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Cutting simulations of two gear steels with microstructure dependent material laws

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Abstract

Within this work, a multiscale approach is presented investigating the effect of the ferrite-pearlite microstructure after annealing on the subsequent machining process of a steel gear. The case-hardening steel 18CrNiMo7-6 and a cost efficient alternative with reduced Cr and Ni content have been studied. Based on an advanced microstructure characterization an effective Johnson-Cook hardening law is derived for both steel grades via homogenization and is used in subsequent orthogonal cutting simulations based on the Coupled Eulerian-Lagrange approach. Machinability predictions are validated by comparing with cutting experiments proving the adopted multiscale approach.

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Keywords: Orthogonal Cutting; Microstructure Characterization; Multiscale Modelling; Homogenization; Johnson-Cook Material Law.

1. Introduction

Hot-forged steel gear wheels are widely used e.g. in wind energy converters. Their manufacturing process chain involves various process steps such as continuous casting, hot rod rolling and forging, followed by a direct annealing to produce a ferrite-pearlite microstructure suitable for machining the gear preform.

In this study, two different steel grades are retained to manufacture gear preforms: the reference 18CrNiMo7-6 alloy, commonly used in automotive gears, and a lower cost variant. Indeed, in order to reduce the production costs and increase its performance, a variant, named “substitute”, has been developed recently by removing the expensive Ni, reducing Cr and adding Mn and Mo [1]. In order to investigate the impact of their chemistry and ferrite-pearlite microstructure after annealing on the subsequent cutting process step, predictive micro-models have to be established and integrated into a comprehensive virtual simulation platform [2]. Such platform allows the consideration of all relevant phenomena at the micro-scale within the macro-simulations of the gear production.

As extreme conditions (high strain rates, elevated temperatures) occur during the cutting process, specific effective material laws of the steel grades have to be derived for the orthogonal cutting simulation. One of the common models is the Johnson-Cook (JC) model [3], in which the strain hardening, the strain rate and temperature dependent material parameters are determined by fitting experimental dynamic flow curves at various strain rates and temperatures. These constants do not include microstructure dependent parameters such as grain size, phases and dislocation densities, although they influence the material dynamic response [4-5].

Thus, in the present study, the aim is to derive microstructure dependent hardening parameters of the JC model. To achieve this goal, material models have to be specified for each involved phase at the microscale. Experimental characterization of both

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steel grades, outlined in section 2, determines their microstructural features (grain size, the interlamellar spacing, pearlite content) and identifies the nature and shape of the inclusions in the ferrite matrix. As pearlite is a eutectoid phase mixture, composed of alternate ferrite and cementite lamellae, three different scales have been distinguished for the ferrite-pearlite steel gear grades: the *microscale* where e.g. the pearlite is modeled by a repetition of ferrite/cementite bi-lamellas, *the mesoscale* of the ferrite-pearlite microstructure and the *macroscale* of the cutting process.

A two-stage homogenization scheme is adopted here, avoiding time consuming homogenization of a single RVE with a detailed description of all inclusions and a fine lamella description within each pearlite grain. This two-level scheme has been applied in the past with success to the derivation of anisotropic flow curves of a ferrite-pearlite pipeline steel [6]. Then, at the mesoscale, effective flow curves of the ferrite-pearlite microstructures are derived for each steel grade. From these curves, microstructure dependent strain hardening parameters of the JC model are determined by least-square fitting. Eventually, to evaluate and compare the machinability of both alloys, orthogonal FE cutting simulations with the identified JC model are performed in Abaqus by means of the Coupled Eulerian-Lagrangian (CEL) formulation.

2. Materials Characterization

The chemical composition of the investigated steel grades is given in Table 1. The Georgsmarienhütte provided the reference steel while the substitute steel was cast at the Institute for Ferrous Metallurgy (IEHK) of Aachen University.

Table 1. Chemical composition in wt % of the reference 18CrNiMo7-6 and of the substitute grade.

Steel	C	Cr	Ni	Mo	Mn	Nb	Al	Cu	Si
Ref.	0.18	1.55	1.6	0.27	0.5	0	0.31	0.30	0.24
Subst.	0.21	1.3	0	0.50	1.5	0.04	0.04	0.25	0.24

As expected, the Electron Probe Micro-Analyzes (EPMA) showed after the annealing step a ferrite-pearlite microstructure in both steel grades (see Fig. 1) in the bulk of the gear preforms. The lamellas of ferrite and cementite in the pearlite of the substitute grade are not so parallel and present some wrinkles; whereas the pearlite of the reference steel presents quasi-parallel lamellas.

EPMA images of the ferrite matrix show that small MnS inclusions exist in the 18CrNiMo7-6 alloy (see Fig. 2 a); whereas in the substitute steel small hard NbC carbides and few large CeS inclusions are detected in its ferrite matrix (Fig. 2 b and c). To identify the nature of the foreign phases in both ferrite matrices, the technique of Wavelength Dispersive X-ray Spectroscopy (WDS) was used, allowing the quantification of the chemical composition of the inclusions.

Using the image software AZtec, the number of inclusions, their shape and area are measured in microstructure windows of 1 mm^2 (see Table 2). The pearlite contents, given in Table 2, correspond to the local value at the same bulk location of both preforms. In the reference grade, 8495 MnS particles with an ellipsoidal shape are count (mean size: 0.132 μm^2). In the substitute steel 1474 small NbC carbides of ellipsoidal or prismatic shape having a mean size of 0.216 μm^2 and 198 large, quasi-spherical CeS inclusions with a mean size of 37.45 μm^2 are detected. The grain size of ferrite and pearlite is similar, so that their size is outlined together in Table 3 for both steel variants. Eventually, the lamella spacing and its extension are given also in Table 3. Compared to the 18CrNiMo7-6 steel, the substitute variant presents smaller grain sizes, a noticeable increase of pearlite content and a smaller interlamellar spacing, which induce a hardener flow behavior.

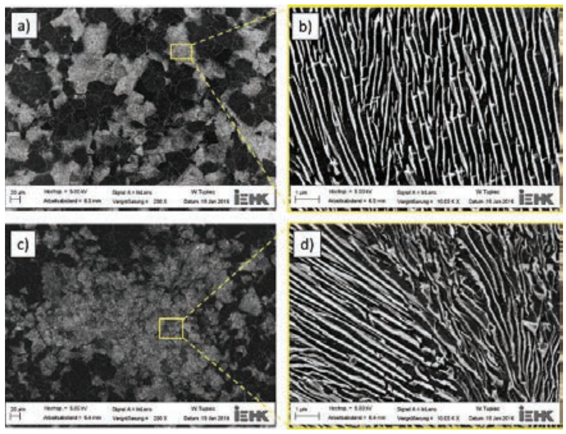

Fig. 1. EPMA analyses of the annealed 18CrNiMo7-6 steel a) and b) and of the substitute grade c) and d).

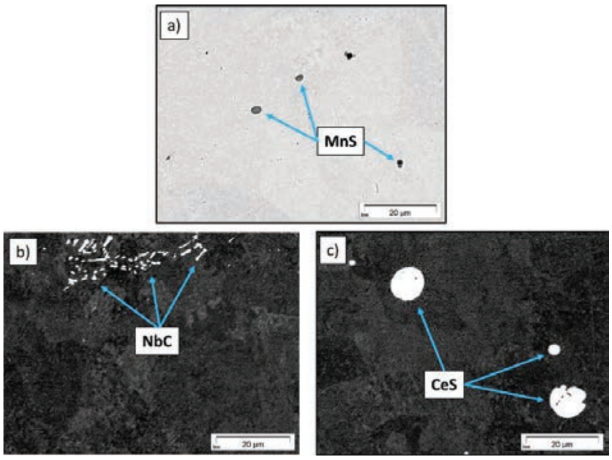

Fig. 2. EPMA image of the matrix of the reference steel a) and the annealed substitute grade b, c) showing detected inclusions.

Table 2. Phase content in wt % of both grades in the bulk of the gear preform.

Grade	Ferrite	Pearlite	Inclusions		
			MnS	NbC	CeS
Ref.	61	39	0.13	-	-
Subst.	51	49	-	0.021	0.322