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A study on the multi-phase transformation kinetics of ultra-high-strength steel and application in thermal-mechanical-phase coupling simulation of hot stamping process

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ABSTRACT

It is a significant issue to deeply understand the phase transformation kinetics and further predict the multi-phase compositions of hot stamping part with finite element method (FEM). As for BR1500HS ultra-high-strength steel, a time-temperature-transformation (TTT) test schedule from austenitizing temperature (1100 °C) to different transforming temperatures (380–750 °C) was conducted on Gleeble 3800 machine. On the basis of microstructure observations, ferrite+pearlite region (600–740 °C), bainite region (420–600 °C) and martensite region (lower than 420 °C) were distinguished. According to the acquired dilatometric curves, the starting and ending TTT curves were fitted. Subsequently, Johnson-Mehl-Avrami type kinetics equation and Magee's equation were respectively solved to describe the diffusional and non-diffusional transformation kinetics as follows: the diffusional transformation efficiency increases to a maximum value followed by a gradual decrease till 100% with time extending; the non-diffusional transformation degree gradually increases with decreasing temperature without time influence. Eventually, the multi-phase transformation kinetics were applied to the construction of the thermal-mechanical-phase dynamic coupling finite element (FE) model of hot stamping process and analysis of the multi-phase evolution and distribution in a hot stamping part. Eventually, the hot stamping process experiment was conducted and proved that the simulation results were effective.

1. Introduction

In recent years, under the background of worldwide energy crisis and environment pressure, global vehicle industry focuses on light weight design on the premise of safety guarantee, which induces wide spread use in high-strength steel (HSS) (yield strength of 210–550 MPa and tensile strength of 270–700 MPa) and even ultra-high-strength steel (UHSS) (yield strength greater than 550 MPa and tensile strength greater than 700 MPa). As for the forming of HSS or UHSS sheet, hot stamping process [1] with a schematic diagram as Fig. 1 is popularly considered as an efficient and novel solution avoiding fracture and spring-back at room temperature. In Fig. 1, firstly, sheet is heated up to austenitizing temperature (A_{C3}) and above, secondly, held at this temperature for sufficient time ensuring original pearlite-ferrite microstructures transformed to austenite completely, thirdly, quickly transferred to the die with a synchronous water cooling system and immediately stamped, finally, the synchronous water cooling system goes into a quenching operation as soon as stamping is ended, meanwhile a holding pressure is still imposed on the sheet [2]. It is worth adding that the synchronous quenching for complete transformation from hot austenite with lower strength to martensite with higher strength is ensured by the rapid heat transfer under a large temperature gradient between upper/down die and sheet, and the sufficient contact of object surfaces under a certain pressure [3]. The tensile strength of UHSS components with 100% martensite achieved by synchronous quenching hot stamping process reaches 1500 MPa or more [4]. It is obvious that 100% martensite is ideally desired for a UHSS component pursuing highest strength. However, its actual phase compositions are multiple involving martensite, bainite, pearlite, ferrite and retained austenite due to the fact that the heat transfer rates are not evenly distributed on the die-sheet contact surfaces. The multiple phase compositions determine the mechanical properties of alloys. Consequently, it is a valuable issue to numerically compute the phase transformation process and even predict the phase compositions of components in the early stage of the product development process.

Finite element method (FEM) with thermal-mechanical-phase

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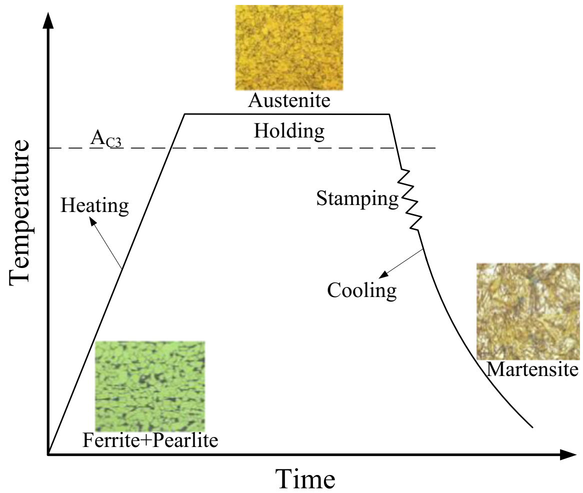

Fig. 1. The principle and procedures of hot stamping process.

dynamic coupling solver supplies an efficient solution for phase transformation computation, by which hot stamping and synchronous quenching parameters can be designed and even optimized. As for the simulation of phase transformation in any forming process by FEM with thermal-mechanical-phase dynamic coupling solver, basic material data including stress-strain data and especially phase transformation kinetics are essential for a FEM analysis model. In the past, many researchers have devoted to modelling phase transformation kinetics. Min J etc. [5] systematically studied the isothermal ferrite and bainite transformation kinetics of 22MnB5 steel. Catteau etc. [6] investigated the carbon and nitrogen effects on the bainitic transformation kinetics in a low-alloyed steel. Kim etc. [7] modelled the martensitic transformation kinetics of a TRIP-assisted steel and investigated the influence of parameters including stress, strain and temperature on it. Kim S etc. [8] adopted a modified KM model to describe the martensitic transformation of Q&P steel. Cui etc. [9] obtained the TTT-diagram by the material performance simulation software of Jmatpro. Bok etc. [10] theoretically solved a Kirkcaldy-Venugopalan type model for the diffusional transformation kinetics and a Koistinen-Marburger type model for the non-diffusional transformation kinetics of an ultra high strength steel.

In fact, in the actual synchronous quenching hot stamping process, different two phase transformation types, i.e., diffusional phase transformation for bainite, pearlite, and ferrite, and non-diffusional transformation for martensite, always coexist due to different heat transfer rates on different positions of the solid-solid contacting surface between mould and deformed sheet. The accurate computation of phase transformation process requires accurate modelling the phase transformation kinetics considering both diffusional and non-diffusional types. The current reported works [5–8] focused more attention on diffusional or non-diffusional, one type transformation ignoring the coexistence of multi-type transformations in a complex quenching process. Moreover, accurate modelling is a significant issue which needs a large amount of testing data corresponding to a wide range of phase transition conditions including temperature and heat transfer rate. In order to avoiding the cost and time exhausting of physical tests, a lot of researchers [9,10] adopted a relative simple way of analytical or theoretical calculation for the phase transformation kinetics. On this regard, the reliabilities of these calculation results cannot be guaranteed. A series of thermal dilation tests for time-temperature-transformation (TTT) on the basis of volume expansion and shrinkage induced by phase transformations, superior to analytical calculation, provide a true data source for solving transformation kinetics. Nowadays a thermal dilation test on thermal physical simulator (machine) is commonly accepted by researchers due to its high accuracy and wide adjustable conditions. In the past, Kuo etc. [11] and Li etc. [12] have successfully applied a Gleeble-1500 thermal physical simulator in the thermal dilation test to measure the TTT curves of A533 alloy and 55CrMo steel.

This work focused on the construction of multi-phase transformation kinetics for ultra-high-strength steel BR1500HS and its application in numerical simulation of hot stamping process. The fundamental data were obtained from a series of phase transformation tests conducted by Gleeble 3800 thermal physical simulator. Then Johnson-Mehl-Avrami type kinetics equation and Magee's equations were respectively adopted and solved as diffusion transformation kinetics from austenite to pearlite+ferrite and bainite, and non-diffusion transformation kinetics from austenite to martensite. After that, by integrating the phase transformation kinetics with a thermal-mechanical coupled FE model, a thermal-mechanical-phase dynamic coupling model for hot stamping process was established. Furthermore, the phase evolutions and distributions on hot stamped sheet were analyzed by simulations. Finally, hot stamping experiment was conducted and the simulated phase distributions were verified by microstructure observations.

2. Measurement and modelling of phase transformation kinetics

2.1. Thermal dilation tests for time-temperature-transformation (TTT) diagrams

Thermal dilation method is often employed to analyze the phase transformations of metal and alloys according to the volume expansion and shrinkage induced by phase transformations since different phases have different densities. It is a fact that austenite has the largest density, then pearlite, ferrite and martensite follow a descending order in density. Therefore, the phase transformation from other phases to austenite brings the volume shrinkage of steel. On the contrary, the dissolution of austenite causes the volume expansion of steel. Thus, during the heating and cooling process, not only thermal expansion effects but also phase transformations induce volume changes of steel. Therefore, by recording the thermal dilatometric curve as Fig. 2 and analyzing its characteristics, the phase transformations of materials can be revealed.

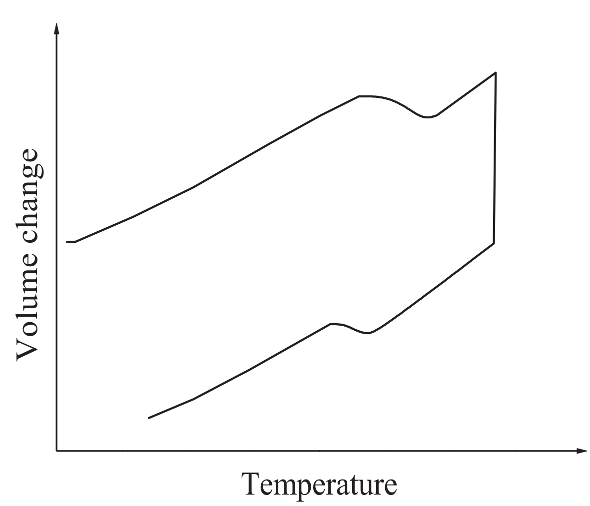

Fig. 2. The schematic diagram of thermal dilatometric curve.