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Research paper

Comparison of the methods for calculating the interfacial heat transfer coefficient in hot stamping

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HIGHLIGHTS

- A theoretical formula was derived for direct calculation of IHTC.
- The Beck's method is a robust and accurate method for identifying IHTC.
- Finite element method can be used to identify an overall equivalent IHTC.

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ABSTRACT

This paper presents a hot stamping experimentation and three methods for calculating the Interfacial Heat Transfer Coefficient (IHTC) of 22MnB5 boron steel. Comparison of the calculation results shows an average error of 7.5% for the heat balance method, 3.7% for the Beck's nonlinear inverse estimation method (the Beck's method), and 10.3% for the finite-element-analysis-based optimization method (the FEA method). The Beck's method is a robust and accurate method for identifying the IHTC in hot stamping applications. The numerical simulation using the IHTC identified by the Beck's method can predict the temperature field with a high accuracy.

1. Introduction

The hot stamping process is defined as the boron steel sheets such as 22MnB5 are heated to over 900 °C for completely uniform austenitizing and then transferred to water-cooling dies for stamping and quenching at cooling rates of over 27 °C/s. Hot stamped high-strength steel parts have the advantages of high strength, high hardness, little springback and significant weight reduction, all of which make hot stamping the best process for producing complex automotive structural components such as A-pillars, B-pillars and side impact beams etc.

During forming and subsequent quenching, heat transfers between high-temperature blank and low-temperature die. The interfacial heat transfer coefficient (IHTC) between blank and die is an important thermophysical parameter indicating heat transferability. The IHTC directly impacts the temperature distribution in the blank and consequently affects the mechanical property and microstructure of the formed part.

In heat transfer theory, the IHTC is a parameter to describe the heat transfer between interfaces and considered as a constant value in ideal condition. However, an ideal condition is difficult to achieve in practice and the IHTC changes in value as the part is formed and quenched. Merklei et al. [1] and Bosetti [2] studied the contact heat transfer coefficients for given contact pressure and temperature difference at the interface and the gap heat transfer coefficients for various gap values. Abdulhay et al. [3,4] evaluated the heat transfer during hot stamping of a U channel and estimated the thermal contact resistance as a power function of contact pressure.

There are three methods for calculating the transient IHTC. The first method is called heat balance method which is based on the Newton's law of cooling with the assumptions of constant die temperature and small *Biot* number. The die temperature actually changes during forming and quenching, therefore the original Newton's law of cooling needs revision. Hao et al. [5] presented a

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theoretical formula based on the heat balance method and calculated the IHTC of Usibor 1500P steel. The formula is relatively simple in that all material thermophysical properties are assumed constant and Forward Euler integration scheme is used. The second method is to treat the problem as an inverse heat conduction problem, i.e. inversely solve the heat flux and temperature at the interface from the measured temperature fields of the blank and die, given IHTC as boundary conditions, and the optimal IHTC values are obtained by minimizing the difference between the calculated and measured temperatures of the blank and die. Bai et al. [6] and Hu et al. [7] illustrated how this type of method was used in estimating heat transfer coefficient and thermal contact resistance. The inverse estimation method in general relies on measuring the inside temperatures of the die and blank. Calibration of the measurement locations and accuracy in temperature acquisition are necessary to minimize the delaying and lagging effect of the heat transfer itself. The third method is to simulate the temperature field by using a finite element model and determine the optimal IHTC value through an iteration process. This method was used by Guo et al. [8] in prediction of the interfacial heat flux. One limitation of the FEM based optimization method, as demonstrated by Wendelstorf et al. [9], is that it typically only provides a single equivalent IHTC, which cannot reflect the actual changes of the IHTC during the forming and quenching process.

This paper introduced our in-house designed hot stamping experimental devices that can detect and collect the real-time surface and inside temperatures of the die and blank. A theoretical formula based on the heat balance method was derived for direct calculation of the IHTC. A computer program based on Beck's [10] nonlinear inverse estimation method (the Beck's method) was developed to inversely estimate the IHTC. A finite-element-analysis-based optimization method (the FEA method) was also used to calculate the IHTC. The accuracy of these methods were analyzed and compared.

2. Experimentation

2.1. Description of the experiment

The experiment setup illustrated in Fig. 1 consists of a 40-ton hydraulic press, an electric furnace, a two-piece cylindrical die (upper and lower), a circular 22MnB5 steel blank of 2.0 mm thickness, five Φ 0.5 mm K-type thermocouples, a data acquisition device MX100 and a desktop computer. The spherical contact in the support helps balance the lower die and ensure an uniform contact pressure on the blank. Fig. 2 shows the dimensions of the die and blank (specimen), and the temperature collecting positions. One thermocouple is fusion welded onto the surface of the upper die and smoothed flat. The temperature collected by this thermocouple is considered the temperature on the die surface. Three thermocouples are installed in the lower die at 2 mm, 4 mm, 6 mm below the die surface, respectively. One thermocouple is installed right in the middle of the blank.

The K-type armored thermocouples used in experiments were manufactured by B + B Thermo-Technik GmbH in Germany. The product model of the thermocouple inserted in the blank is ETK4/500.05.150.212.110.1500/K and the model of the thermocouples fixed in the die is ETK4/500.10.150.212.110.1500/K. The difference is the diameter of the flexible thermode, namely the diameter of the thermode for the blank is 0.5 mm and for the dies is 1.0 mm. Fig. 3 shows the blank with thermocouple inserted, the position of the thermocouple, and comparison of the thermocouple diameter and the blank thickness.

In the experiment, the blank was heated in the furnace to 900 °C and kept for 3 min, then quickly transferred onto the lower die. The upper die slid down and pressed the blank against the lower die at a certain pressure. Fig. 4 shows the heated specimen and thermocouple wiring. The measured temperatures of the blank and the #45 tool steel die for 1.0 MPa contact pressure are plotted in Fig. 5.

2.2. Analysis of the experiment

It is worthwhile to look into the experiment before the calculation of IHTC is carried out. Among heat conduction, heat radiation and heat convection in hot stamping, the latter two forms are so small that they can be neglected. The consequence of only considering heat conduction between blank and die is a slight overestimation of the IHTC.

The specimen is a circular 22MnB5 steel blank of 2.0 mm thickness and 75.0 mm diameter. The *Biot* number is define as:

$$Bi = \frac{hl}{\lambda} \tag{1}$$

where h is the interfacial heat transfer coefficient, λ the thermal conductivity coefficient, and l the characteristic length. In our experiment, the maximum h is 8×10^3 W/(m^2 K), λ is 40 W/(m K), and l is half the specimen thickness, i.e. 1.0 mm, because the specimen conducts heat from its top and bottom surfaces evenly and only a half model needs to be considered. Substitution of these numbers into Eq. (1) yields $Bi = 0.2$, indicating that the conduction resistance is much smaller than the transfer resistance so the

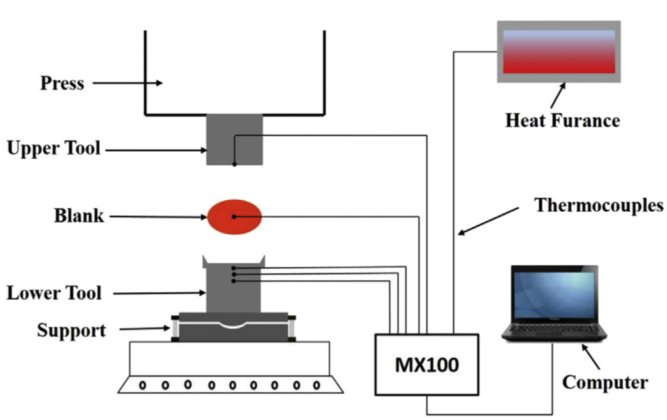

Fig. 1. Schematic illustration of the experiment setup.

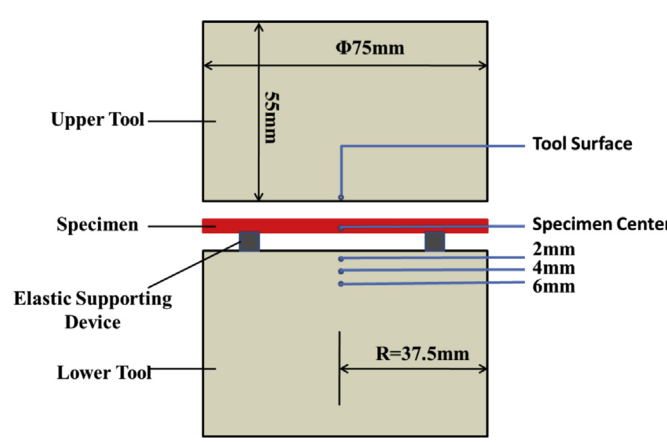

Fig. 2. Dimensions of the heat transfer device and the thermocouple positions.