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Development of the multi-scale model of cold rolling based on physical and numerical investigation of ferritic–pearlitic steels

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ABSTRACT

With the aim of developing dual phase (DP) microstructure using a continuous annealing process, four steels with different chemical compositions were investigated in the axisymmetrical plastometric tests and during the cold rolling process. The rheological model for these steels was developed using the results of the plastometric tests and application of the inverse analysis. Load–displacement curves were used to identify parameters of the rheological model, which was incorporated into the finite element code for rolling. First, the model was validated with experiments realized on the laboratory cold rolling mill. Calculated loads were compared with experimental data and good agreement was obtained. Beyond this, metallographic analysis was performed and deformation of the ferritic–pearlitic microstructure during rolling was investigated. Finally, the generated results were combined in the form of the multi-scale numerical model based on the digital material representation approach capable of investigating local microstructural inhomogeneities.

1. Introduction

Expectations from the automotive and aerospace industries regarding new metallic materials with exceptional properties are the driving force for the development of innovative experimental approach and multi-scale numerical modelling. Such materials have to meet increasing requirements regarding weight/property ratio, as well as combination of high strength and high ductility. As a result, extensive development of the modern steel grades has been observed during recent years e.g. third generation of AHSS (*Advanced High Strength Steels*) [1,2], bainitic, nano-bainitic steels [3], etc. Various mechanisms which refine grain size and improve mechanical properties of steels were investigated and identified [4–6].

One of the most important categories of the new steel grades is the group of AHSS. The major advantage of these steels is that they provide a possibility of reducing the automobile weight (increase of the fuel efficiency), while maintaining or even increasing their safety under exploitation conditions (crash

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worthiness). Particular focus in the present research is put on DP (*dual phase*) steel, as a representative of the AHSS group.

The DP strips are characterized by a combination of high strength, good formability, high bake hardenability and crash worthiness. These properties are derived from the properly designed microstructure consisting of ferritic matrix (around 70–90%) and hard martensitic phase islands (around 10–30%). The most direct way of obtaining DP ferritic–martensitic structures is continuous annealing of a steel in the ferrite–austenite ($\alpha + \gamma$) two-phase region, called intercritical annealing, followed by controlled cooling, causing the austenite to transform into martensite [7]. This advanced process of DP microstructure formation involves heating and soaking of cold rolled sheet in the intercritical temperature range, followed by two- or three-stage cooling. Experimental design of this process is usually time consuming and expensive. That is why a lot of attention has been recently paid to the development of accurate numerical models of the continuous annealing. Such models can be used to support design of efficient manufacturing cycles, which allow to obtain required morphology of the DP steel. Knowledge concerning microstructure of the steel after cold rolling, including information concerning morphology of ferrite and perlite and distribution of the energy accumulated during deformation is crucial for further realistic modelling of the annealing.

Therefore, this work is focused on modelling of one of the stages of the DP steel manufacturing cycle, namely cold rolling of ferritic/pearlitic strips. The main aim of this research is to develop a reliable multi-scale finite element cold rolling model that can predict local inhomogeneities occurring along microstructural features. The key aspect in the model development was confirmation of its accuracy and reliability, and such a confirmation was made possible by model experimental verification and validation.

2. Development of the material models

2.1. Testing materials

Four experimental steels characterized by different chemical composition were designed for the purpose of the investigation and were cast with VSG 100S laboratory furnace into 70 kg slabs. The chemical composition of the heats is given in Table 1.

The cast material was then forged into squared bars 35 mm × 35 mm in cross section. The forging temperature was held in the range of 1200–1000 °C. Next, bars were rolled on the laboratory reversing rolling mill into 3.5 mm thick plates. The soaking temperature prior to rolling was 1200 °C and the holding time at this temperature was 30 min. The rolling was conducted in eight passes with pass reduction in the range 15–25%. The finish rolling temperature was approximately 870 °C. After the last rolling pass plates were transferred into the resistance heated furnace and held at 600 °C and allowed to cool after switching off the heating in order to simulate the slow cooling in a coil. The average cooling rate in the range 800–500 °C was around 50 °C/h. However, due to the low thickness, the temperature of the plates dropped slightly below 600 °C during transferring to the furnace. Examples of microstructures from investigates plates after cooling to ambient temperature are shown in Fig. 1. A drop in temperature of the plates during transferring from the run out table to the furnace caused the occurrence of small islands of bainitic phase in the microstructure.

The increase in carbon and alloying elements content in the experimental steels resulted in the increase of bainite volume fraction, which is associated with changes in the hardenability. It is noteworthy that different bainite morphologies were developed in the plates that can be categorized into fine (Bainite 1) and coarse bainite (Bainite 2). The constituents of the plates' microstructure are indicated with arrows in Fig. 1. Fig. 2 presents the results of the measurement of the volume fraction of the samples' microstructure constituents, as well as ferrite grain size (equivalent diameter). Measurements were performed with Automatic Image Analyser combined with light optical microscopy (LOM). The results of mechanical properties measurement of the plates are given in Table 2. The increase of bainite content and microstructure refinement caused an increase in strength of the plates. The high strength of the plate from heat S246 is due to the highest volume fraction of bainite in this plate and ferrite grain size refinement in comparison to other steels.

As seen in Table 2, the as hot-rolled microstructure of laboratory heats S243–S246 is characterized by increasing content of bainite due to the chemical composition effect (Fig. 2). The difference in the initial microstructure will have a substantial effect on the cold rolled microstructure presented in subsequent sections.

The hot rolled steel plates were further used during laboratory plastometric investigation to evaluate their hardening behaviour on the basis of the inverse analysis approach.

2.2. Inverse analysis

Due to various disturbances (effect of friction, deformation heating, etc.), different plastometric tests involve irregular strain distribution and other deformation inhomogeneities. Thus, a direct comparison of results of various tests is not possible. It is shown in a number of publications [8–10] that application of the inverse analysis to the interpretation of tests minimizes the influence of these disturbances and allows flow stress to be determined independent of the method of testing. The inverse algorithm developed at AGH and described in [8]

Table 1 – Chemical composition of the investigated steel, wt%.

	C	Si	Mn	P	S	Al	Cu	Cr	Ni	Mo	V
S243	0.09	0.10	1.42	0.011	0.010	0.053	0.03	0.35	0.01	0.005	0.001
S244	0.13	0.10	1.50	0.011	0.011	0.026	0.02	0.23	0.02	0.005	0.001
S245	0.08	0.12	1.74	0.010	0.010	0.028	0.04	0.56	0.02	0.01	0.001
S246	0.08	0.12	1.74	0.009	0.010	0.025	0	0.23	0	0.43	0.001