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ANALYSIS OF THE HEATING OF STEEL WIRES DURING HIGH SPEED MULTIPASS DRAWING PROCESS

ANALIZA NAGRZEWANIA SIĘ DRUTÓW STALOWYCH W PROCESIE CIĄGNIENIA WIELOSTOPNIOWEGO Z DUŻYMI PRĘDKOŚCIAMI

The analysis of the heating of the wire including theoretical studies showed that in the multistage drawing process a increase drawing speed causes intense heating of a thin surface layer of the wire to a temperature exceeding 1100°C, which should be explained by the accumulation of heat due to friction at the interface between wire and die. It has been shown that with increasing of drawing speed the heated surface layer thickness measured at the exit of the wire from the dies is reduced significantly and at drawing speed of 25 m/s is equal to about 68 μm. The decrease in the thickness of this layer can be explained by a shorter time of heat transfer to the wire, which causes additional heat accumulation in the surface layer. Thus fivefold increase in drawing speed caused an approximately 110% increase in the temperature in the surface layer of the wire. Experimental studies have shown that the increase of drawing speed of 5 to 25 m/s will increase the temperature of the wire after coiled on the spool more than 400%.
Keywords: high carbon steel wires, drawing speed, temperature

Analiza nagrzewania się drutu obejmująca badania teoretyczne, wykazała że w procesie ciągnienia wielostopniowego wzrost prędkości ciągnienia powoduje intensywne nagrzewanie się cienkiej warstwy wierzchniej drutu, do temperatury przekraczającej 1100°C co należy tłumaczyć kumulacją ciepła spowodowanego tarciem na styku drutu i ciągadła. Wykazano, że wraz ze wzrostem prędkości ciągnienia grubość nagrzanej powierzchniowej warstwy drutu mierzonej na wyjściu z drutu z ciągadła zmniejsza się znacząco i przy prędkości ciągnienia 25 m/s wynosi ona około 68 μm. Spadek grubości tej warstwy można tłumaczyć krótszym czasem wnikania ciepła do drutu, co powoduje dodatkową kumulację ciepła w jego warstwie wierzchniej. Stąd pięciokrotny wzrost prędkości ciągnienia spowodował około 110% wzrost temperatury w warstwie wierzchniej drutu. Badania eksperymentalne wykazały, że wzrost prędkości ciągnienia z 5 do 25 m/s spowoduje wzrost temperatury drutu po nawinięciu na szpulę zbiorczą o ponad 400%.

1. Introduction

Following the development of drawing industry in recent years, there have been noticeable drawing technology development to improve process efficiency and quality of drawn wires [1-2]. The intensification of the process of drawing changes the conditions of deformation, forcing producers to use new technological solutions in the field of surface treatment, lubrication and drawing process. Modern multi-stage drawing machines allow dry wire drawing at high speeds exceeding 25 m/s. From the literature, as well as the author's own studies [3-4] show that the process of multistage drawing intense heating of the wire surface layer significantly contributes to the deterioration of lubrication. Thus, for good lubrication conditions and to provide specific industry standards drawing speed in the last draft typically do not exceed 15 m/s.

In the drawing process the factor determining the high-temperature surface of the wire is caused by the heat of friction, which leads to an increase in temperature of the surface layer of the wire and die nib [5]. The amount of heat generated at the boundary surface of the wire and the die is dependent on friction, the yield stress and drawing speed. The higher the drawing speed, the greater the amount of heat generated per unit time. According to Łuksza [6], the temperature of the wire in the die increases approximately in proportion to the cube root of the drawing speed.

In the process of drawing the wire temperature increases the length of contact with the die. In the initial stage, at the entrance the wire to die the lubricant becomes plastic, and further increase in temperature due to dissolved, forming a thick film layer in the zone of deformation, wherein the amount of lubricant decreases gradually over the length of the contact wire of the die [7]. The heat generated as a result of the deformation work causes the temperature of lubricant, thereby contributing to a reduction in its viscosity [8-9]. This in turn leads to a decrease in the thickness of the lubricant, which is not completely separated from the tool surface of the wire, and the wire drawing at a speed of 20 m/s may occur dry friction conditions [4].

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TABLE 1

Distribution of individual drafts G_p and total draft G_c

Draft	0	1	2	3	4	5	6	7	8	9	10	11	12
φ, mm	5.50	5.00	4.48	4.00	3.60	3.24	2.92	2.64	2.40	2.19	2.01	1.85	1.70
G_p, %	–	17,.4	19.7	20.3	19.0	19.0	18.8	18.3	17.4	16.7	15.8	15.3	15.6
G_c, %	–	17.4	33.7	47.1	57.2	65.3	71.8	77.0	81.0	84.2	86.6	88.7	90.5

Therefore, the aim of this study is to determine the effect of high drawing speed in conventional dies on temperature of high carbon steel wires.

2. Material and applied drawing technologies

The investigation of high speed multipass drawing process was performed for high carbon steel wire grade C78D (0.79% C). Before drawing, the wire rod was patented, itched and phosphated. The drawing process of φ5.5 mm wires in the final wire of φ1.7 mm was conducted in 12 passes, in industrial conditions, by means of a modern multi-die drawing machine Koch KGT 25/12, using conventional dies with an angle of drawing 2α =12°. The drawing speeds in the last pass, depending on the variant of the drawing, were respectively: 5, 10, 15, 20, 25 m/s. Individual drafts, G_p, and total draft, G_c, are summarized in Table 1 while drawing speeds, v, are presented in Fig. 1.

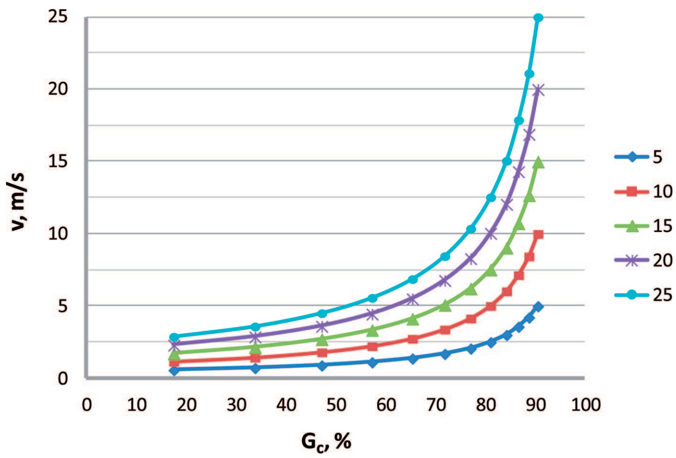

Fig. 1. Drawing speed in total draft function

3. The theoretical analysis of wiredrawing process

Theoretical analysis of the heating of the wire in the high speed multistage drawing process was carried out on software Drawing 2D [10], in which the temperature on the surface and in the axis of the wires, on the exit form sizing part of die, has been estimated. In addition, the paper defines also the average temperature of drawn wires.

The simulation of the multistage drawing process was performed for a wire with plastic properties corresponding to those of the pearlitic steel C78 (~0.78 %C). It was assumed that the drawing process took place with the identical distribution of single and total drafts and drawing speeds to that of the experimental tests (Table 1 and Fig. 1) at the coefficients of friction μ = 0.08. Initial temperature of the wire prior to entering the first and following dies was 20°C.

In Fig. 2 is an example of the temperature distribution for the φ1.7 mm wire drawn at speed v = 25 m/s.

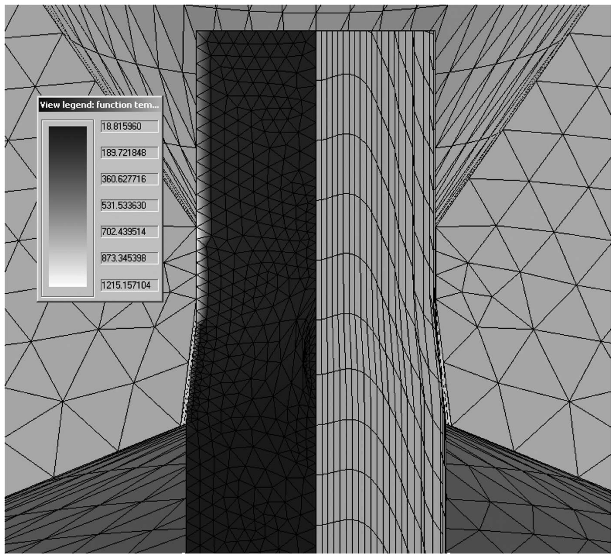

Fig. 2. The temperature distribution for the final 1.7 mm wire drawn at speed v=25 m/s

The results of numerical calculations showing the impact of drawing speed on the temperature of the wires, on the exit form sizing part of die, in multistage drawing process is shown in Figs. 3-5.

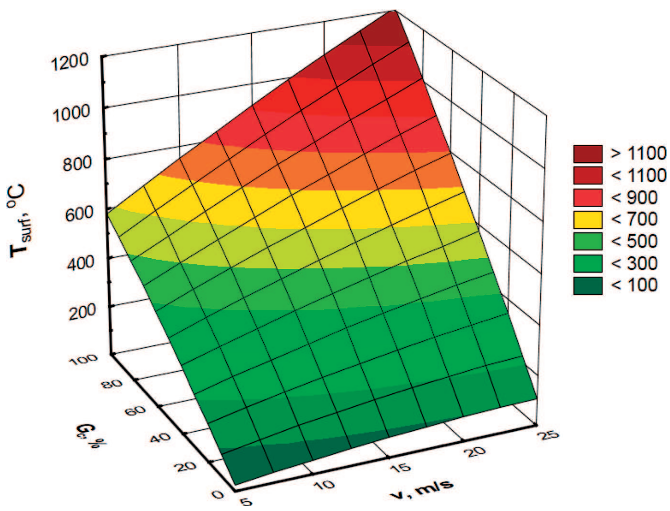

Fig. 3. The plane defining the relationship between the temperature on the wire surface T_{surf} and total draft G_c and drawing speed v

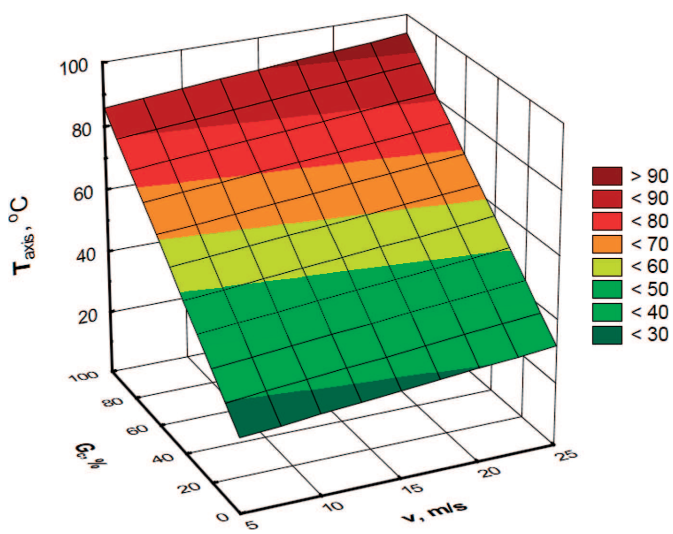

Fig. 4. The plane defining the relationship between the temperature in the wire axis T_{axis} and total draft G_c and drawing speed v

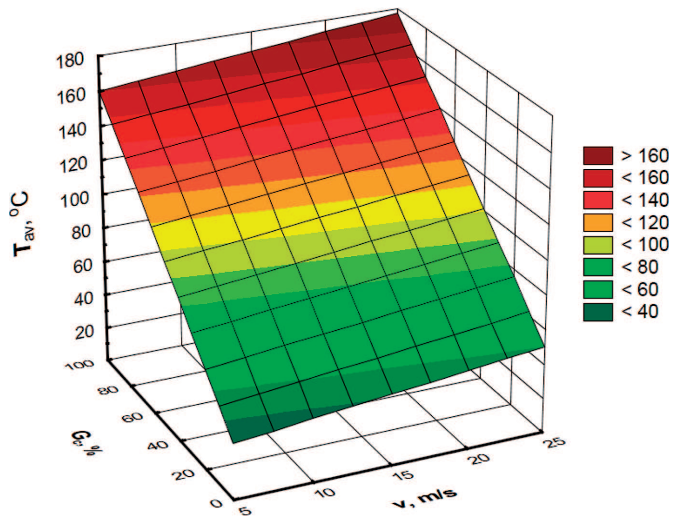

Fig. 5. The plane defining the relationship between the average temperature of the wires T_{av} and total draft G_c and drawing speed v

Numerical analysis showed a significant effect of drawing speed on the temperature of the drawn wires. Data presented in Figure 3 shows that in the multistage drawing process a increase of drawing speed causes intense heating of a thin surface layer of the wire to a temperature exceeding 1100°C. Increasing the drawing speed of 5 to 25 m/s resulted in an increase of temperature on the wires surface, average about 110%. However, in the axis of the wire differences in the obtained values ??of the temperature existing between the variants were significantly lower and amounted to an average of 13% (Fig. 4). Thus, the main factor determining the increase in the average temperature of the wire is the temperature of the surface layer of wire. It was found that five-fold increase in the drawing speed causes, depending on the total draft, an increase from 12 to 22% of the average temperature of the wires (Fig. 5).

In the drawing process the factor determining the high temperature on the wire surface is the heat caused by friction, which leads to an increase in temperature of the surface layer of the wire. Thus it can be assumed that the thinner the layer of friction material heated, the greater the amount of heat accumulated in the surface layer of the wire. The literature suggests that the temperature distribution in the present layer, a parabolic function of the wire is dependent on its thickness. The thickness of the surface layer of the heated wire was calculated using the formula developed by Tarnavski [11]:

$$b = \sqrt{6 \cdot \frac{l}{v} \cdot \frac{\lambda}{c_w \cdot \rho}} \qquad (1)$$

where:

b – thickness of wire layer heated by friction, cm,

l – the length of the contact surface of the wire and die, cm,

$l = l_z + l_k$

l_z – the length of the contact surface of the wire and die approach, cm

l_k – the length of sizing part of die, cm

λ – thermal conductivity, kcal/cm·s·°C,

v – drawing speed, cm/s,

c_w – specific heat, kcal/kg·°C,

ρ – density of steel, kg/cm^3.

In Fig. 6 shows the changing of the thickness of the wire layer heated by friction as a drawing speed function for the wires drawn with a diameter of 1.85 mm to 1.7 mm.

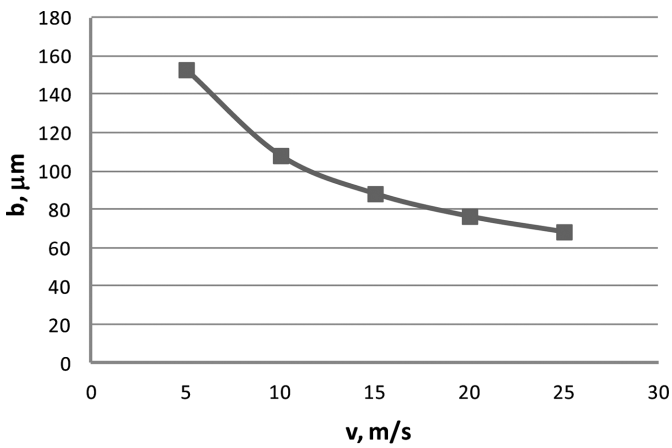

Fig. 6. The changing of the thickness of the wire layer heated by friction as a drawing speed function

In Fig. 6 it follows that with increasing of drawing speed the heated surface layer thickness measured at the exit of the wire from the dies is reduced significantly and at drawing speed of 25 m/s is equal to about 68 μm. The decrease in the thickness of this layer can be explained by a shorter duration of heat transfer to the wire, which causes additional heat accumulation in the wire surface layer. Accordingly, obtained in work such high temperatures on the surface of drawn wires at high speeds seem to be justified. Otherwise, it would mean that a five-fold increase in drawing speed, resulting in five times the amount of heat generated per unit of time, the two further smaller thickness of the material heated by friction, there is no significant effect on the temperature of the wire, which – according to the author – seems to be a controversial statement. In the drawing process both the deformation work and work to overcome friction is converted into heat, which then proceeds to the wire. This results in a temperature increase of the wire, and in particular of the surface layer.

Hence, the greater the amount of heat generated, the higher the temperature of the wire.

The calculations based on the Tarnavski formula confirm the results of computer simulation. In Fig. 7 shows the temperature distribution on the cross section of the φ1.7 mm wire as a function of the radius R (v=25 m/s).

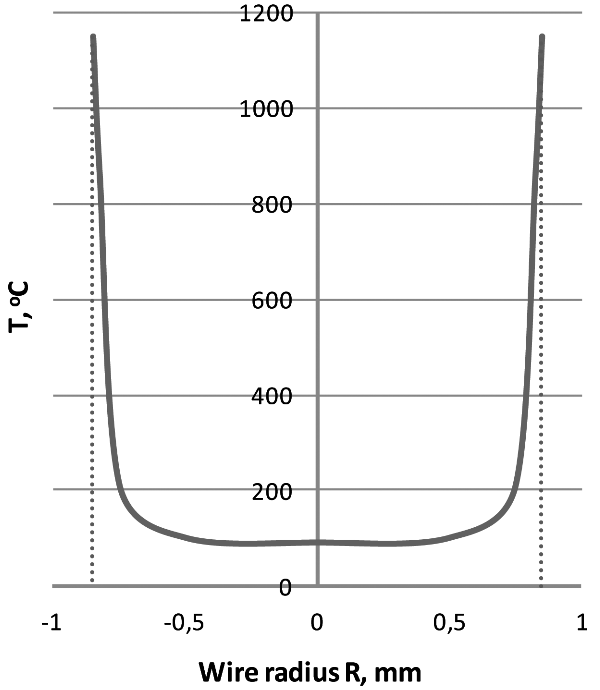

Fig. 7. The temperature distribution on the cross section of the φ1.7 mm wire as a function of the wire radius R (v = 25 m/s)

The temperature distribution presented in Fig. 7 confirms earlier calculation that the wire temperature as high as 1100°C occurs only at the interface of the wire-drawing die, or at most only a small surface layer of wire, of the order of a few micrometers. Due to the large difference in temperature on the surface and the axis of the wire there is a very rapid temperature decrease. The literature suggests that within a hundredth of a second temperature at the surface of the wire is reduced by half its value [11].

According to the author, the cooling process after exit wire from die consists of two stages. In the first stage of cooling is rapid, so-called the discrete decrease of temperature and mainly refers to the surface layer of the wire. After some time, the second stage of cooling, in which there is a gradual equalization the wire temperature throughout its cross-section. It can be assumed that first step of cooling the wire after drawing refers to the inertia time, i.e. the time after which the temperature begins to rise in the axis of the wire. Inertia time can be calculated from the formula [1]:

$$\tau = \frac{1}{8} \cdot \frac{R^2}{a} \tag{2}$$

where:

τ – inertia time, s,

R – wire radius, m,

a – temperature thermal conductivity, m^2/s,

$$a = \frac{\lambda}{c \cdot \rho},$$

λ – thermal conductivity, W/m·K,

c – specific heat, J/kg·K,

ρ – density of steel, kg/m^3.

The conducted calculations show that for the case at the time of inertia is approximately 0.008 s, and the time needed for drawing 1 m wire at v = 25 m/s is 0.04 s. Therefore, after about 20 cm after leaving the wire from the die profile the temperature is already formed and the shape of the parabola, and the cooling rate of each layer depends on the interaction of the wire three heat transfer mechanisms, such as radiation, convection and conduction.

The heat is transferred to the environment by radiation and convection, while the wire by conduction. Wherein the amount of heat received by the environment is much less than the amount of heat lost through the wire and hence the frictional heat, build-up in the outer layer is mainly conducted in the inner layers until the wire, followed by equalization of temperatures.

4. Verification of theoretical research

The theoretical analysis shows that a multistage drawing process at high speeds, there is a short intense heat of the surface layer of the wire to temperatures at which thermal decomposition of the lubricant should be occur. These supposing confirmed the industrial trials of drawing. In Fig. 8 shows partial "carbonization" of the lubricant in the high speeds drawing process.

Fig. 8. Sintered lubricant removed from the exit bell of a die after drawing process at a speed of v = 25 m/s

In the presented above figure shows that in the process multistage drawing at high speeds at the exit of the die is formed sintered lubricant, which on the one hand, confirms the possibility of drawing process at very high temperatures in excess of 1100°C, on the other hand – may suggest that the sizing part of die, in which the wire reaches the highest temperature, the lubricant in the form of a sinter can cause the increase of friction and even lead to an additional "grind" of the wire surface. In consequence it can leads to even greater temperature increase on the surface of the wire.

In order to verify the results of modeling an attempt to estimate the temperature of drawn wires at high speeds. Unfortunately, available in the literature formulas to calculate the wire temperature were developed for the far smaller drawing speed of the order of 1-10 m/s. The Steininger [12] and Krasilshchikov formulas [13] indicate that the surface temperature of the wire at drawing speeds above 20 m/s exceeds 1500°C, which – according to the author – is impossible because it would mean that the surface temperature of the wire is close to the melting point of steel. Therefore, the study attempts to estimate the temperature in the real wire drawing process. The exact determination of the surface temperature of the drawn wire is very difficult to do, as soon as the exit wire a rapid temperature decrease occurs.

At a distance of about 1 m from the die after 0.04 s (v = 25 m/s) the wire is coiling on the drum. Temperature measurement using a pyrometer has shown that the surface temperature of the wire on the entering to the drum does not exceed 170°C (average temperature of a number of coils of wire). Therefore, to be able to estimate the temperature of the wire at the interface between wire and die, the temperature measurement would have to take place immediately at the exit wire from the die.

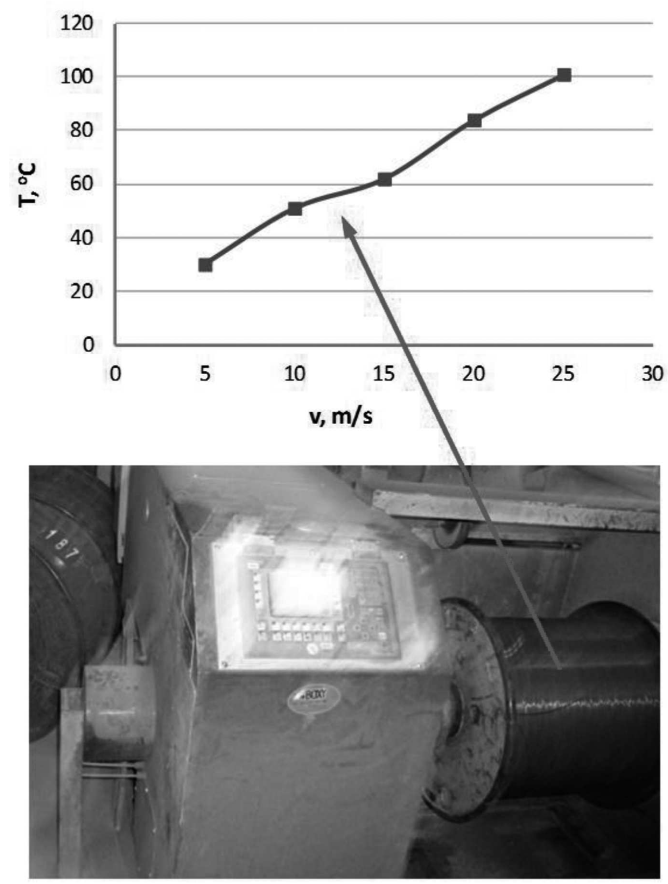

Fig. 9. The influence of drawing speed on wire temperature on the spools

The use of a thermal imaging camera or pyrometer to measure the temperature of the wire surface φ1.7 mm drawn at a speed of 25 m/s (80 km/h) is difficult to implement, since the measurement area (spots) this type of equipment is much larger than 2 mm. Additionally, the wire after exiting die vibrates at a certain frequency, which causes difficulty in determining the measurement base. Hence, in order to check the correctness of the calculation of theoretical work temperature measured bulk spools of wire weighing about 250 kg each. In the multistage wire drawing at the last draft after exiting from the drum, a wire passes through the roller system and then is coiled on a spool. It can be assumed that the measured in this way the temperature is the average temperature wire partially cooled. Defined in this way, the wire temperature using pyrometer gives only a general view on the impact of drawing speed on the final temperature of wires and can be an indicator of quality. However, the measured temperature in this way is subject to the more little error that the individual layers of wire coiled on the spool by conduction dissipates heat outside, which results in a very slow cooling of the wire. The measurement results are shown in Fig. 9.

Data investigation presented in Fig. 9 shows that the increase in drawing speed of 5 to 25 m/s caused an increase in wire temperature of the on spools by over 400%. This can be explained by the fact that with the increase in drawing speed increases the temperature of the wire due to the work of deformation and friction, while reducing the cooling time of wire on the drums. Therefore, when drawing at speed of 25 m/s temperature wire on spools was still about 100°C. Therefore, in high speed multistage wire drawing process installed cooling systems of dies and drums can not keep up with the disposal of such a large amount of heat generated.

5. Conclusion

From the theoretical and experimental tests that have been carried out, the following findings and conclusions are drawn:

1. The analysis of the heating of the wire showed that in the multistage drawing process a increase drawing speed causes intense heating of a thin surface layer of the wire to a temperature exceeding 1100°C, which should be explained by the accumulation of heat due to friction at the interface between wire and die. It has been shown that with increasing of drawing speed the heated surface layer thickness measured at the exit of the wire from the dies is reduced significantly and at drawing speed of 25 m/s is equal to about 68 μm. The decrease in the thickness of this layer can be explained by a shorter time of heat transfer to the wire, which causes additional heat accumulation in the surface layer.
2. The amount of heat generated is proportional to the drawing speed. At high drawing speeds, the order of 25 m/s, the temperature of the surface layer of the wire is increased to the range of temperatures at which thermal decomposition of the lubricant occurs and at the exit of the die sintered lubricant is formed. The sizing part of the die, in which the wire reaches the highest temperature, the lubricant in the form of a sinter can cause the increase of friction and even lead to an additional ”grind” of the wire surface.
3. It was stated that the time of the appearance of high temperature on the wire surface is very short. The conducted calculations have shown that a distance of about 20 cm from the die, the wire temperature profile is already formed and the shape of the parabola, and the cooling rate of each layer depends on the interaction of the wire three heat transfer mechanisms, such as radiation, convection and conduction. The rapid decrease of temperature in the surface layer of wire is also confirmed by experimental

studies, which show that the surface temperature of the incoming wire on the drum does not exceed 170°C (average temperature of several coils of wire).

4. Experimental investigation showed that the increase in drawing speed of 5 to 25 m/s caused an increase in wire temperature of the on spools by over 400%. For the wires drawn at speed of 25 m/s temperature wire on spools was still about 100°C. Therefore, in high speed multistage wire drawing process installed cooling systems of dies and drums can not keep up with the disposal of such a large amount of heat generated.
5. The obtained data of investigations can be applied in wire industry while implementing the new technologies of manufactures of high carbon steel wires.

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