Integrated Microstructure Based Modelling of Process-Chain for Cold Rolled Dual Phase Steels

Danish Khan, Ayush Suhane, P. Srimannarayana, Akash Bhattacharjee, Gerald Tennyson, Pramod Zagade and B.P. Gautham

Abstract The properties of dual phase (DP) steels are governed by the underlying microstructure, the evolution of which is determined by the processing route. In order to design a dual phase steel with tailored properties, it is therefore important to model and design each of the process involved at the microstructure level in an integrated fashion. In this work, an integrated approach is used to predict the final microstructure and mechanical properties of dual phase steels through microstructure based modelling of cold rolling, intercritical annealing and quenching processes. Starting with a representative volume element (RVE) of initial ferrite-pearlite microstructure, cold-reduction during rolling is simulated in a FEM based micromechanics approach under appropriate boundary conditions. The deformed microstructure with plastic strain energy distribution after cold-reduction serves as input for modelling static recrystallization and ferrite/pearlite to austenite transformation during intercritical annealing using a phase-field approach. A micromechanics based quenching simulation is then used to model austenite to martensite transformation, related volume expansion and evolution of transformational stress/strain fields. The resultant microstructure with its complete state is used to evaluate the flow behavior under uniaxial loading conditions in a FEM based micromechanics approach under periodic boundary conditions. Property variation for different initial microstructure, composition and processing conditions are studied and discussed.

Keywords Micromechanics · Phase-field · Intercritical annealing · Process integration · Microstructure modelling · Phase transformation · Property prediction

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Introduction

Cold rolled dual phase steels are known for their high strength, high toughness and high formability. This makes them a suitable candidate for producing strength-relevant and crash-relevant body-in-white components having complex geometries such as cross-beams, pillars and other reinforcements [1]. This has been possible due to the multiphase nature of these steels wherein the different microstructure constituents impart varied properties to the steels. The constant pursuit of the auto-makers to cater to the increasing fuel-efficiency demands and safety regulations have led to the necessity of continual improvement and optimization of the properties and hence the microstructure of these steels.

Researchers have continuously tried to optimize the properties of the dual phase steels with new processing routes and processing conditions [2, 3]. The final properties of dual phase steels not only depend upon the individual properties of these micro-constituents but also on their morphology and distribution. On the other hand, the properties of the individual phases, their morphology and distribution depend upon the processing history of the steel. Therefore, in order to optimize the final properties of steels in a systematic way, it is not only important to optimize the individual processes involved but also the entire process-chain with explicit tracking of the microstructure evolution. With the advent of microstructure based process-structure [4, 5] and structure-property [6, 7] modelling techniques, it is now possible to model the evolution of microstructure and properties with the processing conditions. Apart from that, with more efforts being put towards solving problem through ICME route, optimizing the entire process-chains of the products in a closed-loop with systematic decision making at each decision point is the need of the hour.

The final steps of a typical processing route for the production of cold-rolled dual phase steels is shown in Fig. 1. There has been number of attempts in past for sequential integration of microstructure based process models as well as integration of process-property models. Madej et al. [8] carried out microstructure based modelling of cold-rolling of ferritic-pearlitic steels using FEM and used its plastic energy distribution output for modelling static recrystallization (SRX) during inter-critical annealing (ICA) using cellular automata in a digital material

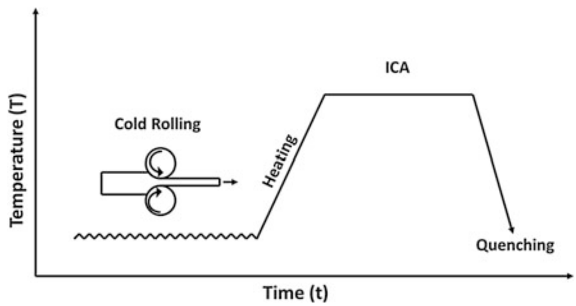

Fig. 1 A typical processing route for cold-rolled dual phase steels

representation framework. Rudinizki [9] on the other hand studied the through process modelling of production of dual phase steels by modelling ICA using phase-field approach followed by property prediction of the microstructure thus obtained using FEM based micromechanics approach. Ramazani et al. [10] modelled the process chain for dual-phase by integrating a similar phase-field approach based ICA model with FEM based micromechanics model of property prediction that took into account the effect of geometrically necessary dislocation formed during quenching on the final properties. However, none of these efforts attempt the integration of process-chain right from the cold-rolling till the final property-predictions in an ICME framework.

The present work involves the integration of microstructure based models of cold-deformation, inter-critical annealing and quenching processes to take into account the effect of each of them on the final microstructure and properties prediction of a cold-rolled dual phase steel. The focus is on the integration of models on an ICME-enabling platform that allows running the process-chain simulations in a loop with decision-making at each stage, thereby opening up the opportunity for optimizing the process-chain in a closed-loop.

Integrated Numerical Models

Figure 2 shows the integration of various micro-scale process models used in this study along with relevant phenomena modelled and related information exchange. The process-chain simulation starts with a 2D RVE of ferritic-pearlitic microstructure having certain statistics defined in terms of ferrite grain size, pearlite colony size etc. This RVE represents a typical ferritic-pearlitic microstructure obtained at the end of runout table (ROT). A typical RVE used in this study is shown in Fig. 3a. The microstructure RVE was subjected to different mechanical and thermal boundary conditions of the subsequent processes and the essential physics involved was modelled to keep track of the evolution of microstructure along with its state of stress and strain. Following sections describe the details of the various microstructure-scale process and property models used.

Cold-Rolling

Cold reduction was modelled as a plain-strain compression of the RVE under homogenous boundary conditions using a FEM model in ABAQUS^{TM}. Chemical composition based flow curves for ferrite and pearlite [11], were used as input for the model. Based on the stress and strain partitioning between ferrite and pearlite phases, plastic strain energy was calculated at each material point of the RVE. A typical plastic strain energy distribution in a ferritic-pearlitic RVE having 14% pearlite, deformed to 50% cold reduction is shown in Fig. 3b.

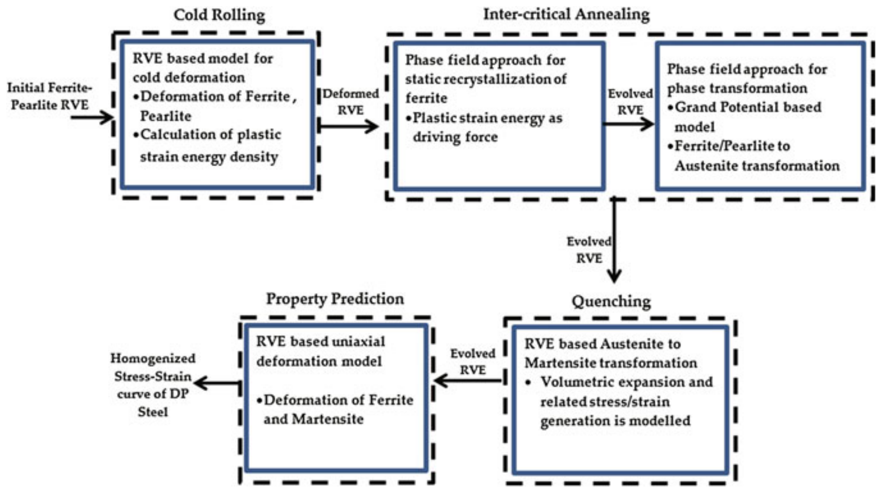

Fig. 2 Integration of various micro-scale process models along with information exchange

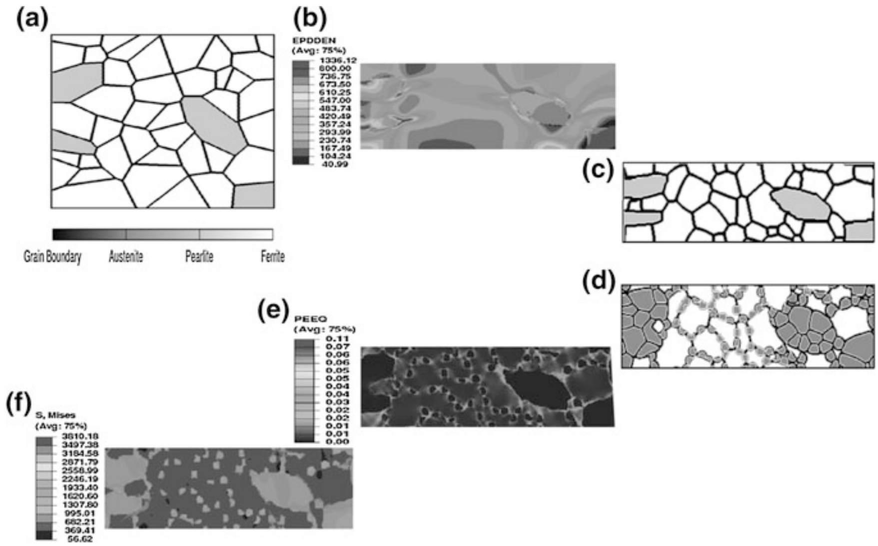

Fig. 3 Microstructures involved at different stages of micro-scale process-chain simulations. **a** Initial ferritic-pearlitic RVE. **b** Plastic strain energy density (J/mm^3) distribution in deformed RVE at the end of cold-reduction. **c** Microstructure obtained at the end of ferrite recrystallization during ICA. **d** Final microstructure obtained at the end of ICA simulation. **e** Plastic strain distribution in the microstructure at the end of quenching simulation. **f** Stress (MPa) distribution in the final ferritic-martensitic microstructure at the end of uniaxial loading

Inter-critical Annealing (ICA)

ICA involves two key microstructural phenomena viz., static recrystallization of ferrite and phase transformation from ferrite/pearlite to austenite. Two different phase-field approaches were used to model recrystallization [4] and phase transformation [12]. Stored plastic strain energy within the deformed grains from the cold-rolling model was used as the driving force for recrystallization and a grand potential difference was used as the driving force for phase transformation. Binary Fe–C was considered for the simulations assuming no recrystallization in pearlite phase which was assumed to be homogenous and hard [4]. Periodic boundary conditions were considered throughout the model. All grain boundaries were assumed to be high angle boundaries and respective orientation effects were neglected. Grain boundary properties were taken from Raabe and Hantcherli [13]. Typical microstructures obtained during ICA, isothermally held at 760 °C for 3 min are shown in Fig. 3c, d.

Quenching

In order to model the effect of volume expansion and transformation strain associated with austenite to martensite ($\gamma \rightarrow \alpha'$) transformation, and calculation of resultant residual stresses, a microstructure based quenching simulation was set-up as a FEM micromechanics model in ABAQUS™. The microstructure obtained from the phase field models of ICA serves as input for the model. Temperature profile was imposed on the microstructure as thermal load under periodic boundary conditions and the volume expansion associated with $\gamma \rightarrow \alpha'$ transformation was modelled using different temperature dependent thermal expansion coefficients [10] for ferrite and austenite/martensite. High temperature flow curves for ferrite and austenite/martensite were modelled as ratios of room-temperature flow curves, as used by Ramazani et al. [10]. Calculated plastic strain distribution at α/α' interface, due to $\gamma \rightarrow \alpha'$ transformation, at the end of quenching simulation is shown in Fig. 3e.

Property Prediction

The microstructure obtained at the end of quenching simulation, with its complete state of stress and strain, was subjected to uniaxial loading conditions in a FEM micromechanics model under periodic boundary conditions. Chemical composition dependent phenomenological work hardening models for individual phases, as developed by Rodriguez and Gutierrez [14], were used as input for the model. First order volumetric homogenisation of the calculated stress and plastic strain values

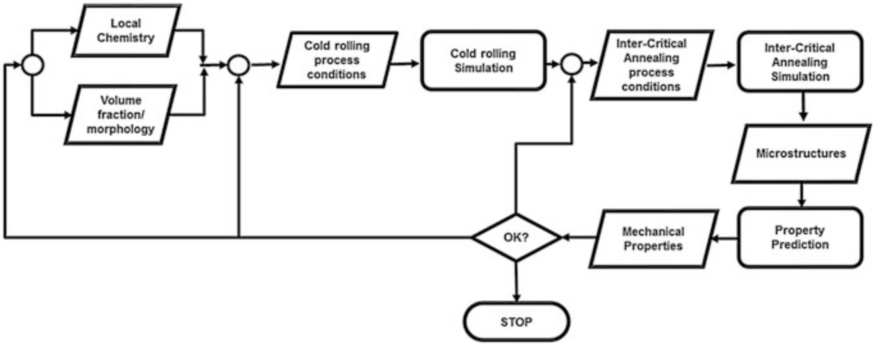

Fig. 4 Integrated work-flow of all the micro-scale models on the ICME platform, TCS PREMAP

was carried out over the entire RVE, at each time-step of the analysis, in order to calculate the uniaxial flow curve for the steel. Stress distribution in the deformed microstructure at the end of uniaxial loading is shown in Fig. 3f.

Figure 4 shows the integrated workflow of the various models on the ICME enabling platform, TCS PREMAP [15]. Such a workflow enables a systematic optimisation of the dual phase steels properties by running the process-chain simulations in a loop and enabling the user to make decisions at different stages of the process-flow in order to arrive at the most-suitable process-conditions.

Figure 5 shows the comparison of final flow curves of dual phase steels obtained after running the process-chain simulations for 50% cold-reduction followed by 3 min Inter-critical annealing at 760 and 780 °C.

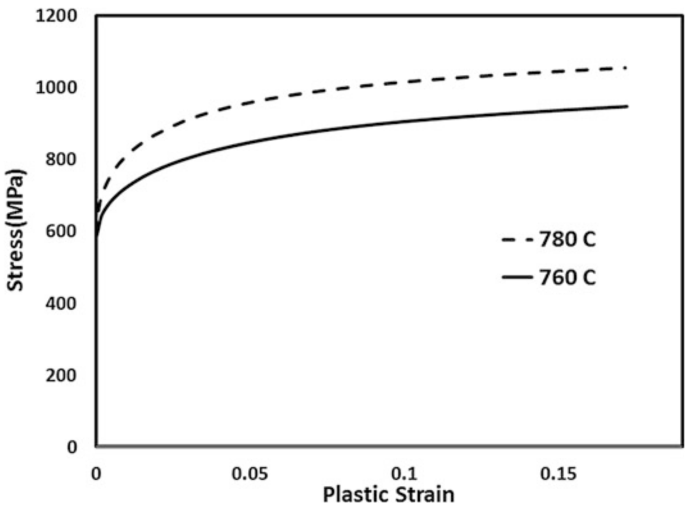

Fig. 5 Flow curves for two dual phase steels obtained after 50% cold-reduction followed by ICA at 760 and 780 °C

Summary

Cold-rolled dual phase steels are an important class of AHSS steels that are finding increasing usage in the automotive bodies in order to achieve desired targets of mass saving and safety regulations. Based on the increasing requirements of the industries, optimising the properties and hence the microstructure of these steels, in a systematic way, to find user-specific suitable combination of composition and processing conditions, is very much needed. In order to achieve this, microstructure based models for different processes and property prediction were implemented and integrated in a work-flow that enables the user to explore various processing scenarios. The idea has been demonstrated by running the process-chain models for different processing scenarios and the results have been reported.

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