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Hardening of Carbon Steel by Water Impinging Jet Quenching Technique

Differential Cooling of Steel Sheets and
Quenching of Cylindrical Bars

Pavel Romanov

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Quenching of Cylindrical Bars

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Abstract

Austenitization followed by quenching is a well-known conventional heat-treating procedure which is widely used on carbon steels with the aim to obtain high strength in as-quenched condition. Such quenching is usually done by immersing a steel product into the cooling medium which provides a uniform cooling of the surface. The cooling rate can be adjusted to a certain degree on a “component” length-scale by using different cooling mediums such as water, oil, polymer solution, etc. However, certain steel products such as beams, pillars in automobile industry or different machinery parts in agriculture require a proper and controllable cooling gradient and thus mechanical property gradient within the product. It is difficult to control the cooling rates locally on the length-scale smaller than the product only by replacing the quenching medium. In addition, quenching by immersing the product into the cooling medium is accompanied by thermal stresses due to the different cooling rates of the surface and the core, and also accompanied by transformation stresses due to the volume change during phase transformations. These stresses may lead to negative effects such as undesired residual stresses or even cracks. Therefore, cooling must be properly optimized and controlled to eliminate these drawbacks. Such a controllable cooling can be performed by several impingements of the water jets onto a hot austenitized surface at certain locations. By controlling the water flow, number of jets, their locations and other parameters, the global and the local cooling rates can be optimized for a specific industrial application later on.

This thesis demonstrates the potential and capability of the water Impinging Jet Quenching Technique (IJQT) to provide a flexible and controllable cooling for both differential and for uniform quenching cases. The test rig of IJQT was developed in the University of Gävle and was used to perform quenching experiments in this study: differential cooling of thick sheets and uniform quenching of bars to different depths. Differential cooling was performed on square-shaped carbon steel sheets with thickness of 15 mm, and the uniform quenching with different flow rates was performed on carbon steel cylindrical bars with 100 mm in diameter. Along with the physical experiments, Comsol Multiphysics 5.6 software was used to solve a 1D heat transfer problem to estimate the cooling rate profile along the radius of the bar. The experiments were verified by observations and characterization of the microstructure using light optical microscopy (LOM), and by examining the mechanical properties through tensile tests and hardness measurements. The results of the quenching experiments and verifications showed a high

potential and flexibility of the IJQT in differential cooling case as well as in the uniform quenching case.

Keywords: Differential cooling, impinging jet quenching, microstructure gradient, hardening

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Appended Manuscripts

1. P. Romanov, M. Jahedi, A. Petersson, B. Moshfegh, M. Calmunger. Microstructure and Property Gradient of Boron Steels Obtained by Water Impinging Jet Quenching Technique – Submitted to a *journal* – 2021

I contributed to the design of experiments, performed metallurgical sample preparation, material characterization, microscopy investigation, majority of the mechanical testing, was the main contributor of the manuscript writing.

2. P. Romanov, M. Jahedi, A. Carlestam, B. Moshfegh, V. Norman, M. Calmunger. Hardening of Cylindrical Bars by Water Impinging Jet Quenching Technique – *In manuscript*

I contributed to the design of experiments, performed metallurgical sample preparation, material characterization, microscopy investigation, mechanical tests, was the main contributor of the manuscript writing.

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Abbreviations

BCC	body centered cubic
BCT	body centered tetragonal
CCR	critical cooling rate
CCT	continuous cooling transformation
FCC	face centered cubic
IJQT	impinging jet quenching technique
PAG	prior austenite grain
TTT	time temperature transformation

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Part I

Background, experiments and conclusions

1. Introduction

1.1 Background

Quenching of carbon steel components through immersion into a cooling medium is a widely used heat-treating step to obtain high strength and hardness in as-quenched condition. However, this process is associated with consequences such as undesired residual stresses and even cracks that can lead to a premature fracture of a steel component [1]–[3]. Moreover, the demand for steel components with tailored mechanical properties is constantly growing [4]–[7]. This cannot be obtained by immersion into quenching medium; therefore, cooling must be performed in an optimized and controllable way in order to affect the microstructure in an intended manner thus obtaining necessary mechanical properties, as well as to avoid undesired consequences and to reduce the consumption of unnecessary resources.

One way to control the cooling process is to control the cooling rate of the component using water jet impingements with different flow rates and other parameters, such as the size of the nozzles and their configuration and location over the cooling surface, the water jet velocity, jet-to-surface distances and other parameters. This is an advanced cooling concept that requires extensive research. A test rig for Impinging Jet Cooling Technique (IJQT) was developed in University of Gävle and its potential is studied in this work.

1.2 Project Description

This thesis is a part of a project financially supported by Swedish Innovation Agency Vinnova, Swedish Knowledge Foundation, SSAB, Väderstad Components AB and University of Gävle. The project is focused on the creation of an advanced cooling concept (IJQT) to provide a deeper knowledge of the material behavior, which in turn will help to optimize and improve the heat treatment route.

A proper control of the cooling process using IJQT can help to optimize the heat treatment and eliminate the formation of undesired phases. Another potential advantage of IJQT is that a proper control of the local cooling rates within a single component can help to obtain components with specifically tailored microstructures and mechanical properties. It

can be obtained by targeting the specific surface area of the component with a unique configuration of water jets which results in a cooling gradient along the component leading to a gradient in mechanical properties.

These optimizations can reduce the amount of resources used for cooling and thus decrease the emission of carbon dioxide. The concept can be implemented further on in industry to obtain better quality components with optimal performance depending on the application. To make the implementation of IJQT in industry possible, extensive tests and evaluations of the technique are systematically investigated in this thesis.

1.3 Aim

The general aim of this thesis is to study the capability of IJQT of providing various intended cooling effects on different steel components. The study is focused on the investigation of a differential cooling effect on microstructure and mechanical properties of thick square sheets, and on the investigation of a quenching effect on hardening depths of cylindrical bars with the following research questions:

1. *Is IJQT capable of providing a differential cooling of sheets of different types of steel resulting in a mechanical property gradient, as well as of hardening the cylindrical bars to different depths?*
2. *What parameters or material properties have the largest impact on controllability of the technique in the context of the two cooling cases studied?*

1.4 Approach

To answer the research questions, two independent studies were conducted using two different setups of the IJQT test-rig. Setup 1 is used for the differential cooling of steel sheets to obtain microstructure and mechanical property gradients (Manuscript 1). Setup 2 is used for hardening of cylindrical bars to different hardening depths (Manuscript 2).

1.5 Outline

This thesis consists of 2 parts.

Part I:

Description of the theoretical background, experiments and conclusions.

Part II:

Appended manuscripts.

2. Theoretical Background

This chapter briefly describes the theoretical background required to understand the underlying processes of material behavior. The brought up theoretical areas include carbon steel, the effect of alloying elements, hardening mechanism, hardenability, and phase transformations relevant for the quenching experiments conducted to answer the research questions of this thesis.

2.1 Carbon Steel and Alloying Elements

Carbon steel is a widely used engineering material for enormous number of applications, from pipes, beams, concrete reinforcing steel bars to products or machinery parts consisting entirely of carbon steel. It has iron (Fe) as the main element and carbon (C) as an interstitial alloying element which increases the total strength due to solid solution strengthening effect. Carbon steel is generally divided into three groups depending on its carbon content: low carbon steel contains up to 0.3 mass-% C, medium carbon steel contains up to 0.6 mass-% C, high carbon steel contains more than 0.6 mass-% C [8].

Depending on the mechanical property requirements a certain product is supposed to fulfill, carbon steel is usually alloyed with additional alloying elements, such as manganese (Mn), silicon (Si), chromium (Cr), molybdenum (Mo), boron (B) and others. The content of these alloying elements, including carbon, affect the mechanical properties of the alloy and increases its hardenability, which is described in chapter 2.3 [9].

2.2 Hardening of Carbon Steel

It has been known for many decades that rapid cooling of carbon steel results in a diffusionless phase transformation from austenite to martensite. Martensite is supersaturated with carbon which hinders the movement of dislocations within its crystal structure and increases the steel's strength. To obtain the hardening effect, carbon steel has to be austenitized at a certain temperature, held for a certain time at this temperature to obtain fully austenitic condition, and then quenched quickly enough [2]. Steel in this condition is considered as "hardened" or in a "hardened condition".

When heated to a desired austenitization temperature (red arrow in Figure 1 in chapter 2.3) steel changes its crystal structure to a Face

Centered Cubic (FCC) crystal structure which corresponds to the phase austenite. A certain dwell time is required for the product to become homogeneously consisting of austenite. Longer austenitization time results in grain growth [10], however, this effect is not considered in this thesis.

When the desired austenitization temperature and time are reached, steel is quenched rapidly which eliminates the diffusion of carbon, thus resulting in a diffusionless transformation to the meta-stable phase martensite. Martensite is supersaturated with carbon and has a Body Centered Tetragonal (BCT) crystal structure [2]. This hardened condition may be then tempered to reduce the brittleness and increase ductility and toughness of the component according to the target application scenarios.

Rapid cooling of steel can involve large temperature gradients between the surface and the core leading to stresses in the material due to restrained thermal expansion. Apart from thermal expansion, steel is subjected to volume change due to phase transformations, which causes additional stresses in the material. These stresses may result in remaining consequences, such as quenching cracks or undesired residual stresses [1]–[3].

Another consequence of martensite hardening of steel is retained austenite: when martensite is formed it can isolate some of the volume of austenite thus hindering the retained austenite to transform to martensite. The amount of retained austenite increases with increasing carbon content and considering the steels used in this work, its amount is not taken into consideration in this thesis [11].

2.3 Hardenability

Hardenability is a material property of steel that gives understanding to what extent the steel can be hardened. It is defined as the ability of steel to form martensite, which is usually measured experimentally with a Jominy or a Grossman hardenability test [12].

The ability of steel to form martensite, i.e. the hardenability of steel, is controlled by the chemical composition of steel and the austenite grain size [2], [13]. As mentioned in chapter 2.1, alloying elements increase the hardenability of steel, which means that the formation of non-martensite is delayed. It is also said that the formation of non-martensite is shifted to longer times. This is clearly seen in time-temperature-transformation (TTT) or in continuous-cooling-transformation (CCT)

diagrams (black arrow in Figure 1). Both diagrams are useful tools for heat-treatment of steel and provide information about which phases are formed from austenite, when they are formed and to what extent. These diagrams can be calculated using a computer-aided materials simulation software or can be found in literature [14], [15]. Dilatometry is also a useful tool for experimental determination of phase transformation diagrams [16], [17].

TTT diagrams describe the isothermal phase transformations and CCT diagrams describe phase transformations during continuous cooling, which is relevant for this thesis. A simplified CCT diagram as an example is shown below.

Figure 1: Schematic explanation of a CCT diagram.

The solid lines in Figure 1 indicate the beginning of phase transformation from austenite and usually correspond to a 1% transformation. The horizontal red line indicates a temperature (A_3) above which the steel in equilibrium consists entirely of austenite. If steel is austenitized at lower temperature than A_3 , the initial condition would not be fully austenitic, but partly consisting of ferrite which will remain after cooling.

Different cooling rates (1, 2, 3) are indicated by dashed lines that cross different regions of corresponding phases. For example, cooling rate 1

indicates that steel contains only martensite after cooling, cooling rate 2 contains bainite, and cooling rate 3 contains both ferrite and bainite since the cooling curve goes through both regions. A useful characteristic of hardenability is martensite critical cooling rate (CCR), which is defined as the lowest cooling rate required to obtain fully martensitic structure [18]. As seen in Figure 1, every cooling rate lower than CCR crosses a non-martensite region.

2.4 Austenite Decomposition

Depending on which phase is transforming from austenite, transformation can be diffusive (diffusion-based) or diffusionless. Diffusive transformations involve the diffusion of carbon, which requires time, therefore diffusive transformations are likely to occur when low cooling rates are used i.e., when there is more time available for carbon to diffuse from saturated austenite. The product of diffusive transformation can be a single phase or combination of ferrite, pearlite, bainite depending on the thermal history and chemical composition. Ferrite is a stable phase of iron that has a Body Centered Cubic (BCC) structure and has 0.028 mass-% carbon or lower, depending on the temperature of steel in its equilibrium condition. Pearlite and bainite are microconstituents of ferrite and cementite that may appear in different morphologies [19]. Cementite is a metastable phase relative to the equilibrium between iron and graphite, and has 6.67 mass-% carbon [2]. The presence of mentioned constituents in a martensitic matrix decreases the overall strength of steel because martensite is harder than ferrite, pearlite and bainite.

Diffusionless phase transformation from austenite to martensite occurs fast, and as soon as the transformation begins, the amount of transformed martensite is only temperature dependent, which means that with lower temperature, the amount of martensite increases regardless of the cooling rate [20]. Therefore, as long as the cooling is faster than CCR and martensite start temperature is reached before the other phases start to decompose from austenite, the product of decomposition of austenite will be entirely martensite given that the cooling continues.

3. Experimental Work

To answer the research questions two independent studies were designed and carried out using the test rig for IJQT. To show how the heat treatment was done, the working principle of the test rig and two experimental setups are described in this chapter: setup 1 for steel sheets and setup 2 for steel bars.

3.1 Test Rig

The test rig for IJQT is shown in Figure 2.

Figure 2: The schematic of the test rig (courtesy of Jahedi [21])

The setup consists of a test chamber, where the heating and cooling is done, and the induction heater that can slide into the test chamber. The

general working principal is the following: the sample with embedded thermocouples is first attached to the holder inside the test chamber. The holder can rotate if needed and if the test object's geometry allows that. The induction heater is then moved on rails into the test chamber to heat the sample. When the target austenitization temperature and time are reached, the induction heater is then replaced by a setup of a nozzle pattern.

This setup was designed individually for the test objects studied in this work and described further. The temperature evolution from N-type thermocouples was monitored and recorded by a LabVIEW program in a similar manner as in previous publications associated with the IJQT test rig [22]–[26]. The reader can find a detailed description of the setup in work of Jahedi [21].

3.2 Setup 1: Steel Sheets

To study the technique's capability of providing microstructure gradients and thus mechanical property gradients by differential cooling, 15 mm thick square (10x10 cm²) steel sheets were used. To understand the technique's limitations and important parameters the steels had different carbon content.

Figure 3: The schematic of the differential cooling experiments.

Figure 3 shows the idea of differential cooling of sheets to obtain a property gradient along the length of the sheet. The quenching was performed by two nozzles placed at the left half of the sample symmetrically – one on each side at its lower corner. An obstructive separator fitted to the sample was also used in the center of the sample to isolate the right side from water and thus lower the cooling rate. Both steels were heat-treated in the same manner. For a detailed description of this differential cooling case the reader is referred to appended Manuscript 1 in this thesis.

3.3 Setup 2: Steel Bars

To understand if the test rig is capable of hardening the cylindrical bars to provide different hardening depths, two quenching experiments were performed using different water flow rates.

Figure 4: The schematic of the quenching process of a cylindrical bar (units in mm).

Two 100 mm cylindrical bars were austenitized for a couple of minutes and then quenched as shown in Figure 4. The first test bar (test 1) was quenched with a higher water flow rate to obtain a larger hardening depth than in the second bar (test 2). The analysis of different hardening depths will help to answer the research question about the capabilities of the technique. The steel used in this setup has though 0.26 mass-% carbon, it has higher hardenability than both steels in setup 1, which makes the experiments more diverse and contributes to better understanding of the role of hardenability for studied setups. For more detailed description of this setup the reader is referred to appended Manuscript 2 in this thesis.

4. Experimental Methodology

In this chapter the methods related to the quenching experiments are described. Specifically, the material that was used, the sample preparation procedure and the equipment that was used in order to answer the research questions raised in Chapter 1.3.

4.1 Material

Three steels that were used in this study are two low and one medium carbon steels, each containing 0.26, 0.27 and 0.38 mass-% carbon (C) correspondingly as well as a certain amount of other alloying elements such as Mn, Si, Cr, B etc. All material was delivered in soft “hot-rolled” condition, containing a mix of microconstituents pearlite and ferrite. The hardness of 0.26 mass-% C steel in hardened condition is 51 HRC (528 HV) according to the manufacturer [27]. The typical hardness values of 0.27 and 0.38 mass-% C in hardened condition are approximately 548 HV and 627 HV correspondingly according to the manufacturer [28], [29].

Different chemical compositions of these steels will result in different hardening effects and thus allowing to conduct a more in-depth study of the IJQT’s flexibility. The variation in chemical composition is also essential to better evaluate the critical material properties and their effect on the hardening effect of the technique. More detailed description of the steels can be found in appended manuscripts in Part II of this thesis.

4.2 Sample preparation

All samples underwent three preparation procedures, mainly cutting, polishing and etching as described below.

4.2.1 Cutting

The cutting strategy for quenching of sheets and bars is illustrated in Figure 5.

Figure 5: Drawings of the samples with EDM cutting lines in red; (a) a sheet for differential cooling experiments; (b) a cylindrical bar for hardening experiments; (units in mm).

The bars and sheets were cut into several smaller pieces using electrical discharged machining (EDM, marked with red) to minimize the risk of affecting the microstructure by deformation or heat, which other methods such as cutting with a disc may bring. Water jet cutting was not an option either because tolerances would be highly affected due to large thickness of the studied cylinders. All the cut specimens in Figure 5(a, b) were used for microstructure characterization and hardness measurements, except for the thinner specimens in (a) that were used for tensile tests described further in this chapter.

4.2.2 Polishing

The specimens for microstructure characterization and hardness measurements were carefully cleaned with ethanol and their sides were slightly grinded to remove oxides. The specimens were then mounted in Struers PolyFast and prepared for metallographic examination using a Struers Tegramin-30 grinding and polishing machine. Polishing was done using 500, 1500, and 2000 grit SiC foils followed by 3, 1 and 0.25 μm diamond suspensions.

4.2.3 Etching

The etching was done at room temperature using a solution of nitric acid in ethanol (3% Nital) by dripping a few drops onto the mirror-like finished surface of the sample for a couple of seconds. The sample was then rinsed using ethanol and dried using compressed air. A thorough polishing and accurate etching are key steps for a successful metallurgical examination.

4.3 Hardness Measurements

Hardness measurement is a proper method for a general examination of the condition of steels: for a given carbon content typical values of hardness can be calculated or found in literature for hardened conditions [3]. The decrease in hardness is also indicative for a softer phase formation in the microstructure, such as ferrite. To assess the IJQT's effect on mechanical properties of the studied steels, hardness evaluation is widely used in this thesis. It was performed following ASTM E384 standard using a Struers DuraScan 70 G5 hardness tester equipped with a Vickers diamond indenter [30].

According to the initial observation of the microstructure, the size of the prior austenite grains (PAG) was approximately 20-40 μm and since it is the hardness of bulk material which is of interest and not the hardness of individual grains, phases or microconstituents, the load was chosen to be 5 kgf. Choosing a higher load resulted in a larger indentation area which, following the standard, limits the number of indentations. Therefore, this load is reasonable to choose because it leaves an indentation with a diagonal of approximately 150 μm which covers several PAGs and the chance to hit a single hard particle is minimized.

Figure 6: Hardness measurement lines showed on a sheet (a) and on a half of a cylindrical bar (b).

Hardness of the sheets was measured inside (7.5 mm from both surfaces) along the measurement line as shown in Figure 6(a). Hardness of the cylindrical bars was measured at every second millimeter along the radius as shown in Figure 6(b). Five closely placed indentations per position were made in all experiments and the dispersion of values was measured with standard deviation of the mean values.

4.4 Tensile Tests

To provide additional information about the strength of steel and how it was affected by the IJQT, tensile tests were performed.

Figure 7: Geometry of a tensile specimen used in this study, units in mm. The thickness of the specimen is 2 mm.

Tensile specimen shown in Figure 7 were also cut using EDM from the thinner specimens in Figure 5(a). The width of the specimen corresponds to the thickness of the steel sheets (15 mm) used in setup 1. The length was chosen as short as possible to minimize the variation of mechanical properties along the specimen, and long enough to be clamped into the tensile testing machine. Tensile tests were performed with a 10^{-3} strain rate and 50 Hz logging frequency using Alwetron TCT50 machine equipped with 100kN load cell and Inersjö CyclicEdc application software.

4.5 Optical Microscopy

As the conditions of previously described steels were expected to be fully or partly hardened, optical microscopy was used to perform observations and characterizations of the microstructures. For this, Leica DM6 M light optical microscope was used, and the microstructures were imaged from an etched surface using the Leica LAS X software. It was selected since the microstructures expected to consist of martensite, ferrite, bainite and the chemical reaction during etching reveals the features of such structure providing necessary information for answering the previously defined research questions. In addition, optical microscopy is widely used in literature for microstructure characterization of carbon steels [31].

5. Results

In this chapter the main results from the experimental work described in Chapter 3 obtained by methods described in Chapter 4 are shown in connection to the previously defined research questions.

5.1 Differential Cooling

The differential properties of B27 and B38 steel sheets obtained by water jet quenching (see Chapter 3.2 Setup 1: Steel Sheets) are shown in Figure 8.

Figure 8: Strength and hardness profiles of B27 and B38 steel samples as a function of distance.

Hardness and tensile strength values of both steels shown in Figure 8 decrease with the increasing distance along the measurement line (Figure 6(a)) but in different manner due to the difference in their chemical composition. For the lower-carbon steel (B27), both tensile

strength and hardness gradually decrease from high to low values. For the higher-carbon steel (B38), a steep decline in tensile strength and hardness profiles was only observed in the last few measurements. The property profiles were verified by the microstructure characterization together with the cooling profiles in correlation with CCT diagrams (see appended Manuscript 1).

5.2 Quenching of Bars

The main results from quenching of cylindrical bars of 0.26 mass-% carbon steel (described in 3.3 Setup 2: Steel Bars) are shown in Figure 9. The hardness was measured according to Figure 6(b).

Figure 9: Hardness profiles and hardening depths of two cylindrical bars: bar 1 – 37 mm, bar 2 - 25 mm.

Bar 1 was quenched with a higher water flow rate than the bar 2 thus obtaining a larger hardening depth (37 mm) than bar 2 (25 mm), as seen in Figure 9. Hardness levels of both bars vary around 490-510 HV

followed by a decrease after a corresponding hardening depth. The hardening depths were verified by the microstructure characterization. The increase of hardness of test 1 after 42 mm may be a result of an insufficiently low finish temperature, but the exact reason remains to be explored.

The temperature evolution along the radius of the bars (between the center of the bar and the point located 17.5 mm far from the outer surface of the bar) was estimated by solving a 1D heat transfer problem using the recorded temperature data as boundary conditions. Using the obtained thermal history, the cooling rates were calculated and are shown for several locations in Figure 10. (The reader is referred to manuscript 2 for a detailed description of the heat transfer simulation and cooling rate calculation.)

Figure 10: Cooling rate profiles of test 1 and 2 with corresponding hardening depths.

As seen in Figure 10, the hardening depths correspond to the cooling rate of approximately 5 °C/s for both samples.

6. Discussion

The results from both experimental setups are discussed in this chapter with the focus on the research questions defined previously.

6.1 Capability of the Technique

The differential cooling of 0.27 mass-% carbon steel sheets resulted in a wide range of hardness and tensile strength of the material well fitted into a 10 cm wide sheet (see Figure 8), however some adjustments of the water-cooled side and the air-cooled side may provide a wider gradient and also lift up the property profile to higher levels. This may be beneficial for some machinery parts where one side of the product is required to be slightly softer than the other for practical reasons, and while the whole part in general must still withstand high loads.

The differential cooling of 0.38 mass-% carbon steel sheet showed some strength and hardness variations but not as wide as the 0.27 mass-% carbon steel (see Figure 8). The improvement to obtain a more diverse gradient for this steel can be a replacement of the cooling of the water side with compressed air cooling. In general, the cooling rate of the whole sheet will then be decreased, but the left side will still be cooled more rapidly than the right side and subcritical cooling rates will then be achieved, which will result in a similar gradient as 0.27 mass-% carbon steel but with higher values. Nevertheless, the results showed that the fully hardened condition of B38 was obtained.

The results from the second experimental setup also show that the test rig is capable of hardening cylindrical bars of carbon steel and in addition generates different hardening depths, providing hardness gradient along the radius (see Figure 9). The results also show the importance of final temperature because the reheating effect may influence the hardness if the cooling stops too early, however this particular phenomenon still remains to be explored for this setup.

6.2 Material Properties and Limitations

The results showed, however, some limitations of the technique that should be considered. The experiments are focused on the workpieces of a limited size, meaning that in case of a larger test object the test rig should be accurately adjusted or redesigned for both heating and cooling.

In both experimental setups the hardenability of steel is a key factor that affects the process since it is directly linked to the ability of steel to form martensite during cooling. On one hand, the negative aspect of high hardenability is that it becomes difficult to control the diversity of the property gradient, because the steel easily hardens (as in case of 0.38 mass-% carbon steel), and on the other hand a higher hardenability is beneficial because the bars can be hardened with less effort i.e., with a lower cooling rate.

Considering both hardenability and carbon content of all steels studied in this thesis it is worth noticing that while the carbon content mainly affects the overall level of mechanical properties, the hardenability in turn has more effect on the diversity of the microstructure and thus on mechanical properties in both experimental setups.

During the verification of the hardening depths in the second experimental setup it was noticed (see appended Manuscript 2) that initial quenching temperature as well as the accurate phase transformation data of studied steel are very important for hardening depth estimation.

It is also worth noticing that though the 0.26 mass-% carbon steel used in the second setup has the lowest carbon content, it has the highest hardenability with the lowest CCR due to other alloying elements. Taking this into account, it was noticed that the higher hardenability the steel has, the more difficult it becomes to locate the region with subcritical or near critical cooling rates, therefore an accurate information about martensite CCR with its corresponding austenitization temperature are of importance to make hardening depth estimation more precise.

According to the materials supplier, the CCR of 0.26 mass-% carbon steel based on 836 °C start temperature is 7 °C/s, and based on 930 °C is 2.9 °C/s. The results in Figure 10 showed that the hardening depths and thus CCRs correspond to a cooling rate of approximately 5 °C/s, based on quenching start temperature 912 °C. The results seem reasonable; however, the latent heat was not considered in the heat transfer problem which brings additional uncertainties. This uncertainty and the lack of accurate phase transformation data makes the hardness measurement and microstructure observation an integral part of hardening depth acquisition.

7. Conclusions

Considering the experience and the results from both experimental setups described and discussed in this thesis the following conclusions answering the research questions are drawn:

1. *Is IJQT capable of providing a differential cooling of sheets of different types of steel resulting in a mechanical property gradient, as well as of hardening the cylindrical bars to different depths?*

The test rig for IJQT is capable of providing a differential cooling of 15 mm thick steel sheets containing 0.27 mass-% carbon and affecting the microstructure in a way to provide a wide range of mechanical properties. The test rig is also capable of hardening 100 mm cylindrical bars in a controllable way to obtain different hardening depths.

2. *What parameters or material properties have the largest impact on controllability of the technique in the context of the two cooling cases studied?*

The hardenability of steel is a key material property for controlling the hardening depth of cylindrical bars. Considering the property gradients in sheets – both hardenability and chemical composition are key parameters in order to obtain diverse mechanical property gradients. A precise martensite CCR with its corresponding austenitization temperature is of importance for hardening depth prediction, for predicting the martensitic to martensitic/bainitic transition region, and thus for better controllability of the IJQT.

8. Future Work

8.1 Differential Cooling of Sheets

Differential cooling of steel sheets with 0.38 mass-% carbon requires additional experiments with different cooling strategies, resulting in lower local cooling rates, to make the mechanical property gradient more diverse.

To shift the gradient of 0.27 mass-% C to higher values, additional experiments are required to be conducted, in order to establish a perfect combination of water jet cooling of one side of the sample with a simultaneous compressed air cooling of the other side.

8.2 Hardening of Cylindrical Bars

The future work regarding the hardening of cylindrical bars is to propose a quenching model including the phase transformations that occur during cooling. For this, the thermal history closer to the bars' surfaces will be studied.

The future work also involves a study of the change in mechanical properties and a study of residual stresses as the consequence of the water impinging jet quenching, which will be integrated into the model.

The results from the model will be analyzed and compared with the physical experiments. The prediction of the spatial and temporal behavior of steel during cooling using a complete quenching model will contribute to the improvement of the controllability of the IJQT.

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Part II

Appended Manuscripts

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

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