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Exact and approximate methods for determining the thermal parameters of the forging process

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Abstract

Numerical simulation of the forged body plastic flow is a very important and indispensable technique in the mechanical forming. The correct simulation of changing the shape of a hot blank requires the use of very accurately determined physical parameters. There is thus a pressing need to create and supplement a database containing the exact physical parameters of forged materials. The following paper shows the results of development of methods to determine two thermal parameters of a solid body: the average value of the total emissivity and the average coefficient of heat transfer by convection. The methods of determining thermal parameters, described below, are considerably simpler than traditional ones, and they do not require the use of complicated equipment. The exact method is based only on processing of experimental data. In the approximate method, both the experimental data and theoretical values of thermal parameters available in the literature are used.

The developed methods were applied to determine thermal parameters of test bodies of SAE 1045 steel and ABNT 6061 aluminum alloy.

Keywords: Hot forging; Thermal parameters; Convection heat transfer coefficient; Total emissivity

1. Introduction

Thermal forged parameters are very important data for numeric and experimental simulations of plastic deformation in this industrial process. This family of parameters generally defines the thermal state of the forged piece. Therefore, it is important to determine their exact values. In the past, scientists from many countries have used different methods to study and determine thermal parameters.

According to British [1], German [2] and other researchers, experimental data of test piece cooling are obtained and put into a black-box type "industrial package" with programs using the finite elements method for calculation purposes. Results of this calculation are satisfactory, but these studies cannot be used as a standard to determine thermal parameters since the information presented in the articles is incomplete.

Therefore, it is necessary to develop methods based on simple mathematical models of heat transfer, which can be used to obtain satisfactory results.

2. Mathematical model of test piece cooling in the combined radiation, convection and conduction processes

The authors considered a simulation of the cooling process of the forged piece, shown in Fig. 1.

The mathematical model of forged piece cooling shown in Fig. 1 is based on the Law of Energy Conservation of the thermodynamic system applied to the cooling process of this piece. Variation of the thermal energy of the test piece, in units of time, is equal to the sum of the energy losses in the piece cooling processes by conduction, radiation and convection:

$$Q = q_{\text{cond}} + q_{\text{rad}} + q_{\text{conv}} \tag{1}$$

where q_{cond} is the thermal energy lost by the piece, in units of time, by the conduction, and it is expressed by the Fourier's

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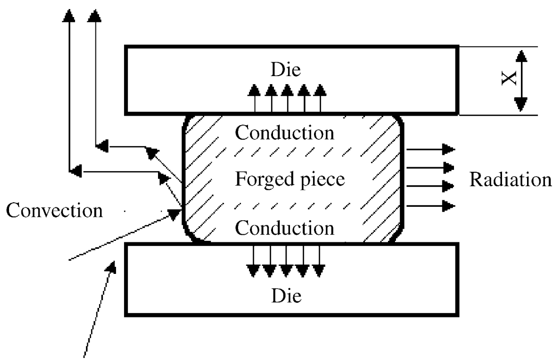

Fig. 1. Scheme of forged piece cooling.

Law as follows:

$$q_{\mathrm{cond}} = -k \cdot A_k \cdot \frac{\mathrm{d}T_k}{\mathrm{d}x}$$

where q_{rad} is the thermal energy lost by the body, in units of time, by the radiation, and it is expressed by the Stefan–Boltzmann equation as follows:

$$q_{\mathrm{rad}} = \sigma \cdot A_{\mathrm{rad}} \cdot \varepsilon(T) \cdot (T^4 - T_\infty^4)$$

where q_{conv} is the thermal energy lost by the body, in units of time, by the conduction, and it is expressed by the Newton's Law as follows:

$$q_{\mathrm{conv}} = h \cdot A_{\mathrm{conv}} \cdot (\Delta T)$$

The resulting equation, which expresses the Law of Energy Conservation, is:

$$\begin{aligned} m \cdot C_{\mathrm{p}} \cdot \frac{\mathrm{d}T_m}{\mathrm{d}t} &= -k \cdot A_{\mathrm{cond}} \cdot \frac{\mathrm{d}T_k}{\mathrm{d}x} \\ &\quad + \sigma \cdot A_{\mathrm{rad}} \cdot \varepsilon(T) \cdot (T^4 - T_\infty^4) \\ &\quad + h(T, D, V) \cdot A_{\mathrm{conv}} \cdot (T - T_\infty) \end{aligned} \tag{2}$$

where m is mass of the test piece; C_{p} the specific heat of the test piece material; k the thermal conductivity of the test piece material; σ the Stefan–Boltzmann constant; A_{cond} the area of the heat transfer by conduction; A_{rad} the area of the heat transfer by radiation; A_{conv} the area of the heat transfer by convection; t the time of test piece cooling; T the absolute temperature of the free cooled surface (K); T_m the average temperature of the test piece (K); T_∞ the absolute temperature of the environment (K); ΔT the difference of the temperatures between the free cooled surface and air; $\frac{\mathrm{d}T_k}{\mathrm{d}x}$ the temperature gradient of the conduction heat flow in direction x; $\frac{\mathrm{d}T_m}{\mathrm{d}t}$ the velocity of test piece cooling; $\varepsilon(T)$ the total emissivity coefficient of the free cooled surface; h the convection heat transfer coefficient; h a function [3] of A_{conv} surface temperature T, cooled system geometry D, air flow velocity V, i.e. $h = h\ (T, D, V)$.

The intervals of possible values of the functions $\varepsilon = \varepsilon(T)$ and $h = h\ (T, D, V)$ are defined by the physical model of the cooling process and are as follows:

$$0 < \varepsilon(T) < 1;$$

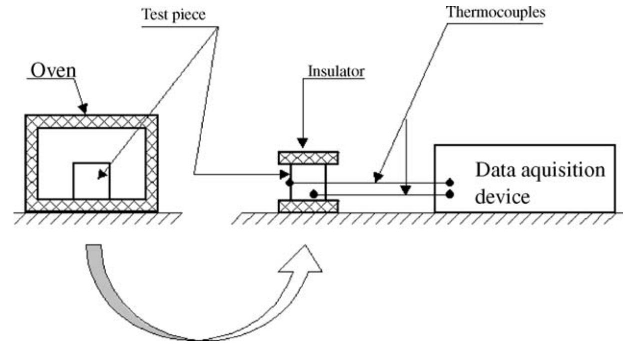

Fig. 2. Schematic drawing of the basic experiment.

$$h\ (T, D, V) > 0.$$

The basic Eq. (2) obtained is used to calculate the values of the ε emissivity coefficient of the free cooled surface and theconvection heat transfer coefficient h from this surface to the environment.

All necessary calculations to determine the coefficients ε and h were based on the corresponding parameters obtained from the literature, as well as on the velocity of test piece cooling obtained by experiment.

3. Experimental installation

The description of the basic experiment for the steel ABNT 1045 test piece is as follows: the Ø 54 mm × 54 mm cylindrical test piece was put into the "Heraus" muffle oven heated to 900 °C.

The oven temperature was controlled by internal thermocouples. After the test piece was put into it, the oven was heated for 2 h up to 1030 ± 15 °C. Then, the test piece was placed between two heated asbestos plates on a laboratory table.

While in this position, the test piece was cooled by natural convection, conduction and radiation to 700 °C in a 270 s period. The temperatures both of the centre and surface of the cooling test piece were recorded at a frequency of three measurements per second. Two thermocouples of type "K" and the data acquisition device "Spider-8" were used to record the temperatures.

The experimental installation is shown in Fig. 2.

4. Typical example of the calculation of the total emissivity average coefficient and the *h* coefficient for the test piece of ABNT 6061 alloy, using the approximate method

4.1. Determination of the cooling speed of the test piece

The test piece cooling speed is equal to the first derivate of the function $T_m = T_m(t)$, which describes the experimental curve of cooling processs, as related to time t.

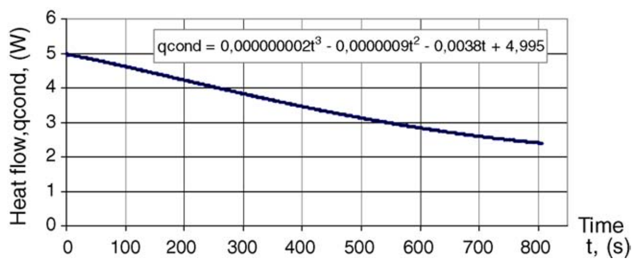

Fig. 3. Conductive heat losses q_{cond} from the test piece of ABNT 6061alloy within the temperature range 300–500 °C, in the basic experiment.

4.2. *Calculation of the heat flow through insulating plates*

The experimental method developed by Polozine and Schaeffer and described in the literature [4] was used to evaluate the heat flow q_{cond} from the test piece of aluminum ABNT 6061 through the insulating plates (support device), shown in Figs. 1 and 2. The method is as follows.

Total heat flow Q_{basic}, lost by the test piece in the basic experiment (Fig. 2), is compared with the total heat flow $Q_{additional}$, lost by the identical body placed into the insulating box, in an another experiment.

Heat losses by conduction q_{cond} were calculated by the procedure described in detail from the same source. Fig. 3 shows the result of this calculation in a graphic and in the analytical form.

4.3. *Calculation of the convection heat transfer coefficient*

The rough value of the convection heat transfer coefficient h was calculated by the empirical formula described in the literature [1]:

$$h \approx 3 \cdot \left(\frac{T - T_\infty}{K}\right)^{0.25} (\mathrm{W/(m^2\,K)}) \quad (3)$$

The rough value of the average coefficient h, obtained by the formula (3) for the range 300–500 °C, is as follows:

$$h \approx 13.1\,(\mathrm{W/(m^2\,K)})$$

The rough value h obtained from the source [5] is as follows:

$$h \approx 10\,(\mathrm{W/(m^2\,K)}).$$

4.4. *Calculation of a rough value of the total emissivity coefficient for the ABNT 6061 alloy*

Calculation of the total emissivity coefficient for the ABNT 6061 alloy was performed using the basic Eq. (2). Substituting numeric values in this equation and solving it relatively to the function $\varepsilon(T)$, the total emissivity coefficient of the test piece is obtained for the temperature T. The average coefficient of the total emissivity ($\varepsilon_{average}$) is calculated for the temperature range 300–500 °C. Results of this calculation are shown in Table 1.

5. Typical example of the calculation of the total emissivity average coefficient and the *h* coefficient for the test piece of SAE 1045 steel, using the exact method

Cooling speed of the SAE 1045 steel test piece and the heat flow q_{cond} from this piece in the support device is determined similarly to what has been done in the case of the 6061 alloy.

The h coefficient of heat transfer by convection was determined with the help of the basic Eq. (2), for the $\varepsilon_{average}$

Table 1
Comparison of calculated values of the coefficients $\varepsilon_{average}$ with data from the literature for the test piece of 6061 alloy (temperature range, 300–500 °C)

Parameter	Calculated values[a]		Data from the literature
Average coefficient of total emissivity	0.17 (for h = 10)	0.09 (for h = 13.1)	0.16 [6] 0.41 [7]
Standard deviation of the calculated curve from the experimental curve	8 °C	21 °C	–

[a] Values of the convection heat transfer coefficient h are represented in W/(m² K).

Table 2
Calculations of thermal parameters and the standard deviation for the temperature range 700–950 °C

Parameter	Unit	Calculated values[a,b]							
$\varepsilon_{average}$	–	0.91	0.90	0.89	0.87	**0.828**	0.80	0.705	0.70
h	W/(m² K)	−4.3	−3.4	−2.4	−0.5	**3.53***	6.28	15.82	15.9
d	°C	4.66	4.53	4.56	4.74	**5.14**	5.91	9.77	10.1

[a] The symbol (*) indicates the lower admissible boundary of h. Below this boundary, the function $h(T)$ accepts negative values for the temperature range 700–950 °C, which is inconsistent with the physical meaning of the function.
[b] Values shown in bold represent the final results of calculations.

Table 3
Comparison of parameters values obtained by calculations with data from the literature for the test piece of SAE 1045 steel (temperature range 700–950 °C)

Parameter	Symbol	Unit	Calculated values	Data from the literature
Convection heat transfer coefficient	h	$W/(m^2 K)$	3.53	–
Average coefficient of total emissivity	$\varepsilon_{average}$	–	0.828	0.79–0.82 [6] 0.89–0.90 [7]
Standard deviation of the calculated curve from the experimental curve	d	°C	5.14	–

Table 4
Comparison of methods developed for determining the parameters[a,b] h, $\varepsilon_{average}$ and d

Method	Variations of the parameters for the temperature range 300–500 °C			Variations of the parameters for the temperature range 700–900 °C		
	h	$\varepsilon_{average}$	d	h	$\varepsilon_{average}$	d
Approximate	±14	±31	8–21	±22.5	±3.8	7–10
Exact	0	0	1	0	0	5

[a] Variations of coefficients h and $\varepsilon_{average}$ have been calculated as to their average values in %.
[b] Standard deviation d of the calculated curve from the experimental curve is given in °C.

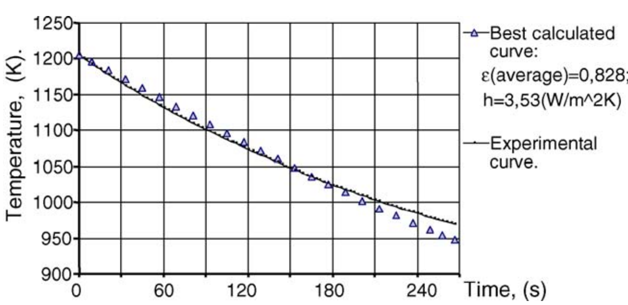

Fig. 4. Experimental cooling curve and the best calculated cooling curve of the SAE 1045 steel for the temperature range 950–1200 K.

randomly chosen $\varepsilon_{average}$ value. Results of this calculation are shown in Table 2.

The comparison of calculated values with data from the literature is shown in Table 3.

The best theoretical cooling curve plotted based on data in Table 2, as well as the experimental curve, are shown in Fig. 4.

Deviations d of the calculated cooling curve from the experimental cooling curve are as follows:

d (maximum) = +18 K;
d (minimum = +0.2 K;
d (average) = +5.1 K.

6. Comparison of the methods developed for determining of thermal parameters $\varepsilon_{average}$ and h

Comparison of the methods (Table 4) has been performed based on data in Tables 1 and 3.

7. Conclusions

Methods of determining the thermal parameters of metals, presented in this work, were tested in the range of moderate temperatures (300–500 °C), and high temperatures (700–950 °C). Analysis of results obtained shows the following.

The approximate method depends on data from the literature, which are not exact. Accuracy of the approximate method is low in the range of moderate temperatures, because the thermal losses by convection are comparable with the simultaneous thermal losses by radiation in this range. Therefore, any error in determining the convection causes the considerable error for the respective calculated emissivity.

Accuracy of the approximate method is satisfactory in the range of high temperatures, because the thermal losses by convection are considerably less than the simultaneous thermal losses by radiation. Therefore, the influence of an uncertain convection value on the calculated emissivity is insignificant.

Accuracy of the exact method does not depend on data from the literature and it is high for all temperatures. However, the method is too laborious. In view of this fact, the possibility of applying the exact method in the industry depends on the development of relevant software.

Both methods can be used to calculate of average values of the mentioned thermal parameters of metals.

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