Monitoring and evaluation of the wire drawing process using thermal imaging

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Abstract

Wire drawing is a cold work metal forming process which is dependant of a functional lubrication process. If the lubrication fails, there is a risk that both the tools and the produced wire will be damaged. Process monitoring of wire drawing is rare in today's industry since there are no commercialised methods that deliver consistent results. In this paper, a method for monitoring of the wire drawing process is proposed and evaluated. A thermal imaging camera was used for acquiring thermal images of the wire as it leaves the drawing tool. It was found that the proposed method could capture changes in the wire drawing process and had correlation to the drawing force. An equation for estimating the friction condition between the wire and the drawing die using the wire temperature was also proposed and evaluated against experiments. The results showed that the new equation produced results that correlated well to results obtained using a conventional equation that use drawing force.

Keywords Wire drawing · Thermal imaging camera · Process monitoring

1 Introduction

Wire drawing is a metal forming process where warm rolled wire is refined. The dimensional tolerances and mechanical properties are set during this process. The wire is drawn through conical dies and becomes hardened due to the large deformation in the cold work process. In theory, it is possible to have strains up to 63.2%, but in practice, this is not possible due to friction and redundant work [1]. During the pass through the first die, it is in practice possible to have strains up to 43% [2]. These high strains cause a high pressure inside the drawing die and in order to protect the wire from metallic contact with the die, it is important to have a functional lubrication process. Wire drawing is divided into two different categories depending on which type of lubricant is used in the process: dry drawing and wet drawing. Dry drawing is

normally used for larger dimensions (over 1 mm in diameter) and wet drawing for smaller dimensions. The dry drawing method provides the lowest coefficient of friction between the wire and the die and a friction coefficient between 0.01 and 0.07 can be considered as good if the process is functioning as intended. For wet drawing, the coefficient of friction is normally between 0.08 and 0.15 [3]. In dry drawing, the lubricant used is either a calcium- or a sodium-based soap. If the lubrication process malfunctions, there might be metallic contact between the wire and the die, resulting in high friction and process failure.

In today's wire drawing process, it is not common to use a system that will predict or even give a warning if the process fails. If quality inspection of the wire is required, it is done on the finished wire product. This is usually done with the eddy-current (EC) testing method [2].

During the last four decades, different monitoring methods for the wire drawing process have been studied. Experiments performed in the 1980s focused on a device that measured the electrical resistance between the wire and the die. The group claimed that this resistance would indicate on the condition of the lubrication in the wire drawing process. If the lubrication layer thickness between the wire and the die would change, the resistance between them would also change. Thus, poor lubrication would result in low resistance. An industrial monitoring system was also developed called the "Tearing

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detector” which used the technique. The product was sold in a small number at the time when it was released [4–9]. In 1984, a patent for flaw detection in wire drawing using acoustic emission was filed. This was inspired by a paper published in 1980 about assessment of the frictional condition in wire drawing of aluminium using acoustic emission [10, 11]. During the 1980s, several attempts were made using acoustic emission for monitoring the lubrication process in wire drawing [12, 13]. Acoustic emission as a process monitoring tool for wire drawing has also been studied more recently leading to a patent and a product [14]. Measurements of vibrations using accelerometers instead of acoustic emission have also been studied recently, showing promising results [15].

In 2001, studies on different ways to monitor the drawing process using indirect measurements were investigated. Four methods were suggested: thermoelectric voltage occurring between core and case, thermoelectric voltage occurring between core and wire, acoustic emission, and the electric contact resistance between the wire and die [16]. In 2014, an investigation of possible monitoring processes for the detection of defects in the wire during the wire drawing process was made. One of the methods that were investigated was the use of a pyrometer to monitor the wire drawing process as the wire was already wound up on the block in the drawing machine. Experiments displayed promising results in detecting complete loss of lubrication, not because the pyrometer could detect changes in wire temperature, but due to its ability to detect changes in the emissivity of the wire surface. However, when using a pyrometer, there is a disadvantage, the exact position and size of the measuring point is unknown. At the distance which the pyrometer was mounted from the block, the measuring point was larger than the diameter of the wire. This resulted in problems when the wire was unevenly wound on the block, the pyrometer would measure the temperature of the block instead of the wire [17]. In 2017, a paper was published where a CCD-sensor was used to monitor the lubrication process of the wire drawing process. This was done by studying the reflectivity of the wire as it passed by the sensor in a box with a controlled light source. The method showed promising results when compared to drawing force measurements [18].

Several techniques have been evaluated for monitoring the wire drawing process, but still, there is no system that is used in the industry today. In recent years, the prices of thermal imaging cameras have dropped which makes the technique more available. Today, it is found in many vastly different areas, such as human emotion detection, fault diagnostic in rotary machinery, monitoring of heat distribution systems, control of laser welding, and fault detection in induction motors [19–23].

Tool condition monitoring with focus on process monitoring of metal cutting has been investigated showing that the same types of process monitoring sensors that have been

evaluated for process monitoring of the wire drawing process also are used for process monitoring of metal cutting. Thermal imaging cameras were suggested in the study, but were considered only to be suitable for laboratory tests at that time (1995) [24]. In 2016, a paper was published where an infrared thermal camera was used to monitor the tool condition in a turning process. The signal from the thermal imaging camera was compared to data from optical acoustic emission measurements with encouraging results [25].

The purpose of this paper was to investigate if monitoring of the wire drawing process using a thermal imaging camera is viable. The hypothesis is that if the lubrication conditions of the wire drawing process changes, then the signal from the thermal imaging camera will also change. The change in the signal is most likely depending on three process factors:

- The temperature of the wire: an increase of the friction between the wire and the die leads to an increased amount of energy that goes to the wire, which causes a higher wire surface temperature.
- The emissivity of the wire surface: there is a significant difference in the reflectivity between an unlubricated and a lubricated wire surface [18].
- Damage on the wire surface: if the lubrication process fails galling may occur, which can lead to large scratches forming on the wire surface. This can cause patterns in the thermal images caused by both changes in temperature and emissivity.

2 Materials and methods

To test the hypothesis, a thermal camera was placed in front of the drawing machine acquiring images of the wire as it was leaving the drawing die. The distribution among values from the pixels in the images from the thermal imaging camera was studied by looking at pixel value standard deviation of a small area of the wire surface. If the lubrication process is functioning as intended, the measured values inside this area will be similar in every pixel. With an unstable or malfunctioning lubrication process, there should be detectable difference in measured values among the pixels. The signal level (absolute temperature) of the pixels is not of interest for monitoring purposes because the instantaneous emissivity of the wire surface is unknown. A change in emissivity has a significant influence on the signal; this can cause a change in wire temperature to be compensated by a lower emissivity. However, in this study, the emissivity of the wire from different stages of the drawing process was measured after the wire

drawing experiments had been performed for evaluation purposes.

The signal from the thermal imaging camera was compared to the signal from drawing force sensors, which is influenced by frictional changes. Two experiments were performed with different wire materials and lubricants to investigate if the monitoring process could detect changes in the process, for different drawing processes with different wire surface properties. All the tests were performed using a single-block wire drawing machine, seen in Fig. 1.

The monitoring method was evaluated by correlation to the drawing force signal and to surface analysis of the wire using scanning electron microscopy (SEM) (Hitachi S3200N) and tactile surface roughness measurements along the curvature of the wire (Mahr Perthometer PGK).

2.1 Materials

It was desirable to use materials with large differences in brightness to evaluate the stability of the monitoring system in different conditions. The process parameters, lubricants, and wire types used in this work are presented in Table 1.

Chemical composition, physical and mechanical properties for the wire materials used in the different experiments are presented in Tables 2, 3, and 4. The material properties were collected from tensile tests (Instron 4486) performed on the wire material before and after the pass through the die.

2.2 Thermal imaging monitoring

Thermal images were recorded using a FLIR A600 series thermal imaging camera. The camera has a spatial resolution of 0.68 mrad, a field of view of $25^\circ \times 19^\circ$, a minimum focus distance of 0.25 m, a focal length of 24.6 mm, an IR resolution of 640×480 pixels, a pixel pitch of $17 \mu\text{m}$, thermal sensitivity $< 0.05^\circ\text{C}$ at $+30^\circ\text{C}$, and a detector time constant that

typically is 8 ms. The manufacturer specifies an accuracy of $\pm 2^\circ\text{C}$ or $\pm 2\%$ of reading [26]. The temperature measurement range used was $0\text{--}650^\circ\text{C}$ and the camera was placed approximately 300 mm from the wire. The emissivity factor was set to 0.95 (which does not correspond to the different wire surfaces emissivity) and the image frequency used was 200 Hz. With chosen image frequency, the camera use windowing, meaning a subset of the total image is selectively read out. At 200 Hz, the camera can handle a window of 640×120 pixels. The software that was used to capture the thermal images and later for analysing the data was the ResearchIR from FLIR [27].

The monitoring method this paper focuses on is to use the pixel value distribution over a small area of the wire surface. The pixel value standard deviation of an area consisting of 100 pixels (approximately 25 mm^2) is calculated in each thermal image using,

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \gamma)^2} \quad (1)$$

where N is the number of pixels in one picture, x_i is the value of one pixel and,

$$\gamma = \frac{1}{N} \sum_{i=1}^N x_i \quad (2)$$

Additional filtering was added by applying a calculation of the maximum standard deviation among captured images for each individual second of the experiment (200 frames/s). The following equation was used on the data from each individual second in the complete dataset,

$$T_s = \max_{i=1}^n \sigma_i \quad (3)$$

where n is the number of frames per second and T_s is the thermal image monitoring signal.

Fig. 1 Research drawing line at Örebro University containing a rotating pay off and a single-block drawing machine

Table 1 Experimental setups used to evaluate the monitoring process

Experiment	Wire material	Lubricant	Lubricant carrier	Starting wire diameter	Reduction	Die angle	Drawing speed
1	Carbon-steel	Calcium soap	Salt based	5.85 mm	24%	14°	0.33 m/s
2	Stainless-steel	Sodium soap	None	4.69 mm	15.9%	12°	0.13 m/s

Table 2 Chemical composition (in wt%) of the wires used in the experiments. Carbon-steel wire, En 10270-2 VDSiCr and stainless-steel wire, EN 10270-3 X10 CrNi 18-8 HS

Steel grade	C	Si	P _{max}	S _{max}	Cr	Mo _{max}	N _{max}	Mn	Fe
VDSiCr	0.50–0.60	1.20–1.60	0.025	0.02	0.50–0.80	–	–	0.50–0.80	Balance
X10 CrNi 18-8 HS	0.05–0.15	Max 2.00	0.045	0.015	16.0–19.0	0.8	0.11	Max 2.00	Balance

2.3 Drawing force monitoring

Drawing force was measured using two force sensors fitted to the lubrication box. The force sensors were of KIS-2 type which has a range of 0–30 kN. Figure 2 shows the lubrication box and the force sensors. The signals from the sensors were collected by a BLH G4-RM, which is an industrial process controller, at a sample rate of 800 Hz. The signal was then processed in the LabVIEW software [28]. Drawing force data presented in this paper is mean values for each second of the experiments.

Previous studies have used drawing force for evaluating process monitoring systems [11–13, 15–18]. The drawing force reflects the lubrication situation in the system. A change in the friction between the wire and the die will show in the drawing force signal.

Drawing force can be calculated theoretically, and this is commonly done using the formula derived by Siebel and Kobitzsch [29],

$$F = A_1 R_{em} \left(\ln \frac{A_0}{A_1} + \frac{2\alpha}{3} + \frac{\mu}{\alpha} \ln \frac{A_0}{A_1} \right) \quad (4)$$

where F is the total drawing force, A_0 and A_1 are the area of the wires cross section before and after the reduction, R_{em} is the mean flow tension for the material before and after the reduction, 2α is the semi-die angle, and μ the coefficient of friction between the wire and the die. For the lubricated part of the experiments, the friction coefficient should be between 0.01 and 0.07 [3]. Theoretical drawing forces for the lubricated parts of the experiments have been calculated using Eq. (4) and Table 4. For the carbon-steel, the drawing force should lie between 6925 N and 9425 N and for the stainless-steel, between 3360 N and 4645 N.

2.4 Wire temperature

With the thermal imaging data that is captured for monitoring purpose, it is also possible to measure the temperature of the wire. This type of measurements is however not reliable since the emissivity of the drawn wire changes during the process. The method is also sensitive to external disturbances, such as background emission and lightning. In this study, the emissivity of the wire surface from each individual stage of the experiments was measured subsequently to the wire drawing

Table 3 Physical properties for the wire material used in the experiments

Steel grade	Density (kg/m ³)	Specific heat capacity (J/kg °C)	Thermal conductivity (W/m °C)
VDSiCr	7850	480	54
X10 CrNi 18-8 HS	7900	500	15

Table 4 Mechanical properties for the wire material used in the experiments

Steel grade	Diameter (mm)	Yield stress (MPa)	Tensile strength (MPa)	Strain at peak (%)
VDSiCr (before)	5.85	710	1060	10
VDSiCr (after)	5.10	1000	1210	2
X10 CrNi 18-8 HS (before)	4.69	810	1020	12
X10 CrNi 18-8 HS (after)	4.30	970	1260	3

Fig. 2 Placement of thermal imaging camera, which focus on the wire as it leaves the drawing box

experiments. This was done by using a tactile temperature measuring device and the thermal imaging camera simultaneously and iterating the emissivity factor in the thermal image capturing software until both measuring devices showed the same temperature reading.

The temperature of the wire increases as it is drawn through the die. The increase in temperature is mostly not only due to the plastic deformation, but also because of the friction between the wire and the die. The temperature increase in one reduction step can be estimated using the following equation, [2]

$$\Delta T = k \frac{F/A_1}{\rho C_p} \quad (5)$$

where ΔT is the temperature increase, F is the drawing force, A_1 is the wire area after the reduction, ρ is the density of the wire, C_p is the wire materials specific heat capacity, and k is a correction factor. The loss of energy from the wire that the constant k represents is mostly due to the cooling of the wire in the drawing die, which is depending on the design of the die cooling system and the thermal conductivity of the wire and die material. Up to 15% of the energy that is added to the wire during the reduction is removed due to the cooling in the drawing die [2].

Using Tables 1, 3, and 4, Eqs. (4) and (5), ambient temperature (23 °C), μ (0.01–0.07), and k (0.85–1), the theoretical wire temperatures for the lubricated parts of the experiments can be calculated [2, 3]. For the carbon-steel, this results in a wire temperature between 100 and 145 °C and for the stainless-steel 70–104 °C.

2.5 Friction coefficient

If the lubrication fails in the wire drawing process, there will be an increase in the drawing force, because the friction coefficient between the wire and the die increases. To calculate the friction coefficient between the wire and the die using the measured drawing force, Eq. (4) has been rearranged with respect to the coefficient of friction which results in,

$$\mu = \alpha \frac{F - A_1 R_{em} \left(\ln \frac{A_0}{A_1} - \frac{2\alpha}{3} \right)}{A_1 R_{em} \ln \frac{A_0}{A_1}} \quad (6)$$

An industrial wire drawing machine is rarely equipped with force sensors, meaning that the drawing force is seldom measured. To measure the temperature of the wire surface is however possible, at least if the wire drawing process is stopped. If the wire is stationary, it is possible to use a tactile temperature measurement device, such as a thermocouple.

Equations (5) and (6) have been combined and rearranged with respect of the coefficient of friction resulting in an equation to calculate the coefficient of friction using the measured wire temperature,

$$\mu = \frac{\alpha \Delta T \rho C_p}{\ln \frac{A_0}{A_1} K R_{em}} - \alpha - \frac{2\alpha^2}{3 \ln \frac{A_0}{A_1}} \quad (7)$$

Note that when an optical temperature measuring equipment (as in this study) is used, the temperature output is affected by the emissivity of the measured surface. In a dry wire drawing process, the emissivity of the drawn wire will change when the friction conditions in the process changes, leading to incorrect temperature measurements. Thus, the wire temperature measured with a thermal imaging camera is not a suitable monitoring method. In this paper, the emissivity of the wires drawn with and without a functional lubrication process has been measured after the performed experiments.

To evaluate Eq. (7), the friction coefficient during the experiments has been calculated with both Eqs. (6) and (7) by using Tables 1, 3, and 4, the measured drawing force, and the signal from the thermal imaging camera (that had been adjusted using the measured emissivity for wire drawn with and without a functional lubrication process).

2.6 Procedure

The experimental procedure used in this study has been used for evaluating process monitoring systems for the wire drawing process in previous works [18]. The procedure is as follow:

- Engage monitoring equipment
- Engage the wire drawing, with lubrication
- Run the lubricated process for approximately 3 min, ensuring that there are stable monitoring signals
- Remove the lubricant from the lubricant box
- Disengage the wire drawing process when the lubrication process has failed (indicated by an increase in the drawing force)
- Disengage the monitoring equipment

The single-block drawing machine, the lubrication box, and the placement of the thermal imaging camera used in the experiments can be seen in Fig. 2.

2.7 Analysis of variance

The resulting process monitoring signal from the thermal imaging camera, drawing force signal, and surface roughness measurements were analysed with respect to the difference of their means using an analysis of variance (ANOVA). The results from both experiments for each data input were divided into two groups; functional lubrication and unfunctional lubrication. Surface roughness measurements were performed on 10 regions of the wire for each group. The null hypothesis of the analysis was that the mean of the different datasets was equal.

3 Results

The results from the experiments are presented as plots with both drawing force signal and the monitoring signal from the thermal imaging camera. To provide more understanding of what type of data the thermal imaging camera processes, three example thermal images are shown in Fig. 3. These thermal images were captured during different stages of experiment 2. The drawing direction is from left to right in the images; at the left side, the wire has just exit the drawing die. Figure 3a shows an image that was captured when the wire drawing process were running with functional lubrication. The colour distribution is equal over the wire surface and compared to Fig. 3b, c, the colour shows that the thermal signal was lower. The image in Fig. 3b was taken at the moment as the wire just had started to heavily tear due to lack of lubrication. To the right, the colour is evenly distributed; in the middle, the colour has changed, and the thermal signal is higher. This could be because of a micro weld between the wire and the drawing die, this occurs when there is excessively contact between the two. To the left in Fig. 3b, the colour of the wire surface is no longer evenly distributed, indicating severe wear on the wire surface. Figure 3c was taken as the process was producing severe damaged wire, as can be seen the colour is not distributed evenly.

3.1 Experiment 1—carbon-steel

The maximum standard deviation for each second from the specified area in thermal images, and drawing force signal, from experiment 1 are shown in Fig. 4.

Fig. 3 Example of thermal images from experiment 2. a) Drawing process functioning as intended; b) drawing without a functioning lubrication process, picture showing where the wire starts to tear; c) unfunctional process producing scratched wire

Fig. 4 Drawing force and max standard deviation from thermal images for each second from experiment 1. Four regions can be distinguished in the signals and they are discussed in the text

The regions seen in Fig. 4 all correspond to what was occurring in the wire drawing process. Region A is before the wire drawing process had started, showing a drawing force of 0 N and a low thermal image standard deviation. The transition from region A into region B is where the wire drawing process was started. There is a spike in both the signals at the transition; in the thermal image data, this is a result of the change in temperature as the wire goes from room temperature to production temperature. In the drawing force signal, the spike corresponds to the static friction. In region B, the drawing process was functioning as intended, with lubricant in the drawing box. In this region, the mean drawing force was 8485 N which is inside the prediction. This represents a friction coefficient of 0.047, which was calculated using Table 1, Table 4, and Eq. (5). The transition from region B to region C indicates where the lubricant has been depleted because of the removal of the lubricant from the lubricant box. This was detected by both the drawing force and the thermal imaging camera signal. In region C, the friction coefficient increases up

to 0.14. The signal from the thermal imaging camera follows the drawing force signal. The transition from region C to region D shows where the wire drawing process was stopped. Region D is the disengaged state at which the drawing force was 0 N. In region B, the emissivity of the wire surface was measured to 0.8 and in region C, to 0.75. Using the emissivity for the different regions, wire temperatures could be measured. In region B, the mean wire temperature was 125 °C which is between the theoretically predicted temperatures; in region C, the wire temperature increases to 172 °C. The coefficient of friction was calculated using both the drawing force (Eq. (6)) and the measured and adjusted (with respect to emissivity) wire temperature (Eq. (7)), this is shown in Fig. 5. The constant k was set to 0.925 (which represent a cooling capacity of 7.5% in the drawing die). As can be seen, the two different ways to calculate the coefficient of friction have a close correlation.

The surface of the wire from regions B and C can be seen in Figs. 6 and 7. Cracks oriented perpendicular to the sliding

Fig. 5 Friction coefficient calculated for experiment 1. The coefficient has been calculated using the measured drawing force and the measured wire temperature (with respect of the emissivity change between the regions)

Fig. 6 Surface of the carbon-steel wire analysed from region B (functional lubrication) at $\times 70$ (a) and $\times 1000$ (b) magnification by means of SEM. Surface cracks oriented perpendicular to the sliding direction were observed (b)

Fig. 7 Results from surface analysis of the carbon-steel wire from region C (unfunctional lubrication) in SEM displaying regions with flattened surface and (a, b) and some minor scratching in the sliding direction (a)

Fig. 8 Surface roughness measurement values from the different regions from experiment 1

Fig. 9 Typical surface roughness measurements of the carbon-steel wire in a region B (functional lubrication) and b region C (unfunctional lubrication). The surfaces were measured along the curvature of the wire

Table 5 ANOVA of the drawing force signal. The signals compared were from the transition B, C to A and from B to C and forwards for the same number of data points

	SS	df	MS	<i>F</i>	<i>P</i>
Groups	1.85e9	1	1.85e9	5.41e4	< 0.001
Error	1.68e7	490	3.42e4		
Total	1.87e9	491			

direction were observed on the surface of the carbon-steel wire analysed from region B (functional lubrication) by means of SEM. Surface analysis of the carbon-steel wire from region C (unfunctional lubrication) in SEM, however, generally illustrated a more flattened surface with some minor scratching visible in the sliding direction as can be seen in Fig. 7.

Surface roughness measurements of the wire in regions B and C can be seen in Fig. 8. The presented values are mean values from surface roughness measurements performed on the wire samples from the experiment. The error bars represent scattering in measured surface roughness values. The mean surface roughness of the wire was $R_a = 0.59 \mu\text{m}$ in the lubricated region and $R_a = 0.19 \mu\text{m}$ in the unlubricated region. In Fig. 9, typical surface measurements from the two regions are shown.

To statically clarify that there are differences in the monitoring signals and resulting wire surfaces from the different stages of experiment 1, three one-way analyses of variance (ANOVAs) were performed. The results of the ANOVA performed on the drawing force signal, signal from thermal imaging camera, and surface roughness measurements can be seen in Table 5, where SS is the sum of squares due to each source, df is the degrees of freedom associated with each source, MS is the mean squares for each source which is the ratio of SS/df, *F* is the ratio of the mean squares, and *P* is the probability that the data from the different datasets would belong to the same dataset (Table 6 and Table 7).

Where SS is the sum of squares due to each source, df is the degrees of freedom associated with each source, MS is the mean squares for each source which is the ratio of SS/df, *F* is the ratio

Table 6 ANOVA of the signal from the thermal imaging camera. The signals compared were from the transition B, C to A and from B to C and forwards for the same number of data points

	SS	df	MS	<i>F</i>	<i>P</i>
Groups	2023.56	1	2023.56	3727.7	< 0.001
Error	243.19	448	0.54		
Total	2266.76	449			

Table 7 ANOVA of the surface roughness measurements (R_a value). The measurements compared were made on the wire from regions B and C

	SS	df	MS	<i>F</i>	<i>P</i>
Groups	0.776	1	0.776	168.33	< 0.001
Error	0.083	18	0.005		
Total	0.859	19			

of the mean squares, and *P* is the probability that the data from the different datasets would belong to the same dataset.

The tables show that both the process signals and the surface roughness measurements from region B and region C are statistically different. As can be seen from the tables, there was a > 99.9% probability that the measurements taken from different stages in the process came from different datasets.

3.2 Experiment 2—stainless-steel

The signal from the thermal imaging camera, and drawing force signal, from experiment 2, can be seen in Fig. 10.

The signals summarised in Fig. 10 were divided into six regions. Region A is before the drawing process was engaged, the drawing force was 0 N and the signal from the thermal camera was stable. The transition from regions A to B indicates where the wire drawing process was engaged. In region B, the wire drawing process was functioning as intended, with functional lubrication, the drawing force was 4645 N which gives a friction coefficient of 0.070. The transition from region B to region C is where the lubricant was removed. Unlike in experiment 1, the behaviour of region C does not display an increase in the drawing force signal; some spikes can be seen in the signal from the thermal imaging camera. It takes 160 s before the effects of removing the lubricant from the lubricant box can be seen on the drawing force signal. At the transition from region C to D the lubrication in the process has partly failed which was indicated by the drawing force signal. The transition from region D to E is where the loss of lubrication is detected by the thermal image signal. The coefficient of friction increased to over 0.3 before the wire drawing process was stopped indicated by the transition E to F. Region F is the disengaged state. In region B, the emissivity of the wire surface was measured to 0.4 and in region E, to 0.25. Using the emissivity for the different regions, wire temperatures could be measured; in region B, the mean wire temperature was 103 °C which is inside the predicted temperature values. In region E, the mean temperature was 156 °C. The coefficient of friction was calculated using both the

Fig. 10 Drawing force and max standard deviation from thermal images for each second from experiment 2. The experiment was divided into six regions and they are discussed in the text

Fig. 11 Friction coefficient calculated for experiment 2. The coefficient has been calculated using the measured drawing force and the measured wire temperature (with respect of emissivity change in region B and region E)

Fig. 12 Surface of the stainless-steel wire in region B (functional lubrication) (a) and magnification of the wire surface in region B displaying surface asperity flattening (b)

Fig. 13 Wire surface from region C (no lubricant in lubricant box). One scratch can be seen on the wire surface and the surface beside the scratch is similar to the surface in region B. **a** Protrusions were observed in the

scratched region on the wire surface and in **b**, protrusions rising above the surface are illustrated

Fig. 14 The typical surface of the wire in region E (unfunctional lubrication) illustrating the observed protrusions in SEM at magnifications of $\times 70$ (a) and $\times 1000$ (b)

Fig. 15 Surface roughness measurement values from the different regions from experiment 2

measured drawing force and the adjusted with respect of emissivity measured wire temperatures, this is shown in Fig. 11.

The constant k was set to 1 which is higher than in experiment 1, this is because the stainless-steel has a lower thermal

Fig. 16 Typical surface roughness measurements of the stainless-steel wire in **a** region B (functional lubrication), **b** region C (no lubricant in lubricant box), and **c** region E (unfunctional lubrication). The surfaces were measured along the curvature of the wire

Table 8 ANOVA of the drawing force signal. The signals compared were from the transition C, D to F and from C to D and backwards for the same number of samples

	SS	df	MS	<i>F</i>	<i>P</i>
Groups	6.72e7	1	6.72e7	52.51	< 0.001
Error	1.28e8	100	1.28e6		
Total	1.95e8	101			

conductivity than the carbon-steel used in the previous experiment. As can be seen, the two different ways to calculate the coefficient of friction seems to be in good agreement.

The wire surface from region B, C, and E can be seen in Figs. 12, 13, and 14. Surface analysis of the stainless-steel wire from regions B and C by means of SEM revealed surface asperity flattening. Additionally, in region C, a large scratch with diameter of approximately 500 μm was observed. In the scratched region, protrusions rising above the surface were observed (Fig. 13b). Surface analysis of the wire from region E in SEM also revealed surface protrusions as can be seen in Fig. 14 and in region E, the surface was completely damaged, and the protrusions were the main wear pattern.

Surface roughness measurements of the wire in regions B, C, and E can be seen in Fig. 15. The presented values are mean values from all the performed surface roughness measurements. The error bars represent the actual spread. The mean roughness of the wire was $R_a = 1.09 \mu\text{m}$ in region B, $R_a = 0.98 \mu\text{m}$ in region C, and $R_a = 6.13 \mu\text{m}$ in region E. Figure 16 show a typical surface measurement from each region of the experiment. The scratch that was found in region C in the microscopy (Fig. 13) was also detected by the surface roughness measurements (Fig. 16b). The surface measurement in Fig. 16c shows that the wire from region E is heavily damaged.

To check if the differences found in the monitoring signals and surface roughness measurements from the different regions of experiment 2 are statistically different, four ANOVA were performed. The results of the ANOVA performed on the results of the drawing force, signal from thermal imaging camera, and surface roughness measurements can be seen in Table 8, Table 9, and Table 10. These show that both the process signals and the surface roughness measurements from region B (functional lubrication)

Table 9 ANOVA of the signal from the thermal imaging camera. The signals compared were from the transition D, E to F and from D to E and backwards for the same number of samples

	SS	df	MS	<i>F</i>	<i>P</i>
Groups	2764.38	1	2764.38	183.07	< 0.001
Error	573.82	38	15.10		
Total	3338.20	39			

Table 10 ANOVA of the surface roughness measurements (R_a value). The measurements compared were made on the wire from regions B and E

	SS	df	MS	<i>F</i>	<i>P</i>
Groups	127.311	1	127.311	427.64	< 0.001
Error	5.359	18	0.298		
Total	132.669	19			

and region E (unfunctional lubrication, indicated by both sensors) are statistically different. Table 11 shows an ANOVA performed on the surface roughness measurement from region B and region C.

As in experiment 1, there was a > 99.9% probability that the measurements taken from the different process stages came from different datasets, except for surface roughness measurements from region B and region C which had a probability of 18% to belong to the same dataset.

4 Discussion

The purpose of this work was to determine if a thermal imaging camera could be used to monitor a wire drawing process. Studying Figs. 4 and 10, it was found that the standard deviation of the signal from the thermal image camera correlated to some extent with the signal from the drawing force sensors, which previously has shown to give clear indications of changes in the process [11–13], [15–18]. It was found that the evaluated method gave satisfactory results in both experiments and this was also shown statistically by the performed analyses of variance as seen in Table 5, where SS is the sum of squares due to each source, df is the degrees of freedom associated with each source, MS is the mean squares for each source which is the ratio of SS/df, *F* is the ratio of the mean squares, and *P* is the probability that the data from the different datasets would belong to the same dataset.

Table 6, Table 8, and Table 9 show that the probability that the signals from both process monitoring sensors from the different regions would belong to the same dataset is low. The surface roughness measurements from the different regions also proved to be statistically different (Table 7 and Table 10). For all the above analysis, there was a > 99.9% probability that the

Table 11 ANOVA of the surface roughness measurements (R_a value). The measurements compared were made on the wire from regions B and C

	SS	df	MS	<i>F</i>	<i>P</i>
Groups	0.053	1	0.053	1.95	0.179
Error	0.489	18	0.027		
Total	0.542	19			

measurements acquired from the different process stages came from different datasets. These differences are also supported by the performed surface analysis. In experiment 1 (carbon-steel, Figs. 6 and 7), it can be seen that the wire becomes flattened when the lubrication process fails. This was also shown in Fig. 8 (surface roughness measurements), where the wire produced without a functional lubrication process generally had lower surface roughness values. In experiment 2 (stainless-steel, Figs. 12 and 14), severe wear was observed on the surface of the wire produced without functional lubrication and this was supported by the surface roughness measurements, Fig. 15. In both the experiments, the monitoring signal from the thermal imaging camera was found to have a correlation to the drawing force signal. However, in experiment 2 (Fig. 10), the thermal imaging camera technique might give some more information than the drawing force measurement.

As seen in Fig. 10, during experiment 2 in region C, there were some spikes in the monitoring signal from the thermal imaging camera, which were not detected by the drawing force measurements. It has been shown that in tests simulating the contact conditions found in forming operations, such as sheet metal forming of stainless-steel, material transfer to the tool surface occurs [30]. This is generally known as galling, which is a kind of severe adhesive wear [31]. The transferred material causes scratching of the sheet surface resulting in the typical surface pattern observed in the scratched area on the wire surface from region C (Fig. 13), where protrusions rise above the surface. In the present study, this occurred locally in region C and the protrusions were observed over the whole wire surface after further sliding as seen in Fig. 14 showing the wire surface analysed from region E. Thus, the spikes in the signal from the thermal imaging camera in region C may be an indication of the early stage of galling in the wire drawing process as galling occurred locally, Fig. 13. Only using drawing force measurements as process monitoring would in this case not give an indication of a scratch. Thus, if the lubrication process would stabilise again, the process could continue to produce wire with a scratch for a long time.

Table 11 shows an ANNOVA performed on the surface roughness measurements from experiment 2. The results from the ANNOVA indicate that the scratched surface

from region C could belong to region B (lubricated, functional process). Although the differences between the wire surfaces from these different regions appear to be clear if Figs. 12 and 16a are compared to Figs. 13 and 16b. The R_a surface roughness measurement value is commonly used for evaluating wire surface, but it is possibly not a suitable tool for evaluating the quality of a wire surfaces. Studying Fig. 15, it can be seen that none of the standardised surface roughness measurement values could give an indication of a scratch on the surface in region C when the values are compared to values from region B. The scratch found on the wire surface in region C was critical and would in production, cause the production to be stopped, the tool to be replaced and the wire to be scrapped.

(Figs. 4 and 10), it would be possible to add a threshold where an imaginable process monitoring system could send a warning. In both experiments, a threshold of 1.75 times the mean value of the signal from the lubricated region would have given satisfying results, even though the mean level of the two signals was different. Figure 17 shows the thermal imaging signal from both experiments with the threshold added. In general, such a threshold would most likely need to be determined for each individual process.

The coefficient of friction was also studied during the two experiments and is shown in Figs. 5 and 11. The friction coefficient was calculated using two different approaches (Eqs. (6) and (7)). The new approach using wire temperature seems to be in good agreement with the conventional way using drawing force. However, using this type of calculation with data from optical temperature measurements for monitoring the wire drawing process is not a viable way. There are many of uncertainties that play a vital role; the temperature measurement is dependent on a correct emissivity, which will change with the lubrication state of the process. External disturbances, such as background emission and lighting, can affect the measurements. Also, changes in wire properties such as dimension or yield strength can be factors that will affect the measurements. However, as a method to evaluate a drawing process, e.g. when trying out a new lubricant, this equation could be useful.

Fig. 17 Signal from thermal imaging camera from the experiments with an added threshold where a warning signal could be sent by a possible process monitoring system. a) Experiment 1 (carbon-steel), b) experiment 2 (stainless-steel)

5 Conclusion

A method for monitoring the wire drawing process using thermal imaging was developed and evaluated. A thermal imaging camera was used to capture images of the wire surface as the wire exit drawing die. In every captured frame the standard deviation of a small specified area of the wire surface was calculated. The resulting signal was evaluated against the drawing force in two experiments, both experiments showed promising results.

The monitoring signal from the thermal imaging camera had correlation with the drawing force measurements which previously have been used for evaluating process monitoring systems for the wire drawing process. Meaning that with the suggested method, thermal imaging could possibly be used in a process monitoring system for the wire drawing process. However, the endurance and monitoring accuracy in an industrial wire drawing environment needs to be evaluated. For this evaluation, the method needs to be integrated in an industrial drawing line.

Also, an equation for estimating the friction coefficient between the drawn wire and the drawing die using the temperature of the drawn wire has been suggested and evaluated. The equation was evaluated against friction coefficient calculated using drawing force from experiments. The new method produced results that correlated well to results obtained using the drawing force.

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