

INTERLABORATORY COMPARISON FOR HEAT TRANSFER COEFFICIENT IDENTIFICATION IN HOT STAMPING OF HIGH STRENGTH STEELS

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ABSTRACT: The topic of the paper is the identification of the heat transfer coefficient (HTC) in hot stamping of boron steel sheets under conditions very close to the industrial ones. Two approaches followed by one lab in Germany and one lab in Italy are presented for HTC identification, showing the two experimental apparatuses that were set-up to conduct the tests, the procedures developed and applied to identify the HTC. The obtained results are compared in terms of dependence of HTC from the applied contact pressure, the similarities and the differences of the two approaches are outlined and commented.

KEYWORDS: Hot stamping, Heat transfer coefficient, Inverse analysis

1 INTRODUCTION

Nowadays, hot stamping of high strength steel sheets is more and more utilized in the automotive industry to produce parts of the car body-in-white, which have to be characterized by a high ratio between strength and mass. The industrial processing route to manufacture such parts comprises the blank heating inside a furnace, its rapid transfer to the forming press, where it is formed and quenched at the same time. Accordingly, the formed part presents at the end of the process a fully martensitic microstructure whose resistance can reach 1500 MPa, with still acceptable ductility.

Even if the process has been industrialized for a few years, optimization is still challenging since the standard design tools (e.g. FEM-based models) are far from being completely established and reliable. One of the main reasons relies in the fact that such models need to be fed by a relevant number of data, in terms of material rheology, microstructural parameters, formability limits, boundary conditions. The scientific community is working in this direction, by studying the fundamental aspects of material behaviour when subjected to severe thermal and mechanical cycles like the ones characteristic of hot stamping. Several papers are present in literature, devoted to the description of innovative testing procedures to evaluate material resistance to deformation as function of temperature and strain rate [1-2], formability limits in terms of FLDs [3], friction coefficient at the interface between dies and blank [4-5],

phase transformation kinetics as function of applied stress and strain [3].

It is worth to underline that the above mentioned parameters strictly depend on temperature: therefore, the correct evaluation of temperature evolution inside the blank is fundamental in order to correctly describe all the complex and interacting phenomena taking place during hot stamping operations.

In turn, temperature evolution inside the blank is strictly related to heat transfer phenomena at the interface between the blank and the forming dies. These phenomena are particularly severe, since the dies are usually water-cooled (in order to assure the quench of the components along the whole production run) and the blank is characterized by a very low thermal inertia. Therefore, dedicated testing and modelling have to be set-up, in order to identify the heat transfer coefficient (HTC) at the blank-dies interface as function of applied pressure.

The objective of the paper is to present two different approaches, developed at two laboratories, one in Germany and one in Italy, in order to identify the HTC as function of applied pressure, under processing conditions that are very close to the hot stamping ones. The experimental set-ups and related testing procedures will be described, and then the analytical or numerical identification of HTC will be discussed. Finally, the results obtained in terms of HTC dependence from applied pressure will be presented, and the differences outlined and commented.

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2 TESTING APPARATUSES

The chapter presents the testing equipment and the experimental procedures developed and set-up at DIMS and LFT in order to acquire data for the HTC identification.

For both experimentation, the material of the metal blank was the boron steel Usibor 1500TM patented by Arcelor-Mittal, and the die material was a hot working die steel.

2.1 APPARATUS #1

The testing procedure consists of the compression of the metal blank between two flat dies at imposed value of applied pressure, without large-scale sheet deformation. Four levels of contact pressure are applied, namely 5, 10, 20, and 30 MPa; each test is repeated at least five times in order to ensure repeatability of results. The metal blank is heated up in an external muffle furnace until austenitization temperature (approximately 950°C) and then rapidly transferred to a 100 kN InstronTM press where the test takes place. A special clamping device was designed and constructed in order to ensure that the moving of blank from the furnace to press would result as rapid as possible. Surface temperature measurements acquired through an infrared thermocamera showed that average temperature loss in the blank before die closure was less than 150°C, which is comparable to typical values of industrial hot stamping processes. This ensures that the test takes place in the same thermal conditions and that the material presents at the test beginning the same microstructural state of the industrial process. As soon as the blank is positioned on the lower die, the upper die is closed and the pressure applied almost instantaneously. Figure 1 shows the developed experimental apparatus with indication of the clamping device.

During tests, the temperature field inside the dies is continuously recorded through thermocouples lodged in three grooves within both upper and lower dies. The thermocouple named A nearest to the surface (at 0.5 mm) is the one utilized in the HTC identification procedure described in §3, while the other two called B (symmetric at 1.5 mm from the die surface) are utilized to validate the obtained results of HTC [6]. More details about the equipment and procedure can be found in [7].

2.2 APPARATUS #2

For the determination of the heat transfer coefficient under process relevant conditions between blank and die a special tool (Figure 2) was constructed and validated within the FOSTA project P644 at the Chair of Manufacturing Technology at LFT. This tool was implemented in an universal mechanical testing machine (SchenckTrebel RM400) with a maximum axial force of 400 kN. The quenching device mainly consists of two 10 mm exchangeable water cooled contact plates where rectangular, thermocouple equipped specimens (160 x 58 mm²) are manually placed on four spring

seated pins after undergoing a previous homogeneous austenitization at a temperature of 900 °C in a furnace under atmospheric conditions. By using a set-point testing software the specimens can be loaded during quenching with a defined nominal contact pressure up to 40 MPa. During the test, the temperatures of the blank and of both contact plates are recorded by using integrated Ni/Cr-Ni-thermocouples [8].

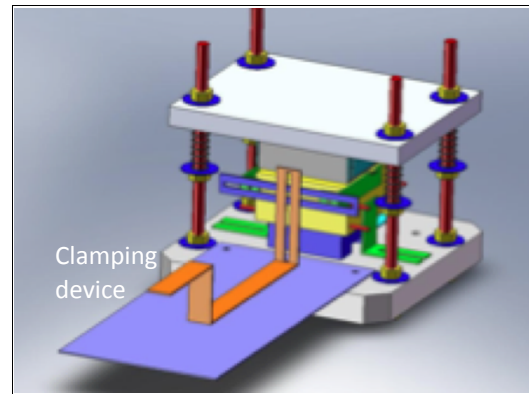


Figure 1: Testing set-up for apparatus #1

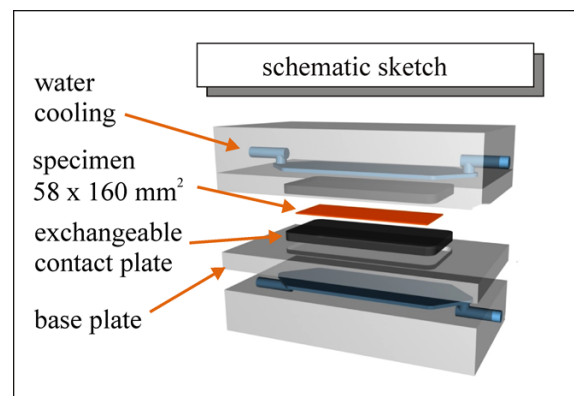


Figure 2: Schematic sketch of apparatus #2

3 HEAT TRANSFER COEFFICIENT IDENTIFICATION

The chapter presents the analytical and numerical procedures developed and set-up at DIMS and LFT in order to identify HTC as function of applied pressure.

3.1 PROCEDURE #1

HTC as function of applied pressure was identified through inverse analysis by comparing experimentally acquired and numerically calculated temperature profiles. A numerical model of the test was developed by using the multi-physics FEM software ComsolTM 3.4, which can take into account all the thermal contributions of the studied problem. According to that, a purely thermal 2-D model was set up, by assuming the applied pressure as uniform and equal to the nominal value.

Thermo-physical properties of both the blank and die materials were imposed as by literature values. The heat exchange of blank surfaces not in contact with the dies was modeled as convective heat exchange, with a coefficient set as constant and equal to $100 \text{ W/m}^2\text{K}$; the latter value was identified from thermographic analysis. The thermal resistance at the interface between the blank and the dies was modeled through a feature implemented in Comsol called “thin thermally resistive layer”. This 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.

It is worth noting that, since the dies were machined with grooves for thermocouple lodging, the numerical modeling should be 3-D: nevertheless, the results from a 3-D model, when the actual die geometry is considered, show that the grooves influence is negligible with regards to the thermal field inside the dies (see Figure 3). The 2-D FE model is divided into two steps: the first one reproduces the sheet thermal evolution from the furnace exit to complete closure of dies, while the second step is representative of the pressure application and is the one devoted to HTC identification.

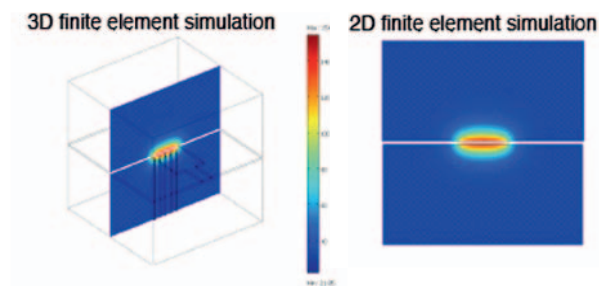


Figure 3: Comparison between 3-D and 2-D models predictions of thermal field inside the dies (procedure #1)

The first step is mandatory to calculate the thermal field assumed as initial condition of the test; the initial blank temperature in the first step is set uniform and constant equal to the one measured by the infrared thermocamera. As soon as the first step is concluded, the calculated thermal field is transferred to the second one. An inverse analysis routine was written in Comsol script 1.1 and the procedure was performed over the second step of simulation: this routine changes the HTC between the blank and the dies until the experimental and numerical temperature evolutions acquired by the nearest to surface thermocouple (thermocouple A) are in good agreement. More details about the inverse analysis procedure can be found in [7].

Table 1 reports the obtained values of HTC as function of applied pressure: it can be seen that heat transfer phenomena are enhanced at increasing contact pressure. Figure 4 reports the comparison between measured and numerically calculated temperature evolutions for thermocouple A (used for HTC identification) and for thermocouple B (used for validation); the numerical

evolution of thermocouple B is calculated by using the identified value of HTC in the numerical model of the test. The quite satisfactory agreement between experimental and numerical values thus proves the reliability of the inverse analysis procedure.

Table 1: HTC values from procedure #1

Contact pressure [MPa]	HTC [$\text{W/m}^2\text{K}$]
5	1000
10	1500
20	1700
30	2500

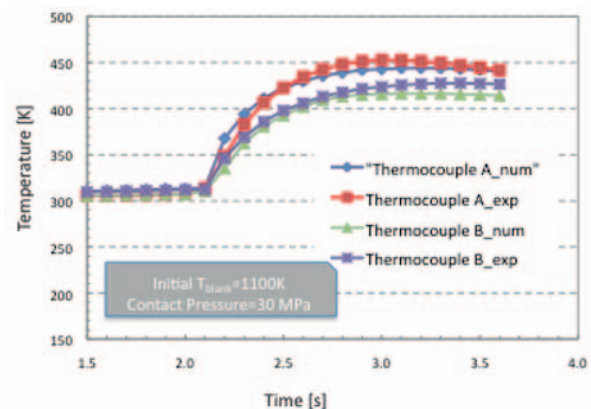


Figure 4: Comparison between experimental and numerical temperature evolution for thermocouples A and B inside the dies

3.2 PROCEDURE #2

The heat transfer coefficient α between blank and die can be calculated on the basis of the measured cooling curves in dependency of the respective target value — as for example the contact pressure — following Newton’s cooling law:

$$T(t) = (T_0 - T_u) \cdot e^{-\alpha \cdot \frac{A}{c_p} \cdot t} + T_u \quad (1)$$

Hereby, T_0 and $T(t)$ indicate the initial and the actual temperature of the specimen during the cooling experiment and T_u the tool temperature. The constant A quantifies the geometric contact surface and c_p the effective heat capacity. The applicability of the methodology explained above was sufficiently shown in previous publications [8].

To investigate the pressure dependency of the heat transfer coefficient between blank and die under process relevant conditions for full metallic contact, quenching experiments were performed. During the tests, specimens of the investigated material were imposed to various contact pressures in a range between 0 MPa and 40 MPa after a previous austenitization at $T_\gamma = 900 \text{ }^\circ\text{C}$

for five minutes ($t_f = 5$ min). To confirm the experimental data each test run was performed at least five times.

Table 2 displays the heat transfer coefficients for the boron-manganese steel determined analytically according to equation (1). The steel grade exhibits a significant increase of the occurring heat transfer between tool and workpiece with increasing contact pressure, whereby maximum values of $HTC \approx 3.300 \text{ W/m}^2\text{K}$ are achieved. This effect is caused by the increase of the effective contact surface between the two contact partners through smoothing of the surfaces [9]. Consequently, more and more real metallic-metallic contact areas occur enforcing direct heat conductance effects, which are capable to transfer more thermal energy between to contact bodies [10].

Table 2: *HTC values from procedure #2 [11]*

Contact pressure [MPa]	HTC [$\text{W/m}^2\text{K}$]	Standard deviation [$\text{W/m}^2\text{K}$]
0	1231	82
5	1484	27
10	2025	37
20	2395	69
30	3065	117
40	3308	159

4 CONCLUDING REMARKS

The paper presents two different approaches for determining heat transfer coefficient during hot stamping operations of high strength steel sheets. The importance of having accurate data of heat transfer as function of contact pressure is evident for the accurate numerical modelling of such processes.

Both the approaches are based on dedicated lab experiments set-up to replicate as close as possible the industrial operating conditions. The experimental data are then elaborated either analytically or numerically through inverse analysis technique. In both cases, the dependence from the contact pressure is evidenced, showing that, by increasing contact pressure, the heat exchange between the blank and dies increases as well, as a consequence of the increased real contact area between blank and dies. Therefore, in order to provide accurate evolution of temperature in the deforming blank, the boundary conditions in the hot stamping numerical model must include the dependence of HTC on pressure.

The slight discrepancy between the HTC values found by the two labs can be ascribed to the differences in the testing procedures and analysis methods.

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