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SIMULATION AND MEASUREMENT OF TEMPERATURE IN HIGH SPEED DRAWING PROCESS OF STEEL WIRES

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Abstract

Theoretical and experimental investigations of steel wire heating up and cooling down in the high-speed drawing process have been carried out in the study. The theoretical investigation encompassed simulations of the drawing process using the Forge2011® program, in which the temperature distributions at the wire exit from the die and the temperature of wire after being wound onto the drum were determined. To verify the obtained theoretical investigation results, the experimental measurement of the temperature of wires on the drum and on the storage reel was carried out in industrial conditions. It has been demonstrated that intensive and short-duration heating of a thin, approximately 50μm-thick wire subsurface layer up to temperatures not exceeding 1000°C occurs in the high-speed drawing process. By contrast, immediately after wire exit from the die, intensive cooling of the wire over a length of about 0.2 m down to a temperature of below 200°C takes place.

Key words: wire, drawing, temperature measurement, numerical modelling, FEM

1. INTRODUCTION

The temperature of wire in the process of drawing significantly influences the lubrication conditions, the life of the dies and the properties of the drawn products (El-Domiaty & Kassat, 1998; Damm, 2011; Roger, 1997). In the multi-stage drawing process, intensive heating of the top wire layer occurs, with the temperature of that layer being dependent on the drawing speed (Suliga, 2013). The data reported in work (Suliga, 2014) indicates that the fivefold increase in drawing speed results in about a twofold decrease in the thickness of the top wire layer heated up by friction action. This, in turn, causes a temperature increase in the top wire layer, shortens the drum wire cooling duration compared to drawing at lower speeds, and raises the initial wire temperature in the next draw. The temperature increase impairs also the lubrication conditions, which may affect the temperature distribution in the wire.

In view of the above, when designing a new technology for high-speed multi-stage drawing, it is essential to define the wire temperature in the drawing process. Thus, the aim of this study was to determine the distribution of temperature in the wire based on the numerical computations of the heating of steel wire in the last draw and then its cooling in receiving devices. Theoretical studies were performed using the Forge2011® computer program, while the verification of the results was made in one of the state-of-the-art steel wire drawing mills based on the measurements of the temperature of wires on the drum and on the storage reel, respectively.

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2. THE THEORETICAL ANALYSIS OF WIRE DRAWING PROCESS

Mathematical modelling of the high-speed wire drawing process was carried out using the Forge2011® software program, that uses a mathematical model in which the mechanical state of the deformed material is described by the Norton-Hoff law (Norton, 1929; Hoff, 1954).

Temperature changes for finished 1.7 mm-diameter wire were analyzed in the study. The drawing process was conducted in 12 draws. The study limited itself to the analysis of the last draw, in which drawing speed is the highest, and therefore also its effect on wire temperature is most important. Simulation of the drawing process was carried out for pre-hardened wire with the plastic properties of steel C75; the rheological properties were taken from the material database of the program used. Strain intensity values were entered to the simulation in a tabular form using data obtained from simulations of 11 draws, performed with the use of the Drawing 2D program (Milenin, 2005). Data on the drawing of wire from the diameter of 5.5 mm to the diameter of 1.85 were taken from the work by Suliga (Suliga, 2013).

It was assumed that the process of drawing wire of a diameter of 1.85 mm to a diameter of 1.7 mm occurred in conventional drawing dies with an inclination angle of $2\alpha = 12°$, at a drawing speed of $v = 25$ m/s. The following input data were taken for the theoretical analysis of the drawing process: wire temperature and tool and ambient temperature – 20°C; emissivity = 0.8; friction coefficient – $\mu = 0.11$; coefficient of heat exchange between the material and the tool – $\alpha = 5000$ W/(K·m^2); coefficient of heat exchange between the material and the *air* – α_{air}=400 W/(K·m^2). To shorten the computation time, the ¼ of the wire cross-section was modelled. Whereas, due to the fact of the highest temperature increase in surface wire areas, the finite element grid was densified in that region.

Figures 1 and 2 show the results of the simulation of drawing wires from the diameter 1.85 mm to the diameter 1.7 mm. The distribution of temperature on the longitudinal wire section at the material exit from the sizing die portion is included in the diagrams under examination.

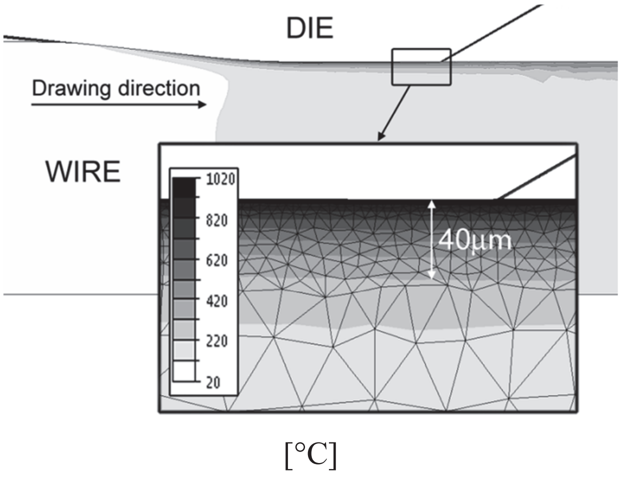

Fig. 1. *Temperature distribution in wire drawn from the diameter 1.85 mm to the diameter 1.7 mm*

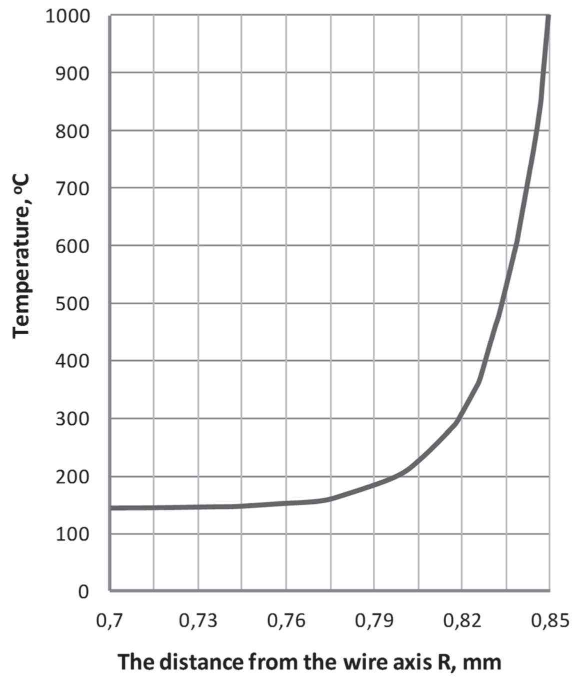

Fig. 2. *Temperature distribution on the cross-section of ϕ1.7 mm-diameter wire (in the plane of material exit from the sizing die portion)*

From the theoretical study results, intensive heating of the top layer of wires drawn at high speeds can be observed. At a friction coefficient of $\mu = 0.11$ and a drawing speed of 25 m/s, the wire temperature at the die exit was approx. 1000ºC. The simulation results have shown that, in the drawing process, wire heating only occurs in a thin, approx. 40 µm-thick, surface wire layer, and the distribution of temperature on the wire cross-section is a parabolic function.

The data in figure 1 indicates that the wire temperature increase along the die contact length, therefore gradual worsening of lubrication conditions can be presumed. While in the initial deformation phase the lubrication conditions are very good, already at wire entry to the sizing die portion the high wire temperature of above 700ºC should cause a considerable impairment of lubrication conditions and lubricant evaporation. It can be concluded, therefore, that drawing wires at high speeds causes an increase in friction coefficient in the die sizing portion, which might considerably exceed the value of 0.1 In drawing at high speeds of around 25 m/s under unfavourable conditions, i.e. in the conditions of dry friction caused by a partial loss of the lubricating properties and evaporation of the lubricant in the die sizing portion, a rapid wear of the dies takes place. The operational life of dies at high temperatures is very short, and the wire drawing process become practically impossible to accomplish. Thus, the speed of drawing high-carbon steel wires in industrial practice does not usually exceed 20 m/s, in spite of the fact that multi-stage drawing machines available in the market allow drawing at speeds as high as above 40 m/s.

The obtained theoretical study results have also confirmed that, in the drawing process, a very fast cooling of the top wire surface occurs immediately after the wire exit from the die (figure 3). At a distance of about 4 mm from the plane of wire exit from the die, the wire surface temperature drops by more than 500°C, causing at the same time a temperature increase in wire sub-surface layers, which can be explained by thermal conduction.

Figure 3 shows that over a length of approx. 0.5 mm after wire exit from the die, the wire temperature drops by over 50%. Whereas, at a distance of about 1 mm from the die, the wire cooling curve assumes a linear shape, that is the decrease of wire temperature on the wire surface is proportional to the cooling time.

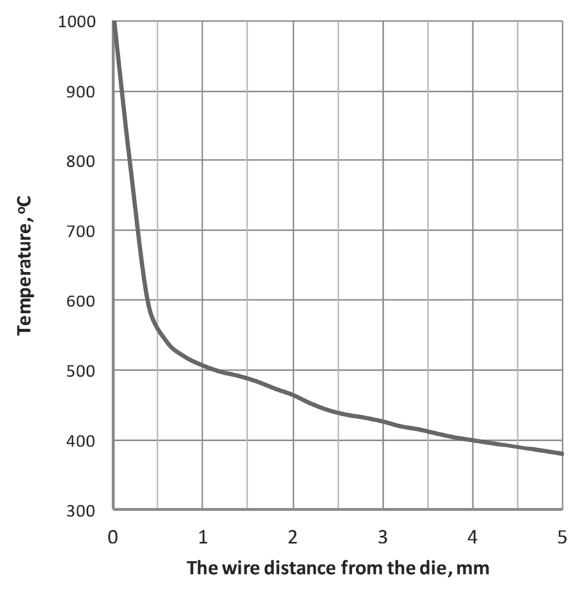

Fig. 3. *Variation in wire surface temperature upon wire exit from the die*

To make a detailed analysis of temperature variations at characteristic points on the drawn wire, 3 sensors were installed in the stock material (figure 4). As characteristic points for the wire drawing process, at which the largest temperature changes can be observed, three points were singled out. Sensors 1 and 3 were placed on the stock perimeter, with sensor 3 being positioned at the wire and drum contact location, while sensor 2, in the stock axis.

The scheme of wire cooling after the last draw adopted in numerical modelling, allowing for wire winding onto the drum and then the reel (figure 5), was based on the technical parameters of a typical steel wire production line (a KGT 12/25 Koch drawing machine), which was subsequently used for the verification of the numerical simulation results. In the multi-stage drawing process, after exiting the die, the wire is wound onto a drum, while the quantity of wire on the drum ranges from 10 to 40 coils, depending on the drawing technology. Then the wire is drawn in the next draw. After leaving the last drum, on which intensive wire cooling takes place, the wire passes through a system of rollers and then is wound onto a storage reel. The storage reel allows up to 1000 kg of wire to be wound on it. The last stage of wire cooling involves gradual cooling the wire down to ambient temperature, with the duration of this cooling being dependent on the initial temperature and the reel mass.

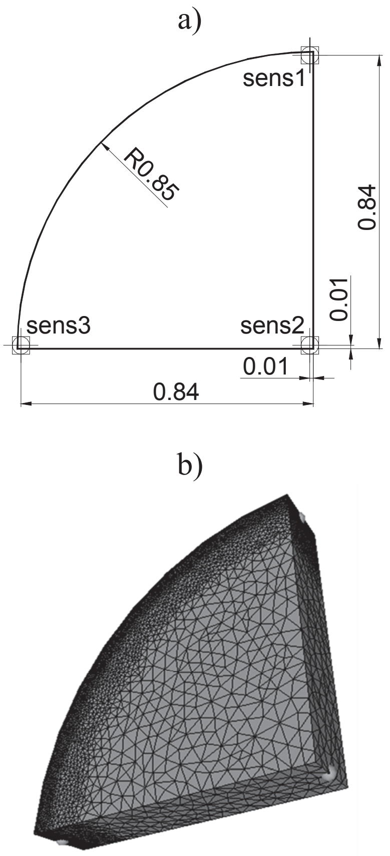

Fig. 4. Positions of sensors inside of ¼ symmetrical wire: a) shape and dimensions, b) mesh of ¼ wire

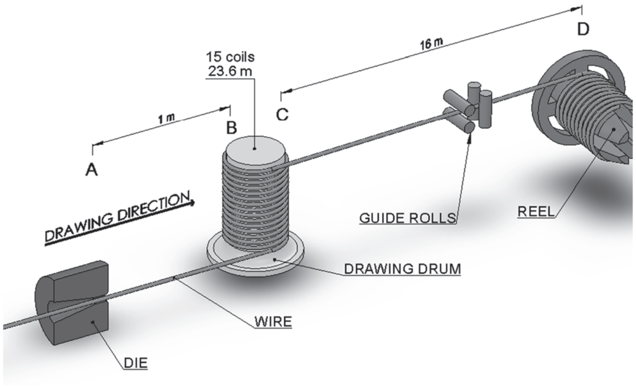

Fig. 5. Scheme of drawing process with marking the A-D cross-sections on a length of drawing line

The obtained computation results for the distribution of wire temperature at individual cooling stages (stage A-D) are shown in figure 6. Figure 7, on the other hand, represents the variation of temperature at characteristic points as a function of wire distance from the die exit plane. The distances between individual cooling stages, given in this paper, are close to the actual dimensions of the new generation of high-carbon steel wire production lines. In drawing at high speeds at the last drawing stage, due to technical reasons, the quantity of wire on the drawing machine's drum is limited. Thus, computations for 15 wire coils were made in the computer simulations.

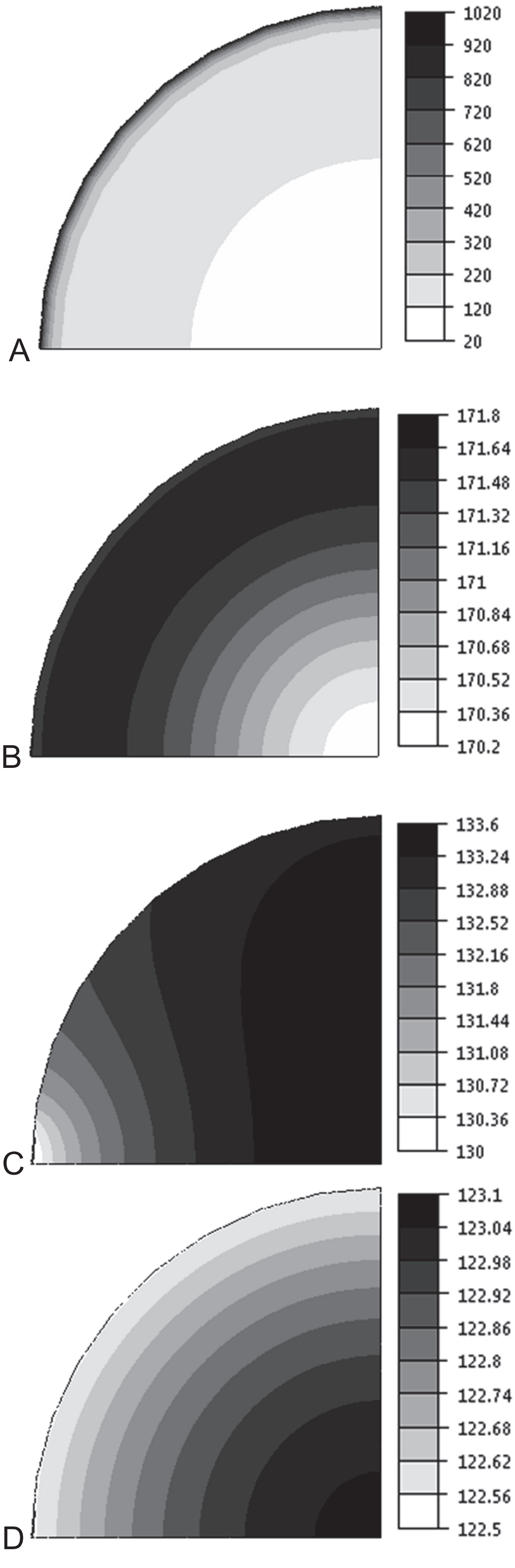

Fig. 6. Distributions of temperature on the cross-section of wire after drawing, °C

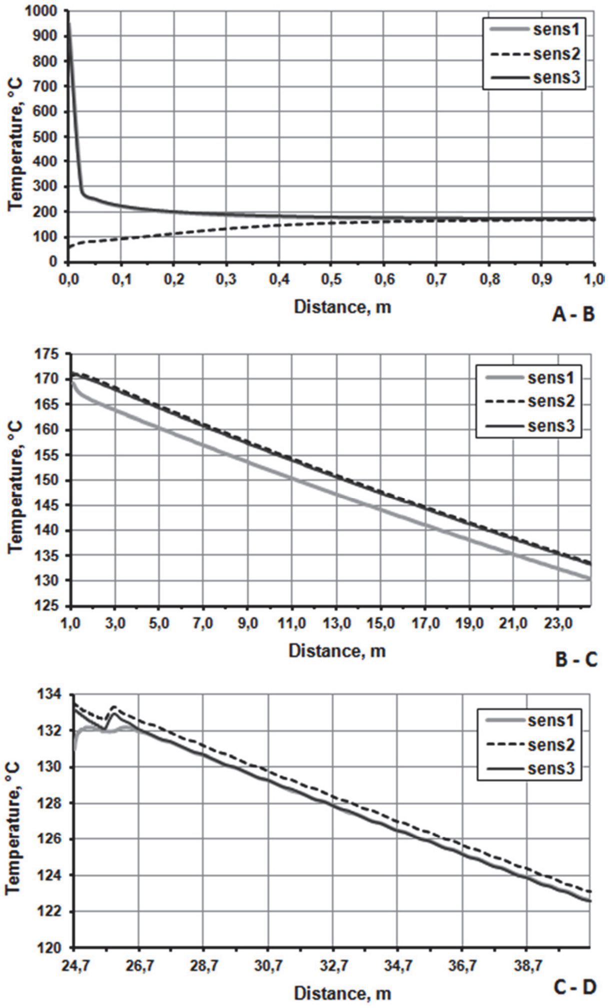

Fig. 7. *Variation of temperature in wire (in 3 characteristic points) after drawing process on 40.6 m distance*

The data represented in figure 7 shows that after the drawing process upon wire exit from the die, intensive cooling of wire sub-surface layers occurs over the entire wire perimeter. At a distance of about 1 m from the die (segment A-B), the equalization of wire temperature on the wire cross-section takes place.

At the next cooling stage, the wire is wound onto the drum. To increase the amount of heat taken away, drawing machine drums are water cooled from the inside. This considerably increases the rate of heat removal on the wire and drum contact surface. As this contact does not hold on the entire surface, an uneven distribution of temperature over the wire perimeter can be noticed, which is confirmed by sensors 1 and 2 positioned on segment B-C.

In the third cooling stage, after the wire has exited the drum (segment C-D), a fast equalization of temperature over the wire perimeter follows. This phenomena is accompanied by the top wire layers gradually giving up heat to the environment. Thus, the wire axis temperature, as compared to the wire surface temperature, is higher by about 4ºC.

The too short time of wire residence on the drum causes the wire to be only partially cooled down to a temperature of approx. 133ºC, therefore the temperature of the wire coming onto the storage reel still exceeded 120ºC. Winding a large mass of wire (even up to 1000 kg) at a temperature not exceeding 100ºC onto the storage reel causes the wire to cool down very slowly, even for up to 60 minutes. In the authors' view, prolonged holding wire at a temperature of 100ºC might initiate the wire ageing phenomenon, which contributes of a worsening of the mechanical and engineering properties of the wire.

3. THE MEASUREMENT OF WIRE TEMPERATURE UNDER INDUSTRIAL CONDITIONS

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

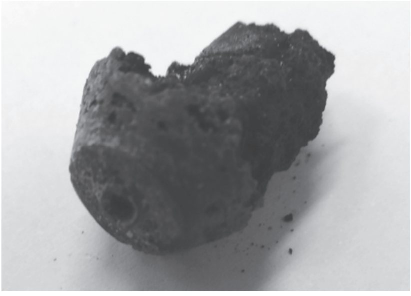

Fig. 8. *Sintered lubricant removed from the exit cone of a die after drawing process at a speed of 25 m/s*

In order to verify the results of theoretical investigations the wire temperature measurement in industrial conditions was conducted.

In the actual drawing process, there is practically no possibility of measuring the wire temperature in the die; therefore, to verify the numerical computation results, the measurements of wire temperature, respectively, on the drum and on the reel were taken. The measurement itself of 1.7 mm-diameter wire is very difficult, too; whereas, the drum and the reel, where we have several wire coils available, make this measurement easier. The results are shown in figure 9.

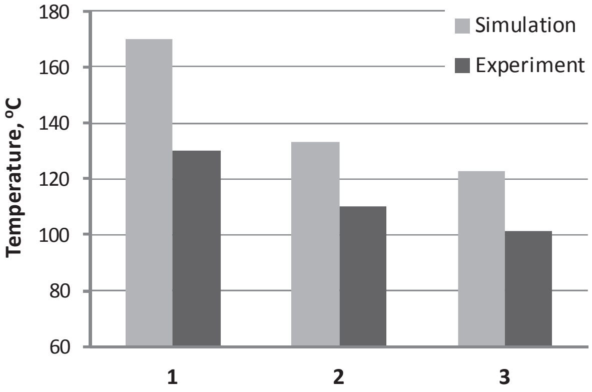

Fig. 9. *Wire temperature, where: 1 – wire entering the drum, 2 – wire exiting the drum, 3 – wire on the reel*

By comparing the temperature values obtained from numerical computations and from experimental tests it can be found that the differences between those results are contained in the range from 17 to 23%, depending on the measurement location. In the experimental tests, the wire temperature was measured with a pyrometer, which only allows the estimation of the average wire temperature of several coils, i.e. the coil coming onto the drum and the coils of partially cooled wire. Thus, the actual temperature of the wire surface at individual cooling stages may be higher than the measured temperature. The data in figure 9 has also confirmed that in the high-speed steel wire drawing process, the installed cooling systems do not cope with removing such a large amount of heat. Therefore, after drawing, the temperature of wire on the storage reel can reach 100ºC, which will contribute to a worsening of the mechanical and engineering properties of the wire.

4. CONCLUSIONS

From the theoretical and experimental investigations carried out it can be found that:

1. Drawing steel wires at high speeds causes intensive, though short-lasting heating of a thin, approx. 50 μm-thick wire layer in the die up to temperatures exceeding 1000ºC and then, immediately after the drawing process, its intensive cooling down to a temperature below 200ºC along a wire length of about 0.2 m.
2. After an abrupt drop in wire sub-surface layer temperature, lasting only about 0.04 s, much less intensive wire cooling follows; however, the temperature of wire wound onto the storage reel after individual cooling stages still exceeds 100ºC.
3. The industrial trials confirmed that high speed multipass drawing process causes a short intense heating of the surface layer of the wire to temperatures at which thermal decomposition of the lubricant should be observed. The appearance of sintered lubricant at the exit wire from the die, called in wire industry plug, creates the conditions in which dry friction occur.

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SYMULACJA I POMIAR TEMPERATURY W PROCESIE CIĄGNIENIA DRUTÓW STALOWYCH Z DUŻYMI PRĘDKOŚCIAMI

Streszczenie

W pracy przeprowadzono badania teoretyczno-doświadczalne nagrzewania i chłodzenia się drutu stalowego w procesie ciągnienia z dużymi prędkościami. Badania teoretyczne obejmowały symulacje procesu ciągnienia za pomocą programu Forge2011®, w których wyznaczono rozkłady temperatury na wyjściu drutu z ciągadła oraz określono temperaturę drutu po nawinięciu na bęben. W celu weryfikacji uzyskanych wyników badań teoretycznych przeprowadzono w warunkach przemysłowych eksperymentalny pomiar temperatury drutów na bębnie oraz na szpuli zbiorczej. Wykazano, że w procesie ciągnienia z dużymi prędkościami w ciągadle występuje intensywne i krótkotrwałe nagrzewanie się cienkiej, przypowierzchniowej ok. 50 µm warstwy drutu do temperatur przekraczających 1000°C. Natomiast bezpośrednio po wyjściu drutu z ciągadła na odcinku około 0,2 m następuje intensywne chłodzenie drutu do temperatury poniżej 200°C.

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