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Multi scale cellular automata and finite element based model for cold deformation and annealing of a ferritic–pearlitic microstructure

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ABSTRACT

Numerical modelling of microstructure evolution during cold rolling and the subsequent annealing of a two phase ferritic–pearlitic sample under an α/γ phase transformation regime is the subject of the present work. The multi scale model based on the digital material representation taking into account exact representation of the microstructure morphology is used in the research to investigate inhomogeneous strain distribution during cold rolling. Obtained results are then incorporated into the discrete cellular automata model of static recrystallization. Data transfer between the finite element and cellular automata models is performed by means of the interpolation method based on the Smoothed Particle Hydrodynamic. Details about the developed cellular automata model of static recrystallization are presented within the paper. The complete multi scale model is finally validated against a series of experimental cold rolling and subsequent annealing operations. Various annealing conditions were used as case studies to prove robustness of the developed numerical approach.

1. Introduction

The main driving force of innovative experimental and numerical research is the significant need for new metallic materials manifested by the automotive and aerospace industries. Such materials have to meet increasing requirements regarding weight/property ratio, as well as a combination of high strength and high ductility. As a result, dynamic development of the modern steel grades has been observed over the last years. The number of new steel grades which have been developed since the year 2000 has been increased, which is clearly visible in Fig. 1. Currently, a wide range of innovative steels (third generation of AHSS (*Advanced High Strength Steels*), Bainitic, nano-Bainitic, etc.) as well as other metallic materials, e.g. aluminium, magnesium, titanium or copper alloys, is being developed in research laboratories around the world [1–4]. Complex mechanical and thermal cycles are applied to obtain very sophisticated microstructures with a combination of various micro scale features: large grains, small grains, inclusions, precipitates, multi-phase structures, etc. These microstructural features and interactions between them at the micro-scale level during manufacturing or exploitation stages can eventually lead to superior material properties at the macro-scale level. Finally, some of these innovative steels developed in laboratory conditions find their application in manufacturing auto body components in industrial conditions [5–7].

One of the most important groups of new steel grades is the AHSS group. A major advantage of these steels is that they provide the possibility of reducing automobile weight (increasing fuel efficiency), while maintaining or even increasing their safety under exploitation conditions (crash worthiness). Particular focus in the present research is put on DP (*Dual Phase*) steel as a representative of the AHSS group.

DP thin sheets with tensile strength of 400–1200 MPa have been successfully applied in the production of automobile structural parts because they are characterized by a combination of high strength, good formability, high bake hardenability and crash worthiness. These properties are the result of properly designed microstructure consisting mainly of ferrite matrix (around 70–90%) and hard martensitic phase islands (around 10–30%), as seen in Fig. 2.

The most direct way of obtaining DP ferritic–martensitic structures is the annealing of steel in the ferrite–austenite ($\alpha + \gamma$) two-phase region, called intercritical annealing, followed by controlled cooling, causing the austenite to transform into martensite [9–11]. A more advanced process of DP microstructure formation, called continuous annealing, involves heating and soaking of cold rolled sheets in the intercritical temperature range, followed by two-stage cooling. The first stage with moderate cooling rate is intended to produce the required volume fraction of ferrite in the microstructure. The aim of the second stage is to transform the remaining austenite into martensite. However, experimental

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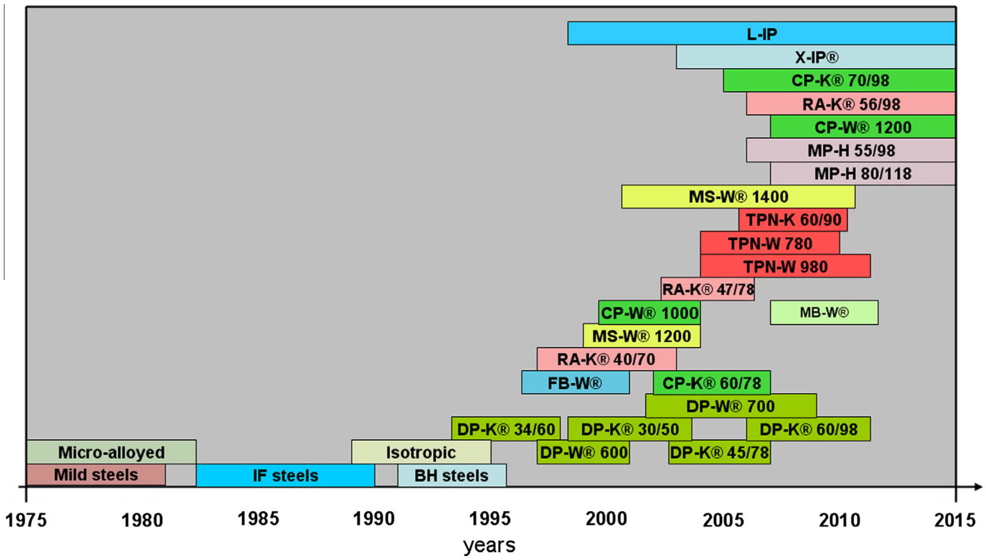

Fig. 1. New steel grade development chart in the ThyssenKrupp Steel company (DP – dual phase, BH – baking hardening, IF – interstitial free, CP – complex phases, MS – martensitic, FB – ferrite–bainite, RA – retained-austenite, TPN – three-phase nano, X-IP – iron-manganese TWIP, L-IP – light induced plasticity) [8].

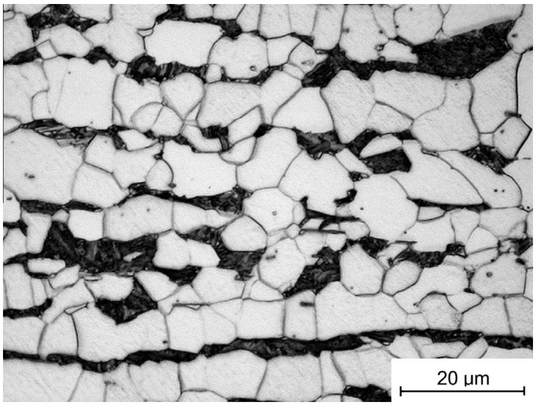

Fig. 2. Dual phase steel containing 27% of martensite: white phase – ferrite, dark phase – martensite; LOM (*Light Optical Microscopy*).

process design is usually time consuming and expensive, which is why much attention has been recently paid to the development of accurate numerical models. Such models can be used to support the design of efficient manufacturing cycles, which allow obtainment of the required DP steel morphology.

The investigation of the SRX (*Static Recrystallization*) phenomenon during the first stage of the process, namely the annealing of a cold deformed ferritic–pearlitic structure to the intercritical temperature range, is the subject of the present work. Firstly, the results of the experimental analysis are presented within the paper. They clearly show the importance of the proper capturing of material inhomogeneities in the numerical model in order to predict real material behavior. Secondly, the developed multi scale model combined with the SRX model is discussed in detail and compared with the obtained experimental results.

2. Experimental investigation of static recrystallization

As mentioned, the first stage in manufacturing DP steel is the cold rolling of ferritic–pearlitic microstructure followed by the SRX. This part is analyzed within the present research. A low carbon, cold rolled steel sheet, 1 mm thick was subjected to heating. The progress of the SRX at various temperatures was investigated.

Table 1
Chemical composition of experimental steel (wt.%).

C	Mn	Si	P	S	Cr	Ni	Mo	Ti	Al
0.09	1.42	0.10	0.011	0.010	0.35	0.01	0.02	0.001	0.043

The chemical composition of the investigated steel is given in Table 1. First, the material was casted into a 70 kg ingot using a laboratory vacuum induction furnace. Second, the ingot was forged into bars having a squared cross section of 45 mm × 45 mm. Next, the bars were hot rolled into a 3 mm thick plate with the use of a laboratory reversing mill and cooled in such a way to enable the development of the ferritic–pearlitic microstructure until reaching the ambient temperature. Subsequent cold rolling into a 1 mm thick sheet was also conducted using a laboratory rolling mill.

The recrystallization process was investigated using the dilatometer DIL 805A/D manufactured by Bächr Termoanalyse GmbH. The kinetics of the SRX was investigated in 1 mm × 7 mm samples cut from the cold rolled sheet parallel to the rolling direction. The initial microstructure of the sheet after cold rolling is presented in Fig. 3a. The samples were then heated to different temperatures in the range of 600–750 °C at a rate of 3 °C/s. After reaching the defined temperatures, the samples were subjected to fast cooling with nitrogen in order to freeze the microstructure. Selected scanning electron micrographs of the samples after reaching the required temperatures are shown in Fig. 3b–d. Images were taken in the middle of the samples, and this location is further tracked within the experimental as well as numerical investigation.

As can be seen in Fig. 3a, the microstructure in the cold rolled state is composed of banded, severely deformed, ferrite grains and comparably deformed aggregates of pearlite colonies. The relationship between the band width and length, called aspect ratio, is consistent with the degree of macroscopic deformation in the cold rolling process. During the heating process, the beginning of the SRX is observed at around 600 °C.

The recrystallization process is composed of two steps, namely nucleation and growth of nuclei. Looking at the partly recrystallized microstructure of the samples, one may say that the nucleation process is not clearly connected with the favorable sites, such as grain boundaries or deformation bands. Instead, the nucleation starts in the regions of maximum stored energy. Generally,