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Inverse Analysis for HTC Identification

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Abstract: The hot stamping of boron steels for producing complex structural components of the car body-in-white is more and more widespread, since the parts produced by this technology are characterized by an high strength to weight ratio due to the simultaneous forming and quenching stages they undergo during manufacturing. Despite its worldwide use in production lines, optimization of sheet forming technologies at elevated temperatures is still troublesome, since the thermal, mechanical and metallurgical phenomena interacting during hot stamping force to feed the numerical model of the process by a huge amount of data, most of wich implying not standardized tests. This is the case of the evaluation of heat transfer coefficient between the metal sheet and the forming dies.

The objective of the paper is therefore the development of a robust procedure to evaluate the heat transfer coefficient (HTC) with dies in hot stamping operations of boron steels; the developed procedure is based on the joint use of experimental and numerical techniques. This procedure is used to identify the htc between 4 different die materials (a die steel and three advanced ceramics) and a blank made of boron steel. Presented results show that heat transfer depends on the applied pressure and that thermal evolution inside the sheet can be drastically modified by using different die materials.

Keywords: hot stamping, process simulation, heat transfer coefficient, inverse analysis, optimization

1 Introduction

Hot stamping process of high strength boron steels is widely recognized as the best solution to produce structural components of the car body-in-white characterized by an high ratio between strength and mass. The standard process route comprises the complete austenitization of the steel sheet into a furnace, its rapid transfer to the forming machine, where simultaneous forming and quenching stages take place. The most widely utilized sheet material is the boron steel 22MnB5, commercially known as Usibor 1500. The most widely utilized die material is the steel AISI h11: the thermal properties of this material and its htc with the blank induce a cooling rate in the blank that produces a martensitic component, widely used for automotive industry.

This paper presents an HTC identification approach, using a joint numerical-experimental procedure; describes the test and measurements, the FE model of the test and the optimization technique for inverse analysis. Presented results show that: (*i*) the proposed procedure can be successfully validated and be thus considered reliable; (*ii*) HTC depends on the level of applied pressure for the analyzed die materials; (*iii*) heat transfer can be drastically modified when using other materials than steel for the dies, in turn modifying the thermal field inside the formed component.

2 HTC Identification Approach

The identification of heat transfer coefficient through inverse analysis requires a test reproducing industrial conditions and a numerical model of the test itself. The development of the model and of the test are parallel and interconnected: the model must be robust, the test must be simple, repeatable and must reply the industrial process.

HTC depends on several conditions [1, 4, 2, 3], which can be divided into two broad categories:

- system inherent properties: geometry, materials, thermal properties,...
- external system conditions: applied pressure, contact surface conditions

(roughness, cleanless),...

In this paper only the ifluence on the HTC of dies material thermal properties and of applied pressure considered. In order to standardize the other factors (which can be considered disturbance factors) and minimize their influence on the value of identified HTC, very simply geometry is chosen: a rectangular metal blank compressed between two flat die. This choice allows a robust test, in which the influence of disturbance factors on HTC is minimized.

The test consists of four steps (see Figure 4): heating in a external fournace (1), blank transfer (2), approach to the dies (3), compression between the dies (4). Only the last two steps are numerically modelled. The thermal cycle on the blank is the same of the industrial process.

In order to minimize the computational time of inverse analysis, the geometry of the test is chosen so as to reduce the FE model from 3-D to 2-D.

3 Test Design

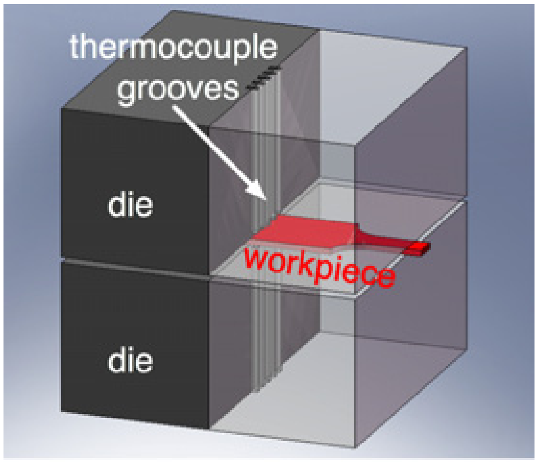

Figure 1: Sketch of dies and blank.

A sketch of both the dies and the metal blank is shown in Figure 1. The presence of grooves for locations of thermocouple makes in principle the thermal problem a 3-D one, even if the overall geometry of dies and sheet can be regarded as 2-D. Thermocouple locations with respect to the die surface have to be chosen in order to guarantee stability of the inverse problem to be set-up for HTC identification. In particular — for each one of the four die materials that are object of the analysis — the depth of the central thermocouple is designed calculating the associated Fourier number F_0 [**?**]:

$$F_0 = \frac{\alpha \Delta t}{e^2} \tag{1}$$

where e is the depth of the reference thermal sensor, Δt is the time step of data acquisition, and α is the thermal diffusivity of the considered die material.

Being F_0 for all the four considered die materials always between 1 and 0.01 (see Table 1), it can be stated that records from the thermocouple located at 0.5 mm from the die surface can be utilized to gain a reliable solution of the inverse problem. The four materials that have been used for the dies and reported in Table 1 are the traditional hot working steel AISI h11 and three advanced ceramics, high-purity alumina, machinable glass-ceramic Macor and zirconia.

4 Test FE Model

A finite element model of the above described test has been developed with the following aims:

- to detailedly describe the three dimensional temperature field in the test configuration;
- to reduce the 3-D model in 2-D;
- to calculate HTC values by means of reverse analysis technique, exploiting the 2-D model;
- to calculate HTC for most tests and to investigate the influence of different dies materials and applied contact pressure on HTC.

The tool used for numerical modelling is the multi-physics FE-based software Comsol 3.5, which offers a comprehensive handling of thermal problems.

The input variables are:

- geometry;
- thermal properties of die and workpiece materials;
- boundary conditions;

- initial thermal conditions inside workpiece and dies.

Thermal and mechanical parameters of dies and workpiece materials as function of temperature have been found in literature and are reported of the appendix. Boundary conditions on the thermal model — although of little effect as shown by the sensitivity analysis — have been set as fixed temperature on external surfaces (Figure 1) and as convective heat exchange on the die surfaces, along the area not in contact with the sheet (Figure 1). A convective heat exchange coefficient of 20 W/m^2/K has been chosen.

The thermocouple grooves have been modelled as cylindrical blind holes, filled with a continuous phase of ceramic bond from the surface down to 4 mm from the hole end (see Figure 1). The interface between the ceramic bond and the die material is adiabatic in the case of steel dies and continuous (*i.e. zero resistance*) in the case of ceramic dies. The terminal cavity is considered as adiabatic in the FE model, since it describes a small cavity of still air at relatively low temperature (thus with no significative convection nor radiation) and since the thermocouple wires have negligible thermal capacity.

The thermal resistance at the interface between sheet and dies (Figure 1) has been modelled in Comsol by means of the so called “thin thermally resistive layer”. It is a layer of 2-D elements whose thermal flux has only orthogonal component, and whose temperature gradient is proportional to the thermal flux. The inverse of the thermal resistance represents the HTC, and is the varying parameter in the inverse analysis described in Section 7.

The 3-D model above described showed that the thermal field along the measurement plane — the one defined by the thermocouple grooves — is negligibly affected by the presence of the thermocouples, as illustrated in Figure 2. Consequently, the FE model can be reduced from 3-D to 2-D, without loosing accuracy, if the 2-D model corresponds to the section along the measurement plane of the 3-D model without the thermocouple grooves. Materials parameters and boundary conditions are correspondingly adopted from the 3-D model.

The solution time of the reduced model is about 10 times shorter than that of the full 3-D model, thus allowing an effective and viable inverse analysis by iterative optimization.

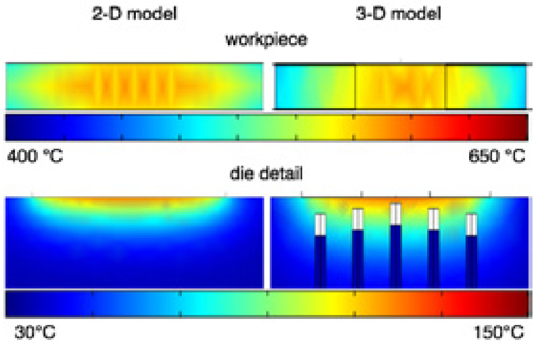

Figure 2: Effect of thermocouple grooves on die thermal field.

5 Experiments

The test developed and set-up for acquiring data to HTC identification is the compression of a metal blank between two flat dies at imposed value of contact pressure. The metal blank is made of Usibor 1500. For the dies the hot working steel H11 and the three advanced ceramics high-purity alumina, Macor and zirconia are utilized. The test takes places in a 100 kN Instron press where the pressure is applied to the upper die almost instantaneously; four levels of contact pressure (from 5 to 35 MPa) are considered repeating each test for each material couple three times in a random order.

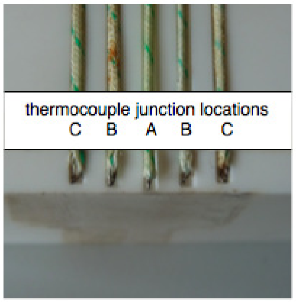

Figure 3: Thermocouple junctions position.

During transfer time, the blank temperature is measured and recorded through an infra-red thermocamera (see Figure 4, time t_0). During compression time, the dies thermal field is measured through thermocouples, located in grooves as shown in Figure 3. The junctions of the thermocouples are at different depths with respect to the die surface (nominally, one at 0.5 mm, two symmetric at 1.0 mm and other two symmetric at 1.5 mm). The actual position of the thermocouple hot junctions were measured after the tests, when the dies is open, in order to consider the exact position in the numerical model of the test. Temperature recorded inside the dies represents the observable parameter for the subsequent inverse analysis procedure. In particular, the record of the thermocouple nearest to the die surface is chosen for HTC identification, while the other thermocouples measurements are used to validate the identification procedure.

6 Test Numerical Simulation

The FE model of the test is solved in a two-step time dependent simulation. HTC identification is based on the second step, while the first one is needed for the calculation of the thermal field assumed as initial condition in the second step.

The first step (*approach*, 3 in the Figure 4) goes from the introduction of sheet metal sample within the dies until the complete closure of dies. The second step (*compression*, 4 in the Figure 4) has a fixed duration (20 s for steel and alumina, 40 s for Macor and zirconia) and simulates the gradual thermal diffusion between sheet and dies. Temperature vs. time diagram of the test with indication of numerically simulated steps is reported in Figure 4.

With respect to the real test, the first step begins when the thermocamera acquires the sample temperature surface field, just before it enters in the dies, and ends when the load cell of the testing machine indicates that the preset load has been reached. Figure 4 shows a termocamera image of blank surface temperature in approaching the dies: it can be seen that temperature is rather constant, thus justifying the assumption of constant initial temperature in sheet at the beginning of the first step.

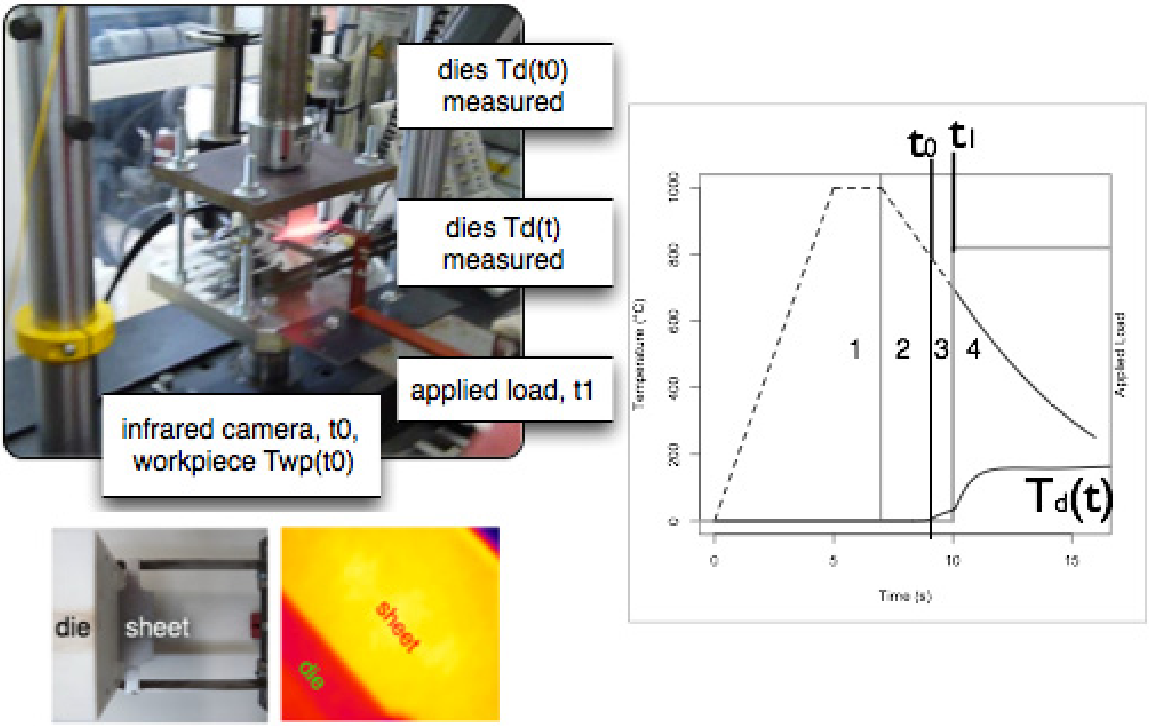

Figure 4: Thermal evolution of the test.

The simulation time of the first step is equal to its actual duration as measured by the test set-up instrumentation (thermocamera and testing machine; the duration of first step being about 1 second for all tests). The initial conditions are set as uniform room temperature on the dies, and the initial heat transfer coefficient between dies and sheet metal sample is zero. Then the sample starts to exchange heat with dies by convection and radiation, with coefficients that linearly increase simulating the effect of the increasing normal load during the die closing phase.

During the test, the heat exchange by radiation is much greater compared to that by convection: at beginning, the dies are 2.5 mm distant (the workpiece thikness is 1.5 mm) and the thin air film betwen workpiece and die does not allow a significant convection heat exchange. On the other side, the radiation increases (like increase the factor of view) when the workpiece enters between the dies and when the upper die approches. The assumption that the global HTC increases linearly in the first step is confirmed by the evolution of thermal field acquired by thermocouples. This effect has been obtained by setting the resistance coefficient of the above cited thin thermally resistive layer as a function of time that has been calibrated in order to produce a thermal field in good relationship with that measured by thermocouples.

During the second step the HTC is held constant. Although this is generally not true — since HTC is a function of temperature — this simplification is justified by the weak relationship between HTC and temperature (in the range of considered temperatures) and by the fact that, in terms of inverse analysis, this allows to calculate an effective value of HTC which is suitable for process simulation to be conducted in the same temperature interval.

7 Inverse Analysis

The HTC can be calculated by means of a single-target inverse analysis having as observable quantity the temperature measured by the thermocouple in position A (see Figure 3). Thermocouples in position B and C provide redundant measurements, useful for quality analysis of tests and to detect sheet positioning errors, Note that, in accordance with the Fourier analysis, the thermocouple in position A is the one that ensures the most robust inverse analysis.

The flow chart of the proposed inverse analysis is shown in Figure 6. The first step (3 in Figure 4) is simulated only once for each optimization. The inverse analysis is performed over the second step (4 in Figure 4) only: three simulations are carriedout using three different trial HTC values: for each simulation the standardize residuals between temperature evolution in position A measured and simulated are computed. The value of standardized residuals are plotted versus HTC and interpolated by a parable. At the minimum of the parable the right value of HTC. This procedure gives correct results if the trial HTC value are close to right value of HTC. The correct trial HTC values are calculated by the solution of the electrical analogy proposed in Figure 5.

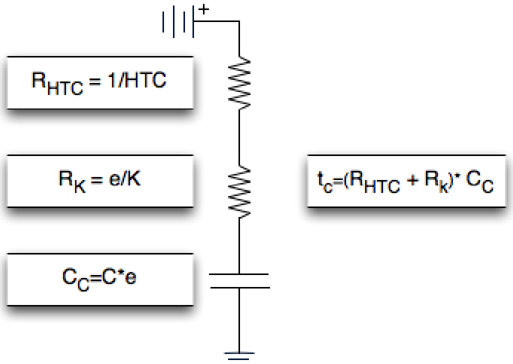

Figure 5: Electrical analogy.

The first resistance (R_{HTC}) is the surface-surface thermal resistance; the second resistance represents the resistance of the material that separates the contact surface from the joint of central thermocouple (see Figure 3). The time costant of the system is given by the t_C, and is the charging time of capacitor, which is the time for reaching the maximum temperature for the central thermocouple (called t_m, measured), divided by 3 times. For the simplified thermal model, it is possible to write the following equation:

$$t_m = 3 * ((R_{HTC} + R_k) * C_C)$$

where C and e is given in Table 1, and t_m is measured in each test.

The theoretical right value of HTC is:

$$HTC^* = \frac{3*C*e*k}{k*t_m - 3*C*e^2}$$

where C are given in $\frac{J}{m^3*K}$.
As trial HTC values HTC^*, $1.3*HTC^*$ and $0.7*HTC^*$.
For each test, the value of standardized residuals corresponding to right HTC value provides an indication of the quality of the test.

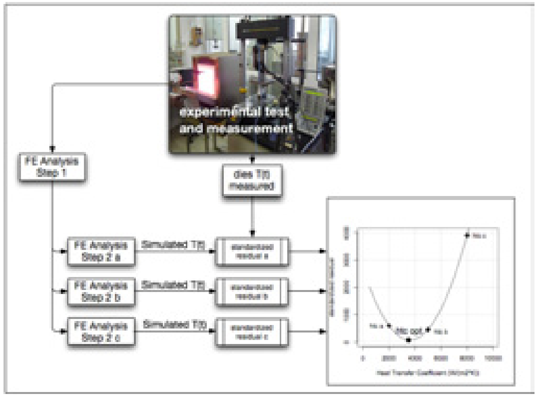

Figure 6: Flow chart of inverse analysis.

8 Results and Discussion

In this Section relevant results of this study are presented and general conclusions are drawn. Figure 7 shows the good fitting between experimental and numerically calculated temperature evolutions for thermocouple A in the case of the four tested die materials. For AISI h11 and alumina, a steep increase of temperature as soon as the pressure is applied can be seen, and the same steep decrease is observed after having reached the maximum of temperature. On the other hand, the Macor and zirconia present a very different behaviour: due to its higher heat capacity and lower thermal conductivity (resulting in a lower thermal diffusivity), time needed to reach the maximum temperature into the die is much higher than in the case of steel and alumina, and the heat release is lower as well.

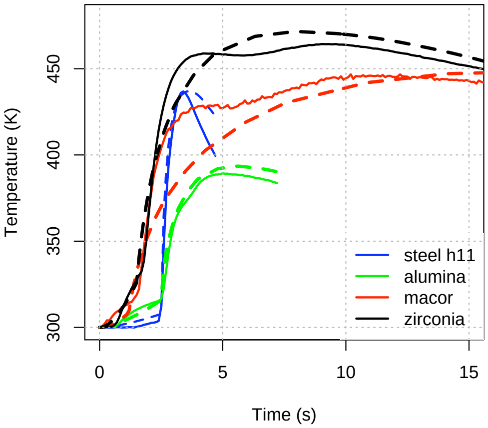

Figure 7: Comparison between numerical and experimental temperature evolution at thermocouple A location for the four die materials (contact pressure 25 MPa; initial blank temperature 950K).

Identified values of heat transfer coefficients are shown in Figure 8 as function of applied pressure for the four die materials. HTC strongly depends on pressure for steel and alumina, while Macor heat transfer sensitivity to pressure can be regarded as negligible; the reason can be again ascribed to their very different thermal properties compared to the other two die materials. According to these results, the heat transfer coefficient between dies and sheet can be modelled as constant when Macor inserts are used, while in the other two cases its dependency on applied pressure has to be considered.

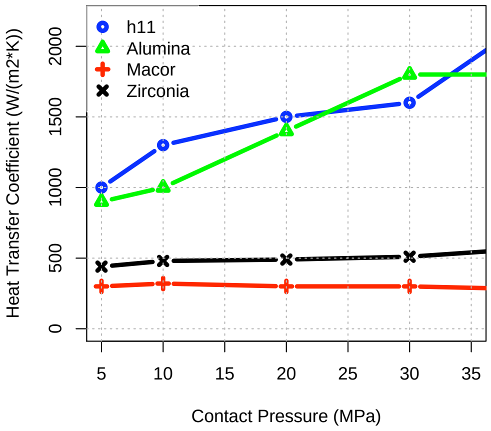

Figure 8: HTC as function of applied contact pressure for the three die materials.

Figure 9 represents the sheet cooling as numerically calculated when using the four die materials: in the case of steel and alumina, the severe cooling assures a complete martensite transformation inside the sheet (from Usibor 1500 CCT curves, the critical cooling rate to martensite transformation is 30 K/s). The use of Macor or zirconia as insert material can reduce the sheet cooling rate to such an extent to partially avoid the martensitic transformation.

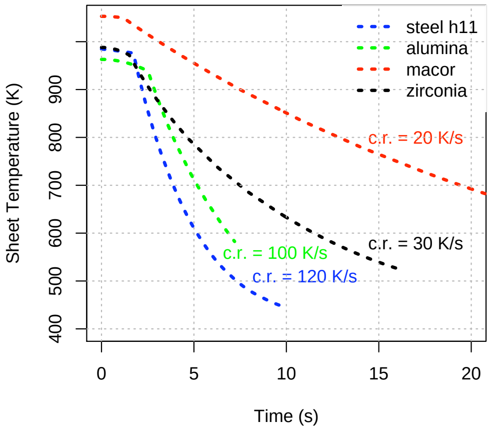

Figure 9: Sheet cooling routes when using different die materials.

The above presented results have demonstrated that (*i*) a robust procedure has been developed and applied to identify heat transfer coefficient between sheet and dies when carrying out elevated temperature sheet working operations; (*ii*) die inserts made of materials characterised by a low thermal conductivity can represent a substitute of die steels when gradients of cooling are desirable inside the metal sheet.

References

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Appendix

		AISI h11	alumina	Macor	zirconia
E	GPa	210	360	67	210
K	W/m/K	22	20	1.46	2.5
C	J/Kg/K	450	510	790	400
ρ	Kg/m^3	7750	3850	2520	6040
α	m^2/s	6.31×10^{-6}	1.02×10^{-5}	7.33×10^{-7}	1.03×10^{-6}
dt	s	0.01	0.01	0.01	0.01
e	mm	0.91	0.57	0.51	0.48
F0		0.0762	0.3135	0.0282	0.0447

Table 1: Die materials properties and Fourier analysis.

		Value	Range ($^\circ C$)
E	GPa	210	[20,1200]
C	J/kg/K	$425 + 7.73 \times 10^{-1}T - 1.69 \times 10^{-3}T^2 + +2.22 \times 10^{-6}T^3$	[20,600]
		$666 + 13002/(738 - T)$	[600,735]
		$545 + 17820/(T - 731)$	[735,900]
		650	[900,1200]
K	W/m/K	$54 - 3.33 \times 10^{-2}T$	[20,800]
		27.3	[800,1200]
α	–	$-2.416 \times 10^{-4} + 1.2 \times 10^{-5}T + 0.4 \times 10^{-8}T^2$	[20,750]
		1.1×10^{-2}	[750,860]
		$-6.2 \times 10^{-3} + 2 \times 10^{-5}T$	[860,1200]
ρ	kg/m^3	7860	[20,1200]

Table 2: Usibor 1500 properties.