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THE INFLUENCE OF THE SCALE FORMATION AND THE DIE ANGLE ON THE HEAT TRANSFER IN THE DRAWING OUT PROCESS

BEATA HADAŁA, ZBIGNIEW MALINOWSKI

AGH University of Science and Technology, Al. Mickiewicza 30, Krakow

Abstract

The article describes the influence of the scale formation and the die angle on the heat transfer in the drawing out process. The die angle affects the surface of contact of the ingot with the anvils and it results the heat flux transferred to the air and tools. In order to describe the heat transfer boundary conditions in the zone of material contact with the dies the secondary scale formation as a function of time and a forged steel surface temperature have been taken into account. The scale thickness has been calculated on the basis of the experimental equation defining the growth of the weight of scale while steel cooling in the air. It has made it possible to vary the heat transfer coefficient as a function of process time and the scale thickness. The dependence of the heat transfer coefficient on the type of anvil has been determined by taking into account the die angle and the deformation ratio during the drawing out operation. The empirical functions have been established to approximate the ratio of material contact with the anvils. The tape of anvil and the deformation ratio have been taken into account. On the basis of the developed heat transfer boundary conditions, the temperature fields of the forged shaft have been calculated.

Key words: heat transfer, scale formation, drawing out process, finite element method

1. INTRODUCTION

In open die forging a variety of products can be produced with the relatively simple anvils. However, it can be achieved after a complex sequence of the deformation steps. It makes the process control very complex. Several thermal and mechanical phenomena take place during open die forging, the most important are material shape change due to large numbers of partial deformations, heat generation, heat transfer to the air and anvils. These processes have significant influence on the workpiece temperature. The major problems are concerned with the description of the heat transfer to the anvils. It is caused by the difficulty of the heat transfer coefficient determination and the calculation of the real area of contact. The heat transfer coefficient reported in the literature varies from 4000 to 40000 W/m^2K. In metal forming operation the heat transfer to the tools can be calculated by matching the computation results to the measured temperature while metal forming (Pietrzyk at al. 1994). The heat transfer coefficient is affected by the scale formation and the ratio of deformation as reported by Kukuryk (1994). However, reported results do not give the possibility to develop empirical equation which can be used to calculate the heat transfer coefficient for forging operation. Lenard (1990) has reported that lubricant or scale on the surface of contact essentially affects the heat transfer problem in a way more important than the deformation ratio, rate of the deformation or material surface temperature. Murata at al. (1984) measured the heat transfer coefficient in order to determine the influence of scale formation and lubrication. It has been noted that these factors

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essentially lower the heat transfer in comparison to clean surfaces. Pawelski (1969) reported that the time of contact can affect the heat transfer coefficient. Scale formation and the heat conduction coefficient have also influence on the heat flux in metal forming processes. The work by Lenard (1990) points on the quality of the surface of contact as an important factor in the heat transfer problems.

2. HEAT TRANSFER MODEL

The temperature field has been computed by solving the heat transfer equation:

$$K_{ij}(\tau)T_j(\tau) + C_{ij}(\tau)\dot{T}_j(\tau) = G_i(\tau) \quad (1)$$

where:
K_{ij} - thermal conductivity matrix,
C_{ij} - heat capacity matrix,
G_i - heat load vector,
T_j - nodal temperature vector,
$\dot{T}_j$ - time derivatives of nodal temperatures,
τ - time, s.

Galerkin integration scheme employed to the equation (1) leads to the set of algebraic equation. Linear interpolation of the temperature over the time increment $\Delta\tau \in (\tau, \tau+\Delta\tau)$ has been used in the finite element method. The detailed description of the solution method is given by Malinowski (2005). Open die forging employs three major heat transfer processes:

- workpiece cooling in the air,
- workpiece reheating in the chamber furnace,
- heat transfer while drawing out of the workpiece.

Therefore, the heat boundary conditions must be specified for these processes in order to follow the material temperature change over the manufacturing process.

3. BOUNDARY CONDITIONS

The boundary conditions for air cooling of steel are generally well recognized. In the case of the drawing out operation the heat radiation losses are the most important. The heat convection losses to the air are negligible, and can be taken into account as a part of the heat transfer coefficient given by Malinowski et al. (1994):

$$\alpha = \left(1.2 - 0.52\frac{t}{1000}\right)5.675\cdot 10^{-8}\frac{t^4 - t_a^4}{t - t_a} \quad (2)$$

In the case of heat transfer in the chamber furnace the heat convection and radiation is given by:

$$\alpha = 1.16(4.8 + 3.4v) + \varepsilon_w 5.675\cdot 10^{-8}\frac{t^4 - t_s^4}{t - t_s} \quad (3)$$

where:
t - material surface temperature °C,
t_a - air temperature, °C
t_s - combustion gas temperature, °C,
v - combustion gas velocity, m/s.

The average emissivity ε_w of steel surface and combustion gas has been calculated using the equation given by Senkara (1983):

$$\varepsilon_w = \frac{\varepsilon_g \varepsilon_m}{\varepsilon_g + \varepsilon_m(1 - \varepsilon_g)} \quad (4)$$

The combustion gas emissivity ε_g has been approximated to the data given by Senkara (1983):

$$\varepsilon_g = 0.4977 - 0.00016714 t_s \quad (5)$$

The steel surface emissivity ε_m has been calculated from the equation given by Devadas & Samarasekera (1986):

$$\varepsilon_m = 1.1 + \frac{t}{1000}\left(0.125\frac{t}{1000} - 0.38\right) \quad (6)$$

The heat transfer while drawing out is more complex. It involves the heat flow to the air and anvils. Based on the experimental data the time of bite τ_n has to be determined. The time of a single bite τ_n can be divided between the time of material-anvil contact τ_s and the time of workpiece air cooling τ_p. The time of material-anvil contact may be expressed as follows:

$$\tau_s = w_p w_k \tau_n \quad (7)$$

The coefficient w_p has been introduced in order to determine a ratio of the material-anvil time of contact for a given time of a single bite. However, during the drawing out operation only a part of the workpiece surface is in contact with the anvils. Therefore, it is necessary to calculate the ratio of the workpiece cross-section circumference which touches the anvils. The ratio of material-anvil surface of contact w_k depends on shape of anvils and the applied strain. Empirical formulas given in table 1 have been developed based on the finite element modeling of the drawing out processes accomplished by Banaszek (2002):

Table 1. *Material – anvils ratio of surface contact w_k as a function of engineering strain ε and shape of anvils.*

Shape of anvils	Formula
Flat anvils	$w_k = 0.5$
Upper flat, lower rhombic $\alpha = 120°$	$w_k = -0{,}038\varepsilon^2 + 2{,}4914\varepsilon$
Upper flat, lower rhombic $\alpha = 90°$	$w_k = -0{,}0595\varepsilon^2 + 3{,}3667\varepsilon$
Radial anvils	$w_k = -0{,}0438\varepsilon^2 + 2{,}7236\varepsilon$
Upper and lower rhombic $\alpha = 120°$	$w_k = -0{,}221\varepsilon^2 + 7{,}3496\varepsilon$
Upper and lower rhombic $\alpha = 90°$	$w_k = -0{,}3436\varepsilon^2 + 10{,}316\varepsilon$
Asymmetric anvils	$w_k = -0{,}0813\varepsilon^2 + 3{,}7569\varepsilon$

When the time of contact τ_s is known, the time of air cooling τ_p for a single bite can be calculated from the equation:

$$\tau_p = \tau_n - \tau_s \qquad (8)$$

The solution to the heat conduction equation (1) with the boundary conditions described by the heat transfer coefficient (2) gives the temperature field after the time of air cooling τ_p. Over the time of contact τ_s the heat transfer coefficient is calculated from the following equation:

$$\alpha = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta_{zg}}{\lambda}} \qquad (9)$$

The heat transfer coefficient between the workpiece and the anvils under high pressure can be calculated from the equations 10 and 11 given by Malinowski (2001):

$$\alpha_1 = 20438 - 5936\frac{T-273}{1000} + 16943\left(\frac{T-273}{1000}\right)^2 \quad \text{for } T < 973\text{K} \qquad (10)$$

$$\alpha_1 = 115566 - 190554\frac{T-273}{1000} + 85068\left(\frac{T-273}{1000}\right)^2 \quad \text{for } T > 973\text{K} \qquad (11)$$

where T is the material surface temperature, K.

Cooling of the hot steel in the air involves formation of the secondary scale. The thickness of the secondary scale can be calculated based on the increase of scale mass Δm_1. The increase of scale mass while air cooling has been calculated from the equations given in table 2. The equations has been developed by Opel at al. (1974). The increase of scale mass depends on cooling time τ and the material surface temperature t.

Table 2. *The increase of scale mass as a function of material surface temperature and cooling time.*

Temperature t, °C	Scale mass increase, mg/cm^2
1200	$\Delta m_1 = 88\ \tau^{0,46}$
1100	$\Delta m_1 = 58{,}2\ \tau^{0,57}$
1000	$\Delta m_1 = 20{,}9\ \tau^{0,66}$
900	$\Delta m_1 = 7{,}7\ \tau^{0,81}$
800	$\Delta m_1 = 6{,}0\ \tau^{0,9}$

It has been assumed that the sale formed while heating of the workpiece in the chamber furnace was removed during preliminary operation. Further, it is assumed the heat conduction along the workpiece is negligible in comparison to the heat flow in the cross-section of the workpiece. The drawing out can be used to produce a variety of workpiece shapes with relatively simple anvils. Computation of a workpiece shape change after each single bite is a very complicated and time consuming method. In the present solution a material shape change has been taken into account with the aid of linear transformation of the element nodes from initial to final configuration. The heat generation due to plastic work has been added to the heat balance as an internal heat equal to the plastic work. The heat conduction coefficient has been calculated from the equation given by (Senkara 1983):

$$\lambda = 1{,}5 + 1{,}5 \cdot 10^{-3}(t - 800) \qquad (12)$$

4. RESULTS OF COMPUTATIONS

The computation of the temperature field has been performed for the drawing out of 50Mg ingot made of 34CrNiMo6 steel. The computation has been curried out for date measured while shaft forging at the industrial plant. Data collected concerned times of forging, cooling and shape measurement. Based on these data it was possible to build the finite element model of the heat transfer process. Prior to the forging the ingot was heated up in the chamber furnace to the temperature of 1220°C. Heating time was equal to 15h and 30 minutes. The anvil surface temperature for finite element computation has been set to 600°C.

The ingot after heating was transported to the press and the manipulator holder has been drawn out. The holder diameter was equal to 880mm. Next the workpiece was drawn out to the diameter of

1050mm. The time from the end of heating to the end of holder forging was equal to 20 minutes. Drawing out to the diameter of 1050mm with flat anvils has taken 14 minutes of time. The time of the workpiece surface cleaning after whose operation was equal to 36 minutes. The workpiece temperature drop was too high and it was necessary to start the reheating process. The finite element computation of the workpiece temperature field has been performed for the described scheme of drawing out. In figure 1 the selected results of temperature computation have been presented. Variations of the minimum, maximum and average workpiece temperatures as a function of time have been shown. Drawing out results in significant temperature drop of the workpiece surface. After the end of forging the surface temperature increases slightly over the time of approximately 10 minutes, further temperature drop tipical for air cooling is observed. In order to examine the influence of the heat flow to the anvils on the workpiece temperature additional computations have been performed for air cooling only even for the time of material contact with the anvils. However, the change of the material shape has been taken into account. These results are marked in figures as "air cooling only". Drawing out with flat anvils results in the temperature drop higher of about 20°C if compare to "air cooling only". The temperature difference between whose two cases decreases after cooling of the workpiece in the air. Only minor differences in the secondary scale formation has been shown in figure 2 while drawing out with flat anvils and air cooling of the workpiece.

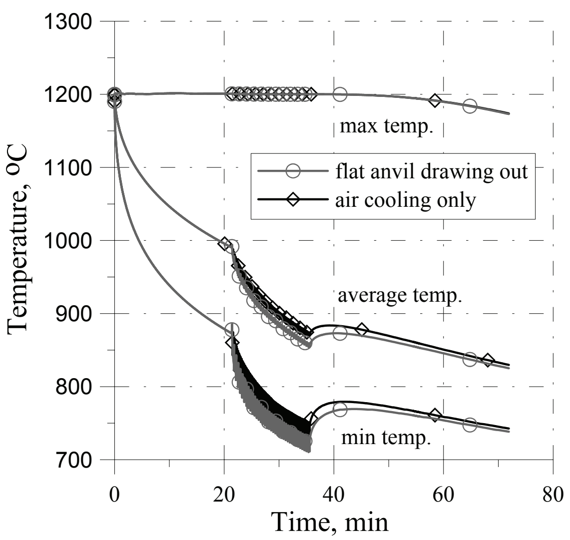

Fig. 1. Variation of minimum, maximum and average workpiece surface temperature while drawing out with flat anvils and for air cooling only.

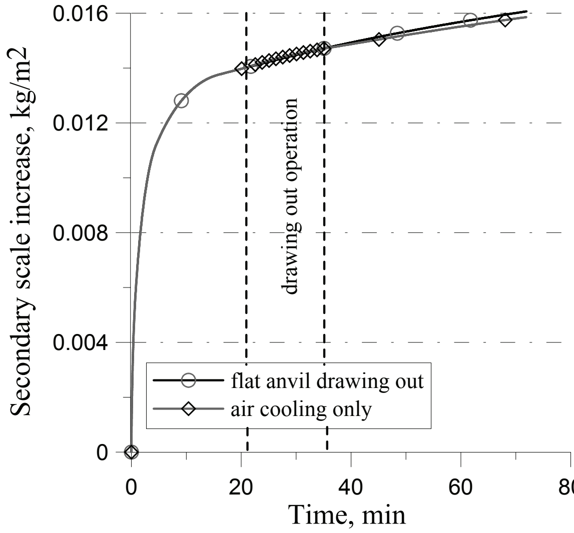

Fig. 2. Increase of the secondary scale mass while drawing out with flat anvils and for air cooling only.

The difference in the workpiece surface temperature for drawing out and cooling in the air results from the change of the heat flux. In figure 3 the variation of the heat transfer coefficient as a function of process time has been presented. For air cooling of the workpiece the heat transfer coefficient is approximately equal to 100 W/m^2K. However, while the material contacts the anvils it increases to about 900 W/m^2K. Relatively low heat transfer coefficient for material die contact while drawing out can be explained by the intermediate layer of scale which is formed on material and anvil surfaces.

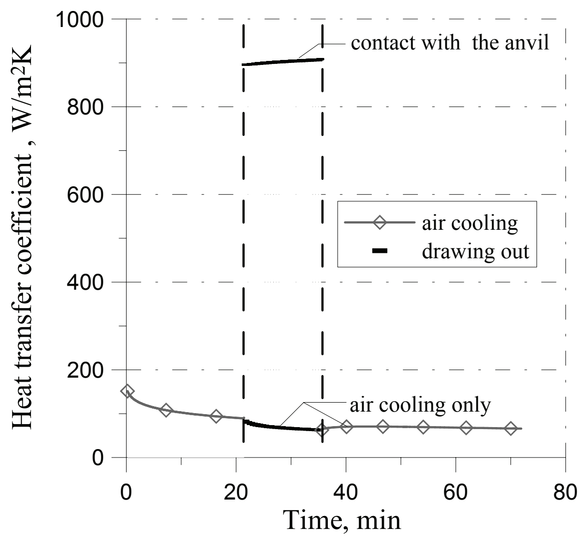

Fig. 3. Variation of the heat transfer coefficient while drawing out and cooling in the air.

The results of the workpiece temperature computations have been compared to the measurement of the surface temperature. The workpiece surface temperature was measured with the thermovision camera while the drawing out to the diameter of 1050 mm, reheating and further drawing out to the diameter of 900 mm. The results have been shown in figure 4. The results from thermal camera compare well to the average surface temperature. Similar results has been presented in figure 5, which shows the material surface temperature for the drawing out to the diameter of 900 mm after reheating of the workpiece in the chamber furnace.

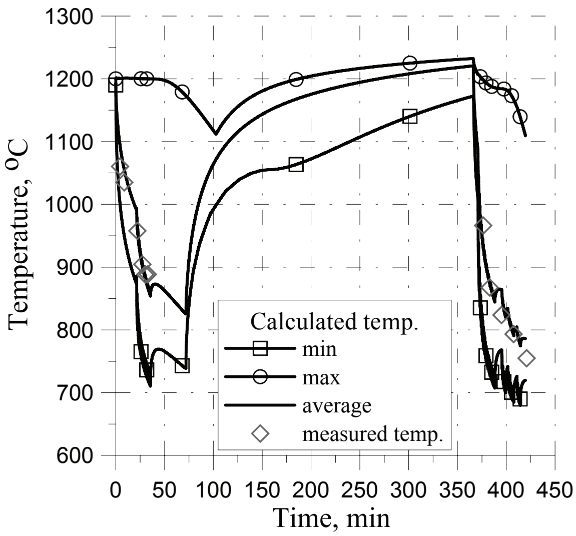

Fig. 4. *Variation of minimum, maximum and average workpiece surface temperature while drawing out, reheating and auxiliary operations computed and measured with thermovision camera.*

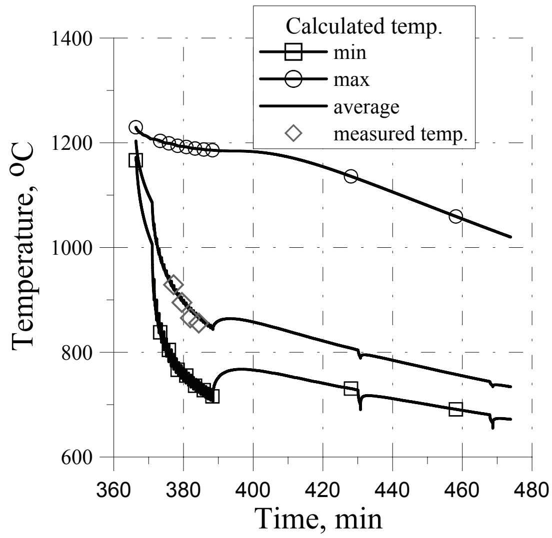

Fig. 5. Variation of minimum, maximum and average workpiece surface temperature while drawing out computed and measured with thermovision camera.

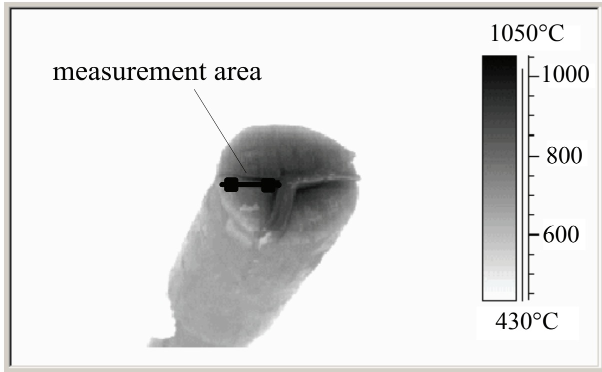

Fig. 6. *Thermal photograph of the workpiece surface and cross-section after drawing out to the diameter of 900 mm.*

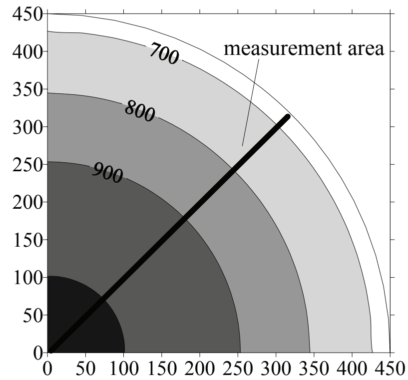

Fig. 7. *Temperature distribution in the workpiece cross-section after drawing out to the diameter of 900 mm, computed with the developed numerical model.*

In figure 6 the thermal photograph of the workpiece temperature in the cross-section after drawing out to the diameter of 900 mm has been presented. After drawing out to the diameter of 900 mm the workpiece has been cut into two pieces. It made it possible to measure the temperature distribution in the shaft cross-section. The computed temperature field for this cross-section of the material has been presented in figure 7. The surface temperature has the highest value in the material axis and is approximately equal to 1020°C. The computed surface temperature of the material is about 670°C. The measured temperature of the shaft cross section is lower from the computed one of about 20°C to 30°C. The difference results from the rapid cooling of the shaft surface after cutting due to secondary scale formation. Further it is very difficult to locate the real position of the measurement point based on the thermal photograph. Due to this problem the comparison of the measured and computed temperatures have been shown in figure 8 in dimensionless coordinates.

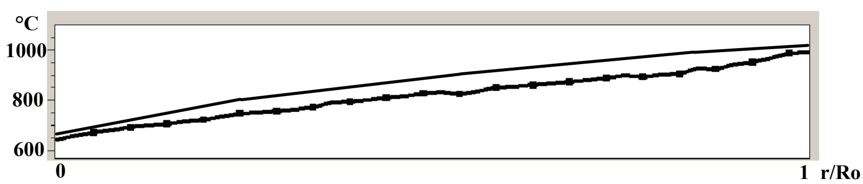

Fig. 8. *Temperature variation in the ingot cross-section after drawing out to the diameter of 900 mm. Upper curve – finite element method computation. Lower curve - data from thermovision camera.*

5. CONCLUSIONS

The finite element model for the temperature field computation for the drawing out process has been developed. The simplicity of the temperature field computation is based on neglecting the material flow computation with the use of the finite element method. Instead of it the linear transformation of the material cross-section has been applied in the numerical model. The heat generation due to plastic work has been introduced as an average value resulting from the change of the material cross-section. The developed boundary conditions describe well the heat transfer problem while the drawing out and reheating operations. The heat flux to the anvils has been modeled with the use of an average heat transfer coefficient which takes into account the secondary scale formation. Simplified formulas can be used to calculate the ratio of the surface of material contact with the dies. It has been shown that it does not significantly affects the heat transfer problem while the drawing out process.

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WPŁYW ZGORZELINY I KĄTA KOWADEŁ NA WYMIANĘ CIEPŁA W PROCESACH KUCIA SWOBODNEGO

Streszczenie

W artykule przedstawiono analizę wpływu zgorzeliny i kąta kowadeł na wymianę ciepła w procesie wydłużania swobodnego wlewka. Kąt kowadeł wpływa na powierzchnię styku kutego materiału z kowadłami i w rezultacie zmienia się strumień ciepła odprowadzanego do kowadeł i przejmowanego przez powietrze. W celu ustalenia warunków brzegowych w strefie kontaktu wlewek – kowadło, uwzględniono wzrost grubości zgorzeliny wtórnej w zależności od czasu i temperatury powierzchni kutej stali. Grubość zgorzeliny wyliczono na podstawie eksperymentalnych zależności przyrostu masy zgorzeliny podczas chłodzenia w powietrzu po operacji nagrzewania. Założono, że zgorzelina pierwotna, powstała podczas nagrzewania w piecu, została usunięta w czasie wydłużania wstępnego. Pozwoliło to na wykazanie zmienności współczynnika wymiany ciepła w zależności od grubości zgorzeliny i czasu trwania procesu. Wykazano także zależność współczynnika wymiany ciepła od rodzaju zastosowanych kowadeł z uwzględnieniem kąta rozwarcia powierzchni roboczej kowadła i wielkości gniotu stosowanego podczas operacji kucia. Dla każdego z kowadeł została przyjęta funkcja empiryczna umożliwiająca przybliżenie udziału pola powierzchni styku. Na podstawie ustalonych zależności wykonano obliczenia pola temperatury wlewka i przedstawiono przykładowe wyniki rozkładu temperatury w przekroju poprzecznym w strefie styku kowadła z odkształcanym materiałem. Obliczenia zostały dokonane za pomocą metody elementów skończonych.

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