Experimental characterisation of the effects of thermal conditions on austenite formation for hot stamping of boron steel

N. Li [a], J. Lin [a], D.S. Balint [a,*], T.A. Dean [b]

[a] *Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK*
[b] *School of Mechanical Engineering, The University of Birmingham, Birmingham B15 2TT, UK*

ABSTRACT

The formation of austenite in manganese-boron steels during selective heat treatment has great significance in the application of innovative hot stamping processes. Heat treatment tests were designed according to the thermal cycle of industrial heating and hot stamping processes and were conducted on a Gleeble 3800 thermomechanical testing system. Specimens were subjected to non-isothermal (heating rates: 1 K/s–25 K/s) and isothermal (soaking temperatures: 1023 K–1173 K) temperature profiles. A high-resolution dilatometer was employed to detect the dimensional change of the specimens associated with austenitization. The dilatometric measurement was quantitatively related to the volume fraction of austenite. By analysing the evolution curves of austenite fraction, the effects of heating rate and temperature on the progress of austenite formation under both non-isothermal and isothermal conditions were investigated and characterised, improving the current understanding of the mechanisms that control austenite formation in manganese-boron steels.

1. Introduction

The rising demand for increased safety and reduced weight of car bodies has stimulated technological innovation in sheet metal forming. According to Karbasian and Tekkaya (2010), hot stamping of boron steel in order to obtain lightweight, strong components is now a well developed process. In the process blanks are austenitized then formed and quenched in cold dies so that ultra-high strength parts in the martensite phase are obtained. Currently, great attention is being paid to improving the process to produce parts with tailored distributions of mechanical properties, allowing parts to be made that conform more fully to functional requirements. For example, in safety critical beams in automobiles, instead of utilising a fully martensite phase, regions of ductile phases, such as ferrite and pearlite, can be incorporated to enhance energy absorption or tune crash deceleration pulses; this concept is described in a patent by Thomas and Detwiler (2009) on optimizing structural performance by microstructural design, which can be realized by controlling thermal conditions during forming. As a result, comprehensive studies have been carried out on the phase transformation behaviour of boron steels during cooling,

such as the experimental characterisation of cooling rate effects (Gárlipp et al., 2001), and modelling of austenite decomposition (Åkerström and Oldenburg, 2006). This knowledge could be applied to selective quenching in hot stamping. However, because a long cooling time is required to achieve ductile phases, there is an intrinsic conflict with the industrial requirement for short cycle times. Therefore, a novel strategy for selective heating of boron steels has been proposed by the authors (Li et al., 2012, 2014): A blank is heated under tailored thermal conditions, which enables part of the steel to be fully or partially austenitized with the remainder experiencing no phase transformation. Subsequently, the blank is formed and rapidly quenched in cold dies as in conventional hot stamping operations. The fraction and distribution of martensite in the formed part is determined by the extent of austenitization. Hence the formation of austenite during the heating process is of primary importance in determining the final properties of a given part. Therefore, understanding the kinetics of austenite formation is essential in optimizing the design of the heat treatment conditions for innovative hot stamping processes.

Studies on austenite formation have been carried out by many researchers. Roberts and Mehl (1943) established the nucleation and growth character of the transformation in steels with different starting microstructures. However, compared with the number of investigations into decomposition of austenite during cooling, studies on austenite formation have been few. As stated by Reed

* Corresponding author.
 E-mail address: d.balint@imperial.ac.uk (D.S. Balint).

Nomenclature

α	Ferrite
θ	Cementite
ψ	Parent phase of the studied steel
γ	Austenite
A_{e1}, A_{e3}	Temperature to start and complete austenite formation under equilibrium conditions
A_{c1}, A_{c3}	Temperature to start and complete austenite formation during continuous heating
W_0, W	Initial and instantaneous specimen width
ΔW	Change in specimen width
V_0, V	Initial and instantaneous specimen volume
v	Relative volume change
$v_{\psi 0}, v_\psi(T)$	Relative volume change of the parent phase at 873 K and at any temperature, respectively
$v_{\gamma 0}, v_\gamma(T)$	Relative volume change of austenite at 873 K and at any temperature, respectively
C_ψ, C_γ	Thermal expansion coefficient of the parent phase and austenite, respectively
f	Volume fraction of austenite
f_s	Saturated volume fraction of austenite
$\dot{N}$	Austenite nucleation rate
$\dot{G}$	Austenite growth rate
N_0, G_0, C	Pre-exponent parameters
Q_N, Q_G, Q_C	Activation energy
R	Gas constant
h	Heating rate
T	Absolute temperature (in Kelvin)
T_x	Temperature corresponding to certain volume fraction of austenite
e.g. $T_{50\%}$	is the temperature when volume fraction of austenite reaches 50%
t	Instantaneous time (origin: time at temperature of 873 K)
$t_{A_{c1}}$	Time to start austenite formation (same origin as t)
t_x	Time corresponding to certain volume fraction of austenite (same origin as t)
e.g. $t_{80\%}$	is the time when volume fraction of austenite reaches 80%
Δt	Soaking time increment
Δt_{x1-x2}	Time to increase volume fraction of austenite from x1 to x2 during soaking
e.g. $\Delta t_{80\%fs-90\%fs}$	is the time to increase volume fraction of austenite from 80% of f_s to 90% of f_s during soaking
$\Delta t'$	Time increment during continuous heating
$\Delta t'_{A_{c1}-x}$	Time increment from starting austenite formation to reaching certain volume fraction of austenite during continuous heating

Fig. 1. The formation of austenite in a hypoeutectoid steel (containing less than 0.76 wt% C), illustrated by (a) the schematic representations of the microstructure and (b) the evolution in a Fe–C phase diagram (only hypoeutectoid part).

et al. (1998) and Schmidt et al. (2007), this is primarily because it is difficult to retain austenite at room temperature for inspection and characterisation, which makes observation of the progress of austenite formation difficult. Stimulated by automotive applications, the development of advanced high strength steels has recently revived interest in the heating stage of the heat treatment cycle. Initially, attention was focused on partial austenite formation in intercritical annealing practices, since this offers a means of optimizing the mechanical properties of dual-phase steels. More extensive and systematic research on the formation of austenite has been conducted during the last decade, in order to achieve quantitative understanding of microstructural evolution during transformation and the mechanisms that control it under different conditions. For example, Asadi Asadabad et al. (2008) characterised
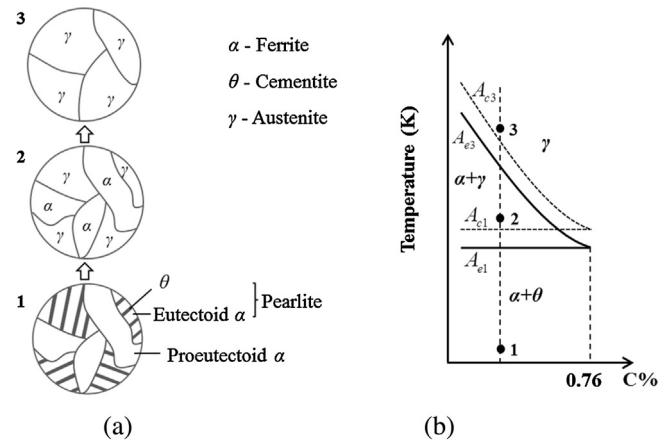
the relationship between temperature and time of intercritical annealing and transformed fraction of austenite in dual phase steels; Oliveira et al. (2007) investigated the effects of heating rates on critical temperatures of austenite formation in a low carbon steel. However, information on austenite formation in boron steels for hot stamping applications is still limited; Cai (2011) focused on only full austenite formation under continuous heating conditions. Little research has been carried out on the intercritical soaking of boron steels. In addition, the influence of temperature and heating rate on the progress of the transformation to austenite has always been studied separately under isothermal conditions and non-isothermal, respectively. In a real situation, the conditions for work-piece preheating for hot pressing are first increasing temperature followed by steady-state temperature. This should be recognised if an accurate evaluation of austenite evolution is to be obtained.

As stated by Thibaux et al. (2007), formation of austenite is a diffusion-controlled process and is primarily determined by the initial microstructure of the material. In this study, the kinetics of austenitization is assumed to be mainly a carbon diffusion-controlled process. This is because the diffusivity of carbon in steel is nearly 10^5–10^6 times greater than that of substitutional solutes (e.g. Mn), as reported by Khaira et al. (1993). Therefore, for hot stamping of boron steels in industrial applications, within the practical soaking time, the establishment of equilibrium is with respect to carbon without taking substitution solutes into account. As the carbon content is in the range of 0.02–0.76 wt.%, the boron steel studied here is a hypoeutectoid steel. Fig. 1(a) schematically illustrates the phase composition of a hypoeutectoid steel prior to (a-1), during (a-2), and upon completion of austenitization (a-3). The austenite formation in a hypoeutectoid steel proceeds in two stages. Firstly, from the research results by Caballero et al. (2000), austenite nucleation takes place at the interfaces of ferrite-cementite lamellae within a colony, as well as at the intersections or interfaces of pearlite colonies. The new grains of austenite grow into pearlite colonies to replace the eutectoid ferrite; at the same time, the cementite dissolves in the austenite. Secondly, from the research results by Jacot and Rappaz (1999), the reaction proceeds into the remaining pro-eutectoid ferrite. The transformation from pro-eutectoid ferrite to austenite is enabled by the diffusion of carbon atoms from inside the enriched γ grains to γ/α interfaces, so that the γ/α interfaces gradually move towards α phase regions. This process continues until the average carbon content in the austenite becomes equal to the carbon content of the steel. This phase transformation is a thermodynamic process and signif-