Determination of Interfacial Heat Transfer Coefficient of 22MnB5 Boron Steel in Hot Forming Based on Inverse Heat Transfer Method

Gang Xiao1,2,*, Zhiwei Zan2
1Collaborative Innovation Center of Engineering Technology, Jiangxi University of Applied Science, Nanchang, 330100, China
2College of Mechanical and Electrical Engineering, Central South University of Forestry and Technology, Changsha, 410004, China

*Corresponding author e-mail: xiao1221@hnu.edu.cn

Abstract. The heat transfer coefficient at the blank-die interface is difficult to determine the values from experiments due to the influence of various factors, such as forming load, coating material, coating thickness, roughness of surfaces and gap formation caused by the deformation of blank and die, etc. In the present paper, the interfacial heat transfer coefficient (IHTC) between the blank and die is identified by using the method of inverse analysis based on measured temperatures. The results show that the method of inverse analysis is a feasible and effective tool for determination of the blank-die IHTC. In addition, it is found that the identified IHTC varies with temperature and load during hot stamping. The characteristics of the IHTC variation have also been discussed.

Keywords: 22MnB5, hot stamping, IHTC, inverse heat transfer method, interface.

1. Introduction
As an important way of energy saving and emission reduction, automobile lightweight has become an inevitable choice to develop automobile industry and improve global competitiveness [1-4]. The hot stamping technology of high strength steels is a new forming technology which can meet the requirements of automobile lightweight. The high strength steel formed by this process has been used in aerospace and transportation because of its light weight and high specific strength. In hot stamping process, the heat transfer behavior between the blank and die has a vital impact on the forming quality of parts. At present, the numerical simulation technology is widely used in the field of hot forming [5-8]. As one of the key boundary conditions, the interfacial heat transfer coefficient between the blank and the die directly affects the accuracy of the solution of temperature field, stress-strain field and microstructure field. In recent years, the heat transfer coefficients have been studied in various degrees [9-16].

According to the interfacial heat transfer behavior of titanium alloys and die materials under different loads, a high accuracy empirical formula of IHTC has been established [10, 11]. The heat transfer coefficient and variation law under different loads have been compared with the results obtained by heat conduction test and element calculation [11]. Based on an in-house designed hot
stamping device and the Beck's nonlinear reverse estimation method, the effect of topography on the IHTC of 22MnB5 boron steel blanks have been systematically studied [12] and the results illustrated that the heat transfer coefficients vary with the blank surface roughness and contact pressure [13, 14]. The Beck's method is a robust and accurate method for identifying the IHTC and the temperature field in hot stamping applications [15]. The injection pressure, spray height and initial quenching temperature all have significant influence on temperature-dependent IHTC of 22MnB5 high strength steel during spray quenching process, and the injection pressure is the most significant factor [16].

In this work, the IHTC between the blank and the die has been estimated using the inverse heat conduction (IHC) method based on temperatures measured in the blank during hot stamping. This method has the potential to be useful in situations where it is difficult to obtain the heat boundary condition by experimental method. The characteristics of the temperature-varying IHTC under different forming loads are discussed in the view of thermal deformation, contact interface and phase transformation.

2. Experimental procedure
The experimental equipment of hot forming used in present work consists of four parts: heating furnace, hot stamping die, cooling system and data acquisition system. The hot stamping die and the structural arrangement of cooling pipes are shown in Fig. 1. Fig. 2 is the schematic diagram of experimental setup with the data acquisition system. The data acquisition system is equipped with a K-type thermocouple to collect the temperature data during the hot forming process. The K-type thermocouple is fixed on the flange, side wall and bottom corner of the U-shaped part. In order to prevent the thermocouple from being pressed during the forming process, the edge of the blank is selected at all three locations, as shown in Fig. 3. The investigated material is an aluminum coated 22MnB5 boron steel with 240 mm in length, 160 mm in width and 2 mm in thickness. The die is made by 4Cr5MoSiV1 tool steel. The corresponding thermophysical parameters of materials are shown in Tab. 1. The maximum force of press during hot stamping is 3000 KN. The experiments were carried out at the loads of 0.05 Mpa, 1 MPa, 2 MPa, 5 MPa and 15 MPa, respectively. The chamber type electric resistance furnace with a rated temperature of 1200 ℃ was employed to heat the studied blank. In the hot press hardening, the Boron alloy steel blank was first austenitized for 10-20 min in a furnace at a temperature of 900 ℃. After having achieved a homogeneous austenitic microstructure, the blank was formed and quenched between cold molds. The water-cooling system in the punch and die was designed to quench the hot part effectively and to obtain an efficient cooling rate. The schematic representation of the hot stamping process is shown as Fig. 4.

Figure 1. The hot stamping die and the cooling system
3. Inverse Model

An algorithm flow chart for the IHC method is shown in Fig. 5. The IHC method seeks to estimate the variation of heat flux $q_m(t)$ at the blank with time by an assessment of the error between the measured and calculated temperature at each time interval. An objective function $F(q_m'(t))$ defined in the following expression to assess the error in $q_m'(t)$:
\[ F(q_m(t)) = \sum (T_{m+\Delta t} - Y_{m+\Delta t})^2 \]  

(1)

where \( m \) represents the time-step counter associated with integration in time. \( T_{m+\Delta t} \) is the calculated temperature at time \( m + \Delta t \). \( Y_{m+\Delta t} \) is the measured temperature at time \( m + \Delta t \). The function \( F \) is minimized through an iteration process.

**Figure 5.** Flow chart of IHC algorithm [4]

4. Results and discussions

Among the cooling curves obtained above, the temperature data of sidewall at the location L2 in the U-shaped blank is the one with close contact and minimum contact clearance. Therefore, the measured temperature data at the location L2 is used as the known temperature history for identifying the IHTC between the blank and the die by the IHC method. Fig. 6 shows the variations of the calculated IHTC with temperature under different forming loads during hot stamping. It can be seen that the IHTC under different loads increases first and then decreases with the decrease of forming temperature, and increases with the increase of stamping load. This is because the forming load will not only change the contact gap between blank and die, but also affect the deformation extent of asperity at the contact interface. With the increase of forming load, the asperity generates elastic-plastic composite deformation in the form of point contact. This leads to the increase of the contact times and the actual contact area at the interface. The heat transfer capacity and flow density increase correspondingly. Finally, the IHTC increases gradually. In addition, a turning point in the process of the IHTC change occurs with the temperature decreasing to 410 ℃. However, the phenomenon is not obvious under the load of 5MPa and 15MPa. The possible reason is that the martensitic transformation begins at 410 ℃ and the released latent heat along with the martensitic transformation slows down the increase of the
heat transfer coefficient. Furthermore, the rapid forming speed of blank under high forming load makes the martensitic transformation too rapid to release the latent heat. This is maybe the reason for the not obvious turning point under the load of 5MPa and 15MPa. Finally, the temperature difference between the blank and die and the degree of heat transfer decreases with the completion of the phase transformation. The IHTC changes into the decreasing stage.

![Figure 6. Identified IHTC variation with temperature under different forming loads](image)

5. Conclusions
The blank-die IHTC has been successfully determined by using the method of inverse analysis based on measured temperatures. The identified IHTC varies with temperature and loads during hot stamping. The IHTC under different loads increases first and then decreases with the decrease of forming temperature, and increases with the increase of stamping load. Moreover, the IHTC variation with temperature is complex. This may be attributed to the complex heat transfer during the hot stamping. During the entire period of forming, many factors, such as the contact form at the interface, latent heat release of phase transformation and volume expansion etc, affect heavily the heat transfer between the blank and die and finally affect the change of IHTC.

Acknowledgements
This work was financially supported by National Engineering Research Center of Near-Net-Shape Forming for Metallic Materials Open Fund, SCUT (No. 2020013); Open Foundation of Guangxi Key Laboratory of Processing for Non-ferrous Metals and Featured Materials, Guangxi University (No. 2020GXYSOF16).

References
[1] Z. Tang, Z. Gu, L. Jia, et al. Research on lightweight design and indirect hot stamping process of the new ultra-high strength steel seat bracket, Metals 9 (2019) 833-844.
[2] L. Tajul, T. Maeno, T. Kinoshita, et al. Successive forging of tailored blank having thickness distribution for hot stamping, Int. J. Adv. Manuf. Tech. 89 (2017) 3731-3739.
[3] P. Guo, L. Qian, J. Meng, et al. Low-cycle fatigue behavior of a high manganese austenitic twin-induced plasticity steel, Mat. Sci. Eng. A 584 (2013) 133-142.
[4] L.Q. Zhang, C. Reilly, L.X. Li, et al. Development of an inverse heat conduction model and its application to determination of heat transfer coefficient during casting solidification, Heat Mass Transfer. 50 (2014) 945-955.
[5] M.G. Lee, S.J. Kim, H.N. Han, et al. Application of hot press forming process to manufacture an automotive part and its finite element analysis considering phase transformation plasticity, Int. J. Mech. Sci. 51 (2009) 888-898.

[6] H.H. Bok, J.W. Choi, F. Barlat, et al. Thermo-mechanical-metallurgical modeling for hot-press forming in consideration of the prior austenite deformation effect, Int. J. Plasticity. 58 (2014) 154-183.

[7] B. Tang, Q. Wang, Z. Wei, et al. FE simulation models for hot stamping an automobile component with tailor-welded high-strength steels, J. Mater. Eng. Perform. 25 (2016) 1709-1721.

[8] Z.Q. Zhang, Z.C. Ye, Y.S. Zhang, et al. Numerical analysis on hot stamping of B pillar reinforcement of automobiles, Adv. Mat. Res. 97 (2010) 282-285.

[9] J. Mendiguren, R. Ortubay, E.S. Argandoña, et al. Experimental characterization of the heat transfer coefficient under different close loop controlled pressures and die temperatures, Appl. Therm. Eng. 99 (2016) 813-824.

[10] M. Xu, R. Ling, Z. Zhang, et al. Study on interfacial heat transfer behavior of TA15 titanium alloy and die materials, Int. J. Heat Mass Tran. 108 (2017) 1573-1578.

[11] Q. Chu, M. Zhang, J. Li, et al. Experimental and numerical investigation of microstructure and mechanical behavior of titanium/steel interfaces prepared by explosive welding, Mat. Sci. Eng. A 689 (2017) 323-331.

[12] M. Merklein, J. Lechler, T. Stoehr. Investigations on the thermal behavior of ultra high strength boron manganese steels within hot stamping, Int. J. Mater. Form. 2 (2009) 259.

[13] Y. Chang, S. Li, X. Li, et al. Effect of contact pressure on IHTC and the formability of hot-formed 22MnB5 automotive parts, Appl. Therm. Eng. 99 (2016) 419-428.

[14] Y. Chang, X. Tang, K. Zhao, et al. Investigation of the factors influencing the interfacial heat transfer coefficient in hot stamping, J. Mater. Process. Tech. 228 (2016) 25-33.

[15] K. Zhao, B. Wang, Y. Chang, et al. Comparison of the methods for calculating the interfacial heat transfer coefficient in hot stamping, Appl. Therm. Eng. 79 (2015) 17-26.

[16] L. Ying, T. Gao, M. Dai, et al. Experimental investigation of temperature-dependent interfacial heat transfer mechanism with spray quenching for 22MnB5 steel, Appl. Therm. Eng. 121 (2017) 48-66.