Investigation of interfacial heat transfer characterization for TC4 alloy in triple-layer sheet hot stamping process

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Abstract
During the hot stamping process, heat exchange always occurs between the hot sheet and cold tools. The interfacial heat transfer in the whole-forming process will not only affects the forming quality of the parts but also partially determines their post-form mechanical properties and microstructure distribution. As an essential parameter, the interface heat transfer coefficient (IHTC) is of great significance for the prediction of temperature fields in the finite element simulations, especially for the novel-forming process named triple-layer sheet hot stamping. In this study, the triple-layer sheet heat exchange experiment is carried out to investigate the interfacial heat transfer behavior of the titanium alloy sheet in the triple-layer sheet hot stamping process. The effects of contact pressure, cladding steel sheet thickness, and contact gap on the interfacial heat transfer behavior and post-form mechanical properties of titanium alloy sheet are analyzed, and the interface heat transfer coefficient between the titanium alloy and high-strength steel sheets is calculated. The finite element model of triple-layer sheet heat transfer is established to verify the accuracy of the calculated interfacial heat transfer coefficient. The results show that the upper and lower steel sheets maintain the temperature of the titanium alloy sheets at a higher level in the triple-layer sheet hot stamping compared with the single-layer one. The temperature of the titanium alloy sheet under the single-layer hot stamping decreases from 900 to 781.6 °C after transferring, a decrease of 118.4 °C. The temperature of the titanium alloy sheet only declines by 57.5 °C during this period in the triple-layer sheet hot stamping process. In addition, the titanium alloy parts obtained by the triple-layer sheet hot stamping process have better mechanical properties. The IHTC increases with the increase of contact pressure and decreases with the increase of steel sheet thickness and contact gap. The accuracy of the calculated IHTC between the titanium alloy and cladding steel sheets is validated by comparing the results of the experiment and simulation. The maximum error between the simulation results and the experimental measurements is 5.5%.

Keywords Interfacial heat transfer · Triple-layer sheet hot stamping · Titanium alloy · Mechanical property

1 Introduction
The titanium alloy is widely used in aircrafts due to its excellent specific strength, corrosion resistance, and high-temperature resistance [1, 2]. However, the traditional forming methods of titanium alloy, which are superplastic forming [3], creep forming [4], isothermal hot forming [5], and so on, have the disadvantages of high-energy consumption and low productivity. The novel technology named the triple-layer sheet hot stamping process is capable of improving the formability of the sheet [6]. The triple-layer sheet hot stamping process is defined as a titanium alloy sheet clamped by two steel sheets for heating, transferring, and forming. There is no adhesive among the sheets, just stacking them follows the steel-titanium alloy-steel layered order together. In addition, the novel technology reduces energy consumption and improves productivity. On the other hand, the new process is proposed to prevent excessive heat loss of titanium alloy sheets in the cold die hot stamping process. The heat exchange will occur between the heated titanium alloy sheet and tool in the forming process, resulting
in the reduction of forming temperature [7]. Therefore, there are urgent research issues that how the temperature field changes and the heat transfer characteristics during stamping.

Hot stamping is a complex thermo-mechanical forming process, and the interfacial heat transfer coefficient (IHTC), which is an important parameter, is of great significance for this technology [8]. In the research of the past few years, a lot of computing methods for determining the IHTC in various hot forming processes have been reported. The IHTC of Ti6Al4V alloy in hot forging process has been measured by Bai et al. [9]. A workpiece was located on die in the experiments, and the thermocouple was embedded in the workpiece to measure its temperature change. The IHTC was calculated by using an efficient numerical model, and the results obtained from the experiment and simulation confirmed that the calculated value of IHTC is accurate. The high-speed infrared camera was used to record the temperature field variation, and the inverse method was employed to calculate the IHTC by Fieberg and Kneer [10]. A simplified assumption, the heat conduction between the workpiece and the dies is one dimensional, was proposed and applied to the calculation of IHTC in Nshama et al. [11]. The determined IHTC according to this simplification is valid by comparing the predicted and experimental temperature. The similar consideration can be found in the investigations by Hu et al. [12] and Wilson et al. [13]. An effective method was used to calculate the IHTC of AA7075 sheet by Xiao et al. [14]. The results show that the IHTC of the sheet can be conveniently and precisely calculated using this method. Caron et al. [15] studied the interfacial heat behavior between 1500P boron steel sheet and AISI 4140 tool steel die using the semi-empirical thermal contact conduction models. The IHTC was calculated using the general model introduced by Cetinkale and Fishenden [16].

Three calculation methods were used to investigate the IHTC of 22MnB5 boron steel under the hot stamping conditions by Zhao et al. [17]. They argue that the Beck’s nonlinear inverse estimation method has a higher prediction accuracy. Caron et al. [7] investigated the IHTC of ultra-high strength steel in the hot stamping process. It is found that the value of IHTC increases with the initial die temperature rises up. The IHTC of aluminum alloy was calculated by Liu et al. [18] in the different initial blank temperature conditions during the warm and hot stamping process. It is found that the IHTC is affected by the strength of the aluminum alloy sheet. Ying et al. [19] investigated the IHTC of AA7075-T6 during the hot stamping process. The accuracy of the Beck’s nonlinear estimation method and heat balance method was compared. The results indicate that the Beck’s method has a high predictive accuracy. Besides, they found the IHTC decreases with the increasing surface roughness of the sheet. Liu et al. [20] studied the effects of contact pressure, lubricant, surface roughness, and tool material on the IHTC of titanium alloy sheet, and a mechanism-based model was established to calculate the IHTC. The results show that the contact pressure is an important influential factor on the IHTC.

In the present investigation, the heat transfer tests are conducted to calculate the IHTC of titanium alloy sheets in the triple-layer sheet hot stamping process. The influence of cladding sheet thickness, contact pressure, and contact gap on the interfacial heat transfer characterization is studied. An efficient calculation method is used to calculate the IHTC of titanium alloy sheets. A finite element (FE) model is established to verify the calculated IHTC value. Then, the temperature change of the U-shaped part is simulated, and the FE simulation results are compared with the experimental measurements. Furthermore, the mechanical property testing and microstructure observation of titanium alloy are conducted as well.

## 2 Experimental tests

### 2.1 Experimental setup

The heat transfer tests were conducted with a set of flat dies on which the tools and sheet temperature histories were measured and recorded. The set of flat dies was installed on the 60-ton hydraulic press machine, as shown in Fig. 1. The whole heat transfer testing device contains three components as follows: flat stamping dies, temperature monitoring installation, and temperature signaling collection. The hot sheet is taken out of the heating furnace and quickly transferred to the springs on the bottom die, which is to prevent severe temperature drop of the sheets before the top and bottom dies close. Two deep holes with a diameter of 1 mm were drilled near the circle center of the bottom die, and their depths are determined by the distance from the bottom die surface, which are 1 and 2 mm, respectively. The K-type thermocouples are fixed and sealed in the deep holes. The temperature signal is collected by the temperature signal acquisition device, and the temperature history is monitored and recorded by the temperature monitoring system.

The testing circular sheets with a diameter of 100 mm were cut from the raw titanium alloy and steel slabs. A deep hole with a diameter of 1 mm has been drilled on the lateral side of titanium alloy circular sheets, and its depth approximates 50 mm to ensure that the thermocouple can measure the temperature around the center of the circle sheets. For drilling with ease, the TC4 sheets with 3 mm in thickness were chosen for the heat transfer testing. Similarly, the K-type thermocouple was inserted in the hole of TC4 sheets. The antioxidant was painted on the titanium alloy sheet surface to prevent the degeneration of mechanical properties.
caused by oxidation. HS1500HC steel, a type of hot stamping steel, is selected as the cladding steel sheets in the tests.

2.2 Experimental procedure

In the tests, three sheets (assembling as the sandwich structure) were simultaneously heated in the furnace. Once the sheet temperature reached the test temperature, the sheets would be soaked in the furnace for 5 min ensuring the sheet temperature is uniformly distributed. These sheets will be transferred to the bottom die after the heating and soaking, and then, the top die will move down to complete the die cooling stage. During the whole heating, transferring, and die cooling process, the temperature histories of the bottom die and sheets were recorded by the temperature collection system through the K-type thermocouple. The temperature changes of cladding steel sheets were also recorded by the same method. The effects of contact pressure and steel sheet thickness on the temperature of TC4 titanium alloy were studied. The investigated process parameters are listed in Table 1. The steel sheet thickness of 0 mm represents the single-layer sheet titanium alloy hot stamping condition.

During the tests, the pressure can be adjusted by the press to obtain different contact pressures. When the thickness of steel is 0 mm in the experimental scheme, it represents the testing case without a steel sheet. The cushion block is placed on the outer ring of tools to achieve different contact gaps, as shown in Fig. 2. The thickness of the cushion block is thicker than that of the three sheets. During the unilateral gap experiment, the cushion block is placed on the outer ring of lower die, and the spring is installed in the middle of lower die. When the upper die moves down, the sheet contacts the upper die and does not contact the lower die under the action of the spring and cushion block. The different gaps can be achieved by controlling the thickness of the cushion block. During the bilateral gap experiment, the ring-shaped steel foils with different thicknesses are stacked on the outer ring of lower die to generate the gap between the sheets and lower die, and the cushion block is also placed on the outer ring of lower die to distance the sheets from the upper die.

In the latter section for the calculation of IHTC and the verification by using FE simulation, the thermophysical parameters of the die material, titanium alloy sheet, and steel sheet need to be given as known conditions. A typical hot working tool steel, AISI-H13, is used as the tool material. The thermophysical parameters of materials published in Yang’s paper [6] used in this study are presented in Table 2.

After the tests, the mechanical properties of the die-quenched titanium alloy sheet were tested by conducting tensile testing at room temperature. All the two dog bone specimens were tested for obtaining mechanical properties for each condition, and the average value of the test was used. Meanwhile, a
square specimen with the sizes of 10 × 10 mm² was cut from the center of the titanium alloy sheets for microstructure observation. The geometry size and shape of the tensile and microstructure specimens are shown in Fig. 3. The Kroll solution (HF:HNO₃:H₂O = 1:3:7) was used to etch the microstructure specimens which has been polished by the emery papers.

3 Calculation method of interfacial heat transfer coefficient

The IHTC is an important thermophysical parameter between sheet and tool. However, the interfacial heat transfer coefficient of the titanium alloy sheet has not been studied in the triple-layer sheet hot stamping process. The investigation and calculation of the heat transfer coefficient of titanium alloy sheet can more accurately predict the distribution of stress and temperature under the triple-layer sheet hot stamping condition. For the triple-layer sheet hot stamping process, there are two contact modes, which are the steel sheet-die contact pairs and the steel sheet-titanium alloy sheet contact pairs, and the heat exchange behavior is different from that in the traditional single-layer sheet hot stamping. In order to simplify the solution procedure, the efficient determination methodology is used to solve the heat exchange coefficient of TC4 titanium alloy under the triple-layer sheet hot stamping condition. According to the heat balance relation, the IHTC can be defined as [14]:

\[ h = \frac{q}{T_{bs} - T_{ds}} \]  

(1)

where \( h \) is the interfacial heat transfer coefficient, \( q \) is the heat flux density, and \( T_{bs} \) and \( T_{ds} \) are the temperatures of sheet and die, respectively. For calculating the heat transfer coefficient between the titanium alloy and steel sheet, \( T_{bs} \) is the temperature of titanium alloy sheet and \( T_{ds} \) is the temperature of steel sheet.

Table 2 The thermophysical parameters of the tool and sheet materials [6]

| Parameters          | Values  |
|---------------------|---------|
| Temperature (°C)    | 25 200  400 600 800 1000 |
| TC4                 | 412 414 420 430 444 462 |
| HS1500HC            | 440 520 561 581 590 603 |
| H13                 | 460 510 548 590 640 - |
| Specific heat (J/kg·K) | 6.95 8.87 10.5 12.9 15 17.4 |
| TC4                 | 30.7 30 21.7 23.6 25.6 27.6 |
| HS1500HC            | 24.4 29.2 29.9 30 30.7 - |
Because the heat conduction is assumed as a one-dimensional problem, the heat conduction equation can be described as follows:

$$C_d \frac{\partial T(x, t)}{\partial t} = \lambda_d \frac{\partial^2 T(x, t)}{\partial x^2}$$  \hspace{1cm} (2)

where $C_d$ is the specific heat capacity of the die, $\rho_d$ is the density of the die, $\lambda_d$ is the thermal conductivity of the die, and $T(x, t)$ represents the temperature at a distance of $x$ mm from the die surface when the time is $t$ s.

The following formula can be obtained by using the finite difference method:

$$C_d \rho_d \frac{T_2(t) - T_1(t)}{\Delta t} = \lambda_d \frac{T_0(t) - 2T_1(t) + T_2(t)}{(\Delta x)^2}$$  \hspace{1cm} (3)

where $T_0$, $T_1$, and $T_2$ are the temperature of the die surface, the temperature 1 mm away from the die surface, and the temperature 2 mm away from the die surface, respectively. $\Delta t$ is the time increment. $\Delta x$ is the displacement increment, which is taken as 1 mm in this paper.

The formula (3) can be transformed into:

$$T_0(t) = 2T_1(t) - T_2(t) + \frac{C_d \rho_d (T_1(t) + \Delta t) - T_1(t)}{\lambda_d \Delta t}$$  \hspace{1cm} (4)

During the heat exchange, the high-temperature sheet was constantly dissipating heat, and the released heat can be calculated by using the following equation [18]:

$$Q = C_b m \Delta T$$  \hspace{1cm} (5)

where $C_b$ is the specific heat capacity of sheet which is shown in Table 2. $m$ is the mass of sheet; $\Delta T$ is the temperature difference when the sheet releases heat, which can be calculated as $\Delta T = T_{\text{ini}} - T_{\text{end}}$. $T_{\text{ini}}$ is the initial temperature of the sheet, and $T_{\text{end}}$ is the temperature after the sheet releases heat.

The expression of heat flux is:

$$q = \frac{Q}{S \times \Delta t} = \frac{C_b \rho_b V_b (T_{\text{end}} - T_{\text{ini}})}{S(t_{\text{ini}} - t_{\text{end}})} = C_b \rho_b a V_b$$  \hspace{1cm} (6)

where $S$ is the nominal contact area between the sheet and die, $\rho_b$ is the density of sheet, the density of the titanium alloy is 4.5 g/cm$^3$, and the density of the steel sheet is 7.8 g/cm$^3$. $a$ is the sheet thickness, and the thickness of titanium alloy sheet is 3 mm. $V_b$ is the cooling rate of sheet, and the value of $V_b$ can be calculated by the equation: $V_b = \Delta T / \Delta t$.

Based on the above equations, the heat transfer coefficient can be calculated by the following equation:

$$h = \frac{C_b \rho_b a V_b}{(T_{\text{bs}} - T_{\text{ds}})}$$  \hspace{1cm} (7)

In the experiment, the change of the temperature versus time was measured. The effective interfacial heat transfer coefficient can be determined by substituting the cooling rate into Eq. (7).
4 Results and discussion

4.1 Temperature variation during testing

Figure 4 shows the temperature change of the titanium alloy sheet with different steel sheet thicknesses during heating. It can be seen that it takes nearly 290 s for the titanium alloy sheet to be heated to 900 °C without the protection of the steel sheet. With the increase of the thickness of steel sheet, the time required for the titanium alloy sheet to be heated to the specified temperature also increases. It takes 740 s to heat the titanium alloy sheet to 900 °C when the thickness of the steel sheet is 1.6 mm. The increase of heating time will cause the rapid growth of grain size which will produce an effect on the deformation behavior and final mechanical properties. Therefore, the steel sheet thickness should be appropriately selected to ensure that the temperature of titanium alloy sheet hardly fluctuates much in the transferring and forming process.

The temperature changes of sheet and tool are shown in Fig. 5 during the die cooling stage. As can be seen from Fig. 5a, the temperature of titanium alloy sheet does not change significantly during the transferring stage. Within 2.7 s after transferring and placement on the bottom die, the temperature of titanium alloy sheet only decreases by 57.5 °C, while the temperature of steel sheet rapidly decreases. This is because the upper and lower layers of steel sheet will exchange heat with the air during the transferring and moving on the tool. The maximum cooling rate of titanium alloy sheet is 18.97 °C/s in this stage. The temperature decreases rapidly after the sheet contacts with the tool, and the maximum cooling rate of titanium alloy sheet increases rapidly to 58.29 °C/s. The tool temperature rises when the sheet contacts with the tool. The maximum temperature difference is 29.8 °C between the two temperature sampling points set on the bottom die.

In the triple-layer sheet hot stamping process, the temperature change of titanium alloy sheet can be divided into three stages: the first stage is transferring in which the sheet has been placed on the tool for about 3 s. In this stage, the temperature of titanium alloy sheet is practically stable, which is the stage of slow cooling at high temperature as shown in Fig. 5a. At this period, heat convection and radiation occur between the steel sheet and air. The second stage is the heat exchange between the steel sheet and tool, and the temperature of the steel sheet rapidly decreases resulting in a great temperature difference between the steel and titanium alloy sheets. The heat quantity of the titanium alloy sheet flows to the steel sheet which has a lower heat quantity resulting in the decrease of the temperature of the titanium alloy sheet, which is called the rapid cooling stage. The third stage is from the moment that the heat exchange lasts for a certain time to the temperature of the steel and titanium alloy sheets tends to be stable. The temperature change of titanium alloy sheet is small, which is named a low-temperature slow cooling stage.
Figure 5b shows the temperature changes of the titanium alloy sheets under different stamping processes. It can be seen that the temperature of the titanium alloy sheet under single-layer hot stamping decreases from 900 °C in the heating furnace to 781.6 °C after transferring, a decrease of 118.4 °C. However, the temperature of the titanium alloy sheet only decreases by 57.5 °C during this period in the triple-layer sheet hot stamping process. During the heat exchange process, it takes 5.4 s and 10.6 s for the temperature of the titanium alloy sheet to drop from 900 to 500 °C, respectively. After the triple-layer sheet hot stamping, the titanium alloy sheet can be maintained at a high temperature for a long time. Therefore, the sheet can be formed at a higher temperature which improves the formability and forming limit of the sheet. Compared with the single-layer hot stamping process, the triple-layer sheet hot stamping process can effectively control the temperature of the titanium alloy sheet and keep it forming at a higher temperature.

4.2 Effect of steel sheet thickness on IHTC

The temperature change of the titanium alloy sheet is shown in Fig. 6 under different steel sheet thicknesses with the contact pressure of 19.1 MPa. With the increase of steel sheet thickness, the decreasing trend of titanium alloy sheet temperature gradually slows down. The temperature of the titanium alloy sheet decreases the fastest in the single-layer sheet hot stamping process. Under the single-layer sheet hot stamping condition, the temperature of the titanium alloy sheet decreases to 800 °C after contacting the tool for 1 s, and the temperature of the titanium alloy sheet decreases to 200 °C after contacting for 9.8 s. When the thickness of the steel sheet is 1.6 mm, the temperature of the titanium alloy sheet decreases to 800 °C after contact with the die for 6 s, and the temperature of the titanium alloy sheet decreases to 200 °C after contacting for 26 s. It shows that the process of using two-layer steel sheets to clamp the titanium alloy sheet for transferring and forming can better control the temperature of the titanium alloy sheet.

The change of cooling rate of titanium alloy sheet under different steel sheet thicknesses is shown in Fig. 7. The change of cooling rate with time is shown in Fig. 7a. The maximum cooling rate of the titanium alloy sheet decreases with the increase of steel sheet thickness. With the increase of steel sheet thickness, the time for the titanium alloy sheet to obtain the maximum cooling rate also increases. According to the above analysis, the temperature change of the titanium alloy sheet will experience through three stages: slow cooling at high temperature, rapid cooling, and slow cooling at low temperature. With the increase of the thickness of the steel sheet, more heat will be stored in the titanium alloy sheet and it is not easy to dissipate. The duration of the titanium alloy sheet in the high-temperature slow cooling stage will increase.

![Fig. 6](image1.png)  
**Fig. 6** The change of titanium alloy sheet temperature at different steel sheet thicknesses

![Fig. 7](image2.png)  
**Fig. 7** The effect of steel sheet thickness on cooling rate: a the change of cooling rate with time and b the change of cooling rate with sheet temperature
After the sheet contacts the die, the rate of heat loss in the steel sheet is slow, and the temperature difference between the sheets is small. Therefore, the cooling rate of the titanium alloy sheet will decrease and the cooling curves will tend to be flat.

The change of cooling rate of titanium alloy sheet with temperature is shown in Fig. 7b. When the titanium alloy sheet is not clamped by the steel sheet, the cooling rate of the sheet increases with the increase of temperature, and the maximum cooling rate is 102.4 °C/s. The heat exchange between the titanium alloy sheet and the tool will continue until its temperature level is consistent when there is no steel sheet. After the titanium alloy sheet is clamped by two steel sheets, the curve of cooling rate changes. It increases firstly and then decreases with the decrease of sheet temperature. When the steel sheet thickness is 1.6 mm, the maximum cooling rate of the titanium alloy sheet is 38.5 °C/s. This is because the titanium alloy plate does not immediately exchange heat with the steel sheet when the sheet contacts the tool in the triple-layer sheet hot stamping process. The sheet temperature can be maintained at a high level, and the cooling rate of the sheet is small. With the increase of contact time, the temperature of steel sheet declines obviously, and there is a large temperature difference between the titanium alloy and steel sheets. As a result, the cooling rate of titanium alloy sheet increases. After a long holding time, the temperature of the titanium alloy and steel sheets tends to be identical, so the cooling rate of titanium alloy sheet decreases. Therefore, the stamping speed should be controlled to ensure that the titanium alloy sheet can be formed when the cooling speed is small. For this experimental scheme, the titanium alloy sheet should be formed before the temperature drops to 800 °C when the steel sheet thickness is 1.6 mm.

The effect of steel thickness on the IHTC of titanium alloy sheet is shown in Fig. 8 when the contact pressure is 19.1 MPa. The IHTC decreases with the increase of steel sheet thickness. In single-layer sheet hot stamping, the IHTC of titanium alloy sheet is 2155.6 W/(m²K). When the thickness of steel sheet increases to 1.6 mm, the IHTC of the titanium alloy sheet decreases to 732 W/(m²K). It shows that the temperature of the titanium alloy sheet decreases slowly and the heat loss is less under the triple-layer sheet hot stamping condition. The existence of upper and lower steel plates which is heated together with the titanium alloy sheet diminishes the heat loss of the titanium alloy sheet.

4.3 Effect of contact pressure on IHTC

The temperature change of the titanium alloy sheet is shown in Fig. 9 under different contact pressures when the thickness of the steel sheet is 1.4 mm. The cooling rate of the titanium alloy sheet increases gradually with the increase of contact pressure. The temperature of the titanium alloy sheet decreases from 403.37 °C at 6.4 MPa to 230.45 °C at 31.8 MPa when the sheet is cooled by the tool for 15 s. The effect of contact pressure on the temperature of the titanium alloy sheet is evident after the sheets contacting the tool. It can be seen that the temperature change of the titanium alloy sheet is not obvious after the sheet is transferred from the heating furnace. The contact pressure has a great influence on the temperature of the titanium alloy sheet when the sheet is transferred to the tool for a period of time. In conclusion, a smaller blank holder force should be used in the hot stamping process on the premise of no wrinkling, if the good formability of titanium alloy is desired.

The effect of contact pressure on the cooling rate of the titanium alloy sheet is shown in Fig. 10. The variation curve
of cooling rate with time is described in Fig. 10a. The cooling rate of the titanium alloy sheet first increases and then decreases with the increase of time. Before reaching the peak value, the cooling rate increases with the increase of contact pressure. This is because the heat exchange between the steel sheet and tool increases with the increase of the contact pressure. The temperature of the titanium alloy sheet rapidly decreases because that the temperature difference between the plates increases. After reaching the peak value, the cooling rate decreases with the increase of contact pressure.

The change of cooling rate with sheet temperature is shown in Fig. 10b. It can be seen that the cooling rate first increases and then decreases with the decrease of sheet temperature. The maximum cooling rate of the titanium alloy sheet increases from 45.4 °C/s of 6.4 MPa to 80 °C/s of 31.8 MPa with the increase of contact pressure. The reason can be considered that the contact surface between the titanium alloy plate, steel plate, and die becomes greater after the contact pressure increases. The titanium asperities were deformed and then meshed to those on the steel sheets during holding the contact pressure. Therefore, the real contact area between the sheets increases resulting in the increase of the cooling rate of the titanium alloy sheet.

The variation of IHTC of titanium alloy sheet is shown in Fig. 11 under different steel sheet thicknesses. It can be seen that the IHTC increases with the increase of contact pressure, and the IHTC between the titanium alloy and steel sheet is much less than that between the titanium alloy and tool. For example, when the contact pressure is 12.7 MPa, the IHTC of titanium alloy sheet obtained by the triple-layer sheet hot stamping process is 435.2 W/(m²·K). However, the IHTC of the titanium alloy sheet obtained by the single-layer hot stamping process is 1432.3 W/(m²·K). The greater IHTC shows that more heat will be lost during the deformation of the titanium alloy sheet. Under the triple-layer sheet hot stamping condition, the upper and lower surfaces of titanium alloy sheet which has less heat loss are protected by steel sheet, so that it can be maintained at high temperature for a long time. Under the triple-layer sheet hot stamping condition, the variation of IHTC of titanium alloy sheet becomes convergent and increases slowly when the contact pressure exceeds 19.1 MPa. It shows that the heat loss of titanium alloy can be effectively controlled using the triple-layer sheet hot stamping process.

4.4 Effect of contact gap on IHTC

In the hot stamping process, the sheet blank does not always contact with the tools. Inevitable gaps are existing between the part and tool at some positions. The contact heat exchange among the sheets and tools becomes the heat exchange between the sheet metal, air, and tools, when the gap is considered in the hot forming process. To analyze the effect of different contact gaps on the temperature of titanium alloy sheet, the results presented in Fig. 12.
are obtained through experiments. It can be seen that the temperature of the titanium alloy sheet decreases with the increase of the contact gap between the steel sheets and tool. When the contact gap is 0.2 mm or 0.5 mm, the titanium alloy sheet first cools rapidly and then cools slowly at the unilateral gap condition.

The variation of cooling rate of titanium alloy sheet with sheet temperature under different contact gaps is shown in Fig. 13. It can be seen from the figure that the cooling mode of the titanium alloy sheet is mainly heat exchange with the tool when the clearance is small, such as the unilateral clearance of 0.2 mm and 0.5 mm. The maximum cooling rate is obtained when the unilateral clearance is 0.2 mm, and its value is 42.8 °C/s. When the contact gap between the steel sheet and tool gradually increases, the cooling mode of the steel sheet has changed from die cooling to air cooling. Therefore, the temperature difference between the titanium alloy sheet and the steel sheet will not increase drastically. The three-layer sheet is cooling slowly. In addition, the air between the sheet and the tool is heated after the gap increases, and the indirect heat exchange occurs between the sheet and the tool. The hot air between the upper and lower tools is difficult to be emitted, so the cooling rate of the sheet is small.

The change of IHTC between the titanium alloy and steel sheets is shown in Fig. 14 under different contact gap conditions. The IHTC decreases with the increase of the contact gap. The downturn of IHTC is more significant under the bilateral gap condition. When the bilateral gap increases from 0 to 1 mm, the IHTC decreases from 331 W/(m²·K) to 46.8 W/(m²·K), which decreases by 284.2 W/(m²·K). The reason is that the steel sheet does not contact the tool under the bilateral gap condition, and the steel sheet temperature is high resulting in the slow decline of the temperature of the titanium alloy sheet.

Fig. 12 The temperature change of titanium alloy sheet at different contact gaps (steel sheet thickness = 1.4 mm). a The unilateral gap and b the bilateral gap

Fig. 13 The change of cooling rate at different contact gaps

Fig. 14 The effect of contact gap on the IHTC
5 FE simulation and validation of IHTC

In order to verify the accuracy of IHTC, a FE model is established in Abaqus software to simulate the temperature variation of the titanium alloy sheet during the hot stamping process, in which the dimensions are consistent with those used in the heat transfer test. Explicit axisymmetric plane elements of $0.2 \times 0.2$ mm$^2$ are employed for meshing the tools and sheets. A typical hot working tool steel, AISI-H13, is used as the tool materials. The thermophysical parameters of the materials used in the experimental tests are listed in Table 2. To obtain more accurate simulation results, the simulation process can be described as follows: The sheet is cooled at the air for 2 s, and then, the sheet is quenched by the flat tools. The initial temperature of the sheet is set as 900 °C.

The simulation model and the temperature change of the tool and sheet are shown in Fig. 15. Figure 15a shows the FE model of the triple-layer sheet heat transfer test, and Fig. 15b shows the temperature distribution of the tool and sheet under the contact pressure is 19.1 MPa and the pressure is maintained for 15 s. It can be seen that the temperature in the central area of the tool is almost evenly distributed, which conforms to the one-dimensional heat transfer assumption of the tests. It can be seen that if the diameter is less than 40 mm, the temperature of titanium alloy sheet and tool surface changes little in the diameter direction, which can be considered that the temperature is evenly distributed. The change of sheet temperature at different distances from the center is shown in Fig. 15c. It can be found that the change of the sheet temperature is steady, and the temperature through the sheet is evenly distributed.

The results of the titanium alloy sheet temperature obtained from the experiment (symbols) and simulation (solid lines) are shown in Fig. 16a under different contact pressures and the steel sheet thickness of 1.4 mm. The measured temperature point is the center of the sheet. It can be seen that the established model gives a nice prediction for the temperature change of the titanium alloy sheet during the cooling process. It also proves that the calculated IHTC is accurate for capturing the heat exchange behavior of sheets in the triple-layer hot stamping process. Under different contact pressures, the average error between the simulation results and the experimental values is less than 6%. The maximum average error is 5.5% when the contact pressure is 6.4 MPa.

A U-shaped confirmatory part was designed and formed by using the single-layer and triple-layer sheet hot stamping processes in the laboratory. The experimental tool and simulation model are shown in Fig. 16b. Before the tests, the titanium alloy and steel sheet were cut into a sample having a size of 180 mm × 50 mm × 1.6 mm. During the tests, the sheet was placed in a heating furnace and heated to forming temperature ranging from 900 °C for 300 s. Then, the blank is rapidly transferred to the tool and the 60 T press worked...
to complete the stamping. The blank holder is supported by a nitrogen gas spring and exerts a fixed blank holder force on the blank. After the stamping, the sheet was held between the cold punch and die to quench for 90 s ensuring sufficient cooling of the blank.

The relevant forming processes are simulated by the finite element software Abaqus to analyze the evolution of temperature fields of parts, in which the different IHTCs with various contact pressures and gaps shown in Figs. 11 and 14 are input as the boundary conditions of FE models. The formed part is a symmetry part, and half of the cut-out part was modeled. In the model, the sheet elements are elastic–plastic elements, the mesh size is 0.5 mm, and the material stress–strain curve adopts the curve shown in Yang’s paper [6]. The physical properties of the materials are shown in Table 2. In order to simplify the calculation, the tools were set to be a rigid body, with an average element size of 2 mm, and the tool temperature is set to room temperature. The friction coefficient between the sheet and the mold is set to a fixed value of 0.15. Finally, the temperature field of U-shaped parts obtained by simulation will be compared with the temperature field measured in the experiment.

The thermal imager was used to track and record the temperature change of the titanium alloy sheet after hot stamping. The temperature distribution of the titanium alloy U-shaped parts is shown in Fig. 16c after stamping. The initial sheet temperature is 850 °C. After hot stamping, the formed parts still have a high temperature in the triple-layer sheet hot stamping process. However, the temperature of the titanium alloy parts decreases from the 850 to 195.6 °C in the single-layer sheet hot stamping process, which has great heat loss.

6 Microstructure and mechanical properties

The metallographs of the quenched parts are shown in Fig. 17 under different stamping processes. For the two-phase TC4 titanium alloy, the microstructure mainly contains two compositions: the hexagonal close-packed (HCP) α phase and the body-centered cubic (BCC) β phase. The α phase will transfer to the β phase with the change of deformation temperature. The β phase has more slip systems and lower deformation resistance compared with the α phase. It can be seen from Fig. 17 that the phase transformation has occurred in the TC4 titanium alloy sheets at different stamping processes. In the single-layer sheet hot stamping process, there is insufficient time from the β phase to the α phase due to the fast cooling rate. Hence, the microstructure of the quenched sheet shows the metastable β phase and the hexagonal martensite α’ phase, and the subsequent heat treatment is indispensable to stabilize the microstructure. Compared with the single-layer quenched sheet, the slow cooling rate results in sufficient transformation time in the triple-layer sheet hot stamping process. Finally, the stable α + β phase-mixed microstructure can be obtained at room temperature, which improves the mechanical properties of the sheet. In addition, the globularization process is found in the triple-layer sheet quenching results. The globularization of the α phase is easy to obtained due to the high temperature of the sheet in the triple-layer sheet hot stamping process, which increases the formability of the sheet.
The mechanical properties of the sheet are shown in Fig. 18 after the die cooling when the contact pressure is 19.1 MPa, the steel sheet thickness is 1.6 mm, and the heated temperature is 900 °C. It can be seen from Fig. 18 that good mechanical properties can be obtained in the triple-layer sheet hot stamping process. The yield and ultimate strengths and elongation after the triple-layer die quenching are similar to that of the as-delivered sheet. However, the ultimate strength obtained from the single-layer sheet die quenching drops to 963.4 MPa due to the high cooling rate, decreasing 8.3% compared with the initial sheet. This is because that the rapid cooling rate makes more β phase remain in the quenched sheet after the single-layer sheet die quenching. Compared with the α phase, the β phase manifests the lower deformation resistance.

7 Conclusions

The interfacial heat transfer characterization of titanium alloy sheet is studied under the triple-layer sheet hot stamping condition. The IHTC and mechanical properties of titanium alloy are calculated and measured, respectively. The FE simulation model of heat exchange is established to verify the accuracy of IHTC. The conclusions are summarized as follows:

1. The maximum cooling rate of the titanium alloy sheet increases with the increase of contact pressure, decreases with the increase of steel sheet thickness, and decreases with the increase of contact gap. Under the single-layer sheet hot stamping condition, the maximum cooling rate of the titanium alloy sheet is 102.4 °C/s, and the cooling rate of the titanium alloy sheet falls to 38.5 °C/s in the triple-layer sheet hot stamping process. Compared with the single-layer sheet hot stamping, the triple-layer sheet hot stamping is capable of maintaining the forming temperature of titanium alloy sheet at a higher temperature and can obtain titanium alloy parts with better mechanical properties.

2. The IHTC between titanium alloy sheet and steel sheet increases gradually with the increase of contact pressure. When the thickness of the steel sheet increases from 1.4 to 1.6 mm, the IHTC of the titanium alloy sheet decreases by 29 W/(m²·K). The IHTC of the titanium alloy sheet decreases with the increase of the contact gap. When the bilateral gap increases from 0 to 1 mm, the interfacial heat transfer coefficient decreases by 284.2 W/(m²·K).

3. The accuracy of the calculated IHTC of the titanium alloy sheet is proved by comparing the temperature obtained by experiment and simulation. The maximum error between the simulation result and the experimental value is 5.5%. The established finite element simulation model can be used to simulate the cooling process of titanium alloy triple-layer sheet hot stamping.
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Code availability The code used or analyzed during the current study is available from the corresponding author on reasonable request.

Declarations

Ethical approval No ethical approval was required for this research.

Consent to participate All authors approved to participate.

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