Journal of Materials Processing Technology 237 (2016) 394–401

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Modelling of austenite formation during heating in boron steel hot stamping processes

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ARTICLE INFO

Article history:
Received 25 March 2016
Received in revised form 23 May 2016
Accepted 4 June 2016
Available online 5 June 2016

Keywords:
Austenite formation
Boron steel
Constitutive modelling
Hot stamping
Phase transformation
Heating rate

ABSTRACT

A physically-based material model has been developed to describe the austenite formation in a manganese-boron steel during heating in hot stamping processes. The equations were formulated based on three austenite formation mechanisms: nucleation, growth and impingement. It is able to characterize the phase transformation process under both non-isothermal and isothermal conditions, where the effects of heating rate and soaking temperature on the austenite formation have been rationalised. Heat treatment tests of the manganese-boron steel were performed on a Gleeble 3800 subjected to various heating conditions (heating rate: 1–25 K/s, soaking temperature: 1023–1273 K). The dimensional changes of specimens associated with the phase transformation, which was measured using a high resolution dilatometer, has been quantitatively related to the volume fraction of austenite formation. The experimental data were used to calibrate and validate the equations. Good agreement between the experimental and predicted results has been obtained. Further analysis has been made to illustrate the significance of the model in applications.

1. Introduction

The rising demand for increasing safety and reducing weight of car bodies in the automotive industry has stimulated technological innovation in sheet metal forming. Hot stamping of boron steel for safety critical parts has therefore been well developed. Conventionally, as summarised by Karbasian and Tekkaya (2010), during the process blanks are firstly austenitized, and subsequently formed and quenched in cold dies, so that ultra-high strength parts in the martensite phase are obtained. Now, a novel strategy about selective heating and press hardening of boron steels has been proposed by the authors (Li et al., 2012, 2014) to produce parts with a tailored distribution of mechanical properties, which introduces the potential for making parts that conform to functional requirements. In this process, a blank is heated under tailored thermal conditions, which enables part of the steel to be fully or partially austenitized while the other part experiences no phase transformation. Thus, after hot stamping and cold die quenching, the fraction and distribution of martensite in the as-formed part is determined by the extent of austenitization, which means that control of austenitization during the heating process is of primary importance in deciding the final properties for a given part. Therefore, understanding and modelling the relationship between heating conditions and the formation of austenite are paramount to optimizing the thermal cycle for innovative hot stamping processes.

Studies on austenite formation, compared with the number of investigations into the decomposition of austenite during cooling, have been few and incoherent until the 1980's, as stated by Law and Edmonds (1980). Then, as reported by Garcia and Deardo (1981), driven by automotive applications, great interest in the heating stage of thermal cycles was stirred by the development of advanced high strength steels (AHSS). Attention was drawn from full austenitization to partial austenitization in intercritical annealing practices, since it offers a means of optimizing the mechanical properties of dual-phase steels. A classic study on the kinetics of austenite formation in dual-phase steels containing different percent of carbon during intercritical annealing was conducted by Speich et al. (1981). Since then, more extensive and systematic research on the austenite formation has been carried out to gain quantitative understanding of microstructural evolution during the transformation and the mechanisms that control it under different conditions. For example, Asadi Asadabad et al. (2008) characterised the relationship between temperature and time of intercritical annealing and transformed fraction of austenite in dual phase steels; Oliveira et al. (2007) investigated the effects of heating rates on critical temperatures of austenite formation in a low

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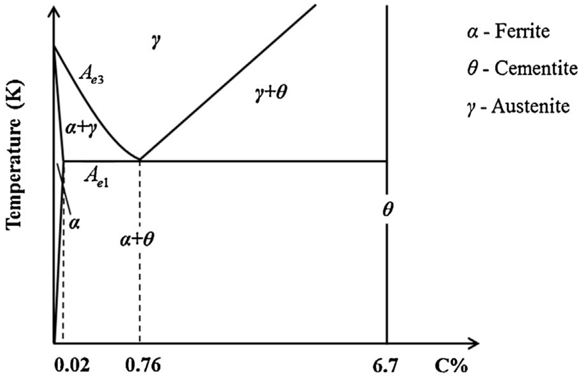
http://dx.doi.org/10.1016/j.jmatprotec.2016.06.006
0924-0136/

carbon steel. However, information on austenitization in boron steels for hot stamping application is still sparse. Cai (2011) focused only on full austenitization under continuous heating-up without considering isothermal annealing. The effects of heating rate and temperature on the full/partial transformation of austenite in boron steels, under both non-isothermal and isothermal conditions, were characterised for the first time by the authors (Li et al., 2016).

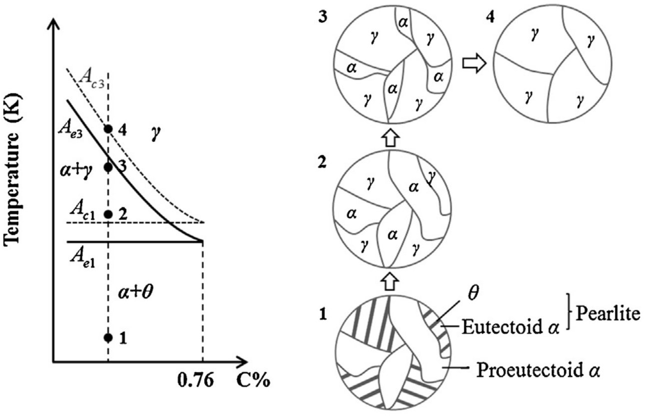
Various austenitization models have been developed in recent years. According to Savran (2009), these can generally be classified as probabilistic models and deterministic models. The former type introduces the stochastic variables into calculation process, which can account for the stochastic character of the phase transformation and give qualitative representation of the microstructure, e.g. Haddad-Sabzevar et al. (2009) employed a stochastic model to simulate the austenite phase formation and its growth during welding of a low alloy steel and to visualize the topology of the austenite phase. The latter type is based on the time-integration of equations consisting of certain state variables, so as to characterize the microstructural evolution, at various length scales, depending on the features of interest, throughout the phase transformation. As reported by Azizi-Alizamini (2010), deterministic models for describing the austenite formation are predominant in the literature, developed using analytical and phenomenological approaches. Analytical approaches are mainly based on the analysis of mechanisms which control the austenite front migration, which requires assumptions (e.g. on growth modes) that are strictly defined in advance. However, this may not be easy when the phase transformation mode is of a complex character, which was pointed out by Parris and McLellan (1976). According to the investigation by Schmidt et al. (2007), for austenitization in a manganese-boron steel with a ferrite-pearlite starting microstructure, depending on heating conditions, the growth of the austenite phase can be controlled by interface reaction or volume diffusion, and the latter could be carbon diffusion in austenite or manganese diffusion in ferrite. In this case, an analytical approach may not be efficient. Phenomenological approaches are mainly conducted by relating the transformation progress to the change of austenite volume fraction with time. Chen et al. (2010) reported that Avrami's equation plays a critical role in the fundamental understanding of the transformation but it is too simple to adapt to any specific case, e.g. a transformation that has mixed nucleation or an alternate growth mode. Hence extensive studies have been conducted to further develop this equation, so as to fit it to different transformation conditions.

However, the transformations of austenite under isothermal and non-isothermal conditions have always been modelled separately. Thus the effects of heating rate on the subsequent isothermal transformation cannot be accounted for. In hot stamping, the boron steel is treated with continuous heating followed by steady soaking; in addition, intercritical annealing for partial austenitization is involved under selective heating conditions. Therefore, an austenite formation model which can be applied to this complex heating condition is needed.

The main aim of this work was to develop a set of equations that can effectively describe the austenite formation in boron steel, under both non-isothermal and isothermal conditions within or above intercritical temperatures, for hot stamping processes. The development of the model is based on theoretical analysis of the nucleation, growth and impingement mechanisms for austenite formation. Phenomenological approaches are adopted to characterize the effects of heating conditions on the transformation. Experimental data on boron steel subjected to different heating rates and temperatures was used to determine and calibrate the model.



(a) Fe-C equilibrium phase diagram



(b) The phase transformation process

Fig. 1. Austenite formation in a hypoeutectoid steel (containing less than 0.76 wt.% C).
(a) Fe-C equilibrium phase diagram (b) Phase diagram of hypoeutectoid steel and the schematic representations of the microstructure evolution.

2. Mechanisms of austenite formation in hypoeutectoid steels

For the study of the constitution and structure of steels, stated by Azizi-Alizamini (2010), the Fe-C equilibrium diagram is the most widely-used way to represent the existence of different phases in equilibrium depending on carbon content and temperature. As shown in Fig. 1(a), the equilibrium conditions for thermodynamically distinct phases are illustrated. Only the hypoeutectoid part of the equilibrium diagram, where 0.02 wt.% < C% < 0.76 wt.%, is studied in this paper. Regarding this part, there are two features which are critical: first, the starting temperature A_{e1} at which the eutectoid reaction occurs; second, the finishing temperature A_{e3} at which the ferrite (α) can fully transform to austenite (γ). The A_{e1} is normally a single temperature above 973 K; whereas the A_{e3} is about 1183 K for pure iron and progressively decreases by the addition of carbon. As summarised by Garcia de Andrés et al. (2002) and Surm et al. (2004), this is because the solubility of carbon in ferrite (α) is low and ferrite alone can only begin to transform to austenite (γ) at high temperatures, but if cementite decomposes and yields its carbon to the transformation front, the reaction from ferrite to austenite can proceed at lower temperatures.

However, the preheating of steel is continuous for most practical hot forming applications. The formation of austenite in a hypoeutectoid steel generally involves heating an aggregate of ferrite + cementite (α + θ) through the two phase (α + γ) region into a