In-situ evaluation of the performance of wire drawing using multiple sensors

Joakim Larsson*[1], Patrik Karlsson[1] and Anton Jansson[2]

[1]Örebro University, School of Science and Technology, Fakultetsgatan 1, 701 82 Örebro, Sweden
[2]Jönköping University, School of Engineering, Gjuterigatan 5, 553 18 Jönköping, Sweden

*Corresponding author joakim.larsson@oru.se

Abstract

In-situ evaluation (monitoring) of the wire drawing process is often performed manually in today's industry which is a difficult task for the operator, requiring both time and experience. Previous research at Örebro university has been performed to identify and evaluate automated in-situ monitoring methods for the wire drawing process. From this research, several methods that can be applied for monitoring purposes have been identified. However, the advantage of using multiple sensors has not yet been investigated. How data from different monitoring sensor signals correlates with each other and if they can be combined to obtain a better understanding of the wire drawing process will be investigated and discussed in this work. Four different sensor signals; vibration, wire temperature, brightness of the wire surface and drawing force, will be compared and evaluated in wire drawing experiments where the process conditions are controlled. The results show that all the evaluated sensors indicate similar to deviations in the lubrication process, however, some problems could only be detected by some sensors. Using multiple sensors can have advantages in both detection and misrepresentation of problems and might be used to classify specific types of problems in the process.

1. Introduction

The possibilities of in-situ evaluation of the lubrication process in wire drawing have been explored by researchers for the last four decades. During twenty years (1980-2000) a Swedish research group developed a device that measured the electrical resistance between the wire and the die [1–5]. The research hypothesis was that 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 detector", which used the developed technique and the product was sold in a small number at the time when it was released [6]. 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 using acoustic emission [7], [8]. During the 1980s, several attempts were made using acoustic emission for monitoring the lubrication process in wire drawing [9], [10]. Acoustic emission as a process monitoring tool for wire drawing has also been studied more recently leading to a patent and a product [11]. Measurements of vibrations using accelerometers instead of acoustic emission has also been studied recently, showing promising results [12].

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 [5]. 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 studied, 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 detected changes in the emissivity of the wire surface. However, using a pyrometer on wound wire has its disadvantages, the exact position and size of the measuring point is unknow. 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 winded on the block, the pyrometer would measure the temperature of the block instead of the wire [13]. 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 [14]. In 2019, a method to monitor the process using thermal imaging was developed and evaluated with good results [15].

Even though the problem of monitoring the wire drawing process have been studied by many researchers during a long period of time, the industry standard is still that the operator visually inspects the wire.

In an effort to make research results available to the industry, researchers at Örebro University combined two of the presented methods, and developed a sensor utilizing vibrational and optical sensors [16], [17]. The system has been further developed and now includes three different types of sensors; Vibration, CCD-sensors and temperature sensor [18]. This system will also be used for the measurements in the present study.

As shown above, researchers have found several different methods that show promising results and they may be used for in-situ process evaluation of the wire drawing process. However, the advantage of using multiple sensors have not yet been investigated. How data from different monitoring sensor signals correlates with each other and if they can be combined to obtain better understanding of the wire drawing process will be investigated and discussed in this paper. Four different sensor signals; vibration, wire temperature, brightness of the wire and drawing force, will be compared and evaluated in wire drawing experiments where the process conditions are controlled.

2. Materials and Methods

2.1 Experimental setup

To investigate the correlation between the different process measurement signals, quantitative studies were performed in form of controlled wire drawing experiments. The experiments were performed in an industrial-like wire drawing setup at Örebro University shown in *Figure 1*.

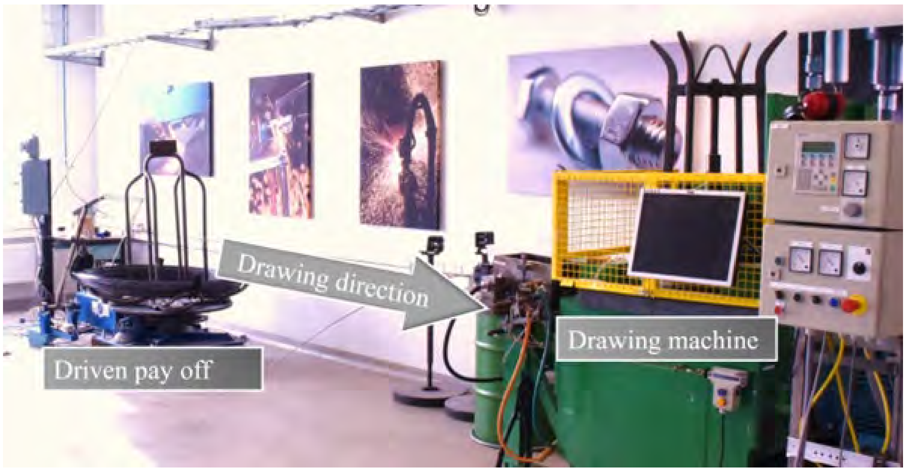

Figure 1. Research wire drawing line at Örebro University.

One type of wire material and drawing die was used for all experiments. Parameters such as lubrication state, temperature of ingoing wire, cooling and drawing speed were changed to be able to evaluate how the sensors react to the changes. The wire material used in the study was a carbon-steel wire, VDSiCr according to En 10270-2. The wire rod had a starting diameter of 5.85 mm and was lightly coated with a salt based lubricant carrier. Mechanical properties of the wire were investigated by means of tensile tests using an *Instron 4486* prior and after the performed wire drawing are presented in *Table 1*. The drawing die used in this study, which was of the interchangeable type (TR6 nibs from Paramount), had a diameter of 5.10 mm, die angle of 12°, a bearing length of 30% and was made of a cemented tungsten carbide with 10% cobalt binder. A calcium-based powder lubricant was used for all the experiments.

Table 1. Material properties of the wire used in the experiments.

	Dimension (mm)	*Yield Stress (MPa)*	*Ultimate Tensile strength (MPa)*
Before reduction	5.85	710	1060
After reduction	5.10	1000	1210

2.2 In-situ process monitoring measurement signals

2.2.1 Drawing force

The force required to draw the wire through the die was captured using two force sensors fitted to the drawing box. *Figure 2* shows the drawing box and the force sensors. The force sensors were of KIS-2 type with a force range of 0-30 kN. 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 a LabVIEW software [19]. The drawing force data presented in this paper is mean values for each second of the experiments.

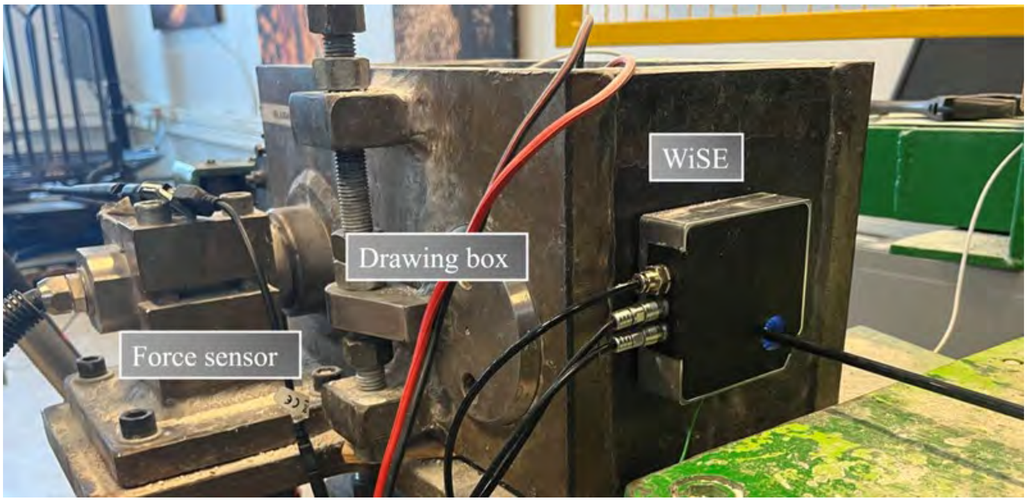

Figure 2. Drawing box fitted with force sensors.

Previous studies have used drawing force for evaluating process monitoring systems [8–10], [12], [14], [15]. The drawing force has been shown to reflect the lubrication situation in the system. A change in the friction between the wire and the die will affect the drawing force signal. This makes the drawing force an important input signal, which is useful for evaluating the wire drawing process and other process measuring methods.

Drawing force can be calculated theoretically, this is commonly done using the formula derived by Siebel and Kobitzsch [20],

$$F = A_1 R_{em} \left(ln\frac{A_0}{A_1} + \frac{2\alpha}{3} + \frac{\mu}{\alpha} ln\frac{A_0}{A_1} \right), \quad (1)$$

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. To be able to evaluate the performance of the lubrication system in the drawing process, the equation can be re-written with respect to the coefficient of friction resulting in,

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

For the lubricated part of the experiments the friction coefficient should be between 0.01 and 0.07 [21]. Friction coefficients have been calculated for all the experiments and are presented in the results for each experiment and lubrication state respectively.

2.2.2 Process signals from the WiSE process monitoring system

The vibration, brightness of wire and wire temperature were captured using the WiSE process monitoring system shown in *Figure 2*. The sensor is installed on the exit side of the drawing box and the wire passes through the sensor. The sensor has a magnetic fastening, no screws are used to fasten the sensor to the drawing box. The three different signals were sampled by the system, approximately three measurements per second for each type of measurement were stored, where each measurement is means of many measurements, how many depending on which signal. In this paper mean values for each second are presented.

The vibration is measured by accelerometers that connect to the drawing box through magnets. The brightness of the wire is measured with area CCD sensors that covers the full circumference of the wire. Finally, the temperature signal is captured using an infrared temperature sensor.

2.3 Experiments

To compare the different in-situ process monitoring signals. several different experiments were performed, the process conditions were changed during the experiments to mimic common problems of the wire drawing process. The following process conditions were investigated during the experiments. During each experiment several hundreds of meters of wire were drawn.

Running out of lubricant

During this experiment the lubricant was left to run out naturally. This is a problem that can occur in the industry when the operator is not able to keep a good level of lubricant in the drawing box or if other problems occurs such as tunneling in the lubricant or blockage at the die entrance. The experiment was let to run until the drawing force level reached elevated levels.

Lost and restored lubricant supply

The experiment was performed to mimic lubrication problems that could be temporary such as tunneling in the lubricant or a temporary blockage of the entrance of the drawing die. During this experiment the lubricant was removed from the drawing box. This was done by vacuuming the lubricant from the box and from the inlet of the drawing die. When an increased friction between the wire and the drawing die was indicated by the drawing force signal, the supply of lubricant was restored by adding lubricant powder to the soap box.

Issues from previous draws

This experiment mimic problems with previous draws in the process and was done to investigate if problems in draws previous to the draw where the monitoring equipment is placed can be detected. In this case the incoming wire had an increased temperature for a period of time, creating problems with the performance of the lubricant in the investigated draw. This is a problem, which can occur due to several different reasons, problems in the prior draw such as die damages, insufficient lubrication, die cooling not working and others. The problem can also occur due to an increase in productivity (drawing speed), leading to that the wire does not decrease enough in temperature on the capstan prior to the drawing die. This is a common problem in todays wire drawing industry due to the demand of higher productivity. The increase in temperature of the ingoing wire was created by heating the wire using induction heating. The temperature was increased to roughly 100 °C and was constant throughout the heating period.

Long shallow cosmetic artificial defect

During this experiment the wire surface was subjected to grinding using a handheld circular grinder. This created a very shallow scratch, the scratch was not possible to feel by hand, neither before or after the wire was drawn. This simulates a scratch created in a previous draw to the draw being monitored or in previous processes to the drawing process such as handling or heat treatment.

Running the drawing process without cooling until problems can be detected by machine operator

This experiment was performed to see when changes in the process can be detected by the machine operator. The process was run without cooling and the temperature of the ingoing wire was increased during the experiment. The experiment was stopped when the operator noticed problems in the process.

3. Results and discussion

The experiments presented in section 2.2 were performed using the same type of lubricant, meaning that the coefficient of friction should be similar in all the performed experiments when there is a good lubrication situation. When comparing the drawing force from the performed experiments it was found that this was the case, the mean value from each of the experiments in the lubricated parts was 9100 ± 100 N. Using *Equation 2, Table 1* and the geometrical properties of the drawing die, the coefficient of friction was calculated for the lubricated parts, resulting in a coefficient of 0.05, which is between 0.01-0.07 as the literature states to normal for a well lubricated dry drawing process [21]. The results from the experiment are presented below. In some of the experiments the signal representing the wire temperature show a slight increase throughout the experiment, this is probably due to that the wire drawing process had not yet reached steady state temperature when the experiment was performed.

Running out of lubricant

Figure 3 shows the measured signals from the experiment where the lubricant was let to run out.

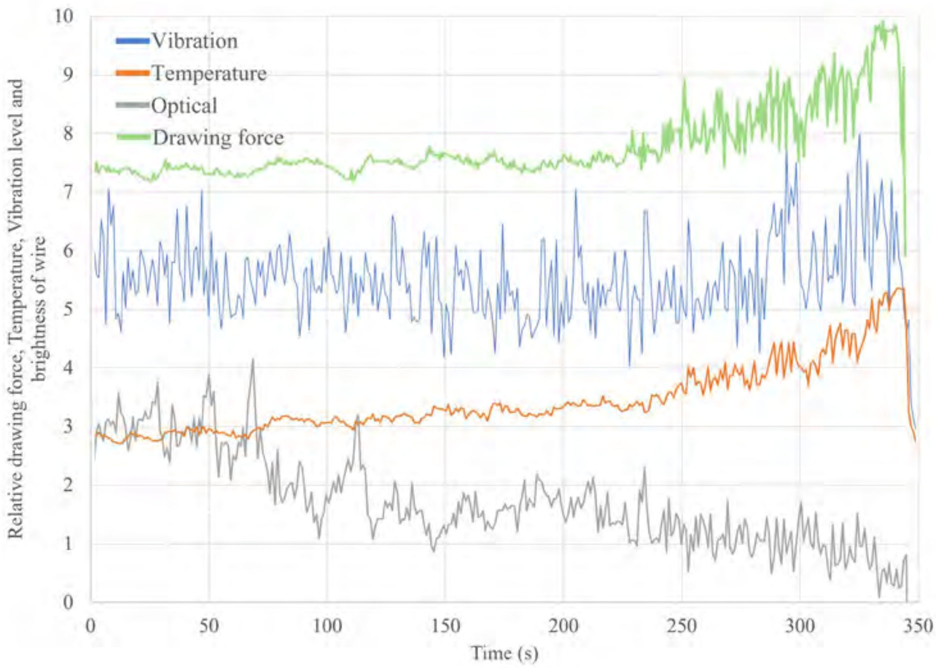

Figure 3. Results from the experiment where the lubricant was let to run out. The figure shows the four measured signals, Vibration, Wire temperature, wire brightness (Optical) and drawing force.

During the experiment a critical low level of lubricant was left to be present at the start of the experiment, and the process then ran until the force level reached critical high levels. The result from the experiment is *Figure 3*, displaying vibration, wire temperature, optical signal and drawing force. The vibration, wire temperature and drawing force signals show a similar behavior. All signals indicates that there are some changes in the process from around 225 seconds (a bit later for the vibration signal). This is likely due to the increased friction in the process due to the lack of lubricant. The coefficient of friction increases from 0.05 up to 0.16 in the end of the experiment. 0.16 is over the 0.07 stated in the literature to be normal for a well-functioning process, but not much higher than what to be expected in a normal wet drawing process [22]. It has also been shown in previous research that the wire temperature follows the drawing force, and that the coefficient of friction can be estimated using the temperature of the wire as well as the drawing force [15]. The optical signal, representing the brightness of the wire, shows that this signal registers the problem before the other signals can detect the lack of the lubricant, *Figure 3*. This is probably because the brightness of the wire changes (due to the lack of lubricant) before the loss of lubricant affects the friction of the system. This means that the brightness of the wire could be used to prevent to process of getting to a poorly lubricated state, since it indicates before the f drawing force increases. Worth to note is that the wire after the performed experiment did not display any damage when optical inspected, implying that this problem can be solved without the need to scrap the wire and the tools if the problem can be detected in time. In this experiment, the process was stopped before any damage occurred in the tool or on the wire, there was also no indication that could be detected by the machine operator that there would be any problem in the process.

Lost and restored lubricant supply

Figure 5 show the results from the experiment simulating a problem in the drawing process where the lubricant supply is lost for a period of time and then restored.

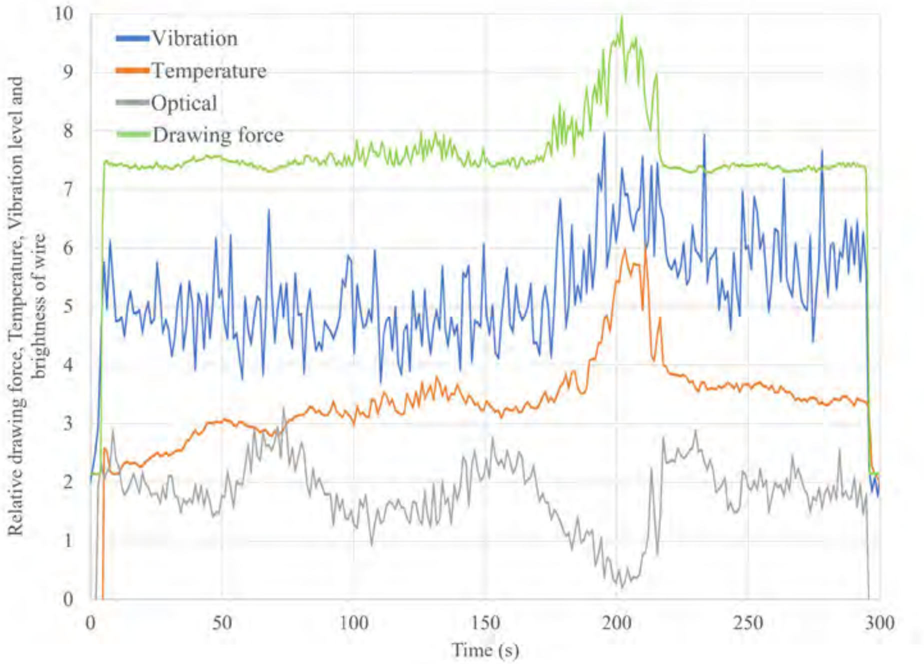

Figure 4. Results from the experiment simulating lost and restored supply of lubricant. The figure shows the four measured signals, Vibration, Wire temperature, wire brightness (Optical) and drawing force.

In the beginning of the experiment (0-150 seconds) the lubrication quality is pending, which is captured by the drawing force signal, the optical signal and the wire temperature sensor. This is due to the lack of lubricant supplied into the drawing die. After 175 seconds larger deviations in the performance of the lubrication system occurs, which is captured by all the sensors, the coefficient of friction increases to 0.16. At 220 seconds the lubricant supply is returned, and the lubrication function returnes to normal which is also shown by the sensor signals. No damages could be found on the wire from the experiments.

Issues from previous draws

Figure 4 shows the results from the experiment simulating a problem in a previous draw, leading to increased ingoing wire temperature.

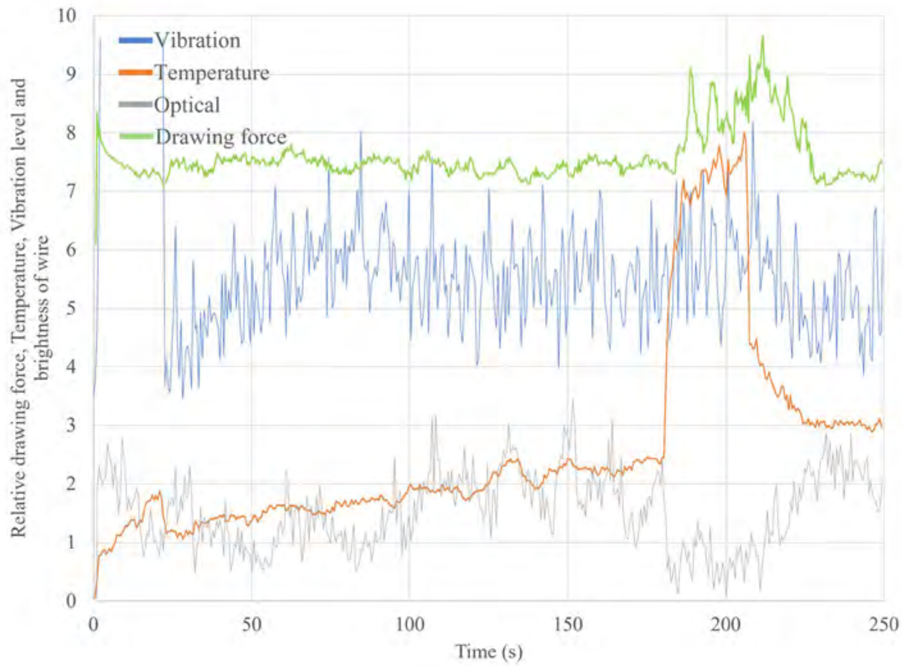

Figure 5. Results from the experiment simulating problem in a previous draw to the one being monitored. The figure shows the four measured signals, Vibration, Wire temperature, wire brightness (Optical) and drawing force.

As shown in the figure, the wire with increased temperature reaches the studied process after around 140 seconds, the problem is restored, and the wire is cooled of at approximately 180 seconds. The temperature of the wire was increased to roughly 100 °C during that time. The increase in temperature seems to have led to some problems with the lubrication as shown by the increase in drawing force indicating an increase in the coefficient of friction, the coefficient increases to 0.12. The problem occurring in the process could also be detected by analyzing the optical signal as well as by the drawn wire temperature signal. The vibration signal gives a similar response. However, for this specific case it is not as clear as the other signals. When the temperature decreases the process is going back to a normal state. There is a delay from when the ingoing wire temperature goes down until the temperature of the drawn wire is back to normal, this is due to the cooling of the drawing die, it takes some time for it to go back to normal temperature.

The result show that it would be possible to detect a problem in a draw previous to the monitored draw.

Long shallow cosmetic artificial defect

Figure 6 shows the resulting scratch after passing through the drawing die, the scratch is very shallow and cannot be felt by hand.

Figure 6. Shallow artificial scratch after being reduced in the drawing die.

The resulting measurement data from the experiment is presented in *Figure 7*

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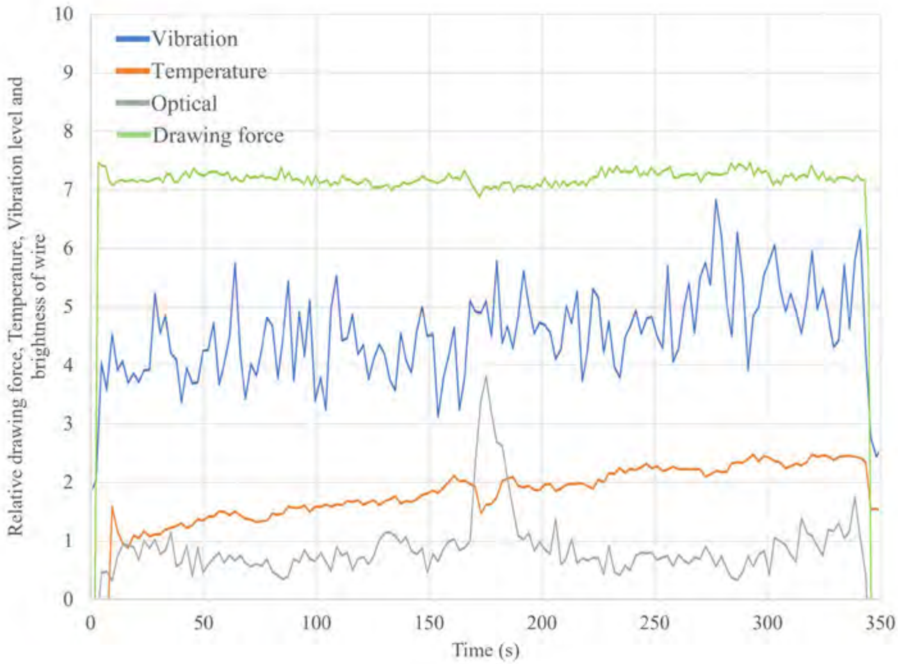

Figure 7. Results from the experiment where an artificial cosmetic scratch investigated. The figure shows the four measured signals, Vibration, Wire temperature, wire brightness (Optical) and drawing force.

The scratch passes through the drawing die after around 160 seconds, which clearly shows on the optical signal, a small indication can also be seen on the temperature signal. The difference in temperature is probably not due to an actual change in wire temperature, since the scratch is very shallow but due to the change in emissivity, the scratch is much brighter than the undamaged wire surface, which can be seen on the increase in the optical signal. And as the wire surface becomes brighter the measured temperature value gets lower.

Running the drawing process without cooling until problems can be detected by machine operator

The results from the experiment where the process was let to run withing cooling until problems with the process could be detected by the operator is presented in *Figure 8.*

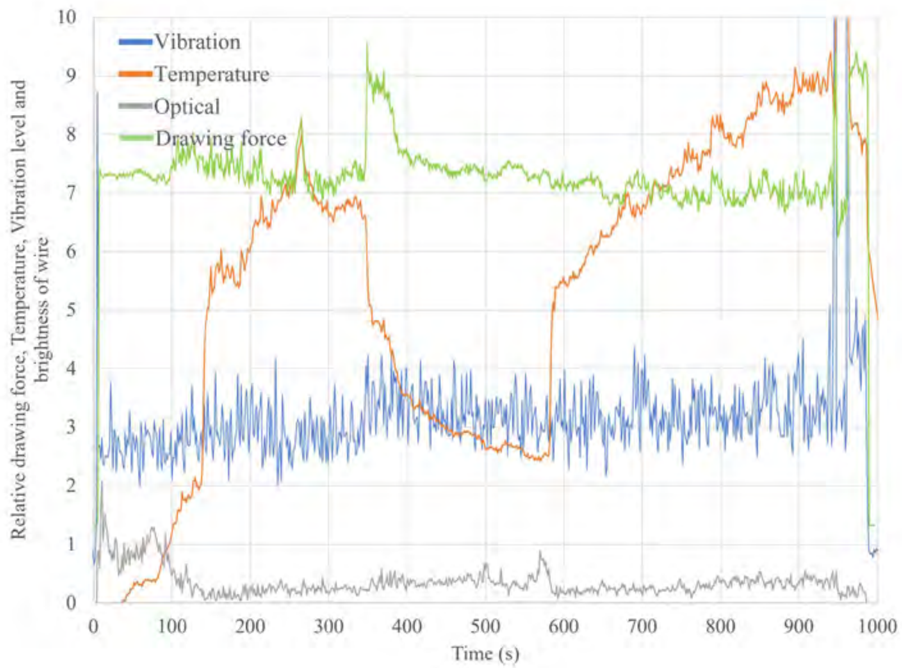

Figure 8. Results from the experiments where the process was let to run without cooling until the operator would detect that there is a problem in the process. The figure shows the four measured signals, Vibration, Wire temperature, wire brightness (Optical) and drawing force.

At the beginning of the experiment the process was left to run in a normal state, after 150 seconds the ingoing wire temperature was increased to 100 °C. This increase in temperature results in a less favorable lubrication situation, which is indicated by all the used sensors in *Figure 8*. After 200 seconds the cooling of the drawing die is removed which also leads to an increased temperature of the drawn wire. After approximately 100 additional seconds, the lubrication condition degrades further for a short period of time which is indicated by the wire temperature and the drawing force measurements. At 400 seconds the ingoing wire temperature is decreased to room temperature, this somehow leads to even an even worse lubrication situation for a while, which is indicated by the drawing force signal. At 600 seconds the lubrication seems to start to stabilize due to the decrease in tool temperature, at this point the ingoing wire temperature is increased from room temperature up to 100 °C again, which is indicated by the increase in wire temperature. After around 950 seconds the temperature in the tool has increased to levels which causes the lubrication to completely malfunction, which is indicated by all the monitoring signals. The coefficient of friction is at this point 0.16 and the process is left to continue. The vibration level and wire temperature are not ideally displayed in *Figure 8*, but the level is more than 200 times higher for vibration signal than the mean value from the rest of the experiment and the temperature signal is roughly twice as high as displayed. At this point, the problems in the process could be detected by the machine operator due to a strange noise from the drawing die and the process was stopped. However, when optical inspecting the wire after the experiment, no clear defect could be seen, however, the wire surface seems to be brighter, but it is difficult to tell when studying the wire with the human eye.

3.6 Summary

The four sensor signals used to monitor the drawing process all showed similar tendencies when the lubrication state of the investigated wire drawing process changed. One problem investigated in this study where only one sensor gave a response was the experiment with an artificial cosmetic scratch, this was only detected by the optical signal. Also, in the case of issues in a previous draw the vibration signal did not give of a clear indication.

Clearly, using multiple sensors can have benefits. One is that the risk of misclassification of a problem becomes lower. It can be seen that the sensors react similarly to lubrication problems. This can be used to set off reliable alarms when at least two sensors indicate a problem. Inaccurate warnings could be reduced significantly using such a method. Also, the optical sensors can be used to classify the types of problems that occur. If a significant change is found in only one of the optical sensors but no change is seen on the other process signals, the reason is likely because there is a shallow scratch on the wire surface. If changes are seen on all sensors there is likely an issue with the lubrication.

4. Conclusion

In this paper, five common problems that can occur in the wire drawing process were investigated using four different type of sensor signals. The sensor data was analyzed and correlated to each other.

In all the evaluated cases, problems with the lubrication, causing an increased coefficient of friction between the drawn wire and the wire drawing die could be detected by the drawing force as well as by the process signals collected using the WiSE-sensor. In the case of the shallow artificial cosmetic scratch, the only sensor that could pick up the scratch was one of the optical sensors.

In all the performed experiments, problems with the lubrication process could be detected before any damages occurred on the wire or in the tool. For all the experiments except for the last one, no problem could be detected by the machine operator. This indicates that there is a large potential to monitor the wire drawing process using sensors, since there are possibilities to adjust or stop the process before any permanent damage occurs.

Conflicts of interest

The sensor system (WiSE) used to capture three of the four investigated types of sensor signals used in this study is being developed by two of the authors of this study. Two authors also work at and are stockholders of Wire Innovations Sweden AB which is developing and producing the WiSE-sensor. The company is a small start-up tech company partly owned by Örebro university, sprung from the research within the field of wire drawing.

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