



Microstructure based modeling of the strain rate history effect in wear resistant Hadfield steels



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ABSTRACT

The strain rate history dependency of Hadfield steel is investigated by numerical modeling. A crystal plasticity model is employed to study the effect of strain rate jump/drop on the material's strain hardening and twinning propensity. Single crystal orientations are first examined to assess the importance of the strain rate and its history effects. Then a representative 3D microstructure aggregate is used to investigate the effects of strain rate history in a polycrystalline structure. It was found that strain rate affects the evolution of deformation twins in the microstructure, generating a strain rate history dependent deformation and hardening response. A Hadfield steel used in mineral crushing conditions is also characterized to provide details of the deformation and hardening behavior of the material under realistic low/high strain rate loading conditions. The importance of strain rate changes to strengthening and increasing the hardness of the polycrystal microstructure is discussed and considered from the wear resistance point of view.

1. Introduction

The use of high manganese austenitic steels of various compositions covers a wide scale of applications due to extraordinary characteristics of this class of materials, including an excellent strain hardening capability, good ductility and wear resistance. One example of such steels is the Hadfield steel that is often chosen for mineral crushing applications, e.g., for the jaws of jaw crushers. During crushing, these materials have the ability to strain harden at the surface but still remain sufficiently ductile, providing good wear resistance against abrading and impacting rocks at a reasonable material cost.

It has been well established that Hadfield steels deform by dislocation slip and deformation twinning. The strong strain hardening combined with good ductility of Hadfield steels originate from several hardening mechanisms, including a high concentration of interstitial atoms interacting with dislocations, dynamic strain aging, slip-twin interactions, and interactions between different twin systems [6,30,1,15,24,11,5,10]. In addition, deformation twinning features strain and strain path dependent evolution of the microstructure in terms of the development of intra-grain twin-matrix bundles and tension-compression asymmetry. Although the Hadfield steel is known to be a strain rate sensitive material, it is an often overlooked aspect that adds to the complexity of the deformation behavior of this material. The

time dependent nature of deformation and thus its relation to the hardening mechanisms can be expected to lead also to strain rate history dependency. For example, impact loads facilitate high strain rate conditions that can affect the competition between dislocation slip and deformation twinning, leading to a different contribution of these mechanisms [29,17]. In such a case, it becomes apparent that the strain rate history of the material will affect its subsequent deformation and hardening behavior.

In stainless steels, loading conditions such as strain rate and temperature have a major influence on the strain hardening of the material due to the phase transformation kinetics from metastable austenite phase to α' -martensite [12]. It follows that also the strain rate history then has great relevance to the material's deformation behavior. Isakov et al. [12] found that strain rate jumps cause notable differences in the martensite volume fraction as well as in the flow stress and strain hardening rate of the material in comparison to constant strain rate cases. In some cases strain rate jump experiments are simply performed to calibrate the strain rate sensitivity parameters [23]. However, in other cases it is of interest to understand the dependency of a particular deformation mechanism on strain rate. For example, Huang et al. [9] and Shen et al. [28] observed that twinning affects the strain rate sensitivity, strain hardening rate, and evolution of the microstructure of copper, suggesting that twinning can have a pre-dominant role in

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facilitating the strain rate history effects.

In some Hadfield steel grades, a negative strain rate dependency from low to moderate strain rates is observed due to dynamic strain aging (DSA) [4,2]. Gupta et al. [8] observed that DSA can cause a limited strain rate history effect, as DSA related plastic instabilities were activated dynamically during the strain rate jumps. However, the effect of DSA may also be restricted to certain temperature ranges only [25]. These results suggest that DSA can have a notable effect on the formation of instabilities (e.g., Lüders banding) as a consequence of strain rate changes, but such localization behavior has been observed only to a limited extent in Hadfield steel single crystals [15]. The negative strain rate sensitivity effect generated by DSA is even more limited or even fully masked in other Hadfield grades [19,16], as the steels exhibit positive strain rate dependency in a wide range from low to high strain rates.

Deformation twinning has been shown to have great influence on the material's hardening behavior [19], especially at high strain rates. However the experiments in all of the cases related to Hadfield steels mentioned above were carried out at constant strain rates. Therefore they do not offer information about the behavior of the material during or after rapid changes in the loading rate. This is important because in practical applications the deformation of the material does not necessarily take place at a constant strain rate. For example, such conditions could be considered in mineral crushing due to the combination of rocks abrading the surface together with sudden impacts by hard particles.

The present study focuses on the effect of strain rate jumps and their history effects on the material behavior. A rate-dependent crystal plasticity model, including dislocation slip and deformation twinning, is used. Simulations are first performed on single crystals and then on a representative 3D polycrystal microstructure aggregate. The aim of the work is to investigate the effects of strain rate history on the evolution of the material's microstructure (slip and twinning) and hardening in Hadfield steels. A Hadfield steel sample used in a jaw crusher is also characterized to provide additional information about the hardening mechanisms and relationship of twinning to material hardness. Furthermore, the simulation results are assessed by looking at the strain rate history effects from the wear resistance point of view in jaw crushers to provide a link between theory and practice.

2. Materials and methods

2.1. Material

The investigated material is Hadfield steel with a nominal composition of 16.5-wt% Mn, 1.05-wt% C, 1.8-wt% Cr, small quantities of aluminium and molybdenum, and balance of Fe. The microstructure of the cast and annealed is metastable austenite at room temperature. The grain size varied generally between 200 – 800 μm , but occasionally even larger grains can be found depending on the cast section thickness. The bulk macroscopic hardness of the material is 250–300 HV.

2.2. Material application

The material is typically used in the wear parts of jaw crushers used for mineral crushing. Fig. 1 idealizes some of the loading conditions present on the steel surface during the crushing process. While the jaw is moving during the crushing sequence, the rocks are impacted onto the surface from the supply funnel causing oblique angle erosion wear. However, again depending on the crusher setup, the supply funnel may be continuously filled so that the rocks themselves absorb part of the impacts when they collide with each other during the feed process. In the main event, cyclic crushing forces are subjected to the jaws when the rock comminution is executed. The forces can reach very high values depending on the mechanical strength of the rocks. This phase is followed by sliding of the rocks on the surface causing abrasion, which

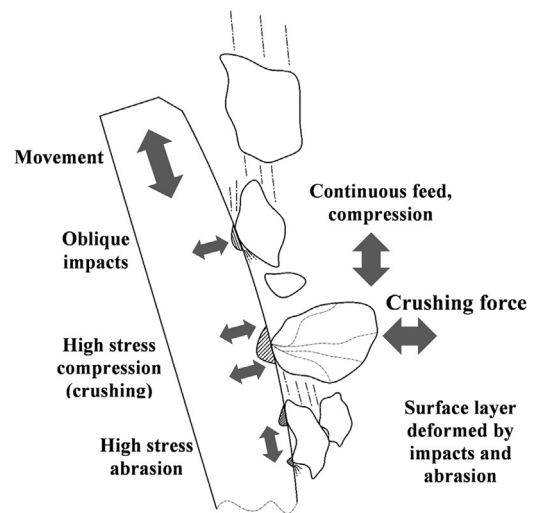


Fig. 1. Idealized schematic of mineral crushing (jaw crusher).

can be considered as high stress abrasion because of the continued refinement of the rocks during this stage. Finally, the effect of different rock species on the wear rate is not clear; some rock types can be very aggressive such as quartzite, as they tend to fracture into sharp bits that cause severe cutting type abrasion to the surface [26]. As a summary of the process, the Hadfield steel used in the jaws is in most cases required to withstand impacts, high stress abrasion, cyclic loadings, added effect from corrosion, and relatively high strain rates occurring in the process.

2.3. Characterization of an in-service sample

The material used in this study has been previously studied in high stress abrasion and impact conditions [19]. However, in order to understand the importance of the material's hardening mechanisms, characterization was performed also on a material used in-service mineral crushing conditions. The Scanning Electron Microscope (SEM) band contrast image in Fig. 2a shows a cross-section of the microstructure with grains having a high number of wide slip bands and deformation twins. No distinctive martensite transformation was observed in this steel grade. It can be seen that the region close to the loaded surface has deformed extremely heavily. However, the indexing of the surface region is poor because of the heavy deformation causing extensive distortions, high dislocation densities and twin boundaries, which restrict reliable identification of the twins and slip bands separately. Hence, it is apparent that both slip and twinning have a major contribution to the generation of the hardened layer, which can be understood as a functional tribolayer of the material in the process. The hardness profile, in Fig. 2b confirms that the strongest hardening is observed only in the layer with thickness of ca. 1 mm, which in the coarse grained material corresponds to only about one to three grain diameters. The hardness variations deeper in the material seem to depend on the amount of twins/slip bands in the grains. The maximum hardness of the investigated material deformed in the in-service conditions was around 680–720 HV, which is close to three times the hardness of the bulk material (250–300 HV).

The intensity of twins/slip bands decreases deeper in the material, which is also observed in the hardness profile as gradually decreasing hardness. Furthermore, for example at the depth of 2 mm, where the hardness is still notably elevated, the grains still show similar behavior as the surface grains with multiple twin bands crossing and interacting. A summary of the hardening mechanisms is collectively illustrated in Fig. 2c. The EBSD data showed that twins interact with twins and both thin and wide twin bundles are observed. Wide slip bands, having notable misorientations (e.g., 10–30 degrees) to the parent grain, appear in the microstructure and they have an effect on the twin behavior by

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