International Journal of Plasticity 58 (2014) 154–183

Contents lists available at ScienceDirect

International Journal of Plasticity

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

Thermo-mechanical-metallurgical modeling for hot-press forming in consideration of the prior austenite deformation effect

Hyun-Ho Bok [a], JongWon Choi [a,b], Frédéric Barlat [a], Dong Woo Suh [a], Myoung-Gyu Lee [a,*]

[a] Graduate Institute of Ferrous Technology, Pohang University of Science and Technology (POSTECH), San 31, Hyoja-dong, Nam-gu, Pohang-si, Gyeongsangbuk-do 790-784, South Korea

[b] POSCO, 699 Geumho-dong, Gwangyang-si, Jeollanam-do 545-875, South Korea

ARTICLE INFO

Article history:
Received 21 June 2013
Received in final revised form 16 September 2013
Available online 17 December 2013

Keywords:
Hot-press forming
Austenite grain refinement
Thermo-mechanical-metallurgical simulation
A. Phase transformation

ABSTRACT

In this study, a prior austenite grain refinement model was incorporated into semi-empirical diffusive transformation kinetics for application to hot-press forming. In particular, the kinetics equations were modified to include the effects of boron addition and austenite deformation on transformation behaviors during forming. To simulate the hot-press forming process, a thermo-mechanical-metallurgical model was formulated implicitly and implemented into the finite element program ABAQUS using the user subroutines UMAT and UMATHT. This nonconventional finite element modeling is appropriate to consider thermal- and transformation-associated strains. The proposed model was validated through simple finite element simulation examples, i.e., dilatometry simulation with and without external loading, and hot torsion and quenching of a rod. Finally, the hot-press forming of a U-channel-type part was simulated to study the effect of austenite deformation on the phase kinetics, hardness and residual stress. The simulation results showed that the austenite deformation had considerable influence on the final strength and residual stress distribution in the hot-press formed sheet, which resulted from an increase in ferritic phases due to the modified kinetics. In particular, the austenite deformation effect was more noticeable in the side-wall region of the U-channel where plastic deformation was the most severe.

1. Introduction

The hot-press forming[1] (HPF) process has drawn considerable attention in the automotive industry because parts produced by this technology can meet the requirements for passenger safety and fuel efficiency. The HPF process consists of high-temperature forming of a boron steel sheet at around 800 °C and subsequent quenching inside the tools (die quenching). For die quenching, specialized tools containing cooling channels are used to rapidly lower the temperature of the formed part. An almost fully martensitic microstructure can be obtained in the formed part, which results in a strength of 1500 MPa with 22MnB5 steels. In principle, the process is equivalent to conventional heat treatment, but HPF uses direct metal-to-metal contact between the hot sheet and the surrounding tools. Therefore, a wide range of part strengths can be obtained by controlling the hardenability of the steel sheet and the cooling capability of the tools.

* Corresponding author. Tel.: +82 54 279 9034; fax: +82 54 279 9299.
E-mail address: mglee@postech.ac.kr (M.-G. Lee).

[1] Hot-press forming is referred to by various terms, e.g., "hot stamping," "press hardening," and "press quenching." However, a distinction should be made with "warm forming" or "forming at elevated temperature" because hot-press forming (or equivalent terms) is associated with a phase transformation.

0749-6419/$ - see front matter
http://dx.doi.org/10.1016/j.ijplas.2013.12.002

In order to investigate material behavior of steels subjected to solid-to-solid phase transformation in transient thermal filed, various thermo-mechanical-metallurgical constitutive models have been proposed and implemented (Kim et al., 2005; Andrade-Campos, 2010; Moumni et al., 2011; Fischlschweiger et al., 2012; Mahnken et al., 2012). Similarly, a number of finite element (FE) simulations of HPF processes considering phase transformation have been carried out to optimize the quality of the HPF product, such as the part strength, shape fixability and formability (Åkerström and Oldenburg, 2006; Turetta et al., 2006; Hoffmann et al., 2007; Tekkaya et al., 2007; Lee et al., 2009; Bok et al., 2010, 2011; Choi et al., 2012, 2013; Kim et al., 2013; Park et al., 2013).

In general, microstructural defects introduced by the plastic strain enhances the diffusive transformation kinetics, while displacive martensitic kinetics is suppressed by strain hardening of the deformed austenite, i.e., mechanical austenite stabilization (Tamura et al., 1988; Bhadeshia and Honeycombe, 2006). This phenomenon has frequently been observed in modern steels during hot rolling (Umemoto et al., 1992; Senuma et al., 1992). For instance, slabs in a hot-rolling mill are subjected to a series of severe plastic deformations in the austenite state. Prior austenite grains can be refined from grain diameters of 10^2 μm to 10 μm. The drastic grain refinement is mainly attributed to dynamic/static austenite recrystallization above the austenite recrystallization stop temperature T_{nr}. As the thickness of a slab is reduced during hot rolling, the temperature rapidly decreases below T_{nr}; however, refinement can also take place even without recrystallization. In this case, austenite grains are directly refined through grain elongation or the formation of deformation bands, which provide additional nucleation sites of diffusive trnasformation (Kern et al., 1992; Zrnik et al., 2003). Therefore, the refined austenite enhances phase transformations and determines the grain size of the final ferritic phases (Sun et al., 2002; Maalekian et al., 2007; Kruglova et al., 2007; Eghbali, 2010).

As for boron-added steels, many observations have also been reported on this acceleration of diffusive kinetics due to plastic strain in the prior austenite. For example, a drastic loss in the hardness of hot pre-strained (up to 17%) and quenched 22MnB5 steel was observed; this was attributed to the enhanced diffusive transformation by grain refinement (Barcellona and Palmeri, 2009). Somani et al. (2001) reported that the phase fraction of ferrite in 0.22C–1.1Mn–0.2Cr–0.0034B steel was increased by 22% and 48% with pre-strains of 0.16 and 0.39, respectively, under a cooling rate of 50 °C/s. An increase in the bainite start temperature and decrease in the martensite start temperature resulting from the hot deformation and dynamic recrystallization of prior austenite were observed in 22MnB5 steel (Nikravesh et al., 2012). The bainite transformation started earlier, while the transformation of martensite was delayed. Fan et al. (2008) reported a shift of the nose of transformation curves to earlier time region in the continuous cooling transformation (CCT) diagram of a boron-bearing C–Mn steel when hot compression was applied before quenching. Consequently, ferrite and bainite transformations were enhanced at low and intermediate cooling rates, respectively. Ti added 22SiMn2TiB boron steel promoted diffusive transformation and suppressed displacive transformation after the quenching of non-isothermally deformed austenite (Shi et al., 2012). A uniaxial stress field in austenite is known to accelerate both diffusive (Jepson and Thomson, 1949; Bhattacharyya and Kehl, 1955) and displacive (Kulin et al., 1952; Patel and Cohen, 1953) martensite transformation kinetics.

However, few simulations have considered the effect of austenite deformation on the phase transformation in spite of the importance of this issue (Esaka et al., 1986; Min et al., 2012). In the present study, a coupled thermo-mechanical-metallurgical FE model including the austenite deformation effect on subsequent diffusive transformation was developed to better predict the microstructure, mechanical properties and residual stress distribution in a hot-press formed part. For the interaction between deformation and phase transformation, a dislocation-density-based austenite grain refinement model was introduced into a semi-empirical diffusive transformation kinetics model. This is the main idea of the present work. The constitutive models were implemented in the implicit FE software ABAQUS/Standard using UMAT and UMATHT for mechanical and thermal user material subroutines, respectively. Related stress integration and microstructure evolution algorithms were also developed. The overall developed material description was applied to several applications: (1) dilatometry test to validate fundamental kinetics without external loading; (2) dilatometry test to validate the kinetics under external loading, which introduces transformation plasticity; (3) quenching distortion; (4) hot torsion and quenching; and (5) hot-press forming of a U-channel shaped part.

2. Material modeling

2.1. Microstructure evolution in low-alloy steels

2.1.1. Austenite grain refinement

Accurate estimation of the austenite grain size (AGS) at hot working temperatures is important because the austenite grain boundary area (i.e., number of nuclei) is known to have a considerable influence on the phase transformation kinetics (Cahn, 1956; Kirkaldy et al., 1978). Therefore, the AGS is a factor that controls the final mechanical properties of steel parts after heat treatment. Austenite deformation is associated with grain elongation and the increase in dislocation density along austenite grain boundaries. Therefore, nucleation rates of ferritic phases at grain boundaries increase considerably due to the dislocations; this enhances the mobility of diffusing atoms in austenite. Newly generated deformation bands and annealing twins become additional nucleation sites for ferritic phases inside austenite grains (Tamura et al., 1988; Walker and Honeycombe, 1978; Umemoto et al., 1984). Consequently, the overall transformation rate increases considerably.