International Journal of Heat and Mass Transfer 91 (2015) 401–415

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Research on the effect of boundary pressure on the boundary heat transfer coefficients between hot stamping die and boron steel

Li Huiping *, He Lianfang, Zhang Chunzhi, Cui Hongzhi

*School of Materials Science and Engineering, Shandong University of Science and Technology, Qingdao, Shandong 266590, PR China*

A R T I C L E I N F O

*Article history:*
Received 30 September 2014
Received in revised form 14 May 2015
Accepted 23 July 2015

*Keywords:*
Boundary heat transfer coefficient
Inverse heat conduction
Hot stamping
Finite element method

A B S T R A C T

Boundary heat transfer coefficient (BHTC) between the hot stamping die and boron steel is one of the most important thermal physical parameters in the hot stamping. A software of inverse heat conduction problem (IHTP) was developed based on the optimization method and finite element method. NiCr–NiSi thermocouples were used to measure the temperature of sample, and the high speed data collection device was used to acquisite the electrical signal from the thermocouples. The BHTC between hot stamping die and boron steel was calculated by the IHTP software according to the temperature curve. Main factors affecting the evaluation accuracy of BHTC were discussed, such as surface temperature of test device, surface temperature of sample, height to diameter ratio ($H/D$) of sample, boundary pressure between the test device and sample. The research results show that, the surface temperatures of test device and sample have little effect on the BHTC. The heat conduction of sample with thermal insulation material can be simplified into one-dimensional process if $H/D$ is not more than 0.6. The boundary pressure has a significant effect on the BHTC. The relationship between the BHTC and boundary pressure is approximately linear.



## 1. Introduction

By using advanced high-strength steels (AHSS) and ultra high-strength steels (UHSS), the car's safety can be improved, and its weight will be reduced remarkably. Whereas, with tensile strength enhancement of AHSS and UHSS, the formability of steel reduces correspondingly, and some defects, such as cracking, corrugation, spring-back and so on, easily appear in the sheet cold forming. In order to improve the forming performance of UHSS sheets, hot stamping for quenchable boron steel sheets was presented and developed in recent years.

At present, lots of research works about the hot stamping of quenchable boron steel sheets have been done in the world, such as the investigation of high-strength steel forming technology, design of hot stamping tools with cooling system, constitutive relationships of boron steel at high temperature, formability of quenchable boron steel sheets and so on. Kolleck et al. [1] studied the induction heating of boron steel in the hot stamping process. The grade of austenitization as well as the mechanical properties of the quenched component has been taken into account in the research. This heating method can reduce the heating time, the investment costs and the floor space for the heating device. Min et al. [2] presented a prediction model for hot forming limits of steel 22MnB5 based on Storen and Rice's Vertex theory and Logan–Hosford yield criterion. By comparison, the calculated FLD based on the Vertex theory and four-order Logan–Hosford yield criterion is in good accordance with the measured FLD. Nikravesh et al. [3] described the effect of hot plastic deformation and cooling rate on the final properties of 22MnB5 steel in hot deformation process by means of deformation dilatometer. Li et al. [4] used the modified Arrhenius model and improved Johson–Cook model to describe the thermo dynamics behavior of boron steel. The constitutive equations depending on the strain, strain rate and temperature were attained by the regression analysis to the experiment data of flow stress, strain, strain rate, temperature, etc.

At present, many researchers have focused their emphasis on the study of numerical simulation of hot stamping process. Aiming at a notable decrease in computation time, Tekkaya et al. [5] presented the finite element simulation of hot stamping process by means of experimental material data, and described a number of procedures for the simulation of hot stamping. So et al. [6] studied the warm blanking and cold blanking of 22MnB5 steel, and compared the experiment results with the simulation results

* Corresponding author at: School of Materials Science and Engineering, Shandong University of Science and Technology, 579 Qianwangang Road, Economic & Technical Development Zone, Qingdao, Shandong 266590, PR China.

*E-mail address:* lihuiping99@163.com (H. Li).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.102
0017-9310/

of finite element method (FEM). Xing et al. [7] built a material model under hot stamping condition of quenchable steel according to the experiment data of mechanics and thermal physical properties. The numerical simulation of hot stamping process was done by ABAQUS software. The simulation results are basically in agreement with experiment results. Lei et al. [8] simulated the cooling process of hot-stamping dies by CFX software, and studied the effect of processing parameters, such as pressure holding time and cooling water velocity, on the temperature of hot-stamping dies.

In the simulation, the thermal physical parameters in the hot stamping process have an significant effect on the calculation accuracy of physical fields, and the boundary heat transfer coefficient (BHTC) is one of the most important thermal physical parameters. In the hot stamping process, there are two types of BHTC, one is the BHTC between the cooling water and hot stamping die, the other is the BHTC between the boron steel plate and hot stamping die. Evaluation of the BHTC according to the temperature variation is one of inverse heat conduction problem (IHCP). For the normal heat exchange problem, temperature field of sample can be calculated according to the known initial condition and boundary condition by the mathematic analytics method. But IHCP is an ill-posed problem, which is different from the normal heat exchange problem, and more difficult to be solved by some methods. For IHCP, the thermocouples should be put into the special position of sample to record the temperature variations in the interior or on the surface of sample. The unknown initial condition or boundary condition can be evaluated according to the temperature variation of sample by some special method.

Many researchers have studied the solution of IHCP, and presented some useful methods. Lesnic et al. [9,10], Kim et al. [11], Shen [12], Tseng et al. [13], Park et al. [14] and Wang et al. [15] respectively presented the boundary element method, decomposition method, integral method, Tikhonov's regularization method, direct sensitivity coefficient method and Karhunen–Loève Galerkin method to solve the IHCP. For the BHTC between the boron steel plate and hot stamping die, Bosetti et al. [16] calculated the heat transfer coefficient in the hot stamping of boron steel sheets under conditions very close to the industrial ones. Abdulhay et al. [17,18] designed an experiment device to determine the thermal contact resistance by the one-dimensional non-linear inverse technique based on the sequential method. Merklein et al. [19] measured the temperature of boron steel plate under different temperature of hot stamping die, and calculated the heat transfer coefficient by Newton's cooling law. Hu et al. [20] developed an optimization based on numerical procedure to determine the temperature-dependent BHTC, and the effects of temperature, pressure and oxide scale thickness on the BHTC were analyzed. Caron et al. [21] investigated the influence of parameters such as pressure and blank and tool temperatures on the heat transfer coefficient between a boron steel blank and a heated tool. All the research about the BHTC of hot stamping process show that, the BHTC strongly depends on the boundary pressure between the hot stamping die and boron steel plate. But the difference of research results is remarkable because of the effect of simplified FEM model used to evaluate the BHTC, as shown in Fig. 1.

In the paper, an IHCP software was developed based on the optimization method and FEM, and was used to calculate the BHTC between the hot stamping die and boron steel. NiCr–NiSi thermocouples were used to measure the temperature of sample. The high speed data collection device was used to acquisite the electrical signal from the thermocouples. Some main factors affecting the evaluation accuracy of BHTC were discussed, such as surface temperature of test device, surface temperature of sample, height to diameter ratio ($H/D$) of sample, boundary pressure between the test device and sample, etc. The accurate FEM model used to evaluate the BHTC of hot stamping is built according to the analysis for these factors. The BHTC between hot stamping die and boron steel was calculated by the IHTP software according to the temperature curve.

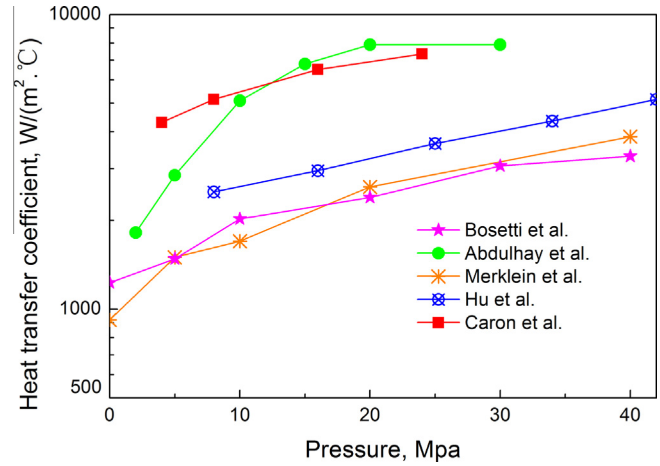


**Fig. 1.** BHTC attained by other researchers.

## 2. Equations of temperature field

In Cartesian coordinates system, the heat conduction of hot stamping die and boron steel part can be described as

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q_v=\rho c_p\frac{\partial T}{\partial t} \tag{1}$$

where $k$ is the thermal conductivity (W/(m °C)), $\rho$ is the density (kg/m$^3$), $c_p$ is the constant-pressure specific heat (J/(kg °C)), $T$ is the temperature (°C), $q_v$ is the phase-transformation latent-heat (J/m$^3$), $t$ is time (s), $x$, $y$ and $z$ are the rectangular coordinates (m).

The initial temperature of boron steel part and hot stamping die can be described as

$$T|_{t=0}=T_0(x,y,z) \tag{2}$$

where $T_0(x,y,z)$ is the function of initial temperature (°C).

In the hot stamping, the heat exchange between the boron steel part and hot stamping die is the third-type condition, and can be described as

$$-k\frac{\partial T}{\partial n}|_{\Gamma}=H(T_w-T_c) \tag{3}$$

where $T_w$ is the temperature of boron steel part (°C), $T_c$ is the temperature of hot stamping die (°C). $H$ is the BHTC (W/(m$^2$ °C)), which will be calculated by FEM and optimization method according to the temperatures measured in the experiment.

## 3. Method of calculating BHTC

### 3.1. Criteria of convergence

In the calculation of BHTC, FEM is used to calculate the temperatures of boron steel part and hot stamping die. The optimization method is used to search and narrow the interval in which the extremum is known to exist, and finally attains the BHTC. The convergence criterion of iteration is constructed using the temperature $T$ measured by sensor and the temperature $\hat{T}$ evaluated by FEM. It can be described as