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Modelling kinetics of phase transformation for the indirect hot stamping process to focus on car body parts with tailored properties

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ABSTRACT

To design the indirect hot stamping process, a finite element method (FEM) based prediction of the part geometry and the mechanical properties is required. In case of indirect hot stamping processes, producing car body parts with tailored properties, cooling paths occur causing diffusionless and diffusion controlled phase transformations. The volume expansion caused by the phase transformation of face-centred cubic (fcc) into body-centred cubic (bcc) and the martensitic formation of body-centred tetragonal (bct) leads to transformation induced strains that are important for the calculation of overall stresses in hot stamped car body parts. To calculate the strain and stress state correctly, it is necessary to model the diffusionless and diffusion controlled phase transformation phenomena, taking into account the boundary conditions of indirect hot stamping processes. The existing material models are analysed and extended in order to improve their prediction accuracy in calculating the amount and distribution of ferrite, perlite, bainite and martensite during the whole process of annealing. For industrial use the new approaches are implemented in the FE-code LS-DYNA 971 (Livermore Software Technology Corporation, 2006).

1. Introduction

The use of the finite element method has received a lot of attention over the past several years, especially regarding the design of hot stamping processes (Finkler et al., 2013) and for manufacturing car body parts with tailored properties that are described by Banik et al. (2011). The hot stamping process describes a heat treatment process of the mainly used material 22MnB5. The aim of this process must be the manufacturing of weight optimized car body parts meeting the respective specific requirements of structural complexity and strength for a good crash performance by using the mechanisms of phase transformation in steel by different process techniques described by Mori (2012). Therefore an austenitized blank is simultaneously formed and quenched (direct hot stamping) or a cold formed car body part is austenitized and quenched (indirect hot stamping) in a cooled tool. In dependency on the temperature history, different phase transformations from austenite into ferrite, perlite, bainite and martensite can occur (Karbasian and Tekkaya, 2010). The complexity of the occurring phase transformations in steel can be described by numerical approaches that are discussed by Olle (2010) and Behrens et al. (2012) or that are implemented in commercial material models like *MAT_244 (Livermore Software Technology Corporation, 2014) in the FE-code LS-DYNA 971 developed by Livermore Software Technology Corporation (2006). This material model, developed by Åkerström (2006), is primarily used for the prediction of the amount and distribution of ferrite, perlite, bainite and martensite for calculating the mechanical properties of hot stamped car body parts like those with tailored properties as described by George et al. (2011).

Analyses by Hippchen et al. (2012a,b) regarding the kinetics of the formation of martensite have shown that an alternative approach is necessary, especially to focus on car body parts with tailored properties. This is recommended out of the reason that the presented approach was not designed to calculate the kinetics of phase transformation for the combination of diffusionless and diffusion controlled formed phases. To model diffusionless phase transformations according to the boundary conditions of an indirect hot stamping process a new martensite model was developed which is introduced in this study.

Further analyses to material model *MAT_244 (Livermore Software Technology Corporation, 2014) have shown that the

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diffusion controlled phase transformation phenomena cannot be modelled close to the measured data of material tests performed in dilatometric testing by Hippchen et al. (2012a); thus the study describes an approach calculating the mechanical properties and geometry of indirect hot stamped car body parts with tailored properties by coupling the diffusion controlled kinetics of phase transformation with a thermo-mechanically coupled material model. The aim is to consider the composition of the volume fractions, phase transformation induced strain and plasticity, and hardening over the entire process of annealing. This is mandatory for calculating overall strains and stresses for springback simulation immediately after the hardening process and for the simulation of thermal deformations while supercooling to room temperature.

2. Examined material

The examined material 22MnB5 (HC380WD + Z140), a fine grained boron manganese steel with zinc coating, is produced by Voestalpine Stahl GmbH (2014) known under the name of phs-ultraform 1500 Z140. The initial blank thickness is 1.5 mm. The measured chemical composition is shown in Table 1.

The average austenite grain size is $d = 8\,\mu\text{m}$. It was analysed in metallographic examinations by etching after Bechet Beaujard (2003). The austenite grain size corresponds to $G_{\text{ASTM}} = 11$. It is autonomous from the effective plastic strain which is induced by a cold forming process due to the indirect hot stamping process. The thermal properties of this material such as conductivity, specific heat and the thermo-mechanical properties can be found in Hochholdinger (2012).

3. Experimental setup and corresponding simulation model

The experimental investigations to the kinetics of phase transformation were performed in dilatometric testing in a BÄHR DIL 805A/D (BÄHR-Thermoanalyse GmbH, 2014). Taking into account the boundary conditions of an indirect hot stamping process the time dependent temperature curves of an indirect hot stamping process were analysed (Fig. 1(a)). Additionally, investigations to the microstructure and measurements of retained austenite, using the Joch-Isthmus-Method as described by Zhao et al. (2001), were conducted.

In order to investigate the quality of prediction of material model *MAT_244 (Livermore Software Technology Corporation, 2014), which is implemented in the FE-code LS-DYNA 971, relating to the experimental setup a FE-model is used. It is based on a single element test as shown in Fig. 1(a). The time dependent temperature curves measured in dilatometric testing are modelled by a Dirichlet boundary condition. The FE-model is solved considering thermo-mechanical coupling with a fully integrated four node shell-element (Bathe, 2002) using thermal-shell option (Bergman and Oldenburg, 1997, 2004) and integration points across the shell thickness (Fig. 1(b)).

4. Modelling diffusionless kinetics of phase transformation

The modelling of diffusionless kinetics of phase transformation by means of the finite element method is an important step in calculating transformation induced strains and stresses to focus on springback simulation in indirect hot stamping processes.

Regarding the approach of Koistinen and Marburger (1959), which is state of the art in modelling diffusionless kinetics of phase transformation, the progress of phase transformation cannot be approximated in dependency on the supercooling in a sufficient accuracy (Fig. 2(left)) (Hippchen et al., 2012b). The experimental results are shown for an average cooling rate between 800 °C and 500 °C of 100 K/s that represents a martensitic phase transformation. All other cooling rates analysed in this work are defined between 800 °C and 500 °C.

Consequently a new approach was introduced using the constitutive equation of Lee et al. (2010) for modelling diffusionless kinetics of phase transformation. Since the formation of martensite is a time-independent process, Eq. (1) shows a rate based approach to the temperature T describing the formation of martensite (m) as a sigmoid function (Fig. 2(right)). Here, ζ_m is the volume fraction of martensite, M_s the martensite start temperature and T the current temperature. The parameters α, n, φ_m and ψ_m are material model parameters that influence the incubation time and the rate of formation $d\zeta_m/dT$ in dependency to the austenite grain size (Lee et al., 2010). The austenite grain size corresponds to $G_{\text{ASTM}} = 11$ and the martensite start temperature is 410 °C.

$$\frac{d\zeta_m}{dT} = \alpha(M_s - T)^n \zeta_m^{\varphi_m}(1-\zeta_m)^{\psi_m} \tag{1}$$

To use the model proposed by Lee et al. (2010) also for processes and cooling paths with a previous formation of diffusion controlled volume fractions it is mandatory to model the rate of formation of martensite $d\zeta_m/dT$ with a normalized fraction ξ_m called the ghost fraction as shown in Eq. (2). Otherwise the sum of diffusion controlled and diffusionless formed volume fractions will be greater than 100 vol%.

$$\frac{d\xi_m}{dT} = \alpha(M_s - T)^n \xi_m^{\varphi_m}(1-\xi_m)^{\psi_m} \tag{2}$$

Subsequently, the ghost fraction ξ_i, which can be a value between 0 and 1, has to be balanced to the amount of retained austenite ζ_γ at martensite start temperature M_s. This is necessary to get the real amount of martensite ζ_m as defined by Eq. (3).

$$\zeta_m = \xi_m\zeta_\gamma | \zeta_\gamma = 1 - \zeta_f - \zeta_p - \zeta_b|_{T=M_s} \tag{3}$$

Depending on the amount of diffusion controlled formed volume fractions, the rate of formation must be updated taking into account the effect of carbonization of retained austenite. Therefore the rate of Eq. (2) is extended by a linear term in its exponent that describes the saturation of the formation of martensite in dependency on the amount of retained austenite ζ_γ at martensite start temperature M_s Eq. (4).

$$\frac{d\xi_m}{dT} = \alpha(M_s - T)^n \xi_m^{\varphi_m}(1-\xi_m)^{\psi_m(2-\zeta_\gamma)} | \zeta_\gamma = 1 - \zeta_f - \zeta_p - \zeta_b|_{T=M_s} \tag{4}$$

The material model parameters α, n, φ_m and ψ_m were identified for a cooling rate of 100 K/s by using the methods of optimization, for example evolutionary strategies, as described by Hippchen et al. (2013). Subsequently, the linear term was found by numerical modelling using the measurement data of retained austenite at room temperature in dependency on the analysed average cooling rates from 100 K/s to 5 K/s. The slightest amount of retained austenite is 1.1 vol% at an average cooling rate of 100 K/s. The highest amount is 4.0 vol% at an average cooling rate of 10 K/s and 5 K/s.

As exemplarily shown in for an average cooling rate of 30 K/s, the transformation of austenite (Fig. 3(left)) and the rate of transformation of austenite (Fig. 3(right)) can be calculated during the whole process of annealing close to the measured data also for lower cooling rates.

Additionally, the amount of retained austenite at room temperature can be predicted which is an indicator for the end of the phase transformation. This information can be used for efficient process design for the determination of the minimum holding time while hardening for example. Fig. 3(left) also shows that a greater supercooling below the martensite start temperature is necessary for cooling rates with diffusion controlled phase transformations in