ARTICLE IN PRESS

International Journal of Plasticity xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Plasticity

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

Stress development and shape change during press-hardening process using phase-transformation-based finite element analysis

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ARTICLE INFO

Article history:
Received 14 August 2014
Received in final revised form 27 October 2014
Available online xxxx

Keywords:
A. Phase transformation
A. Thermomechanical processes
B. Residual stress
C. Finite elements
Press hardening

ABSTRACT

Elastically driven shape change, or springback, in a press-hardened U-channel part made from a tailor-welded blank (TWB) was simulated using a fully coupled thermo-mechanical–metallurgical finite element (FE) method. The TWB consists of boron steel and high-strength low-alloy steel, which have significantly different hardenabilities. A combined implicit–explicit three-step simulation consisting of air cooling, forming and die quenching, and springback was used for computational efficiency. All the required material models such as the modified phase-transformation kinetics and phase-transformation-related stress-update scheme were implemented in the FE software ABAQUS with the user-defined subroutines UMAT, VUMAT, and HETVAL. The developed FE procedure, including the material models, satisfactorily predicted the experimentally measured shape changes of the TWB part. Here we present an in-depth analysis of the residual stress development during forming and die quenching using different material modeling schemes. It should be noted that the stress evolution of the two materials with high and low hardenabilities were significantly different depending on the phase transformation kinetics during forming and quenching. Moreover, in order to enhance the prediction capability of the press-hardening simulations, it was essential to include the phase-transformation-related strains in the material model.

1. Introduction

Press hardening is a hot-forming process of steel sheets to manufacture crash-relevant parts for autobody structures. Because of its enhanced hardenability, 22MnB5 boron steel has generally been used as a blank material for the press-hardening process (Karbasian and Tekkaya, 2010). The process begins with the austenization of a boron-steel sheet at about 900 °C. The hot austenized blank is then formed by special tools, in which cooling channels allow quenching of the deformed sheet for about 30 s. A substantial amount of martensite can be obtained during this die quenching, mostly by heat transfer between the hot part and the surrounding cooler tools. The strength in the final part reaches values as high as 1500 MPa. For

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http://dx.doi.org/10.1016/j.ijplas.2014.11.004

Please cite this article in press as: Bok, H.H., et al. Stress development and shape change during press-hardening process using phase-transformation-based finite element analysis. Int. J. Plasticity (2014), http://dx.doi.org/10.1016/j.ijplas.2014.11.004

this reason, boron steel is often referred to as press-hardenable steel (PHS). In addition to the high strength induced by the martensitic phase transformation, the almost negligible shape distortion (or springback) is another major advantage of the press-hardening process (Altan, 2006; Lee et al., 2009a, 2009b). The low flow-stress levels of the forming process, attributed to the high forming temperature, and phase-transformation plasticity are known to contribute to this minimal shape change after forming.

Recently, less press-hardenable steels compared to boron steel, such as high-strength low-alloy (HSLA) steels, have been utilized to compensate for the lack of ductility in press-hardened parts made with boron steel. The strength of HSLA steels after press hardening is about 600 MPa (Choi et al., 2012, 2013), but higher uniform elongations can be achieved. Hereafter, the less hardenable steel applied to the press-hardening process is referred to as L-PHS (low hardenability-PHS), while conventional boron steel, which exhibits higher hardenability, is referred to as H-PHS (high hardenability-PHS).

Non-uniform stress distribution over the entire part, resulting from imperfect cooling, has been reported as a source of shape distortion even after press hardening. This shape change occurring after forming and die quenching can be a critical issue in the press-hardening process as well (Wagoner et al., 2013). Moreover, the tailor-welded blank (TWB) approach, in which a blank made of different gauges or PHS sheets, or a blank made of both different gauges and PHS sheets, is used to optimize strength and ductility simultaneously. This requires more investigations regarding the mechanical behavior during the press-hardening process because of a larger shape change on the L-PHS side of a TWB part (Choi et al., 2013). Recently, Choi et al. (2013) conducted press-hardening experiments with a TWB sheet consisting of HSLA steel and boron steel as L-PHS and H-PHS, respectively. The L-PHS side of this sheet exhibited larger shape change than that on the H-PHS side. This experimental observation was counter-intuitive because the strength of the H-PHS part was higher during forming, which contradicts the classical interpretation based on elastic–plasticity; i.e., the higher the strength, the larger the springback. This finding was one of the motivations behind the current study.

In the present study, the development of a stress field during press hardening was simulated using a fully coupled thermo-mechanical–metallurgical finite-element (FE) analysis. A specially designed U-channel, which is an accurate representation of usual autobody structural parts, was adopted in this study to simplify the problem. All the simulations were conducted using the commercial software ABAQUS (Dassault Systèmes), in which the developed material models and phase-transformation kinetics were implemented through the user-defined material subroutines. The phase transformation kinetics considered in this study is phenomenological, which can be readily implemented in the finite element simulations for metal forming process, although there are significant studies on the phase transformation at microscale (Ma and Hartmaier, in press; Ortwein et al., 2014; Auricchio et al., 2014; Kato and Sasaki, 2013; Levitas and Ozsoy, 2009). In the material modeling, the plasticity part of mechanical behavior was described by the classical J2 plasticity theory, to which transformation-induced plasticity (TRIP) was specially added. In other words, constitutive modeling was carried out based on macroscale phenomenological elastic–plastic model, in which the inter-granular (type 2 in Knezevic et al. (2013)) and intra-granular (type 3) stresses in microscale were ignored for practical aspect of simulation for realistic sheet metal forming process.

Using the finite-element model, we attempted to systematically explain the stress development and shape-change mechanism in the press-hardened TWB part. In addition, detailed stress analysis of the blank materials is provided to demonstrate the role of the material model on the prediction capability of the modeling procedure.

2. Thermo-mechanical–metallurgical modeling

When subjected to a heat cycle consisting of heating to the austenizing temperature (A_3) followed by cooling, steel components experience either free dilatation or significant thermal stress development depending on whether there are geometrical constraints. Fig. 1(a) illustrates a steel rod with a free end. When linear heating and cooling is applied to the rod, ferrite-to-austenite transformation ($\alpha \rightarrow \gamma$) occurs during the heating cycle and austenite-to-ferrite transformation ($\gamma \rightarrow \alpha$) occurs during cooling cycle. Because there is no constraint at the end of the rod, free thermal expansion and contraction can be activated without thermal axial stress. In this figure, the S-shape of the strain profiles during the transformations is attributed to the difference between the densities of body-centered cubic (bcc) α phase and the face-centered cubic (fcc) γ phase. Satoh (1972), however, considered a geometrically constrained condition, shown in Fig. 1(b), for the same thermal cycle in order to understand the development of residual stress in welding processes. In this case, large compressive and tensile stresses developed during heating and cooling, respectively, because the constraints at both ends did not allow the development of an axial strain. An opposite sense of stress development is shown in Fig. 1(b) during the phase transformations. The two schematic figures illustrate that it is necessary to consider the effect of phase transformations on the stress and strain development when steel parts are under complicated thermal and geometrical boundary conditions.

2.1. Modeling of phase transformation

Steels subjected to press hardening are designed to undergo solid-to-solid phase transformations in order to obtain the desired part strengths. Depending on the chemical composition, imposed cooling rate, prior austenite state, and so forth, the phase transformations occur either diffusionally or non-diffusionally.

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