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A comparative study of an isotropic and anistropic model to describe the micro-indentation of TWIP steel

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In grinding, the crystal grain size of the workpiece material is relatively same range compared to the removal depth. This raises a question if an anisotropic material model, which considers the effect of the crystal grain size and orientations, would better predict the process forces when compared to an isotropic material model. Initially, a simple micro-indentation process is chosen to compare the two models. In this work, a crystal plasticity model and an isotropic Johnson-Cooke plasticity model are employed to simulate micro-identation of a twinning induced plasticity (TWIP) steel. The results of the two models are compared using the force-displacement curves from the micro-indentation experiments. In the future, the study will be extended to describe the material removal process during a single grit scratch test.

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1 Introduction

In a finite element simulation, material modeling and its parameterization is an innate aspect in predicting the material behaviour when subjected to different loading conditions. Specifically, grinding is a surface finishing process involving interaction of multiple of abrasive grains onto a work-piece. Interestingly, in this manufacturing process, the crystal grain size of the workpiece material is relatively same range compared to the removal depth. Hence, a fundamental research question arises: does an anisotropic material model better describe the grinding process and process forces compared to an isotropic material model? As grinding is a complex material removal process, initially a simple micro-indentation test is chosen to validate and compare two plasticity models. For the anisotropic model, the crystal plasticity finite element method (CPFEM) is employed and for the isotropic model, the Johnson-Cooke (JC) plasticity model is chosen. In this work, micro indentation experiments were performed on a twinning induced plasticity (TWIP) steel and the respective force-displacement curves were obtained. These curves were subsequently used as reference for the chosen plasticity models.

2 Experiment and Simulation

The following sections explain in detail the experimental investigation performed on HSD600 TWIP steel and the simulation frameworks of the two chosen plasticity models.

2.1 Experimental investigations

The experimental investigations of the high manganese HSD600 TWIP steel were performed by Klein, et al. [1]. Firstly, the microstructure of HSD600 TWIP steel was characterized by electron back scatter diffraction (EBSD), of which the average equivalent grain size was found to be 8.6 μm. The data obtained from the microstructure analysis, results like the crystallographic orientation of the indented grain, were used as input in the CPFEM model. Secondly, micro-indentation tests were performed on HSD600 TWIP steel using a Vickers indenter. The specimens were subjected to a maximum load of 1 N for a loading cycle of 6 seconds and the applied load was gradually reduced during the following unloading cycle of 6 seconds. The load-displacement curves obtained from the micro-indentation tests were used as the basis to validate and compare the results from the FEM simulations.

2.2 Simulation Framework

For the isotropic material model, the Johnson-Cooke material model (JC-model) was employed. This computational model for flow stresses include the effects of strain hardening, strain rate hardening and thermal softening. The von Mises flow stress σ, is expressed as the product of the three uncoupled terms,

$$\sigma = [A + B(\varepsilon)^n]\left[1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right]. \tag{1}$$

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In here, A is the quasi-static yield stress, B is the modulus of strain hardening, n is the work hardening exponent, C is the strain rate sensitivity and m defines the temperature sensitivity. The material parameters were initially obtained from [1,2], although parameter optimisations were performed to obtain a better fit with respect to the experimental results. The simulations were performed using the commercial FEM program Abaqus/Standard (version 2019) with the optimised JC-model parameters listed in Table 1.

Table 1: Optimised isotropic Johnson-Cook material parameters

A (MPa)	B (MPa)	C	n	m
619.96	1642.68	0.098	0.29	1.402

For the anisotropic material model to predict the response of the polycrystalline material, the whole material is approximated by smaller, periodically repeating representative volume elements (RVE). The RVE was generated based on the average grain size and texture obtained from the EBSD analysis. The crystal plasticity model employed to reproduce the plastic deformation in the RVE is implemented based on the model described in [3]. The flow rule that expresses accumulative shear rate at each slip system α is given by,

$$\dot{\gamma}_\alpha = \dot{\gamma}_0 \left| \frac{\tau^\alpha}{\hat{\tau}^\alpha} \right|^{p_1} \operatorname{sgn}(\tau^\alpha) \tag{2}$$

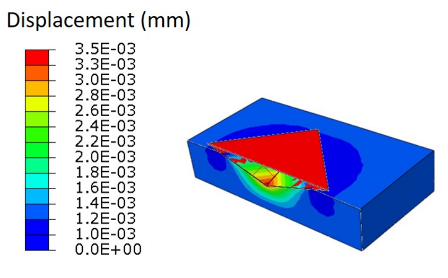
where $\dot{\gamma}_0$ is the reference shear rate, p_1 is the inverse of the strain rate sensitivity, τ^α is the resolved shear stress and $\hat{\tau}^\alpha$ is the slip resistance, which describes the hardening behaviour of the material. Simulations were performed using Abaqus/Standard through a user defined material subroutine with the following optimized parameters.

Table 2: Optimised parameters for HSD600 TWIP steel used in the CPFEM simulations. The elastic constants were obtained from [4]

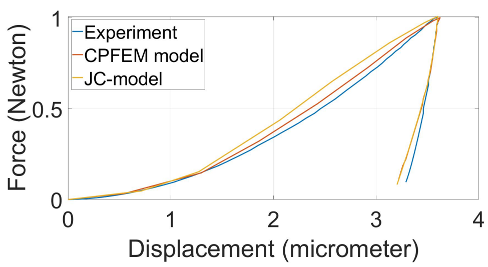
C_{11} (GPa)	C_{12} (GPa)	C_{44} (GPa)	p_1	p_2	$\hat{\tau}_0^\alpha$ (MPa)	$\hat{\tau}_f$ (MPa)	h_0 (MPa)	$\dot{\gamma}_0$ (s^{-1})
174	85	99	13	2.25	200	900	1600	0.001

3 Results and conclusion

Fig.1(b) shows the force-displacement curves from the micro-indentation experiment of HSD600 TWIP steel, in comparison to the simulation results of the JC-model and the CPFEM model. On the first glance, both models show a good agreement with the experimental results and closely predict the maximum displacement of 3.6 μm at a maximum load of 1 N. On looking closely at the material response during the loading cycle, both models show similar response during the elastic domain up to a displacement of 1.5 μm. As the curves progress towards the plastic domain, there is a divergence of the simulation results compared to the experimental result. The fitting to the experimental data is much better for the CPFEM model when compared to JC-model, because the CPFEM model incorporates explicitly the polycrystalline micro-structure in contrast to the isotropic JC-model.



(a)



(b)

Fig. 1: (a) Maximum displacement plot at maximum load; (b) Comparison of force-displacement curves between Experiments, CPFEM model and JC-model

However, the CPFEM model has to be further extended to include the twinning deformation mechanism which is typically observed in TWIP steel for improved prediction of the mechanical behaviour. An extension to this comparative study will be done for a single grain scratch process, to understand the capabilities of both models in describing the complex material removal mechanism.

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