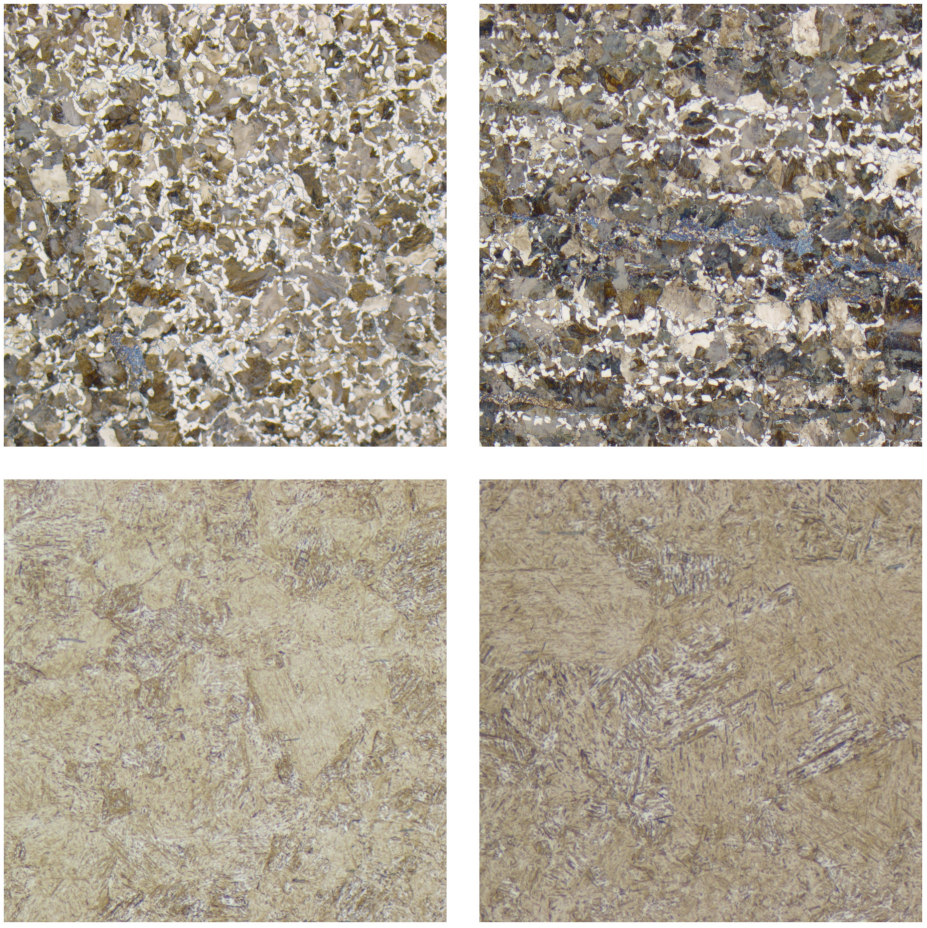
CHALMERS



Effect of heat treatment and batch-to-batch material variations on microstructure of C38 steel

JINLU XIA
SULEYMAN ADDO

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

Bachelor thesis 2024

Effect of heat treatment and batch-to-batch material variations on microstructure of C38 steel

JINLU XIA
SULEYMAN ADDO

CHALMERS

Department of Industrial and Materials Science
Chalmers University of Technology
Gothenburg, Sweden 2024

Effect of heat treatment and batch-to-batch material variations on microstructure of C38 steel
JINLU XIA
SULEYMAN ADDO

Supervisors: Charlie Salame , Philipp Hoier, Chalmers University of Technology
Examiner: Gustav Holmqvist, Chalmers University of Technology

Bachelor Thesis 2024
Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Upper left: Initial microstructure of batch 1 steel sample cross-section. Upper right: Initial microstructure of batch 2 steel sample cross-section. Lower left: Optical micrograph of martensite microstructure, for steel sample heat treated at 1070 °C . Lower right: Optical micrograph of martensite microstructure, for steel sample heat treated at 970 °C.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2024

Abstract

Despite steels from different manufacturers abiding by the same standard specifications, tool wear during grinding of these materials seems to progress differently when comparing batch to batch. Therefore, an investigation was made into the different batches in order to explain this difference in grindability between them. Samples of C38 steel from two different batches were used and heat treated in the same way at three different temperatures. The techniques used in this investigation to assess the difference between batches were light optical microscopy as well as hardness testing. Some differences were observed between the batches before heat treatment but after the heat treatment had been performed there were no differences that could be discerned with an optical microscopy. The hardness tests showed a very small difference where one batch was harder by a maximum of 10 HV. With the tools used in this lab no differences that could lead to a variation in grindability was found. To further investigate the question, more tests need to be run.

Keywords: steel, heat treatment, quenching, microstructure.

Acknowledgements

During our Bachelor's thesis journey, we met some special people whose help and support meant a lot to us. First of all, we would like to express our deepest gratitude to Charlie Salame who is our supervisor. Not only did he let us join his team when we needed help the most, but he also opened up a whole new world to us - a world full of all kinds of lab equipment to finish off our undergraduate careers. His patience and thorough guidance helped us overcome the challenges at the beginning of our experiments, and this patience was a priceless treasure for us.

We are also deeply grateful to Philipp Hoier, who was not only our thesis advisor but also a guiding light on the journey. He was patient and attentive to every little setback we encountered during the experiment, and his advice and creativity added brilliance to our research. We were also in admiration of his calm and logical way of dealing with the situation, and from him we learned how to remain calm and focused when faced with a problem.

We also have to give special thanks to Amir Malakizadi from Chalmers, who not only gave us the precious opportunity to join his team but also took the nerves out of us in that warm and affectionate way he had when we first met. I remember the day he smiled at us and said, "Relax, I was also a student once and I understand how you feel." This understanding and compassion from him made us feel like we had found a friend who could truly listen and understand us and filled our team journey with positive energy and hope from the very beginning.

We would also like to express our gratitude to our dissertation examiner, Gustav Holmqvist. For taking the time to read and listen to our work and provide helpful feedback.

Further we want to thank

- Antonio Mulone for introducing us into the metallography lab,
- Erika Steyn for introducing us to the optical microscope,
- Xiaolong Li for introducing us to the furnace room including safety,

We are grateful to these wonderful people for their help and guidance in our academic journey, it was their support and encouragement that made this journey so much richer and meaningful. We will always remember this experience and the contribution of each and every one of them.

Jinlu Xia & Suleyman Addo, Gothenburg, June 2024

Contents

List of Figures

1
Introduction

1.1 Background

Due to the rapid growth of industrial manufacturing, the use of sustainable machining techniques has become an important factor in improving productivity and resource efficiency. In order to meet the challenge of batch-to-batch material variations in production lines, the introduction of reliable predictive modelling and simulation tools is essential. Small variations in material properties, even within standard specifications, can lead to serious problems on the production line, such as rationalising timely tool changes and machining under optimum conditions that cannot be ignored. Previous work has addressed this issue[1]. However, since crankshafts are big and undergo many processing steps it is difficult to identify the microstructural differences coming from the batch-to-batch variations. An alternative approach is to do controlled tests in the lab where we do grinding tests on material with precisely-defined microstructures. The present thesis deals with investigating how different material batches respond to varying heat treatments. The resulting knowledge will be used to prepare materials with defined microstructures to be used for grinding test in the laboratory.

Heat treatment is a common process for controlling the structure of steel products and their key mechanical properties such as hardness, strength, toughness, ductility and elasticity[2]. However, different suppliers may use different heat treatment processes, resulting in differences in the final structure of the same material. This variation adversely affects the ability to reliably predict tool wear during machining, thus adding to the uncertainty of the production line.

1.2 Aims

The aims are to investigate the microstructural differences in two batches of C38 steel, to find suitable workpiece geometry, and to land in the correct range of hardness. Firstly, the soft, as-received material is investigated. Secondly, different hardening heat treatments and their influence on the two batches' microstructures and hardness are being investigated. The aims of this work are twofold:

- Identification of a suitable geometry of test pieces for grindability tests. The test pieces should be sufficiently large to enable tests while ensuring proper through-hardening during the heat treatment. The resulting microstructure

should be comparable to that present in crankshafts with a hardness in the range of 560 to 675 HV.
- Investigation of microstructural differences in two batches of the investigated material both in as-received condition and after varying hardening heat treatments. Samples of the geometry identified in the aim above are utilized.

1.3 Scope and limitations of the study

This study focuses on the observation of the microstructure of steel samples after heat treatment, and as the associated grinding tests need to be continued in later stages, this experiment only concentrates on the heat treatment aspect. The heat treatments investigated in this work are done using conventional furnaces. No induction hardening as the case for crankshaft production was used. Although the microstructures of only small samples of steel bars were examined in this thesis, the actual heat treatment effects and processing tests on large steel bars require more in-depth follow-up research, which is worth exploring further, but is not included in the scope of this thesis. The comparative material characterization was focused on light optical microscopy of the martensite morphology as well as hardness testing. Further analyses using more advanced characterization techniques such as electron microscopy are needed to study differences of the hardened material microstructures. This thesis only focuses on C38 steel.

2

Theoretical framework

2.1 Classification

C38 steel is a medium-carbon steel, named for its carbon content of about 0.38 percent, and is a hypoeutectoid steel. The main alloying element in this steel is carbon, and the content of other elements is relatively low. In terms of microstructure, C38 steel shows a mixture of ferrite and pearlite. Ferrite is a softer body-centred cubic (BCC) structure with very low carbon content and good ductility. Pearlite is formed by alternating layers of ferrite and cementite (a chemical compound of iron and carbon and is a key component in steel and cast iron), which increases the strength and hardness of the steel[3]. This balanced structure gives C38 steel a medium level of strength and hardness while maintaining significant toughness and machinability[4]. C38 steel exhibits better weldability than high carbon steels, although it is not as easy to weld as low carbon steels. Heat treatments such as quenching and tempering further enhance its mechanical properties by forming martensite, increasing hardness and subsequently tempering to adjust the balance between hardness and toughness. These properties make C38 steel widely used in applications that require a certain level of strength and toughness, such as automotive parts, bearings, gears and other engineered structural components. With a carbon content of less than 0.8 percent, C38 steel is hypoeutectoid steel, which means that it has a good combination of mechanical properties suitable for a wide range of engineering applications, while maintaining good machinability and weldability. The following sections discuss the microstructure of hypoeutectoid steels, focusing on the current microstructure and phases.

2.2 Microstructure, Microconstituents, and Phases

There are many ways to process steels to get different qualities but more generally they fall under heat treatment, alloying and deformation hardening. The reason why steels are so adaptable has to do with the crystallography of iron[5]. Iron, a cornerstone in the field of metallurgy, exhibits remarkable versatility through its ability to exist in multiple crystalline forms naturally. This unique characteristic not only sets iron apart but also lays the foundation for the vast array of its alloys, each possessing distinct properties crucial for various applications. In delving into the study of iron and its derivatives, it becomes evident that temperature-induced

dynamics play a pivotal role in the formation of its different crystalline structures. Notably, ferrite, one of iron's primary phases, presents itself in two specific forms: alpha (α) and delta (δ), which are primarily distinguished by the temperatures at which they form. Despite their formation under different conditions, both versions of ferrite maintain a body-centered cubic (BCC) structure, highlighting a fascinating aspect of iron's structural behavior. This shared structural foundation is a key reason why, in the taxonomy of iron's crystalline phases, we identify three principal structures rather than four. Understanding these structures is essential for grasping the metallurgical behaviors of iron and its alloys, and thus, they are detailed below for further examination:

- α BCC (body-centered cubic) ferrite
- γ FCC (face-centered cubic) austenite
- ϵ HCP (hexagonal close-packed)
- δ Also BCC-formed ferrite, but designated as "delta" when iron is converted at 1390 degrees.

Regarding the stabilities of the forms

BCC ferrite is stable at room temperature, pure Austenite is only stable in high temperatures and pure HCP is only stable in high temperature and pressures. Since HCP is only stable at high pressures it has no engineering relevance.

2.3 Heat-treatment and quenching processes

When heat treated, metals undergo internal microstructural changes, and by adjusting the temperature, it is beneficial to understand exactly how this alteration is achieved.

The atomic bonding of metals is noteworthy for its ability to use heat energy to prompt the rearrangement of atoms while maintaining the overall state of the substance. When the temperature of steel is above the melting point, it causes the steel to melt and convert to a liquid state. In this situation, the steel loses its solid structure and the bonds between the molecules become loose, thus losing solid properties such as hardness and strength. Otherwise steel will always contain crystals (grains), just arranged differently depending on temperature etc. Examples are ferrite at lower temperatures and austenite at higher temperatures. These crystals appear in different locations at the same time, each with a unique orientation. As the temperature continues to drop, the structure that eventually forms is not completely regular, but consists of grains. The boundaries between the contact points of the grains are called grain boundaries, which prevent the displacement of atoms[6]. Controlling the cooling rate regulates the size of the grains. Quenching is the process by which a faster cooling rate increases the number of grain formation sites and shortens the growth time[7]. If the quenching is quick enough martensite forms which means smaller, denser grains are formed, resulting in a harder steel. However, steels are usually brittle and hard after quenching and need to be tempered. This

involves reheating the metal to a specific temperature and cooling it moderately to stabilise its structure, reduce brittleness, and increase toughness and plasticity[8].

2.4 Martensite in the application of crankshafts

The automotive crankshaft is one of the core components of the engine and transfers the vertical motions of pistons into rotatational motion that drives the drive train. Because of the time and economical cost of installing a new crankshaft automotive companies prefer crankshafts with longer lifes. This means that its design must ensure high strength, good toughness, excellent wear resistance and superior fatigue resistance. The realisation of these properties is critical to the reliability of the crankshaft in an environment where it rotates at high speeds and is subjected to heavy loads.

Fatigue resistance heavily correlate to hardness so the material needs to be hard. For these reasons steels that have been surface heat treated into martensite becomes a good choice [9].

Martensitization occurs when austenitic steel is cooled below the martensite start temperature which is the temperature at which martensite begins forming and ends at the martensite finish temperature which is the temperature at which the austenitic steel has been fully transformed [10]. The martensitic transformation is a diffusionless process, meaning that atoms do not move into new lattice positions. Instead, the crystal structure of austenite is sheared into a new position. This transformation occurs so fast that carbon atoms can not diffuse and create cementite or pearlite; thus, the carbon atoms are trapped in their position. This process is typically associated with high hardness and elevated strength of the material but results in increased brittleness.

To counteract this brittleness[11], the martensite must be tempered, where it is brought to temperatures below 500 °C and kept there for some time depending on factors such as size or goal. The tempering leads to a diffusion of carbon that forms carbides. This leads to an increased toughness at the cost of reduced hardness.

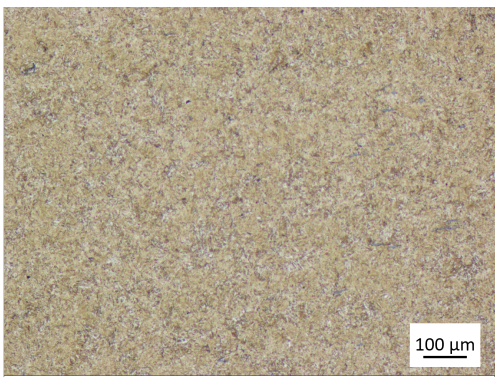


Figure 2.1: Martensitic microstructure

3

Methodology and Experimental Methods

3.1 Methodology

For the investigations, two material batches of C38 steel (Batch 1 and Batch 2) were available. Both batches were in the form of ferritic-pearlitic soft condition and were the as-received material.

The methodology employed in this thesis project comprises two sections. It is shown in Figure 3.1. The first section involves samples of varying size that were cut out from one of the bars being subjected to the same heat treatment and cooling methods. In an initial test series, it was investigated for which sample sizes a homogeneous martensitic, through-hardened microstructure can be achieved. For this purpose, three different sample sizes from batch 1 were tested under the same conditions (austenitization temperature of 870 °C), with cross-sectional area dimensions of large ($2.9 * 1.8$ cm), medium ($1.9 * 1.5$ cm), and small ($1.9 * 1$ cm). This was done to conclude how big our sample for the second section should be. The second section concerns the application of different heat treatment recipes to the two batches of steel bars, all of which are quenched using water which is at the same temperature.

The work in this thesis has mainly concentrated on their microstructure. The differences between the Batch 1 and 2 steel samples in characteristics such as present phases, grain size and martensite packet size were interesting. The crucial step in this study was the adoption of three different austenitization temperatures, followed by quenching in water. Three heat treatment temperatures, 870°C, 970°C, and 1070°C, were chosen to investigate alterations in the material's microstructure under different conditions and whether the two batches react differently to the same heat treatment. The rapid cooling was employed to achieve hardened martensitic microstructures similar to the hardened surfaces on automotive crankshafts.

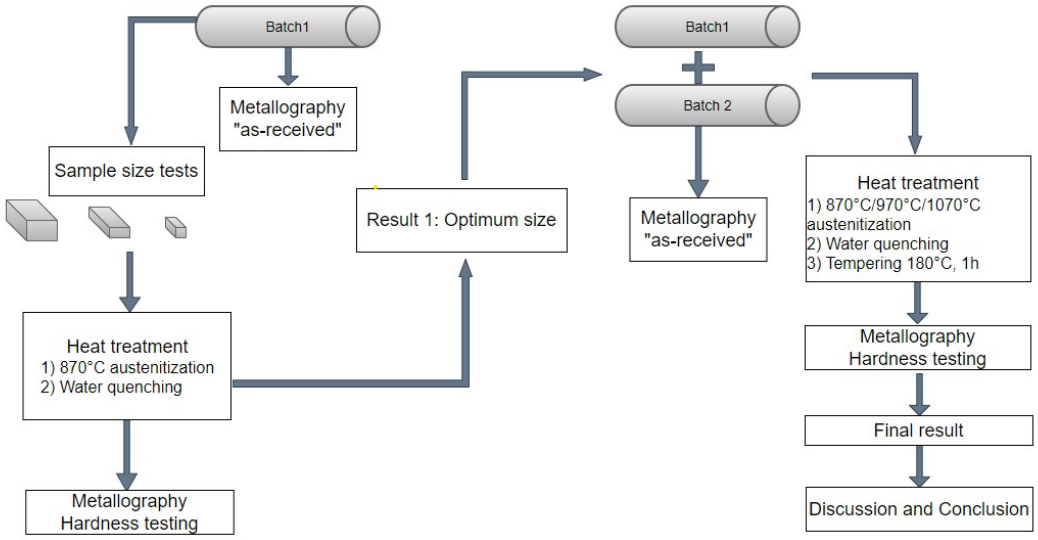


Figure 3.1: Diagram on the methodology followed during the bachelor thesis project.

The main objective of the investigation was to assess the alteration in characteristics of steel bar samples after undergoing heat and cooling treatments by means of hardness testing. Our focus was to analyse the hardness of each sample on the cross-section after cutting, seeking to comprehend the effect of heat treatment and cooling on the material's hardness. To ensure dependable outcomes, we opted for hardness testing at nine distinct points along the middle cut of each sample. Due to the heterogeneity of the microstructure of the samples subsequent to the cooling treatment, discrepancies in hardness occur at each location. Averaging the hardness values at these nine locations enabled us to derive a more precise estimation of the overall hardness of the samples following heat treatment and cooling. A detailed comparison of the hardness values of each sample will furnish us with comprehensive outcomes, enabling us to discuss our findings convincingly. The schematic of the hardness test locations is shown in Figure 3.4.

We have studied these positions using the following methods:

- Different heat treatment formulations
- Sample preparation in order to observe the microstructure
- Etch of prepared samples to make present phases visible, optical microscopy
- Vickers Hardness testing was utilised to analyse the hardness in proximity to the surface of the sidewall and throughout the depth profile.

3.2 Experimental Methods

3.2.1 Heat treatment

The heat treatments investigated in this work are done using conventional furnaces. When the heat treatment was first performed, the expected furnace temperature was 870 °C. However, the final furnace temperature was only 850 °C. A subsequent graphical analysis of the EsaylogGraph showed that the temperature stabilized around 850 °C, which means around 20 °C below the temperature we set at the furnace (Appendix). Therefore, the furnace temperature needed to be adjusted 20 °C above the desired temperature for subsequent heat treatments.

3.2.2 Optical Microscopy on Steel Bars

For optical microscopy observation, this was done both on the as-received material and on the samples after the hardening heat treatments. A resin bonded aluminium oxide cut-off wheel (50A25, Struers) was used to make two/three vertical cuts in the center of the samples, with a one−centimeter distance between them, as illustrated in Figure 3.2 & Figure 3.3. We obtained the middle steel sample, which is required for the analysis. To ensure visibility of the surface of interest in the microstructure, we mounted the surface marked in Figure 3.2 & Figure 3.3 face down in the conductive mounting resin Polyfast (black)/multifast (red) from Struers and mounted it in the CitoPress−20 mounting press using a small sample slot with a diameter of 30 mm. Next, we performed a grinding and polishing process. The specific grinding and polishing parameters can be found in Table A.1 in Appendix 1. Finally, we etched our samples using an etching solution (Nital, 2 %) until the surface was visibly etched in preparation for optical microscopy. This series of steps ensured that our samples clearly demonstrated the desired microstructure under the microscope.

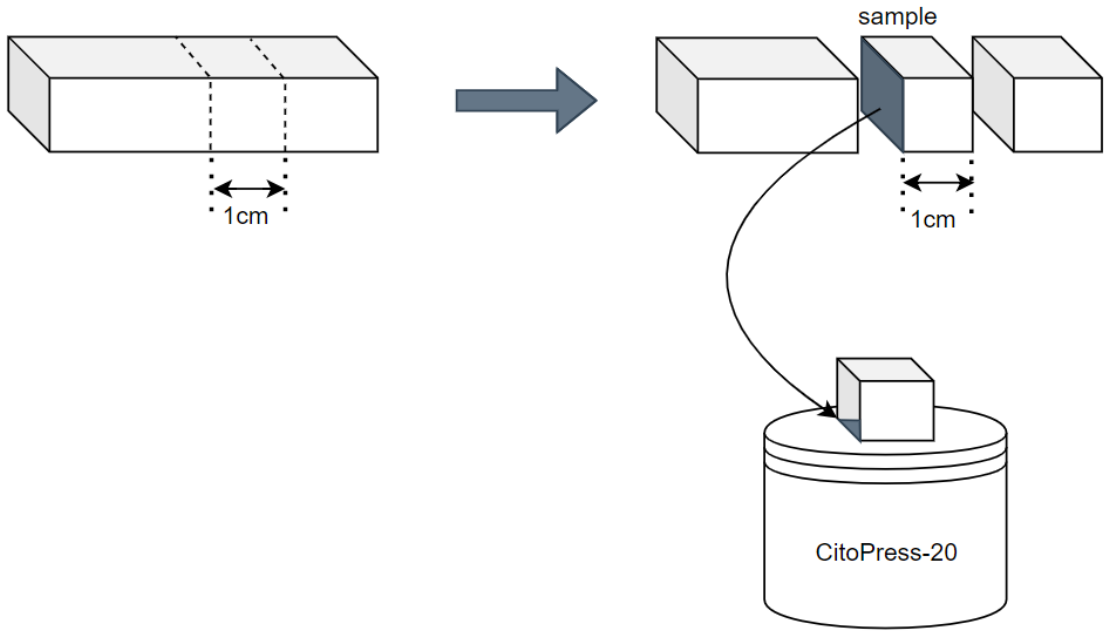


Figure 3.2: Schematic diagram of a steel bar sample cut. A slice is taken from a block of steel to create the final sample. Repeat the steps to cut the sample slices we need from each of the large, medium, and small steel blocks. (the first section)

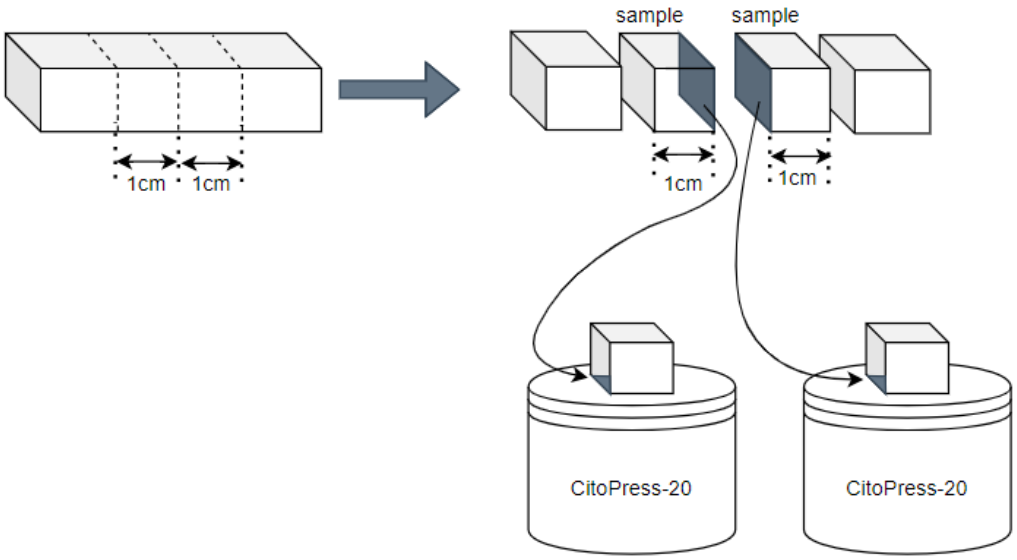


Figure 3.3: Schematic diagram of a steel bar sample cut. Two slices are taken from a block of steel to create the final sample. In this way we get two samples, one of which is used for etching and an other for hardness-testing. (the second section)

3.2.3 Vickers hardness testing

Vickers hardness testing is a method used to measure the hardness of materials. Its operating principle is based on the following steps:

- Indentation with a diamond indenter: A diamond indenter of a specific shape (usually a right pyramid) is pressed into the surface of the material to be tested with a certain force (load).
- Maintaining the force for a set time: This force is maintained for a fixed period, allowing the diamond indenter to penetrate the material.
- Removal of the load: After sufficient time, the load is removed.
- Measuring the indentation: The diagonal length of the indentation left by the diamond indenter is measured using a microscope.
- Calculating the hardness value: The vickers hardness value of the material is calculated using a specific formula as shown in 3.1, based on the size of the indentation and the applied load. alternatively, the hardness values were directly consulted in a table to find the corresponding values(Appendix).

$$HV = 1.8544 \times \frac{F}{d^2} \tag{3.1}$$

Where:

- HV is the vickers hardness value.
- F is the applied force in kilograms-force. (we used $F = 10$kgf)
- d is the diagonal length of the indentation (usually in millimeters, mm).

We are interested in the hardness of the entire sample, so we selected nine points on the sample, arranged in three rows with three points each. The points on the sides are close to the surface of the sample, while the points in the middle are as central as possible. The top and bottom rows are near the surface of the sample, and the middle row is positioned as close to the center of the sample as possible. This arrangement ensures a comprehensive assessment of the sample's hardness from the surface to the core. (Figure 3,4)

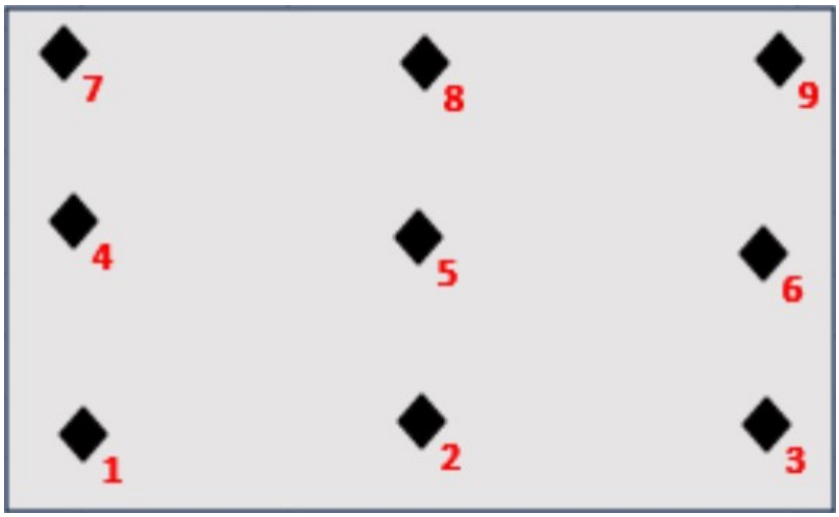


Figure 3.4: Schematic drawing of Vickers hardness testing design on samples. (not to scale)

4

Results

4.1 Microstructure of steel bars

4.1.1 Microstructure of Batch 1 and Batch 2 steel bars in as-received condition

The optical microscope was deployed to examine the microstructure of the steel bars in as-received condition, as seen in Figure 4.1. Both steel batches displayed ferrite-pearlite microstructures. Upon comparing batch 1 and batch 2's microstructures, there is a difference in the grain structure between Batches 1 and 2. Batch 1 seems to have a finer grain structure and seems to have less bainitic colonies within its microstructure as opposed to batch 2. The distribution of ferrite and pearlite in Fig. 4.1 a) appears to be more homogeneous and the grain size is more uniform; whereas the pearlite in Fig. 4.1 b) is more complex and richer in colour and texture, which may indicate that it has undergone a more complex cooling history or heat treatment process. This layered structure of the pearlite may imply that the sample in Fig. 4.1 b) underwent a slower cooling rate or a longer heat treatment time.

In the absence of more quantitative data, the above analyses are based on visual interpretation of the images only, and actual material properties will need to be determined by physical testing. This observation highlights the significance of conducting a thorough microstructural examination to identify slight variations between batches.

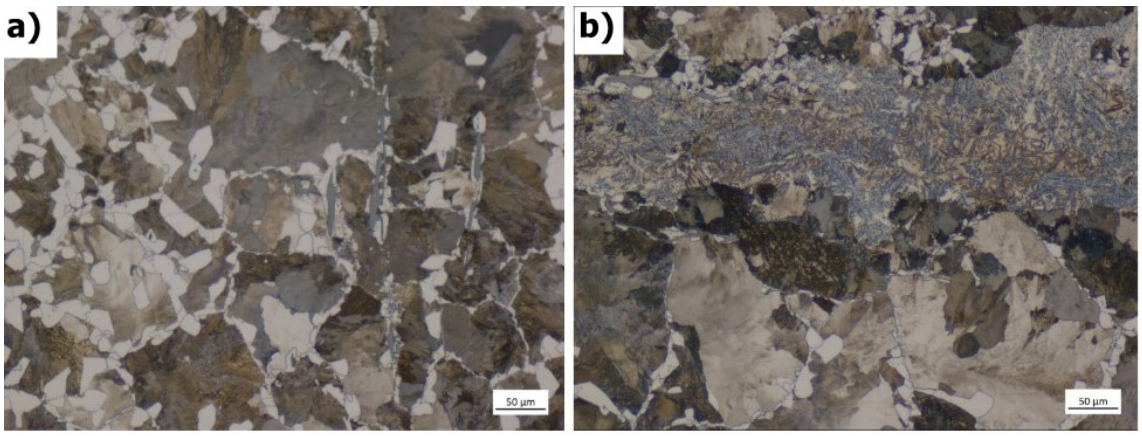


Figure 4.1: Microstructure observed using optical micrsocope for (a) batch 1 and (b) batch 2.

4.1.2 Microstructure of Batch 1 steel bar with varying sizes after heat treatment

In the heat treatment of large steel component samples, the cooling process leads to the formation of different microstructures between the surface and the core. It is due to differences in the cooling rate. The surface of the sample comes into direct contact with the cooling liquid first, while the core of the sample transfers the temperature of the cooling liquid to the inside through the sample itself. Therefore, the cooling rates of the surface and core of the sample are slightly different. Specifically, the surface tends to form a more homogeneous martensitic structure, while the core forms a less homogeneous martensitic structure with larger grains. This phenomenon is manifested as a gradual structural transition from the periphery to the center of the material cross-section. This is demonstrated in Figure 4.2. We find that as the sample size becomes progressively smaller, the microstructure becomes more homogeneous. This is demonstrated in Figure 4.3 and Figure 4.4.

Furthermore, these observations emphasise the importance of size effects in heat treatment and microstructure formation. When designing a heat treatment programme for steel, it is important to consider the effect of material size on the cooling rate and how this effect determines the final properties of the material. The size of the steel part directly affects the uniformity of cooling, which in turn affects the distribution and properties of martensite, and directly affects the overall material properties such as hardness, strength, and fatigue life. Therefore, each sample is heat treated using the same dimensions to ensure that the only variable in the experiment is the change in heat treatment temperature. Our findings were confirmed in the data from the subsequent hardness tests. The hardness test results are described in detail in the following section.

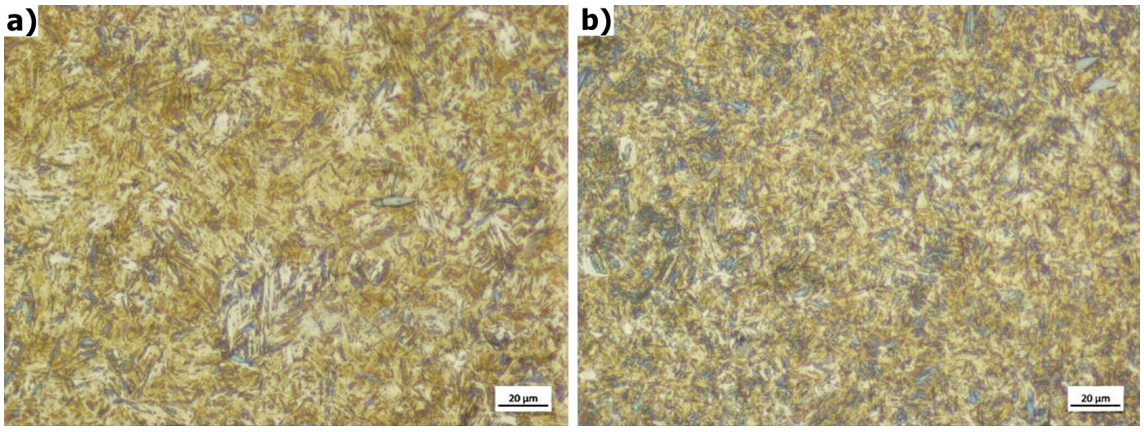


Figure 4.2: Microstructure of a large sample. a) Near the center of the workpiece. b) Near the surface of the workpiece.

Figure 4.2 b) shows the microstructure near the surface of the sample, where the distribution is significantly more homogeneous. This comparative analysis suggests that the cooling rates and phase transition behaviors in the inner and edge portions

of the sample are significantly different during heat treatment, which results in a more homogeneous grain structure near the surface region. This enhanced homogeneity is most likely due to more efficient heat transfer near the surface, compared to the central region of the sample, which was exposed to the heat treatment for a longer period of time.
In conducting a comparative study of the microstructure at the centre of the large and medium samples, we found significant differences between the two. The microstructure at the centre of the large sample exhibits a certain degree of non-uniformity. In contrast, the centre microstructure of the medium-sized sample exhibits a higher degree of homogeneity. Considering that the centre-to-surface distance varies among different sample sizes, this comparison reveals a significant effect of sample size on the cooling process and the homogeneity of the final microstructure. In the medium-sized samples, their smaller size leads to a shorter heat transfer path from the interior to the surface, which in turn contributes to a more rapid and homogeneous cooling effect. This finding is important for a deeper understanding of the relationship between microstructure formation and sample size during heat treatment, and provides valuable information for the prediction and regulation of material properties. However, for the comparative results of microstructures of small and medium samples as shown in Figure 4.4, the microstructures of the medium and small sizes seem to be very similar, and the hardness experiments can be continued in order to confirm whether this conclusion is valid.

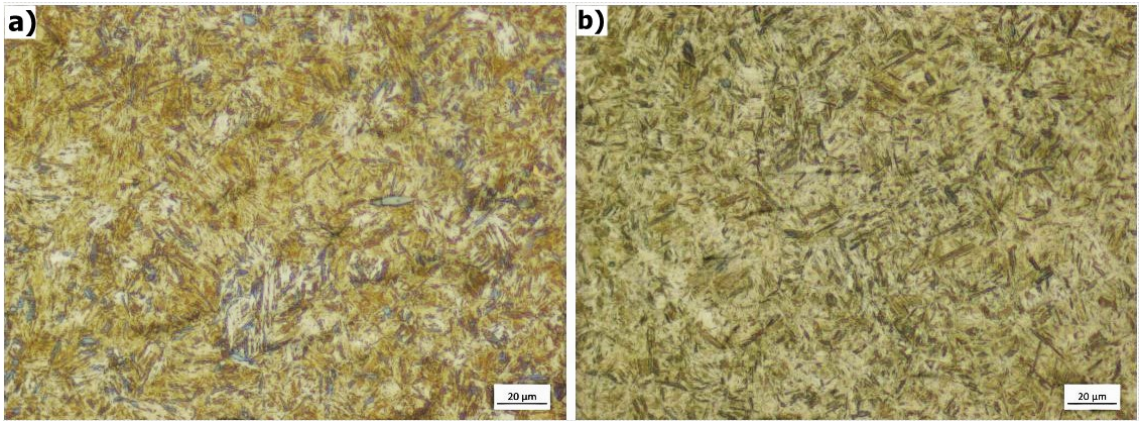


Figure 4.3: Microstructure of a large sample and a medium sample. a) Near the center of the large sample workpiece. b) Near the center of the medium sample workpiece.

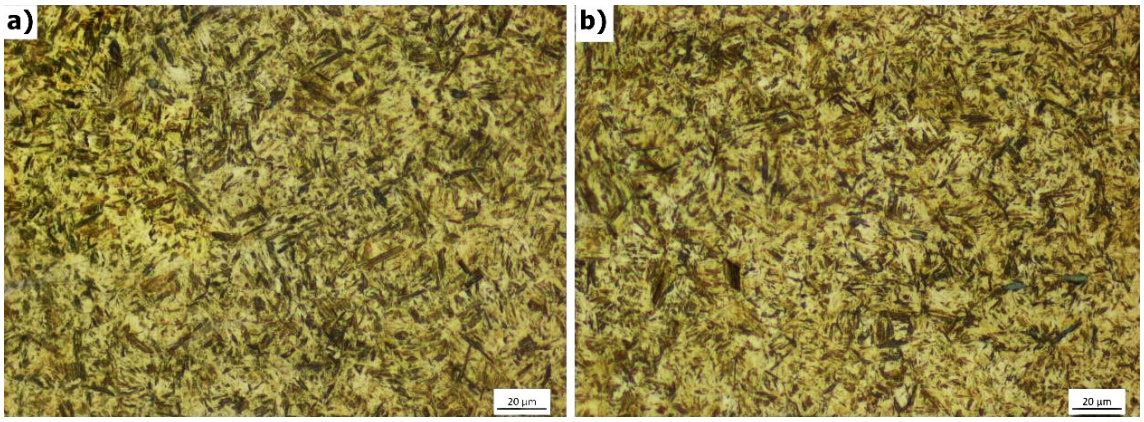


Figure 4.4: Microstructure of a medium sample and a small sample. a) Near the center of the medium sample workpiece. b) Near the center of the small sample workpiece.

In this study, the difference in performance of different size samples was compared by hardness test. The results show that the hardness values of the small and medium-sized samples are higher and the difference between the two is relatively small, with the small-sized sample being slightly higher. This is consistent with the microstructural observations, suggesting that these two sizes have similar microstructural distributions. However, the hardness values were significantly lower for the larger size sample (Fig.4.5). Further analysis shows that in the small-sized samples, the distribution of hardness values is relatively homogeneous, whereas, in the large-sized samples, the distribution of hardness values is more heterogeneous at different locations (Fig.4.5). This finding emphasises the significant influence of microstructure on material hardness and provides insight into understanding the impact of size effects on material properties. It is worth noting that 'Big1' and 'Big2' samples from the same large sample were cut into two parts for analysis to facilitate testing.

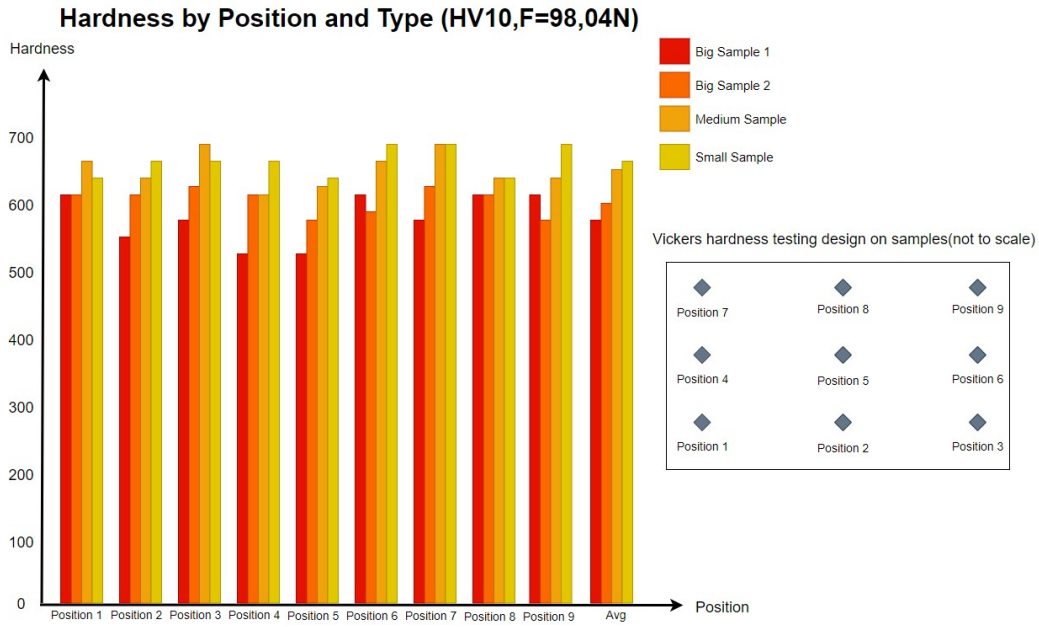


Figure 4.5: Comparative Analysis of Hardness Types Across Different Positions.

4.1.3 Microstructural Changes in two Batches of Steel after Three Different Temperature Heat Treatments and Quenching Processes

The objective of this investigation is to explore alterations in the microstructure of steel when exposed to distinct heat treatment temperatures. Steel samples were heat treated at three different temperatures (870 °C, 970 °C, and 1070 °C). A comparison was drawn between the microstructures of the various steels in order to analyze the impact of the heat treatment temperature on the growth of grains and phase transformation. It is worth mentioning that the identical cold quenching approach was employed for all samples to ensure that two variables: were heat treatment temperature(Austenitization temperature) and material batch.

Figures 4.6 and 4.7 show the microstructure of two different batches of steel after quenching at three different heat treatment temperatures. Figures 4.6 a) (870°C) and 4.7 a) (870°C) show a finer grain structure with a homogeneous microstructure and a relatively small area of the martensite packet size. In Figures 4.6 b) (970°C) and 4.7 b)(970°C), the martensite packet size increases, and both the martensite "needles" and the martensite packet size are slightly larger than at 870°C. Despite the tendency of martensite morphology to get coarser, a relatively regular arrangement is maintained. Figures 4.6 c) (1070°C) and 4.7 c) (1070°C) show the martensite packet size increases more, and both the martensite "needles" and the martensite packet size are significantly larger than at 870°C and 970°C. The coarsening of martensite morphology could be caused by the growth of the austenite grain boundaries during austenitization. Higher austenitization temperature leads to larger austenite grains which in turn affects the morphology of martensite after quenching. A more detailed study of the martensite is needed to confirm this.

Overall, a gradual change from a fine and homogeneous martensite structure to a larger and homogeneous structure of the martensite packet and block was observed with increasing heat treatment temperatures. Furthermore, after hardening heat treatments, no obvious differences between the batches as seen in the as-received condition could be observed any more. However, a deeper analysis of the martensite structure is needed to confirm this.

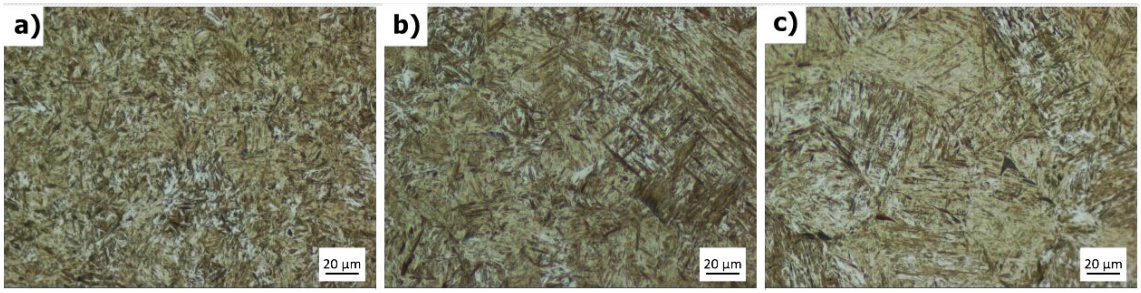


Figure 4.6: Microstructure at three different austenitization temperatures for Batch 1. a) Heat treatment at 870°C. b) Heat treatment at 970°C. c) Heat treatment at 1070°C.

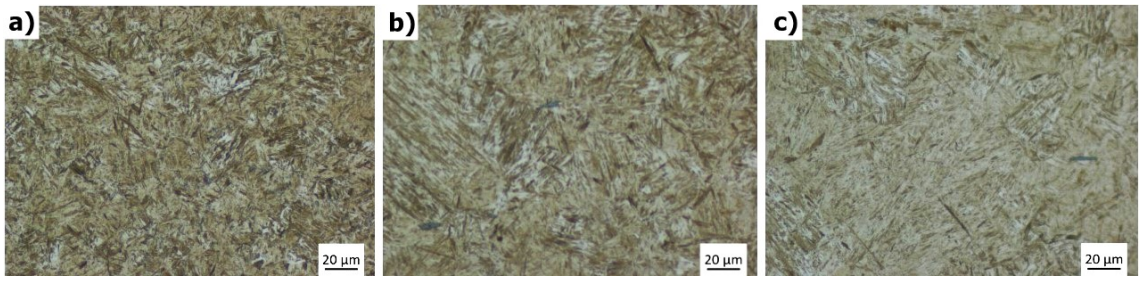


Figure 4.7: Microstructure at three different austenitization temperatures for Batch 2. a) Heat treatment at 870°C. b) Heat treatment at 970°C. c) Heat treatment at 1070°C.

4.2 Analysis of Hardness Testing for Medium-Sized Samples

When two batches of steel of the same dimensions were heat-treated, it was found that the hardness values of the two batches converged as the heat-treatment temperature increased. Specifically, at a heat treatment condition of 870 °C, the steel from the first batch was slightly harder than the second batch. However, as the temperature increased to 970 °C, although the hardness values of the first batch were still higher than those of the second batch, the difference between the two was significantly reduced, suggesting that the hardness values were becoming similar. Ultimately, at 1070 °C, the hardness values of the two different steel batches were

almost identical (Figure 4.8). This result shows that high-temperature heat treatment can effectively reduce the differences in hardness properties between batches of steel, pointing to the important role of temperature in the consistency of steel hardness. This seems to indicate that there are no hardness or minimal hardness differences between the two batches when the material has been fully turned to martensite.

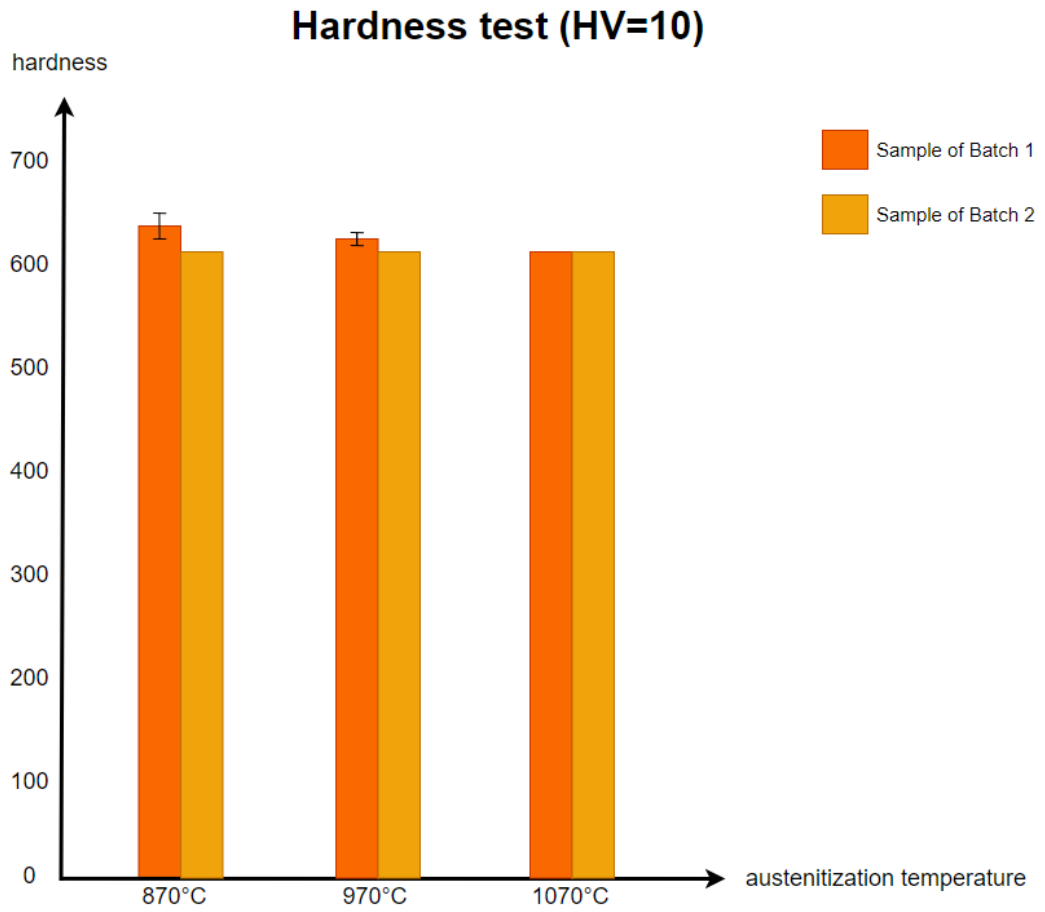


Figure 4.8: Hardness measurement results for samples of Batch 1 and Batch 2.

5

Discussion

There were subtle differences in the microstructure of batch 1 and batch 2 prior to heat treatment. The reasons for these differences may be related to the production of the steel bars. Various factors contribute to the differences in the microstructure of two batches of steel.

Firstly, the cooling rate has a direct influence on the degree of pearlitic fineness: faster cooling tends to result in the formation of fine pearlites, whereas slow cooling may produce a coarser pearlitic structure. Secondly, the microstructure is significantly affected by the chemical composition of the material, with small differences in carbon content leading to variations in the proportion and fineness of the pearlite. The heat treatment history is equally critical, with different heat treatment processes such as annealing or normalizing causing different manifestations of microstructure. In addition, deformations that the steel undergoes during mechanical processes such as rolling or forging can refine the grains and change the distribution of pearlite.The combination of all these factors create the structural differences we see in the microscopic observations.

At 870°C, 970°C and 1070 °C, no grain differences could be observed between batch 1 and batch 2. This seems to indicate that the grain sizes of the different batches got normalized during the austenisation phase since it is in that phase that the grain boundaries for martensite get established. So, when the two samples were austenized at the different temperature, the grain sizes became uniform.

The martensite grain sizes were different between temperatures, where the grain sizes were bigger for higher temperatures and the martensite pattern could more easily be discerned. An assumption can be made regarding the smaller grain-sized martensite having a higher tensile and yield strength due to dislocations having a harder time traversing because of the grain boundary effect. The hardness tests seems to indicate that this difference is negligible; however, it is known that the correlation between hardness and tensile strength has a lot of scatter so this may need to be tested with a tensile test [12].

There is a slight difference in hardness between batch 1 and 2. This difference is most pronounced at 870 °C, where there is a minor difference of about 10 HV and a difference of about 3 HV between batch 1 and batch 2 at 970 °C. There is no hardness difference between the batches at 1070 °C.
Some sources of error are listed below.

- The reading of the hardness value is done manually, and there may be subjective errors in the reading of data by different people. Therefore, in order to minimise such errors, it is recommended that the same person is responsible for reading all the data to ensure consistency of results.

- The furnace used to heat treat the samples took some time to get up into the temperature of interest. The same furnace and process was however used for both batches so the error from this should be minimal.

- For one batch, there was a slight different in height between batches. To observe batch to batch differences as accurately as possible it would be better to make sure that all samples are exactly equally long.

In short, these minor errors can have some impact on the hardness test results. In order to obtain more accurate tests, data operational procedures should be standardised and human error should be minimised. Better yet, in this case perhaps would be to remove the human factor and use automated hardness testing machines.

6

Summary and Future work

Sustainable machining techniques is an important area of focus due to the growth of the manufacturing industry. For efficient and timely tool changes it is important to develop reliable predictive modelling capabilities. In order to achieve this final goal, the most precise results can be obtained by having simulation models take into account many aspects pertaining to the workpiece material, cutting tools, and cutting conditions. In order to achieve this goal, the present study examines the microstructural changes among batches. These changes can then be looked at in further studies to see the impact that it has on the grindability variations of medium carbon steels.

The fundamental premise of this study was that variances in microstructures between different batches would be identified, which would result in significant variations in the batches' measured hardness following heat treatment. To achieve this, one of the aims was choosing a geometry that would be large enough to ensure proper tests but would also undergo complete martensite transformation, achieving a resulting hardness of 560 to 675 HV. This was accomplished by selecting a medium sample with the aforementioned cross-sectional area. However, the results of the trial did not show any variations between the batches. The absence of discernible differences does not necessarily indicate their nonexistence; rather, it suggests that the methods employed within the parameters of this study were insufficient to detect them. In a similar vein, the hardness tests revealed no appreciable variations between the batches, except for the results of batch 1 at 870 °C, which displayed a hardness level 10 HV greater than that of the other samples. No other discernible differences in hardness were observed at any temperature. Given these findings, more in-depth research on the samples may be warranted in the future, focusing on aspects such as measuring grain size, conducting inclusion analysis, and assessing the material's tensile characteristics.

To fully understand the performance of steel bars of different sizes and batches, it is crucial to implement a macro-to-micro multi-scale analysis. The analysis of macro-sample size and microstructure allows for a more comprehensive evaluation of the specific effects of processes such as heat treatment on material properties. This approach helps to reveal the pattern of change in the microstructure of samples at different scales.

Further in-depth analysis tools and equipment is needed for further study of the martensitic microstructure and the variations between batches. The knowledge

aquired from this study will be used to make workpieces with known microstructures that will be evaluated on their grindability.

7
Conclusions

Two batches of C38 steel were heat-treated at three different temperatures and then quickly cooled into martensite to investigate batch-to-batch variations in microstructure. The results of this investigation can be summarized as follows:

- There was no grain size difference between the batches at any of the temperatures after heat treatment.
- There was a small, negligible difference in hardness between the batches at temperatures of 870 °C and 970 °C. At 1070 °C, there was no difference in hardness.

Bibliography

[1] Joshua Michael Pautzke. "Metallurgical Characterisation Comparing Recycled and Ore-based Steels for Automotive Crankshafts". In: (2020).

[2] Bo Jiang et al. "Microstructural characterization, strengthening and toughening mechanisms of a quenched and tempered steel: Effect of heat treatment parameters". In: *Materials Science and Engineering: A* 707 (2017), pp. 306–314.

[3] IW Hamley, JA Pople, and O Diat. "A thermally induced transition from a body-centred to a face-centred cubic lattice in a diblock copolymer gel". In: *Colloid and Polymer Science* 276 (1998), pp. 446–450.

[4] H Al-sharabi et al. "Anti-corrosive properties of Catha Edulis leaves extract on C38 steel in 1 M HCl media. Experimental and theoretical study". In: *Int. J. Corros. Scale Inhib* 11.3 (2022), pp. 956–984.

[5] H.K.D.H. Bhadeshia and Sir Robert Honeycombe. "1 - Iron and its Interstitial Solid Solutions". In: *Steels (Third Edition)*. Ed. by H.K.D.H. Bhadeshia and Sir Robert Honeycombe. Third Edition. Oxford: Butterworth-Heinemann, 2006, pp. 1–16. ISBN: 978-0-7506-8084-4. DOI: https://doi.org/10.1016/B978-075068084-4/50003-0. URL: https://www.sciencedirect.com/science/article/pii/B9780750680844500030.

[6] JA Martinho Simoes and JL Beauchamp. "Transition metal-hydrogen and metal-carbon bond strengths: the keys to catalysis". In: *Chemical Reviews* 90.4 (1990), pp. 629–688.

[7] XiaoYan Long et al. "Roles of cooling rate of undercooled austenite on isothermal transformation kinetics, microstructure, and impact toughness of bainitic steel". In: *Materials Science and Engineering: A* 870 (2023), p. 144821.

[8] TV Rajan, CP Sharma, and Ashok Sharma. *Heat treatment: principles and techniques*. PHI Learning Pvt. Ltd., 2023.

[9] Christopher Derrick and Ali Fatemi. "Correlations of fatigue strength of additively manufactured metals with hardness and defect size". In: *International Journal of Fatigue* 162 (2022), p. 106920. ISSN: 0142-1123. DOI: https://doi.org/10.1016/j.ijfatigue.2022.106920.

[10] R.W.K. Honeycombe H.K.D.H. Bhadeshia. *Steels,Microstructures and properties*. Butterworth-Heinemann, 2017.

[11] Milton Ohring. *Engineering Materials Science*. Elseiver, 1995.

[12] E. J. Pavlina and C. J. Van Tyne. "Correlation of Yield Strength and Tensile Strength with Hardness for Steels". In: *Journal of Materials Engineering and Performance* 17.6 (Dec. 2008), pp. 888–893. DOI: 10.1007/s11665-008-9225-5.

A

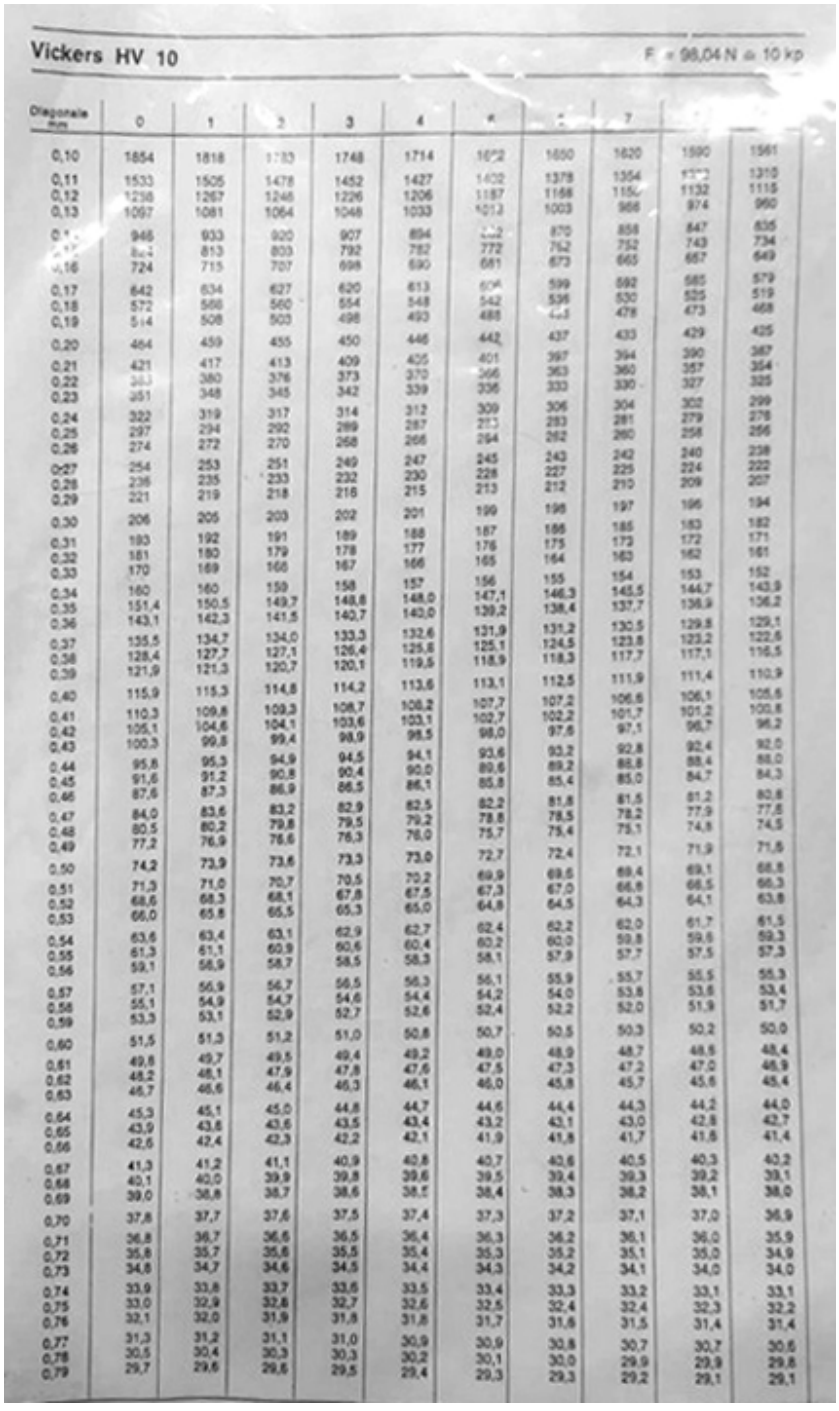
Appendix 1

A.1 Sample Preparation

Step	Grinding/ polishing surface	Abrasive size	Force per sample	Time	RPM	Comment
1	MD Gekko	#220 paper	30N	2 min	150/150	water
2	MD Allegro	9 µm suspension	30N	7 min	150/150	No water suspension
3	MD Dac	3 µm suspension	30N	6 min	150/150	No water suspension
4	MD Nap	1 µm suspension	25N	3 min	150/150	No water suspension

Figure A.1: Gringing and polishing steps and parameters

A.2 Metal hardness value



Vickers HV 10 — F = 98,04 N ≙ 10 kp

Diagonale mm	0	1	2	3	4	5	6	7	8	9
0,10	1854	1818	1783	1748	1714	1682	1650	1620	1590	1561
0,11	1533	1505	1478	1452	1427	1402	1378	1354	1332	1310
0,12	1288	1267	1246	1226	1206	1187	1168	1150	1132	1115
0,13	1097	1081	1064	1048	1033	1018	1003	988	974	960
0,14	946	933	920	907	894	882	870	858	847	835
0,15	824	813	803	792	782	772	762	752	743	734
0,16	724	715	707	698	690	681	673	665	657	649
0,17	642	634	627	620	613	606	599	592	585	579
0,18	572	566	560	554	548	542	536	530	525	519
0,19	514	508	503	498	493	488	483	478	473	468
0,20	464	459	455	450	446	442	437	433	429	425
0,21	421	417	413	409	405	401	397	394	390	387
0,22	383	380	376	373	370	366	363	360	357	354
0,23	351	348	345	342	339	336	333	330	327	325
0,24	322	319	317	314	312	309	306	304	302	299
0,25	297	294	292	289	287	285	283	281	279	276
0,26	274	272	270	268	266	264	262	260	258	256
0,27	254	253	251	249	247	245	243	242	240	238
0,28	236	235	233	232	230	228	227	225	224	222
0,29	221	219	218	216	215	213	212	210	209	207
0,30	206	205	203	202	201	199	198	197	196	194
0,31	193	192	191	189	188	187	186	185	183	182
0,32	181	180	179	178	177	176	175	173	172	171
0,33	170	169	168	167	166	165	164	163	162	161
0,34	160	160	159	158	157	156	155	154	153	152
0,35	151,4	150,5	149,7	148,8	148,0	147,1	146,3	145,5	144,7	143,9
0,36	143,1	142,3	141,5	140,7	140,0	139,2	138,4	137,7	136,9	136,2
0,37	135,5	134,7	134,0	133,3	132,6	131,9	131,2	130,5	129,8	129,1
0,38	128,4	127,7	127,1	126,4	125,8	125,1	124,5	123,8	123,2	122,6
0,39	121,9	121,3	120,7	120,1	119,5	118,9	118,3	117,7	117,1	116,5
0,40	115,9	115,3	114,8	114,2	113,6	113,1	112,5	111,9	111,4	110,9
0,41	110,3	109,8	109,3	108,7	108,2	107,7	107,2	106,6	106,1	105,6
0,42	105,1	104,6	104,1	103,6	103,1	102,7	102,2	101,7	101,2	100,8
0,43	100,3	99,8	99,4	98,9	98,5	98,0	97,6	97,1	96,7	96,2
0,44	95,8	95,3	94,9	94,5	94,1	93,6	93,2	92,8	92,4	92,0
0,45	91,6	91,2	90,8	90,4	90,0	89,6	89,2	88,8	88,4	88,0
0,46	87,6	87,3	86,9	86,5	86,1	85,8	85,4	85,0	84,7	84,3
0,47	84,0	83,6	83,2	82,9	82,5	82,2	81,8	81,5	81,2	80,8
0,48	80,5	80,2	79,8	79,5	79,2	78,8	78,5	78,2	77,9	77,6
0,49	77,2	76,9	76,6	76,3	76,0	75,7	75,4	75,1	74,8	74,5
0,50	74,2	73,9	73,6	73,3	73,0	72,7	72,4	72,1	71,9	71,6
0,51	71,3	71,0	70,7	70,5	70,2	69,9	69,6	69,4	69,1	68,8
0,52	68,6	68,3	68,1	67,8	67,5	67,3	67,0	66,8	66,5	66,3
0,53	66,0	65,8	65,5	65,3	65,0	64,8	64,5	64,3	64,1	63,8
0,54	63,6	63,4	63,1	62,9	62,7	62,4	62,2	62,0	61,7	61,5
0,55	61,3	61,1	60,9	60,6	60,4	60,2	60,0	59,8	59,6	59,3
0,56	59,1	58,9	58,7	58,5	58,3	58,1	57,9	57,7	57,5	57,3
0,57	57,1	56,9	56,7	56,5	56,3	56,1	55,9	55,7	55,5	55,3
0,58	55,1	54,9	54,7	54,6	54,4	54,2	54,0	53,8	53,6	53,4
0,59	53,3	53,1	52,9	52,7	52,6	52,4	52,2	52,0	51,9	51,7
0,60	51,5	51,3	51,2	51,0	50,8	50,7	50,5	50,3	50,2	50,0
0,61	49,8	49,7	49,5	49,4	49,2	49,0	48,9	48,7	48,5	48,4
0,62	48,2	48,1	47,9	47,8	47,6	47,5	47,3	47,2	47,0	46,9
0,63	46,7	46,6	46,4	46,3	46,1	46,0	45,8	45,7	45,6	45,4
0,64	45,3	45,1	45,0	44,8	44,7	44,6	44,4	44,3	44,2	44,0
0,65	43,9	43,8	43,6	43,5	43,4	43,2	43,1	43,0	42,8	42,7
0,66	42,6	42,4	42,3	42,2	42,1	41,9	41,8	41,7	41,6	41,4
0,67	41,3	41,2	41,1	40,9	40,8	40,7	40,6	40,5	40,3	40,2
0,68	40,1	40,0	39,9	39,8	39,6	39,5	39,4	39,3	39,2	39,1
0,69	39,0	38,8	38,7	38,6	38,5	38,4	38,3	38,2	38,1	38,0
0,70	37,8	37,7	37,6	37,5	37,4	37,3	37,2	37,1	37,0	36,9
0,71	36,8	36,7	36,6	36,5	36,4	36,3	36,2	36,1	36,0	35,9
0,72	35,8	35,7	35,6	35,5	35,4	35,3	35,2	35,1	35,0	34,9
0,73	34,8	34,7	34,6	34,5	34,4	34,3	34,2	34,1	34,0	34,0
0,74	33,9	33,8	33,7	33,6	33,5	33,4	33,3	33,2	33,1	33,1
0,75	33,0	32,9	32,8	32,7	32,6	32,5	32,4	32,4	32,3	32,2
0,76	32,1	32,0	31,9	31,8	31,8	31,7	31,6	31,5	31,4	31,4
0,77	31,3	31,2	31,1	31,0	30,9	30,9	30,8	30,7	30,7	30,6
0,78	30,5	30,4	30,3	30,3	30,2	30,1	30,0	29,9	29,9	29,8
0,79	29,7	29,6	29,6	29,5	29,4	29,3	29,3	29,2	29,1	29,1

Figure A.2: Vickers HV 10

A.3 Datalogger of the first heat treatment

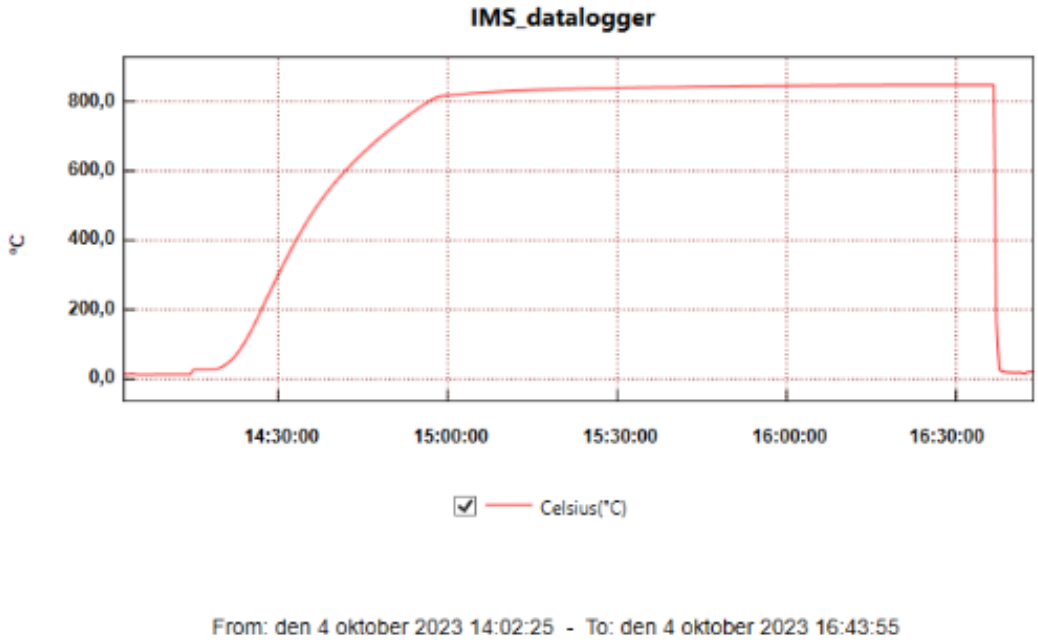


Figure A.3: EsaylogGraph

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS