Enhanced Cooling Design in Wire Drawing Tooling Using Additive Manufacturing

Joakim Larsson(✉), Patrik Karlsson, Jens Ekengren, and Lars Pejryd

School of Science and Technology, Örebro University,
Fakultetsgatan 1, 701 82 Örebro, Sweden
joakim.larsson@oru.se

Abstract. Wire drawing is a manufacturing process in which metal rods or wires are drawn through a single or a series of dies, reducing the wire cross-section and enhancing the mechanical properties of the wire. The tribological conditions in wire drawing are quite extreme and high friction between the wire and the die results in an increased die temperature. Previous studies have shown that by reducing the die temperature the lifetime of the die increases and thus efficient cooling of the die is of high importance.

Additive manufacturing enables fabrication of tools with advanced conformal cooling channels with high cooling efficiency. This technique may, therefore, be of high importance in the design of the cooling system of drawing dies. In the present study, the effect of conformal cooling design of die holder on the die temperature, and thus die performance, was investigated. A die holder was manufactured by means of laser powder bed fusion (LPBF) in an EOS M290 machine using atomized corrosion resistant steel (Corrax). The cooling efficiency of the manufactured tool holder was evaluated in an industrial wire drawing process and further analysed using FEM modelling. This study shows promising results on improved cooling efficiency for die holder designed and manufactured by additive manufacturing.

Keywords: Wire drawing · Cooling · Additive manufacturing

1 Introduction

Wire drawing is a manufacturing process in which metal rods or wires are drawn through a single or a series of dies, reducing the wire cross-section and enhancing the mechanical properties of the wire. Even though the process is defined as a cold working method, heat is generated in the wire and the tool as the wire is deformed. Studies have shown that up to 15% of the total power used for the reduction stays in the drawing die, Enghag [1]. The part of the drawing tool that is in contact with the wire (drawing die) is usually made of either cemented carbide or diamond and can either be integrated in a steel/carbide die or used as nibs in an interchangeable die core system. The cemented carbide used for the dies is sensitive to high temperatures. At 800 °C already 50% of the hardness is lost, according to a producer's data sheet [2].

Finite element studies of an industrial wire drawing situation have previously been reported by Larsson and Jarl [3]. The simulations were verified against the actual

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industrial process and the result showed that temperatures can exceed 800 °C in the drawing die. Improving the cooling of dies is, therefore, of highest importance in order to ensure long life time of the drawing die. In another study, Larsson and Jarl [4] showed that more efficient cooling may indeed extend the life of the die. However, the tool holder used in that particular experiment had a short life time due to the hardness of the used material, making it unsuitable for industrial use. In order to increase the understanding of the factors influencing the performance and for further development of the process to extend the life of the tools, a revisiting of the cooling of drawing dies and nibs was therefore deemed interesting.

Another limiting factor is the lubricants used. The most commonly used in dry drawing wire drawing processes are calcium or sodium soaps that oxidize when exposed to high temperatures. If the lubricant oxidizes, it loses its lubricating abilities [5]. If the cooling of the inlet cone of the die could be improved, increased productivity may be achieved.

The idea to use additive manufacturing (AM) as a production method for metallic tools in order to allow for more freedom in the design of cooling systems is not new. The AM methods have advanced in maturity lately and examples of applications of conformal cooling channels through the use of AM can be found in literature, e.g. Hölker et al. [6] and Jahan and El-Mounayri [7]. Hölker et al. [6] investigated a hot extrusion die for aluminium using AM to produce the tool with conformal cooling channels, claiming a 300% productivity increase. Jahan and El-Mounayri [7] reported on a design process for optimizing the cooling of a die for plastic injection moulding.

Based on the potential seen in the increased life of the drawing tools by improved cooling and the identified possibilities in using AM to accomplish this, the current project was directed towards investigating the cooling capabilities of a tool holder for wire drawing nibs with conformal cooling channels. This was done both by experimental investigations of the cooling process in a controlled laboratory situation and experiments in an industrial wire drawing environment. The data from the experiments was used to verify the finite element model that was developed. The verified model was then used for simulation to give further understanding of the cooling in the wire drawing process.

2 Materials and Methods

2.1 Wire Drawing Theory

The force required to pull the wire through the drawing die can be calculated theoretically. This is commonly done using the formula derived by Siebel and Kobitzsch [8]

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

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 of the die and μ the coefficient of friction between the wire and the die. According to literature, the friction coefficient between the wire and the die lies between 0.01 and 0.07 for a well functional dry lubricated wire drawing process using soap powder as lubrication [9].

The power needed for a pass in a wire drawing process can be calculated as

$$P = VF, \tag{2}$$

where P is the needed power and V is the drawing speed.

When the wire is drawn through the die, heat is generated due to the plastic deformation of the wire and friction between the wire and the die. The temperature increase in the drawn wire during one reduction step can be estimated using the following equation [1],

$$\Delta T = k\frac{F/A_1}{\rho C_p}, \tag{3}$$

where ΔT is the temperature increase, ρ is the density of the wire, C_p is the specific heat capacity of the drawn material 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 die design, drawing speed, die cooling system, drawing tools material, the thermal conductivity of the wire and die material and other parameters.

Literature states that up to 15% of the energy produced in the wire during the reduction process is removed by energy transport to the drawing die and subsequent cooling [1]. Many parameters influence the exact number, but the drawing speed is one of the most important factors. Although the heat generated by the deformation of the wire is independent of the drawing speed, an increase in drawing speed increases the energy released per time unit. This results in an increased die temperature due to insufficient removal of heat from the drawing die. As the die temperature increases this leads to a reduction of the fraction of the total energy that goes to the drawing die. In a previously study, it was shown that as a carbon steel wire was drawn at 0.33 m/s, 7.5% of the total energy went to the drawing die [10].

2.2 Die Holder

There are many different designs of cooling systems for the drawing tool in a conventional wire drawing setup. The most efficient setup is a so called direct cooled die holder. The drawing tool is placed in a die holder and the holder is placed in a cooling body. As the process runs, the cooling body is filled with coolant, meaning that the die holder is surrounded by coolant. Figure 1a and b shows a conventional wire drawing die holder that is made for a directly cooled system. The die is positioned in the conical surface that can be seen inside of the cooling flanges illustrated in Fig. 1 b).

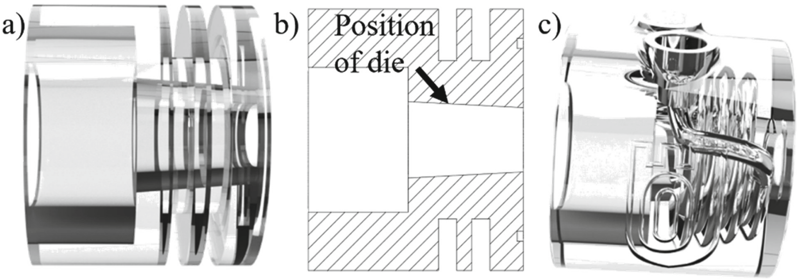

Fig. 1. CAD models of the two tool holders a) the conventional direct cooled b) a schematic cut view of the conventional tool holder c) the new printed design with conformal cooling channels.

As the die holder itself, already in the conventional setup, is submerged in turbulently flowing coolant, the idea to be able to increase the cooling rate of the die is to move the coolant closer to the die. Thus, minimizing the distance between the die and the coolant should result in enhanced cooling of the die. In this study, the die was designed with a cooling channel placed as close to the drawing tool as possible. The cooling channel was designed to revolve around the drawing tool in a helical geometry.

The coolant channel cross-section has the geometry of a teardrop to avoid problems when the roof of the channel was being printed [11]. The top of the teardrop was oriented in the building direction, along the positive Z-axis direction during printing. The cross-sectional area of the channel was designed to be 8.9 mm^2. A more detailed description of the design process for the cooling body can be found in [12]. The resulting cooling body used in this study is shown in Fig. 1c.

2.3 Laboratory Experiments

A previous study reports an experimental trial performed in order to evaluate and compare the cooling capacity between the conventional die holder and the additive manufactured holder in a laboratory setup. The results in form of temperature differences between the coolant and the cooled object placed at the position were the die would sit in an industrial setup is shown in Fig. 2. The graph shows that the die holder with conformal cooling gives roughly 25% lower temperature difference between the coolant and the cooled object, thus increasing the cooling efficiency. During the laboratory experiments, other parameters such as temperature of coolant and flow of coolant was also measured to ensure that the experiments with the different die holders were performed under the same conditions. The results were also used to obtain suitable boundary conditions for finite element simulations (FEM) [12].

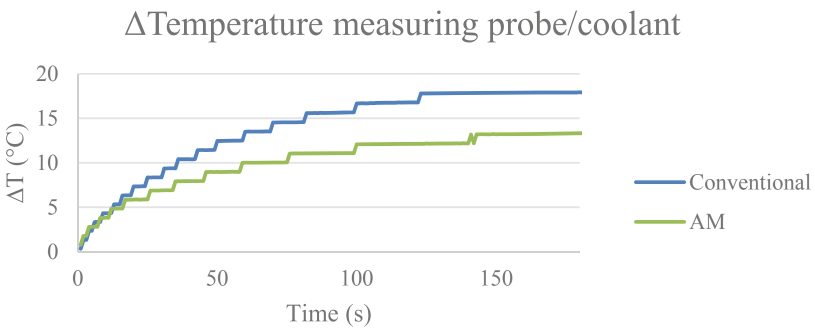

Fig. 2. Results from laboratory experiments using conventional die holder and AM die holder with conformal cooling channels. The graphs show temperature differences between the cooled object and the coolant as a function of running time.

2.4 Finite Element Study

FEM analyses were made using Ansys 2019 R3 [13], using a standard implicit transient heat solver. The models consisted of approximately 19000 elements. Boundary conditions, convection and heat flow, were taken from the laboratory experimental conditions [12]. The convection boundary condition was used to simulate the heat removal, which is done by the coolant. A cut of the mesh (without the die) used for the analysis of the die holder with conformal cooling channels is shown in Fig. 3.

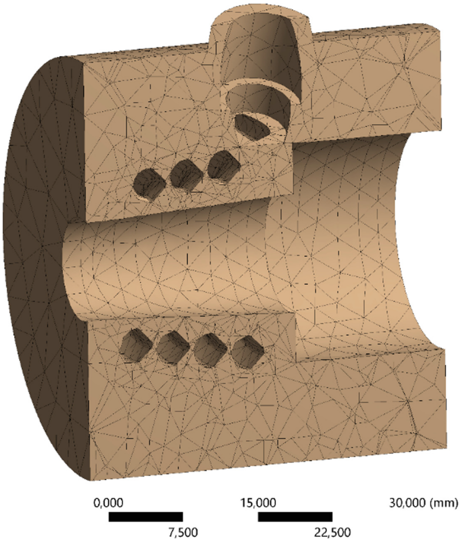

Fig. 3. Sectioned image of the FEM model used in this study

The heat generated by the wire drawing process was added to the model as a heat flow on the inside surface of the drawing die. The heat flow was set to represent the measured results from the industrial experiments.

2.5 Industrial Experiments

In order to verify that the results found in the laboratory experiments are valid for the real application, industrial experiments were made. The die holder was used in the last draw of an industrial drawing machine with 9 steps. In the process, a high carbon steel wire was produced and at the finishing block the wire had a diameter of 4.24 mm and a maximum speed of 7.5 m/s (multiple drawing speeds were tested during the experiments). To be able to compare the conventional die holder with the additive manufactured tool holder, data for the conventional tool holder first needed to be acquired. The same experimental procedure was used for the two die holders.

To study the differences in cooling efficiency between the two die holders, the drawing dies used in the experiments were equipped with type k thermocouples. The thermocouples were spot welded to the exit side of the dies as shown in Fig. 4.

Fig. 4. Drawing die equipped with a thermocouple on the exit side.

The thermocouples were sampled during the experiments using a Testo 176T4. The sampling frequency was 1 Hz and the reported measuring error is ±0.5% of measured value.

3 Results and Discussion

3.1 Wire Drawing Experiments

In the industrial wire drawing tests, the additively manufactured die holder with conformal cooling channels was mounted in the same manner as a conventional die holder. The coolant was feed to the die holder through an 8 mm (28 mm^2) hose. The coolant outlet of the die holder was equipped with a short hose in order to steer the coolant into the standard outlet of the coolant container. An image of the die holder mounted in the cooling body can be seen in Fig. 5.

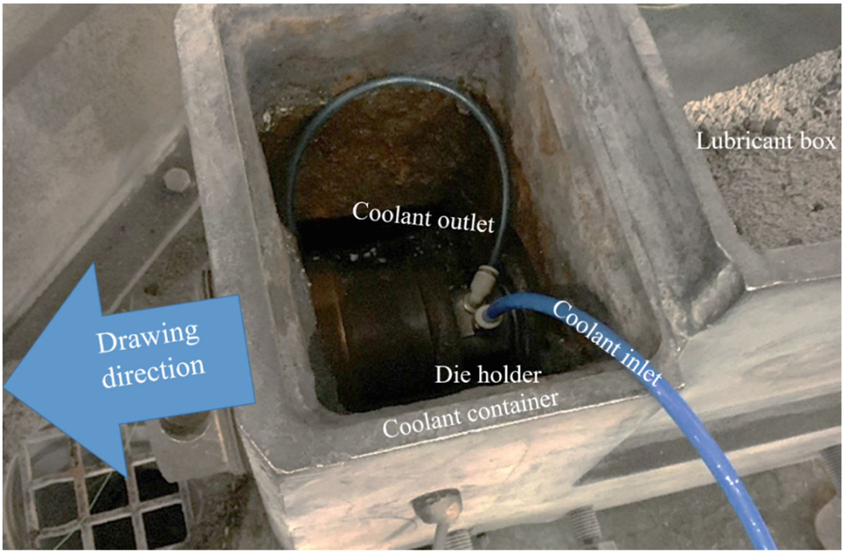

Fig. 5. Additively manufactured die holder mounted in a conventional wire drawing machine.

During the experiment, five different drawing speeds were used in order to study if any differences could be found depending on the drawing speed. The highest drawing speed used in the experiments, 7.5 m/s, is the normally used speed for the specific product. To ensure a good lubrication in the start, the highest speed was used in the beginning, as the lubricant used was chosen for that speed. The highest drawing speed

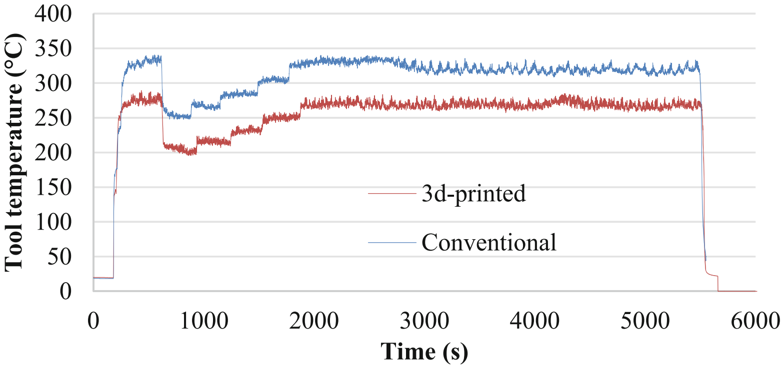

Fig. 6. Measured temperatures from the two different experiments. Five different drawing speeds were used (one specific was used twice, resulting in six distinct levels).

was also used for an extended time at the end of the experiments. Results from the experiments, in form of temperature measured at the exit side of the drawing die, is shown in Fig. 6.

The temperature curves have been analysed and mean temperature values for the different drawing speeds have been extracted, as presented in Table 1.

Table 1. Mean temperatures from the performed industrial experiments.

Drawing speed (m/s)	Conventional (°C)	Additive manufactured (°C)	Difference (K)
3	253	206	47
4	265	216	49
5	285	231	54
6	305	250	55
7,5	329	269	60

As shown, both the temperature itself and the temperature difference between the conventional die holder and the additive manufactured die holder increase with increased drawing speed. This is explained by the higher power added to the system at a higher drawing speed. However, if the percentage difference is studied for the different drawing speed almost no difference can be seen, the result show that the die holder with conformal cooling channels gives roughly 18% lower temperatures than the conventional die holder for all drawing speeds.

3.2 Finite Element Analysis

To be able to evaluate the cooling process in the industrial wire drawing process by FEM, the amount of energy that goes into the die needs to be evaluated. This was done by iterating the value of the boundary condition (heat flow) for the ingoing heat until the surface where the thermocouple was mounted during the experiments showed the same value as from the experiments. This calibration was performed for all different drawing speeds for the conventional die holder case. The heat flows used in the simulations of the additively manufactured die holder by FEM were those obtained by calibrating the simulations of the conventional die holder to the measured temperatures, for each drawing speed. The rest of the boundary conditions used were the same as in the FEM study reported earlier [12].

For the normal production speed (7.5 m/s), it was estimated that around 485 W is going into the drawing die. Using Eq. 1 and 2, an approximate power of 33.25 kW was needed for the specific case, meaning that around 1.5% of the total power that was used in the forming process went to the drawing die as heat. These parameters were put into the FEM models for the conventional case and for the case with the additive manufactured die holder. The resulting temperature plots from the end (steady state) of two of the FEM simulations can be seen in Fig. 7.

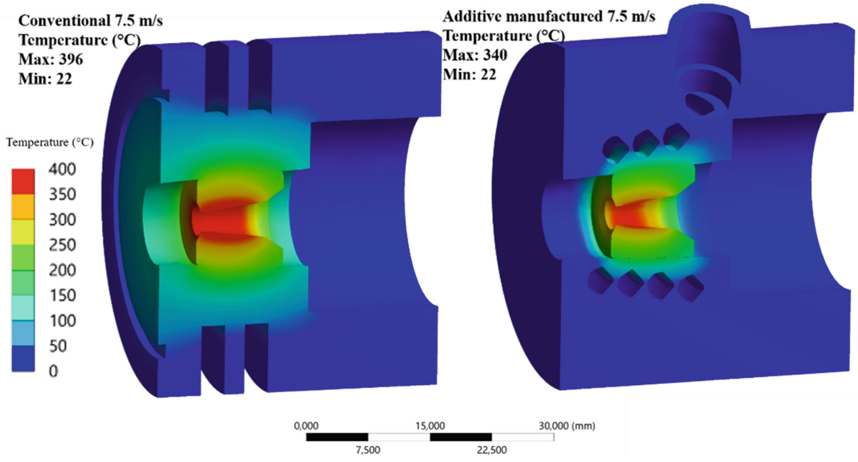

Fig. 7. Temperature result plot from FEM simulations. Left: conventional die holder. Right: AM die holder with conformal cooling channels.

As can be seen, the estimated maximum temperature of the die is much lower when using the additively manufactured die holder. In the real process, there will be much higher temperature in local spots where the highest pressures occur during the forming process. To be able to catch these high temperature peaks, a different type of simulation needs to be performed. However, to reach a steady state situation regarding temperature, with the cooling body modelled, would with that type of simulation take immense time and computer power. To reach steady state approximately 15 min of process needs to be simulated, each second 7.5 m of wire is drawn. This means that around 6 750 m of wire drawing needs to be simulated to reach a steady state using a transient mode simulation. Researchers at Örebro University have simulated wire drawing processes including wire deformation. These simulations only handled a few centimetres of wire being drawn, and still the simulations took hours.

The results from the simulations with the other drawing speeds from the experiments are presented in Table 2. Power_T is the total power needed for the reduction pass calculated using Eq. 1 and 2, Power_D is the power that was found going to the drawing die, AM represents the new die holder with enchanted cooling, C represents the conventional die holder, T_m is the maximum temperature from the simulation, T_{mp} is the temperature from the simulation in the point where the temperature was measured during the industrial experiments and Δ%EvFEM is the percentage temperature difference between the simulations and the experiments in the measuring point.

Although a larger power is needed to perform the drawing at higher drawing speeds, a lower fraction of that power is transferred as heat to the die holder. Figure 8 graphically show the results regarding the percentage of the energy that goes to the drawing die.

Table 2. Results from the FEM studies

Speed (m/s)	$Power_T$ (W)	$Power_D$ (W)	$Power_D$ (%)	AM T_M (°C)	C T_M (°C)	AM T_{mp} (°C)	C T_{mp} (°C)	C Δ% EvFEM (%)	AM Δ% EvFEM (%)
3	13000	370	2,8	264	307	212	254	0,5	2,8
4	17300	390	2,3	278	323	223	267	0,7	3,2
5	21700	420	1,9	297	346	238	286	0,5	3,1
6	26000	450	1,7	317	369	254	304	0,3	1,7
7,5	32500	485	1,5	340	396	272	327	0,6	1,0

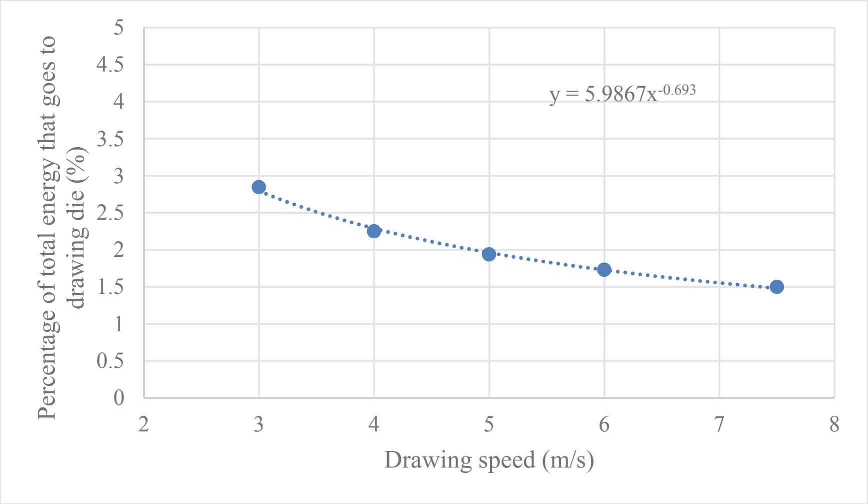

Fig. 8. Percentage of the total energy needed for the drawing pass that ends up in the drawing die.

4 Conclusions and Future Work

In the present study, a conventional tool holder for the wire drawing process was compared to a tool holder with conformal cooling channels manufactured in an anti-corrosive tool steel using additive manufacturing. The additive manufactured tool holder had cooling channels placed as close as possible to the drawing die. The goal of the project was to increase the cooling of the drawing die, and thereby increase the lifetime of the drawing die.

The cooling efficiency was evaluated in an industrial wire drawing process. Multiple production speeds were used to study the influence of the drawing speed. To be able to compare the two die holders, the dies used in the experiments were equipped with thermocouples. The results from the experiments show that the die cooled using the additive manufactured tool holder had roughly 18% lower temperature for all drawing speeds.

Finite element calculations were performed for the different experimental situations and the result from the simulations were in good agreement with experimental results. The models can be used to further understand and develop cooling systems for the wire drawing process.

The present study has shown the potential of additively manufactured tool holder for wire drawing processes. New design of the holder resulted in enhanced cooling of the die, which may enable longer tool life or increased production speed. At a set speed, there will be a lower temperature in the die and thus also in the lubricant. The cooling may be used to extend the life of the tool, and may also be used to increase drawing speed while still working in a temperature range where the lubricant is working properly. Wire drawing lubricants are designed for optimal properties in different temperature regions and increased cooling would extend the useable production speed window for the specific lubricant.

However, to be able to verify these benefits, further studies need to be conducted. To study the effect of the increased cooling capacity on the lifetime of the drawing dies, longer industrial experiments need to be performed, where the wear is measured over time.

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