Measurement of Cooling Time in Welding

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

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Rajesh Khatri

ABSTRACT

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Author	Rajesh Khatri	**Year** 2020
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Supervisor(s)	Jarmo Havula	

ABSTRACT

The purpose of thesis was to develop a simplified method to evaluate the cooling time of Heat Affected Zone (HAZ) based on surface temperature measurement with (infrared camera) to avoid using thermocouples. This thesis work was commissioned by HAMK Tech, one of the research units of Häme University of Applied Sciences.

The thesis project started with welding at the HAMK laboratory in Riihimäki where welding was carried out using Universal Robot (UR). The robot was used for precise and uniform welding. A Thermal camera was used to measure the surface temperature and thermocouples were used to measure the inner temperature in HAZ. The, obtained data was recorded analyzed and simulated in ANSYS to eliminate the use of thermocouples. Welding simulation in ANSYS was carried out with the same boundary conditions, materials properties, and geometry as in a real experiment. This research project simplified the overall process of evaluation of cooling time in a Heat Affected Zone (HAZ).

This thesis describes all the procedures carried out during the research project to obtain the solution and it presents a co-relation which can be used in the welding process to evaluate the cooling time. The Cooling time in the heat affected zone during welding can be measured without using thermocouples which will save a significant amount of time and effort. This thesis work is useful and can be used as reference while evaluating cooling time during welding in the future and it serves as a document for further research on heat measurement in welding.

Keywords heat Input, heat affected zone, thermocouple, welding, t8/5

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1 Introduction

Structural steel is one of the widely used building materials in the construction industry and is also the most studied and best understood. Its behavior is predictable and subject to various standards and codes established by agencies such as Eurocodes that define its specific shape, cross-section, chemical composition, and mechanical properties. But most of its chemical and mechanical properties change during a widely used welding process, especially in case of high strength steels. The changes in the properties of base material depends on the cooling time during the welding process especially in heat affected zone. The Heat Affected Zone (HAZ) is a non-melted area of metal that has undergone changes in material properties because of being exposed to high temperatures. These changes in material property are usually because of welding or high heat cutting. The HAZ is the area between the weld or cut and the base, parent metal. Most of the metallurgical changes occur when the temperature decreases from 800 to 500 Celsius. The cooling time from 800 to 500 Celsius is generally expressed as t8/5 cooling time. Thus, measurement of cooling time, especially t8/5, in heat affected zone is the aim of this study. (Velling, 2020)

During the welding process, the surfaces of the components are raised locally to melting point by a source of heat by a variety of welding methods based on an electric arc, electrical resistance, or a flame. The amount of heat during welding is called the heat input which is ratio of the total energy expended per unit length of the weld. The heat from the welding process and subsequent re-cooling changes the microstructure and thus, the physical properties of the area close to the weld. This area is called the heat affected zone HAZ. The welded joint then becomes homogenous, consisting of the parent material, the welded joint and the HAZ. The change of physical properties, which depends largely on heat input and cooling time directly affects the performance of the joint. (Velling, 2020)

High heat input leads to longer cooling time, thus increasing the size of the HAZ, and prolonging the decline of the joint quality. However, too rapid cooling time from inadequate heat input also results in defective or weak joints because of the insufficient penetration and incomplete material fusion. Consequently, it is important to regulate closely the heat input and the cooling time during welding to achieve the best quality of the joint. (Nguyen, 2018, s. 1)

Commissioning Party and Goals

This research work was commissioned by HAMK Tech which is one of the research units of HAMK University of Applied Sciences. It is working on various fields such as materials, long term durability of materials, 3D scanning, Robotics, steel structures and energy efficiency. HAMK Tech is working on research and study of changes in properties of materials during welding in HAZ. To assist the task, I was assigned to measure the cooling time in heat-affected zone of the welding.

2 Theoretical Input

Heat input can be referred to as "the electrical energy supplied by the welding arc to the workpiece." (Welding, The ABC's of Arc, 2020) In practice, however, heat input can be characterized as the ratio of the arc power supplied to the electrode to the arc travel speed. Heat input is a critical parameter that must be controlled to ensure consistent weld quality. There are several ways of calculating the energy put into a weld. The most common approach to calculate the heat for non-waveform-controlled welding is to use the welding current, voltage, and travel speed. European Standard supplements EN ISO 1011-1 gives general guidance for the satisfactory production and control of welds in Steels which specifies the equation to calculate the heat input as presented in equation 1.

$$Q = \varepsilon \times \frac{V \times I \times 60}{S \times 1000} \qquad (1)$$

Where
Q = Heat Input (kJ/mm)
ε = Thermal efficiency of welding process
V = Voltage (V)
I = Current (I)
S = Welding Speed (mm/min)

Current, Voltage and welding speed are recorded by welding machine during the process of welding. Value of thermal efficiency is different for different welding processes and are determined according to EN ISO 1011-1, see Table 1.

Table 1 Value of Thermal Efficiency *(Anand, 2017)*

S.N	Welding Process	Thermal Efficiency
1	Submerged Arc Welding (SAW)	1.0
2	Shielded Metal Arc Welding (SMAW)	0.8
3	Gas Metal Arc Welding (GMAW)	0.8
4	Flux Cored Arc Welding (FCAW)	0.8
5	Gas Tungsten Arc Welding (GTAW)	0.6
6	Plasma Arc Welding (PAW)	0.6

Thermal efficiency in our welding process was chosen as 0.8 according to the EN ISO 1011-1 standards.

The most important characteristic of the heat input is that it governs the cooling rates in welds and thereby affects the microstructure of the weld metal and heat-affected zone. A change in microstructure directly affects the mechanical properties of welds. Therefore, the control of heat input is very important in arc welding in terms of quality control. From 900 °C to 1300 °C, the iron in steel undergoes a phase transition into Austenite steel that dissolves a considerable amount of carbon. As the temperature drops, depending on the carbon content, the alloy can ideally form Pearlite, a layering of carbon rich cementite and carbon poor ferrite is formed. Pearlite is one of the strongest bulk materials on Earth. However, if the cooling time is not enough for the carbon to diffuse, the trapped carbon will combine with iron and form martensite, which cracks at lower strain. As the result, the rate of cooling determines the percentage of different crystal structures of the alloy, and therefore determines the mechanical properties of the resulting steel, such as hardness and tensile strength. The changes in the microstructure of steel depending upon temperature is shown in Figure 1.

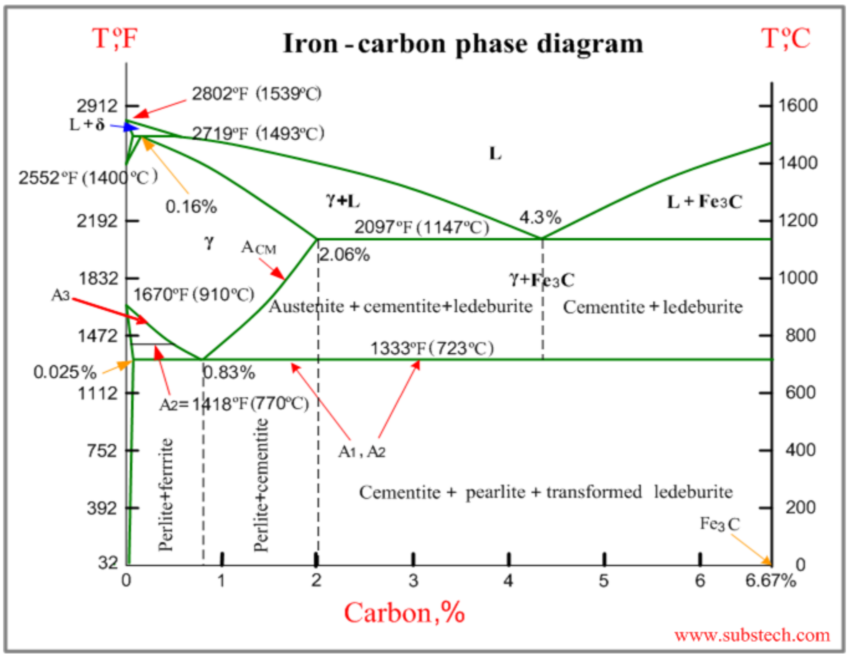


Figure 1 Iron-Carbon Phase Diagram (Kopeliovich, 2012)

The cooling time between 800°C and 500°C (t8/5) is the most important parameter to determine the welding parameters applied during welding of fine-grain structural steels.

In case of three-dimensional heat flux the cooling time t8/5 can be calculated as presented in equation 2.

$$t\frac{8}{5} = \left(6700 - 5 \times T_p\right) \times Q \times \left(\frac{1}{500 - T_p}\right) - \left(\frac{1}{800 - T_p}\right) \times F_3 \qquad (2)$$

We can easily calculate an estimation of this cooling time by specifying the following values:

Q= Heat Input (kJ/mm)

T_p = Preheating Temperature °C

F_2/F_3 = Welding geometry Factors

d = Plate thickness (mm)

From the data given above the cooling time $t_{8/5}$ can be calculated if a three-dimensional heat flux is assumed as presented in equation 3.

$$t_{\frac{8}{5}} = \left(4300 - 4.3 \times T_p\right) \times \frac{10^5 \times Q^2}{d^2} \times \left(\frac{1}{(500-T_p)^2}\right) - \left(\frac{1}{(800-T_p)^2}\right) \times F_2 \qquad (3)$$

According to DIN EN1011-2, aspects of the part geometry such as sheet thickness, welding seam geometry, and partially buildup sequence are considered using correction factors. Calculating the $t_{8/5}$ values even with the correction factors by the seam geometry F_2 and F_3 are separated by the welded sheet thickness and the ratio of heat input in two or three dimensional heat dissipation. The suitable welding geometry must be selected from Table 2, moreover also a free input in the range 0 to 1.0 is possible.

Table 2 Correction Factors *(Welding, 2017)*

Welding seam geometry	F2	F3
Bead on plate	1.0	1.0
Interlayer	0.9	0.9
Fillet weld – edge	0.67...0.9	0.67
Fillet weld – T-Joint	0.45...0.67	0.67

3 Test Preparation

Mild steel with grade S355J2 was used for this project. Steels was received in the form of long bars from Temeko Oy and were cut into the required dimension of 350×150×8 mm using an electric saw machine at HAMK Laboratory as well as the end of each plate was cut at an angle of 60° which made it easy for V groove butt welding. A drilling machine was used to drill holes into the test specimens where thermocouples were installed to measure the temperature at that point. Figure 2 shows the 3D model of welding plates and Figure 3 shows the dimensions of test specimens.

Unit of the dimensions shown in the Figure 3 are in millimeters (mm).

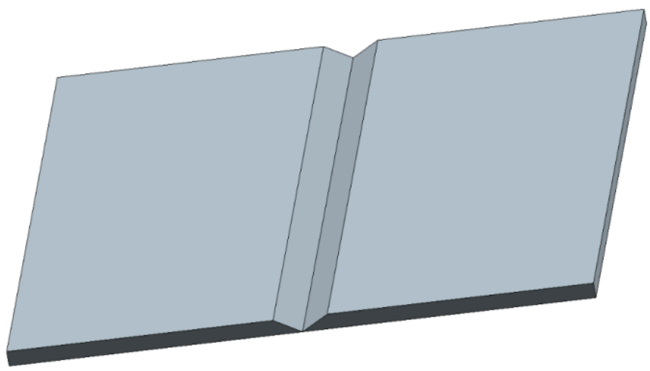


Figure 2 3D model of welding Plates

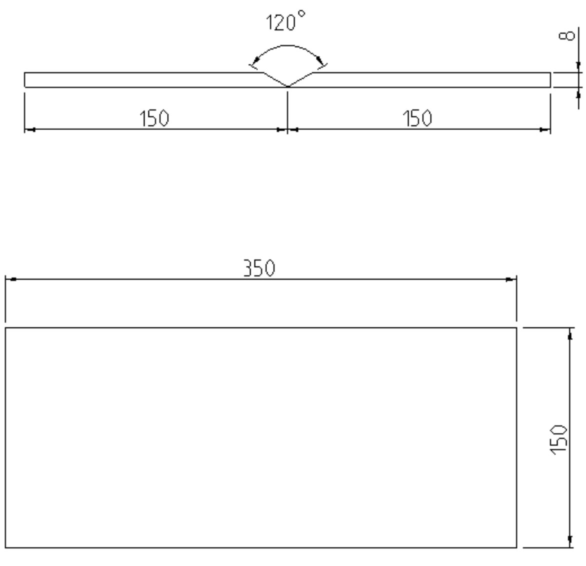


Figure 3 Dimensions of test specimen

3.1 Thermocouple

A thermocouple is an electrical device consisting of two dissimilar electrical conductors forming electrical junctions at differing temperatures. A thermocouple produces a temperature-dependent voltage because of the thermoelectric effect, and this voltage can be interpreted to measure temperature.

In welding, with the influence of heat at the welded junction, a DC voltage (thermocouple voltage) is produced between the two metals which can be measured and used to provide information about the prevailing temperature.

Measurement with the thermocouple is a contact thermometry and when attaching the thermocouples, energy is dissipated. So, to measure the temperature at heat affected zone a thermocouple type K is recommended, since the thermal conductivity for this type is lowest and therefore less energy is dissipated than with other types. To minimize the occurrence of systematic errors, the dimensions of the thermocouple should be as small as possible. Figure 4 shows different types of thermocouples with their material compositions and temperature range whereas Figure 5 shows structure of thermocouple type K .

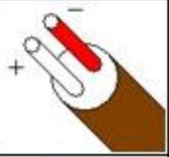
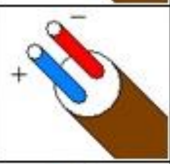
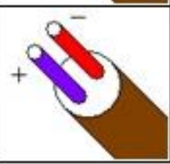
Type	Material		Color Code	Range (°C)	
Thermocouple Grade	Positive Wire	Negative Wire		Minimum	Maximum
J	Iron	Constantan		0	750
K	Chromel	Alumel		-200	1250
T	Copper	Constantan		-200	350
E	Chromel	Constantan		-200	900

Figure 4 Types of thermocouples *(WatElectrical, 2019)*

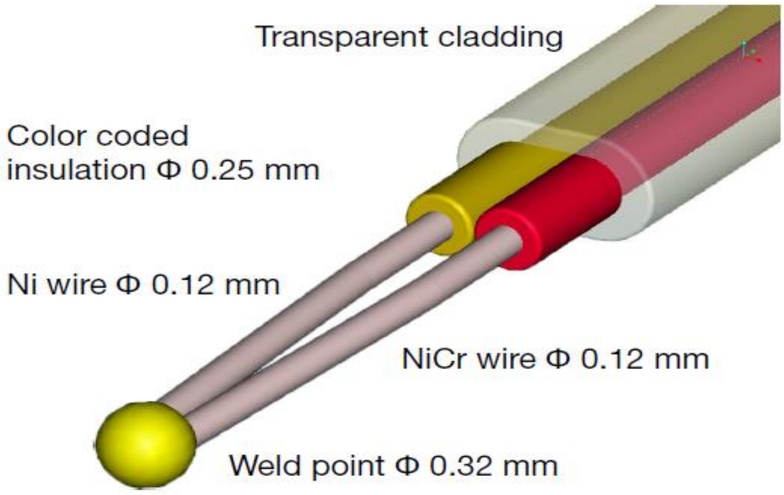


Figure 5 Type K thermocouple *(EE Publishers, 2016)*

3.2 Infrared Camera

An infrared camera is a non-contact device that detects infrared energy (heat) and converts it into an electronic signal, which is then processed to produce a thermal image on a video monitor and perform temperature calculations. Heat sensed by an infrared camera can be very precisely quantified, or measured, allowing us to not only monitor thermal performance, but also identify and evaluate the relative severity of heat-related problems.

Accuracy specification of used FLIR infrared camera is ±2ºC or 2% of the reading. Figure 6 shows the infrared camera used to record the surface temperature.

Figure 6 Infrared Camera *(flircameras, 2020)*

3.3 Robotic Welding with Universal Robot

Robotics have expanded their applications lately and there are different types of Robots used in welding process. Universal Robot (UR) was chosen for welding for this research purpose. The UR is the perfect solution for custom or small template welding application set within its reach. It can improve the quantity and quality of welding throughout while also providing easy programming, increased worker safety, and better versatility on production including super simple re-deployment.

User with zero programming experience can also easily program and operate an UR robot. We can choose to hand lead and guide the robot through the “lead-through method” which manually teaches the robot the correct path parameters for accurate completion of automated welding task. The precision hands on "drag and point" system is complimented by the ability to manually set points for the robot through the teach pendant. Figure 7 shows the type of robot used in welding process.

A Collaborative Universal robot was used because of the following features:

1. Safety Monitored Stop:

This kind of collaborative feature is used when a robot is mostly working on its own, but occasionally a human might need to enter its workspace.

2. Hand Guiding:

This type of collaborative application is used for hand guiding or path teaching. So, if we want to teach paths quickly for pick and place applications for instance, we might use this type of application.

3. Power and forcing limit:

This is the type of robot that everybody calls a collaborative robot. So yes, this is probably the most worker friendly robot since it can work alongside humans without any additional safety devices.

4. Force limited features

First, the main feature of these robots is their ability to read forces in their joints. This allows them to detect when abnormal forces are applied on them while they are working. In these situations, they can be programmed to stop or sometimes reverse positions mediating the initial contact.

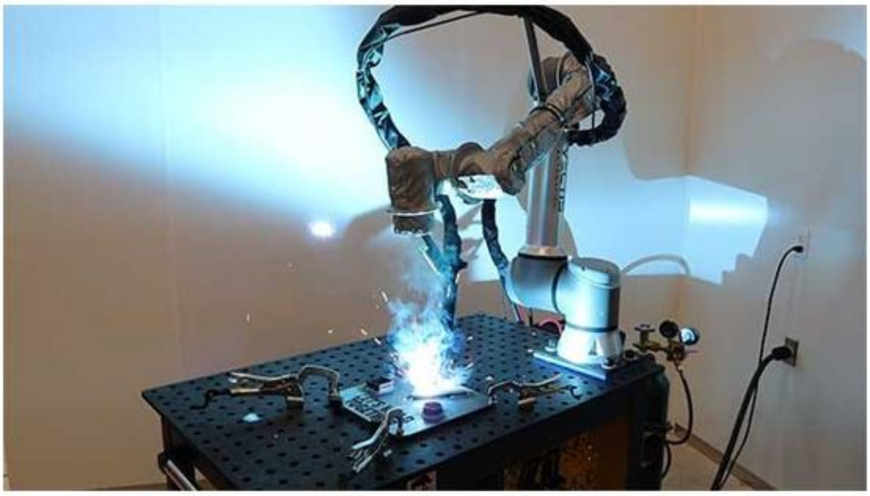


Figure 7 Universal Welding Robot *(Universal Robots, 2020)*

3.4 Welding table for specimen

For accurate and precise the welding using a robot, a fixed welding table for the test specimen was required. Welding table was necessary for the easy installation of thermocouple as well. To achieve this task, a welding table as shown in Figure 8 was designed and manufactured using waterjet cutting, drilling, and milling at HAMK laboratory. It was easy and time saving for the accurate positioning of test specimen in front of welding robot with the help of welding table. Figure 8 shows welding table used for placing test specimens.

Figure 8 Welding table for specimen

4 Thermocouple instillation

The contact of two wires in a thermocouple at the point of the measurement was the determining factor in the recorded data. If the wires of the thermocouple are joined with each other at several points, then it will measure temperature at various points and the measurement will not be scientific or accurate. To achieve the best configuration of a thermocouple, it was welded at the tip with the help of a thermocouple welder. The following process was used to set up the thermocouple and to insert it into the hole in a welding plate. Figure 9 shows the welding of two wires of a thermocouple at one point and Figure 10 shows the installation of a thermocouple to the test specimen using a thermocouple welder.

1. Two wires of thermocouple were welded together at the tip of the thermocouple by a special thermocouple welder so that the thermocouple only measure temperature at only one point.

2. The thermocouples were installed into the holes in the test specimen with the help of a thermocouple welder.

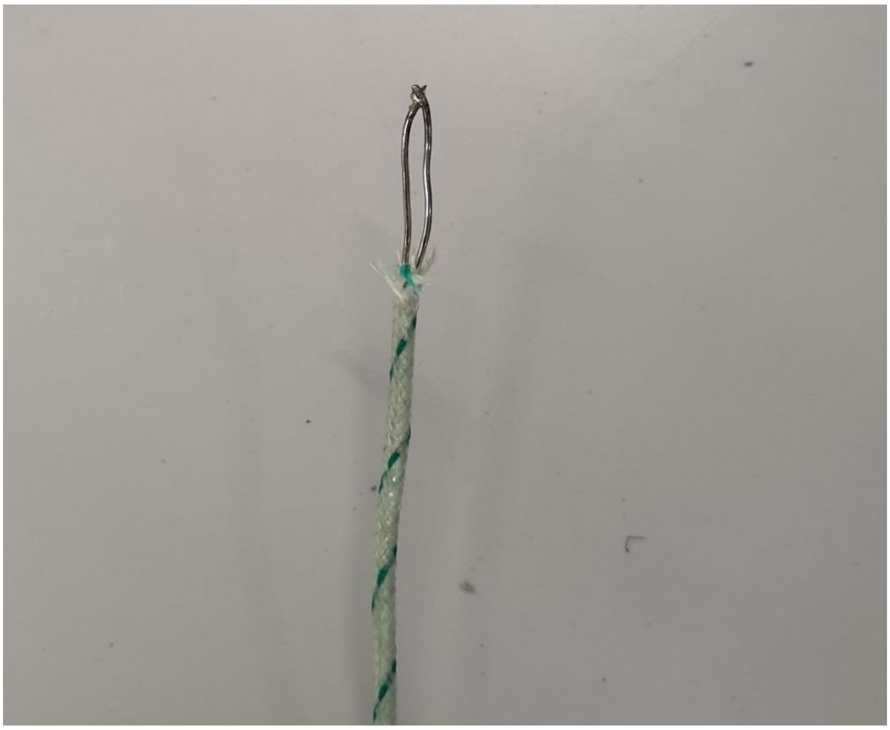


Figure 9 Welding of thermocouple

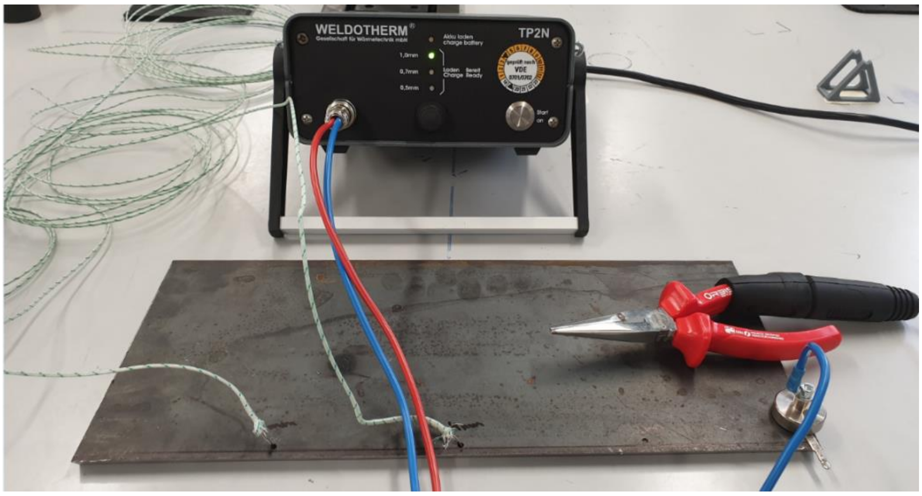


Figure 10 Installation of thermocouple

Thus, prepared test specimens were welded together using UR with the gap between the plates being approximately 2mm. Filler material with diameter 1mm was used according to classification EN ISO 14341-A. During the welding process, plates were heated to the peak temperature and were left to cool down. The amount of heat applied in welding was recorded with welding power supply machine. The cooling time t8/5 from 800˚C to 500˚C was recorded using both infrared camera and thermocouples. The infrared camera recorded the surface temperature of the plates and thermocouples recorded the inner temperature of steel plates, respectively. After analysis of the data obtained from thermocouple and infrared camera simulation was carried out in Ansys to predict maximum temperature in heat affected zone.

Installation of thermocouple is very crucial to measure accurate temperature in heat affected zone. Several experiments were carried out to achieve the optimum position of thermocouple in heat affected zone. With different locations of thermocouple, there were variations in the recorded temperature in heat affected zone.

The first position of hole was designed in such a way that it was 1.5mm away from projection line of top edge to the bottom side in the direction opposite from weld. Problem with this hole location was it was too far from weld surface and the temperature recorded were not as expected. The first hole position was as shown in Figure 11 .

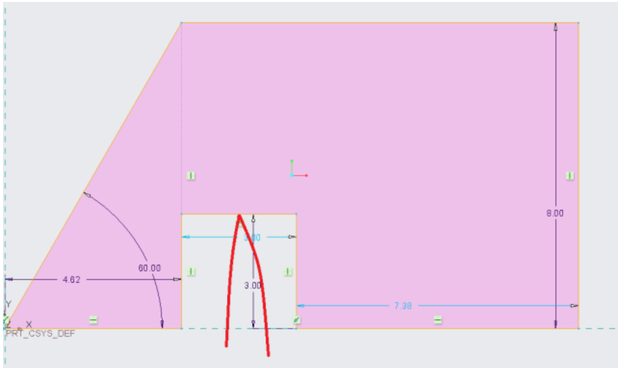


Figure 11 First Hole Position for Thermocouple

Hole position was moved straight under top edge of the welding plates nearer to the HAZ than in the first experiment to measure temperature above 800°C, but due to high temperature thermocouples were burnt and detached from the welding plate before reaching 800°C. Second hole position for thermocouple is shown in Figure 12.

Figure 12 Second Hole Position for Thermocouple

Figure 13 shows the thermocouples measurement for 1st and 2nd hole positions. It is evident from the figure that in the 1st hole position only one thermocouple measured temperature above 800°C and in the 2nd hole position none of the thermocouples measured temperature above 800°C.

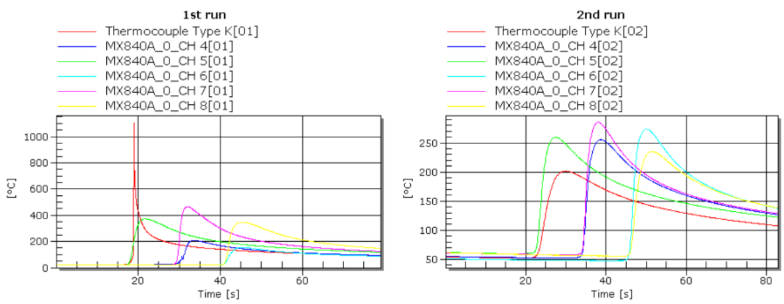


Figure 13 Thermocouple Recordings

After series of experiments and analysis a jig for the plates to drill holes for thermocouples perpendicular to welding surface was designed by Ilia Tikhonov, project assistant at Häme University of Applied Sciences. Thus, designed jig was 3D printed and metal plate was attached on the jig for extra holding of a drill in needed place. The jig gave the advantage to drill holes at an angle near to the HAZ as shown in Figure 14.

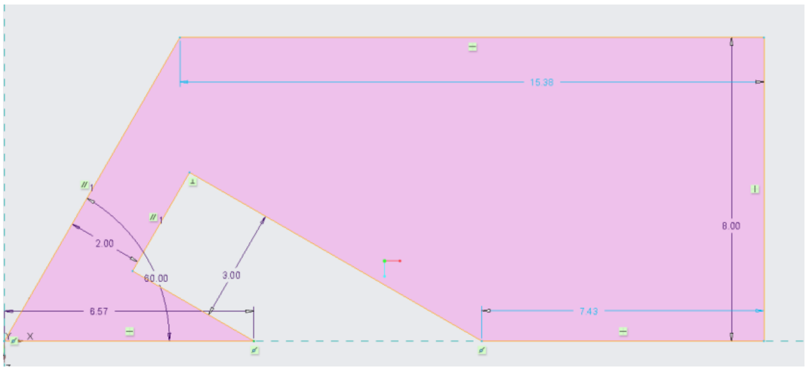


Figure 14 Finalized Hole Position in HAZ (Tikhonov, 2020)

With the Finalized hole position welding was carried out and temperature recorded by thermocouples in each welding run was measured and analyzed. There were two thermocouples that recorded temperature above 800°C. Thermocouples recording for the 1st run is shown in Figure 15, thermocouples recording for the 2nd run is shown in Figure 16 and thermocouples recording for 3rd run is shown in Figure 17.

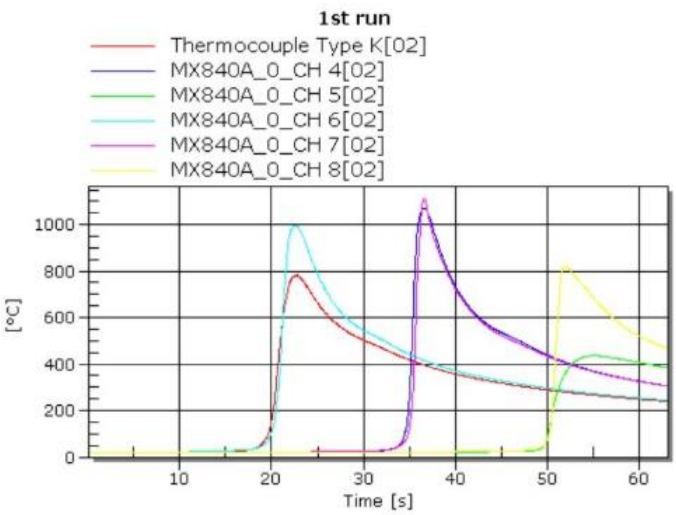


Figure 15 Finalized Recording of thermocouple for First Run

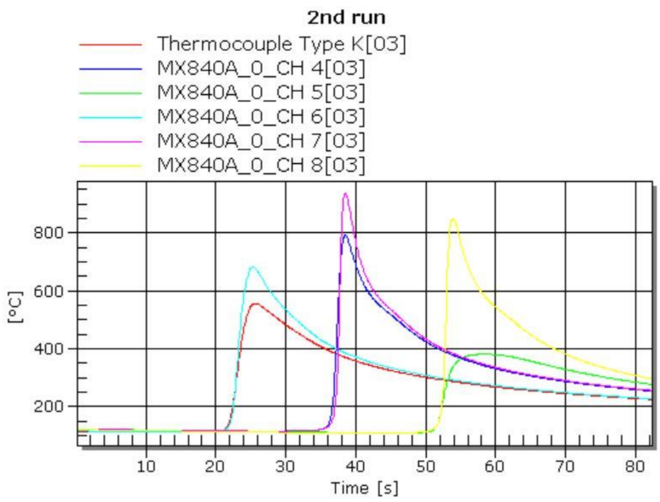


Figure 16 Finalized Recording of Thermocouple for Second Run

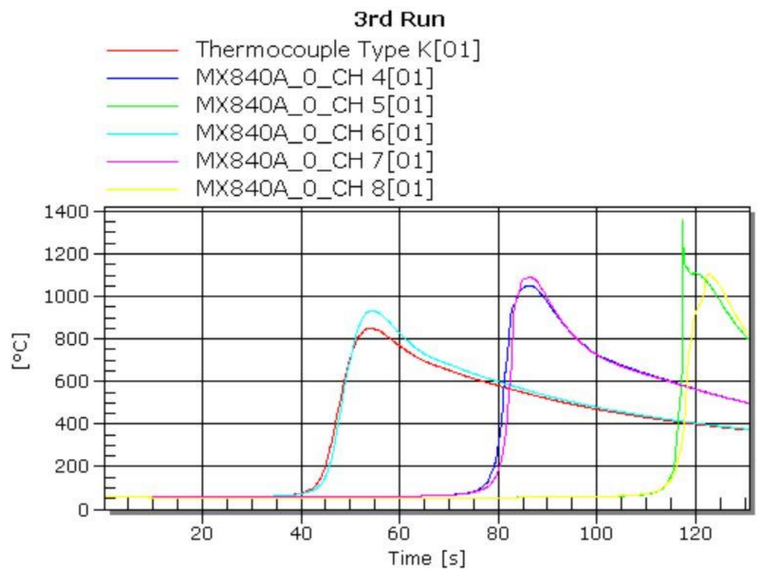


Figure 17 Finalized Recording of Thermocouple for Third Run

5 Welding and quality check

To obtain the smooth and good quality of welding it is very crucial to apply the recommended amount of heat. The heat applied can be changed through altering current and voltage in welding. In this research work Robot was used for welding which compensated the poor quality of weld made by human being. But, in addition to this, a proper setting for heat input was needed to obtain accurate results. So, the welding took place under the supervision of welding professional Mr. Harri Nieminen to ensure the quality of weld. Kemppi´s Welding Procedure Specification was also followed to obtain optimum quality of weld.

For the measurement of cooling time in heat affected zone, welding was carried out using three weld runs. For the 1st run heat input was highest of all three as heat input is used to melt the filler material and to make the full penetration of the steel and the filler material in the groove of V-joint. While welding with 2nd and 3rd run required less amount of heat because the 1st run has already melted the root of the steel plates. The 2nd and the 3rd runs were used to fill the groove, allowing less cooling time as opposed to single run welding. Figure 18 shows the attachment of welding specimens on the welding table where as Figure 19, Figure 20 and Figure 21 shows the quality of 1st welding run, 2nd welding run and 3rd welding respectively.

Figure 18 Welding Plate Attachment to the Table

Figure 19 Quality of First Weld

Figure 20 Quality of Second Weld Run

Figure 21 Quality of Third Weld Run

6 Measurement of heat input and analysis

With proper test set up and all the measurement equipment installed on right place welding was carried out to perform the test. Heat input was recorded through welding machine. Table 3 shows the details about welding parameters such as Current (A), Voltage(V), Speed(s) and Heat input(Q).

Table 3 Heat Input

First Run			
Current (A)	Voltage (V)	Speed(mm/s)	Heat input (KJ/mm)
130	25.4	7.5	1584
Second Run			
Current (A)	Voltage (V)	Speed(mm/s)	Heat input (KJ/mm)
120	24.7	7.5	1422

6.1 Temperature recorded by thermocouple in 1st run

The maximum temperature recorded by the thermocouple in the 1st welding run is shown in Figure 22. From the figure it is evident that the temperature recorded was above 800°C. Figure 23 shows the time taken to cool down from 800°C to 500°C. The cooling time between 800°C and 500°C (t8/5) = (58.68-53.52) =5.16seconds.

Channel info

Name	Thermocouple Type K
Test	Job1_2020_03_26_12_39_15.bin
In preview	☑
Unit	°C
Samples	4611
Min	18,61
Max	863,12
Mean	170,26
STD	197,43

Figure 22 Maximum Temperature for First Run K (02)

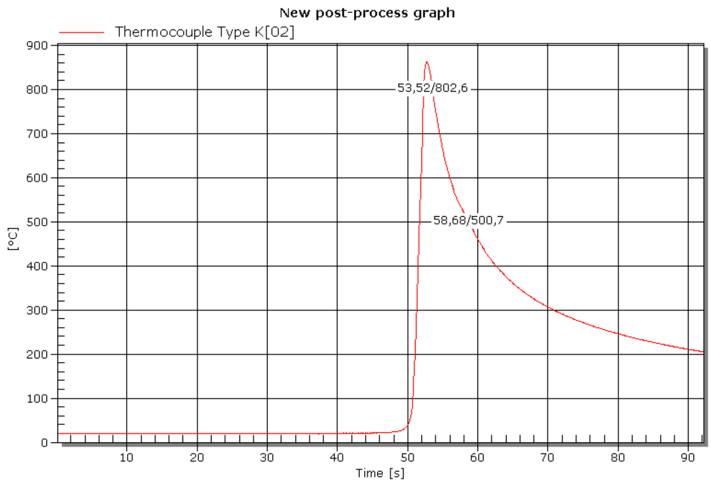


Figure 23 Cooling Time for First Run K (02)

Temperature recorded by thermocouple (CH7) for the 1st welding run was also analyzed. It is evident from the Figure 24 that the recorded temperature was above 800°C. Figure 25 shows the time taken to cool down from 800°C to 500°C. The cooling time between 800°C and 500°C (t8/5) = (72.22-65.98) =6.24seconds.

Channel info	
Name	MX840A_0_CH 7
Test	Job1_2020_03_26_12_39_15.bin
In preview	☑
Unit	°C
Samples	4611
Min	19,94
Max	944,85
Mean	145,31
STD	208,64

Figure 24 Maximum Temperature for First Run (CH7)

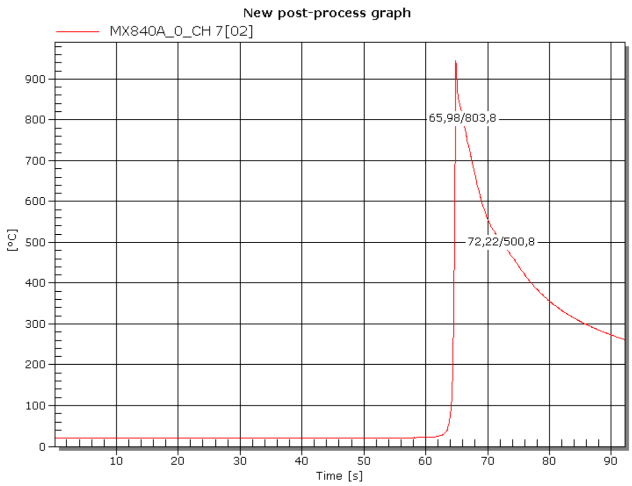


Figure 25 Cooling Time for the First Run (CH7)

To calculate the cooling time in 1st welding run we measured the average cooling time recorded by channel K (02) and (CH7) and value was obtained as shown in equation 4.

$$\frac{5.16+6.24}{2} = 5.7 seconds \qquad (4)$$

6.2 Temperature recorded by thermal camera in 1st run

A thermal camera was set up to record the temperature on the surface of the welding plate. Temperature data and graphs obtained through thermal camera was recorded using FLIR software. Figure 26 shows measurement points on the surface of plates.

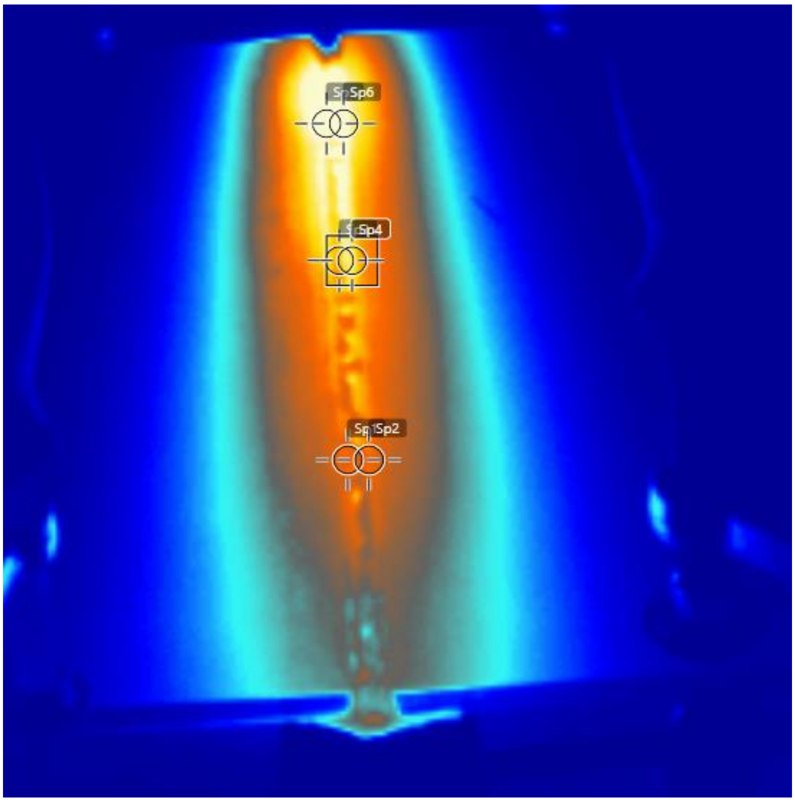


Figure 26 Temperature Measurement Points on Surface of Plate

Figure 27 shows the maximum temperature recorded by thermal camera on the surface of the welding plate right above the point of installation of thermocouple channel K (02). The maximum temperature recorded was 1064°C.

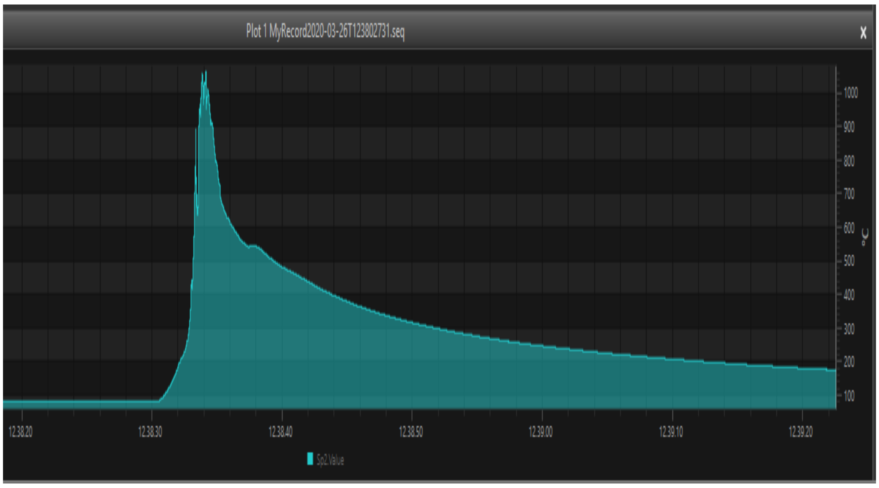


Figure 27 Thermal Camera Recording on the surface above channel K (02)

Similarly, Figure 28 shows the maximum temperature recorded the thermal camera on the surface of the welding plate right above the point of installation of thermocouple CH7. The maximum temperature recorded was 1064°C.

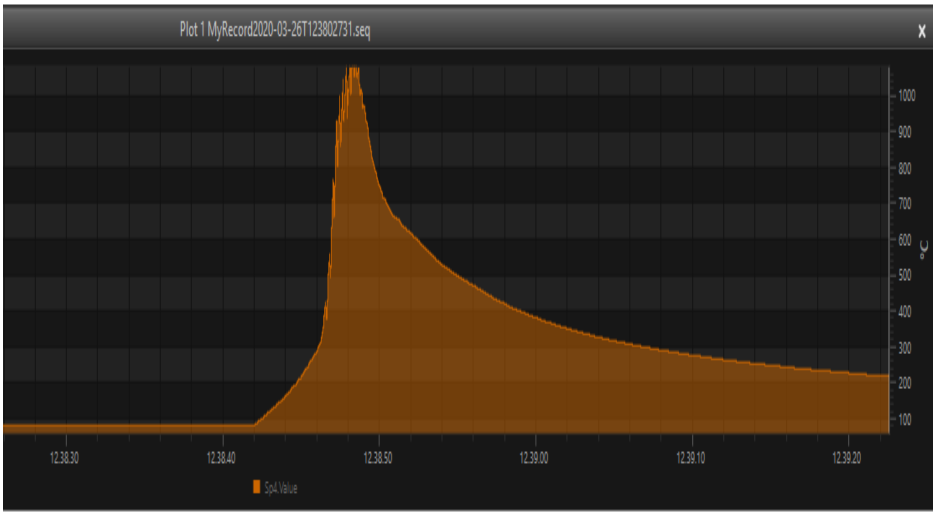


Figure 28 Thermal Camera Recording on the surface above channel CH7

6.3 Temperature recorded by thermocouple in 2nd run

Figure 29 shows the maximum and minimum temperature during the 2nd welding run. From the figure it is evident that the maximum temperature was above 800°C and minimum temperature was at 110°C. At the start of 2nd welding run, temperature was already 110°C because of the 1st welding run, the welding plate was already heated. Figure 30 shows the time taken to cool down from 800°C to 500°C. The cooling time between 800°C and 500°C (t8/5) = (35.74-26.16) =9.58seconds.

Channel info

Name	Thermocouple Type K
Test	Job1_2020_03_26_12_41_40.TST
In preview	☑
Unit	°C
Samples	3055
Min	110,41
Max	843,89
Mean	333,76
STD	205,27

Figure 29 Maximum Temperature for Second Run K (01)

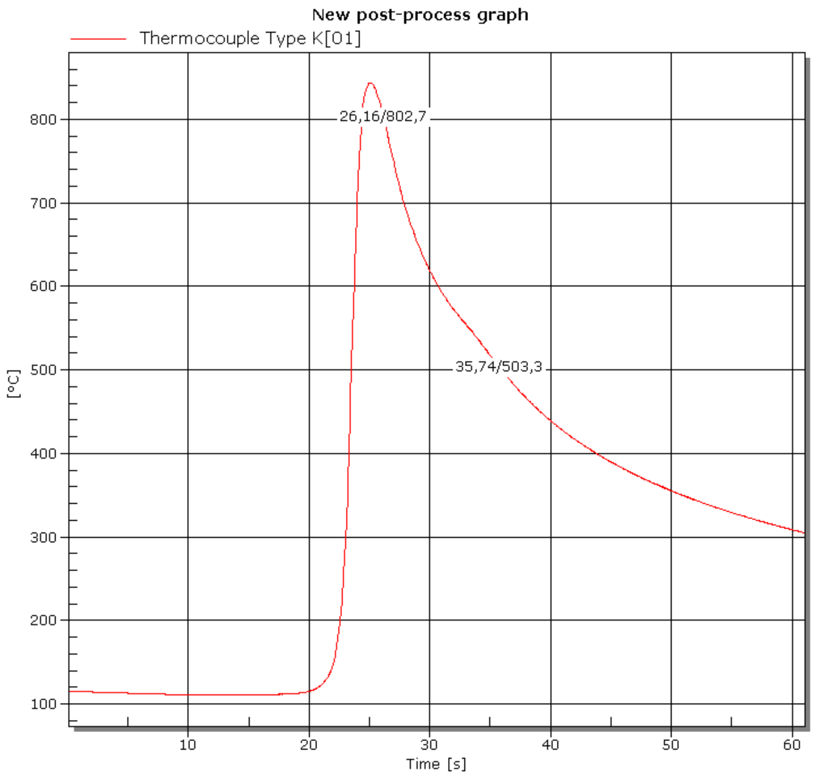


Figure 30 Cooling Time for Second Run K (01)

Temperature recorded by CH7 in 2nd welding run was also analyzed based on the graph and data obtained. Figure 31 shows the maximum temperature recorded by thermocouple which is above 800°C and Figure 32 shows the time taken to cool down from 800°C to 500°C. The cooling time between 800°C and 500°C (t8/5) = (48.70-39.18) =9.52seconds.

Channel info

Name	MX840A_0_CH 7
Test	Job1_2020_03_26_12_41_40.TST
In preview	☑
Unit	°C
Samples	3055
Min	117,94
Max	896,05
Mean	291,09
STD	220,79

Figure 31 Maximum Temperature for Second Run CH7

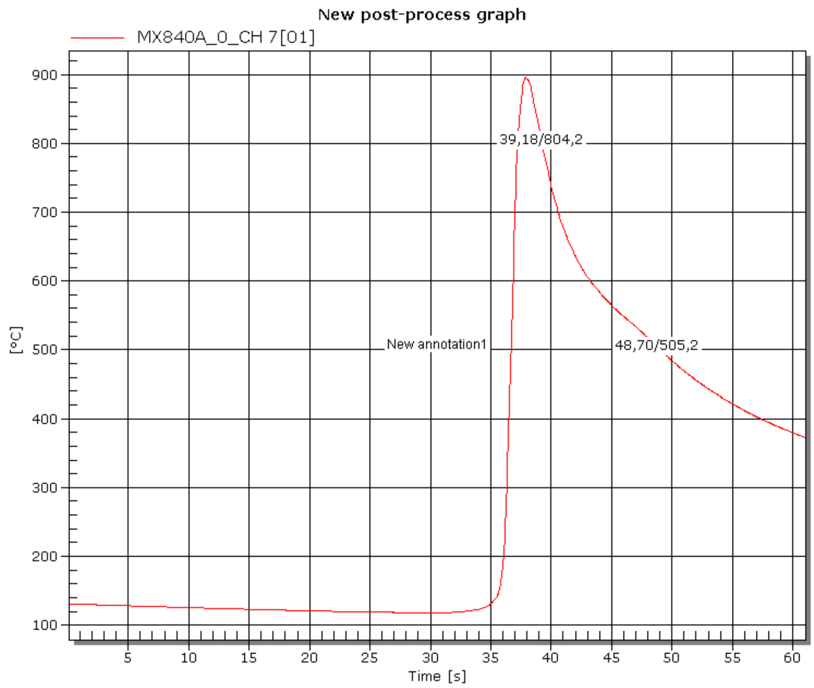


Figure 32 Cooling Time for Second Run CH7

To calculate the cooling time in 2nd welding run we measured the average cooling time recorded by channel K (01) and (CH7) and value was obtained as shown in equation 5.

$$\frac{9.58+9.52}{2} = 9.5\text{seconds} \qquad (5)$$

6.4 Temperature recorded by thermal camera in 2nd run

In the 2nd welding run the surface temperature of the welding plate was recorded using the thermal camera. Figure 33 shows the temperature on the surface above channel K (01) and maximum temperature recorded was 1149°C.

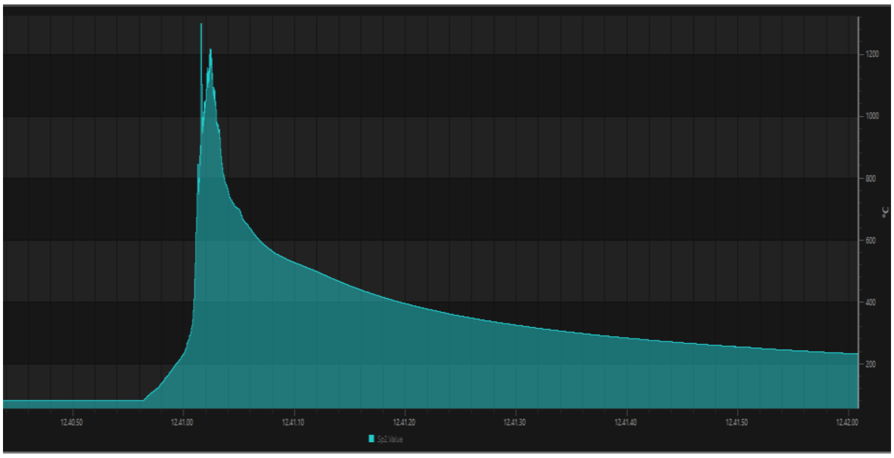


Figure 33 Thermal Camera Recording on the surface above channel K (01)

Similarly, Figure 34 shows the maximum temperature recorded the thermal camera on the surface of the welding plate right above the point of installation of thermocouple CH7. The maximum temperature recorded was 1214°C

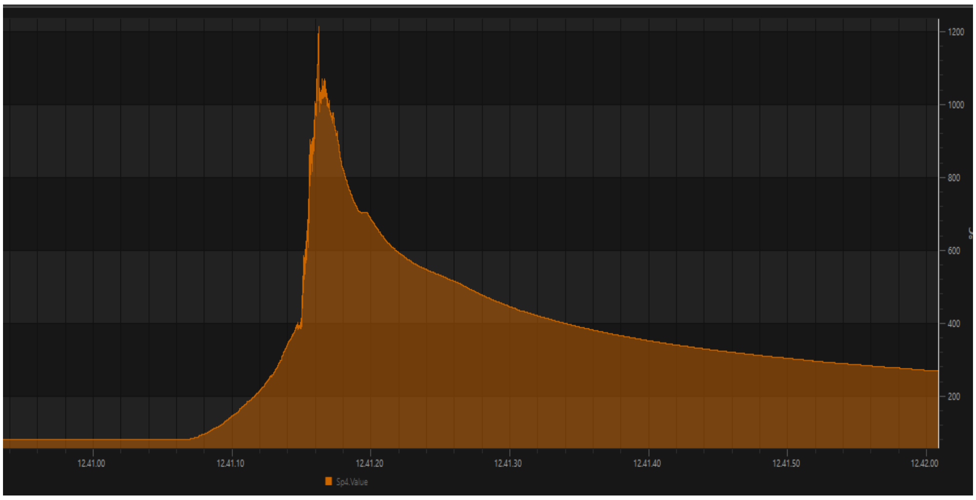


Figure 34 Thermal Camera Recording on the surface above channel K CH7

7 Welding simulation in ANSYS

Modelling and simulation of welding have always been known to pose challenges to the engineers and researchers, due to the complexity involved in the entire process. Capturing welding process using computer simulation involves modelling multiples physics like heat transfer, phase change, moving heat source, nonlinear stress-strain behavior and change in material behavior in HAZ. Therefore, it is a great challenge to consider all factors at the same time; so generally, the models include some approximations as listed below:

1 The displacement of the parts, during the welding, do not affect the thermal distribution of the parts themselves.

2 All the material properties are described till to the liquid phase of metal.

3 Convection and radiation effects are considered.

7.1 Thermal model

The heat source was modelled as a distributed heat flux depending on arc speed. The rate of arc travel and current were varied, and these parameters were noted along with the temperature data. The radius of the arc spread was estimated by considering the electrode diameter and bead widths of welds formed during experiments. The moving heat load applied in the finite element model was taken as a distributed heat flux as described by equation 6. Figure 35 explains the path on which equation 6 follows.

$$q = C_2\, e^{\frac{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2}{c_1{}^2}} \qquad (6)$$

Where

q = heat flux on the desired surface

$c_{1=}$ Radius of the beam

$c_{1=}$ Source Power Intensity

$x_{0,}\ y_0, Z_0$= Instantaneous position of the center of the heat flux which is on the `path` at the distance v$\times$ t from the ´start point´.

v= Velocity of the moving heat source

t= Time

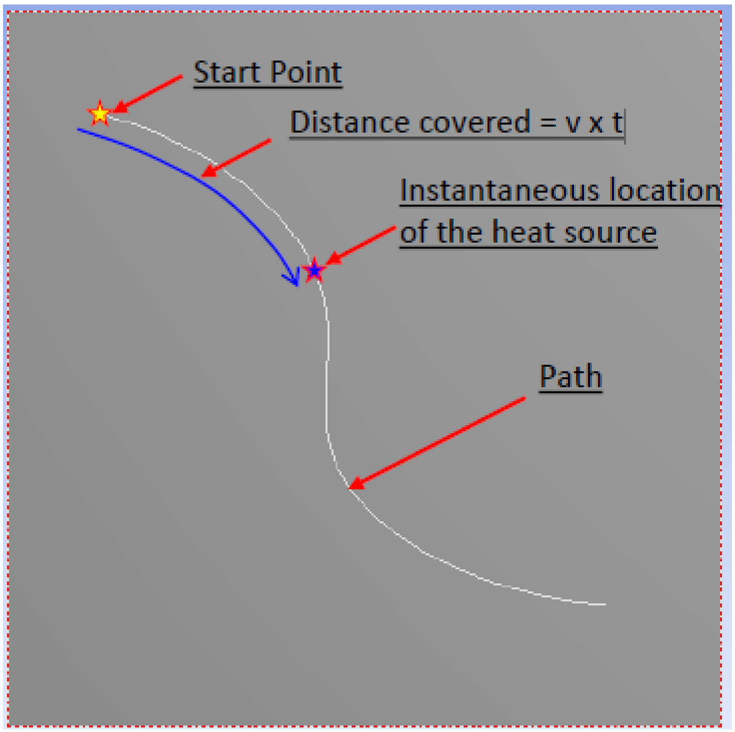


Figure 35 Gaussian Heat Flux Source Equation *(Srivastava, 2020)*

3D model of the plate was designed in Creo parametric software and imported to ANSYS to run welding simulation. Student version of ANSYS was used to simulate the welding so there was limitation in the mesh sizing. ANSYS does not have inbuilt commands to simulate moving heat source so, moving heat source ACT extension was downloaded from ANSYS store to complete the simulation.

7.2 Meshing

The finite element mesh is used to subdivide the CAD model into smaller domains called elements, over which a set of equations are solved. These equations approximately represent the governing equation of interest via a set of polynomial functions defined over each element. Our result and the accuracy of the data obtained from the analysis is also quiet dependent of meshing in our model. Figure 36 shows the mesh structure of our welding model in Ansys. All the welding parameters were defined properly in Ansys. Connection was defined as contact connection, initial temperature was defined as room temperature which was 20°C , and convection coefficient was also defined which are shown in Figure 37.

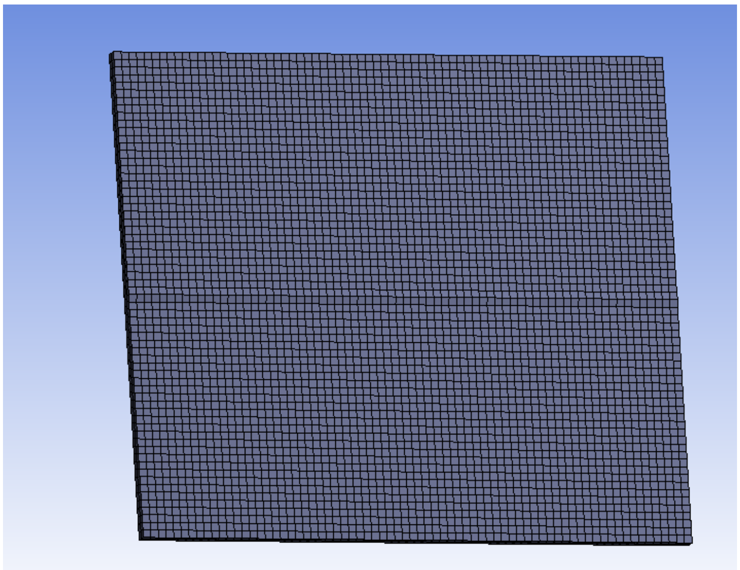


Figure 36 Mesh of Welding Plate in ANSYS

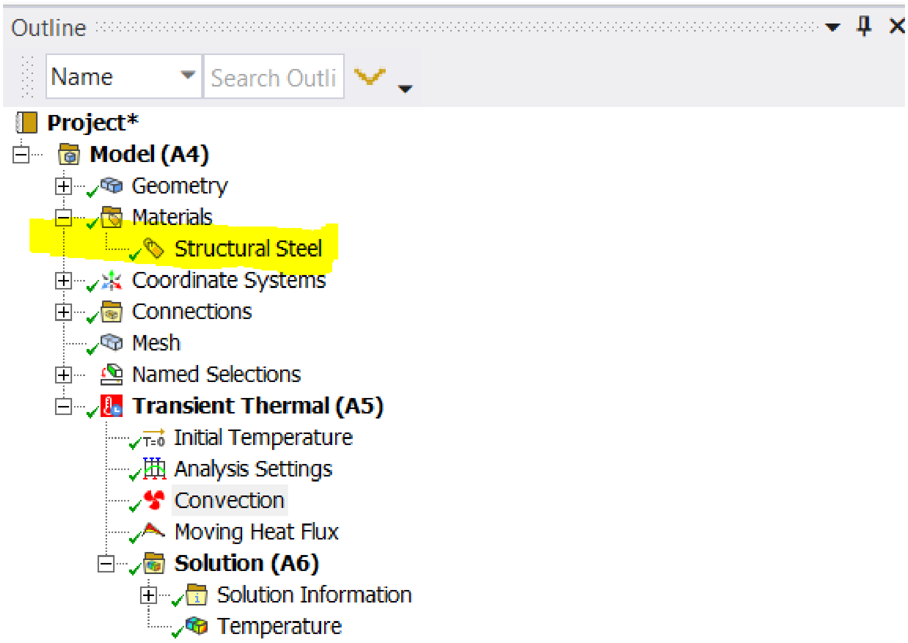


Figure 37 Defining Criteria in ANSYS

7.3 Defining the Material

Material as Structural Steel was defined in ANSYS for welding plate which gives needed properties for the material. It defines thermal properties in simulation. All the boundary conditions were also defined as per the requirement to achieve simulation as perfect as in real experiment. Figure 38 shows the value of thermal conductivity and specific heat constant obtained for structural steel in Ansys during the simulation process.

Thermal	
Isotropic Thermal Conductivity	60.5 W/m·°C
Specific Heat Constant Pressure	434 J/kg·°C

Figure 38 Defining Material Properties (Ansys Simulation, 2020)

7.4 Defining the moving heat flux

Energy generated during welding was applied in the form of moving heat flux. In moving heat several criteria were defined to simulate welding. Face of the body on which heat was applied was defined, edge on which heat travels was selected and the start point of the moving heat was also defined. Velocity of welding torch, radius of the beam as well as end time for welding was also defined in the simulation. Source power intensity was defined to get similar temperature on the surface of the weld as shown by thermal camera. Figure 39 shows the moving heat flux criteria applied in welding in Ansys.

Details of "Moving Heat Flux"	
Geometry	
Scoping Method	Geometry Selection
Geometry	1 Face
Path	
Scoping Method	Geometry Selection
Geometry	1 Edge
Start Point	
Scoping Method	Geometry Selection
Geometry	1 Vertex
Definition	
Index	1
First Patch?	Yes
Last Patch?	Yes
Velocity	0.0075 [m sec^-1]
Radius of the Beam	0.005 [m]
Source Power Intensity	200000000 [W m^-1 m^-1]
Start Time	0 [sec]
End Time	46 [sec]
Number of Segments	200
Minimum Steps for Cooling Phase	200
Material Removal	No
Melting Temperature	800 [C]

Figure 39 Defining Moving Heat Flux

8 Comparing Results of Ansys, Thermal Camera and Thermocouple

Result obtained through thermal camera and thermocouples were applied in Ansys to simulate the welding process. Figure 40 shows the maximum temperature recorded by thermocouple in 1st welding run. It is evident from Figure 40 that the maximum temperature recorded by thermocouple was 863,12°C. Also Figure 41 shows the maximum temperature recorded by thermal camera on the surface of the plate right above the point of installation of thermocouple K(02). We applied the same maximum temperature conditions as shown by thermal camera which was 1064°C to Ansys and found out temperature at the point of installation of thermocouple to be 884,71°C as shown in Figure 42 and

Figure 43. Temperature obtained in HAZ in Ansys simulation differs that of thermocouple with +21°C, which can be solved through more refined mesh structure. There were some problems in simulation as the welded plates cooled down rapidly and it was hard to predict the cooling time through simulation. There might be several reasons behind it and can be solved in future to predict the cooling by refining the mesh, and through detail study of the welding process. But, in this case we can predict the temperature in heat affected zone through analysis.

Channel info

Name	Thermocouple Type K
Test	Job1_2020_03_26_12_39_15.bin
In preview	☑
Unit	°C
Samples	4611
Min	18,61
Max	863,12
Mean	170,26
STD	197,43

Figure 40 Maximum Temperature for First Run by thermocouple K (02)

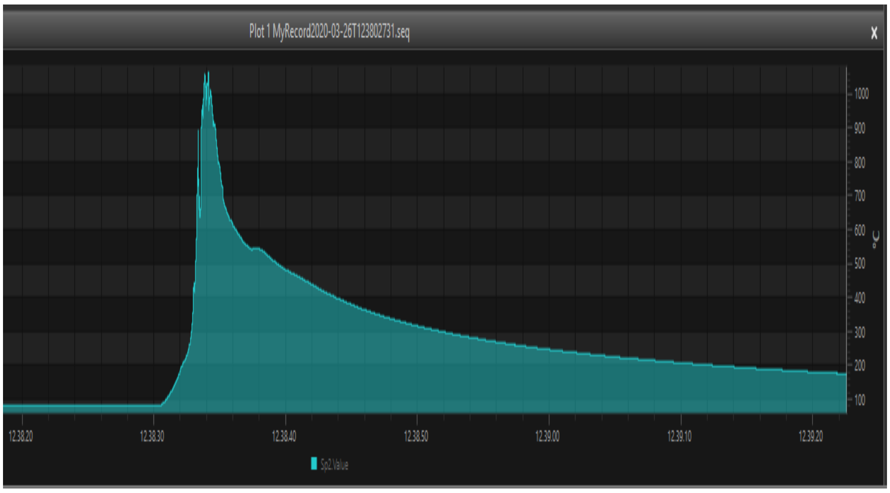


Figure 41 Thermal Camera Recording on the surface above channel K (02)

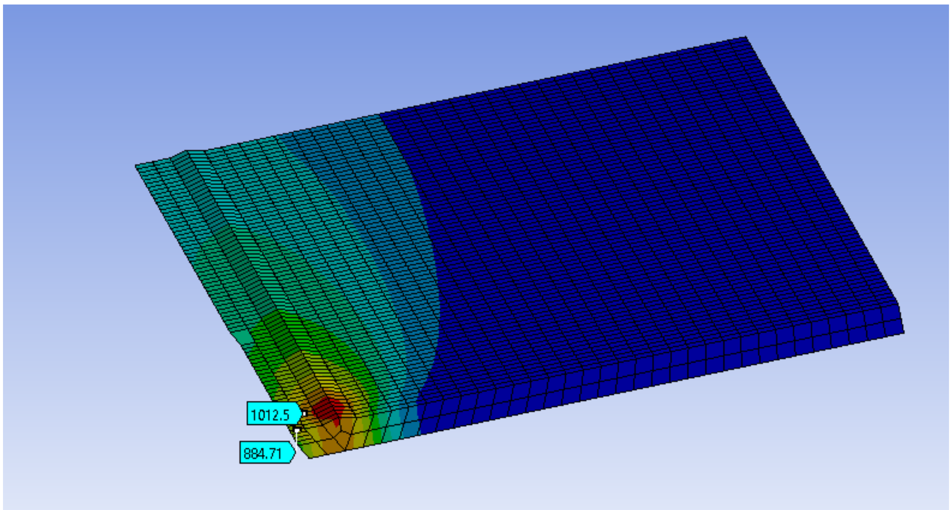


Figure 42 Temperature on Surface and on Heat Affected Zone

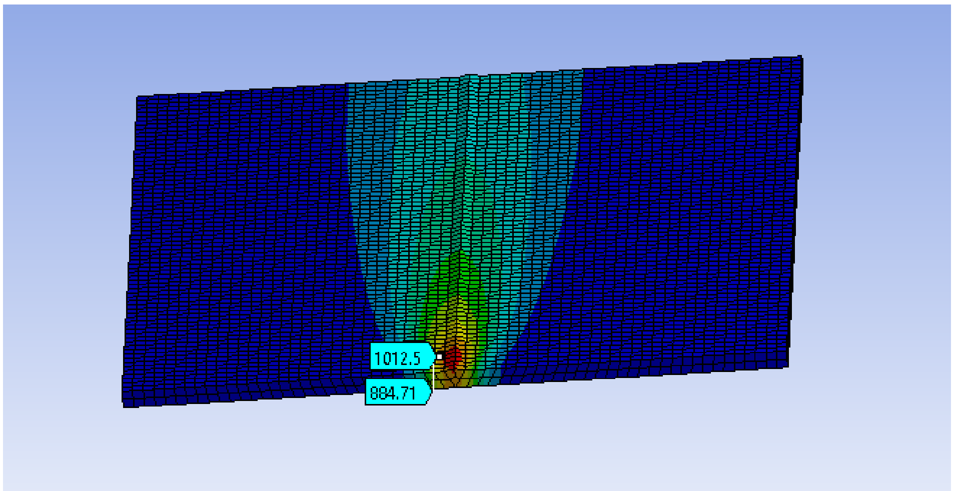


Figure 43 Temperature on Surface and on Heat Affected Zone

9 Conclusion

Through this project, we can conclude that a cooling time of between 800°C and 500°C (t8/5) in the a heat affected zone depends on various welding parameters such as heat input, speed, voltage, and current. It is also very crucial to measure the temperature as near to the heat -affected zone as possible. The thermocouple attachment to the test specimen also determines the accuracy of the measured data. It is also evident that the cooling time increases when the number of welds is increased in welding. In this experiment, it took 5.7 seconds to cool down from 800°C and 500°C (t8/5) in the heat affected zone in the 1st welding run which is shown in equation 4 and in 2nd welding run it took 9.5 seconds which is shown in equation 5. It can be observed that when the heat input was increased the cooling time increased significantly. We can also predict the temperature in a heat affected zone through simulation of welding in ANSYS when we know the surface temperature and all the other welding parameters. The cooling time can also be predicted when the simulation is done with a refined mesh and with a proper ANSYS command.

This research experiment showed that a prediction of maximum temperature in a heat affected zone is possible through ANSYS simulation. Through our Ansys simulation we found the temperature in HAZ in the welding simulation to be approximately equal to the temperature recorded by a thermocouple. To get the proper data, the thermal model, and the boundary conditions in the simulation should be very accurate. With our model it is only possible to predict the maximum temperature in the heat affected zone, but we could not predict the cooling time between 800°C and 500°C (t8/5) in a heat affected zone because of our welding simulation cooled down too rapidly.

The next steps in the experiment would be to conduct a proper simulation of welding in ANSYS which would also produce the cooling time for temperatures of between 800°C and 500°C (t8/5) in a heat-affected zone.

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