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The role of aluminium in chemical and phase segregation in a TRIP-assisted dual phase steel

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ABSTRACT

In this work we demonstrate that micro-segregation patterns of alloying elements present in a high-strength TRIP-assisted DP steel after casting are retained in the microstructure throughout processing, and lead to anisotropy (banding) in the final microstructure. In particular, we have assessed the role of Al on the chemical segregation of Mn, Cr and Si during casting, and their impact on the phase transformations occurring during thermo-mechanical processing of the as-cast material. We have derived the elemental partition coefficients, based on the experimentally determined dendrite spacing and chemical profiles in the as-cast structure, and used them to derive the local austenite-to-ferrite transformation temperature. Our cellular automaton methodology to simulate phase transformations allows reliable prediction of the formation or suppression of banding in the intermediate and final microstructures for different heating or cooling rates. Our results reveal that aluminium exerts the largest individual effect of the substitutional elements on the formation of banding in these steels. Controlling micro-segregation during solidification in advanced high-strength multiphase steels is therefore critical for obtaining homogeneous mechanical properties in the final product, as it controls the phase transformations occurring during thermo-mechanical processing and therefore the final microstructure.

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1. Introduction

Increasing demands of weight reduction and improved safety in the automotive industry have led to the ongoing development of advanced high strength steel grades with increased ductility and microstructural complexity *e.g.* Transformation and Twinning Induced Plasticity steels (TRIP and TWIP respectively) [1,2], Quench and Partitioning (Q&P) steels [3–6] and their derivatives, such as TRIP-assisted dual phase steels. In most of these steels, the local carbon content is controlled during processing to retain a significant amount of metastable austenite at room temperature. The retained austenite confers the steel with enhanced ductility, as a result of the mechanically induced transformation of austenite to martensite. In order to suppress carbide formation during quenching, significant additions of other alloying elements such as

silicon and aluminium are employed [2,7,8]. Silicon is most commonly added as it not only suppresses carbide formation but also contributes to solid solution strengthening; as does manganese. Due to problems during hot-rolling, coating and welding arising from the formation of tenacious Si-based surface oxides, silicon is increasingly being partially or completely replaced by aluminium in high strength-high ductility steels [9–12]. This current practice requires increasing amounts of manganese to compensate for the loss of solid solution strengthening. The trend towards increasingly complex and finer microstructures or increased amounts of retained austenite, requires delicate control of the microstructure and interactions of the alloying elements during processing to achieve the desired structure and stability and, hence, mechanical properties.

Limited solid solubility of alloying elements in steel leads to segregation during casting. During solidification, solute is partitioned between the solid and liquid to either enrich or deplete interdendritic regions. This naturally leads to variations in composition on the scale of micrometres, *i.e.* micro-segregation. Macro-segregation, however, refers to chemical variations over

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length scales approaching the dimensions of the casting, which for large ingots may be of the order of centimetres or metres [13]. At any given temperature, for an alloy with bulk solute concentration C_0 , the solute concentration in the solid may be designated as C_S and that of the liquid as C_L . Redistribution or partitioning of solute is then defined using the equilibrium partitioning coefficient [13]:

$$k = \frac{C_S}{C_L} \quad (1)$$

This forms the basis for the Scheil-Gulliver equation [14] from which the composition of the liquid during solidification can be calculated, thus:

$$C_L = C_0(f_L)^{k-1} \quad (2)$$

And for the solid, thus:

$$C_S = kC_0(1 - f_S)^{k-1} \quad (3)$$

Where f_S and f_L are the weight fractions in the solid and liquid respectively.

Since the solidus and liquidus lines bounding a specific solidification region are approximately straight, k is constant within that (limited) composition range. For many systems, k has a value less than unity *i.e.* the solute is rejected from the solid as it forms and accumulates in the liquid. Average values of k for typical alloying additions in steel obtained from the literature are shown in Table 1. The lack of long-range order in the liquid portion allows a greater uptake of solute than in the crystalline solid [13]. As solidification progresses, the concentration of solute in the liquid increases due to rejection from the solid into the liquid phase, with the highest concentration of solutes in the last portion of liquid to freeze.

Considerable research effort has been devoted to investigating the effect of carbon, manganese and, to a lesser extent, chromium and silicon on the dendrite arm spacing [15–18], microscopic [19–21] and macroscopic segregation [22–24], partitioning during phase transformations [25–30] and on banding [22,31] in steels. There has to date been no systematic study of the role of aluminium segregation in these processes in modern automotive high strength steels. In fact, on the basis of the partition coefficients in Table 1, it would appear that aluminium would not segregate significantly during solidification, although this is almost certainly due to the residual levels of aluminium (< 0.04 wt%) reported in the study [21]. The occurrence of Mn and Al macro-segregation has been recently reported in a medium-Mn multiphase steel [32], but Al seems to homogenise after thermo-mechanical treatment in that case, and the observed martensite-austenite micro-bands were attributed only to the Mn segregation.

The aim of this work is (1) to determine the potential role of aluminium as an alloying addition on the partitioning of the other solute elements in multi-phase steels and (2) to establish the link between chemical segregation in the as-cast structure with the phase transformations taking place during subsequent processing steps that may result in the occurrence of banding in the final

microstructure. Our initial hypothesis is that interdendritic chemical segregation remains after casting and, in particularly in the case of aluminium, is instrumental in causing banding throughout the manufacturing process.

2. Experimental

2.1. Material production

The steel under investigation is a continuously-cast TRIP assisted dual phase steel with the composition given in Table 2. The material is produced via a continuous casting route, followed by hot-rolling (HR), cold-rolling (CR) and continuous annealing. Samples from industrial production material were taken after casting and also after cold-rolling and annealing (CRA) for the experiments and analysis outlined in this work.

Blocks of 75 mm in height (1/3 of the original slab height of 225 mm) were removed from the centre-line of the as-cast (AC) slab, as this is the most common section for the appearance of both chemical macro- and micro-segregation due to (a) increased dendrite arm spacing as a result of slower cooling rates and (b) solute enrichment of the final solidification zone [33]. The blocks were first forged to a thickness of 35 mm, before being reheated to 1250 °C for 30 min and subsequently hot-rolled in six deformation passes to the final thickness of 3.4 mm, see Fig. 1. The temperature after the final reduction was 900 °C and the microstructure at this step is comprised completely of austenite. Different cooling trajectories were subsequently applied aimed to promote (slow cooling rate) or suppress (fast cooling rate) banding as predicted by the cellular-automaton model developed by Bos et al. [34,35], see Section 3.2 for details. Slow cooled samples were first allowed to cool in air to 700 °C, followed by oven cooling to room temperature at 0.2 °C/s; the fast cooled samples were water quenched to 600 °C on a run-out table delivering a continuous flow rate of water to achieve a constant cooling rate of 100 °C/s, this was followed by oven cooling to room temperature at 0.2 °C/s.

The samples were subsequently cold-rolled to 1 mm thickness and annealed in the ferrite (α) + austenite (γ) region, followed by a bainite isothermal holding treatment at 400 °C for 60 s. According to Caballero et al., successful suppression of banding during hot-rolling can be undone during subsequent heat-treatments if the heating rate up to the two-phase region is too low [36]. To avoid, or effectuate the occurrence of banding, the heating rate during annealing was adapted to mirror the cooling rate in the hot-rolling process, within the practical limits of industrial annealing lines. The main process parameters are given in Fig. 1. It should be noted that the total deformation from rolling reductions of material produced in the laboratory (95%) is less than that for the samples taken from the production route (99%), see Table 3.

2.2. Structural characterisation

Microstructural analysis was performed by light optical microscopy and scanning electron microscopy (Zeiss Ultra 55 FEG-SEM). Chemical etchants were used to reveal the microstructure in the HR condition (5% Nital) and in the CRA condition (LePera reagent). Dendrite arm spacing was measured on SEM images using Fiji image analysis software [37]. Images were converted from grey

Table 1
Reported values of the equilibrium partition coefficients for common alloying elements in steel.

Element	Valid composition range, wt%	k	Reference
Mn	1.4–1.5	0.71	[21,25]
Al	0.03–0.05	1.02	[21]
Si	0.3–0.4	0.63	[21]
Cr	–	0.33	[25]

Table 2
Chemical composition of the studied TRIP-assisted dual phase steel grade in wt%.

C	Mn	Al	Si	Cr	Fe
0.15	2.05	0.58	0.42	0.40	Bal.

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