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DETERMINATION OF HEAT TRANSFER COEFFICIENTS UNDER CLOSED LOOP CONTROLLED CONSTANT CONTACT PRESSURES

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Abstract

During hot forming and tailor tempering of boron steels, heat transfer between work-piece and dies has an important effect on the temperature distribution, microstructure evolution and mechanical properties of the final formed parts. In the present paper the interfacial heat transfer coefficient (HTC) has been determined at different contact pressures. Experimental tests have been realized in a SCHMIDT micro servo-press, which is able to compensate the thermal contraction of the blank and tools to precisely keep constant the contact pressure. Temperature evolution of the tools and the blank has been monitored with nine thermocouples.

For the determination of the heat transfer coefficient (HTC), an analytical-numerical method has been used leading to a fast and reliable calculation method able to determine the evolution of the HTC value during the cooling of the blank. This methodology allows the calculation of different HTC values in function of the contact pressure and the instantaneous tool temperature which will improve the accuracy of the numerical models and the prediction of the final properties of the components.

Key words: hot stamping, heat transfer coefficient

1. INTRODUCTION

The increase of the competitiveness of the automotive market together with the sustainability policies is continuously leading to an increment of the strength of the automotive components. One of the actual manufacturing processes that allows the forming of these very high strength components is the hot stamping process. In the hot stamping process, the boron alloy steel is formed at 950ºC achieving very high formabilities at low force values. Once the part has been formed, it is maintained in the closed die forcing it to cool in few seconds generating a quenching process in the material. During this quenching process the austenite transforms into martensite increasing the mechanical properties of the final product, strengths up to 1500 MPa in geometrically complex components are achieved.

Based on the process described before, the automotive industry has also found the possibility of achieving tailored components where different areas of the component offer different mechanical responses: a process named as tailor tempering. These tailored mechanical properties are obtained by imposing different cooling ratios to the component. However, one of the main issues of the hot stamping process and even more important on the tailor tempering is the direct effect that the design of the stamping dies has on the final mechanical properties of the components. These final mechanical proper-

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ties directly depend on the microstructure evolution of the material during the quenching process and therefore on the temperature evolution during the quenching process. Among the different variables involved on the thermal evolution the thermal exchange between the die and the component is one of the most important ones. This thermal exchange is governed by the heat transfer coefficient (HTC) which defines the ratio of heat exchange from one interface surface to the other. This way, the greater the HTC is the faster and more efficient the quenching process can be leading to greater mechanical properties in the final component.

In the last decade the HTC determination for boron alloy steel has been an issue under study Abdulhay et al. (2011a, 2011b), Bai et al. (2012), Caron et al. (2013), Chang and Bramley (2002), Hay et al. (2010), Koistinen and Marburger (1959), Lenard and Davies (1992), Malinowski et al. (1994), Merklein and Lechler (2006, 2009), Salomonsson et al. (2009), Tondini et al. (2011), Wang et al. (2012). A review of all the previous works shows that different techniques and methodologies have been developed for this objective, e.g. FEM inverse modelling, analytical-numerical models.

In this work the heat transfer coefficient (HTC) determination between the ORVAR SUPREME tool steel and the USIBOR 1500P boron alloy steel is carried out for different contact pressures. First, the experimental setup used to analyze the heat transfer on the interface of both materials is shown. Then, the numerical methodology followed to calculate the HTC is presented. Next, the determined HTC values are shown and compared to previous work tendencies. Finally, the main conclusions of the work are presented and the advantages and limitations of the presented methodology are defined.

2. EXPERIMENTAL SETUP AND TEST PROCEDURE

In order to emulate the hot stamping process, a laboratory schematic prototype was constructed (figure 1). As shown in figure 1, the workpiece (USIBOR 1500P steel sheet) is placed between the upper and the lower dies (ORVAR SUPREME tool steel). The dies and the workpiece have a cylindrical shape with a diameter of 50 mm and 30 mm respectively and the workpiece is 1.8 mm on thickness.

The experimental procedure is defined as follows. First, the workpiece is heated in an electrical resistance oven to 950ºC. In order to allow the complete austenitization of the material, the temperature is maintained then during 5 min. After the austenitization is completed the transfer of the workpiece from the oven to the die is carried out. In figure 2 the positioning of the workpiece on the lower die can be observed.

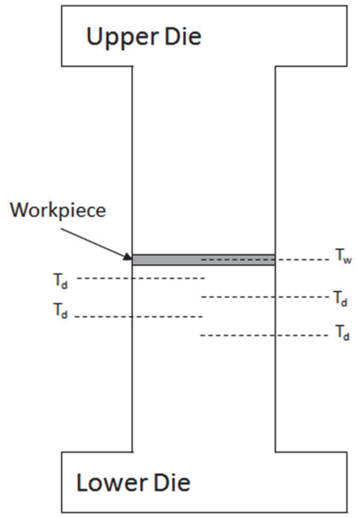

Fig. 1. *Schematic representation of the experimental setup. The setup is composed by the workpiece and the upper and lower die. Four thermocouples are used on the die while a single thermocouple in the middle of the sheet is used on the workpiece.*

Fig. 2. *Experimental setup where the positioning of the workpiece on the lower die can be observed.*

Once that the workpiece is positioned on the die the forming step starts imposing a specific pressure on the material during the quenching. In order to analyze the influence of the pressure on the heat transfer behavior, different pressures have been studied ranging from 1 MPa to 10 MPa. The pressure is imposed using a high precision micro-press Schmidt 420 with a resolution of 0.0032 MPa. This pressure is maintained until the complete cooling of the workpiece (temperatures between 200ºC and 300ºC).

A data acquisition system, National Instruments 9215 hardware at 50 Hz, has been used in order to record the temperature evolution during the quenching process. Four TC Direct 12-K-1000-118-1-21-3P2L-1A30, 1 mm diameter thermocouples, have been used to measure the temperature evolution on the lower die. These thermocouples are located to 2 mm, 4 mm, 6 mm and 8 mm from the interface between the workpiece and the lower die as represented in figure 1. On the workpiece on the other hand, and due to the limited space on the thickness, a single thermocouple on the middle of the thickness, 12-K-1000-118-0,5-2I-3P2L-1A30, 0.5 mm diameter thermocouple has been used. The hole for the thermocouple in the workpiece is critical and EDM has been used for its preparation .

3. NUMERICAL HTC IDENTIFICATION METHODOLOGY

Among the different HTC identification techniques shown on the literature, the analytical-numerical approach has been used in this work. The first hypothesis assumed in this work is that the thermal exchange characterization carried out on the experimental phase (figures 1 and 2) can be simplified as a one-dimensional problem.

The heat transfer coefficient is defined as the ratio between the heat flux and the temperature difference between the surface of the die and the surface of the workpiece

$$h = \frac{Q}{T_{w1}-T_{d1}} \quad (1)$$

where h represents the heat transfer coefficient (HTC) while Q is the heat flux through the interface. The temperature on the workpiece surface at the exchange interface is defined as T_{w1} and the temperature on the die surface at the exchange interface as T_{d1}. However, from the experimental tests the temperatures are only known on the thermocouple positions. Therefore, three steps have to be followed for the HTC calculation. First, the temperature on the die surface has to be calculated from the data recorded by the thermocouples at the die. Next, the temperature on the workpiece surface has to be calculated from the thermocouple placed in the workpiece. Then, the heat flux through the interface has to be calculated. Finally, once that the flux and the difference in temperature are known, the HTC can be calculated following the definition shown in (1).

3.1. Temperature definition on the surface of the die

The heat conduction on the die is supposed to be governed by Fourier's law

$$\frac{\partial T}{\partial t} = \alpha_d \left(\frac{\partial^2 T}{\partial x^2}\right) \quad (2)$$

where T represents the temperature, t is time, x is the space variable and the material properties are introduced by α_d that it is defined as

$$\alpha_d = \frac{k_d}{\rho_d c_d} \quad (3)$$

where k_d is the thermal conductivity, ρ_d represents the density and c_d is the specific heat. In order to numerically solve the partial differential equation shown in (2) a backward time centered space method (BTCS) or full implicit method has been used. In this context the partial derivative of the temperature to the time, $\frac{\partial T}{\partial t}$, is replaced by the first order backward difference and the spatial second partial derivative, $\left(\frac{\partial^2 T}{\partial x^2}\right)$, is replaced by the BTCS method. Therefore the numerical approximation of the Fourier's law results on

$$\frac{T_{d,i}^{n+1} - T_{d,i}^{n}}{\Delta t} = \alpha_d \left(\frac{T_{d,i-1}^{n+1} - 2T_{d,i}^{n+1} + T_{d,i+1}^{n+1}}{(\Delta x)^2}\right) + \mathrm{o}(\Delta t) + \mathrm{o}(\Delta x^2) \quad (4)$$

where $T_{d,i}^{n+1}$ represents the temperature at the $(n+1)$ increment on the (i) point. The time increment from increment to increment is represented as Δt, while the space increment from point to point is represented as Δx. For the development of the numerical model the discretization of equation (4) has been truncated neglecting the error terms $\mathrm{o}(\Delta t)$ and $\mathrm{o}(\Delta x^2)$, these assumptions leads to a first order approximation on time and a second order approximation on space.

The definition of the different points used in this study are shown in figure 3. The first point on the die, T_{d1}, is a point on the surface of the die (not measured in the experiments) and the next four points, T_{d2-5}, correspond to the data measured in the experiments through the thermocouples.

In figure 4 the partial differential equation system to be solved is graphically presented. Supposing Dirichlet boundary conditions (the initial temperature of the surface is the same as the initial temperature of the first thermocouple T_{d2}) the problem to be solved leads to know the temperature of the first point at the end of the increment.

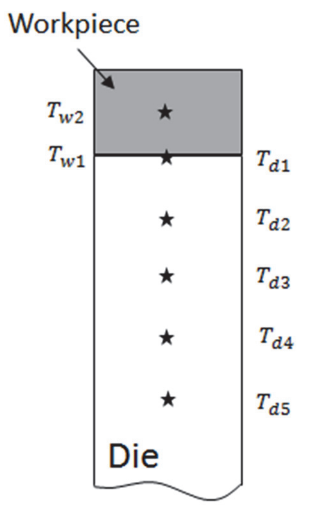

Fig. 3. Schematic representations of the nomenclature of the points analyzed by the numerical method.

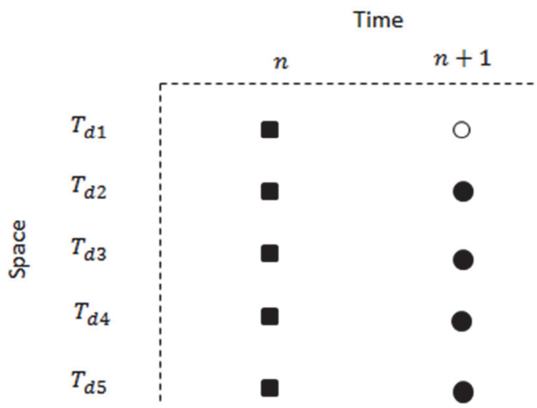

Fig. 4. Schematics of the partial differential equation system.

Previous authors worked on the basics that the thermal properties of the die material are constant as the die temperatures always maintain below 200ºC (Bai et al. 2012). However, the hypothesis of a linear evolution of the properties with the temperature is assumed. in this study. From equation (4) and figure 4 the following mathematical relations can be obtained for the temperatures of the T_{d2}

$$\frac{\Delta T_{d2}}{\Delta t} = \frac{\alpha_d}{(\Delta x)^2}\left(T_{d1}^{n+1} - 2T_{d2}^{n+1} + T_{d3}^{n+1}\right) \quad (5)$$

For the T_{d3} temperature

$$\frac{\Delta T_{d3}}{\Delta t} = \frac{\alpha_d}{(\Delta x)^2}\left(T_{d2}^{n+1} - 2T_{d3}^{n+1} + T_{d4}^{n+1}\right) \quad (6)$$

and for the T_{d4} temperature

$$\frac{\Delta T_{d4}}{\Delta t} = \frac{\alpha_d}{(\Delta x)^2}\left(T_{d3}^{n+1} - 2T_{d4}^{n+1} + T_{d5}^{n+1}\right) \quad (7)$$

It is not possible to develop these expressions for the first and fifth points without introducing a new error due to the truncation of part of the discretization of the $\left(\frac{\partial^2 T}{\partial x^2}\right)$ term. Every temperature on equations (6) and (7) are known (thermocouple readings), leading to different material properties, α_d, to verify the equations. That is why in this study the hypothesis of a linear evolution of these properties is assumed. Therefore the properties of the material, α_d, for both temperatures T_{d3}^{n+1} and T_{d4}^{n+1} can be mathematically obtained. Once that the α_d evolution is known (assuming a linear evolution in this first approach) the material properties at T_{d2}^{n+1} can be calculated.

Once that the material properties are known for T_{d2}^{n+1}, the temperature at the end of the increment on the die surface T_{d1}^{n+1} can be calculated from equation (5).

3.2. Temperature definition on the surface of the workpiece

Since only a single temperature point on the center of the workpiece, T_{w2}, is known, a different technique has been used to calculate the temperature on the surface of the workpiece, T_{w1}. First, the symmetry property of the problem shown in figure 1 is taken into account. Therefore it is assumed that both workpiece surfaces (lower and upper) follow the same thermal evolution. If the discretization of the Fourier's law, equation (4), is applied in this case, the temperature on the surface results

$$T_{w1}^{n+1} = \frac{\Delta T_{w2}}{2\Delta t}\frac{(\Delta xw)^2}{\alpha_w} + T_{w2}^{n+1} \quad (8)$$

where Δxw represents the distance between T_{w1} and T_{w2} points (half of the thickness) and α_w represents the material properties defined as

$$\alpha_w = \frac{k_w}{\rho_w c_w} \quad (9)$$

The evolution of the density ρ_w, specific heat c_w and thermal conductivity k_w of the USIBOR 1500 P has been previously studied by Hay et al. (2010). Both thermal conductivity and specific heat are supposed to be dependent on the martensite volume fraction (each phase, martensite and austenite, have different properties) while the density remains constant in both temperature and crystallographic phase. The specific heat of the austenite is

$$C_{wa} = 426.0 + 0.1538\,T \ \ (\mathrm{J/kg\,K}) \quad (10)$$

while the one of the martensite

$$C_{wm} = 311.2 + 0.439\,T \ \ (\mathrm{J/kg\,K}) \quad (11)$$

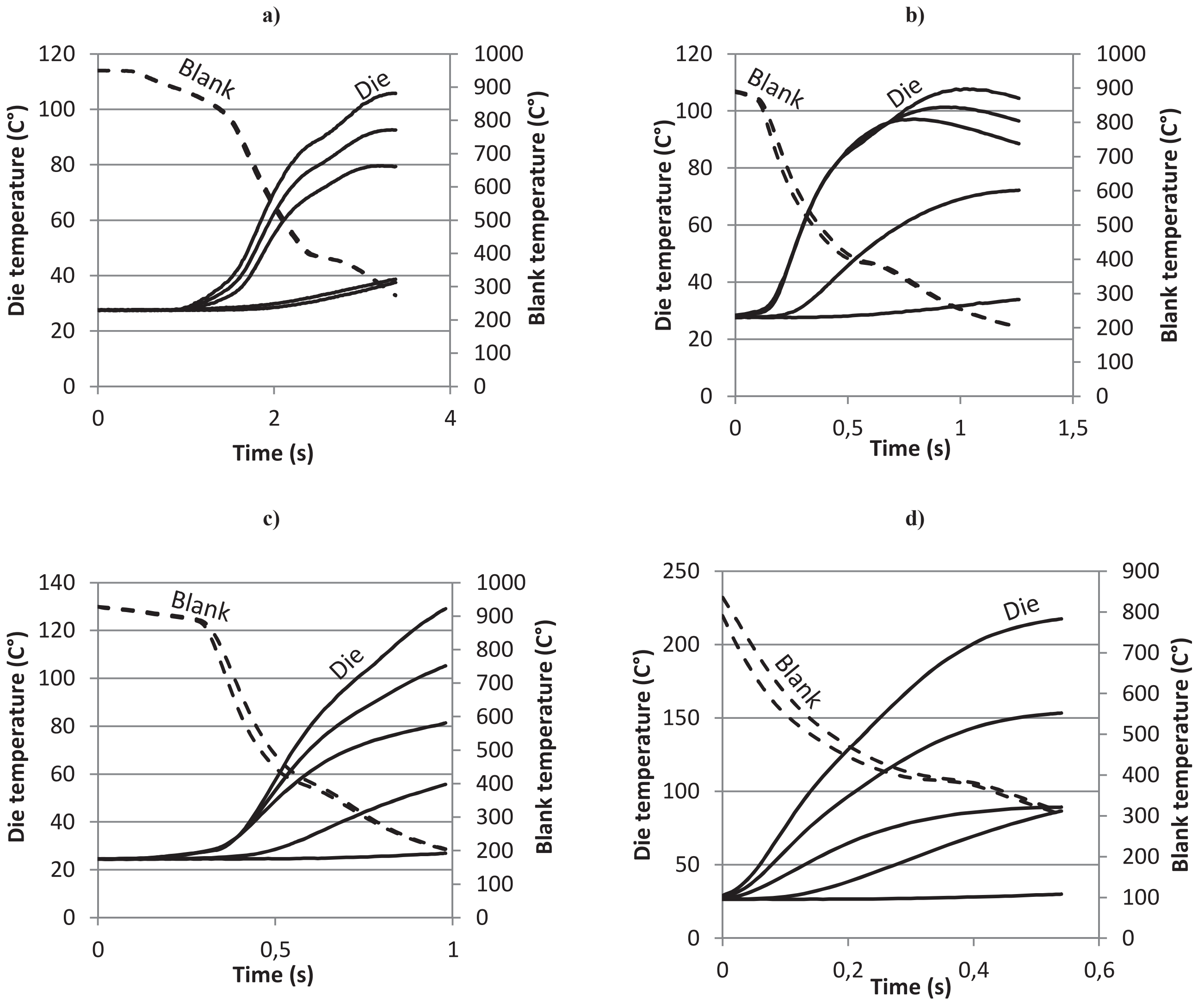

Fig. 5. *Temperature evolution on both die (continuous line) and workpiece (line) for the different testing pressures: 1 MPa (a), 3 MPa (b), 5 MPa (c) and 10 MPa (d).*

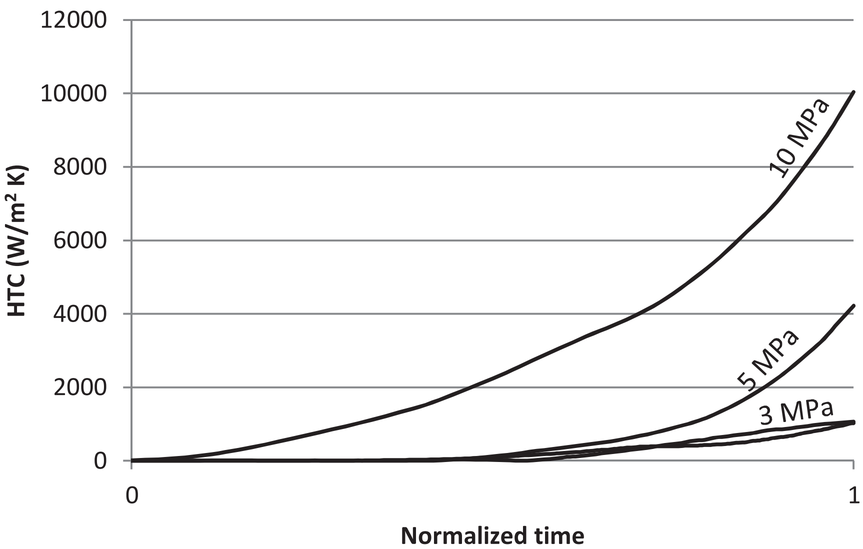

Fig. 6. *Heat transfer coefficient values on normalized time of process.*

where T represents temperature in both cases. The thermal conductivity on the other hand results

$$k_{wa} = 16.27 + 0.010\,T \ \ (\mathrm{W/m\,K}) \tag{12}$$

for the austenite while for the martensite is

$$k_{wm} = 83.73 - 0.245\,T + 5.79 \times 10^{-4} T^2 - 5.18 \times 10^{-7} T^3 \ \ (\mathrm{W/m\,K}) \tag{13}$$

The martensite volume fraction f_m can be calculated following the law Koistinen and Marburger (1959)

$$f_m = 1 - \exp[-0.011(673 - T)] \tag{14}$$

where the martensite volume fraction is set to zero for workpiece temperatures above 673 K.

The thermal conductivity has been calculated following Hay et al. (2010) as

$$k_w = f_m k_{wm} + (1 - f_m) k_{wa} \tag{15}$$

while the specific heat including the heat due to the austenite-to-martensite transformation is defined as

$$C_w = f_m C_{wm} + (1 - f_m) C_{wa} + (1 - f_m)(0.011)(1.35 \times 10^5) \tag{16}$$

Knowing the material properties at different temperatures together with the symmetry assumption and the numerical discretization of the Fourier's law of equation (4), the temperature on the surface of the workpiece can be calculated.

In figure 5 the evolution of the temperature at different points on both the workpiece and the die for the different testing pressures is shown. On continuous lines the temperatures of the die points are shown, the lower temperature is the T_{d5} while the higher one is the temperature on the surface of the die T_{d1}. The dashed lines on the contrary represent the temperature on the workpiece, the higher values corresponds to the center point T_{w2} and the lower ones to the surface of the workpiece T_{w1}.

3.3. Heat flux on the interface

The last variable needed to calculate the heat transfer coefficient is the heat flux though the interface. On this regard in this work it has been assumed the heat flux as

$$Q = k_w \frac{T_{d1} - T_{d2}}{\Delta x} \tag{17}$$

where the thermal conductivity of the ORVAR SUMPREME depending on the temperature has been obtained by interpolating the suppliers specifications with a second order polynomial law

$$k_w = -9.528 \times 10^{-6} T^2 + 1.453 \times 10^{-2} T + 24.71 \tag{18}$$

where the temperature T has been taken on the surface of the die.

4. RESULTS AND DISCUSSION

Following the numerical methodology shown in the previous section, the HTC value has been determined at each time increment of the cooling/quenching process. Figure 6 shows the different values of the HTC on the cooling normalized time. As can be observed in figure 5, each test has a different cooling time. Therefore in order to be able to compare the different evolutions, the normalized cooling time from 0 (before start of the cooling) to 1 (end of the cooling) has been used.

The main result observed in figure 6 is that the HTC values increase with the values of the contact pressure. It can also be concluded from figure 6 that there exists an increment of the HTC value during the process as well. These results agree with previous works where an increase of the HTC was shown in Bai et al. (2012), Caron et al. (2013), Merklein and Lechler (2009), Salomonsson et al. (2009). The increase of the HTC during the process was also previously reported as well by Chang and Bramley (2002).

5. CONCLUSIONS

In this work the heat transfer coefficient (HTC) for the interface between the boron alloy steel USIBOR 1500P and the ORVAR SUMPREME tooling steel has been determined under different contact pressures. An analytical-numerical method has been used for the HTC determination. This numerical methodology allows calculating the evolution of the HTC during the process under some hypothesis. The obtained results agree with the trends shown by previous authors showing an increase of the HTC with the contact pressure and a variation during the process. These results will allow the correct simulation of tailored hot forming parts.

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WYZNACZENIE WSPÓŁCZYNNIKA PRZENIKANIA CIEPŁA W PRASACH Z NAPĘDEM PRACUJĄCYM W ZAMKNIĘTEJ PĘTLI SPRZĘŻENIA ZWROTNEGO KONTROLUJĄCYCH STAŁĄ SIŁĘ NACISKU

Streszczenie

Podczas kształtowania na gorąco oraz hartowania stali borowych, współczynnik przenikania ciepła pomiędzy materiałem a narzędziem znacząco wpływa na rozkład temperatury, rozwój mikrostruktury i w konsekwencji na własności mechaniczne produktu końcowego. W niniejszej pracy został wyznaczony współczynnik przenikania ciepła (HTC) przy różnych siłach nacisku. Doświadczenia zostały wykonane z użyciem mikro serwoprasy SCHMIDT, pozwalającej na kontrolowanie stałej siły nacisku. Zmiany temperatury narzędzia oraz materiału były rejestrowane za pomocą dziewięciu termopar.

Do wyznaczenia współczynnika przenikania ciepła (HTC) została zastosowana metoda analityczno-numeryczna, dzięki której opracowano szybką i niezawodną metodę obliczania zmian współczynnika HTC podczas chłodzenia materiału. Przyjęta metodologia pozwala na obliczanie różnych współczynników HTC w funkcji siły nacisku oraz chwilowej temperatury narzędzia, podnosząc dokładność obliczeń numerycznych i poprawiając ilościowe określenie końcowych własności produktu.

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