystal orientations and polycrystalline aggregates for this Hadfield grade based on these experimental results. The single crystal orientations were biased to slip or twin pre-dominated deformation (Karaman et al., 2000b), which allowed the identification of slip and twin based parameters. The fitted parameters were then used with polycrystal aggregates and compared with the experiments of ref. Karaman et al. (2000b). These parameters, listed in Table 1, are also employed in this study.

Table 1
Model parameters for the 12.34Mn-1.03C Hadfield steel (Lindroos, 2016).

Parameter	Value	Unit
Elastic constants, from ref. Pierce et al. (2013)		
C_{11}	174 000	$[MPa]$
C_{12}	85 000	$[MPa]$
C_{44}	99 000	$[MPa]$
Slip parameters		
τ_0^s	87.0	$[MPa]$
K	87.0	$[MPa.s^{1/n}]$
n	10.0	-
b	2.35	-
Q	140.0	$[MPa]$
h_0	0.12	-
h_1	0.10	-
h_2	1.60	-
h_3	1.85	-
h_4	0.36	-
h_5	0.80	-
Twin parameters		
Kc	0.03	-
τ_0^β	90.0	$[MPa]$
K_t	90.0	$[MPa.s^{1/n}]$
n_t	12.0	-
H_{tw}^{sl}	130.0	$[MPa]$
H_{NC}^{tw}	500.0	$[MPa]$
H_{CO}^{tw}	600.0	$[MPa]$
H_{sl}^{tw}	340.0	$[MPa]$
p	0.5	-
b	0.2	-
g	1.0	-
d	0.7	-

2.2. Microstructure aggregates

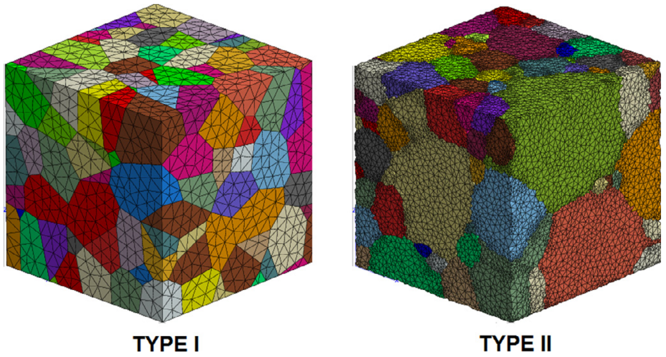

Fig. 1. Microstructural aggregates used in the simulations for the austenitic manganese steel with a) Type I with 250 grains and b) Type II with 183 grains.

Fig. 1 shows the two austenitic microstructures that were investigated. Type I comprises 250 relative uniform 100–200 µm grains. This grain size was chosen to resemble the grain size used in the experiments (Karaman et al., 2000b). The morphology of the 183 grains in Type II includes more size and shape variations with the general grain size being 200–600 µm. The variation from small to large grain size are typical for Hadfield steels manufactured by casting, for example due to the variations in the section thickness affecting the cooling rates of the manufactured parts. One typical application of the material is the jaw of a mineral crusher that has a varying section thickness. Therefore, the grain size 200–600 µm was considered as representative and it was chosen for the investigation. Random grain orientation is assigned to each grain and no misorientation variations exist intra-grain at the beginning of the simulations, as the material does not usually show any significant texture or intra-grain variations in the as-cast state. Both types of microstructure can result from the manufacturing by casting depending on the process parameters such as annealing time and quenching method.

Uniaxial compressive loadings were applied to the aggregates. Two of the edge faces of the aggregates were constraint with multi point constraint to remain flat during the compression to avoid bulging out of the grains. The remaining two edge faces were also constraint to retain the original planarity by the direct displacement constraints. The boundary conditions also rule out any localized instabilities taking place at the free surfaces, since the current study focuses on the hardening and deformation behavior of the material instead of localization of the aggregate geometry.

2.3. Description of the crystal plasticity model

The crystal plasticity model framework describes elasticity of the crystalline material structure and its plasticity at single crystal level according to the available deformation mechanisms. The inelastic deformation takes place by dislocation slip and deformation twinning in the studied material. The model details its and experimental verification are discussed elsewhere Lindroos (2016), but the main ingredients of the model are given in this paper. The implementation of the model was performed into the finite element code Zebulon/Zset (Besson and Foerch, 1998). Finite strain formal-

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