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The development of ultrafine-grained hot rolling products using advanced thermomechanical processing

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ABSTRACT

The aim of the work is development of industry guidance concerning production of ultrafine-grained (UFG) High Strength Low Alloy (HSLA) steels using strain-induced dynamic phase transformations during advanced thermomechanical processing. In the first part of the work, the effect of processing parameters on the grain refinement was studied. Based on the obtained results, a multiscale computer model was developed in the second part of the work that was subsequently used to predict the mechanical response of studied structures. As an overall outcome, a process window was established for the production of UFG steels that can be adopted in existing hot rolling mills.

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1. Introduction

For metal forming it is generally assumed that the shape, properties and dimensions of the final product are directly controlled by the mechanical state of the process and material mechanical response represented by the flow stress, but in practice the microstructure evolution can change the situation drastically. The evolution of the microstructure is connected with physical processes taking place in the deformed steels, such as recrystallization, precipitation and phase transformation, depending on the chemical composition and particular parameters of the metal forming process, i.e. the strain, strain rate and temperature. One example of a modern structural material in which several microstructural phenomena are utilized is ultrafine-grained (UFG) microalloyed steel [1,2]. At present, several different branches of industry are interested in UFG steels [3]. The superior properties of these steels result from microstructural design that utilizes the effects of both processing and work hardening. The development of UFG microalloyed steels will require unique second phase elements/microstructure combinations to achieve the desired properties. A large volume fraction and fine dispersion of a second phase effectively increase the work hardening rate by promoting the accumulation of dislocation around interphase boundaries [4]. Interpreting these microstructures can be difficult with traditional light, transmission or scanning electron microscopy. Electron backscattered diffraction (EBSD) analysis appears to offer a means to quantify such complex microstructures more effectively and will be used in the present study.

Advanced UFG steels are currently the fastest growing group of structural materials. However, progress in their further development requires the use of modeling processes to understand both microstructure development and the mechanisms responsible for the final mechanical properties [5,6]. These models must be capable of predicting deformation conditions at critical locations in the process and over a wide range of steel grades. The real challenge for state-of-the-art modeling of material behavior is the process of UFG microalloyed steel manufacturing. There is a growing market for UFG microalloyed steels, and the factors that encourage this expansion are numerous and complex. In the hot working of niobium-micro-alloyed steels, the initial microstructural inhomogeneity of austenite has a significant influence on the metallurgical state of the finished product. This situation may strongly affect the damage behavior of materials [7]. Monitoring the impact of hot deformation conditions on the microstructure development, precipitation process, and resulting defects (i.e., sub-grains, dislocation structure, and deformation bands) under industrial conditions is difficult and expensive. However, using well constructed and experimentally verified models of microstructure development and strengthening mechanisms, it is possible to control the inhomogeneities in such a way that optimal mechanical properties can be expected in a precise location [8]. These possibilities seem to be

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very attractive in hot rolled or forged shape products, as well as in near shape casting or compact strip production.

In recent years modeling of the phenomena discussed above started to be employed directly in such advanced thermomechanical processing (ATP) as intercritical rolling (i.e., deformation in the austenite-ferrite phase region) or processing based on strain-induced dynamic transformations (SIDT) and in particular strain-induced dynamic ferrite transformation (SIDFT) [9]. In literature, these two terms are used to talk about Strain Induced Dynamic Transformations. It may be used to describe both the austenite to ferrite and reverse dynamic transformation of ferrite to austenite. The term SIDFT is used specifically when one talks about dynamic transformation of austenite to ferrite upon cooling. Here, the idea is to increase the as-hot rolled strength by increasing austenite pancaking, thereby refining and work hardening the ferrite. Deformation controlled austenite morphology or processing in the two-phase region seems to produce higher quality products, which has drawn the attention of scientists. However, more work is needed to maximize the effects of the physically based multiscale modeling in real industrial conditions of metal forming of UFG microalloyed steels. In addition, it is still not well understood how the grain size of austenite and how the history of deformation affect the phase transformation of products. Particular interest should be put on the critical stored energy for triggering the strain-induced ferrite transformation.

Accordingly, the goal of the present study is to investigate the intricate relationship between thermomechanical processing – particularly SIDT – and microstructure refinement of UFG microalloyed steels. This paper will discuss also the direct benefits of computer modeling that can be obtained when multiscale models that have been verified in laboratory conditions are implemented in the real industrial conditions of ATP.

2. Experimental

In order to provide guidance to the metal forming industry on the procedure of finding a process window on how to maximize the grain refinement in microalloyed steels subjected to hot plate rolling, two steel grades were examined. Their basic chemical compositions (in wt%) are: 0.07C/0.29Si/1.36Mn/0.06Nb/0.03Ti/0.0098N/0.003B (Steel MA-I) and 0.08C/0.31Si/1.67Mn/0.06Nb/0.018Ti/0.0316N/0.26Mo (Steel MA-II). In both cases, Nb was used as the most important microalloying element to control the dynamic transformation of austenite. Furthermore, addition of B or Mo, which significantly increased hardenability, was used to expand the thermomechanical processing window.

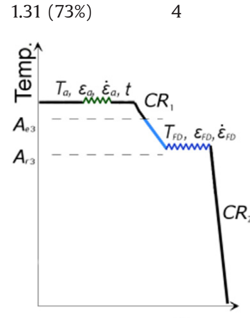
In the present study, laboratory scale through-process modeling of the rolling process was conducted using three types of experiments: flat rolling, torsion and uniaxial compression tests.

Firstly, laboratory plate rolling trials were implemented to study the general effect of processing parameters on grain refinement and level of both microstructure and properties inhomogeneity across the plate thickness. For that purpose, laboratory single pass rolling was carried out using steel MA-II according to deformation schedules summarized in Table 1. Samples with initial dimensions of $140 \times 40 \times 15$ mm^3 (length, width, thickness) were heated to the reheating temperature Ta, held for 300 s then cooled to deformation temperature TD and rolled. After deformation, samples were cooled down to the room temperature using different cooling rates.

Subsequently, in order to study the microstructural and mechanical inhomogeneity of rolled specimens, Vickers hardness measurements were carried out according to the schematic shown in Fig. 3c. The measurements were performed in the middle of the cross section (in transverse direction) and near the surface layer. Next, to estimate the mechanical properties inhomogeneity level, the diagrams of HV5 vs. distance from the origin were evaluated. Finally, based on these results, the process of developing the dynamic ferrite transformation was carried out using two types of plastometric tests: torsion and uniaxial compression. Due to the fact that in the flat rolling process there is a gradient in both microstructure and strain, it has been decided to model the phenomena occurring near the surface of the stock using a plastometric torsion test as it replicates the area of the stock that is close to the plate surface (this area of the rolled stock is subject to shear deformation as a result of the friction between the metal stock and the roll).

For this purpose, standard cylindrical torsion samples with strain gauge diameter of 10 mm and gauge length on 20 mm were machined from steel MA-I. To replicate phenomena occurring in the middle of the rolling stock where plane strain compression dominates, uniaxial compression tests were carried out on MA-II steel. Cylindrical specimens with diameter of 10 mm and height of 15 mm were used. In both cases, specimens were deformed

Table 1
Thermomechanical schedules used in the present study.

Test	Material/sample	T_a (°C)	T_D (°C)	Strain (height reduction)	CR (°C/s)	Ferrite grain size d (*standard deviation*) (μm)
Rolling	MA-II-1	1200	1000	1.05 (65%)	0.2	12.34 (6.11)
	MA-II-2	1200	800	1.05 (65%)	0.2	10.09 (6.01)
	MA-II-3	1200	800	1.05 (65%)	4	8.53 (5.05)
	MA-II-4	1200	840	1.20 (70%)	4	5.28 (3.53)
	MA-II-5	1000	840	1.31 (73%)	4	4.13 (2.14)
	MA-II-6	1000	800	1.31 (73%)	4	3.02 (1.53)
Torsion + uniaxial compression	MA-I-1	T_a – austenitisation temperature; ε_a,$\dot{\varepsilon}_a$ – 1st deformation and strain rate; t – post deformation holding time; CR – cooling rates; T_{FD}, ε_{FD}, $\dot{\varepsilon}_{FD}$ – final deformation temperature, strain and strain rate respectively				
	MA-I-2					
	MA-I-3					
	MA-I-4					
	MA-I-5					
	MA-I-6					
	MA-I-7					
	MA-II-8					
	MA-II-9					
	MA-II-10					
	MA-II-11					
	MA-II-12					
	MA-II-13					
	MA-II-14					

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