Comparison of mechanical properties between HSS Gleeble simulated specimen and welded specimen

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

Bachelor's thesis

Riihimäki, Mechanical Engineering and Production Technology

2022 Spring

Joonsoo Lee

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

Mechanical Engineering and Production Technology Abstract

Author Joonsoo Lee Year 2022
Subject Comparison of mechanical properties between HSS Gleeble simulated specimen and welded specimen
Supervisor Jarmo Havula

High Strength Steel is receiving increasing attention from various industries due to its superior strength-to-weight ratio. There is a growing demand for researches dedicated to how HSS, welded with different heat inputs, will behave. One of the methods to achieve this purpose is to utilize Gleeble simulating system which imitate the heat cycles of welding process easily with desired input parameters. However it is very little known how similarly the Gleeble could simulate the welding. This thesis investigates difference in mechanical properties between welded and thermally simulated (Gleeble-simulated) steels which are affected by same heating curve and T8/5 cooling time.

S700MC Plus 4mm thick plates from SSAB were welded with a single weld run for the experiment. Gleeble specimens were heat-simulated by the Gleeble simulator with the same heating curve and cooling time generated during the welding process. Two plates (T5 and T6) were welded with two different heat inputs (0.38 KJ/mm and 0.68 KJ/mm). On contrary to expectation, tensile strength of welded specimens from both T5 (t8/5=13.45) and T6 (t8/5=33.03) turned out to be almost same. However, as for the Gleeble-simulated specimen, there was a greater reduction in tensile strength from T6 than T5. Significant hardness drop was observed in HAZ of all the samples. Welded specimens from T5 (t8/5=13.45) had higher hardness values than those from T6 (t8/5=33.03). Hardness value in HAZ of welded specimens is almost identical to that of corresponding Gleeble specimens.

It is unclear why the tensile strengths of welded specimens from both T5 and T6 are so similar, while those of Gleeble specimens show different values in general pattern of strength reduction proportional to longer t8/5 cooling times. One possible explanation could be that strength reduction in welded specimen may not occur significantly any more once t8/5 reaches 13 seconds, but samples that are Gleeble-simulated may continuously show linear strength reduction even after t8/5 exceeds 13 seconds. Another explanation is that this could be simply just an error in tensile testing process for welded specimens. In future research, more samples from larger range of heat inputs and t8/5 cooling times are required, so that resulting data can be validated enough.

Because of seemingly unreasonable result of tensile test, this comparison between welded and Gleeble specimen could not be validated. Consequently, meaningful correlation could not be made as well. However, this thesis still successfully set the standard methodology and procedures for comparing welded and Gleeble-simulated steels. Furthermore, it has clearly laid down the next steps of experiment that could help identify exact problem and validate the result.

Keywords S700, high strength steel, Gleeble, HAZ, welding.
Pages 64 pages and appendices 0 pages

Contents

1 Introduction

This thesis is commissioned by HAMK Tech, a research unit in Häme University of Applied Sciences, in Finland. Charles Whipp and Anh Tran, Development Engineers in HAMK Tech, contributed to the thesis by assisting arrangement and execution of welding, tensile test and hardness test. The thesis investigates similarity and potential difference between welded steel and Gleeble-simulated steel for different welding heat inputs and corresponding cooling times.

High Strength Steel (HSS) is receiving significant attention from various industries due to its superior strength-to-weight ratio. However, there is little known about the behavior of HSS when welded. There is a growing demand for research dedicated to how HSS, welded with different heat inputs, will behave, or more specifically how much it will lose its strength and hardness. One of the methods to achieve this purpose is to utilize Gleeble simulating system which imitates heating-cooling curve generated during welding process easily with desired input parameters.

1.1 Background

The softening effect of the Heat Affected Zone in welded HSS has been the subject of concern for many manufactures that are trying to utilize HSS. A lot of research has been conducted to explain this phenomenon and its effect on mechanical properties such as hardness and ultimate strength.

There are many kinds of HSS. Each differs from one another in their strength, microstructure and manufacturing method. All of these steels have to be researched individually to learn their behaviour when welded. One might face various challenges in doing so. For example, establishing welding setups optimized for each specific material might take a significant amount of time and effort. One solution to this problem is a thermal simulation utilizing equipment developed by Gleeble. It provides effective and fast simulation of the thermal effect of welding onto the material. This method can be used to research a number of HSS types in short time and with a relatively small effort.

However, there is only few literature published on whether this thermally simulated specimen can be reliably considered to represent actually welded specimen of the same material. There might be a slight difference in mechanical properties between them that researchers have to compensate when using test datas from Gleeble simulated specimens.

In response to these questions, firstly, this thesis will show how different weld heat inputs and corresponding cooling times will affect mechanical properties of HSS, specifically S700MC Plus. Secondly, this test data of welded HSS specimens will be compared to that of Gleeble simulated specimens in order to establish correlation between them. This correlation will serve as the reference to those who want to further research other HSS materials by using Gleeble welding simulator only.

1.2 Theory

Necessary topics needed to understand the experiment described in the thesis are behavior of Heat Affected Zone (HAZ) when welded, Gleeble system and High strength steel. These are explained in depth in the following paragraphs.

1.2.1 Heat Affected Zone and its effect

Heat Affected Zone (HAZ) refers to an area adjacent to fusion zone which is formed during welding. It is the area where heat is not too high to melt and fuse the base material with weld wire but high enough to change the microstructure of the material in that zone. This change in microstructure can have a negative impact on material´s hardness and strength.

The deteriorating effect of HAZ on mechanical properties is due to a number of factors, such as an increase in grain size and phase transformation of microstructure into inferior phase.

Grains size plays an important role in determining the hardness and strength of a material. Grains are small regions of crystalline metal neighboring each other. The bigger these grains are, the larger the contacting boundaries of these regions become. This causes the grains to be more likely to slide off each other on the contacting boundaries, which in large scale, deforms the material.

HAZ is divided into its subzones depending on its grain size. As shown in figure 1, Coarse Grain Heat Affected Zone (CGHAZ) consists of large non-uniform structure of grains. Further from the Fusion Zone (FZ), there is Fine Grain Heat Affected Zone (FGHAZ) which consists of smaller and finer structure of grains.

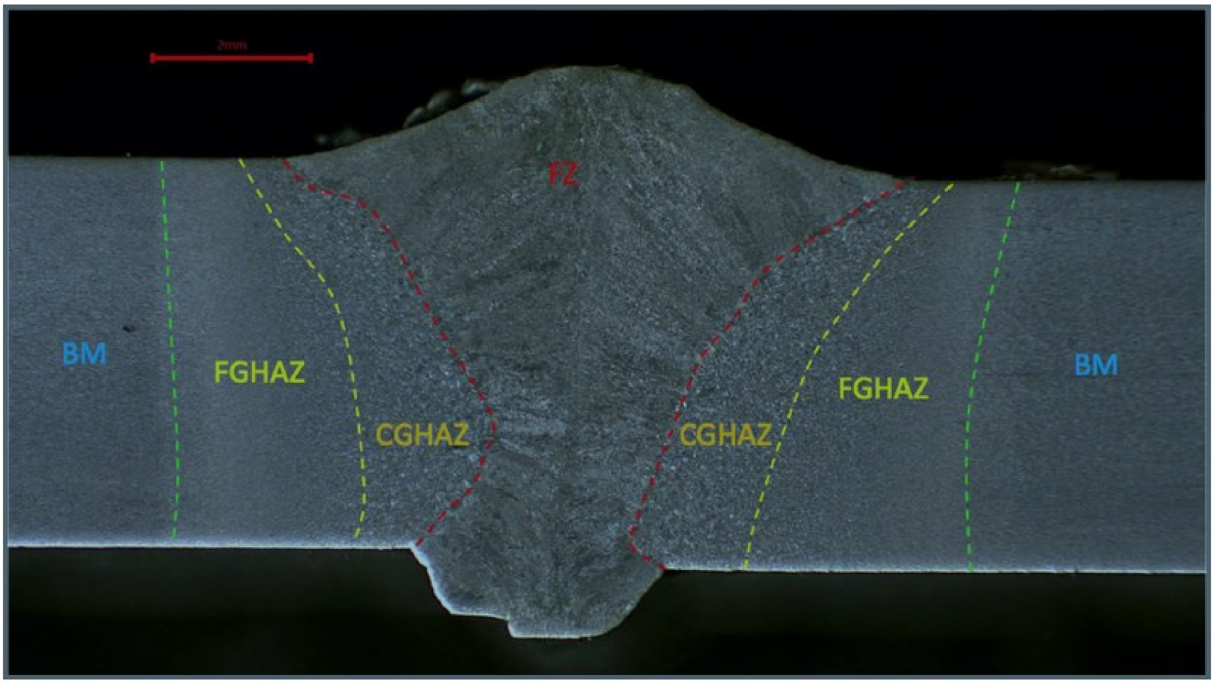


Figure 1. Subzones of HAZ. (Netto, 2019, p. 50)

When metal is heated during welding, microstructures of metal in HAZ undergo phase transformation. Depending on the material´s pre-existing microstructural phases, the high heat generated during welding can cause them to transform into often weaker phases. For example, Quenched and Tempered S690 High Strength Steel (QT S690 HSS) consists mainly of martensite. When martensite is heated above 730 Celsius and cooled, it is transformed into austenite and then decomposed into ferrite or pearlite which are characterized by lower hardness and strength compared to martensite. Figure 2 below shows microstructures of different zones of S690 after welding. In Fine Grain HAZ, the microstructures transforms from martensite to ferrite and pearlite which are bright parts and dark parts respectively. (Chen et al., 2017, pp. 3571-3572)

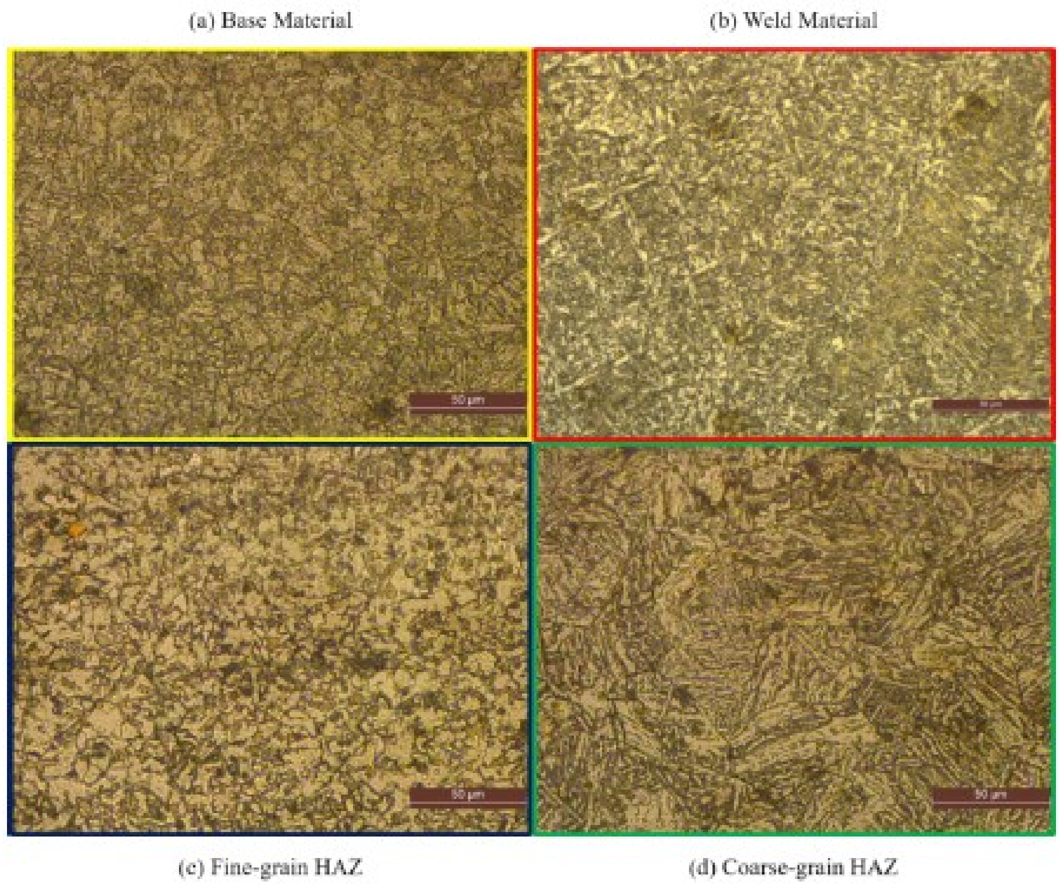


Figure 2. Microstructure of QT S690 HSS after welding. (Chen et al., 2017, p. 3571)

This HAZ softening phenomena results in a decrease in hardness value in that area. Figure 3 illustrates the locations of hardness test indentations on S690 welded specimen. Then in Figure 4, hardness values across the specimens in 3 lines of different height are plotted on the graph. Specimen BJ-3.2 is welded with heat input of 1.42kj/mm and BJ-5.0 with heat input of 2.99kj/mm. significant drop in hardness in FGHAZ is observed because of weaker phases in microstructure. However CGHAZ does not show much drop in hardness despite of its larger grain size. This is because microstructure remained same mainly as martensite In CGHAZ. (Chen et al., 2017, p. 3572)

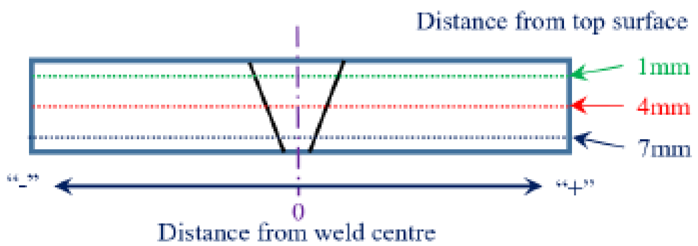
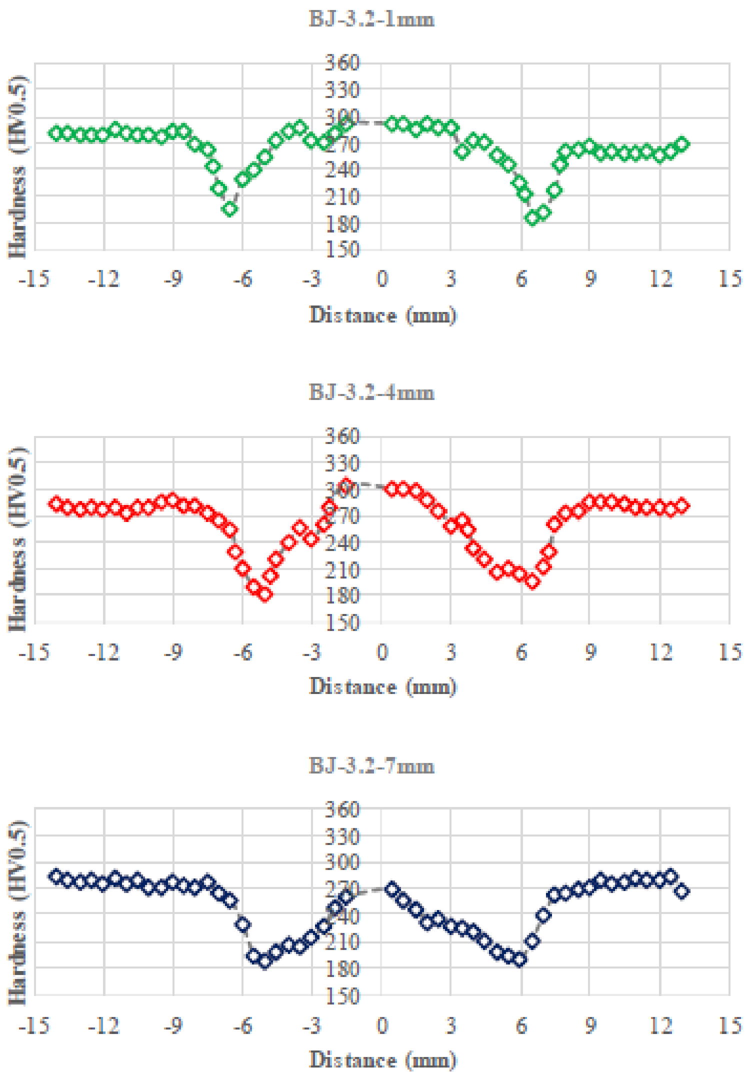
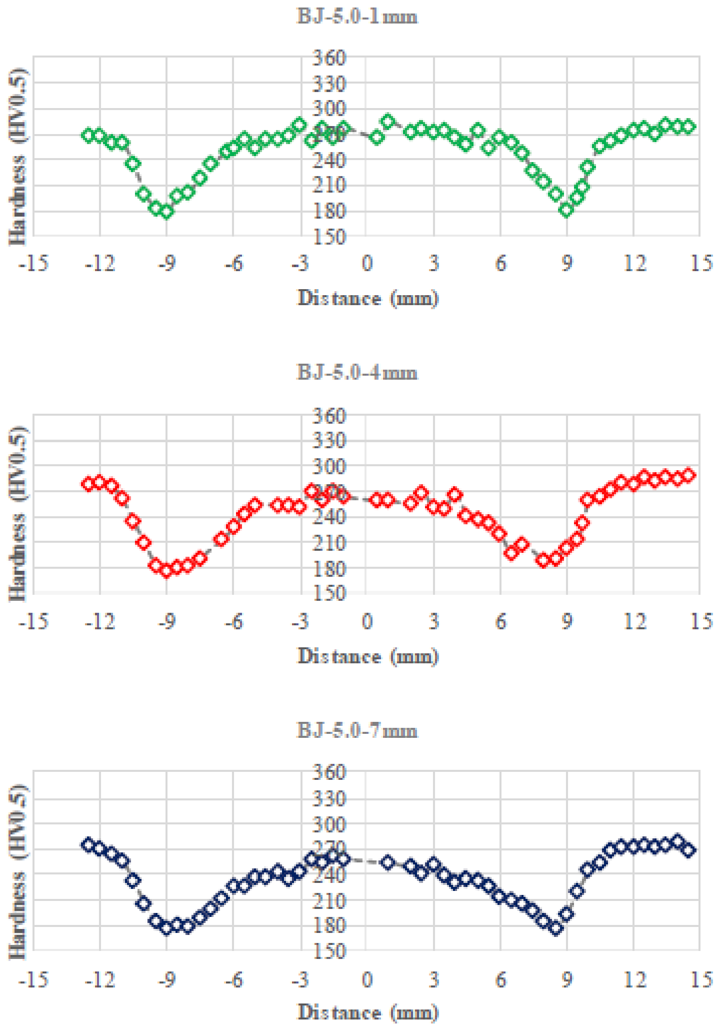


Figure 3. Locations of hardness Indentation across specimen. (Chen et al., 2017, p. 3572)



(a) Hardness values of Specimen BJ-3.2



(b) Hardness values of Specimen BJ-5.0

Figure 4. Hardness values of two specimens welded with (a) heat input of 1.42kj/mm and (b) heat input of 2.99kj/mm. (Chen et al., 2017, p. 3572)

Microstructural change in HAZ of S690 HSS also impacts tensile strength of material. As shown in Figure 5, tensile testing failure occurs in the FGHAZ where microstructural phases transforms into inferior phases. Stress-strain curves of these test specimens is illustrated in Figure 6. All welded specimens exhibits lower yield strength and tensile strength than those of Control coupon (Base material specimen). Table 1 shows numerical values of tensile test results. In table 1, another important thing to notice is that specimens welded with higher heat input shows much more reduction in both yield strength and tensile strength. This is because higher welding heat input leads to longer cooling time in HAZ thus giving more time for microstructure to deteriorate. (Chen et al., 2017, pp. 3574-3575)

Figure 5. Location of failure on S690 HSS welded specimen. (Chen et al., 2017, p. 3574)

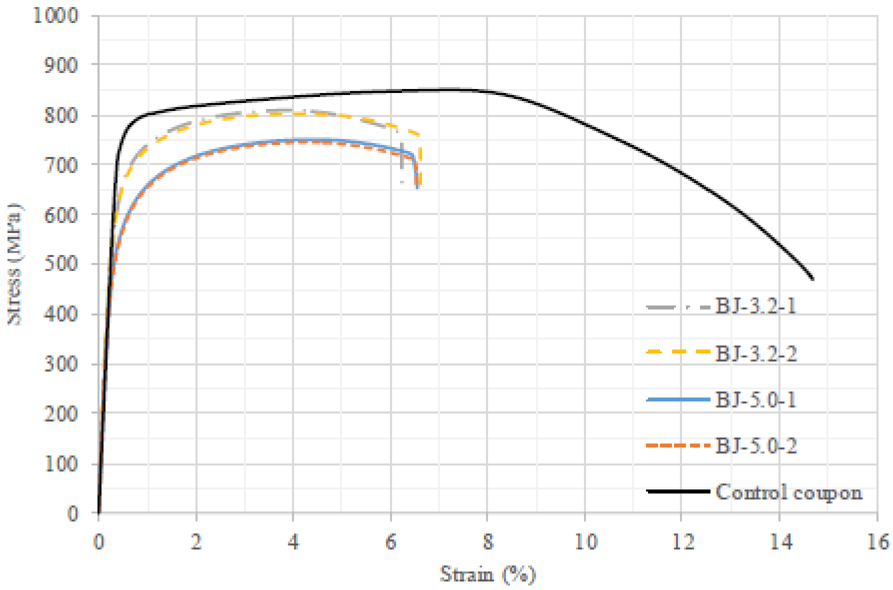


Figure 6. Stress- strain curves of S690 HSS welded specimens and base material specimen. (Chen et al., 2017, p. 3575)

Table 1. Tensile testing result of S690 HSS welded specimens. (Chen et al., 2017, p. 3575)

Coupon	Yield strength (MPa)	Tensile strength (MPa)	Fracture strain (%)
BJ-3.2-1	671.5	808.7	6.2
BJ-3.2-2	666.5	802.3	6.6
BJ-5.0-1	569.4	750.0	6.5
BJ-5.0-2	562.4	745.0	6.5

1.2.2 Gleeble system

Gleeble is the thermal mechanical simulating equipment that can conveniently reproduce the same thermal cycles created during metal welding work onto small Gleeble specimen. As shown in Figure 7, the Gleeble specimen is held between two water-cooled jaws, then heated by AC electric current flowing through it, a process known as AC resistance heating system. During simulation, desired thermal cycle is maintained and controlled by K-type thermocouple spot welded to the middle of sample, which is then connected to a feedback control system. This system monitors and controls the amount of electric current flowing through the specimen, ensuring that the desired thermal cycle is reproduced. (Kou, 2003, P. 59) Figure 8 visually shows details of each components inside of Gleeble 540 and describes their functions.

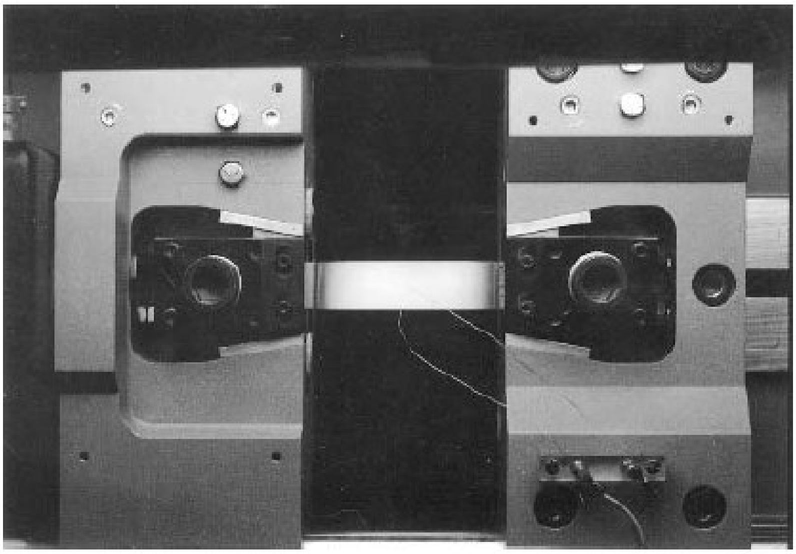


Figure 7. Gleeble specimen installed to the Gleeble simulating equipment. (Kou, 2003, P. 59)

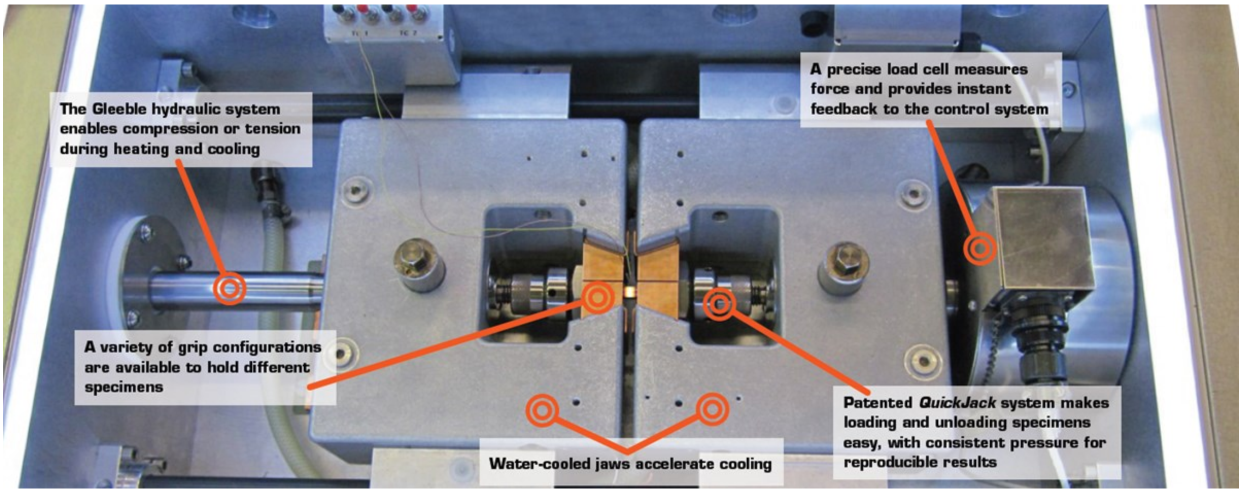


Figure 8. Main components in the vacuum tank of Gleeble 540 and their functions. (Gleeble, n.d.)

Application of Gleeble Welding Simulator can be very versatile. For example, Gleeble 3800 thermomechanical simulator which is used in this project, as shown in Figure 9, offers the versatility and performance needed for demanding contemporary research applications. It has not only welding simulation functions such as Weld HAZ Cycle simulation, but also material testing capabilities such as Fatigue test, Compression Test, Hot Ductility and Tensile testing and material processing simulation functions such as Hot rolling, Forging and Extrusion. (Gleeble, n.d.)

Figure 9. Gleeble 3800 thermomechanical simulator installed at the University of Oulu.

The direct resistance heating system of the Gleeble 3800 can heat specimens at rates of more than 10,000°C/sec, or can hold steady-state equilibrium temperatures within ±1°C. Thermocouples measure temperature of specimen and send feedback to the main system, which then accurately controls the heating of specimen to achieve programed heating curve. Water-cooled jaw carriers hold the specimen, making the Gleeble 3800 capable of high cooling rates up to 100°C/sec. The maximum cooling rate is determined by the size, shape, temperature, and composition of the sample. The thermal system of Gleeble enables an accurate manipulation of cooling rate for any specimen. Maximum loading capacity is 20kN. (Gleeble, n.d.)

1.2.3 High Strength Steel (HSS)

The definition and classification of High strength steel (HSS) is still not well established because of continuing development of such steel grades. According to the current specification such as Eurocode S1993-1-12, steels with nominal yield strength above 460MPa and up to 700MPa are considered as High strength steels. Steels with higher yields strength are categorized as Ultra high strength steels (UHSS). (Amraei et al., 2019, p. 1) HSS and UHSS are also categorized as members of high strength low alloy (HSLA) steels because of their strength levels and low alloy contents (Afkhami et al., 2019, p. 86).

HSS is produced by two major manufacturing methods; quenching and tempering (Q&T), and direct quenching (DQ) (Amraei et al., 2019, p. 2). Q&T type of HSS is strengthened by quenching and tempering to produce microstructures containing martensite and bainite. The maximum yield strength that can be obtained is dependent on the chemical composition and heat treatment. (Kou, 2003, P. 406) DQ type of HSS undergoes hot thermomechanical rolling followed by immediate water quenching (Amraei et al., 2019, p. 2).

Microstructures of HSS are often made up of a mix of irregular ferrite, bainite, martenstie, and retained austenite (Afkhami et al., 2019, p. 86).

The advantages that can be derived from the use of high strength steels are strongly dependent on the project context and the type and function of the structural component considered. The following are some of the potential benefits:

- Taking use of high-yield stress and tensile strength can help to increase design stresses. This may lead to a reduction in the required plate thickness, resulting in a reduction in dead weight.

- If plate thickness reductions are possible, volumes of deposited weld material, and therefore weld consumables and weld times, can be significantly reduced.

- Simplified structural components and construction techniques are possible, particularly in the case of larger structures or heavily loaded sections. As a result, not only may materials be saved, but also manufacturing, shipping, handling and construction.

- Savings can be made in foundation costs and space requirements due to the reduced dead weight of a structure and the reduced physical size of its elements. (Australian Steel Institute, n.d.)

1.3 Objective

The objective of this thesis is to first show how weld heat inputs and corresponding cooling times will affect mechanical properties of S700MC Plus. Secondly, this test data of welded HSS specimens will be compared to that of Gleeble simulated specimens in order to establish a correlation between them. This correlation will serve as the reference material to those who want to further research other HSS materials by using Gleeble welding simulator only.

1.3.1 Research questions

In order to achieve the objective of the projects, it is important to ask the right questions and tailor the direction of the project towards answering the questions. These research questions are as follows:

1. Is it reasonable and reliable to use Gleeble specimen data to predict a behavior of the HAZ of welded specimen?
2. Is there any significant difference in the tensile test results and hardness test results between Gleeble specimen and welded specimen?

3. If difference exists, to what magnitude? How similar can Gleeble specimen become to welded specimen?
4. What causes differences in strength and hardness?
5. Where does the failure occur? At HAZ, fusion line, or base material?

1.3.2 Research plan

Research plan is illustrated in the form of flow chart in figure 10 below.

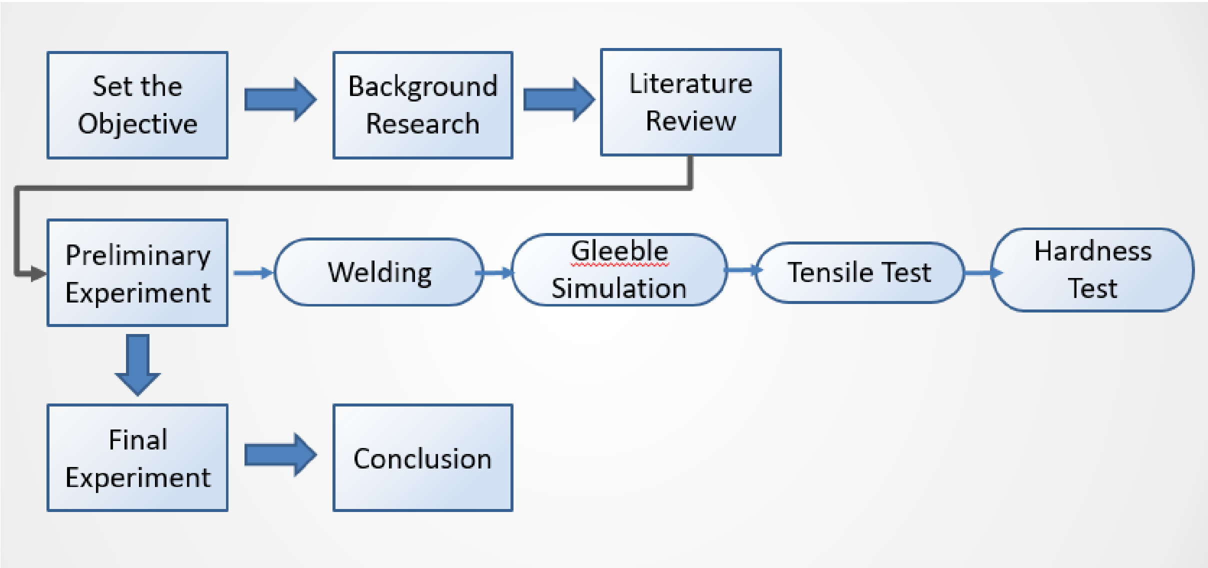


Figure 10. Flow chart for research plan.

2 Literature Review

There was no published literature that investigates the possible difference between Gleeble simulated specimen and welded specimen under the same conditions. However, there was a number of literature in which the Gleeble simulator is utilized in the research investigating the effect of welding heat input and t8/5 cooling time on the properties of different HSS of welded joints. Although they do not test the real welded material to be compared to the simulated material, this research will still be discussed in this section since it is meaningful to see the capabilities of Gleeble simulator and test arrangements for Gleeble simulation.

In the article written by Mician et al, an investigation of the effect of t8/5 cooling rate on the mechanical properties and microstructures of welded joints of S960MC steel was performed by using the Gleeble 3500 simulator. Three different cooling times acquired from metal active gas welding were simulated onto the specimens by the Gleeble simulator. All three specimens after simulation exhibited common pattern of HAZ. The tensile strength and hardness value both decreased more as the cooling time was longer. As for the Charpy pendulum impact test, all three specimens showed the higher absorbed every value than that of base material. There even was a trend of increasing absorbed energy value as the cooling time becomes longer. Details of each experiment steps are described in the following chapters. (Mician et al., 2020, pp. 1-16)

2.1 Material

In the article by Mician et al, the Strenx 960MC produced by SSAB was used. The chemical composition and mechanical properties of the experimental steel is shown in Table 2 and 3 respectively.

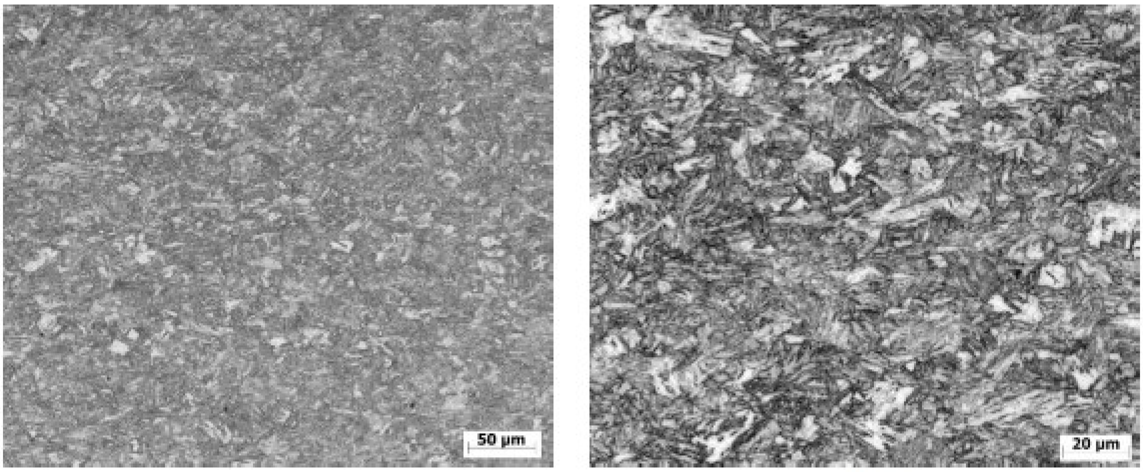
Table 2. Chemical composition of S960 MC.

According to	Chemical Composition [%] wt.—S960MC Steel										
	C	Si	Mn	P	S	Al	Nb	V	Ti	Mo	B
EN 10149-2 *	0.20	0.60	2.20	0.025	0.010	0.015	0.090	0.20	0.250	1.000	0.005
Inspection ** certificate	0.085	0.18	1.06	0.01	0.003	0.036	0.002	0.007	0.026	0.109	0.001

Table 3. Mechanical properties of S960 MC.

According to	Angle to the Rolling Direction	Mechanical Properties S960MC, Thickness 3 mm						
		$R_{p0.2}$ [MPa]	R_m [MPa]	$R_{p0.2}/R_m$	A [%]	Planar Anisotropy Coefficient P [%]		
						PR_m	$PR_{p0.2}$	PA
EN 10149-2	-	min. 960	980–1250	-	min. 7	-	-	-
Experimental measurements	0°	1007	1092	0.92	7.9	-	-	-
	45°	1018	1106	0.92	6.7	1.2	1.1	−14.4
	90°	1044	1124	0.93	6.5	2.9	3.6	−17.0

S960MC is a microalloyed, thermo-mechancally manufactrued HSS, with a microstruture that consists of tempered martensite and rest austenite. Figure 11 below shows the microstures of the base material.



(a) (b)

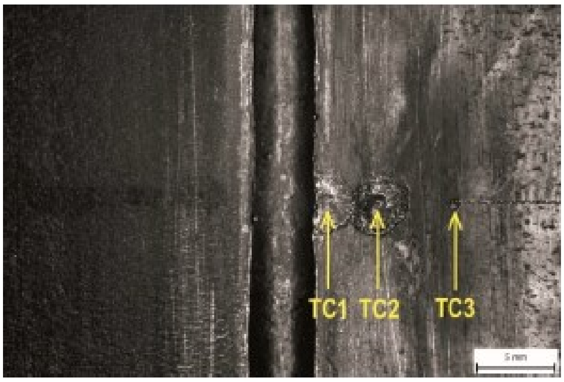
Figure 11. Microstructure of S960MC: (a) magnification 200x; (b) magnification 500x.

2.2 Welding

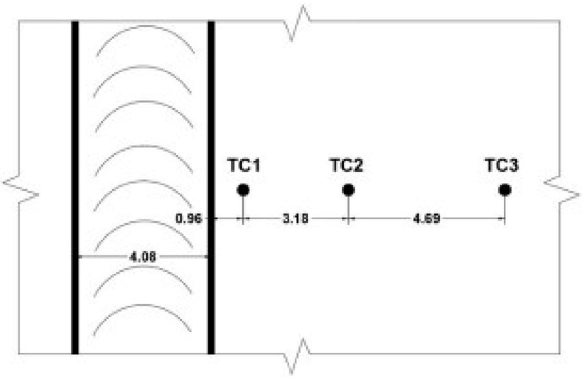
In the article by Mician et al, in order to obtain the real heat cycle to be simulated by Gleeble, the 3mm thick S960MC plates with a butt joint and a root gap of 1.5mm were welded single time using the copper-coated solid wire Union X96. This wire is undermatching filler material with the lower yield strength than that of base material. Automatic machine FVD 15 MF was used to maintain consistent and linear weld operation.

Monitored welding parameters during welding are as follows: mean current I_z = 102 A, wire feed speed v_d = 3.8 m/s, mean voltage U_z = 16.6 V, and welding speed v_z = 3.7 mm/s. Using the energy efficiency factor for MAG welding h = 0.8, the effective heat input was Q_{ef} = 0.37 kJ/mm.

During the welding process, temperature cycles in the HAZ were recorded by the Temperature Input Module NI-9212. T-type thermocouples were condenser welded on the bottom of the plate. Figure 12 shows a bottom of the plate and thermocouple placement.



(a)



(b)

Figure 12. Placement of thermocouples on the bottom of the plate: (a) thermocouple placement on the root side; (b) geometry of the position of thermocouple.

Shape and geometrical value of the single weld joint of 3mm thick plates in the cross-section is shown in Figure 13. The unit is in mm.

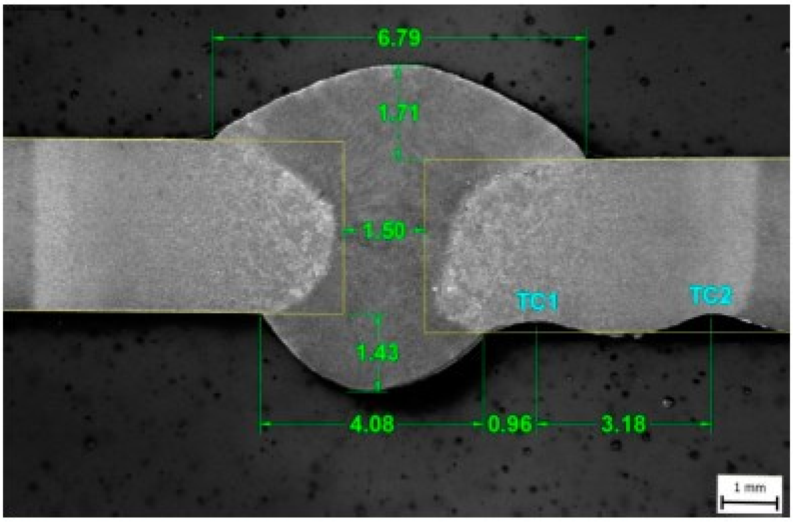


Figure 13. Geometry of the butt weld joint with position of thermocouple.

Only the TC1 thermocouple reached a temperature above 800 Celsius, and the resulting cooling time t8/5 was 17.5 seconds. The thermal cycles from the welding are shown in Figure 14.

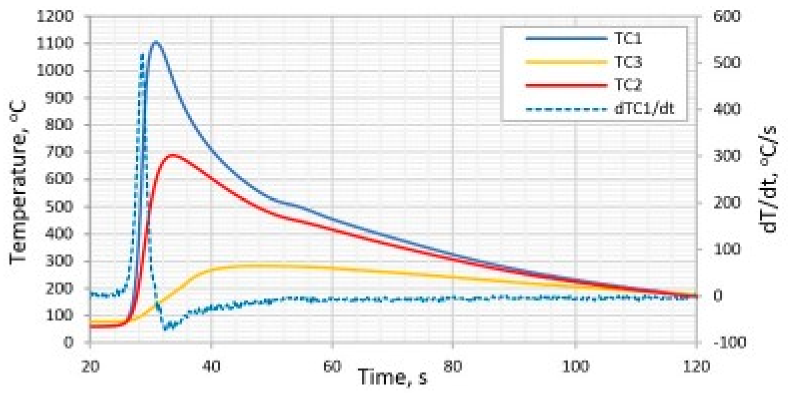


Figure 14. Thermal cycles obtained from the welding of a S960MC butt joint.

2.3 Preparation of Input Data for Gleeble simulation.

In the article by Mician et al, the heating and cooling of the test samples was controlled according to the specified temperature cycle given to the Gleeble simulator. This cycle is called TC_{prog} Program Cycle. This cycle can be generated based on the six different calculation models in QuickSIM2 software according to the type of material, heat input, thickness, welding input parameters. The first function is based on a real measured cycle from welding, and others are derived from heat transfer equations such as the Hannerz eqation, Rykalin 2D and 3D equations and the Rosenthal equation.

As for the experiment in the article by Mician et al, the measured heat cycle from the TC1 thermocouple, which is termed as the TC_{ref} Reference Cycle for further description, was used to generate three different TC_{prog} cycles with three different levels of cooling time t8/5. $TC1_{prog}$ was programmed to have t8/5=7s, $TC2_{prog}$ to have t8/5=10s and $TC3_{prog}$ to have t8/5=17s. Figure 15 shows the programed thermal cycles put into the Gleeble simulator along with the real measured one. 7 seconds was the shortest cooling time t8/5 that could be achieved by Gleeble 3800. This was only possible when the system turned off the power supply at the peak temperature of the cycle, and the specimen was cooled through heat transfer by water-cooled jaws clamping the specimen. That is why it is noticeable that, in figure 15, $TC1_{prog}$ curve drops to the 20 Celsius at the peak temperature which represents the sample temperature requirements of 20 Celsius.

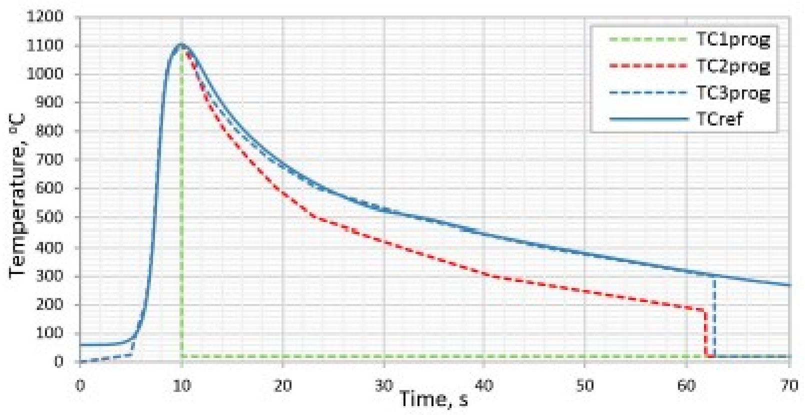


Figure 15. Program thermal cycles for the Gleeble simulation and the real measured thermal cycle TC_{ref}.

2.4 Preparation of test specimens and Gleeble simulation

In the article by Mician et al, dimensions of the tensile test specimen for Gleeble simulation are shown in Figure 16. Unit is in mm.

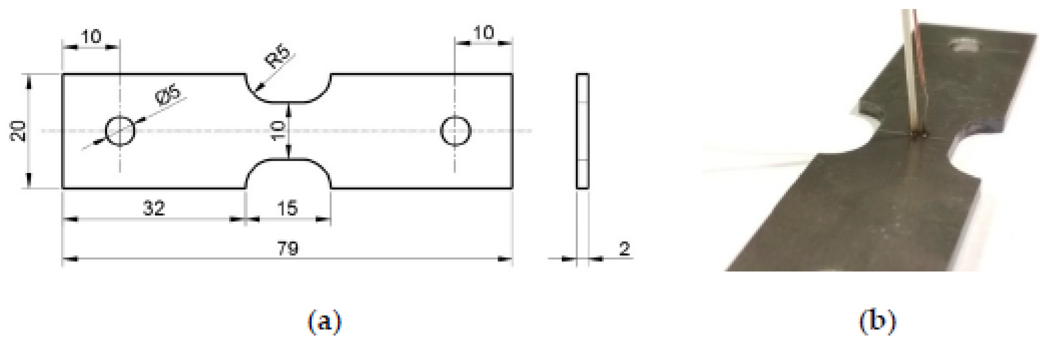


Figure 16. Tensile test specimen ready for Gleeble simulation: (a) dimensions of the specimen; (b) specimen with a thermocouple welded onto it.

As it can be seen in Figure 16, a thermocouple was welded onto the specimen in order to monitor the real temperature during thermal cycle simulation on Gleeble. Simultaneously, this cycle was being compared to the program cycle. This allows the machine to adjust its electric current power to match the two cycles as identically as possible.

The device was set to "Force-Control" when the force F=0. This ensures that the distance between the jaws changes automatically as the specimen slightly expands due to the temperature increase. This was done to prevent any potential internal stresses in the specimen.

The test specimens were labeled according to their cooling time t8/5, namely 7s, 10s, 17s. A record of the real temperature cycles measured during the simulation for different t8/5 is shown in Figure 17. In a temperature cycle corresponding to t8/5=7s, a sudden increase in temperature can be observed at 480 Celsius. This increase was due to the latent heat release during austenite transformation. A similar phenomenon can be observed in the cycle for t8/5 = 10s. This phenomenon was not observed in the cycle for t8/5=17s because the latent heat generated was already cooled down at slower cooling phase in this program cycle.

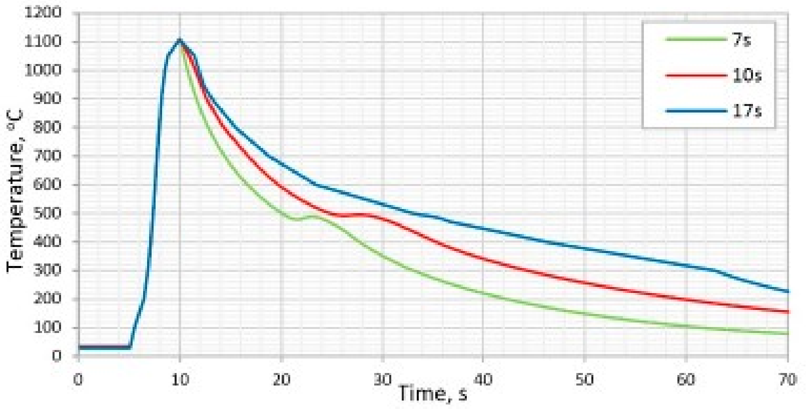


Figure 17. Thermal cycles for different cooling times t8/5 from the Gleeble simulation.

2.5 Tensile Test Result

In the article by Mician et al, these 3 different Gleeble simulated specimens with corresponding t8/5 cooling times were tensile tested to assess their yield strength and tensile strength. The result showed that the cooling rate had a significant impact on the yield strength and tensile strength of the material. For tensile test specimen with cooling time 7s, average tensile strength was 1027.2 MPa, which is 94% of value of the base material. The yield strength was 917.4 MPa, which is 91% of the base material. As for the specimens with cooling times 10s and 17s, their yield strength and tensile strength decreased even more. In other words, there was a trend in which the tensile strength and yield strength decrease as the t8/5 cooling time increases.

Table 4 shows the numerical values of the tensile test result, and Figure 18 graphically illustrates the result.

Table 4. Results of the tensile test for the base material and Gleeble simulated specimens with different cooling times t8/5.

Sample No.	$R_{p0.2}$ [MPa]	Average Value of $R_{p0.2}$ [MPa]	R_m [MPa]	Average Value of R_m [MPa]	$R_{p0.2}/R_m$
BM	1007.2	1007.2	1092.2	1092.2	0.92
7s-01 7s-02	923.1 911.7	917.4	1031.5 1022.9	1027.2	0.89
10s-01 10s-02	873.8 876.5	875.1	974.4 970.9	972.7	0.90
17s-01 17s-02	836.3 868.2	852.2	920.7 952.6	936.6	0.91

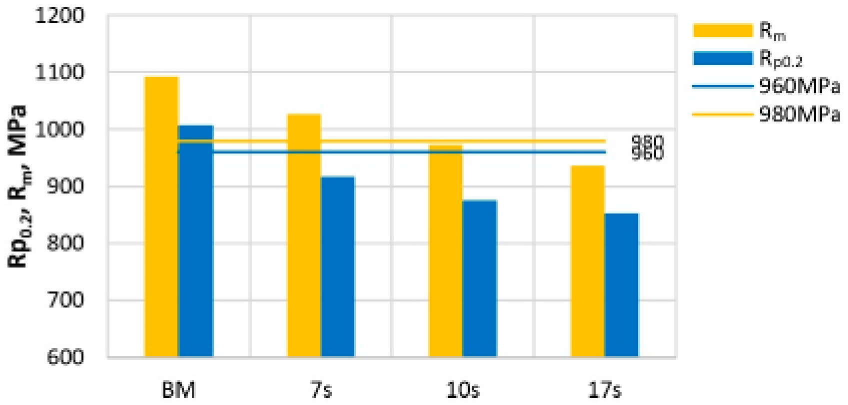


Figure 18. Graphical illustration of the results of the tensile test.

2.6 Charpy Impact Test Result

In the article by Mician et al, base material and Gleeble simulated specimens with 3 different cooling times t8/5 whose width had been reduced to 2mm underwent Charpy pendulum impact test at the temperature of -40 Celsius. The absorbed energy values in all simulated specimens were higher than those of the base material. There was a trend in which an absorbed energy value increases as the t8/5 cooling time increases. This phenomenon could be due to the fact that at slower rate of cooling phase the martensitic structure is tempered more substantially, and tempered martensite is known to be more ductile. The results of the Charpy impact test are shown in Table 5, and graphically illustrated in Figure 19.

Table 5. Results of Charpy impact test for the base material and Gleeble simulated specimens with different cooling times t8/5.

Sample No.	KV [J], 2 × 10 mm	Average Value of KV [J], 2 × 10 mm	KVC [J·cm^{-2}]	KV [J], 10 × 10 mm (Calculated)
BM	17	17	106.3	85.0
7s-01 7s-02	19 21	20	125.0	100.0
10s-01 10s-02	25 22	23,5	146.9	117.5
17s-01 17s-02	26 30	28	175.0	140.0

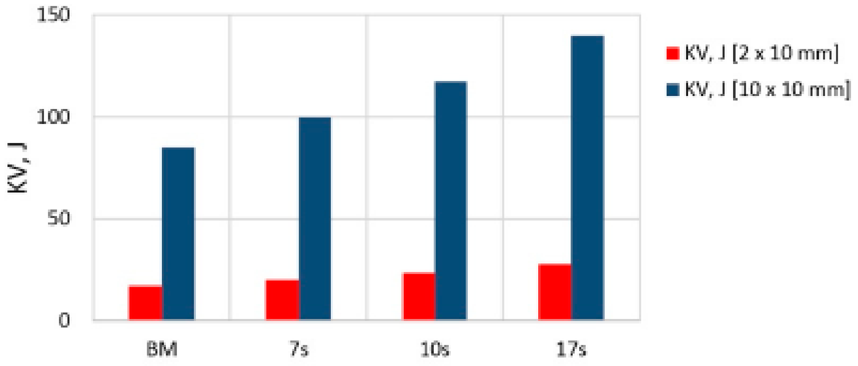


Figure 19. Graphical illustration of the results of the Charpy impact test.

2.7 Hardness Test Result

In the article by Mician et al, Vicker´s hardness test was conducted onto the surface of the base material and Gleeble simulated specimens with 3 different cooling times. An average value was calculated from six hardness measurement values in the range of -1.5mm to 1.5mm from the center of the specimen. The result shows that there is a higher decrease in hardness as the cooling time t8/5 increases. Numerical result is shown in Table 6, and graphical illustration of the result is shown in Figure 20.

Table 6. Results of the Vicker´s hardness test for the base material and the Gleeble simulated specimens with different cooling times t8/5.

Sample No.	Hardness in the Centre of Sample, HV1
BM	361
7s	328
10s	309
17s	302

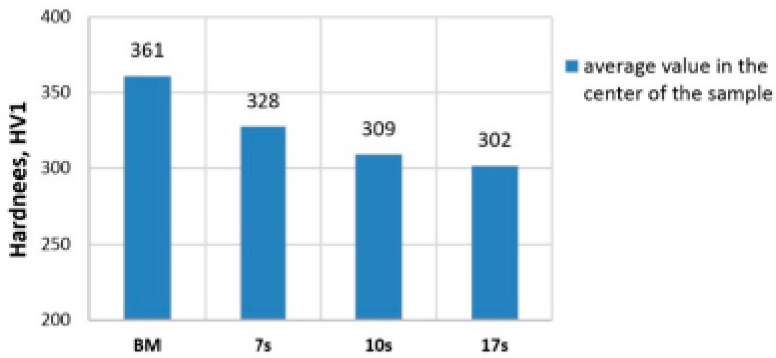


Figure 20. Graphical illustration of the results of the Hardness test.

2.8 Limitation of the research

Including the research discussed above, any accessible research papers, which involve Gleeble simulation method to investigate mechanical properties of steel, do not compare the Gleeble simulated specimens to the welded specimens that are given the same welding parameters. In order to specify the properties of the material using the Gleeble simulation, it is necessary to first validate the reliability of the Gleeble simulation itself and to which degree of similarity it can produce simulated specimen compared to actually welded specimen. Since this research does not consider this matter, reliability of its conclusion decreases significantly.

In response to this problem, this thesis will focus on comparing Gleeble simulated specimen to welded one. It will compare their mechanical properties and draw a correlation between them. This will allow for more reliable and systemized utilization of Gleeble simulation for investigating the properties of materials in the future.

3 Preliminary Experiment (s700_8mm_3R_Test 14)

It had been initially planned to use S700 MC Plus in 8mm plate welded 3 times as the main material for this thesis. However, as the results of Tensile test of Gleeble simulated specimen and the welded specimen differed too much from each other, it was concluded that if the welded plate undergoes 3 times of weld runs, then Gleeble simulated specimen also has to undergo the same number of weld runs with the same heating curves corresponding to each weld runs. Gleeble specimen, simulated in this way only, can be considered to be an actual simulated version of the welded specimen in question.

In order to eliminate the variables that make the Gleeble simulation difficult to imitate the welding, the S700 MC Plus in 4mm with a single weld run was chosen to be the new main material for the thesis. This would allow the Gleeble to simulate the heat cycle only once, thus making the process of imitation of welding conditions much easier. In addition, dimension of welded specimens for tensile testing was adjusted to the same dimension of Gleeble specimens. This new official experiment is discussed in the chapter 4.

Nevertheless, the process and result of the preliminary experiment on S700 MC Plus_8mm_3R is described thoroughly in the sections below.

3.1 Material

The material researched in this project is StrenX 700 MC Plus produced by SSAB. S700MC Plus is the Q&T type high strength structural steel with excellent cold formability and impact toughness for highly demanding application. It meets or exceeds the requirements of S700MC in EN10149-2. It is a hot-rolled flat product made of high yield strength thermo-mechanically rolled steels. Mechanical properties according to the SSAB are shown in Table 7. Chemical composition is specified in Table 8. (SSAB, n.d.)

Table 7. Mechanical properties of S700MC Plus. (SSAB, n.d.)

Thickness (mm)	Yield strength R_{eH} 1)2) (min MPa)	Tensile strength R_m (MPa)	Elongation A_5 (min %)	Min. inner bending radius for a 90° bend3)
3 - 10	700	750 - 950	13	1.0 x t
10.01 - 12	700	750 - 950	13	1.5 x t

Table 8. Chemical composition of S700MC Plus. (SSAB, n.d.)

C (max %)	Si (max %)	Mn (max %)	P (max %)	S (max %)	Al tot (min %)	Nb1) (max %)	V1) (max %)	Ti1) (max %)
0.12	0.25	2.10	0.020	0.010	0.015	0.09	0.20	0.15

3.2 Welding arrangement

Plates to be used were cut at their edges for the butt-welding set up as shown in Figure 21, then it was welded with the welding parameters shown in Table 9. It was welded three times to fill the whole gap by the robot arm, as shown in Figure 22, programmed to travel in straight line which allows for more consistency and precision than manual work.

Figure 21. Welding plate set-up.

Table 9. Welding parameters

Name of tensile test specimen [steel grade_plate thickness_number of passes-R_preparation method (F=flamecut; W=watercut; M=milled)_grinding (G=ground; N=non-	Description	Total welding length [mm]	Calculated welding time [s]	Welding speed [mm/s]	Welding speed [mm/min]	Current I (Actual) [A]	Voltage U [V]	Coefficient of thermal efficiency ε	Heat input Q [kJ/mm]	Working temperature T_0 [°C]	2D Cooling time calculated [s]	3D Cooling time calculated [s]	Cooling time measured [s]
S700_8_3R_F_N_R_2	root weld	391	156.4	2.50	150.0	**91.7**	23.1	0.8	0.68	20	**7.77**	3.58	16.65
	2nd run	391	156.4	2.50	150.0	**90.3**	21.4	0.8	0.62	66	**7.89**	3.71	20.0
	3rd run	391	156.4	2.50	150.0	**92.8**	20.8	0.8	0.62	81	**8.43**	3.87	18.9

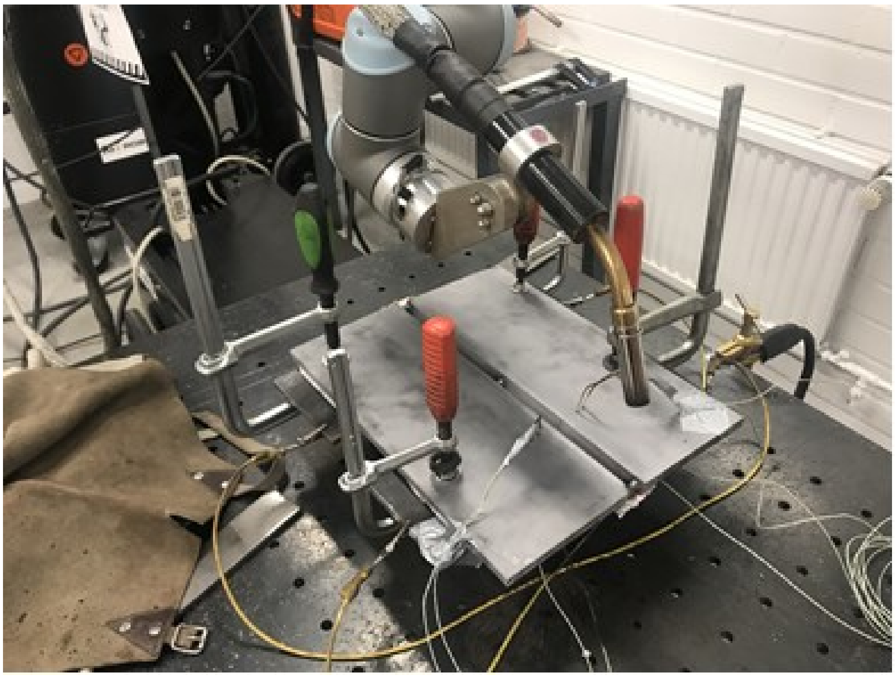


Figure 22. Welding by Robot arm.

In order to measure and record the heating graph, Thermocouples were attached to the plate at the HAZ area as illustrated in Figure 23. Figure 23 is a schematic figure with different steel plate. Three thermocouples were used to record each weld run. Holes for thermocouples to be inserted were drilled at the angle to effectively place thermocouples at the HAZ area. A Fixture for this work was used to enhance the drilling process as shown in Figure 24. Placement of thermocouples on the plate is shown in Figure 25 and 26.

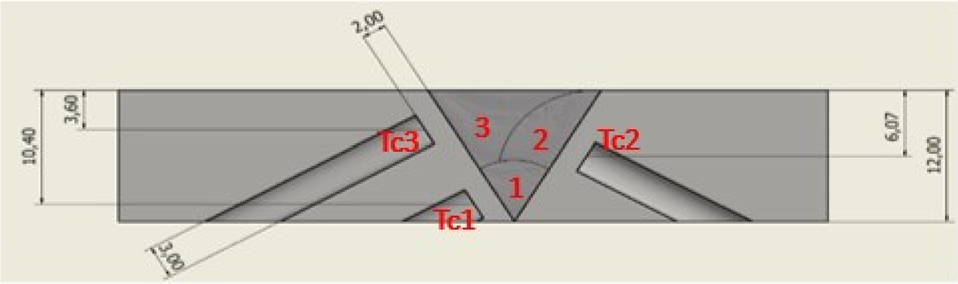


Figure 23. Schematic illustration of cross-sectional view of thermocouple placement.

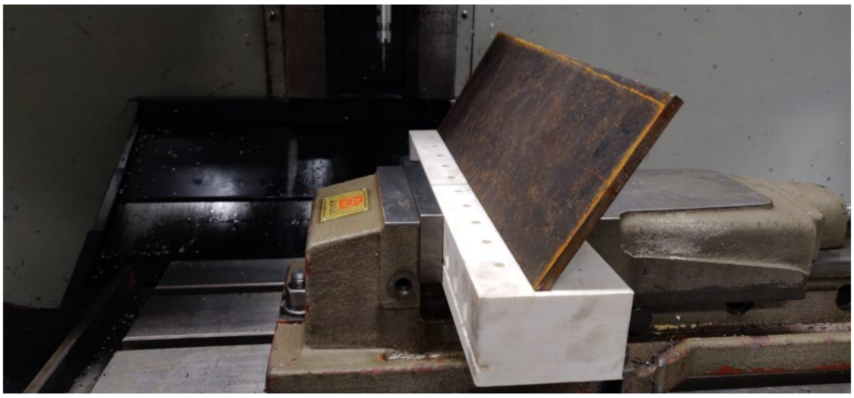


Figure 24. Fixture for drilling.

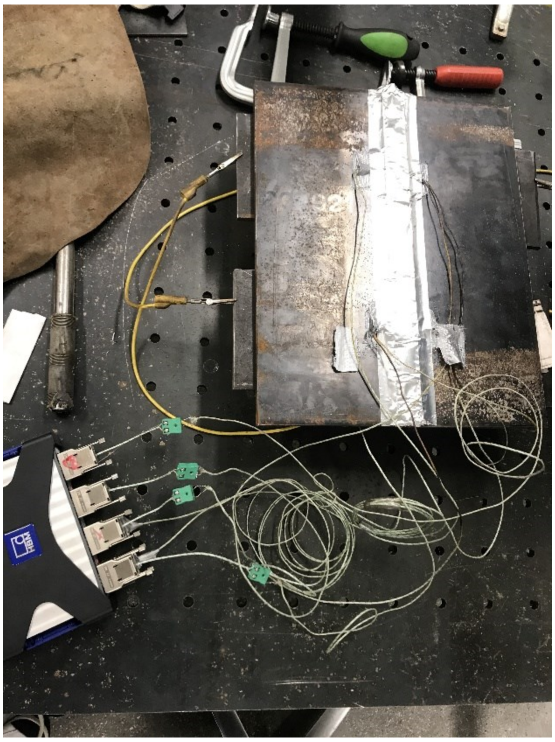


Figure 25. Thermocouple set-up

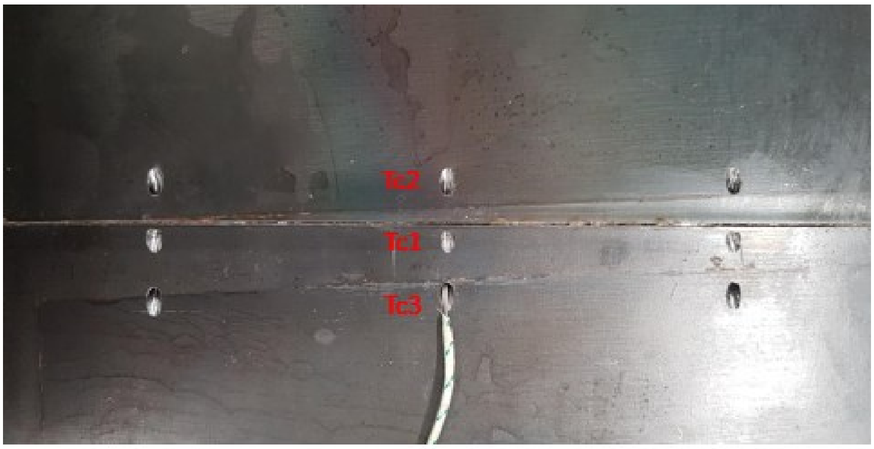


Figure 26. Thermocouple placement from the back view.

Cross sectional view of weldment after welding have been completed is shown in Figure 27. It can be observed that 3 weldments have formed and also 3 layers of HAZ have formed accordingly.

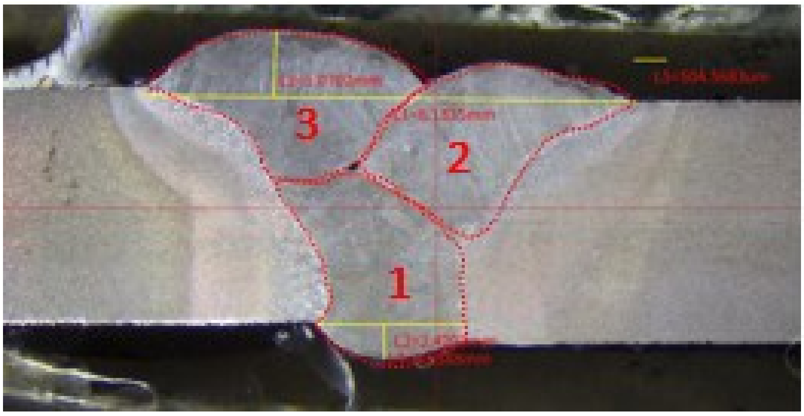


Figure 27. Cross sectional view of weldment.

3.3 Gleeble simulation arrangement

After welding is completed, the plate is water-cut into specimens for different tests according to the drawing shown in Figure 28. Gleeble specimens are shown in close up in Figure 29. A critical dimension is so called Free Span which is a length between necks from each ends. It was initially 33mm, but it was too long to achieve desired, short cooling time. Thus it has been changed to 20mm.

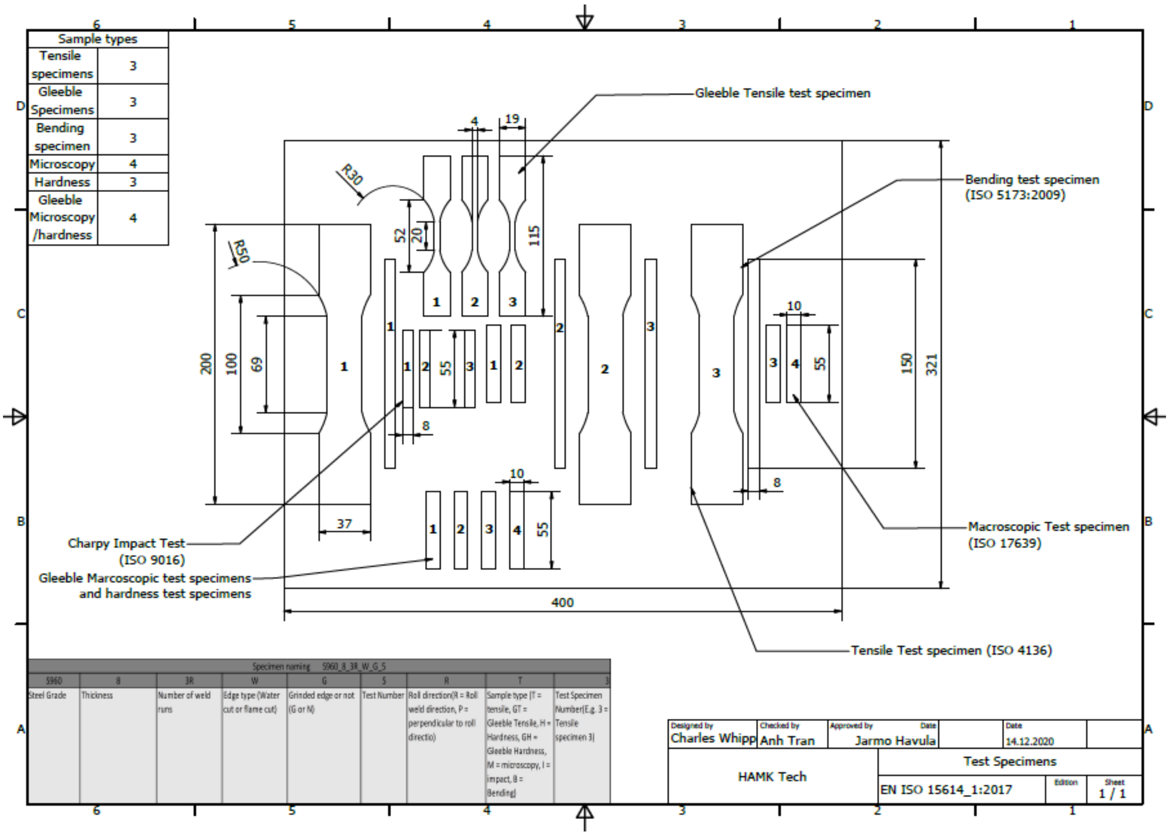


Figure 28. Drawing for water cutting.

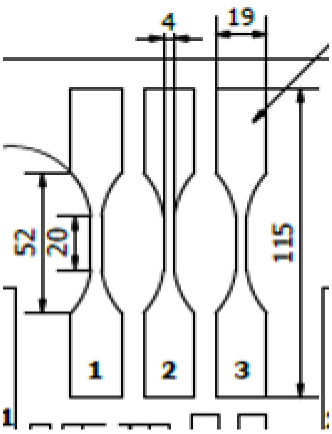


Figure 29. Gleeble specimen drawing.

Three Gleeble specimens cut out of the plate along with the heat cycle history to be imitated were sent to Oulu University to undergo Gleeble simulation. The heat cycle recorded by thermocouple 4 from second weld run, as shown in Figure 30, was selected for the main heat cycle to be simulated. Heat input used for this weld run and measured cooling time for this heat cycle is 0.62 kj/mm and 20s respectively, as indicated in table 10.

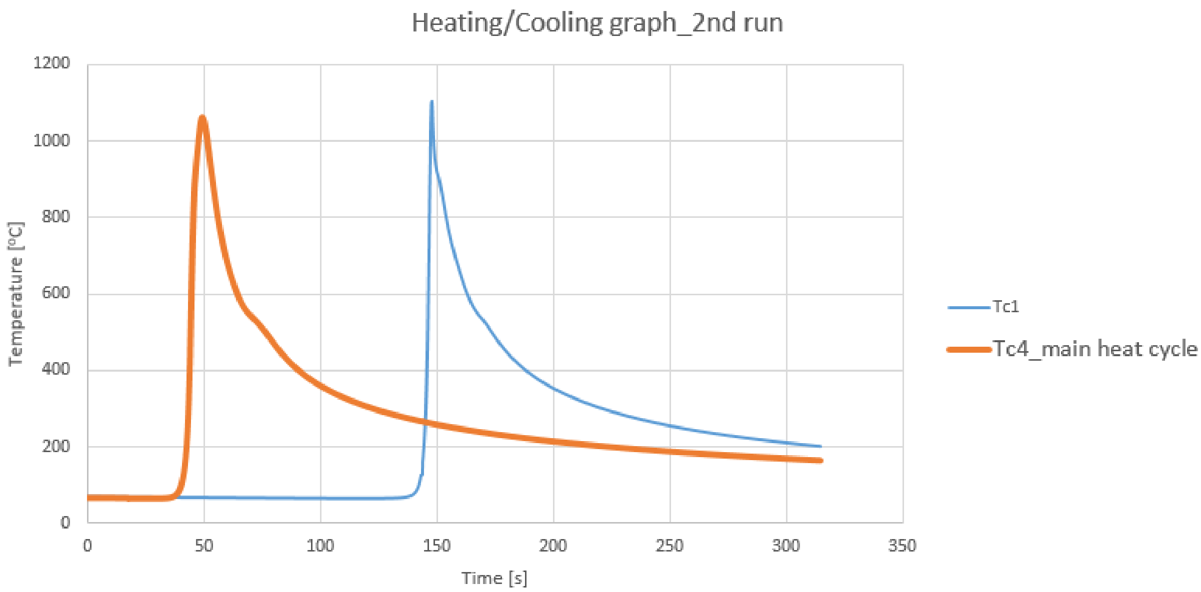


Figure 30. Heat cycle graph recorded by thermocouple.

Table 10. Heat input and measured cooling time.

Name of tensile test specimen	Description	Heat input Q [kJ/mm]	Cooling time measured [s]
S700_8_3R_F_N_R_2	2nd run	0.62	20.0

Figure 31 below shows the resulting graph of simulated heat cycle created by Gleeble machine being compared to original heat cycle from weld. In general, they are very similar except that Gleeble heat cycle tends to be more linear and consistent due to the fact that the heat was generated by programmed machine instead of real weld environment. Despite that, Gleeble specimen achieved identical t8/5 cooling time to that of welded specimen, which is critical since it is the main factor influencing material properties. Figure 32 shows the Gleeble specimens that have been thermally simulated by Gleeble Machine.

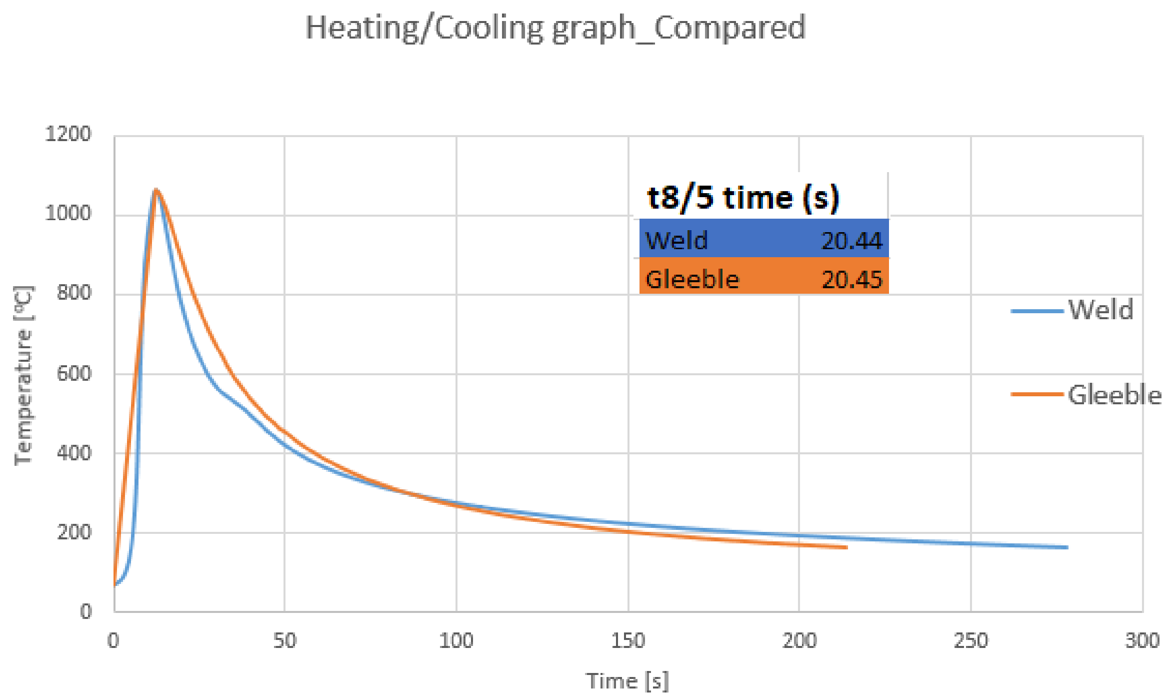


Figure 31. Comparison of actual heat cycle from weld and simulated heat cycle from Gleeble.

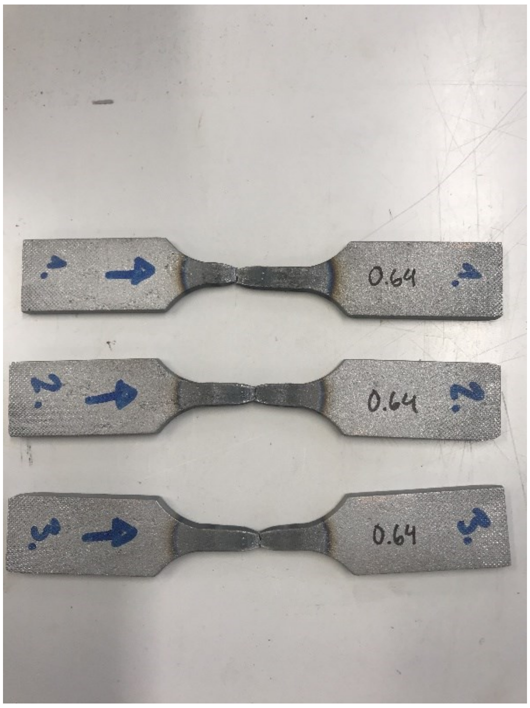


Figure 32. Gleeble specimen after being simulated by Gleeble machine.

3.4 Test arrangement

There are 2 major tests in this research for mechanical properties of the material; tensile test and hardness test. The sample preparation and testing arrangement are described in the following paragraphs.

3.4.1 Tensile test

Three welded tensile specimens from the plate were water-cut out. Tensile specimens and plate that have been water-cut are shown in Figure 33 and Figure 34 respectively. Zwick Roell tensile testing machine shown in Figure 35 was used for the testing. Tensile testing was done according to the standard SFS-EN ISO 6892-1:2019. Dimensions of tensile testing specimens followed ISO 4136 as indicated in Figure 36.

Figure 33. Water-cut tensile specimens.

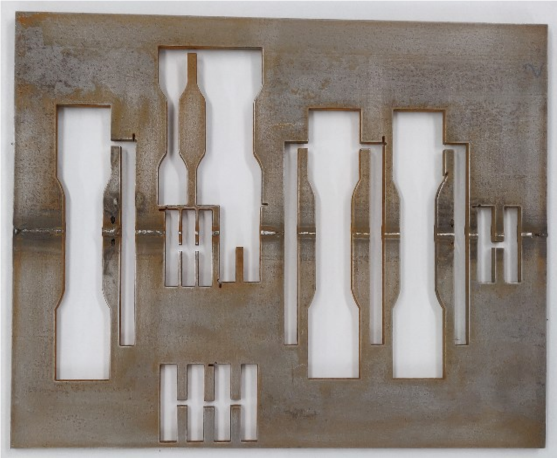


Figure 34. Welding plate after water cutting.

Figure 35. Zwick Roell tensile testing machine.

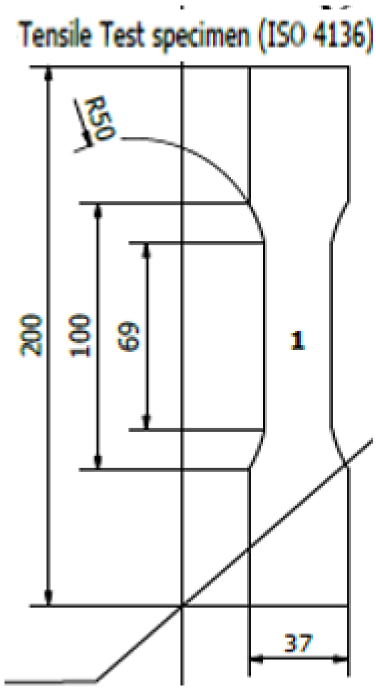


Figure 36. Dimension of tensile testing specimens according to ISO 4136.

3.4.2 Hardness test

Specimens for hardness test must be prepared for the best result before they are hardness tested. First, they were mounted with epoxy resin as shown in Figure 37. Then their surfaces on which the indentation would be marked were grinded and polished with the Struers automatic polishing machine as shown in Figure 38. Grinding and polishing procedures were done according to the Struers standard preparation method for 0.5% C steel (220HV) (Specimen No3) which is shown in Figure 39. Lastly, they were etched with 5% nital etchant, as shown in Figure 40, to expose the grain structure and HAZ, so that these can be observed more clearly. It should be noted that specimens in the following figures are not the main material (S700 MC Plus_8mm_3R) for this thesis. These are meant to enhance the understanding of the preparation process.

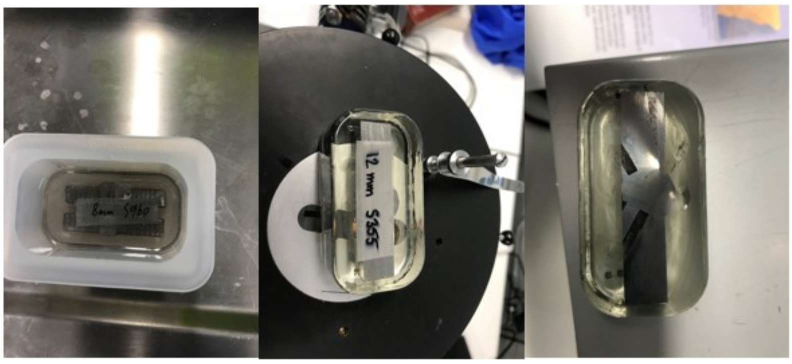
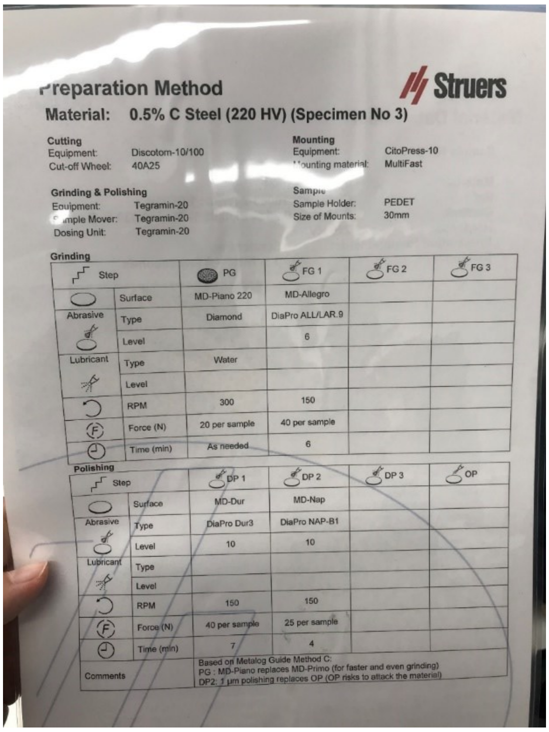


Figure 37. Mounting with epoxy resin.

Figure 38. Grinding and polishing process by Struers automatic polishing machine.



Preparation Method

Struers

Material: 0.5% C Steel (220 HV) (Specimen No 3)

Cutting
Equipment: Discotom-10/100
Cut-off Wheel: 40A25

Mounting
Equipment: CitoPress-10
Mounting material: MultiFast

Grinding & Polishing
Equipment: Tegramin-20
Sample Mover: Tegramin-20
Dosing Unit: Tegramin-20

Sample
Sample Holder: PEDET
Size of Mounts: 30mm

Grinding

Step		PG	FG 1	FG 2	FG 3
	Surface	MD-Piano 220	MD-Allegro		
Abrasive	Type	Diamond	DiaPro ALL/LAR.9		
	Level		6		
Lubricant	Type	Water			
	Level				
	RPM	300	150		
	Force (N)	20 per sample	40 per sample		
	Time (min)	As needed	6		

Polishing

Step		DP 1	DP 2	DP 3	OP
	Surface	MD-Dur	MD-Nap		
Abrasive	Type	DiaPro Dur3	DiaPro NAP-B1		
	Level	10	10		
Lubricant	Type				
	Level				
	RPM	150	150		
	Force (N)	40 per sample	25 per sample		
	Time (min)	7	4		
Comments		Based on Metalog Guide Method C: PG : MD-Piano replaces MD-Primo (for faster and even grinding) DP2: 1 µm polishing replaces OP (OP risks to attack the material)			

Figure 39. Preparation Method.

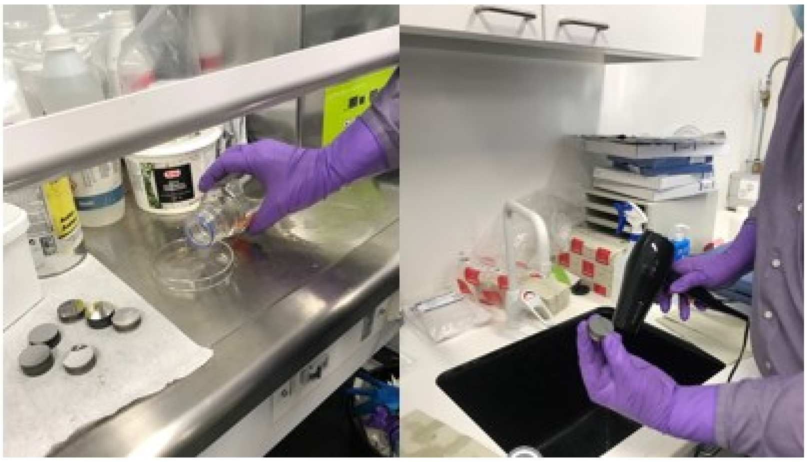


Figure 40. Etching process.

After the specimens were prepared by this procedure to be ready for hardness testing, they were sent to SSAB laboratory and then hardness tested using Vickers Hardness testing method according to standard EN ISO 6507-1.

3.5 Result

The results of the tensile test and hardness test are presented in the following paragraphs. Each test has two categories to show separately the result of welded specimen and Gleeble specimen.

3.5.1 Tensile test

3.5.1.1 Welded specimen

The welded tensile specimens that were tensile tested to the failure point are shown in Figure 41. The left is from the view of the weld top and the right is from the view of the root. The close-up view on failing area is shown in Figure 42. Side view of the tested specimens is shown in Figure 43. Close-up view of the side is shown in Figure 44. It can be observed that all 3 specimens failed at the HAZ.

Figure 41. Welded tensile specimens tensile tested to the failure point.

Figure 42. Close-up view on failing area.

Figure 43. Side view of the tested specimens.

Figure 44. Close-up view of the side of one of the tested specimens.

Test report in Figure 45 shows the numerical result of tensile testing. Figure 46 shows the graphical illustration of stress-strain curves of the result. Ultimate strength (R_m) and 0.2 offset yield strength ($R_{p0.2}$) of all 3 specimens are consistent with each other. However, the elastic modulus (E) of Specimen No 3 is much deviated from the rest. This could be due to wrong installation of extensometer or inhomogeneity of material in welded specimen.

ZwickRoell

Print date: 10.02.21

Test report

Test standard	: DIN EN ISO 6892-1	Pre-treatment	:	
Type and designation	:	Tester	:	
Material	:	Ae determination	:	Method a)
Specimen type	:	Machine data	:	

Test speeds	: Method A(1)		Speed, yield point	: 0,00025	1/s
Pre-load	: 5	MPa	Speed in the yield range	: 0,00025	1/s
Speed, Young's modulus	: 0,00025	1/s	Test speed	: 0,0067	1/s

Test results:

Legend	No.	Specimen ID	m_E GPa	E GPa	$R_{p0.2}$ MPa	R_{eH} MPa	R_{eL} MPa	A_e %	R_m MPa	F_m kN	A_g %	$A_{49,6mm}$ %
	1	3	221	221	695	-	-	-	835	172,99	5,04	-
	2	2	233	233	665	-	-	-	828	172,14	4,91	-
	3	1	155	155	696	-	-	-	825	170,64	4,09	-

Figure 45. Numerical result of tensile testing of welded specimens.

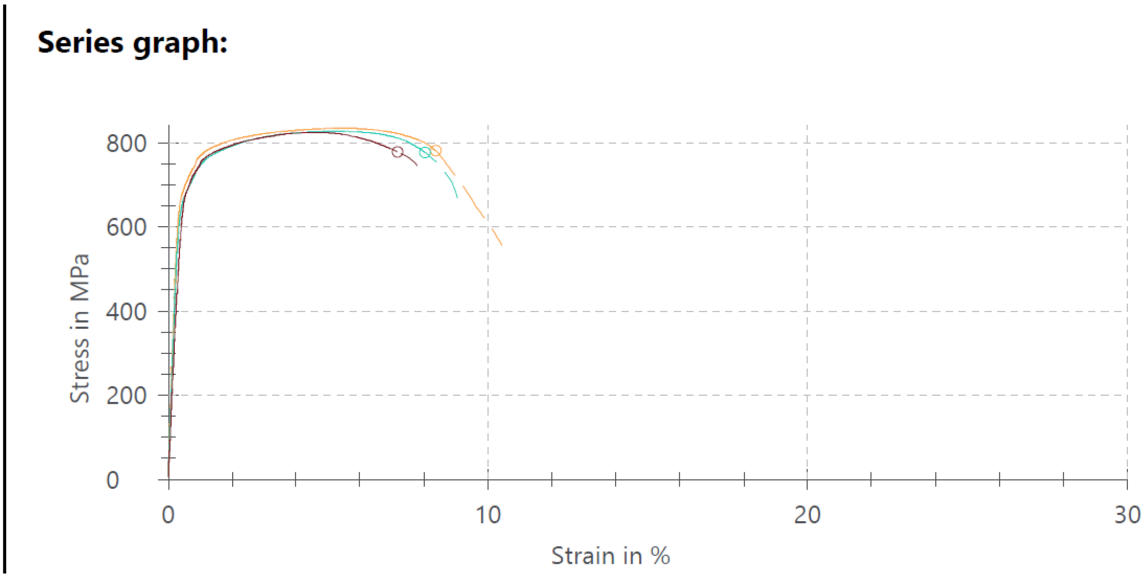


Figure 46. Stress-strain curves of welded specimens.

3.5.1.2 Gleeble specimen

The Gleeble simulated specimens were tensile tested to the failure point. Figure 47 shows the broken specimens after testing. Failure occurred at the middle of heat-tread free span.

Figure 47. Broken Gleeble tensile specimens after tensile testing.

Table 11 below shows the numerical result of tensile test. Ultimate strength, 0.2 offset yield strength and elastic modulus of all 3 specimens were fairly consistent with each other. Figure 48 shows the stress-strain curves of the specimens.

Table 11. Numerical result of tensile test of Gleeble specimens.

No.	m_E GPa	$R_{p0.2}$ MPa	R_{eH} MPa	R_{eL} MPa	A_e %	R_m MPa	F_m kN	A_g %	A_{16mm} %	a_0 mm	b_0 mm	S_0 mm^2
3	231	477	478	474	0,02	637	12,95	10,75	-	3,4	5,977	20,32
4	240	492	-	-	-	646	16,00	10,14	-	4,02	6,167	24,79
5	248	504	511	506	0,02	647	16,27	10,21	-	4,08	6,16	25,13

Series graph:

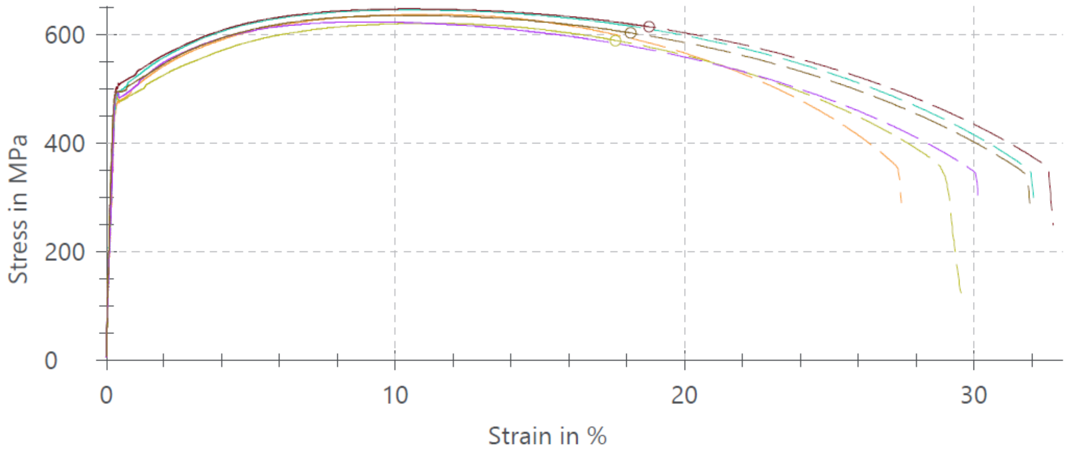


Figure 48. Stress-strain curves of Gleeble specimens.

3.5.2 Hardness test

Hardness test of welded specimen was done at the SSAB lab with the manual Vickers hardness testing machine. Two lines of hardness indentation were implemented; one at the top line which is 1mm down from the top, and the other at the middle line which is 4mm from each sides.

Gleeble specimens were not hardness tested for this preliminary experiment.

3.5.2.1 Welded specimen

Only one welded specimen was hardness tested. Figure 49 below shows the graph of hardness measured along the top line. Indentations were done with the test force of HV1 with distance of 0.15 to 0.3mm apart. Figure 50 shows hardness measurements along the middle line. Indentations were done with the test force of HV0.3, because HV1 was found to be so strong that the positions of indentations became slightly misaligned.

From the result, it can be observed that hardness values drop significantly at the HAZ areas.

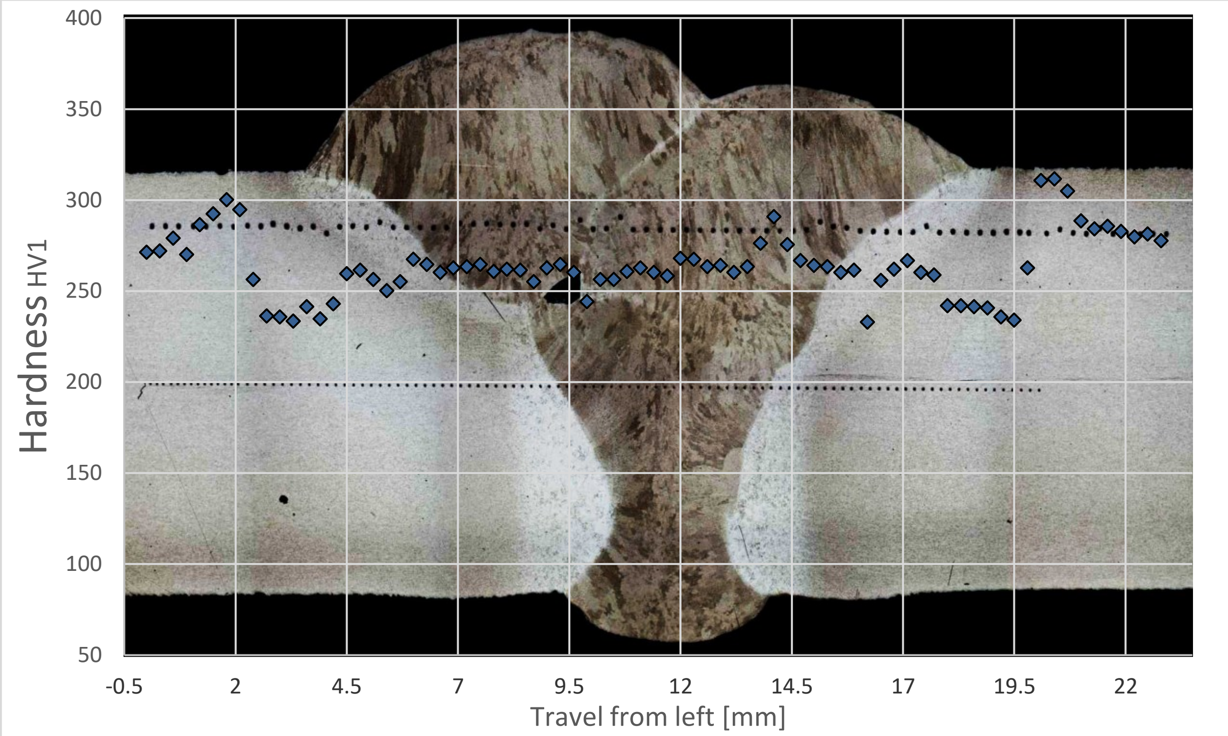


Figure 49. Hardness measurements along the top line.

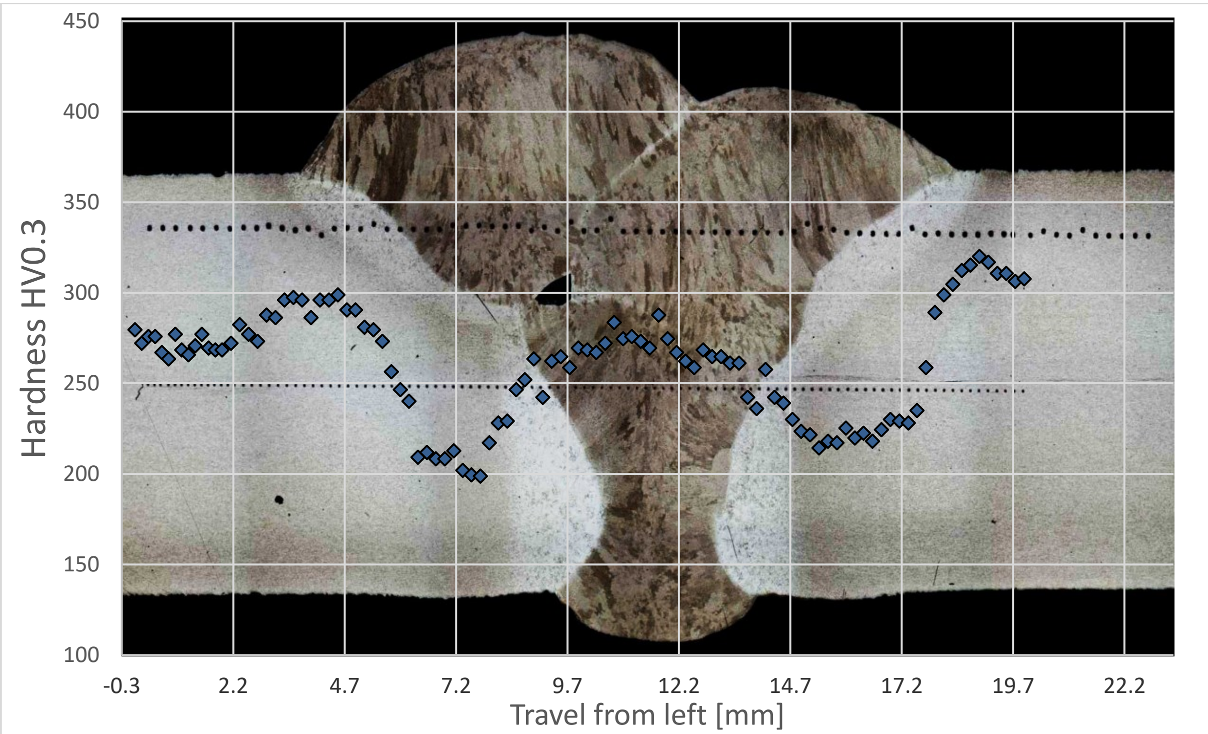


Figure 50. Hardness measurements along the middle line.

3.6 Analysis

The results of tensile test of welded specimens and Gleeble specimen are analyzed and compared. Since Gleeble specimens for hardness test were not tested, there is no comparison in the case of hardness.

3.6.1 Tensile test

In order to compare the tensile strength of welded specimen (W) and Gleeble specimen (G), average value was calculated from 3 samples. Comparison of average tensile strength (Rm) between W and G is shown in Table 12 below. Graphs compared are shown in Figure 51.

It can be observed from the data that tensile strength of G deviates too much from the W. This was an unexpected outcome. This could be due to the fact that G was simulated with single heat cycle while W was welded three times, in other words, underwent 3 heat cycles.

Table 12. Comparison of average tensile strength (Rm) between W and G.

Specimen	Rp0.2 (MPa)	Rm (MPa)
W	685.3	829.3
G	491	643.3

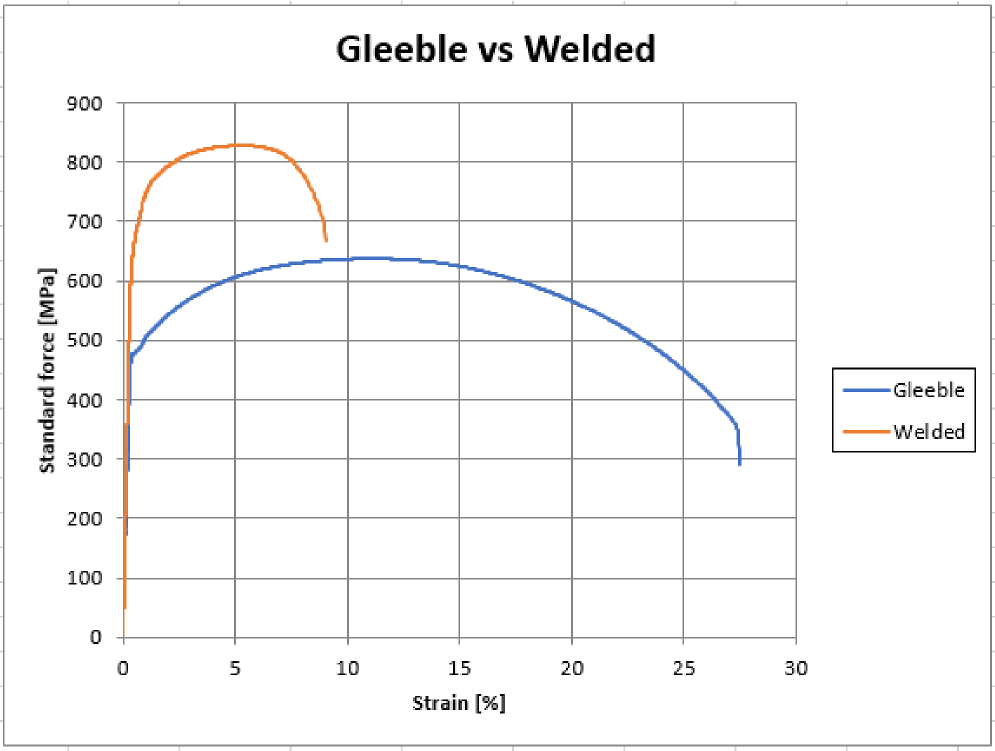


Figure 51. Comparison of stress-strain curves between W and G.

4 Final Experiment (s700_4mm_1R_Test 5&6)

After recognizing the problem when using multiple-welded specimen, the official material for this thesis was changed to 4mm single-welded specimen. This way, the Gleeble specimen could be heat-simulated only one time to imitate the weld done onto the welded specimen. Also, the dimensions of Gleeble specimen and welded specimen were now adjusted to the same size, so that they could have variables as equal as possible. The Gleeble specimen, simulated in this way, can now be considered as a correctly simulated version of the welded specimen in question.

Two plates are welded with two different heat inputs. Consequently they would result in different T8/5 Cooling times. Welded specimens are cut off from the plates then are tensile tested and hardness tested. Intact Gleeble specimens cut off from the plates are heat-simulated by Gleeble with the same cooling time curves as that of welded specimen. Finally, the heat-simulated Gleeble specimens are tested for tensile strength and hardness in order to be compared to the results of welded specimen.

Most of the test arrangement is same as the previous preliminary test, thus the same description of test arrangement is not repeated in the following sections. The focus will be on the comparison between the test results of welded and Gleeble specimens from both plates.

4.1 Welding arrangement

The welding setup for the official plates is mostly same as the previous preliminary test plate. Since only one weld run has to be made to achieve acceptable weld quality, 400 mm x 321 mm x 4mm plates were welded by V-shaped butt weld as illustrated in schematic figure in Figure 52. The thermocouples are attached to the HAZ in the plate.

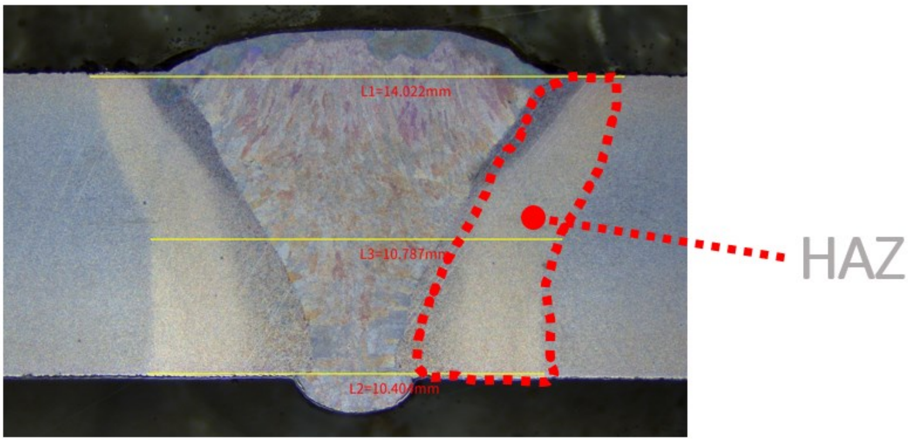


Figure 52. Schematic figure of V-shaped butt weld and location of HAZ.

The only different parameter is that now plates are welded a single time. Table 13 below shows the weld input data and measured cooling times from both plates. Cooling time was measured from the HAZ, not from the surface of the specimen. As can be seen in the table, T5 plate is welded with the low heat input of 0.38KJ/mm, while T6 plate is welded with the high heat input of 0.68KJ/mm. Resulting cooling times are 13.41 s and 33.03 s respectively.

Table 13. Weld input data and cooling times for T5 and T6 plates.

	Weld Parameters				
	Current	Voltage	Speed	Amplitude	(T8/5) Cooling time measured
Low Heat Input S700_4_W_N_R_T5	117 A	18 V	4.5 mm/s	2.4 mm	13.45 s
	Heat Input Q = 0.38 KJ/mm				
	Weld Parameters				
	Current	Voltage	Speed	Amplitude	(T8/5) Cooling time measured
High Heat Input S700_4_W_N_R_T6	146.7 A	19.8 V	3.5 mm/s	2.4 mm	33.03 s
	Heat Input Q = 0.68 KJ/mm				

Figure 53 below shows the welding layout drawing for welding plates of T5 and T6. There are three kinds of tensile test specimens. There are 3 large specimens (From now on referred as LS), 3 small specimens (SS) and 4 Gleeble specimens (GS) for tensile testing. SS and GS are the same size and are the main specimens to be compared with each other. SS in the middle are welded while GS are heat-simulated later by Gleeble. This thesis is a part of the bigger research project, which is why the plate presented in figure 53 includes also other specimens such as Charpy impact test specimens, which were not used in this thesis.

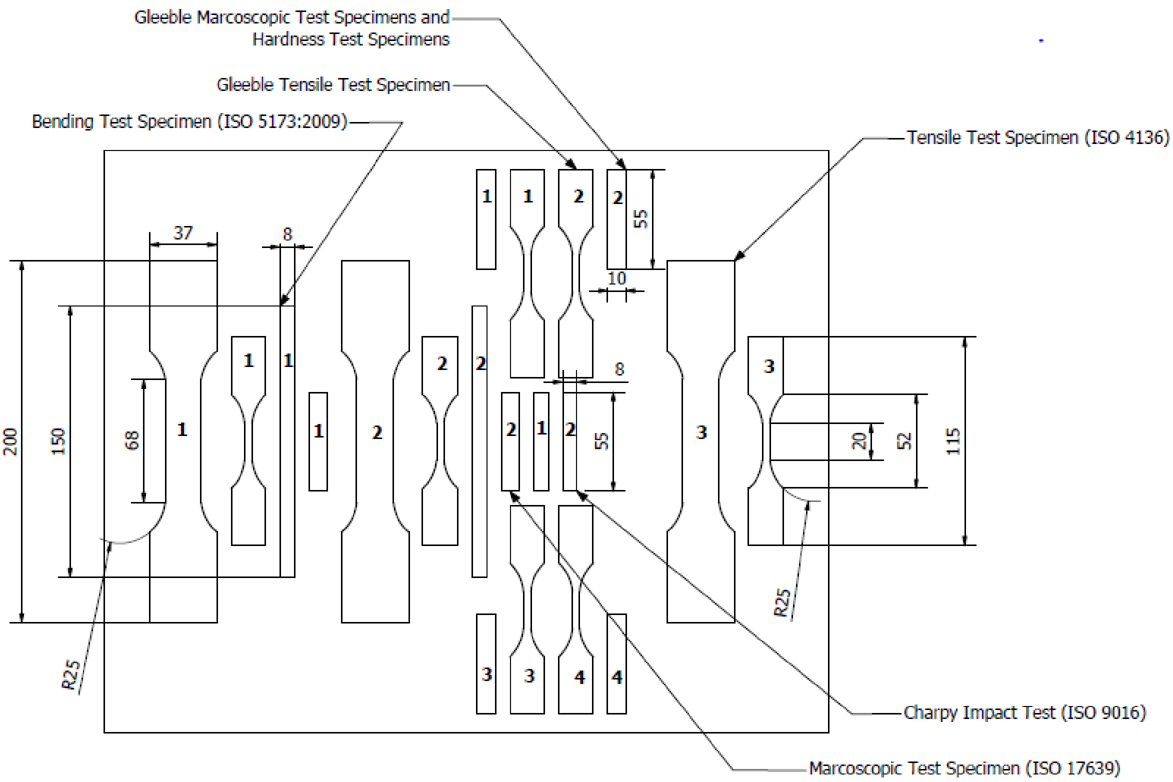


Figure 53. Welding layout drawing.

The heating and cooling data of the weld measured by thermocouples installed onto the plates are illustrated by graphs in the figures 54 and 55 below. Numerical T8/5 values from each TCs are shown in the table 14 below as well. Mean value of the T8/5s from each TCs was used for official T8/5 value.

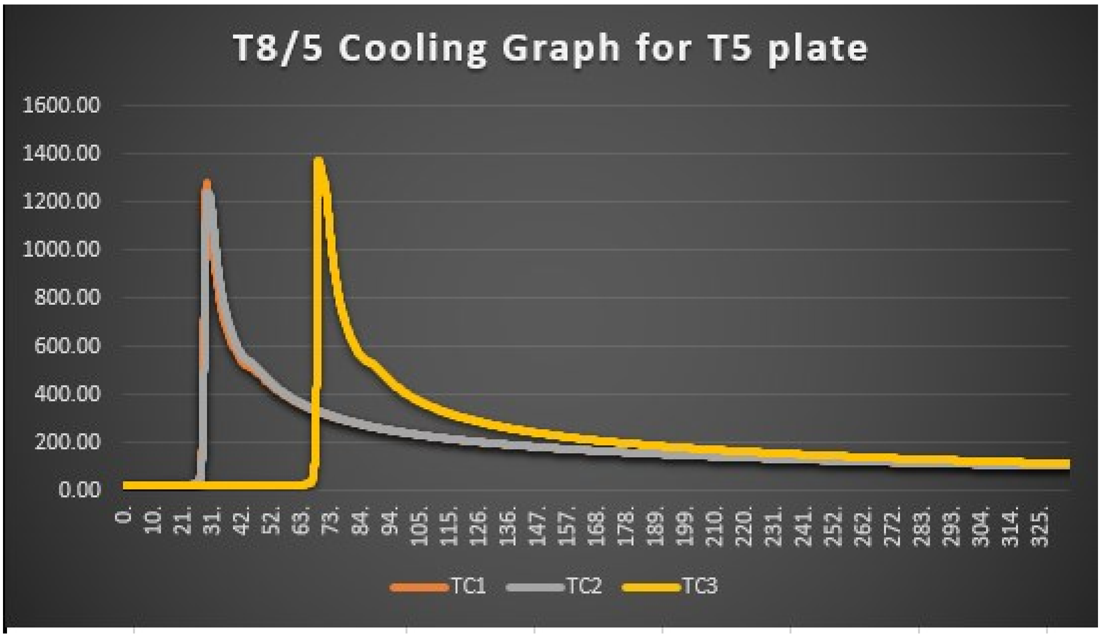


Figure 54. Heating and cooling data graph for T5 plate.

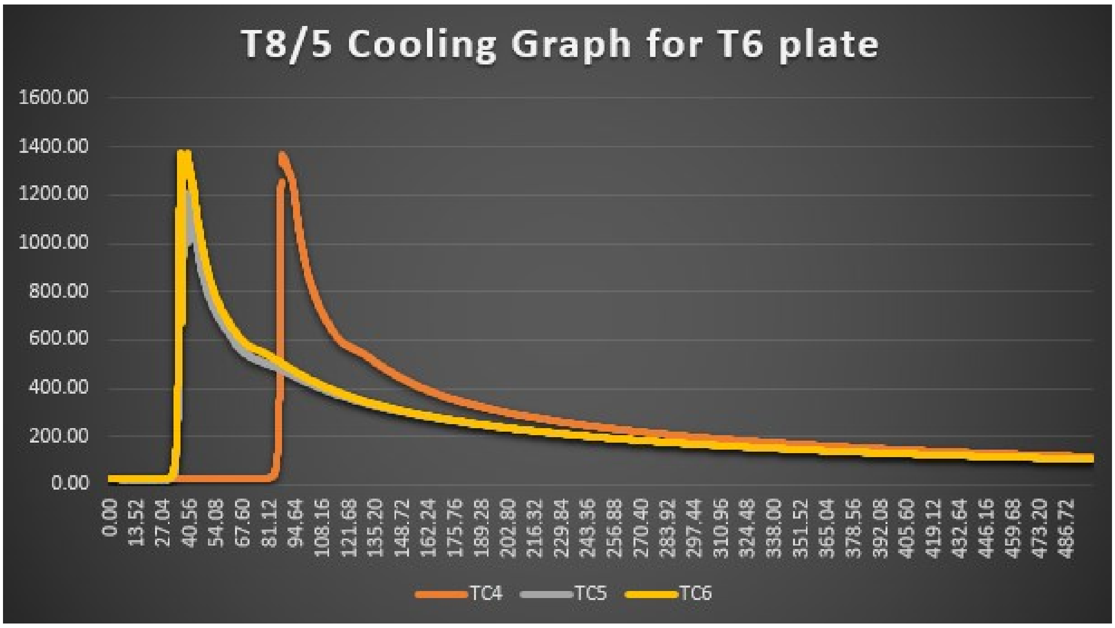


Figure 55. Heating and cooling data graph for T6 plate.

Table 14. Numerical T8/5 values from each TCs.

Thermocouples for T5	TC1	TC2	TC3	Mean
T8/5 Cooling Time (s)	12.96	13.12	14.28	13.45
Thermocouples for T6	TC4	TC5	TC6	Mean
T8/5 Cooling Time (s)	33.18	30.76	35.14	33.03

4.2 Result

The result of the tensile test and hardness test is presented in the following chapters. Tensile test was done for the base material, which is non-welded, original plate, welded specimen and Gleeble-simulated specimen. Hardness test was done for welded and Gleeble specimen.

4.2.1 Tensile test

Firstly, base material was tensile tested. This result serves as the reference point, to which welded and Gleeble specimens are compared in order to investigate the loss of strength. Then 3 welded specimens and 3 Gleeble specimens form each plates (T5 and T6) were tensile tested.

4.2.1.1 Base material

The base material of S700 MC Plus 4mm plate without welding was tensile tested in rolling direction. This data of the base material is used as a standard mechanical property against which all other heat-affected specimens are compared.

Table 15 below shows the Yield strength and Ultimate Tensile Strength of 3 base specimens from the same plate.

Table 15. Yield strength and Ultimate Tensile Strength of 3 base specimens.

	Yield Strength	Ultimate Tensile Strength
	MPa	MPa
S700_base_R_SS1	680.6121621	757.2788093
S700_4_base_R_SS2	708.463773	786.5471258
S700_4_base_R_SS3	719.8570101	796.9513153

Figure 56 below shows the Strength-Strain curves obtained from tensile testing of 3 base specimens.

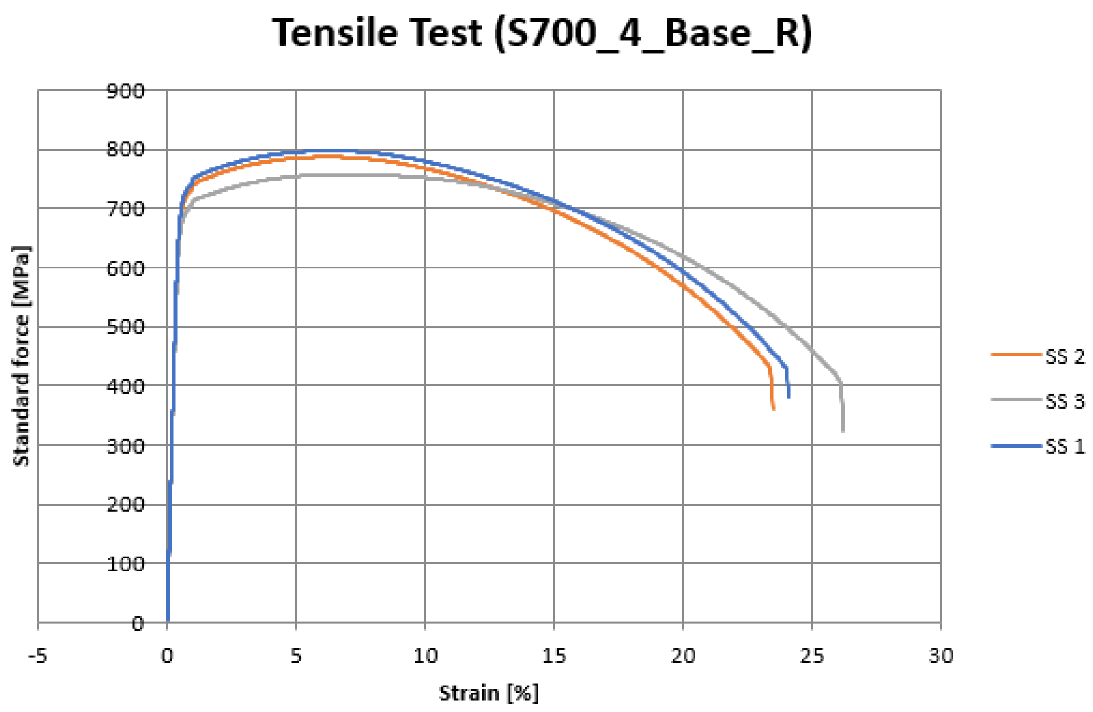


Figure 56. Strength-Strain curves of base specimens.

4.2.1.2 Welded specimen

Three small specimens (SS) from the welded plate labelled as T5, which is welded once with the low heat input, were tensile tested and following figure 57 shows the strength-strain curves of the tests.

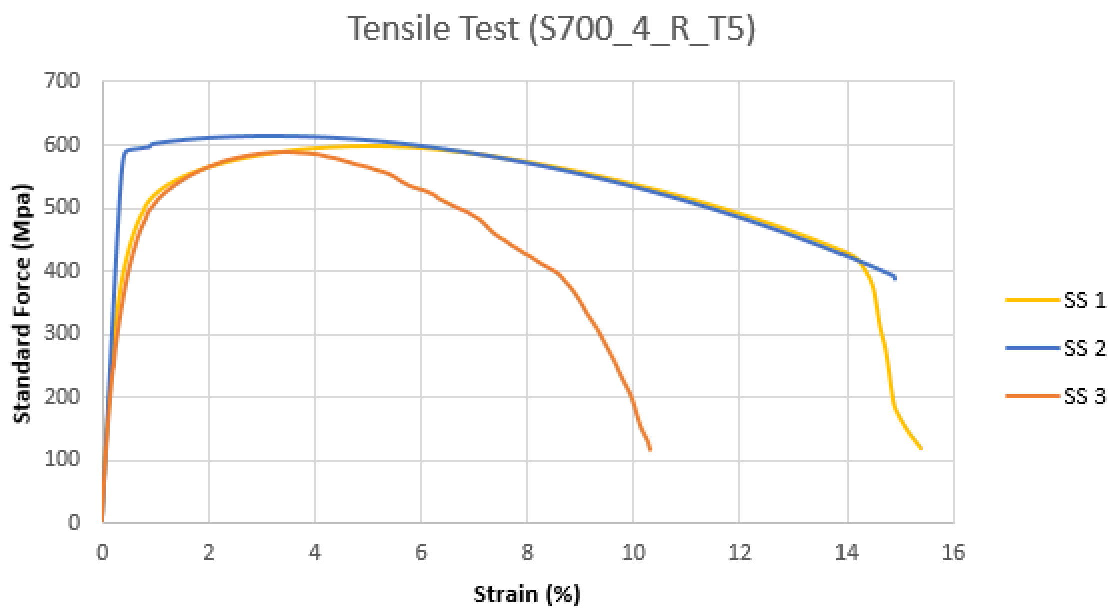


Figure 57. Strength-Strain curves of 3 welded small specimens (SS) from T5.

Table 16 below shows the numerical value of tensile strength of SS from T5.

Table 16. Numerical value of tensile strength of SS from T5.

	Ultimate Tensile Strength
	MPa
S700_4mm_W-N_R_T5_SS1	599.0061335
S700_4mm_W-N_R_T5_SS2	614.81711
S700_4mm_W-N_R_T5_SS3	589.1097813

Three small specimens (SS) from the welded plate labelled as T6, which is welded one time with the high heat input, were tensile tested and following figure 58 shows the strength-strain curves of the tests.

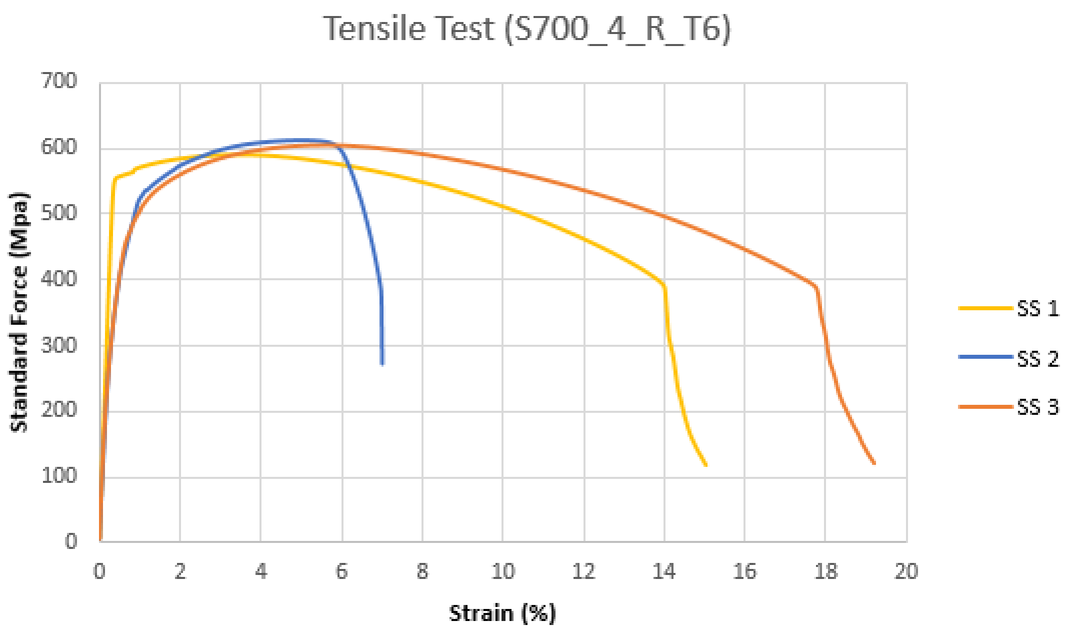


Figure 58. Strength-Strain curves of 3 welded small specimens (SS) from T5.

Table 17 below shows the numerical value of tensile strength of SS from T6.

Table 17. Numerical value of tensile strength of SS from T6.

	Ultimate Tensile Strength
	MPa
S700_4mm_W-N_R_T6_SS1	590.4975647
S700_4mm_W-N_R_T6_SS2	612.5094945
S700_4mm_W-N_R_T6_SS3	605.0904393

4.2.1.3 Gleeble specimen

Gleeble Specimens (GS), heat-simulated to obtain heating curve of T5 welded specimen and T8/5 of 13.45 seconds, were tensile tested to the failure point. Figure 59 below shows stress-strain curves from the tests.

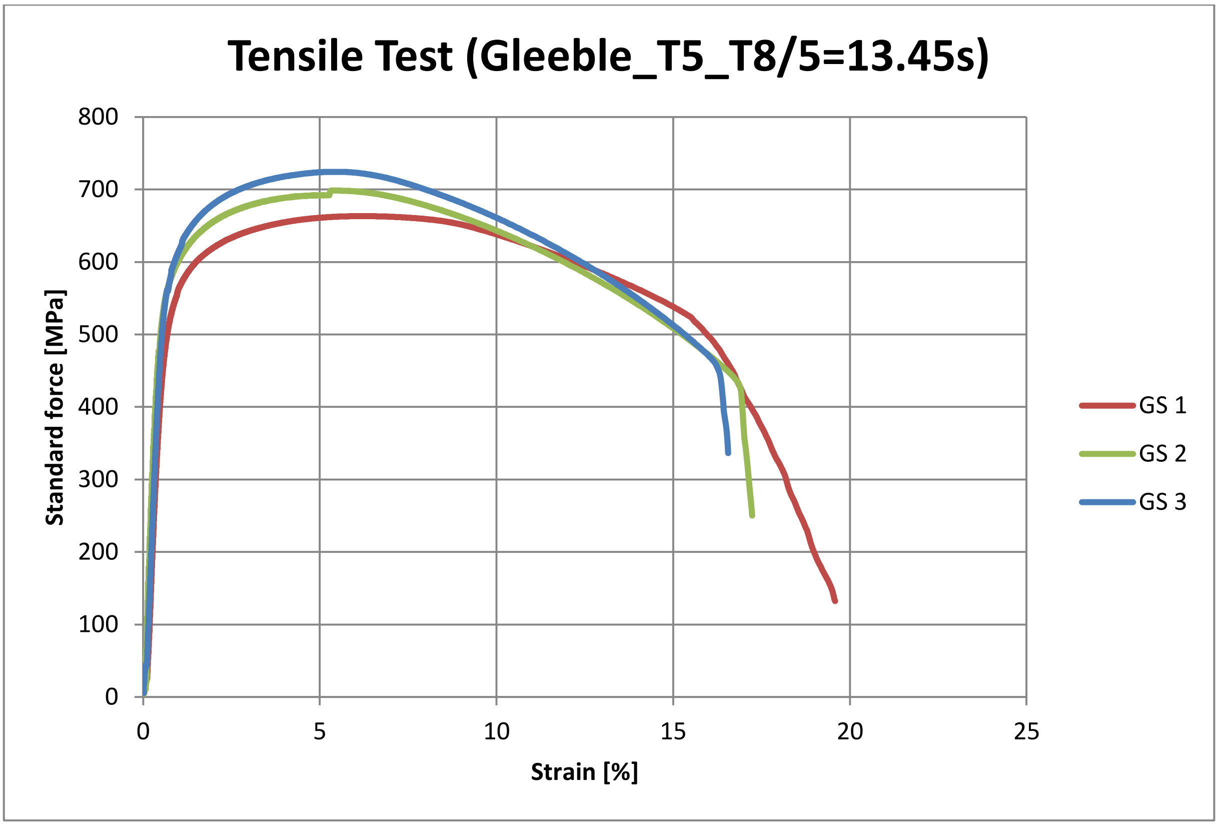


Figure 59. Strength-Strain curves of 3 Gleeble-simulated specimens (GS) with T8/5=13.45s.

Table 18 below shows the numerical value of tensile strength of GS with T8/5=13.45s.

Table 18. Numerical value of tensile strength of GS with T8/5=13.45s.

	Ultimate Tensile Strength
	MPa
S700_4mm_G_R_T5_GS1	663.2881485
S700_4mm_G_R_T5_GS2	698.7753829
S700_4mm_G_R_T5_GS3	724.3783412

Gleeble Specimens (GS), heat-simulated to obtain heating curve of T6 welded specimen and T8/5 of 33 seconds, were tensile tested to the failure point. Figure 60 below shows stress-strain curves from the tests.

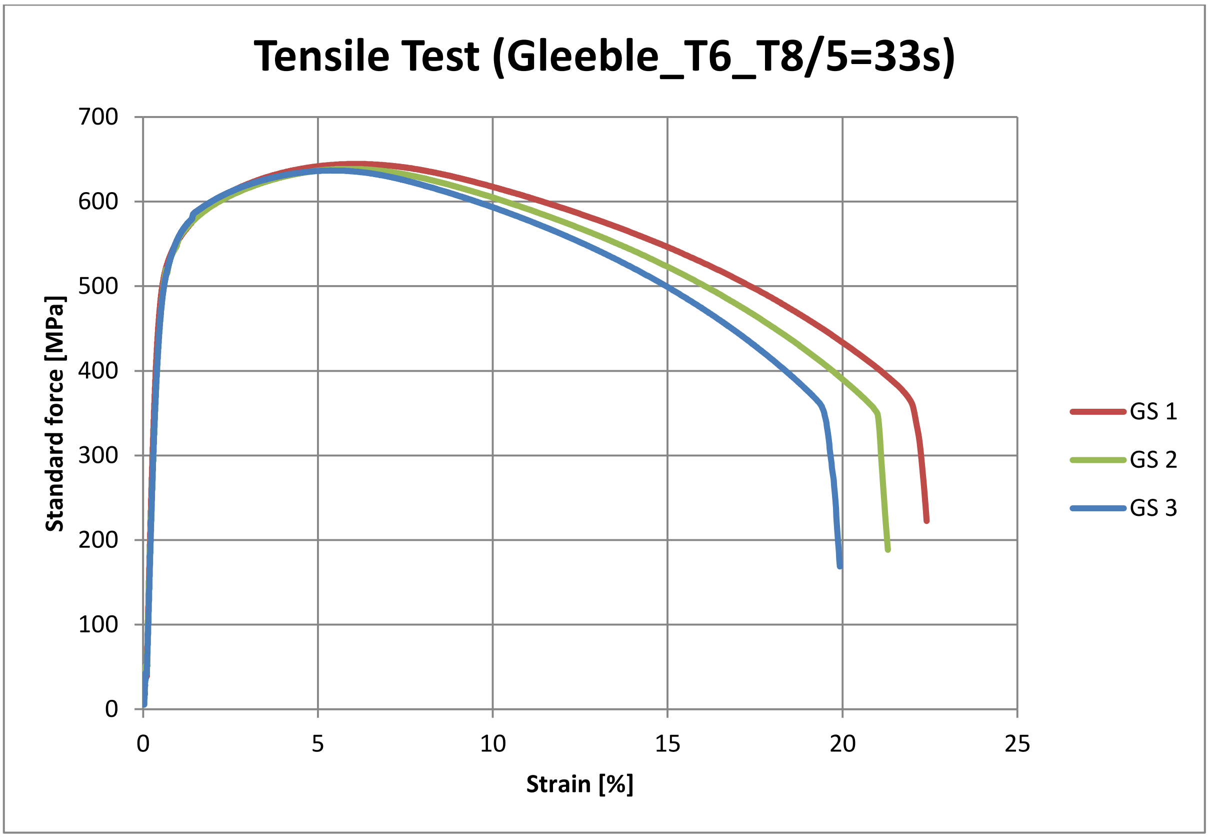


Figure 60. Strength-Strain curves of 3 Gleeble-simulated specimens (GS) with T8/5=33s.

Table 19 below shows the numerical value of tensile strength of GS with T8/5=33s.

Table 19. Numerical value of tensile strength of GS with T8/5=33s.

	Ultimate Tensile Strength
	MPa
S700_4mm_G_R_T6_GS1	644.4983204
S700_4mm_G_R_T6_GS2	638.6685542
S700_4mm_G_R_T6_GS3	636.7931606

4.2.2 Hardness test

Hardness test was done with the Vickers hardness testing machine, NEMESIS 5102. Indentations were done with the test force of HV10. Dwell time is 10 seconds.

2 welded hardness specimens from each test plates T5 and T6 were hardness tested. Then 3 Gleeble-simulated hardness specimens which had imitated the heat cycle of T6 welded

hardness specimens were hardness tested as well in order to be compared to welded ones. However, there is no Gleeble-simulated hardness specimens for T5, thus no comparison is made between the welded and Gleeble hardness specimens in case of T5.

Indentations were made thoroughly across the sample. 3 to 4 indentations were made in each areas of base material, HAZ and weldment, in the pattern illustrated in the figure 61 below.

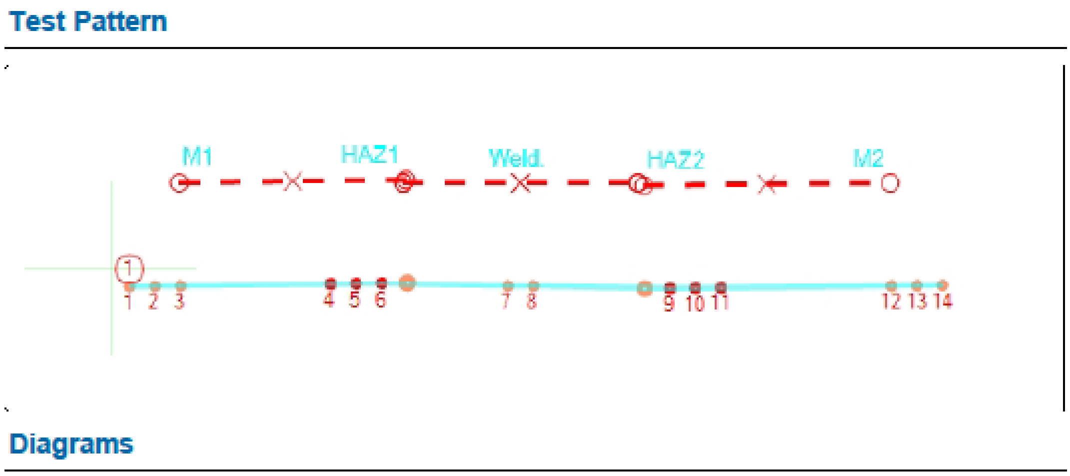


Figure 61. Indentation pattern for hardness testing.

Observing the test results, it can be noticed that hardness values drop significantly at the HAZ due to the HAZ softening effect of welding.

4.2.2.1 Welded specimen

Figure 62 below shows the Hardness test result of welded specimen 1 from T5.

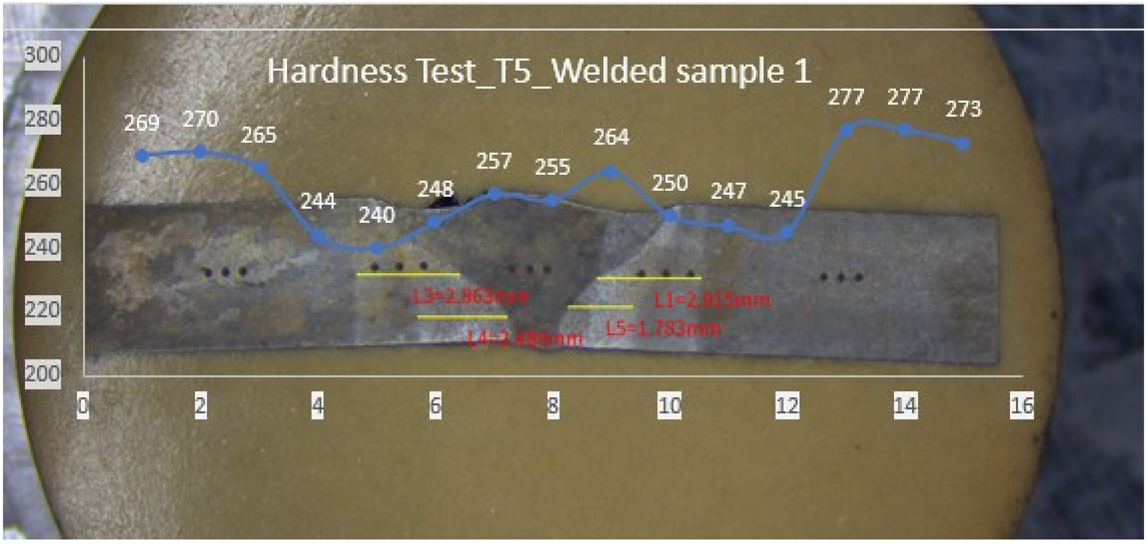


Figure 62. Hardness test result of welded specimen 1 from T5.

Figure 63 below shows the Hardness test result of welded specimen 2 from T5.

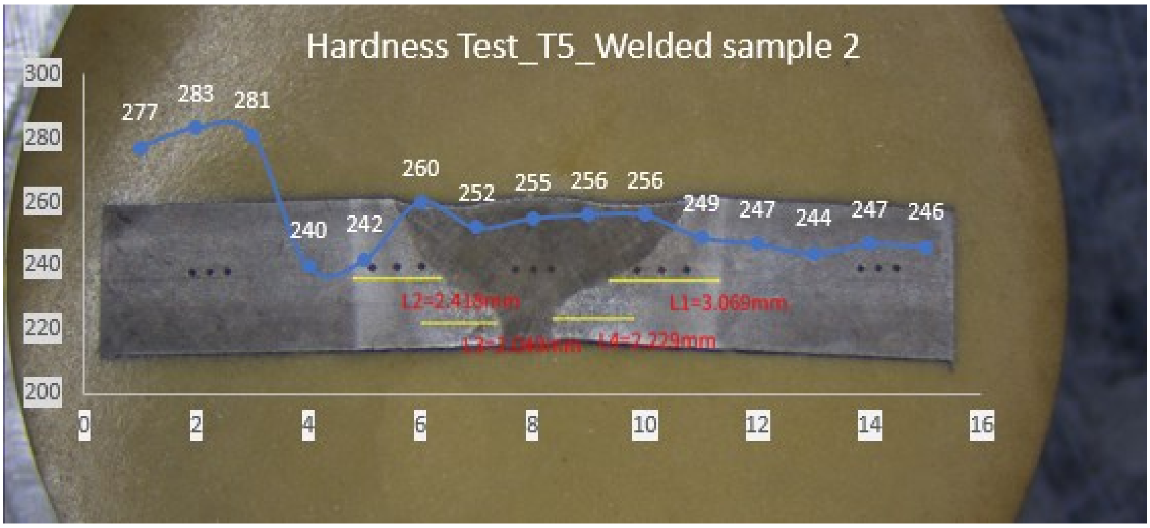


Figure 63. Hardness test result of welded specimen 2 from T5.

Figure 64 below shows the Hardness test result of welded specimen 1 from T6.

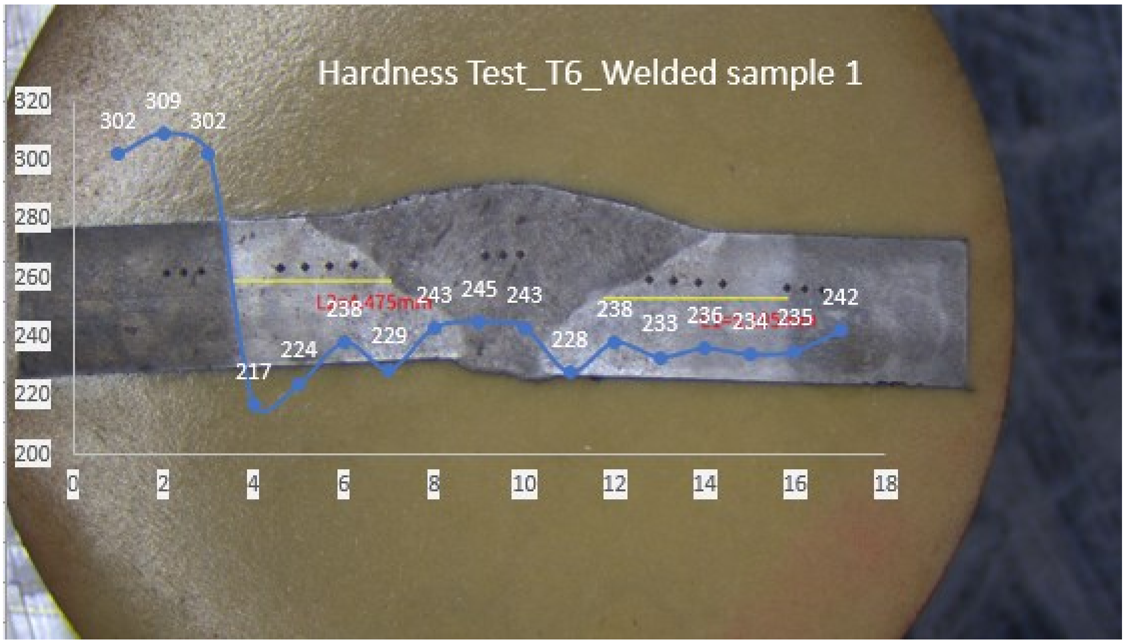


Figure 64. Hardness test result of welded specimen 1 from T6.

Figure 65 below shows the Hardness test result of welded specimen 2 from T6.

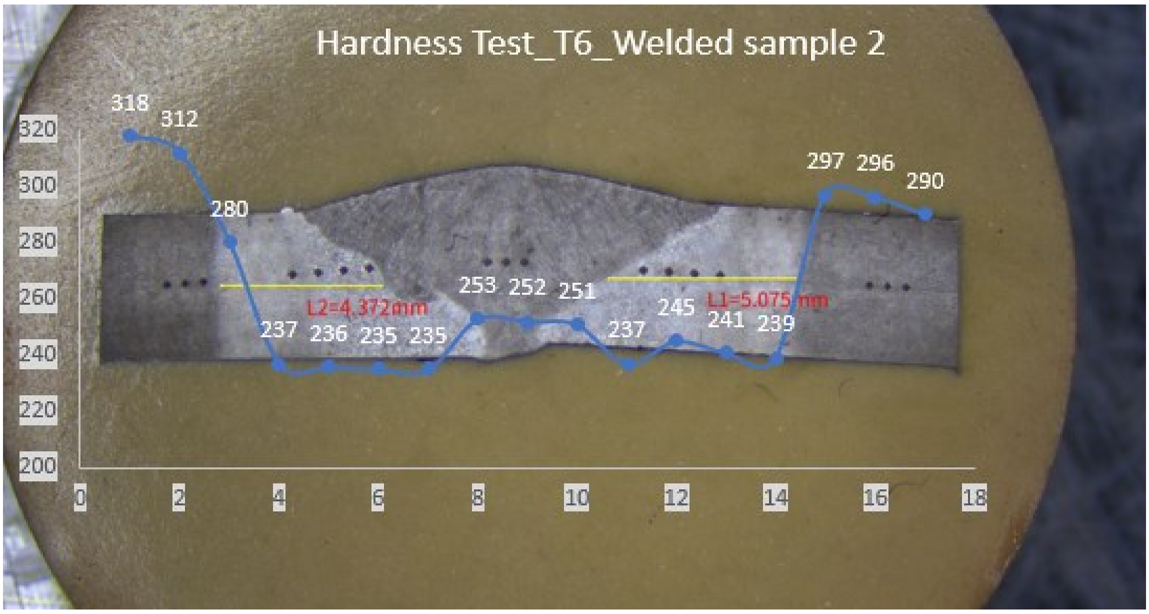


Figure 65. Hardness test result of welded specimen 2 from T6.

4.2.2.2 Gleeble specimen

Figure 66 below shows the Hardness test result of Gleeble specimen 1 from T6.

PM refers to a base material. HAZ refers to a heat affected zone. W refers to a weldment.

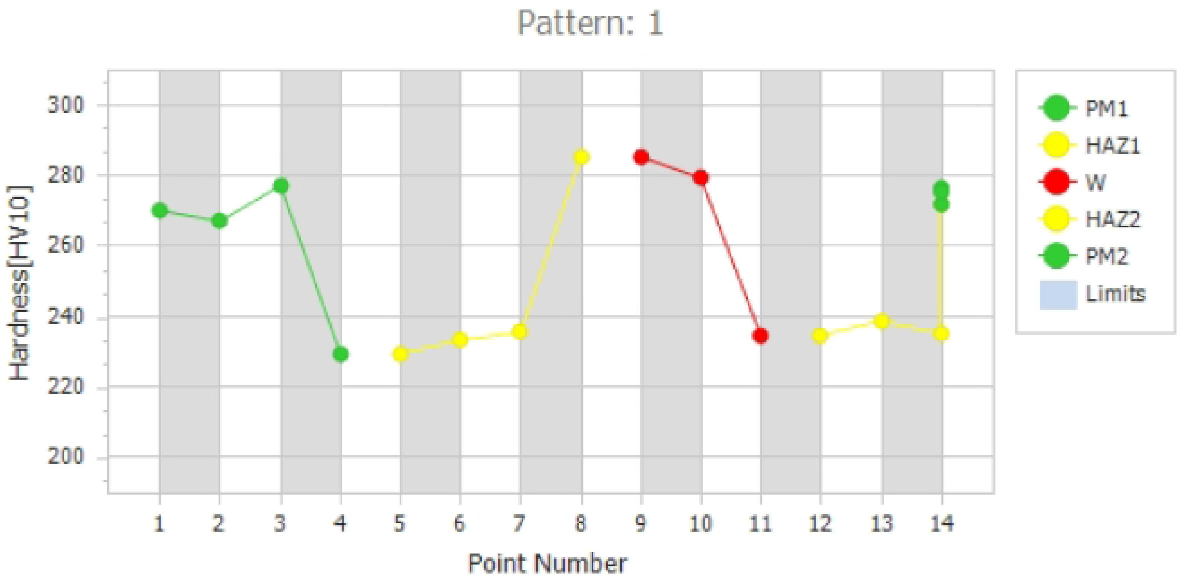


Figure 66. Hardness test result of Gleeble-simulated specimen 1 from T6.

Figure 67 below shows the Hardness test result of Gleeble specimen 2 from T6.

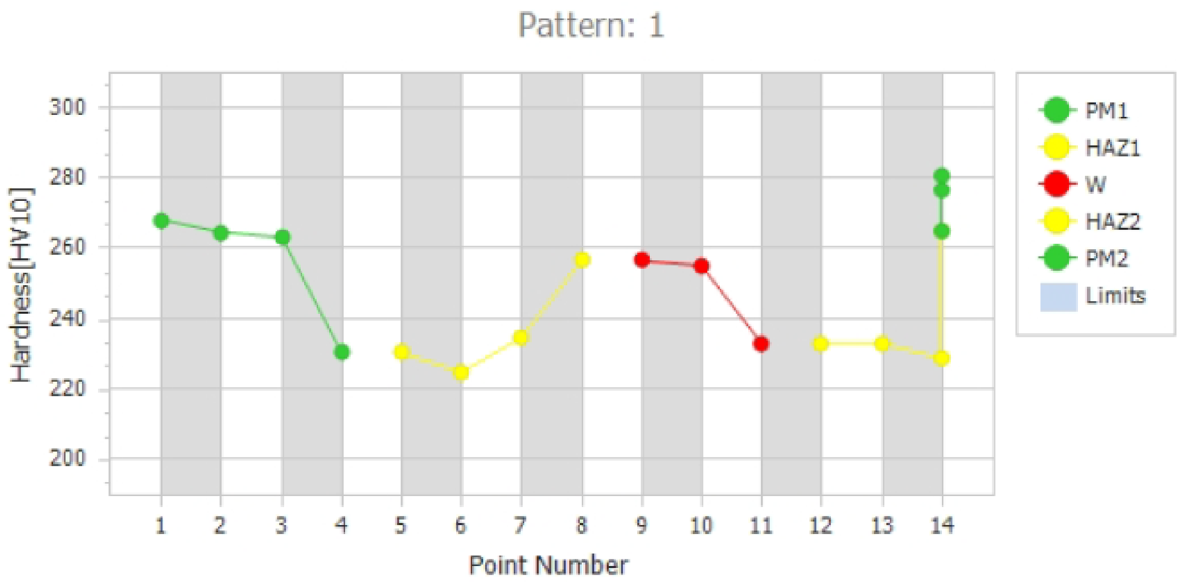


Figure 67. Hardness test result of Gleeble-simulated specimen 2 from T6.

Figure 68 below shows the Hardness test result of Gleeble specimen 3 from T6.

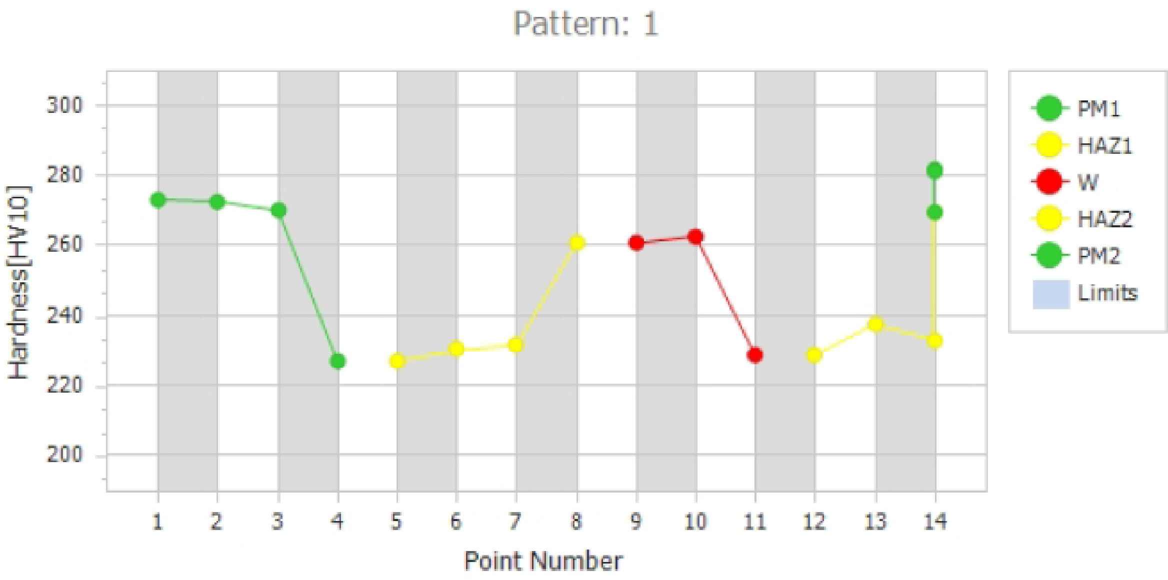


Figure 68. Hardness test result of Gleeble-simulated specimen 3 from T6.

4.3 Analysis

The results of tensile test and hardness test are analyzed. First, the results of specimens from each plate with different heat inputs are compared. Then the welded specimen is compared with its Gleeble specimen which had undergone same heat curve and t8/5 cooling time.

4.3.1 Tensile test

In order to compare the tensile strength of welded small specimen (SS) and Gleeble specimen (GS) from both T5 and T6 plates, an average value was calculated from each 3 samples.

The comparison of the average tensile strength between SS and GS for T6 (t8/5=33.03) is shown in Table 20 below. Graphs compared are shown in Figure 69. It can be observed from the data that tensile strength of GS still deviates significantly from that of SS, even though both kinds of specimens underwent the same single heat cycle this time.

Table 20. Comparison of average tensile strength between SS and GS for T6 (t8/5=33.03).

Sample names	Tensile Strength	Average tensile strength	Percentage Loss Compared to base material (%)	T8/5 Cooling Time
S700_4mm_W-N_R_T6_SS1	590.4975647			
S700_4mm_W-N_R_T6_SS2	612.5094945			
S700_4mm_W-N_R_T6_SS3	605.0904393	602.6991662	22.757	33.03
S700_4mm_G_R_T6_GS1	644.4983204			
S700_4mm_G_R_T6_GS2	638.6685542			
S700_4mm_G_R_T6_GS3	636.7931606	639.9866784	17.978	33.03

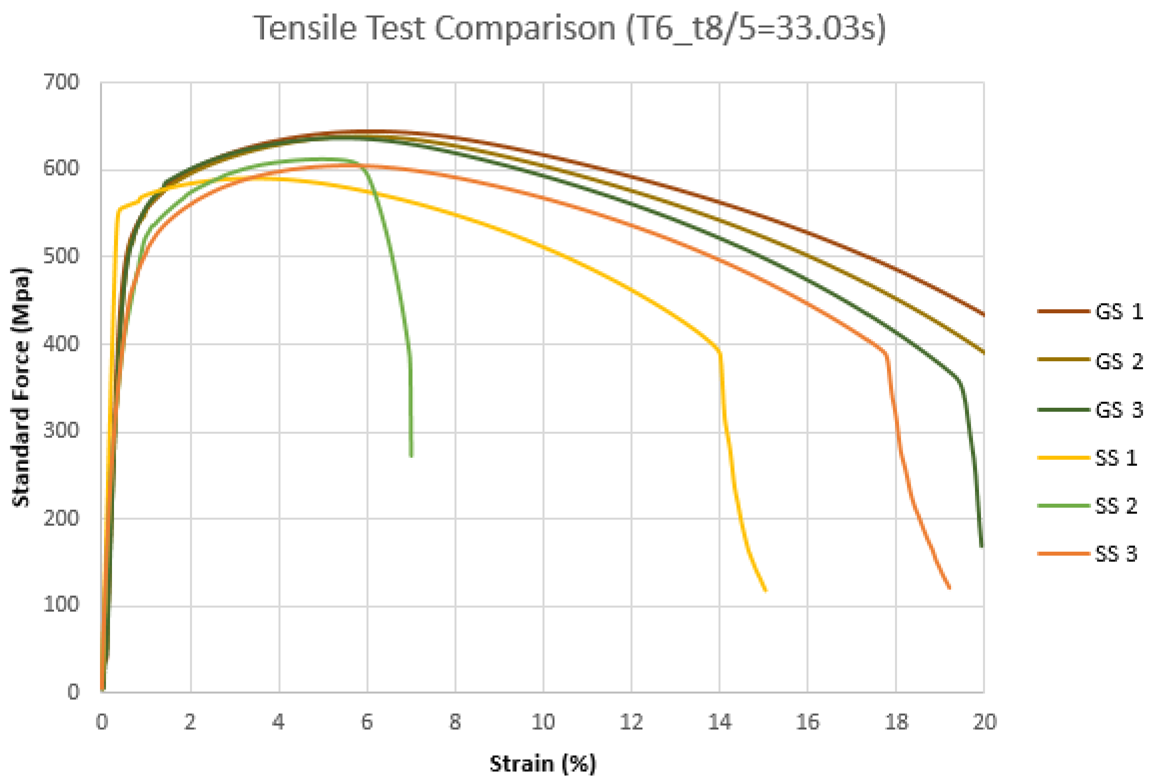


Figure 69. Comparison of Stress-strain curves between SS and GS for T6 (t8/5=33.03).

Comparison of average tensile strength between SS and GS for T5 (t8/5=13.45) is shown in Table 21 below. Graphs compared are shown in Figure 70. It can be observed from the data that tensile strength of GS again deviates even more from that of SS, even though both kinds of specimens underwent the same single heat cycle this time.

Table 21. Comparison of average tensile strength between SS and GS for T5 (t8/5=13.45).

Sample names	Tensile Strength	Average tensile strength	Percentage Loss Compared to base material (%)	T8/5 Cooling Time
S700_4mm_W-N_R_T5_SS1	599.0061335			
S700_4mm_W-N_R_T5_SS2	614.81711			
S700_4mm_W-N_R_T5_SS3	589.1097813	600.977675	22.977	13.45
S700_4mm_G_R_T5_GS1	663.2881485			
S700_4mm_G_R_T5_GS2	698.7753829			
S700_4mm_G_R_T5_GS3	724.3783412	695.4806242	10.865	13.45

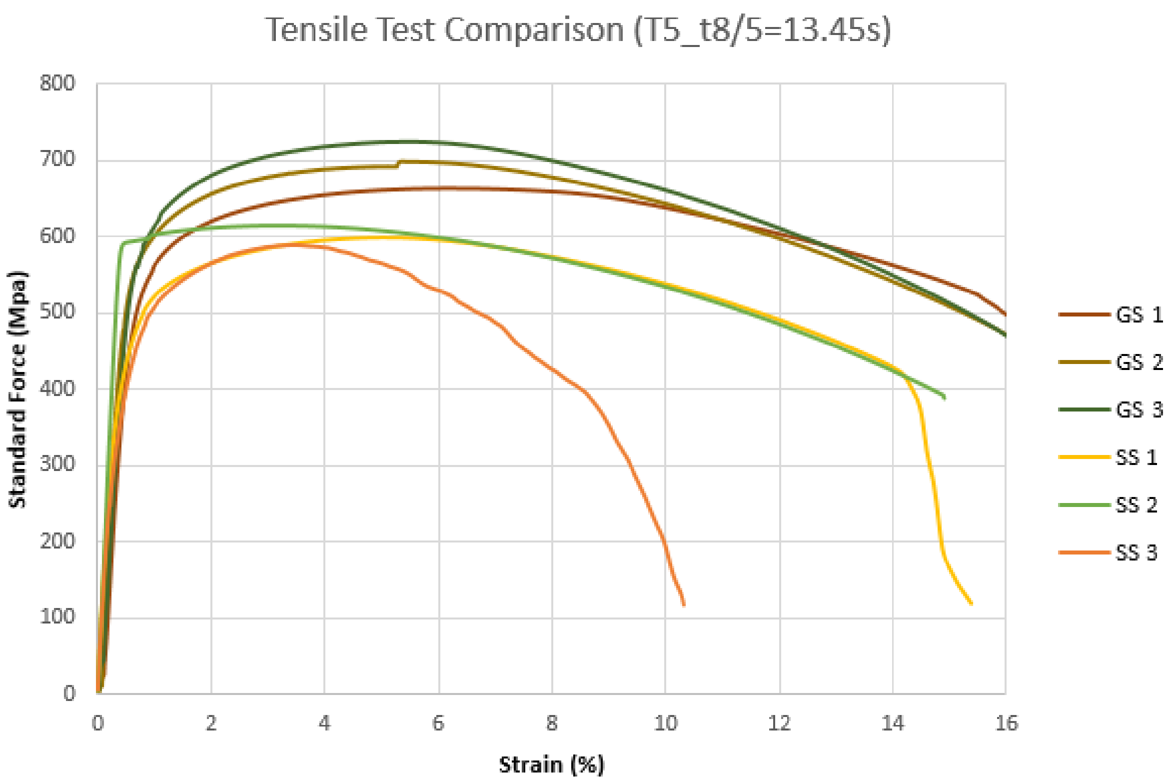


Figure 70. Comparison of Stress-strain curves between SS and GS for T5 (t8/5=13.45).

It is notable that the tensile strength of welded SS from both T5 (t8/5=13.45) and T6 (t8/5=33.03) turned out to be almost the same. This is an unexpected result considering the general observation in which higher heat input and consequently longer t8/5 cooling time usually results in a greater reduction in tensile strength.

On the contrary, as for the GS, it is observable that there is greater reduction in tensile strength from T6 than T5. This result is aligned with general pattern of strength reduction proportional to longer t8/5 cooling times.

Scatter plot in figure 71 below summarizes the percentage loss of tensile strength against t8/5 cooling times, compared to the base material.

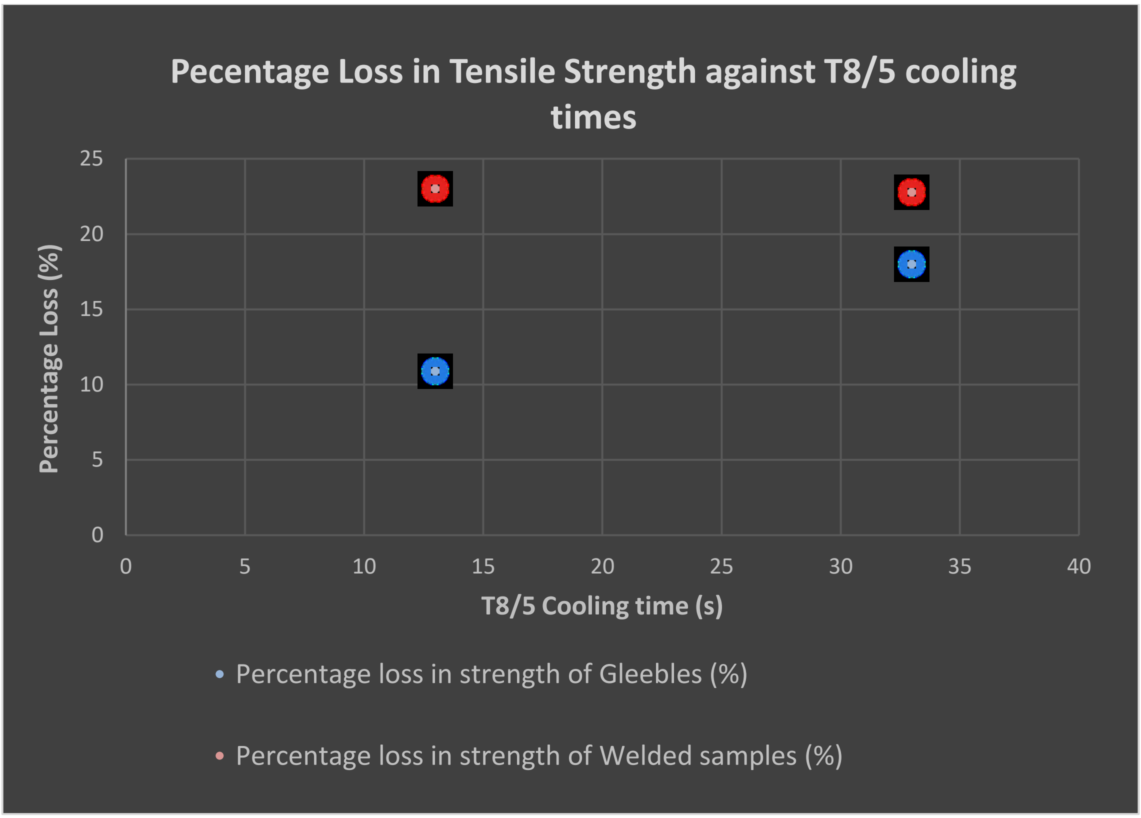


Figure 71. Scatter plot showing the percentage loss of tensile strength against t8/5 cooling times, compared to the base material.

It is uncertain why tensile strength of SS from both T5 and T6, whose cooling times are very different, shows very similar values, while that of GS shows different values in general pattern mentioned above. One possible explanation could be that strength reduction in a welded sample may not occur significantly any more once t8/5 reaches 13 seconds. Samples that are Gleeble-simulated, however, may continuously show linear strength reduction even after t8/5 exceeds 13 seconds.

Another explanation is that this could be simply just an error in tensile testing process for SS. In future research, more samples from larger range of heat input and t8/5 are required, so that resulting data can be validated enough.

4.3.2 Hardness test

Firstly, hardness values in HAZ of welded specimens from T5 and T6 were compared with each other. Table 22 below shows the comparison of mean values of hardness in HAZ. As can be seen from the table, Welded specimens from T5 with T8/5 cooling time of 13.45s have slightly higher hardness values in HAZ compared to the T6 with T8/5 of 33.03s. This result is in line with the general trend of larger decrease in hardness proportional to longer cooling time.

It should be also noted that the difference is magnified at the lowest hardness values. As can be seen in the table 22, lowest hardness value from the HAZ of welded specimens from T5 is 240, while it is 217 from T6. In light of this significant difference in hardness value, the fact that their tensile strength, however, did not differ almost at all becomes more puzzling.

Table 22. Comparison of HAZ hardness between welded specimens from T5 and T6.

	Hardness at HAZ	
	Weld_T5_T8/5=13.45	Weld_T6_T8/5=33.03
	244	217
	240	224
	248	238
	250	229
	247	228
	245	238
		233
	240	236
	242	
	256	237
	249	236
	247	235
		235
		237
		245
		241
		239
Mean	**246.18**	**234.25**

Secondly, Hardness test result of 2 welded specimens from T6 were compared to that of 3 Gleeble-simulated specimens from T6. In order to do that, the hardness values of HAZ from these samples were collected separately and averaged. Since hardness values in HAZ are the lowest in every sample, they are the critical values to be compared.

Table 23 below shows the numerical values of Hardness in HAZ of all samples and their mean values. As can be seen from the table, Hardness value in HAZ of Welded specimens is almost identical to that of Gleeble specimens. This is an anticipated result, since these Gleeble specimens were heat-simulated with the same heating curve and T8/5 cooling time as the welded specimens.

Table 23. Comparison of HAZ hardness between welded and Gleeble specimens from T6.

	Hardness at HAZ	
	Weld	Gleeble
	217	229.31
	224	233.32
	238	235.37
	229	234.55
	228	238.7
	238	234.95
	233	
	236	230.11
		224.62
	237	234.55
	236	232.91
	235	232.92
	235	228.52
	237	
	245	226.7
	241	230.1
	239	231.3
		228.52
		237.44
		232.9
Mean	234.25	232.0439

5 Conclusion

The objective of this thesis is to show first how weld heat inputs and corresponding cooling times will affect the mechanical properties of S700MC Plus. Secondly, this test data of welded HSS specimens is compared to that of Gleeble simulated specimens in order to establish a correlation between them. This correlation may serve as the reference for the further research of other HSS materials by using Gleeble welding simulator only.

A preliminary experiment was conducted using S700MC Plus 8mm high strength steel made by SSAB. This steel was welded three times, tensile tested and hardness tested. Its heating curve and cooling time information, which had been recorded by thermocouples, was used in the Gleeble simulator to produce Gleeble simulated specimen version of the same weld parameters. However, contrary to expectations, the tensile strength of the welded specimen differed by a large degree from the Gleeble specimen. It was concluded that, since this steel underwent 3 weld runs but its Gleeble specimen was heat simulated only once, this could be the reason for the large deviation. Therefore, new experminet was carried out, this time with single-welded 4mm plate.

In the Final Experiment, S700 MC Plus 4mm with a single weld run was used. This could make the Gleeble to simulate the heat cycle only once, thus making the process simpler without potential errors. Two plates were tested with different heat inputs and corresponding cooling times. T5 plate was welded with relatively low heat inputs and T6 with high heat inputs. Tensile strength of welded specimens from both T5 (t8/5=13.45) and T6 (t8/5=33.03) turned out to be almost same. This is an unexpected result considering the general observation where higher heat input and longer t8/5 cooling time usually results in a greater reduction in tensile strength. On the contrary, as for the Gleeble specimen, there was a greater reduction in tensile strength from T6 than T5. This result is in line with general pattern of strength reduction proportional to longer t8/5 cooling times.

Hardness dropped significantly in HAZ areas. Welded specimens from T5 with T8/5 cooling time of 13.45s have higher hardness values in HAZ compared to the T6 with T8/5 of 33.03s. Hardness value in HAZ of Welded specimens is almost identical to that of Gleeble specimens. This is an anticipated result, since these Gleeble specimens were heat-simulated with the same heating curve and T8/5 cooling time as the welded specimens.

It is uncertain why tensile strength of welded specimens from both T5 and T6, whose cooling times are very different, shows very similar values, while that of Gleeble specimens shows different values in general trend of strength reduction proportional to longer t8/5 cooling times. One possible explanation could be that strength reduction in welded specimen may not occur significantly any more once t8/5 reaches 13 seconds, but samples that are Gleeble-simulated may continuously show linear strength reduction even after t8/5 exceeds 13 seconds. Another explanation is that this could be simply just an error in tensile testing process for welded specimens. In future research, more samples from larger range of heat inputs and t8/5 cooling times are required, so that resulting data can be validated enough.

Although it is not advisable to establish a firm correlation between welded and Gleeble specimens at this phase because of seemingly unreasonable result of tensile test, this thesis experiment still has successfully set the standard methods and procedures for comparing welded and Gleeble-simulated steels. Furthermore, it has clearly laid down the next steps for experiments that could help identify the exact problem and validate the result. The trials and errors described in the thesis would be a valuable resource for the future research.

References

Afkhami, S., Bjork, T., & Larkiola, J. (2019). Weldability of cold-formed high strength and ultra-high strength steels. *Engineering Structures*. https://doi.org/10.1016/j.jcsr.2019.03.017

Amraei, M., Ahola, A., Afkhami, S., Bjork, T., Heidarpour, A., & Zhao, X. (2019). Effects of heat input on the mechanical properties of butt-welded high and ultra-high strength steels. *Engineering Structures*. https://doi.org/10.1016/j.engstruct.2019.109460

Australian Steel Institute. (n.d.). *HIGH-STRENGTH STEEL*. Retrieved March 23, 2022, from https://www.steel.org.au/focus-areas/innovation/high-strength-steel/

Chen, C., Zhao, M., Fung, T., Chiew, S., & Lee, C. (2017). Influence of welding on mechanical properties of high strength steel butt joints. *Ernst & Sohn*. https://www.researchgate.net/publication/319674876_Influence_of_welding_on_mechanical_properties_of_high_strength_steel_butt_joints

Gleeble. (n.d.). *GLEEBLE 540: WELDING SIMULATOR*. Retrieved March 23, 2022, from https://gleeble.com/products/gleeble-systems/welding-simulator.html

Kou, S. (2003). *Welding Metallurgy*. (Second Edition). John Wiley & Sons.

Mician, M., Harmaniak, D., Novy, F., Winczek, J., Moravec, J., & Trsko, L. (2020). Effect of the t8/5 Cooling Time on the Properties of S960MC Steel in the HAZ of Welded Joints Evaluated by Thermal Physical Simulation. *Metals*. https://doi.org/10.3390/met10020229

Netto, A. (2019). *Optimization of Gas Metal Arc Welding Process Parameters in Ultra High-Strength Steels Based on Prediction* [Master´s thesis, Lappeenranta-Lahti University of Technology]. LUTPub. https://urn.fi/URN:NBN:fi-fe2019111838619

SSAB. (n.d.). *Strenx® 700MC Plus*. Retrieved March 23, 2022, from https://www.ssab.com/products/brands/strenx/products/strenx-700-mc-plus