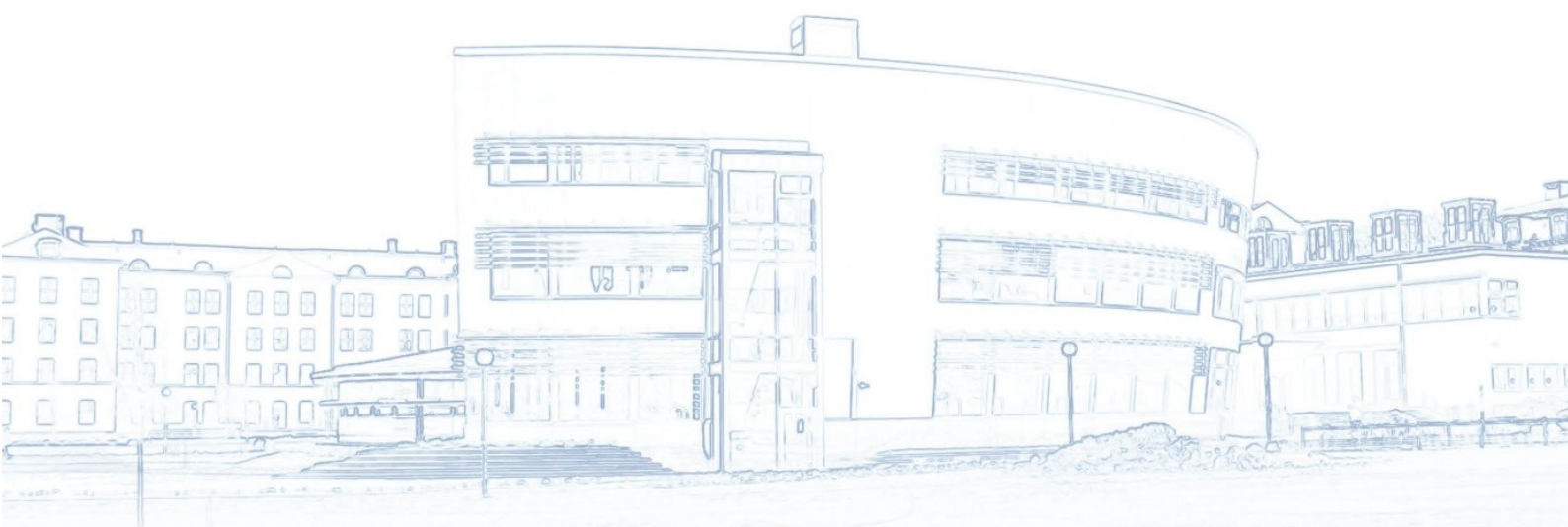


## Effect of spatial-temporal behavior of a newly developed cooling system on carbon and stainless steel bar properties

*G. W. Gebeyaw, P. Romanov, M. Jahedi,  
M. Calmunger, B. Moshfegh*



Denna rapport är publicerad öppet tillgängligt 2023 och licensierad med en Creative Commons Erkännande 4.0 Internationell licens (<https://creativecommons.org/licenses/by/4.0/>).

Working Paper No. 63  
urn:nbn:se:hig:diva-40922

Distribution:  
Gävle University Press  
SE-801 76 Gävle, Sweden  
[gup@hig.se](mailto:gup@hig.se)

# Effect of spatial-temporal behavior of a newly developed cooling system on carbon and stainless steel bar properties

*G. W. Gebeyaw, P. Romanov, M. Jahedi,  
M. Calmunger, B. Moshfegh*

Akademi för teknik och miljö  
Avdelningen för byggnadsteknik, energisystem och miljövetenskap





## Abstract

This report summaries the work within the project "Effect of spatial-temporal behavior of a newly developed cooling system on carbon and stainless-steel bar properties". The project was conducted from 2020-01-01 to 2022-12-31 and was co-produced by SSAB, Outokumpu and University of Gävle (UoG). The Knowledge Foundation, SSAB, Outokumpu and UoG financed the project.

For the Swedish steel companies SSAB and Outokumpu producing special steels, it is very important to be able to control the cooling process in order to produce steel bars with excellent properties. Both steel companies also want to be able to control the cooling process so that the excellent steel properties become even over the bars' spatial configuration.

The aim of the present project is to reveal the spatial-temporal behavior of a newly developed cooling technology in order to produce steel bars with excellent properties and to control the phase transformation to achieve optimal performance of the steel bars.

By using the special test rig at the UoG, detail temperature measurement mapping, invers solution and direct numerical simulation, the present project has identified and quantified several important aspects related to the quenching process, operating conditions, and temperature field development within the investigated products. The result from the proposed cooling process provides an outstanding cooling rate that is very crucial to obtain the required steel phase and thus the correct properties of the bar with different sizes. Results from this study have also shown that the cost per kg product can be reduced by tuning the process parameters such as soaking time and bar temperature before starting the cooling process.

In addition, both experimental and numerical results of the material investigation show that the cooling technology has resulted in the desired phase transformation and subsequently the desired steel phases and material properties. The results show that the cooling technology and the control of the cooling parameters can be used to optimize the material properties of the bar materials.

These good results and conclusions have been obtained via the deep collaboration between the SSAB, Outokumpu and UoG. The co-production, starting in the steering group planning the work along with the combination of research conducted at UoG and at the companies, have led to a successful project with great knowledge transfer in all direction during the duration of the project.

**Keywords:** Thermal management, Advanced cooling, Material characterization and Material modelling

# Sammanfattning

Denna rapport sammanfattar arbetet inom projektet "Effekt av rumsliga temporära beteendet hos en nyutvecklad kylteknik på kol- och rostfritt stål stång egenskaper". Projektet genomfördes under perioden 2020-01-01 till 2022-12-31 och samproducerades av SSAB, Outokumpu och Högskolan i Gävle (HiG). Projektet finansierades av KK-stiftelsen, SSAB, Outokumpu och HiG.

För de svenska stålföretagen SSAB och Outokumpu som tillverkar specialstål är det mycket viktigt att kunna styra kylprocessen för att kunna producera stålstänger med utmärkta egenskaper. Båda stålföretagen vill också kunna styra kylprocessen så att de utmärkta stålegenskaperna blir jämna över stängernas rumsliga konfiguration.

Syftet med detta projekt är att undersöka det rumsliga och temporala beteendet hos en nyutvecklad kylteknik för att producera stålstänger med utmärkta egenskaper genom att kontrollera fasomvandlingar för att uppnå optimal prestanda hos stålstängerna.

Genom att använda den specialbyggda testriggen vid HiG med detaljrika mätningar, inverslösning och direkt numerisk simulering har detta projekt identifierat och kvantifierat flera viktiga aspekter relaterade till släckningsprocessen, driftsförhållanden och temperaturfältutveckling inom de undersökta produkterna. Resultatet från den föreslagna kylningsprocessen ger en enastående kylhastighet vilket är mycket avgörande för att erhålla de eftertraktade stålfaserna och därmed de korrekta egenskaperna hos stängen med olika storlekar. Resultaten från denna studie har också visat att kostnaden per kg produkt kan minskas genom att finjustera processparametrarna som hålltid och stångtemperatur innan kylningsprocessen påbörjas.

Dessutom visar både experimentella och numeriska resultat av materialundersökningen att kyltekniken har resulterat i önskad fastransformation och därefter önskade stålfaser och materialegenskaper. Resultaten visar att kyltekniken och styrningen av kylparametrarna kan användas för att optimera stångmaterialens materialegenskaper.

Dessa goda resultat och slutsatser har uppnåtts genom det djupa samarbetet mellan SSAB, Outokumpu och HiG. Samproduktionen, som började i styrgruppen med planering av arbetet tillsammans med den kombination av forskning som bedrivs på HiG och hos företagen, har lett till ett lyckat projekt med stor kunskapsöverföring i alla riktningar under projektets gång.

**Nyckelord:** Värmebehandling, avancerad kylning, materialkaraktisering och materialmodellering

## Acknowledgements

The authors would like to thank Anders Carlestam and Ulrika Fager at SSAB EMEA AB and Rasmus Kristensen at Outokumpu Degerfors for providing information and data for the case studies as well as project planning, helpful discussions, and future joint publications. The authors would like to thank KK-stiftelsen and University of Gävle (UoG) for the financial support.

Gävle January 2023

Getiye Wodaje Gebeyaw, Pavel Romanov, Mohammad Jahedi, Mattias Calmunger, Bahram Moshfegh





# Table of Contents

Introduction	1
Aim	1
Activities	1
Participating companies in the project	2
Short presentation of the SSAB EMEA AB	2
Short presentation of the Outokumpu company in Degerfors	2
Cooling technology	3
Introduction	3
Methodology	3
Experimental study	3
Numerical study	4
Parametrical study	5
Case study	5
Configuration of multiple arrays of impinging jets	5
Studied objects	6
Studied parameters	6
Temperature measurement set-up	7
Results	9
Temperature drops in one sample	9
Effect of the flow rate on the cooling speed	10
Effect of the subcooling temperature on the cooling speed	10
Prediction of the surface temperature	10
Prediction of the surface heat flux and heat transfer coefficient	11
Conclusions	13
Investigation of the material properties	14
Introduction	14
Methodology	14
Experimental study	14
Numerical study	15
Results	15
Mechanical properties from experiments	15
Microscopy	16
Phase fraction simulation	17
Conclusions	18
References	19



# Introduction

World steel production was 1 912 million tons in 2021 and the Swedish steel industry share was about 0.2% or 4.7 million tons. Thus, the Swedish steel industry is globally a minor steel producer, but most Swedish steel companies are world leaders in different product segments. Almost 80% of Swedish steel products are exported to more than 140 countries. The export worth of the Swedish steel products was about 53 billion SEK 2020. The Swedish steel companies with in-house high level of specialization have succeeded in developing special types of steel within selected market niches. Material development and heat treatment process are key factors for the Swedish steel industry's success. Efficient and environmentally smart steel products from Sweden contribute to less material utilization, longer service life, less wear and tear and improved energy efficiency.

For Swedish steel companies SSAB and Outokumpu producing special steels, it is very important to be able to control the cooling process in order to produce steel bars with excellent properties. SSAB needs to be able to reach high quenching rates of their carbon steel to obtain the required steel phase and thus the correct properties of the bars. In the same manner, Outokumpu needs to obtain high cooling rates for its stainless steel but prevent the occurrence of detrimental phases in the bars. Both steel companies also want to be able to control the cooling process so that the excellent steel properties become even over the bars' spatial configuration.

As a result, there is continuous industrial demand for more advanced thermal management methods in the steel industry to make production with improved quality and material performance, and to reduce the use of expensive alloy materials and thus cost. Among available quenchants on the market, water is one of the most popular in terms of effectivity, use of resources, availability, and cost. Water can be used in both water impinging jet and water spray cooling techniques in industrial quenching systems.

SSAB and Outokumpu ambitions are to bring superior products into the bar market, based on the existing platform for plate manufacturing using low-alloy martensitic steels. Controlling accurately the thermal treatment of carbon and stainless-steel bars both spatially and temporally are key factors of optimizing the properties of the products. SSAB and Outokumpu have a need for increased knowledge of how to optimize the heating and cooling cycles for bar products, in order to further develop the products. The proposed method for developing bar products needs new cooling technology, supported by lab tests in a well-controlled environment, and supported by modelling tools and field measurements as well as skilled personnel.

## Aim

The aim of the present research project, mainly the same as in the application, is to reveal the spatial-temporal behavior of a newly developed cooling technology in order to produce steel bars with excellent properties and to control the phase transformation to achieve optimal performance of the steel bars depending on the application. A vigorous method to achieve the project aim is to combine knowledge and tools from different disciplines, i.e., fluid mechanics, heat transfer, solid mechanics, and material science. Consequently, the project objectives are:

- Explore experimentally the underlying heat transfer mechanisms and spatial-temporal behavior of the proposed cooling technology for heat treatment of carbon and stainless-steel bars.
- Enable optimization of steel bar properties, by controlling the phase transformation for optimal performance of the bar using the new cooling technology.
- Evaluate the material properties, cost-effective flexibility potential and resource efficiency for the heat treatment of steel bars using the new cooling technology.
- Make data and tools available for replication and renewal of science.
- Disseminate results and conclusions to the relevant stakeholders.

## Activities

One of the main activities of this project was to understand thoroughly by means of experimental and numerical investigations the cooling performance of water IJCT, carbon and stainless-steel bars

at a rather high temperature. In addition, the main activity was to evaluate and understand the resulting materials properties based on experimental and numerical work.

## Participating companies in the project

SSAB EMEA AB and Outokumpu Degerfors were the participating companies in the present project. The companies provided information about the type of products to be investigated, product properties and the dynamics of production as well as the results from in-house experimental studies.

### Short presentation of the SSAB EMEA AB

The steel (plate and strip) production plants are in Sweden (Luleå, Borlänge, Oxelösund and Finspång, Finland Raahе and Hämeenlinna), and America (Montpellier and Mobile).

SSAB is the largest steel sheet manufacturer in Scandinavia, with its blast furnace, coking plant, and steelworks located in Luleå and its rolling mills and coating plants in Borlänge—the initial product is sent from one location to the other via train. The division also has a coil coating line, lamination line, and special steels production. SSAB Special Steels in Oxelösund is the only steelworks in Sweden to have its entire vertical production base in one place, from raw material handling to its rolling plates. Ninety percent of its production is exported, with its chief export partner being Germany.

Bars are produced from blooms produced in the Oxelösund metallurgy plant. SSAB has the focus on the high end of the bar-market, with brands as TOOLOX 44 and HARDOX500.

### Short presentation of the Outokumpu company in Degerfors

With the flexible rolling mill in Degerfors, Outokumpu Long Products produces hot-rolled rod and billet. The work mainly produces austenitic, martensitic, ferritic and duplex stainless steel. For the part of the products that require heat treatment, this is done in the company's extinguishing annealing line in Storfors. The extinguishing annealing line is fully automated where the material to be heat treated is laid out on the entrance side of the furnace and comes out heat treated at the other end. see illustration in Figure 1. The furnace is electrically heated and thus the carbon footprint of the heat treatment operation of rod is significantly lower compared to traditionally gas-fired heat treatment furnaces. This is fully in line with Outokumpu's ambition and goal to achieve carbon-neutral steel production. The furnace was originally designed and built to heat treat pipes. When Outokumpu Long Products acquired the facility, some rebuilds, and adaptations have been made to be able to heat treat rods in the extinguishing annealing line. During the UoG project, several steel grades have been qualified and can be produced in the extinguishing annealing line. In addition, operational attempts have been made to harden but also call at carbon steel rods. Today, in addition to Outokumpu Long Products' own stainless-steel products, subcontracting processing of carbon steel bars is also processed. Figure 2 shows when the rod is driven through the cooling zone.

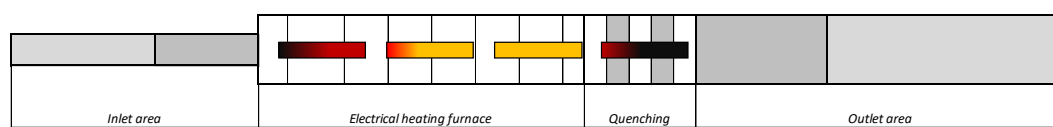


Figure 1: Outokumpu's annealing line.



Figure 2: Rod passing through cooling zone.

# Cooling technology

## Introduction

Accurate control of cooling of carbon and stainless-steel products both spatially and temporally are key factors of optimizing the properties of the carbon and stainless-steel products in the rolling operation of long product. This results in the need for a good understanding of cooling technique and control of the cooling process. Water impinging jet and spray jet cooling techniques provide different cooling performances and possibilities, which are useful to design tailor-made cooling process in the quenching of the operation.

In spray jet cooling technique, uniform cooling rate over the quenching area can be obtained by water drops sprayed from the jets. The different range of size and type of spray nozzles as well as pressure and water flow rates provide excellent flexibility to use the cooling technique for many quenching applications.

However, water impinging jet technique provides possibility to cool down a target local area with impinged water flow. There are several parameters, which may affect on boiling heat transfer and its characteristics results in cooling efficiency of the technique. There are many parameters that affect the cooling rate of quenching by water impinging jet: the water jet velocity [1], size and configuration of jets over cooling surface [2-4], jet-to-jet spacing in the multiple pattern of jets [5, 6], water temperature [7, 8], rotation or movement speed of product in the production line [1, 5-7], thickness of quenching product [9], initial quenching temperature [5, 6] and additive surfactants to water [10].

In the KKS project a multipurpose interrupted cooling (Mulpic) system with some new advantages and features tailor-made for the bar products in a rolling operation has been developed. The development has been done for more than three years by carrying out a wide range of experimental and numerical investigations covering both fundamental study and practical implementation. The multipurpose interrupted cooling (Mulpic) system covers both water spray nozzles and water impinging jets. The system has been tuned for each specific condition at the test facility by analyzing the effect of the important parameters to provide a controllable cooling system for the bar products.

## Methodology

A combination of experimental, numerical, and parametric studies has been employed to investigate the characteristics of boiling heat transfer, the cooling performance of water impinging jet and spray jet cooling techniques. The research methods of the present investigation can be described in the following three steps, i.e., experimental study, numerical study and parametric study.

### *Experimental study*

In the present work an in-house built test rig has been used for measurement of the quenching process. The schematic of experimental test rig of quenching system by water-impinging jets and spray jets are shown in Figure 3. The test chamber is the centre part of the test rig where heating and quenching processes of test object are carried out. The test rig has been designed in such a way to provide flexibility of installing various types of long steel products. The test object can be hollow cylinder, bar, rod, or any other form of similar shape, see Figure 4. As an example, Figure 3 shows an installed cylinder in the schematic of the test rig. The heating of a test object is carried out by an induction heater with moving rail system. The heater is equipped with a smart controlling system to provide accurate heating rate based on the test object temperature during the heating process.

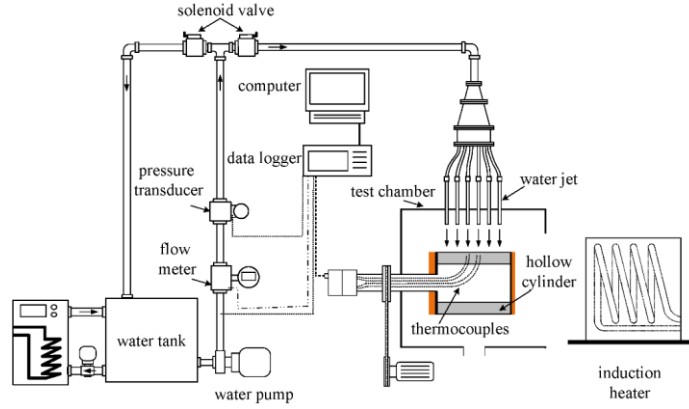


Figure 3. Picture and schematic of the in-house experimental test rig at the UoG.

The water circulation system is equipped with a main pump. The water flow rate and pressure in the circulation system are measured by magnetic flow meter and differential pressure transducer, respectively. Two-way solenoid valves installed in the circulation system control the direction of water flow to start and stop the quenching process based on the signal from the LabVIEW program. The start signal is sent when the desired initial quenching temperature is obtained in the test object (850 to 1200 °C) and quenching experiment is carried out until the final cooling temperature is reached. To introduce rotation to the test specimen to mimic the condition of rolling mill, a servo motor, chain system and a rotary shaft has been installed and coupled to test object. More details of the experimental process have been reported by Jahedi [11]. Temperature measurement is done with embedded thermocouples in the test object. The recorded temperature data during heating and cooling process are used to analyze the quenching process as well as input into the numerical simulation of quenching system, which are described in the next section.

#### *Water impinging and spray jet technique*

Water jet technique is a proper cooling technique for long products. Adding more impinging or spray nozzles in the configuration creates good flexibility to control the cooling rate during the quenching process. However, complexity of the quenching phenomena and heat transfer are raised with more interaction between water flows along each row as well as between multiple rows which is illustrated in Figure 4. In this project a series of comprehensive study conducted on a wide range of parameters as well as effect of number of rows in the multiple array which may influence the boiling heat transfer of multiple arrays of impinging jets have been carried out.

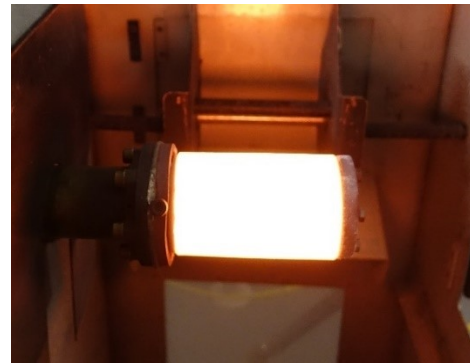
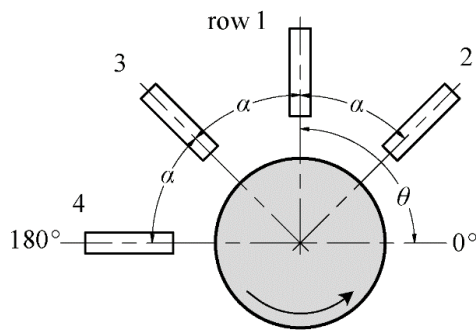


Figure 4: Set up for 4-rows multiple arrays of jets around rotary bar (left) and a heated bar sample (1100 °C) prepared for quenching experiment (right).

#### **Numerical study**

In practice it is very challenging to measure temperature and heat flux over the quenching surface. The measurement instrument cannot be located over the quenching surface as it may disturb the hydrodynamics of the boiling or cannot withstand the harsh conditions of the high temperature and fast cooling rate during the quenching.

One suitable solution to determine the surface temperature and heat flux is to solve an inverse solution based on recorded temperature beneath the quenching surface. The measured temperature data is used to solve a boundary value problem for the heat conduction equation to predict the surface temperature and heat flux. The predicted surface temperature is then used in a direct numerical simulation to predict the temperature in the material during the quenching process. Figure 5 shows the process from experimentation into the inverse simulation and finally heat transfer simulation of quenching in the test object.

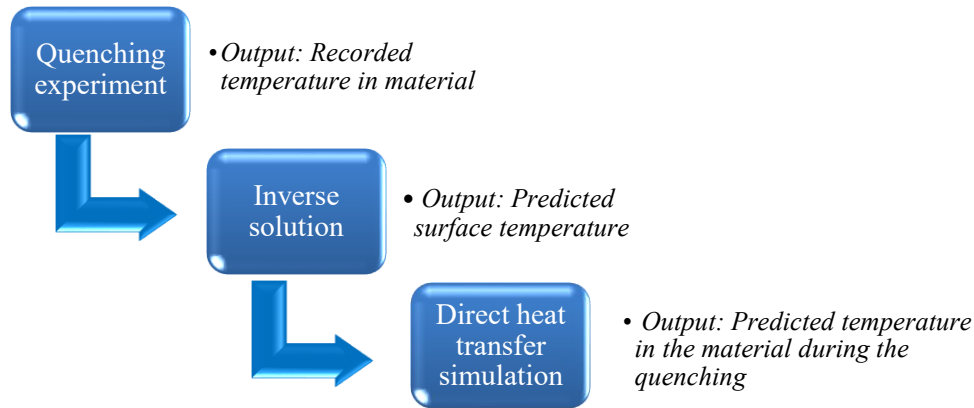


Figure 5: Experimental and numerical procedure to predict temperature variation inside the test object during quenching.

#### *Inverse heat conduction solution*

As it is shown in Figure 5, the input of the inverse solution is the recorded temperature data in the test object during the quenching. In this manner, an inverse numerical simulation has been developed by the research group [11] to apply the GMRES solution [12] into simulation of quenching of bar products by water spray and impinging jets techniques. More details about mathematical method of the developed inverse solution can be read in [11] where results show how the mathematical model can be adjusted for different industrial applications (different cooling rate and initial quenching temperature).

#### *Direct heat transfer simulation*

To simulate the spatio-temporal heat transfer and temperature distribution in solid material during the quenching, numerical analysis is carried out in form of direct simulation of heat transfer which is shown as final step in Figure 5. In this manner, Comsol Multiphysics software 6.1 is used to simulate the heat conduction in the material and the predicted surface temperature of the test object by inverse solution is used as a known boundary condition in the simulation.

#### **Parametrical study**

In addition to the investigation of the hydrodynamic behaviour of the quenching process in the experimental study, a comprehensive parametrical study was carried out. The influence of the following parameters has been investigated: flow rate, sub-cooling temperature, rotation speed, object dimension, jet angle, jet spacing, nozzle diameter, nozzle height, number of rows, in-line and staggered arrays.

#### **Case study**

A comprehensive experimental study has been conducted on a wide range of parameters that may influence the cooling performance of the impinging jets on the studied bars. In the present project, a total of 167 transient quenching experiments have been carried out to fulfil the aim of the project.

#### **Configuration of multiple arrays of impinging jets**

To increase the quenching area over the bar by impinging jets, a multiple array of nozzles has been designed for the experimental study. The multiple arrays of impinging jets will improve the quenching phenomena and heat transfer rate will be increased with more interaction between multiple impinging jets [6]. Both in-line and staggered pattern has been implemented in the configuration of the multiple arrays of impinging jets and studied separately to evaluate the effect

of position of nozzles in the pattern on local and area-averaged heat transfer in terms of surface heat flux and spatio-temporal heat transfer by internal heat conduction in solid material.

### **Studied objects**

The diameter of carbon steel bars tested were 50 mm, 70 mm and 100 mm and the diameter of stainless-steel bar was 80 mm.

### **Studied parameters**

To understand thoroughly the performance of quenching bar by multiple arrays and producing a data map for practical application of multi-jets in quenching of rotary bar, a comprehensive parametric study has been performed on multiple arrays of impinging jets with two configurations, i.e. in-line and staggered pattern.

The parameters studied include initial quenching temperature, jet diameter, cooling water temperature, the rotation speed of the test object, spacing between neighbouring jets, cooling water flow rate and the jet velocity. Furthermore, the effect of different soaking times was studied to see the effect on material structures.

The first carbon steel test on the 100 mm bar was made with initial quenching temperature of 880 °C using jets with 8 mm in diameter while the bar was rotating at 50 rpm and the cooling water temperature was 19 °C. The initial quenching temperature was then increased to 920 °C and some tests were done including the first fresh material test (Test 110\_108), where the bar was rotating at 30 rpm and the cooling water temperature was 23 °C. The cooling water flow rate, and hence, the jet velocity was then varied keeping other parameters constant until the second and third fresh material tests (Test 110\_18 and Test 110\_46) were done. Later, some preliminary tests at 700 °C and different rotation speed, number of jets and cooling water flow rate to get faster cooling than the previous two fresh material tests have been carried out.

After the material analysis of the three fresh material tests and comparing the 700 °C and 900 °C tests, it was decided to avoid the plateau on the cooling curves of those sensors closer to the middle of the bar by successively reducing the initial quenching temperature. Finally, the 100 mm bar tests by doing seven more fresh material tests with initial temperatures ranging from 830 °C to 940 °C with no or 15 minutes of soaking time.

For the 70 mm bars different arrangement and number of jets have been investigated until the test setup with fastest cooling speed was achieved. Five fresh material tests with similar test condition but the initial quenching temperatures ranging from 870 °C to 940 °C have been carried out. Finally, four fresh material tests at 915 °C and varying the cooling water flow rate and number of jets to get four different material phase compositions have been conducted.

Table 1 presents the range of variation for the studied parameters, i.e., jet size, number of jets, rotation speed and starting temperature for three SSAB carbon steel bars. All combinations of variables with three bars sizes, resulting in a total of 130 experiments in the parametric study.

Like the SSAB tests where the objective was to improve the cooling speed and hence the material hardness, the Outokompu tests were done to cool the test objects from the initial quenching temperatures down to 200 °C according to the predefined cooling time requirements of Outokompu for different stainless-steel bar diameters and initial temperatures so that the effect of these cooling times on the mechanical properties of the stainless-steel bars will be known. The stainless-steel bars that were planned to be tested were 80 mm, 100 mm and 125 mm in sizes and the initial quenching temperatures were 1075 °C, 1110 °C, 1092 °C. Due to the challenges mentioned in the previous section, only the 80 mm bar was used for the tests and the initial quenching temperature was 1075 °C. The cooling water temperature was 20 °C and the studied parameters include jet diameter, rotation speed of the bar, number of jets, cooling water flow rate and jet velocity. The jet sizes used for the tests were 6 mm and 8 mm in diameter while three different rotation speeds of the bar, i.e., 30 rpm, 40 rpm and 50 rpm were tested. Various values of flowrate/ or jet velocity were also tested. A single row of jets was used for tests requiring longer cooling times whereas four rows and five rows of jets were used for the other tests which were done with 10 to 15 jets all in staggered arrangement. The project came to conclusion after a total of 37 tests, one of which (Test 23) is a fresh material test. The range of parameters tested, and the number of tests done under these parameters is summarized in Table 2.



Table 1: Number of SSAB tests done under the studied parameters.

Parameter		Number of tests		
		100 mm bar	70 mm bar	50 mm bar
Jet size	8 mm	55	14	1
	6 mm	34	26	-
Number of jets	24	3	-	-
	21	7	-	-
	15	79	-	-
	12		13	-
	11		2	1
	7		3	-
	3		22	-
Rotation speed	20 rpm	2	-	-
	30 rpm	48	1	-
	40 rpm	35	39	-
	50 rpm	4	-	1
Starting temperature	940 °C	1	1	-
	920 °C	8	-	-
	915 °C	50	36	-
	910 °C	-	1	-
	905 °C	1	-	-
	880 °C	2	1	-
	870 °C	2	1	-
	860 °C	1	-	-
	850 °C	1	-	-
	835 °C	1	-	-
	830 °C	1	-	-
	825 °C	1	-	-
	815 °C	1	-	-
	800 °C	2	-	-
	740 °C	-	-	1
	700 °C	17	-	-

Table 2: Number of Outokumpu tests done under the studied parameters.

Parameter		Number of tests
		80 mm bar
Jet size	8 mm	27
	6 mm	10
Number of jets	15	25
	12	5
	11	1
	10	1
	3	3
	2	2
Rotation speed	30 rpm	26
	40 rpm	9
	50 rpm	2
Starting temperature	1075 °C	37

### Temperature measurement set-up

The temperature measurement setup includes machining the long steel bars into 120 to 140 mm long test objects. The bars are then drilled from one face along the radial direction to be able to measure the temperature at different depths. The placement of the temperature measurement sensors inside the test object changed over time due to some issues experienced during the measurements and depending on the size of the test object.

The first setup used two pieces of semi-circular pins where one of the pins is installed with 26 measurement sensors placed in alternating deep and shallow depths to measure temperature at two depths along the longitudinal direction while the other pin completes the cylindrical structure. The

pins are machined from the same material as the bars and have same thermophysical property as the bars. In addition to the 26 sensors installed inside the pin, another sensor placed in the centre of the test object measures the temperature at the core. The pin is then pressed inside a 80 or 100 mm diameter bar that has a hole large enough to accommodate the pin. The setup is shown in the Figure 6.

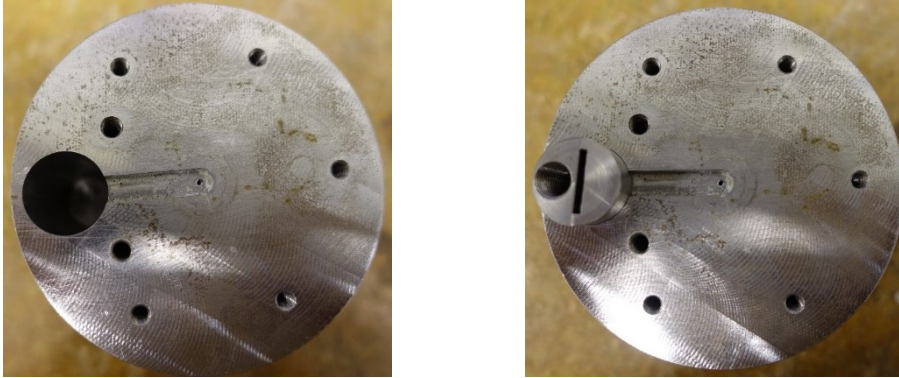


Figure 6: Sample of the configuration of the temperature measurement set-up.

In another setup, the test objects were drilled 30 mm deep from one of the faces to install the measurement sensor. In all of the different variations (see Figure 7), a sensor is placed at the middle of the bar to measure the temperature at the core while the number, spacing and arrangement of the other sensors depends on the size of the test material. The outermost sensor, in most of the cases, is placed 6 mm below the surface as drilling the test material closer to the surface than 6 millimeters may cause the test material to crack during experimentation.

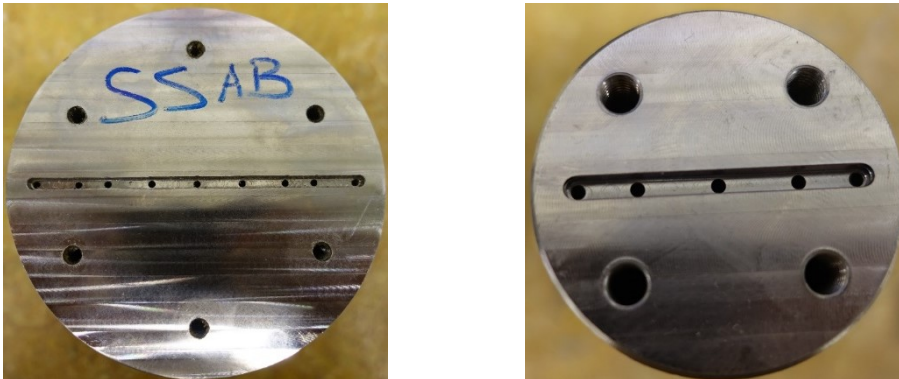


Figure 7: Sample of the position of the temperature measurement sensors.

Another type of setup used for experimentation was a hybrid one that combines the installation of 26 measurement sensors inside a pin and additional seven placed along two radial directions orthogonal to each other. This setup provides comparatively more information about the cooling rate in the material both radially and longitudinally. The differences in the cooling rates of the material reported by pairs of measurement sensors placed at similar radial position but located at different depth from the face using the setup that has no pin installed in the test object have been investigated. The hybrid setup is shown in Figure 8.

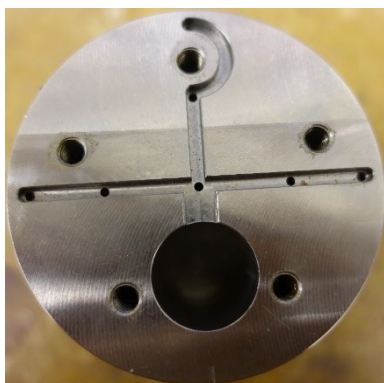


Figure 8: Configuration of the hybrid set-up.

In some cases, the sensors are placed 30 mm deep from the face, or a separate pin that has 26 holes placed in alternating deep and shallow depths to measure. The number of holes drilled to install the measurement sensors (thermocouples) and the spacing between them differs based on the size of the bar.

Also bars with 50 mm diameter with five holes along the diameter (one at the centre, two at 11 mm on either side of the centre, and other two 6 mm below the surface) were machined and tested. However, due to the construction of the coil in the induction heater and the copper flanges at the ends of the bar blocking the magnetic flux, it was not possible to heat the bars up to the required initial quenching temperatures.

In testing of the Outokumpu bars, some issues such as breakage of multiple measurement sensors inside the test material and frequent cracking of the bar have been observed. The initial quenching temperature in some of the tests was higher than those in the SSAB tests and the test object takes significantly larger times to both heat up and cool down. Thus, another setup which involves drilling 4 mm holes inside which 3 mm thick sensors were installed at the centre of the bar and at 24 and 32 mm from the centre in an 80 mm diameter test object as shown in Figure 9 has been implemented. The depth of the measurement locations was also increased to 35 mm from one of the faces.

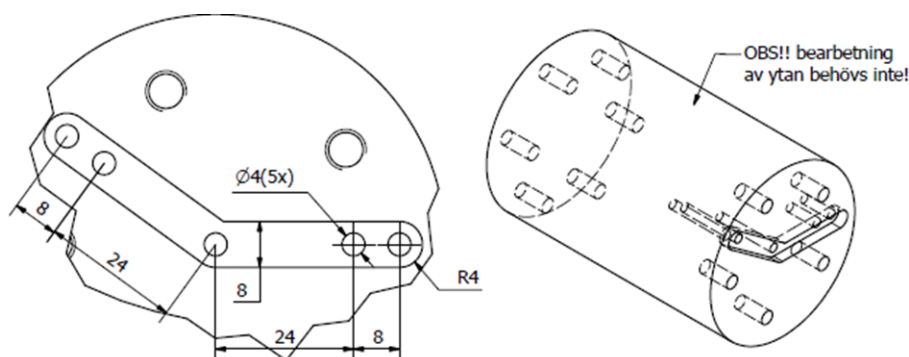


Figure 9: Position of the temperature measurement sensors for the Outokumpu's bar.

## Results

In this section the results from experimental and numerical studies are presented and discussed. The main aim of the section is to introduce flexibility of the research process including the experimentation, inverse solution and direct heat transfer simulations for investigation and optimization of the proposed cooling technology for carbon and stainless-steel bar products.

### *Temperature drops in one sample*

The result in Figure 10 shows the temperature drops at different positions inside the 100 mm carbon steel bar, Test 110\_100. One can observe that a high cooling rate has been achieved close to the surface of the bar and the cooling rate has been reduced from surface of the bar towards the center of the bar.

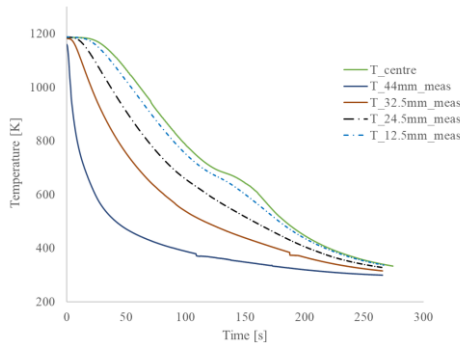


Figure 10: Average temperature drop beneath the outer surface of 100 mm steel bar quenched by water impinging jets.

### **Effect of the flow rate on the cooling speed**

The result in Figure 11 shows the effect of the quenching flow rate on the cooling speed for the 70 mm bars. The results show that a higher flow rate will improve the cooling rate and this effect has been pronounced more for the bar with smaller diameter.

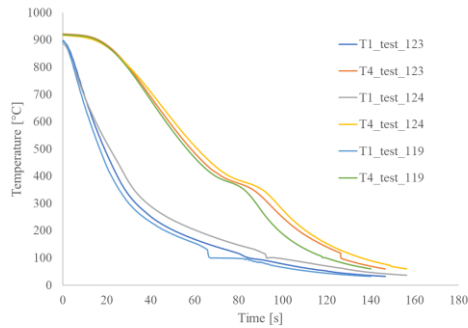


Figure 11: Effect of the quenching flow rate on the cooling speed for the 70 mm bar, T1 and T4 stand for the surface and the center temperature, respectively.

### **Effect of the subcooling temperature on the cooling speed**

The result in Figure 10 shows the effect of the temperature of the quenching fluid on the cooling speed for the 100 mm bar. One can observe in Figure 12 that lower subcooling temperature will enhance the cooling rate not only at the surface but also within the bar.

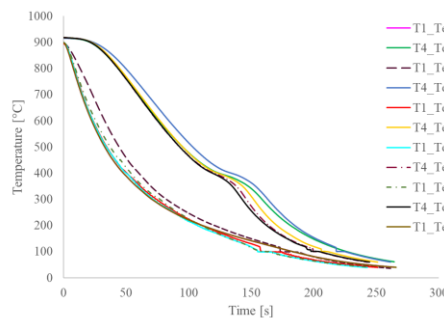


Figure 12: Effect of the subcooling temperature on the cooling speed for the 100 mm bar.

### **Prediction of the surface temperature**

Measured temperature data from several tests were used to predict surface temperature values of the test materials by a 1-dimensional inverse heat conduction model using the invers solution code INTEMP while the temperature at different depth from the surface and the surface heat flux were calculated by COMSOL Multiphysics using thermal conductivity data from Ferritico. Density and specific heat data was provided by SSAB. The results of these calculations are presented in Figure 13. The proposed triangular research method i.e., the experimentation, inverse solution and direct heat transfer simulations can be used to predict the surface temperature of the bar, which is very

challenging task to measure directly over the quenching surface. Because the thermocouples cannot be located over the quenching surface as they may disturb the hydrodynamics of the boiling, or cannot withstand the harsh conditions of the high temperature and fast cooling rate during the quenching.

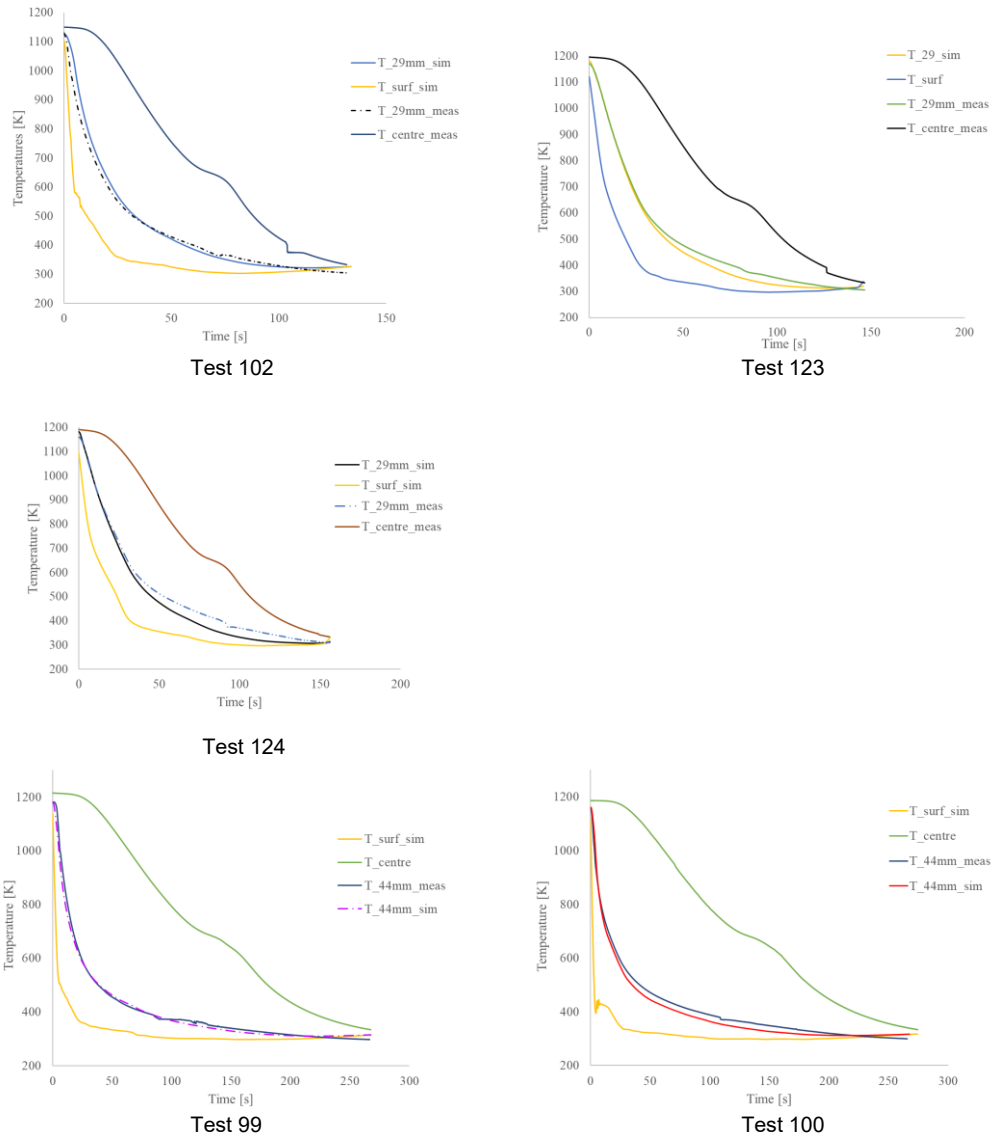


Figure 13: Predicted surface temperature, measured center temperature, simulated and measured temperatures at 29 mm depth for the Test 110\_102, 110\_123, 110\_124, and simulated and measured temperatures at 44 mm depth for the Test 110\_99 and 110\_100.

### **Prediction of the surface heat flux and heat transfer coefficient**

The surface temperature results from the Comsol Multiphysics have been used to predict the surface heat flux and heat transfer coefficient for several cases, see Figure 14 and 15. For heat transfer coefficient calculation, the subcooling temperature has been used as the reference temperature.

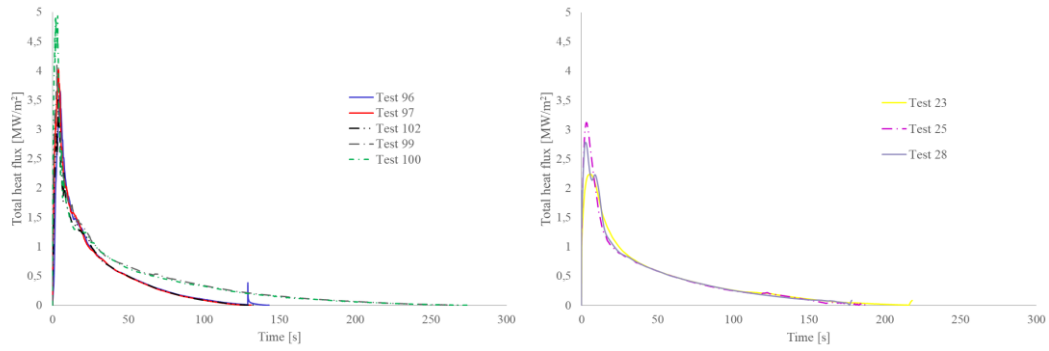


Figure 14: Predicted surface heat flux for the Test 110\_96, 110\_97, 110\_99, 110\_100 and 110\_102 for carbon steel bar (left) and for the Test 108\_23, 108\_25 and 108\_28 for stainless-steel bar (right).

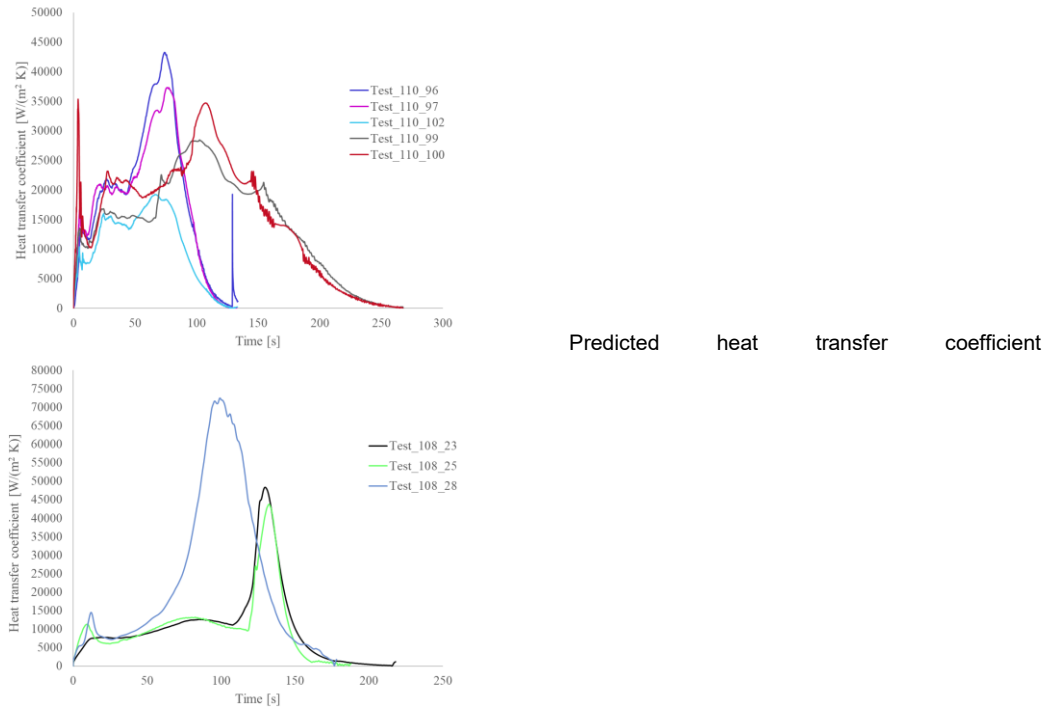


Figure 15: Predicted heat transfer coefficient for the Test 110\_96, 110\_97, 110\_99, 110\_100 and 110\_102 for carbon steel bar (left) and for the Test 108\_23, 108\_25 and 108\_28 for stainless-steel bar (right).

The average value for the heat flux and heat transfer coefficient for the tests 110\_96, 110\_97, 110\_102, 110\_123, 110\_124, 110\_129 and 110\_130 are presented in Table 3. To be able to reach high cooling rate is very crucial in order to obtain the required steel phase and thus the correct properties of the bars. Table 3 shows rather outstanding average heat transfer coefficient rates achieved for the studied cases by implementing the proposed cooling technology.

Table 3: Average Heat flux and Heat transfer coefficient of seven SSAB cooling tests.

Test	Average heat flux [MW/m <sup>2</sup> ]	Average heat transfer coefficient [W/(m <sup>2</sup> .K)]
110_96	0,531	18 404
110_97	0,591	17 405
110_102	0,546	10 425
110_123	0,535	13 789
110_124	0,503	11 028
110_129	0,470	8 839
110_130	0,471	7 484

In addition to successfully implementing the impinging jet technology to fulfil the required cooling speed, the effect of several process parameters such as soaking time and bar temperature have been investigated. The following results have been explored:

- The effect of the soaking time has been investigated in a series of experimental trials both at SSAB and UoG and has been reduced without effecting the material mechanical properties. It was shown that mechanical properties were not affected by the reduced soaking time since the desired steel phase was obtained.
- The effect of the bar temperature before cooling process has also been studied both at SSAB and UoG on the mechanical properties of the bar after cooling process and has been reduced. Since the desired steel phase was obtained at a lower bar temperature before cooling the material properties were not affected.
- The combination of these two new measures will reduce the energy use and process time, which will decrease the cost per kg product.

## Conclusions

One of the aims of the present project was to propose a tailor-made cooling process based on impinging jet technology and by experimental and numerical investigations provide deeper understanding of the spatial-temporal behavior of the carbon steel and the stainless-steel bars.

By using the special test rig at the UoG, detail temperature measurement mapping, invers solution and direct numerical simulation, the present project has identified and quantified several important aspects related to the quenching process, operating conditions, and temperature field development within the investigated products. The result from the proposed cooling process provides an outstanding cooling rate that is very crucial to obtain the required steel phase and thus the correct properties of the bar with different sizes. Results from this study have also shown that the cost per kg product can be reduced by tuning the process parameters such as soaking time and bar temperature before starting the cooling process.

# Investigation of the material properties

## Introduction

The performance of the steel bars relies on the materials properties and hence these are crucial to investigate in order to understand if the cooling processes are successful. The material properties that are of most interest in steel bar applications is the mechanical properties. The mechanical properties are obtained by controlling the phases in the microstructure of the steel. The mechanical properties and microstructural information can be obtained experimentally and by numerical simulation. The experimental approach is a good validation method after cooling experiment to validate if they were successful and the numerical simulation is good for further understanding to be used in optimization of both process and material development.

As mentioned, to further describe and understand the relationship between material properties, composition, microstructure and process conditions of steel bars, thermodynamic modelling has previously been used [13]. In recent work by Stormvinter et al. [14] the transformation of martensite for commercial steels has been modelled using a thermodynamic method. Another way of describing phase transformation is by using continuous cooling transformation (CCT-diagrams) [15]. By knowing the cooling process, in terms of cooling rates at each point of the steel, the obtained phases in the point either can be identified, by CCT-diagrams from literature or simulated data using software's. When the phases in all points are identified, the properties of the steel bar can be described. The knowledge and understanding of the steel phases are vital and creates a basis for describing, understanding, and optimizing the carbon and stainless-steel bars that will be produced using water impinging jet and water spray jet.

## Methodology

In order to investigate the material properties after the cooling experiments an experimental study and a numerical study were performed.

The experimental investigation of the steel bar material properties consisted of the mechanical testing techniques hardness and impact toughness testing. The hardness measurements give information if the needed mechanical properties are obtained, both in terms of hardness but also in terms of strength. Impact toughness reveals if the steel bar has the toughness needed, since this is crucial for many relevant applications. If the toughness is too low the product becomes too brittle, meaning the hardness and strength can be acceptable but the toughness too low. Thus, these two methods complement each other. By producing experimental results and comparing these results from the steel bars produced by investigated cooling techniques with the steel bars from conventional cooling at the companies, information needed to validate if the methods were successful and for further actions were gained.

To be able to further describe and understand the properties of the steel bars, coupled continuum mechanics and thermodynamic models were used. By using the finite element modelling (FEM) software COMSOL linked to thermodynamic models using Thermocalc and Ferritico's CCT-diagram software, the mechanical properties of the steel bars could be described and understood.

## Experimental study

The experimental study was conducted on steel bars that were cut, using electrical discharged machining (EDM), in halves and along the tips of the thermocouples thus along the radius. The samples were cut into several smaller specimens that were mounted in Struers PolyFast and prepared for metallographic examination, including hardness measurement and microscopy, using a Struers Tegramin-30 grinding and polishing machine. The preparation involved using 500, 1500, and 2000 grit SiC foils followed by 3, 1 and 0.25  $\mu\text{m}$  diamond suspensions. For the microscopy an etching was done at room temperature using a solution of nitric acid and ethanol (3% Nital) by dripping a few drops onto the mirror finish polished surface of the specimen for a couple of seconds. The sample was then rinsed using ethanol and dried using compressed air. Microstructures were observed using Leica DM6 M light optical microscope and images were recorded using the Leica LAS X software. Hardness measurements were performed following ASTM E384 standard using a Struers DuraScan 70 G5 hardness tester equipped with a Vickers diamond and using a load of 5 kgf. Five



indentations per position were made and the dispersion of values was measured with standard deviation.

To examine the impact toughness of the steel bar material the Charpy V test method using a standard sample with a dimension of 50×10×10 mm, according to standard EN 10045-1, were used. Impact toughness tests were performed at -20°C for the carbon steel bars. For each steel bar at minimum two samples were tested.

### **Numerical study**

The numerical study was conducted using the FEM software COMSOL linked with thermodynamically data obtained from Thermocalc and Ferritico. A 2D model was developed to describe the obtained material properties of the steel bars. The general idea of the 2D model is coupling of two physics: heat transfer in solids and solid phase transformations. Heat transfer affects the location and the speed of phase transformation, and phase transformation creates latent heat that affects the heat transfer in solids. Effective thermal properties were calculated for the material as a function of its phase fractions that have their individual thermal properties. The model predicts the temperature variation as the function of depth (along the radius of the bar) and phase transformations as well as resulting phase fractions. For phase transformations a phase transformation data source was required, where the Ferritico software was used. Diffusion-based phase transformations (i.e., the steel phases ferrite, pearlite and bainite) was based on the Johnson-Mehl-Avrami-Kolmogorov (JMAK) phase transformation model. Diffusionless (displacive) phase transformation (i.e., the steel phase martensite) was based on the Koistinen-Marburger phase transformation model.

### **Results**

In this section, the results from experimental and numerical studies are presented and discussed. The main aim of the section is to introduce the outcome of the mechanical testing, microscopy and numerical simulations for investigation and understanding, to be used in the future for further optimization of the carbon and stainless-steel bar products properties.

#### **Mechanical properties from experiments**

The results from the experimental study on mechanical properties are divided into hardness and toughness results.

##### *Hardness*

Some of the hardness results are shown in Figure 16, where hardness profiles from the surface into the middle of the bar of four different cooling strategies, denoted test 110\_123, 110\_124, 110\_129 and 110\_130 where 110\_130 is with the slowest and 110\_123 is the fastest cooling rate, are presented. All four strategies show an acceptable hardness level compared to conventional cooling methods (the comparison was done with company data not included in the project), meaning that the microstructure fully contains the wanted phase martensite since the hardness values are around 500 HV. The surface shows a lower hardness, this is normal for such products and is due to decarburisation at the surface.

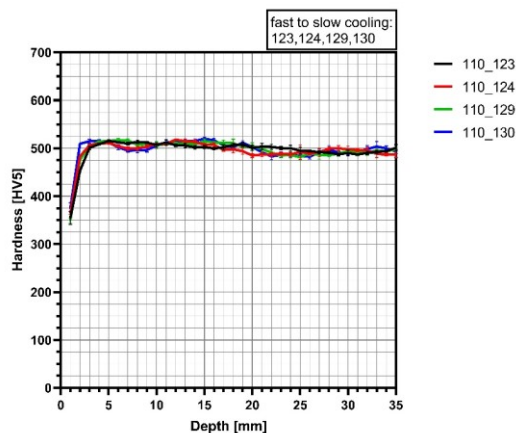


Figure 16: Hardness profiles of HV5 from the surface and into the middle of the bar for test 110\_123, 110\_124, 110\_129 and 110\_130, where 110\_123 has the fastest and 110\_130 the slowest cooling rate.

In Figure 17 two strategies with not fully martensite microstructure are shown, these results were used to develop the numerical simulation method. The difference between the two tests is that during Test 1 a higher cooling rate was used compared to Test 2, thus resulting in a deeper hardening depth.

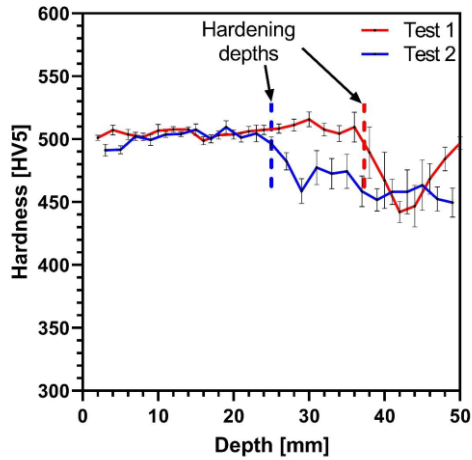


Figure 17: Hardness profiles of HV5 from the surface and into the middle of the bar for two different test, where Test 1 has faster cooling rate compared to Test 2.

In Figure 18 a hardness profile of the stainless-steel sample 108\_23 is presented, the profile is rather even and on an acceptable level compared to industry standard.

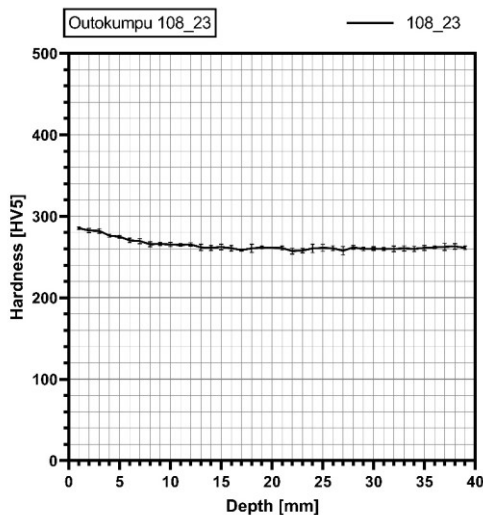


Figure 18: Hardness profile of the stainless-steel sample 108\_23.

### Impact toughness

The impact toughness test was conducted on the tests that were considered successful from the hardness profiles. Since the hardness can be on an acceptable level even though the bar product can be too brittle. This is due to the fact that hardness measure more locally compared to the impact toughness test. However, all tested materials had impact toughness results around or above 40 J, which is an approved level by industry standards and applications.

### Microscopy

For further understanding of the properties of the steel bars, some results from the microstructure investigation of the steels are presented in Figure 19. In this figure the variation of obtained phases is illustrated using the micrographs from different depth in Test 1 above. Figure 19 a) and b) shows microstructures of fully martensite, the same as for test 110\_123, 110\_124, 110\_129 and 110\_130. However, if the cooling is insufficient, i.e., not fast enough, other unwanted phases such as bainite can be present as shown in Figure 19 c) – e). In this project the aim was to achieve as fast cooling as possible, meaning fully martensite was wanted but these results also show the possible flexibility

of the cooling methods since with good control of the cooling process other phases can be obtained such as bainite that can be beneficial for other applications.

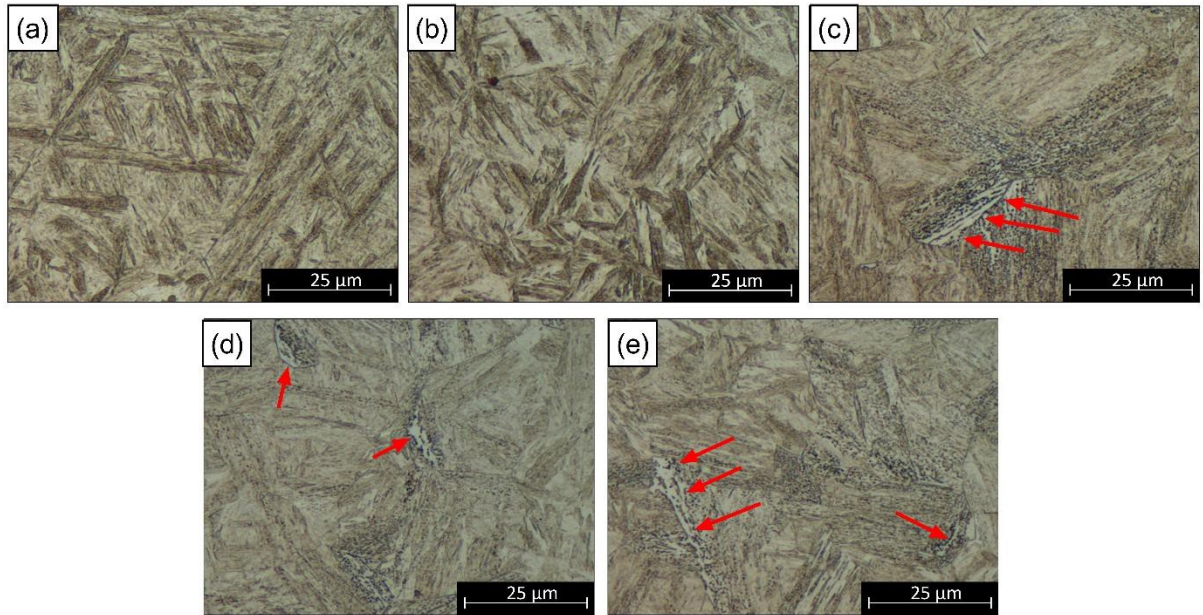


Figure 19: Microstructures of Test 1 - (a) 25 mm, (b) 35 mm, (c) 38 mm, (d) 40 mm, (e) 48 mm from surface correspondingly. Red arrows indicate bainite.

### ***Phase fraction simulation***

In this section results from the 2D modelling using COMSOL with data from Thermocalc and Ferritico software. Figure 20 shows the phase fraction from the surface into the centre of a carbon steel bar. It shows that at the surface of the bar the amount of martensite is higher compared to the centre, since the cooling rate is the highest at the surface. However, the amounts are in an acceptable range and are well aligned with the experimental results since the small amounts of bainite at the surface and centre of the bar suggested by the model are not enough to affect the properties. The next step is to use these phase fractions to obtain simulated mechanical properties, such as hardness. In this way the model can be used to predict properties obtained by a cooling strategy depending on the chemical composition in advance, hence it can be used to optimize the cooling process as well as develop the steels.

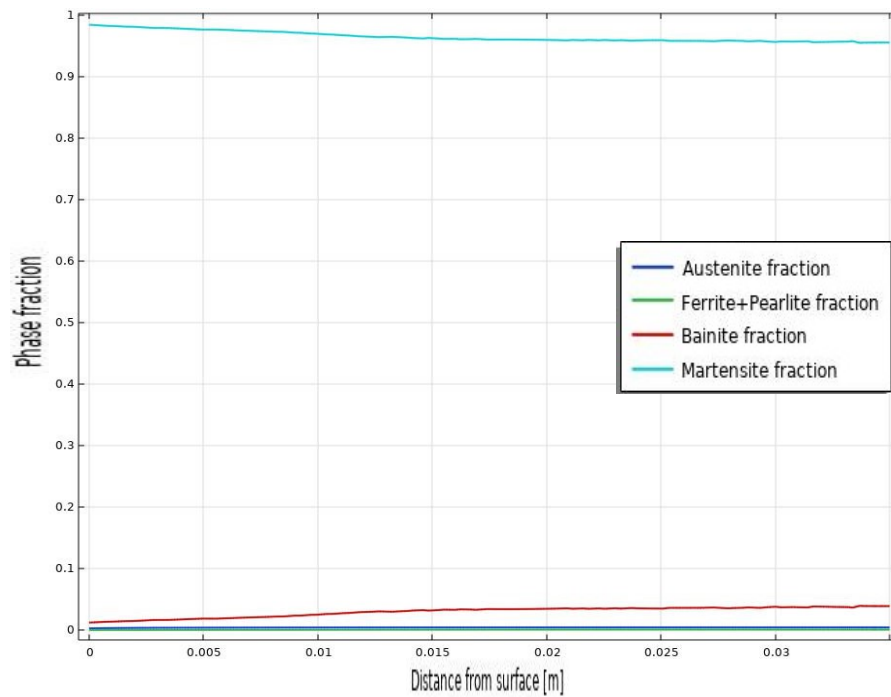


Figure 20: Simulated phase fraction of a 70 mm in diameter carbon steel bar from the surface to the centre.

## Conclusions

One of the aims of the project was to control the phase transformation for optimal performance of the bars using the proposed cooling technology. Both experimental and numerical results show that the cooling technology has resulted in the desired phase transformation and subsequently the desired steel phases.

Another aim was to evaluate the material properties, where hardness and impact toughness have been evaluated from heat treatment using the cooling technology.

## References

1. Mozumder A.K. et al. Subcooled water jet quenching phenomena for a high temperature rotating cylinder. *International Journal of Heat and Mass Transfer*, 2014. 68: 466–478.
2. Agrawal C. et al. Effect of jet diameter on the maximum surface heat flux during quenching of hot surface. *Nuclear Engineering and Design*, 2013. 265: 727–736.
3. Agrawal C. et al. Effect of jet diameter on the rewetting of hot horizontal surfaces during quenching. *Experimental Thermal and Fluid Science*, 2012. 42: 25–37.
4. Zhengdong L. Experiments and mathematical modelling of controlled runout table cooling in a hot rolling mill, 2001, University of British Columbia.
5. Jahedi M. and B. Moshfegh. Experimental study of quenching process on a rotating hollow cylinder by one row of impinging jets. In *Proc. Experimental Heat Transfer, Fluid Mechanics and Thermodynamics*. 2017. Brazil.
6. Jahedi M. and B. Moshfegh. Quenching a hollow rotary cylinder by multiple configurations of water impinging jets. *International Journal of Heat and Mass Transfer*, 2019, 137: 124–137.
7. Gradeck M., et al. Heat transfer from a hot moving cylinder impinged by a planar subcooled water jet. *International Journal of Heat and Mass Transfer*, 2011. 54(25): 5527–5539.
8. Gradeck M., et al. Boiling curves in relation to quenching of a high temperature moving surface with liquid jet impingement. *International Journal of Heat and Mass Transfer*, 2009. 52(5–6): 1094–1104.
9. Agrawal C. et al. Effect of surface thickness on the wetting front velocity during jet impingement surface cooling. *Heat and Mass Transfer*, 2017. 53(2): 733–741.
10. Ravikumar S.V. et al. Experimental investigation of effect of different types of surfactants and jet height on cooling of a hot steel plate. *Journal of Heat Transfer*, 2014. 136(7): 072102.
11. Jahedi M., et al. Transient inverse heat conduction problem of quenching a hollow cylinder by one row of water jets. *International Journal of Heat and Mass Transfer*, 2018. 117: p. 748–756.
12. Elden L. and V. Simoncini. A numerical solution of a cauchy problem for an elliptic equation by krylov subspaces. *Inverse Problems*, 25(6):
13. Lukas H.L. et al. *Computational thermodynamics: The Calphad method*. New York, USA, Cambridge University Press, 2007.
14. Stromvinter A. et al. Thermodynamically Based Prediction of the Martensite Start Temperature for Commercial Steels. *Metallurgical and Materials Transactions A*, 2012. 43(10): 3870–3879.
15. Zhao M.C. et al. Continuous cooling transformation of undeformed and deformed low carbon pipeline steels, *Materials Science and Engineering A*, 2013. 355: 126–136.



## Working Paper Series

54. Invalid weighting in gender-neutral job evaluation tools. Stig Blomskog. Department of Industrial Development, IT and Land Management. 2016.
55. En analys av Arbetsdomstolens arbetsvärdering i ett lönediskrimineringsmål. Stig Blomskog. Avdelningen för industriell utveckling, IT och samhällsbyggnad. 2016.
56. Behov av kompetensutveckling bland verksamhetschefer och biståndshandläggare i Region Gävleborg. Marianne Andrén och Tomas Boman. Avdelningen för socialt arbete och psykologi. 2016.
57. Kartläggning av vindförhållanden på Gävle Strand. Modellprov utförda i vindtunnel vid Akademin för teknik och miljö, Högskolan i Gävle. Leif Claesson. BMG-labbet. 2018.
58. Can Geographic Information System Help us to Better Understand Inequalities in Health Outcomes in the Era of Sustainable Development? Gloria Macassa. Department of Occupational and Public Health Sciences. 2018.
59. Food Insecurity in Mozambique. What Do We Know? And what Can Be Done? Gloria Macassa, Elsa Maria Salvador and Jose da Cruz Francisco. Department of Occupational and Public Health Sciences. 2018.
60. Social Entrepreneurship, Population Health, and Wellbeing in the Swedish Welfare. Opportunities and Challenges. Gloria Macassa, Mamunur Rashid and Agneta Morelli. Department of Public Health and Sport Science. 2020.
61. Mapping Social Enterprises in Gävleborg County, Sweden, 2020: The Social Enterprise for Sustainable Health Promotion Project (SESHP). Agneta Morelli, Mamunur Rashid, Anne-Sofie Hiswåls and Gloria Macassa. Department of Public Health and Sport Science. 2020.
62. Införanden av en dator per elev - en kunskapsöversikt 1:1 i skolors vardag. Sara Mörtzell. Avdelningen för utbildningsvetenskap. 2023.
63. Effect of spatial-temporal behavior of a newly developed cooling system on carbon and stainless steel bar properties. G. W. Gebeyaw, Pavel Romanov, Mohammad Jahedi, Mattias Calmunger and Bahram Moshfegh. Avdelningen för byggnadsteknik, energisystem och miljövetenskap. 2023.

**Published by:**  
Gävle University Press



**Postal address:** SE-801 76 Gävle, Sweden  
**Visiting address:** Kungsbäcksvägen 47  
**Telephone:** +46 26 64 85 00  
[www.hig.se](http://www.hig.se)