Conference Proceedings for the 83rd Annual Convention of the Wire Association International

Temperatures in the wiredrawing process—measurements and simulations

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Abstract:
Temperatures are important in the wiredrawing process, and measurements are very tricky. Simulations show very high temperatures in the contact between wire and die. For this study, thermocouples were welded to the nibs, a very sensitive arrangement in a wiredrawing plant. This paper reports and analyzes measurements of nib temperatures and compares them with FEM simulations. The wire cooling on blocks was measured by pyrometers. These measurements are sensitive to the wire brightness especially for stainless wire.

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Temperatures in the Wire-Drawing Process - Measurements and Simulations

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Introduction

Temperatures are important in the wire-drawing process. The material properties may be deteriorated by a too high wire temperature. The temperature in the drawing die will affect the lubricant and thus the wire drawing process. In 1942 Siebel and Kobitzsch [1] presented an analytical model of the temperature in the contact zone. The wire was assumed to absorb 80 % of the friction heat. The friction also introduces a temperature gradient in the wire. This model was used by Wright [2] and compared with FEM-simulations by Jarl and Överstam [3].

Wire temperatures after equalization may be measured by pyrometers or by contact thermocouples. A direct temperature measurement of the temperature in the contact between wire and die is complicated and a common way is to use simulations to study the temperatures. Nilsson [4] tried to use the wire and the die as a thermocouple. He studied a wire running at 15 m/s in a water emulsion lubricant. His measurements indicated a temperature of about 500 °C in the contact between wire and die.

An overview of wire cooling is given in the handbook “Ferrous Wire” [5]. Most of the energy supplied to the drawing machines motors is transformed to heat in the wire. The wire should be cooled on a block and the cooling power approximately equivalent to the supplied motor power. If this fails the wire temperature will rise. Accumulation of heat, from block to block, may give problems at the end of a continuous drawing machine. The wire may be affected of dynamic strain ageing and the lubricant may heat in the box and form lumps. Cooling systems are of different design. An old design is to let water flow through a pipe to the inner wall of the block. During a period, systems with direct water cooling of the wire were investigated. These systems were used to reduce the wire temperature before entering the block. Papers were published by e. g. Nakamura et al. [6] and Pawelski and Keuper [7]. The “V-track” machine was also designed with direct water cooling of the wire. This machine had a V-groove on the block with direct water cooling [8]. Another method which has been tried is evaporative mist cooling [9]. The idea is that a mist of water is sprayed on the wire and evaporated. Sturgeon and Guy discussed different methods to increase the cooling. Direct water cooling of the wire was deleterious to lubrication and force air cooling gave rise to dust problems. They presented the improved block cooling with a “narrow gap” [5].

Temperature measurements

Temperature measurements in wire drawing are very tricky. Measurements with riding thermocouples have been tried [10]. See Figure 1.

Figure 1. Riding thermocouples

The riding thermocouples were affected by triboelectricity. Changes in speed and lubrication affected the temperature signals. Figure 2 shows an example of temperature signal when the lubrication is deteriorated. This method of temperature measurement was not considered reliable.

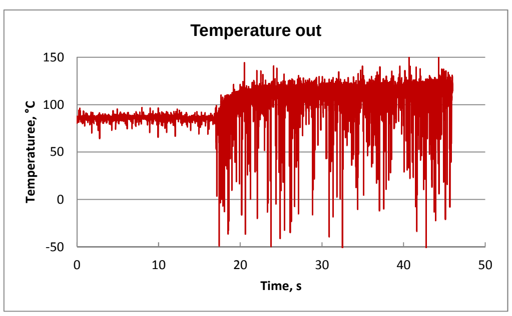

Figure 2. Unfiltered wire temperature signal after drawing die. At 15 seconds the wire was humidified before the die, 2nd draw.

Pyrometers were also used for measurements of wire temperatures. The pyrometers used in this work were Optiris CT from Sensotes, with a measuring angle of 1:22. The pyrometers were about 200 mm from the wire on the blocks. The temperature signals were affected by the brightness of the wire. Sensotet [11] gives the theory for pyrometers: if all radiation energy from a black body is absorbed by a pyrometer the signal shall follow Equation 1.

$$U \sim T^4 \qquad [1]$$

If the emission coefficient is lower than 1, reflected radiation shall be included. Additionally the pyrometer emits radiation. For measurement of opaque objects Equation 2 is valid.

$$U = C[\varepsilon T_{Obj}{}^4 + (1-\varepsilon)T_{Sur}{}^4 - T_{Pyr}{}^4] \qquad [2]$$

U is the pyrometer signal, C a constant for the equipment, ε the emission coefficient, T_{Obj} the measured object's temperature, T_{Sur} the temperature in the surrounding, T_{Pyr} the pyrometer's temperature. All temperatures are in Kelvin. But a pyrometer absorbs radiation only in a limited range; the pyrometers used had a range of 8-14 μm. This may change the exponent in the equations, according to the supplier the exponents may vary between 2 to 17. A simple assumption is that the absorption is constant over the wavelength range 8-14μm. A calculation showed that an exponent of 4 was a good approximation up to a temperature of 150°C. However, the absorption may vary over the wavelengths and, thus, the exponent is uncertain.

In the first measurements the emission coefficient was adjusted to one and the compensation was carried out afterwards by the following procedure: Wire specimens were cut out from each block. Short specimens were arranged side by side and held together by clamps. This arrangement was heated to 100 °C in an oven. The hatch was opened and the temperature was measured by the pyrometer. The recorded temperature was extrapolated to zero time. The emission coefficient was calculated and used to adjust the temperature measurements. In the following trials the measurements on the specimens were repeated with different settings of the pyrometer's emission coefficient and the emission coefficient was found by interpolation. This value was then used as setting in the measurement in the plant. A carbon steel wire had a quite stable emission coefficient in the machine. 0.75 was used. But stainless steel wires had values starting with about the same value as carbon steel but reduced to about 0.5 on the last block.

Nib temperatures were measured with thermocouple wires soldered or welded to the nib. This arrangement is very sensitive in a wire drawing plant and many thermocouples were broken at the assembly of the dies in the machine. The soldered thermocouple wires were more sensitive than the spot-welded. The durability increased when the spot-welds were fixed by heat proof epoxy glue.

Die cooling was measured by a flow meter and two Pt100 sensors.

Block temperatures

The block temperatures were measured on three machines.

Machine 1

The first machine studied was an eight block tuner line machine used for drawing of stainless steel wire. The temperatures were measured on three spots on the block. The block cooling system was a variant of a narrow gap design. In the narrow gap an inclined wiper forces the water downwards. Behind the wiper, water is fed into the gap on three levels.

Temperature measurements were carried out on three levels on the block. Figure 3 shows temperatures at the drawing speed 4 m/s.

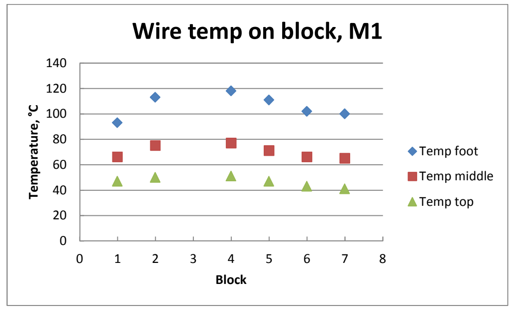

Figure 3. Wire temperature on blocks, 4 m/s. Machine 1.

The wire temperatures are actually decreasing after draw 4. Temperatures are, thus, under control and heat is not accumulating. Measurements on block 7 with increasing drawing speed gave the results according to Figure 4.

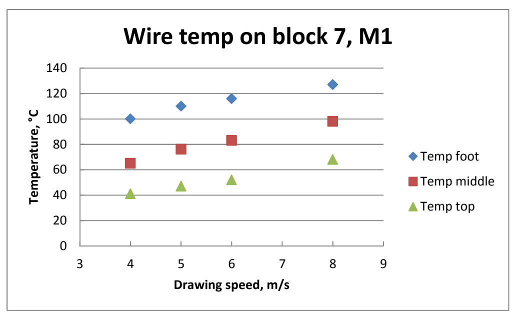

Figure 4. Wire temperatures on block 7 at different drawing speeds. Machine 1.

The temperatures increase when the speed increases. This indicates that higher speeds result in accumulation of heat. The heat transfer coefficients from wire to water are given in Figure 5.

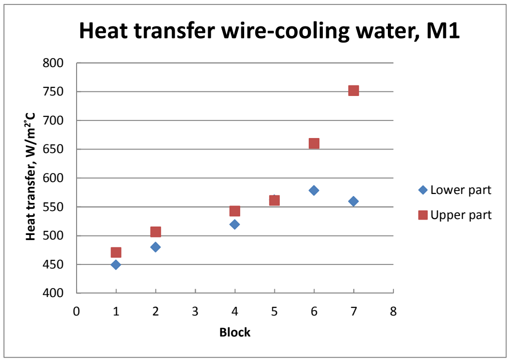

Figure 5. Heat transfer coefficients from wire to water on the upper and lower part of the blocks. Machine 1.

On the first five blocks, the heat transfer coefficients from wire to water seems to be the same on the upper and lower part of the blocks. On block 7, however, the heat transfer coefficients from wire to water are much higher on the upper part of the block.

Machine 2

The second machine was a nine block tuner-line machine used for drawing of high carbon steel wire. The block cooling system is designed as blocks with double mantles. The water is fed in four locations on the top of the blocks and the out flows are in the bottom. The drawing speed was 9 m/s. The temperatures measured on the block 3-6 are given in Figure 6.

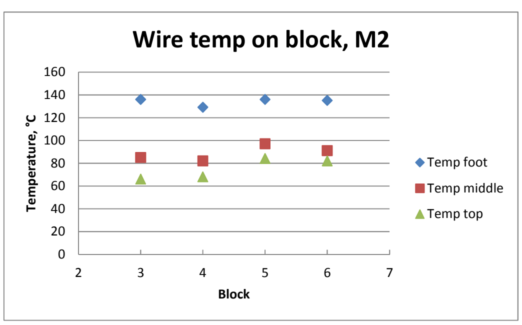

Figure 6. Wire temperature on blocks 3-6, 9 m/s. Machine 2.

The temperatures are rather stable in the machine. The heat transfer coefficients from wire to water are given in Figure 7.

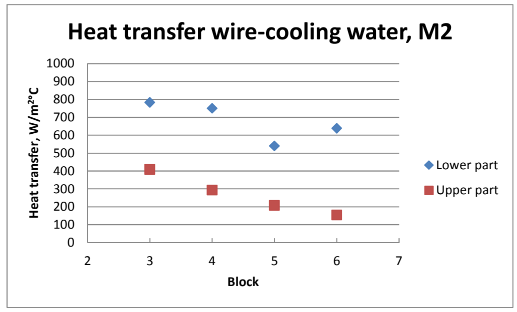

Figure 7. Heat transfer coefficients from wire to water on the upper and lower parts of the blocks 3-6, Machine 2.

The heat transfer coefficients from wire to water decreases with block number, especially on the top part of the machine.

Machine 3

The third machine was an old back-pull drawing machine used for drawing of low carbon steel with five draws. The blocks were low compared to the other machines. The amount of wire on the blocks was too low for measurements with three pyrometers. Two pyrometers were used; they were aimed at the lower and upper part of the block. The measurements at a drawing speed of 4.4 m/s are given in Figure 8.

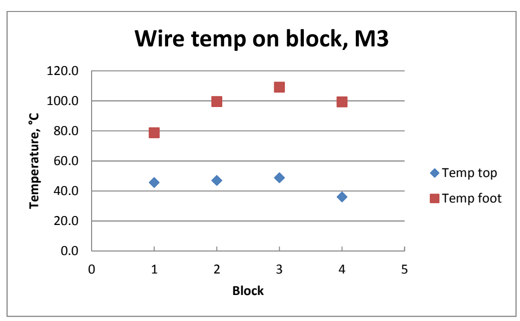

Figure 8. Temperature measured on the blocks. Back-pull machine, carbon steel wire. Machine 3.

The heat transfer coefficients from wire to water are given in Figure 9.

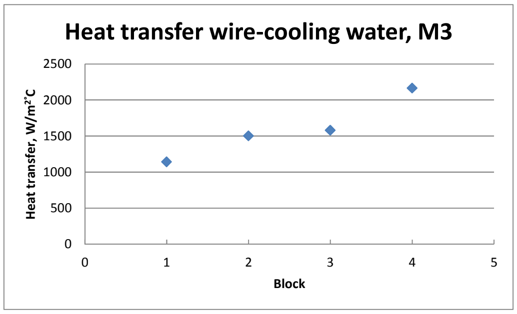

Figure 9. Heat transfer coefficients from wire to water on the upper and lower parts of the blocks 1-4, Machine 3.

The heat transfer coefficients from wire to water were higher in the old machine with a very simple block cooling system. The reason is probably the back-pull control of the wire. This system will force the wire against the block yielding higher heat flow to the block. An interesting observation is that the heat transfer coefficient is increasing with the block number. An evaluation of heat transfer per wire turn on the block is given in Figure 10.

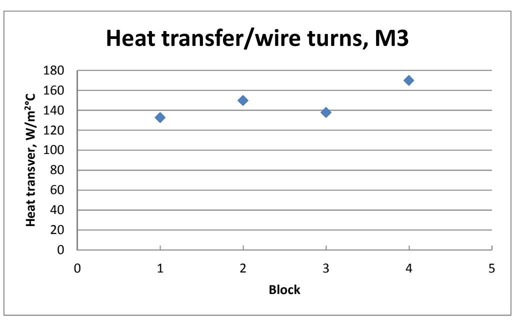

Figure 10. Heat transfer per wire turn on the block. Machine 3.

Heat transfer per wire turn is almost constant. As the length of wire per turn is constant, the heat transfer per wire length is constant.

Nib temperatures

Machine 1

Nib temperatures were measured on the first machine used for stainless steel wire. The machine was designed with indirect cooling of the dies. Figure 11shows the measured temperatures. Measurements were carried out at different drawing speeds.

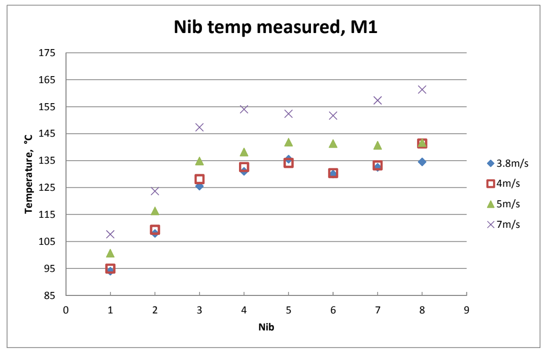

Figure 11. Measured nib temperatures, indirect cooling. Machine 1.

Simulations of the temperatures were done with FEM program Marc Mentat. Figure 12 shows the results at a drawing speed of 5 m/s.

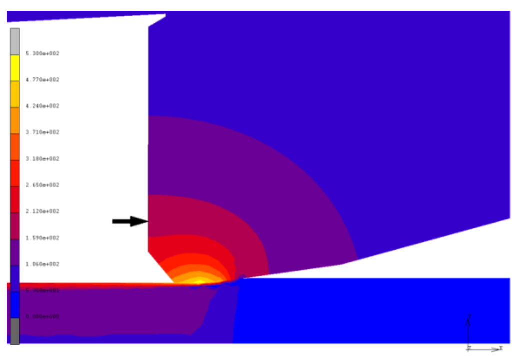

Figure 12. Simulated nib temperatures. Machine 1; drawing speed 5 m/s, nib 8. Arrow marking measurement spot. Max temperature 530°C.

Figure 13 gives the measured and simulated temperatures for machine. The simulations and measurements agree well in the beginning of the machine, but the simulated temperatures are higher compared to the measurements in draw 6-8.

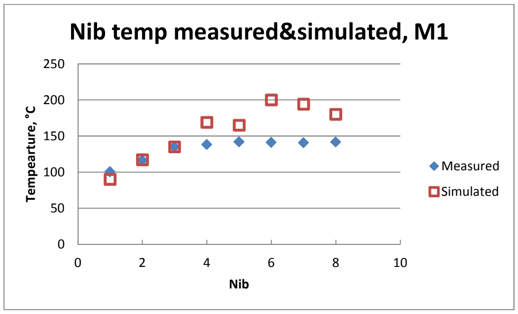

Figure 13. Comparation between simulations and measurements at a drawing speed of 5 m/s. Machine 1.

The maximum temperatures in simulations of drawing speeds 4 and 5 m/s are shown in Figure 14.

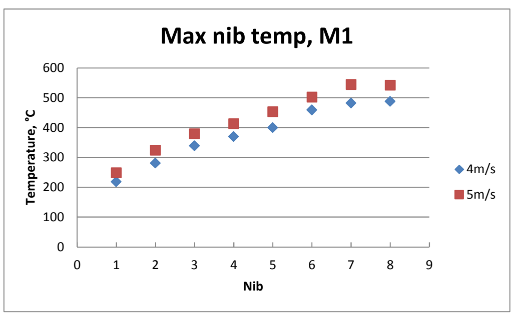

Figure 14. Simulations of maximum temperature in the drawing die at drawing speeds 4 and 5 m/s. Machine 1.

Machine 4

The nib temperatures were also measured on another machine used for stainless steel. This machine had direct cooling of dies. The wire was reduced in 9 draws. The two last draws were made in PCD dies and no measurements were carried out on them. Figure 15 gives the results of nib temperature measurements.

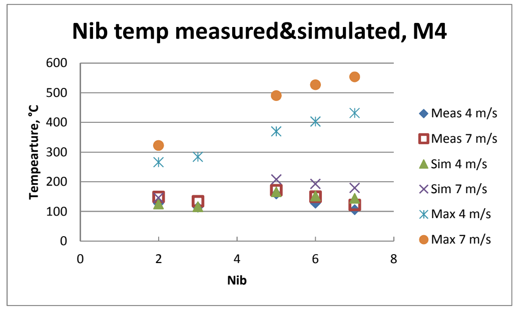

Figure 15. Measured and simulated nib temperatures. Maximum temperatures are from simulations. Machine 4, direct cooling

Figure 15 also include simulated nibs temperatures and simulated maximum temperatures in the nibs. The measurements and simulations gave similar temperatures. The maximum temperatures in the nibs are high, and they increase with drawing speed.

Measurements of die cooling

The die cooling power was measured. These measurements were compared with calculations of the drawing power calculated by the equation given by Siebel [12]. The die cooling powers in Machine 1, (indirect cooling) were measured to 200-250 W at a drawing speed of 4 m/s. The die cooling powers in Machine 4 (direct cooling) were measured to 80 to 150 W. Figure 16 shows the cooling power as part of the calculated power for drawing.

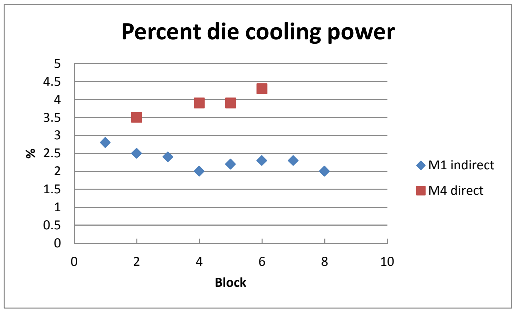

Figure 16. Die cooling power as percent of calculated drawing power. Drawing speed 4 m/s.

Discussion

The measurements of wire temperatures on the blocks gave a surprising result. An old machine with a simple soaking of the block's inside was more efficient compared to modern machines with more advanced block cooling. The amount of wire on the blocks was considerably less on the old machine, but the cooling was sufficient. The reason is most likely that the contact between wire and block was tighter in the back-pull machine. The heat transfer coefficient, α, from wire to water have three parts: heat transfer wire to block, α_W, heat conduction through the block, λ_B, and heat transfer from block to water, α_{Water} . At planar heat transfer and serial coupling, the total heat transfer coefficient may be calculated by Equation 3

$$\frac{1}{\alpha} = \frac{1}{\alpha_{Wire}} + \frac{\delta_B}{\lambda_B} + \frac{1}{\alpha_{Water}} \qquad [3]$$

Where δ_B is the block thickness.

Heat transfer coefficients between wire and block were calculated with block thickness δ_B 25 mm, heat conduction λ_B 42 W/m°C and a three different heat transfer coefficient between block and water α_{Water};1000, 2000 and 4000 W/m^2°C. The results see Figure 17.

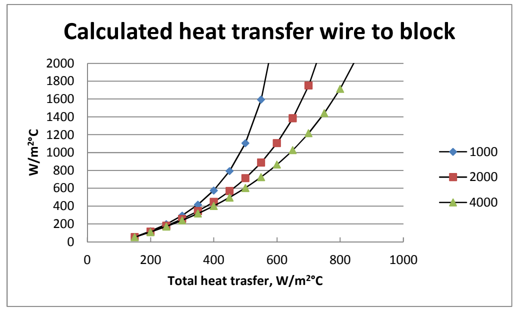

Figure 17. Calculated heat transfer coefficient wire to block with three different heat transfer coefficients block to water, α_{Water}. Block thickness 25 mm. The heat transfer values turn negative at 627 (α_{Water} 1000), 913 (α_{Water} 2000), and 1183 (α_{Water} 4000) respectively.

The equation 3 will turn negative at high total heat transfer coefficients. The results from machine 3 with back-pull (α >1000 W/m^2°C) are, thus, not valid. The reason is probably that the height of wire on the block was only 50 mm. (The distance between the pyrometers only 40 mm.) The assumption of planar heat transfer is, thus, not valid and three-dimensional effects are not negligible. Machine 2 had a low heat transfer on the top part on the blocks. This indicates that the wire windings are loose at the top of the block. Machine 1 had the same heat transfer at the foot and top on the first 5 blocks. The two last blocks had a higher heat transfer on the top of the blocks. The explanation may be: If the wire windings are tighter on the top of the two last blocks compared to the other blocks, the three-dimensional effect may increase the cooling on the top of the two last blocks.

Nib temperatures increase with the drawing speed. Simulations are in most cases in reasonable agreement with the measurements. The maximum temperatures in the nib are so high that the mechanical properties of the cemented carbide may be affected.

Wistreich [13] give the part of the drawing power cooled away in the die cooling to 7% at 1 m/s, 3% at 5 m/s and 1% at 25 m/s. The measured values are in good agreement with Wistreich's statement.

Acknowledgement

This work was founded by The Knowledge Foundation. The experimental work was done at the participating companies; FNsteel Hjulsbro AB, Hörle Wire AB, Fagersta Stainless AB and AB Sandvik Materials Technology. All support is greatly acknowledged.

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