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Influence of the inaccuracy of thermal contact conductance coefficient on the weighted-mean temperature calculated for a forged blank

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ABSTRACT

Modern software intended for the simulation of metal forging processes requires the use of a reliable database composed by physical parameters of materials. One of the most important and poorly studied parameter is the thermal contact conductance coefficient of the blank-die interface, which determines the thermal state of a blank in forging. The absence of information makes engineers use approximate or arbitrary values of the coefficient, without the possibility of estimating a simulation error. In this paper, a new approach to the calculation of the heat flux through the blank-die interface is shown. The values of thermal contact conductance coefficient which are typical for hot forging processes are given for the first time. The errors in determining of the weighted-mean temperature of a blank, caused by the inaccuracy of thermal contact conductance coefficient, are calculated. Some recommendations concerning the use of inaccurate values of this coefficient in the simulation are made.

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1. Introduction

The numerical simulation is currently one of the important methods used in the prediction of plastic deformations. Advanced simulation of hot forging requires the knowledge of physical parameters of materials. To be a result reliable, values of these parameters must be given with the highest accuracy (Kopp and Phillip, 1992).

One of the very important and poorly studied parameters which characterize the thermal state of a forged blank is the coefficient α of heat transfer from a blank to a die. Unfortunately, a plausible database on this physical parameter doesn't exist today yet. The lack of information in this field forces industrial engineers to use approximate and even arbitrary values of the α coefficient in simulations, and there is no possibility to evaluate the simulation error.

A close look at the references (Kopp and Phillip, 1992; Rosochowska et al., 2004; Nshama et al., 1994; Chang and Bramley, 2002; Burte et al., 1990; Jain, 1990; Semiatin et al., 1987; Rosochowska et al., 2003; Goizet et al., 1998; Caliskanoglu et al., 2002) shows that most values of the coefficient α were determined for low and moderate temperatures. The error in determining of this coefficient is not given in most of scientific papers. The influence of the α inaccuracy on results of simulations of the thermal state of a forged blank is not discussed too.

For these reasons, the numerical evaluation of the error in prediction of the thermal state of a hot-forged blank as a result of the coefficient α inaccuracy is urgent.

The following symbols are used in this article:

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Nomenclature

A_{conv}	area of convection heat exchange (m^2)
$A_{interface}$	blank-die interface (m^2)
A_{rad}	area of radiation heat exchange (m^2)
b	height of the blank (m)
C_p	heat capacity of the blank material at constant pressure (J/kg K)
d	diameter of the blank (m)
E	error in calculation of the weighted-mean temperature of the blank, caused by the inaccuracy of the coefficient α (°C)
h_T	convection heat exchange coefficient (W/m^2 K)
m	blank mass (kg)
P	ratio between the arbitrary and correct values of the thermal contact conductance coefficient at the blank-die interface
t	cooling time of the blank (s)
T	temperature of the free surface of the blank (K)
T_{die}	work surface temperature of the die (K)
$T_{initial}$	weighted-mean temperature of the blank at the initial moment of its forging (K)
T_{blank}	temperature of the blank surface in contact with the die (K)
$T_{t(incorrect)}$	weighted-mean temperature of the blank, calculated on the base of the arbitrary coefficient α_1 (K)
$T_{t(real)}$	weighted-mean temperature of the blank, calculated on the base of a correct value of the α (K)
T_∞	temperature of the environment (air) (K)
$q_{interface}$	heat flux density from the blank to the die (W/m^2)
Q_{conv}	convective heat flux from the free surface of the blank (W)
$Q_{interface}$	heat flux from the blank to the die (W)
Q_{rad}	radiant heat flux from the free surface of the blank (W)
Q_{total}	total heat flux from the blank (W)

Greek symbols

α	coefficient of thermal contact conductance for the blank-die interface (W/m^2 K)
α_1	arbitrary value of thermal contact conductance coefficient for the blank-die interface (W/m^2 K)
σ	Stefan–Boltzman constant ($W/m^2 K^4$)
ε_T	total emissivity of the blank free surface at the temperature T

2. Nature of the thermal contact conductance

The heat transfer from a forged blank to a die occurs by conduction, convection and radiation (Kreith and Bohnt, 2003). The model of the blank-die contact zone is shown in Fig. 1.

Fig. 1 shows that the heat flux, which goes through the contact zone, depends on thermophysical properties of surface layers of the blank and die, as well as on the oxide films, air bubbles, etc.

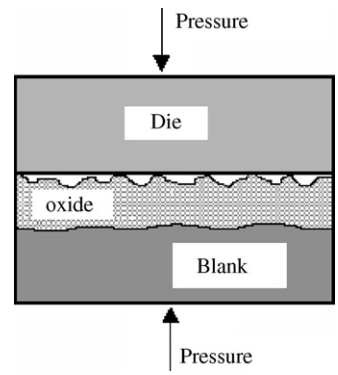

Fig. 1 – Macroscopic model of the blank-die contact zone proposed by Li and Sellars (Li and Sellars, 1996).

Detailed analysis of the contact zone identifies a large number of factors that affect the process of heat transfer through this zone. The factors are as follows:

- Chemical composition of the oxide films in the contact zone.
- Thickness of oxide films in the contact zone.
- Thickness of lubricant layer between the blank and the die.
- Quantity of air in the contact zone.
- Microgeometry of the blank and die surfaces (roughness).
- Blank and die temperatures.
- Pressure in the contact zone.
- Thermophysical properties of the blank and die materials.
- Thermophysical properties of the lubricant.
- Thermophysical properties of the oxide films.

The nature of heat transfer through a contact zone is more complicated (Kreith and Bohnt, 2003) than the heat transfer in a homogeneous medium. Therefore, the Law of Fourier which describes the quantity of thermal energy transferred by conduction through a homogeneous medium cannot be applied in this case.

Listed factors cause great difficulties in experimental studies of thermal contact conductance of the blank-die interface.

Boutonnet (Boutonnet, 1998) cites the simplified (empirical) formula that may be used in calculations of heat transfer through the blank-die interface:

$$Q_{interface} = \alpha \cdot A_{interface} \cdot (T_{blank} - T_{die}). \quad (1)$$

3. Methods of determining the coefficient α

According to the formula (1), in order to determine the coefficient α, it is necessary to know the heat flux $Q_{interface}$ from the blank to the die, the heat transfer area ($A_{interface}$) and the surface temperatures (T_{blank}, T_{die}) in the contact zone.

Measuring the heat transfer area is not any problem. The main problem is determining the surface temperatures in the contact zone and calculating the heat flux through the blank-die interface.

Boutonnet (Boutonnet, 1998) cites three main methods to determine the coefficient α. These methods are as follows:

- Experimental method of direct measurement of surface temperatures in the contact zone.
- Experimental method of indirect determining of surface temperatures in the contact zone.
- Mixed method based on processing experimental data by means of software used for the simulation of the temperature distribution in the blank-die system.

The inaccuracy of the α coefficient obtained by experimental methods (Rosochowska et al., 2004; Nshama et al., 1994) is approximately (5–5.5) % for the small values *and* about (23.5–33) % for the large values.

The determination of the α coefficient by mixed methods (Kopp and Phillip, 1992; Chang and Bramley, 2002; Caliskanoglu et al., 2002) introduces the inaccuracy in the simulation program output. The error of the simulation cannot be evaluated in this case, as available simulation programs require the input of many other parameters whose accurate values are also unknown.

4. Method to evaluate the influence of the α inaccuracy on predicting the real thermal state of the blank

To estimate the numerical error in predicting the thermal state of the hot-forged blank, caused by the α inaccuracy, the following method was used:

- Determining the range of typical (averaged) values of the α coefficient on the base of the formula (1) and statistical data (Kopp and Phillip, 1992) about the heat flux density from the blank to the die, which were obtained for hot forging.
- Determining variations in the weighted-mean temperature of the blank, considering these variations as a function of the extreme values (maximum and minimum) of the α coefficient from the typical ones for hot forging. (Calculation of the weighted-mean temperature is performed on the base of the Law of Energy Conservation.)

5. Theoretical assumptions

The following assumptions are made to study the influence of the α inaccuracy on predicting the real thermal state of the blank in hot forging:

- Instead of unknown or inaccurate values of thermal contact conductance coefficient α are considered its averaged values which can be calculated on the base of typical heat fluxes from the blank to the die (Kopp and Phillip, 1992).
- The minimum value of the α coefficient from the typical ones for hot forging characterizes materials with a thick oxide layer (carbon steels).
- The maximum value of the α coefficient from the typical ones for hot forging is peculiar to materials with a thin oxide layer (aluminium alloys).

Table 1 – Extreme values of the heat flux density according to Kopp and Phillip

Unit	Heat flux density	
	Minimum value	Maximum value
W/m^2	155×10^4	1000×10^4

- Materials with intermediate thickness of an oxide layer have values of the α being between the mentioned extreme values of this coefficient.
- Calculated weighted-mean temperature of the blank at moment t of forging, obtained on the base of a correct value of the α coefficient, is equal to the real weighted-mean temperature $T_{t(real)}$ of the blank at the same moment.

6. Determining the range of α averaged values which are typical for hot forging

The range of α averaged values which are typical for hot forging may be calculated by using heat flux densities. The mathematical relation between the heat flux density $q_{interface}$ and the heat flux $Q_{interface}$ is given by equation:

$$Q_{interface} = q_{interface} \cdot A_{interface}. \quad (2)$$

By combining Eq. (2) and formula (1), the Eq. (3) has been obtained. Eq. (3) expresses the α in terms of the heat flux density:

$$q_{interface} = \alpha \cdot (T_{blank} - T_{die}). \quad (3)$$

The density of heat flux $q_{interface}$ from a blank to a die was determined for hot forging by Kopp and Phillip (Kopp and Phillip, 1992). The extreme values of $q_{interface}$ are shown in Table 1.

The blank materials chosen for calculations were AISI 1045 carbon steel and AA 6061 aluminium alloy. The initial temperatures for these materials were as follows: 1473 K for steel; 773 K for aluminium alloy. The initial temperature of the die is assumed to be 465 K.

By substituting, in the Eq. (3), the values of $q_{interface}$ from the Table 1 and initial temperatures of the blank-die interface, the Eqs. (4) and (5) for calculating the extreme averaged values of the α have been obtained:

$$155 \times 10^4 = \alpha_{minimum} \times (1473 - 475); \quad (4)$$

$$1000 \times 10^4 = \alpha_{maximum} \times (773 - 475). \quad (5)$$

The minimum value of α for steels is shown in Table 2. The maximum value of α for aluminium alloys is shown in Table 3. Thus, as it is possible to see from the Tables 2 and 3, a range of the α coefficient typical values for hot forging is (1550–33560) $W/m^2 \cdot K$.

The same method was used for the calculation of the α for a titanium alloy. In this case, the blank temperature was 900 °C and the weighted-mean temperature of the die was 550 °C. The following averaged values of α have been obtained

Table 2 – The minimum value of the α coefficient for a steel blank in hot forging

Unit	Minimum value from the typical ones	Minimum value according to literature
$W/m^2\,K$	1550[a]	1800[b] (Burte et al., 1990) 2700[c] (Rosochowska et al., 2004)

[a] The value was calculated for AISI 1045 steel.
[b] The value was determined for "H13–H13" steel interface.
[c] The value was determined for "Ma8–H13" steel interface.

Table 3 – The maximum value of the α coefficient for an aluminium blank in hot forging

Unit	Maximum value from the typical ones	Maximum value according to literature
$W/m^2\,K$	33560[a]	30000[b] (Jain, 1990) 50000[c] (Nshama et al., 1994)

[a] The value was calculated for AA6061aluminium alloy.
[b] The value was determined for "Al6061-O"–"H12 steel" interface.
[c] The value was determined for "Al6061-O"–"4140 steel" interface.

(4400–28500) $W/m^2{\cdot}K$. These results are within a range of the α values which are typical for hot forging on the whole. Thus, a range of the α averaged values, which was determined for carbon steels and aluminium alloys, is useful also for materials with intermediate physical properties such as titanium alloys.

7. Balance of thermal energy in hot forging process

In order to obtain the equation that expresses the dependence between the temperature of the forged blank and the α, the blank cooling process (Fig. 2) is examined.

The mathematical model of forged blank cooling is based on the Law of the Energy Conservation (6), on the formula (1) of heat transfer through the contact zone, shown above, on the Stefan–Boltzmann Eq. (7) and the Law of Newton (8):

$$Q_{total} = Q_{interface} + Q_{rad} + Q_{conv}, \tag{6}$$

where:

$$Q_{rad} = \sigma \cdot A_{rad} \cdot \varepsilon_T \cdot (T^4 - T_\infty^4), \tag{7}$$

$$Q_{conv} = h_T \cdot A_{conv} \cdot (T - T_\infty). \tag{8}$$

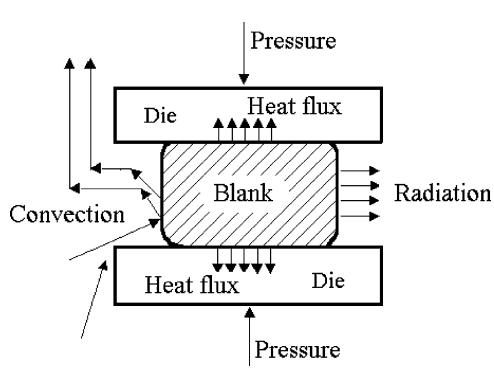

Fig. 2 – Scheme of the blank cooling process.

The resulting equation is:

$$\begin{aligned} Q_{total} &= m \cdot C_p \cdot \frac{dT_{t(real)}}{dt} \\ &= \alpha \cdot A_{interface} \cdot (T_{blank} - T_{die}) \\ &\quad + \sigma \cdot A_{rad} \cdot \varepsilon_T \cdot (T^4 - T_\infty^4) + h_T \cdot A_{conv} \cdot (T - T_\infty). \end{aligned} \tag{9}$$

Taking into consideration that the blank cooling velocity dT_t/dt is approximately equal to

$$\frac{T_{initial} - T_{t(real)}}{t},$$

the Eq. (9) of the energy balance can be rewritten as follows:

$$\begin{aligned} & m \cdot C_p \cdot \frac{T_{initial} - T_{t(real)}}{t} \\ &\approx \alpha \cdot A_{interface} \cdot (T_{blank} - T_{die}) + \sigma \cdot A_{rad} \cdot \varepsilon_T \cdot (T^4 - T_\infty^4) \\ &\quad + h_T \cdot A_{conv} \cdot (T - T_\infty). \end{aligned} \tag{10}$$

8. Error E of the blank weighted-mean temperature

In order to calculate the error E of the temperature $T_{t(incorrect)}$, the following steps are performed:

(a) the Eq. (10) is re-written by substituting a correct value of the α for an arbitrary value of the α_1 and by substituting the temperature T_t for the temperature $T_{t(incorrect)}$ which corresponds to the α_1, i.e.:

$$\begin{aligned} & m \cdot C_p \cdot \frac{T_{initial} - T_{t(incorrect)}}{t} \\ &\approx \alpha_1 \cdot A_{interface} \cdot (T_{blank} - T_{die}) + \sigma \cdot A_{rad} \cdot \varepsilon_T \cdot (T^4 - T_\infty^4) \\ &\quad + h_T \cdot A_{conv} \cdot (T - T_\infty); \end{aligned} \tag{11}$$

Table 4 – Initial conditions of blank hot forging and blank thermophysical parameters

Blank material	$T_{initial}$	T_{blank}	T_{die}	T	T_∞	α	ε_T	h_T
AA 6061	773	773	475	773	298	33560[a]	0.27 (Polozine, 2004)	10 (Schaeffer, 1999)
AISI 1045	1473	1473	475	1473	298	1550[b]	0.83 (Polozine, 2004)	10 (Schaeffer, 1999)

[a] The maximum value of the α coefficient from the typical ones.
[b] The minimum value of the α coefficient from the typical ones.

Table 5 – Varying parameters of hot forging used in the calculation of the *E*

b/d				$P = (\alpha_1/\alpha)$	$T_{t(real)}$
2	1.5	1	0.5	$2.0 \div 0.5$	[773–573][a], [1473–1173][b]

[a] For the blank of aluminium alloy.
[b] For the blank of steel.

(b) the Eq. (10) is divided into the Eq. (11). The resulting expression for closed die forging ($\varepsilon_T = 0$; $h_T = 0$) is as follows:

$$\frac{T_{initial} - T_{t(incorrect)}}{T_{initial} - T_{t(real)}} \approx \frac{\alpha_1}{\alpha} = P, \quad (12)$$

where:

$$E = T_{t(real)} - T_{t(incorrect)}.$$

Thus, to calculate a value of the E, it is necessary to give the $T_{initial}$, $T_{t(real)}$ and P.

The resulting expression for the calculation of the E in the case of open dies ($\varepsilon_T > 0$; $h_T > 0$) is derived similarly. Deriving this expression, it is necessary to give the geometry of a blank as the ratio b/d, where b is a height of a blank and d is its diameter. Calculations for this case are not shown in the given paper.

9. Parameters used to calculate the error *E* of the blank weighted-mean temperature

Initial conditions of blank forging conditions and blank thermophysical parameters that have been used in the calculation of the E are shown in Table 4.

Varying parameters that were used in the calculation of the E are shown in Table 5.

10. Results

The results of the E calculation show the influence of the α inaccuracy on prediction of the thermal state of a hot-forged blank. The calculation of the E value was performed for the following cases:

- Closed die forging.
- Open die forging (for $b/d = 2$).
- $P = 2$; 1.5; 1.25; 0.75; 0.5; 0.25 (arbitrary values).

Expected error E calculated on the base of arbitrary value of the ratio P is shown in Figs. 3–6. The analysis of Figs. 3–6 permits to draw the conclusions about some conditions which determine the simulation error E. These conditions are as follows:

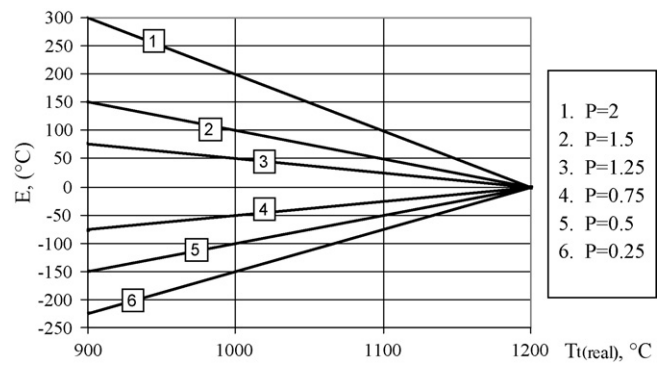

Fig. 3 – Error *E* of the weighted-mean temperature of a blank, caused by the α inaccuracy. Closed die forging, [900–1200] °C range.

(a) Hot forging method (open or closed dies):
- For the range of low temperatures, the error E of the temperature $T_{t(real)}$ of a blank forged in open dies is almost the same as in the case of closed dies i.e:

$$E_{open\ die} = 0.93E_{closed\ die};$$

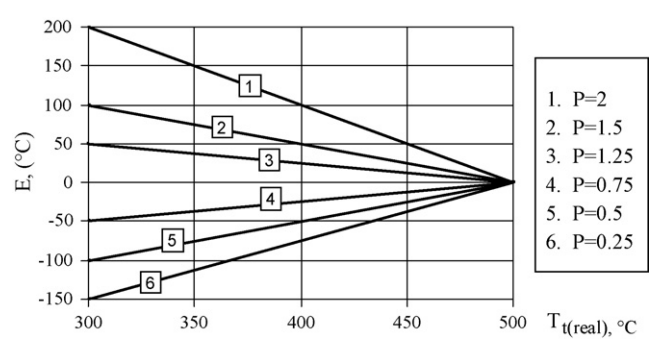

Fig. 4 – Error *E* of the weighted-mean temperature of a blank, caused by the α inaccuracy. Closed die forging, [300–500] °C range.

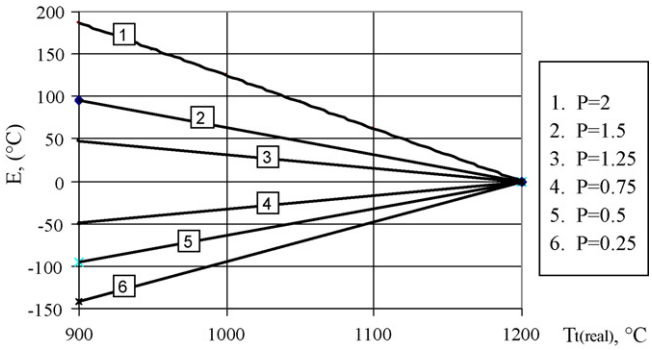

Fig. 5 – Error E of the weighted-mean temperature of a blank, caused by the α inaccuracy. Open die forging, [900–1200] °C range, $b/d = 2$.

- For the range of high temperatures, the error E of the temperature $T_{t(real)}$ of a blank forged in open dies is significantly greater than in the case of closed dies, i.e.
  $E_{\text{open die}} = 0.62E_{\text{closed die}}$.

(b) Range of cooling temperatures of a forged blank:
- The module of the error E of the temperature $T_{t(real)}$ is directly proportional to the width of the range of blank cooling temperatures in forging process.

(c) Ratio P:
- If $P > 1$, the error E of the temperature $T_{t(real)}$ is directly proportional to P;
- If $P < 1$, the module of the error E of temperature $T_{t(real)}$ is inversely proportional to P.

The case, in which the α_1 variate within the limits of experimental error in determining the α (Rosochowska et al., 2004; Nshama et al., 1994), represents an especial interest. The ratio P for this case is as follows:

$P = 1.055$ for a steel forging;
$P = 1.33$ for a aluminium forging.

Expected error E calculated for the coefficient α obtained by experimental way is as follows:

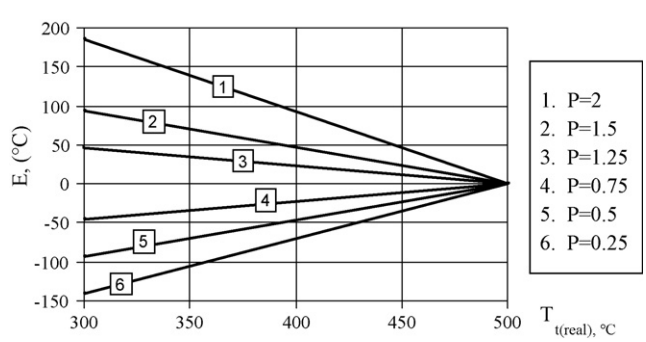

Fig. 6 – Error E of the weighted-mean temperature of a blank, caused by the α inaccuracy. Open die forging, [300–500] °C range, $b/d = 2$.

$E = \pm 16.5\,°C$, ($\alpha_1/\alpha = \pm 1.055$, steel forging for closed dies, cooling interval 300 °C).
$E = \pm 10.3\,°C$, ($\alpha_1/\alpha = \pm 1.055$, steel forging for open dies, cooling interval 300 °C).
$E = \pm 66\,°C$, ($\alpha_1/\alpha = \pm 1.33$, aluminium forging for closed dies, cooling interval 200 °C).
$E = \pm 61.4\,°C$, ($\alpha_1/\alpha = \pm 1.33$, aluminium forging for open dies, cooling interval 200 °C).

Some conclusion may be also deduced by analyses of the expressions of the shape (11) derived for the cases of closed and open dies. These conclusions are the following:

- For closed dies, the error E of the temperature $T_{t(real)}$ of a blank does not depend on the blank macrogeometry;
- For open dies, the error E of the temperature $T_{t(real)}$ of a blank increases in proportion to the ratio between a diameter and height of a blank (ratio b/d).

11. Conclusion

The analysis of results shows that, in general case, if the α coefficient is given incorrectly, this may cause the error of a few tens or even hundreds of degrees Celsius when simulating the thermal state of a blank. Therefore, the α coefficient determined for one blank-die interface should not be used for any other blank-die interface.

The only exception may be made for forging at high temperatures in open dies. In this case, the similarity between the blank-die system with the known coefficient α and the blank-die system under examination must be very high. Besides this, the blank material in the system under examination must have a high emissivity and the interface of this system must have a low value of the coefficient α. Under these conditions, the error E obtained in simulation by using the incorrect α may be acceptable. It should be noted that the simulation error $E \leq 30.7\,°C$ for aluminium alloy blanks and $E \leq 3.4\,°C$ for carbon steel blanks, calculated for each 100 °C of the forged blank cooling, is the best result for today. Hence, such error may be considered as acceptable for hot forging.

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