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Modelling of austenite transformation along arbitrary cooling paths

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ABSTRACT

A computational model based on the Johnson-Mehl-Avrami-Kolmogorov equation for simulating the onset and kinetics of austenite to bainite and martensite transformation has been fitted to experimental continuous cooling data for two different steels. We investigated how deformation below recrystallization temperature affected the transformation onset and kinetics in comparison to the same steel in the undeformed state. The fitted model can be used to simulate phase transformations occurring when the steel is cooled along any cooling path. The model can be fully coupled to heat transfer and conduction simulations in order to optimize cooling practice, for example in industrial thermomechanical processing of steel. The fitted model can also be used to predict the hardness of the steel after cooling.

1. Introduction

In order to be able to control the final mechanical properties of hot-rolled steels, it is important to understand how prior deformation below the no-recrystallization temperature and subsequent fast cooling affect the transformation of austenite into bainite and martensite, as well as how the different phase fractions affect the mechanical properties of the steel. Since the deformation affects the subsequent transformations during cooling, a model which can be fitted to describe the effects is needed. There exist a large number of computational models, which can be used to calculate the austenite decomposition during cooling. Two main types of kinetics models are frequently used, namely the Kirkaldy-Venugopalan model, e.g. [1–4] and the Johnson-Mehl-Avrami-Kolmogorov (JMAK) type model, e.g. [5–12].

In this study, fresh attempts have been made to computationally simulate the effect of deformation on phase transformation by calculating the transformation onset for an arbitrary cooling path and fitting the widely used JMAK equation and Koistinen-Marburger type equation [13] to a discrete sets of experimental data to describe the kinetics after the onset. To calculate transformation onset for an arbitrary cooling path, a method described in Refs. [14–19] is used. For cooling paths leading to mixtures of bainite and martensite, we need to be able to model the case when not all of the austenite is transformed into bainite. Therefore we use the differential form of the JMAK equation [7,8] which includes description for the maximum fraction of bainite that can be transformed at different temperatures. We apply the functional form for the rate parameter obtained from comparison to experimental bainite transformation rate [20]. The aim of the present model is that it can be used in predicting the onset and kinetics of phase transformations and also the hardness of the steel, when it is cooled along any linear or nonlinear cooling path. The model has been fitted to data for two different steels which were either in the undeformed (i.e. recrystallized) or deformed condition, i.e. 0.6 compressively strained below the no-recrystallization temperature Tnr.

The aim of this article is to describe the applied computational method. In the current article the model parameters have been fitted to each case separately. If the presented model is fitted to a large number of different experimental cases, it can be used to investigate systematically how the parameters are affected by the deformation. However, since the exact parameter dependence on deformation conditions and/or steel chemistry, precipitation of the alloying elements etc. requires dedicated experimental programs, this will be the focus of future studies, while the current article provides the computational and theoretical framework that can be used in such studies.

Once the model has been fitted for the corresponding deformation conditions, it is useful in controlling the final mechanical properties of hot-rolled steel by enabling the design of an optimized cooling path commensurate with the actual direct quenching practice. Since the model has been fitted for two steels subjected to two different conditions (deformed below recrystallization temperature vs. undeformed), we can see how the exact deformation condition described here affects the transformation rate for the steels. In addition, since the more detailed microstructure models have to produce correct macroscopic transformation behavior, the fitted model parameters provide information on the possible ranges of parameters in more detailed microstructure models, such as a cellular automata model.

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Table 1
Chemical compositions (wt.%) of the experimental steels along with their M_S [21] and Tnr [22] temperatures.

Steel	C	Si	Mn	Al	Cr	Mo	Ti	Nb	Ni	V	Cu	B	M_S	Tnr
1	0.20	0.34	0.72	0.06	1.00	0.48	0.033	0.002	1.01	0.004	0.013	0.0029	412	881
2	0.20	0.34	1.48	0.06	0.24	0.01	0.031	0.032	1.01	0.004	0.011	0.0028	401	987

2. Materials and experimental

2.1. Compositions of experimental steels

The chemical compositions of the two boron-bearing 0.2 C steels selected for this study are given in Table 1. While Steel 1 has been alloyed with about 1% Cr, 0.48% Mo and relatively lower Mn (0.72%), Steel 2 is microalloyed with 0.032% Nb and has a higher level of Mn (1.48%) and less Cr (0.24%). Both steels were microalloyed with approximately 30 ppm boron, which was protected from reaction with nitrogen (about 40 ppm) by the addition of ≈0.03% Ti, while Si (0.34%) and Ni (1%) were maintained at the same levels for both the steels. Impurity elements like S and P were controlled to below 50 ppm for both the steels.

The steels were cast as 70 kg slabs (500 × 300 × 55 mm) at Outokumpu Stainless Oyj, Tornio, Finland. They were subsequently homogenized and hot rolled at the University of Oulu to 12 mm thick plates. Also included in Table 1 are the martensite start temperature (M_S) [21] (pp. 82–126), and the no-recrystallization temperature (Tnr) [22].

2.2. Dilatation measurements

CCT diagrams were determined with the aid of dilatation measurements using a Gleeble 1500 thermomechanical simulator. Cylindrical specimens of dimensions 6 mm dia × 9 mm were machined from solution treated and water quenched laboratory rolled samples. Two types of dilatation tests were made: with or without prior strain. In the case of straining, samples were heated at 20 °C/s to 1100 °C, held for 4 min, cooled to 850 °C, held 10 s, and then compressed with three hits each having a strain of ~0.2 at a strain rate of 1/s. The time between hits was 25 s. The specimens were then held 25 s before cooling at various linear rates in the range 1.5–48 °C/s, Fig. 1. For comparison, another set of specimens was reheated in a similar manner, cooled at 2 °C/s to 1000 °C and held for 2 min prior to cooling. These two sets of simulation experiments are meant to simulate water cooling (quenching) after hot rolling with high finish rolling temperatures and after controlled rolling finishing at low temperatures below Tnr.

Vickers hardness measurements were carried out on all the specimens using a 5 kg load. Dilatation curves were supplemented in some cases with light optical examinations of the final microstructures. This allowed the presence of small quantities of polygonal ferrite to be ascertained when ferrite formation was not clear on the basis of the dilatation curves alone.

Analysis of dilatation curves showing percent change in diameter vs. temperature was carried out both for unstrained and 3x0.2 strained austenite. Austenite decomposition into ferrite, bainite, martensite or a mixture of these phases can be ascertained by the inflexions in the dilatation curves, as described elsewhere [23]. CCT diagrams were plotted from the dilatation data to delineate the effect of cooling rate and prior strain on the phase transformation characteristics, as revealed by the dilatation curves.

3. Calculations

Our objective is to construct a model, which can be parameterized using experimental dilatometry data, and can give an estimate for the austenite to bainite and/or martensite transformations for *any* cooling path, as well as an estimate for the hardness of the steel after cooling. The model is based on well known phenomenological equations [5,12,13,20], and it is parameterized using continuous cooling data.

3.1. Calculation of transformation onset and kinetics for any cooling path

The volume fraction χ of bainite transformed from austenite during time t at a given temperature can be calculated with the JMAK equation [12], which includes the transformation start time, Eq. (1)

$$\chi = [1-exp(-[k(t-t_{1\%})]^n)]\chi_{max} \quad (1)$$

where $t_{1\%}$ is the start time required for 1% transformation of bainite, which includes the incubation time. The function k and exponent n have to be determined by fitting to experimental data. χ_{max} is the maximum volume fraction that can be transformed, which can be 100% in the temperature regime where martensite does not form. While the parameter n is assumed to be constant, k depends on temperature T, as described later.

To calculate an estimate for the start of the transformation and the subsequent transformation kinetics for any cooling path, the cooling path is divided into small isothermal segments and the transformation start time is calculated by applying the Scheil's additivity rule and the so-called ideal TTT in a similar way as in [15,16,18]. The main idea of

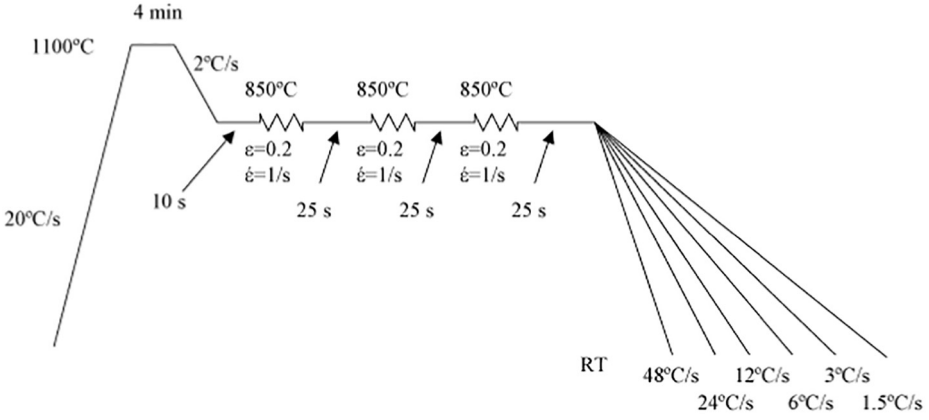

Fig. 1. Simulated dilatation experiments to construct the CCT diagrams – tests after 3 × 0.2 prior strain.