Effect of Welding Preheats on Metallurgical Analysis and Microstructural Development

Mazleenda Mazni*¹, Muhammad Hussain Bin Ismail², Hazriel Faizal Bin Pahroraji², Norjasween Abdul Malik¹, Mohd Ghazali bin Mohd Hamami¹, F. Sukarman¹, Nurulsaidatulsyida Sulong¹

¹Faculty of Mechanical Engineering, Universiti Teknologi MARA, UiTM Cawangan Johor, Pasir Gudang Campus, Jalan Purnama, 81750, Masai, Johor Darul Takzim, Malaysia.
²Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

*mazleenda@johor.uitm.edu.my

Abstract. This project is to study the effect of welding preheat on metallurgical analysis and microstructural development. Variables such as current, speed of welding and size of specimen were fixed. In the present work, a mild steel plate with thickness of 100 mm and width size of 20 mm was used. SMAW (Shielded Metal Arc Welding) technique was chosen as it is the easiest way to perform and widely used in oil & gas and marine industries. Three different preheat temperatures were performed during the study; ambient temperature (no preheat), between 60 °C to 70 °C and greater than 200 °C. The study emphasizes on the minimum preheat temperature that produce good quality welding by taking into account some of metallurgical aspects; microstructure and macrostructure development, hardness distribution at important areas in weld (Heat Affected Zone, parent metal and weld area) through thickness. From this study, code American Welding Society (AWS) D1.1 was used as a reference and it stated that for plate that has 100 mm thickness the preheat temperature should be in the range of 60 °C and 70 °C. The result of microstructure and macrostructure showed that the depth of penetration was not vary too much. Hardness measurement, macro and microstructure observation were performed in order to obtain a good correlation exist between these parameters studied.

1. Introduction
Preheat is a heating procedure that applied to parent metal immediately before welding process is done. Preheat can be considered as one of the welding requirements that specified in many standards such as American Welding Society (AWS) D1.1structural welding code for steel [1]. This standard states that the requirement of preheat temperature depends on the type of steel and also the thickness of the material. Preheat involves heating the base metal, either in its entirety or just the region surrounding the joint, to a specific desired temperature, called the preheat temperature, prior to welding [2]. Many benefits can be obtained from preheat process such as; (1) Lower the cooling rate in weld and base metal, (2) Produce more ductile metallurgical structure with greater resistant to cracking, (3) Help to diffuse out hydrogen without causing crack, (4) To reduce shrinkage stresses in the weld and base metal and (5) Preheat can be used to help ensure specific mechanical properties such as notch toughness [2].

The choice of method of preheating depends on size of material, weldment size and heating equipment available before welding process. The methods can include furnace heating for small...
production of assemblies or gas torch, electric strip heater, induction heaters or radiation heaters for large structural components [3].

The crucial factor affecting from preheat is to slow down the cooling rate. Some alloys have properties that not allowed to cool quickly. This is due to fact that the development of hard or brittle phases in heat affected zone (HAZ) which are may lead to cracking and also reducing toughness in heat affected zone (HAZ). Preheating, is also one of the methods that widely employed in welding operation to prevent cracking [4]. Many welded steel has potential to hydrogen cracking due to fast cooling rate that leads to the formation of hard, susceptible microstructure and also lock hydrogen into the solidifying weld metal [5].

Even though preheat method is applicable in reducing cracking effects there are some material that should not be preheated such as austenitic manganese (13% Mn) steel, austenitic stainless steel, duplex stainless steel and also titanium alloys [5]. However, for many carbon steel and other alloy steels, preheat are required prior to welding process, particularly for thick surface. The thickness of each part is usually averaged over a distance of 75 mm from the weld line. However, the average thickness must depend on type of material, some material require to preheat when the length thickness is more or less 75 mm [6].

Effect of cooling rate on material after welding will determine the quality of welding; this is due to some defect of welding that may occur because of cooling rate such as cold cracking. Cooling rate is a rate of heat loss occurs from the surface of material. It gives an indicator to achieve some mechanical properties of material such as hardness, stress-relieve and also development of microstructure [7]. Cooling rate is significantly influenced from welding heat input and preheat temperature. As the heat input and preheats temperature increases, the rate of cooling decreases for a given base metal thickness. Other than input temperatures that changes the cooling rate, other variables such as material thickness, specific heat, density and thermal conductivity will influence the cooling rate. To simplify the effects of temperature with the cooling rate, Equation (1) shows the relationship between cooling rates, preheat temperature and heat input. Heat input is a relative measure of the energy transferred per unit length of weld. Heat input is typically calculated as the ratio of the power to the velocity of the heat source. To calculate heat input of welding Equation (2) can be used for governing information of welding current, voltage and travel speed [8].

\[
\text{cooling rate, } r \propto \frac{1}{\text{preheat temperature,T} \times \text{heat input,H}}
\]

\[
\text{heat input, } H = \frac{\text{voltage,V} \times \text{current,I} \times 60 \times \text{welding efficiency coefficient} \times \text{travel speed,S} \times 1000}{1}
\]

Metallurgy of carbon steel will give different of transformation according to the cooling time of material. Figure 1 shows the phase changes of Iron Carbon Diagram, which is significant for metallurgical analysis. At the higher temperature for 0.2 % carbon, the steel has austenite microstructure. When it is slowly cooled, the transformation will change into two-phase field of ferrite and austenite. If the temperature keeps decreasing the ferrite starts nucleating around the grain boundaries of austenite. On the slow cooling, the austenite get transform into pearlite. Pearlite is a lamellar mixture of ferrite and cementite. For each microstructure it has specific properties, for example ferrite has soft and ductile properties, while pearlite ... hard and imparts mechanical strength to steel. Therefore, if the pearlite forms in material more than ferrite from result of rapid cooling the material will have hard and brittle properties. Therefore, slow cooling of material will help the material to maintain its behavior even after welding [9].

In this project, the effect of three different preheats temperature before welding was investigated. The material used for this project is mild steel because it is a common material used in fabrication of structure for oil and gas industry. Each specimen underwent metallurgical test such as hardness and the microstructural changes. This study was performed because to study the correlation between different preheat temperature and the quality of welding by referring metallurgical analysis, so that the change of material behavior can be seen especially in weld metal, heat affected zone (HAZ) and parent metal. The change of hardness of material also can be studied and compared. The purposes of this study were; (1)
to determine the effect of preheating on the time of cooling of welded structure, (2) to interpret welding quality in terms of depth of penetration and welding defect as a function of preheat temperature by performing macrostructural analysis, and (3) to analyze the metallurgical aspect of welded structure by performing microstructure analysis and hardness test.

![Iron carbon diagram of carbon steel](image)

**Figure 1.** Iron carbon diagram of carbon steel [9]

### 2. Experimental Procedure

In this experiment, the effect of preheat before welding on mild steel plate was investigated in accordance with the standard AWS D1.1- Structural Welding Code for Steel that used at Labuan Shipyard and Engineering to fabricate steel structure for offshore applications. Material was prepared by the industry according to the standard welding practice that applied in fabrication of steel structure for oil and gas industry. Mild steel was used in this study because it is commonly used in fabrication of platform or other applications and due to its properties which are strength, ductility and ease of machining.

Based on preheat theory on welding, usually effect during welding of high carbon content or welding of thick material that more than 2 inch (50.8 mm). However, for other type of carbon steels, preheat is required if the thickness of weld part meet the requirement of the standard. The size for all specimens set as fixed value so that it will not affect the effect of preheats. The specimen has 75 mm X 20 mm X 100 mm of length, width and thickness as shown on Figure 2.

![Specimen size](image)

**Figure 2.** Figure shows the size of specimen made from mild steel and the position of weld bead

Three conditions of preheat were studied; no preheat labelled as specimen 1, preheat temperature is 60°C to 70°C labelled as specimen 2 and lastly, specimen 3 when the preheat temperature is more than
200°C. The method of preheating used in this study is by using oxy-acetylene gas torch method. To measure the temperature, digital thermometer was used. To avoid heat loss to the surrounding which may affect the properties of welded structure, the welding process was started immediately after preheat process.

Welding process used in this study is shielded metal arc welding as shown schematically in Figure 3 using E7018 type of electrode that is low hydrogen electrode to avoid cracks as shows in Figure 3. Other parameters of welding process were shows in Table 1. The parameter of welding was same for all preheat temperature. After the welding process completed, the cooling time for weld bead was measured for 4 minutes with each 10 seconds the temperature drop recorded.

### Table 1. Parameters of SMAW process

| Properties       | Parameter |
|------------------|-----------|
| Electrode material | Carbon Steel |
| Electrode size   | 4 mm      |
| Polarity         | DCEP      |
| Current          | 145 A     |
| Voltage          | 25 V      |

![Figure 3. Shielded metal arc welding process [10]](image)

To study the changes of macrostructure and microstructure, laboratory metallurgical analysis was carried out. In laboratory experiment, the tests conducted were:

1. Chemical composition test by using Arc Spark Spectrometer.
2. Macrostructure and microstructure analysis.
3. Hardness test through thickness material by using hardness Vickers’s.
4. Image analyzer to determine quantity of grain structure for ferrite and pearlite.

For additional information, image analyzer was conducted to measure the quantity of microstructure developed for each preheat temperature. For etching process the solution used was 2% Nital. Nital contain of 90-99 mL of ethanol and 1-10 mL of HNO3. Etchants will reveal alpha grains boundaries and constituent. The specimen after polishing process was immersed for several seconds before macrostructural and microstructural analysis proceeded.

### 3. Results and Discussion

Cooling rate of weldment was investigated during preparation of specimen. The data of temperature drops after welding for 4 minutes were recorded. Figure 4 shows how the effects of preheat temperature on cooling rate. It is important to investigate the cooling rate of welding because it is one of the factors that contribute to crack. If the cooling rate too fast, it will help the formation of hardening structure such as cementite. Other than that, cooling rate also used to avoid hydrogen trapped in weld metal that will contribute the internal cracking. Lastly, cooling rate also helps to avoid cracks by rapid solidification of weld metal. Generally, to control the cooling rate either by using heat treatment method such as annealing or by controlling preheats and interpass temperature of welding. The relationship of cooling
rate to the preheat temperature and heat input shown in Equation (1). From the relationship, the higher the temperature of preheat the lower the cooling rate of welding, the results of cooling of material shows in Figure 4. From Figure 4, the additional of preheat will give high temperature after welding and by referring the slope of the graph the temperature decrease slowly for preheat temperature between 60°C to 70°C and preheat more than 200°C, compare during no preheat temperature. If the graph continue until time is zero, the specimen with no preheat temperature will reach zero first followed by specimen 2 and 3. From Equation (2) the heat input of welding process with 0.8 welding efficiency coefficient is 1.16 kJ/mm.

**Figure 4.** Relationship between cooling rate and temperature input of mild steel

Three different preheat temperature were applied to three different material having same size and material properties. Arc spark spectrometer were done to check the chemical compositions for each of material, hence calculation of carbon equivalent to check weldability each material can be made. Table 2 shows the chemical composition for each specimen. For specimen 1 and 3 it has nearly same of chemical composition, however for specimen 2 contain of carbon more than others specimen. Specimen 2 also can be considered as mild steel because carbon content less than 0.2 % with slightly different in material properties.

| Specimen 1 | Specimen 2 | Specimen 3 |
|------------|------------|------------|
| C % | Mn % | Ni % | Cr % | Mo % | Cu % | V % | CE |
| 0.152 | 1.84 | 0.012 | 0.119 | 0.013 | 0.027 | 0.0039 | 0.628 |
| C % | Mn % | Ni % | Cr % | Mo % | Cu % | V % | CE |
| 0.192 | 1.86 | 0.013 | 0.12 | 0.014 | 0.028 | 0.0041 | 0.674 |
| C % | Mn % | Ni % | Cr % | Mo % | Cu % | V % | CE |
| 0.157 | 1.86 | 0.012 | 0.121 | 0.015 | 0.028 | 0.0045 | 0.639 |

In this study, the results from arc spark spectrometer were used to define the classification and chemical contain in material. From Table 2 the carbon equivalent content of material is more than 0.5% therefore, according to AWS for each carbon steel that has more 0.5% of carbon equivalence content the material are crack sensitive, therefore to avoid cracks preheat of material before welding process can reduce the formation of crack in welding. Other than that, use of low hydrogen welding procedure also can help minimize the formation of cracks.
Other than weldability of specimen and carbon equivalent content, arc spark spectrometer can also determine the behavior of the base metal itself before welding. Composition of carbon in material shows the toughness properties of material, ductility and crack contributor. For other composition, manganese also will promote crack if the percentage of composition more than 1.4%. For material in this study the amount of manganese is more than 1.4% therefore it will allow cracks to occur if the welding procedure is not properly.

Examination of macrostructure for each different preheat temperature of weld across the thickness of material recorded so that the penetration of the weld area and quality of the weld can be determined. For all the different preheat temperature there is no defects or imperfections occur because of welding, therefore, the parameters used for welding are suitable for welding mild steel. However, the penetrations of weldment gives the different value for different preheat temperature. Figure 5 shows the macrograph of the specimen. From the Figure 5, the depth of penetration were varies with the different preheat temperature. For weldment with no preheat temperature the depth of penetration is smaller compare to during preheat at 60°C and preheat more 200°C. However, macrostructure between 60°C and 200°C preheat temperature there are only slightly different in depth of penetration.

![Macrostructure](image)

**Figure 5.** Macrostructure for; (a) no preheat temperature, (b) preheat between 60°C and 70°C, (c) preheat greater than 200°C
Microstructure examination of material with different preheat temperature were investigated to determine the changes of properties of material. The development of microstructure at base metal, heat affected zone and weld metal were identified to measure the quantity of ferrite and pearlite. For no preheat temperature the structure consist of pro-eutectoid ferrite in the grain boundary and bainitic structure of the columnar grains of deposited metal on the weld metal. At the base metal it consists of ferrite and pearlite where the pearlite is more looks like thin plate and close together. At heat affected zone the development of fine grain of ferrite produce the lower hardness compare to weld metal.

For preheat between 60°C to 70°C the microstructure of weld metal consist of pro-eutectoid ferrite in the grain boundaries. The array of bainitic laths in surround by ferrite grains can be seen. The structure at heat affected zone is shows the grains boundary more coarser structure possessing less toughness. Comparing microstructure from no preheat temperature with preheat temperature at 60°C to 70°C, preheat gives coarse grain structure and gives low toughness of material. For preheat temperature more than 200°C the size of grain is more coarse than grain structure during 60°C to 70°C. The development of microstructure is the same as during preheat temperature between 60°C to 70°C. In term of hardness during preheat more than 200°C the hardness is lower compare to other temperature of preheat. Table 3
shows the microstructure of base metal, heat affected zone and weld metal at different preheat temperature.

The study of preheat temperature also will lead to the changes of hardness of material; usually hardness of mild steel will be in the range of 140 HV to 230 HV. With the increase in temperature the more hardness of material will drop. The drop of hardness of material will gives the properties of ductile to the material. Figure 6 shows the different of hardness value through thickness on the different preheat temperature. Figure 8 shows that the hardness value varies with the temperature input of material, from the graph the higher temperature input will gives low hardness of material. However, for all specimen gives higher value of hardness at weld metal followed by heat affected zone then base metal. The value of hardness at the weld metal is high because of the grain size, amount ferrite and pearlite contain in material, thus it can conclude that the mechanical properties of material at weld metal differ from heat affected zone and base metal. In the base metal the grain size can be classified as fine-grain because it is less hardens, therefore it has fewer tendencies to crack.

**Table 3.** Microstructure at weld metal, heat affected zone and base metal for: (a) no preheat temperature, (b) preheat temperature between 60°C and 70°C, (c) preheat temperature greater than 200°C when using 2% Nital solution of etching solutions.
Table 4. Microstructure at weld metal, heat affected zone and base metal for: (a) no preheat temperature, (b) preheat temperature between 60°C and 70°C, (c) preheat temperature greater than 200°C when Beraha’s solution of etching used.

|        | Weld Metal | Heat Affected Zone | Base Metal |
|--------|------------|--------------------|------------|
| (a)    | ![Weld Metal](image1.png) | ![Heat Affected Zone](image2.png) | ![Base Metal](image3.png) |
| (b)    | ![Weld Metal](image4.png) | ![Heat Affected Zone](image5.png) | ![Base Metal](image6.png) |
| (c)    | ![Weld Metal](image7.png) | ![Heat Affected Zone](image8.png) | ![Base Metal](image9.png) |
Conclusions
The effect of welding preheats temperature for mild steel material with 100 mm thickness plate on metallurgical analysis and microstructural development were investigated. The experiment results showed that different in welding preheat temperature effects the properties of material. Lowered the cooling rate will reduce the cold crack defects. The development of microstructure depended on the cooling rate of welding. Preheat controlled the cooling of material by slower the rate of cooling by increasing preheat temperature. Temperature input also controlled the hardness of material through thickness, where material has low hardness as preheats temperature increased.

Acknowledgement
Special dedication to the persons who involvve in completing this research, especially to Mr. Agus Trang Winarno, Miss Mazlinda binti Sari Hassan, and others from the Labuan Shipyard and Engineering Sdn Bhd for giving fully support to finish this research. I would like also to thanks Mr. Rahimi, the UiTM Material Science lab technician for helping me completing this research.

References
[1] An American National Standard. AWS D1.1/D1.1M: 2008. Structural welding code – steel.
[2] Retrieved on (2013, Oct 21). What is preheat?. Retrieved from www.lincolnelectric.com/en-us/support/process-and-theory/pages/preheat-detail.aspx.
[3] Retrieved on (2014, Apr 7). Why is preheat used when arc welding steel, and how is it applied?. Retrieved from http://www.twi-global.com/technical-knowledge.
[4] Bipin Kumar Srivasrava, Dr. S.P. Teawri and Jyoti Prakash (2010). A review on effect of preheating and/or post weld heat treatment (PWHT) on mechanical behavior of ferrous metals. International Journal of Engineering Science and Technology, Vol. 2(4), 2010, 625-631.
[5] Retrieved on (2013, Oct 21). Preheating of material. Retrieved from http://www.boc.com.au/consumables/preheating of materials.
[6] Retrieved on (2013, Oct 21). Preheating of material. Retrieved from http://www.boc.com.au/consumables/preheating of materials.
[7] B. A. Graville (1973). Welding Cooling Rates and Heat Affected Zone Hardness in Carbon Steel. Welding Journal, American Welding Society.
[8] N. Bailey, F.R. Coe, T.G. Gooch and others, (1973). Welding steels without hydrogen cracking, Woodhead Publishing Ltd.
[9] W. D. Callister, Jr. (2007). Material Science and Engineering, An Introduction. John Wiley & Son. Inc.
[10] Kalpakjian, S., Manufacturing engineering and technology, 10th Edition. Prentice-hall, 2010.
[11] George, S.B., Henry, R.C, & John, A.V., (2002). Material handbook 15th Edition. Mild Steel, pp 172: Mc-Graw Hill.
[12] R.C. Hibbeler. (2008). Mechanics of materials 7th Edition. Mechanical properties of materials, pp 85: Prentice Hall.
[13] Jianguo Lin (Ed.), Daniel, B. (Ed.), & Maciej, P (Ed.). (2012). Microstructure evolution in metal forming processes: Woodhead Publishing.
[14] David, B., & Wayne, D.K. (1999). Microstructural characterization of materials. John Wiley and Sons Ltd.
[15] S.M. Adedayo and S.O. Momoh (2010). Effect of initial elevated metal temperature on mechanical properties of an arc welded mild steel plate. Indian Journal of Science and Technology, Vol. 3, No. 12, 0974-6846.
[16] Enda Keehan (2004). Effect of microstructure on mechanical properties of high strength steel weld metals. Department of Experimental Physics, Chalmers University of Technology, 0346-718X.
[17] Pang, W., Ahmed, N. & Dunne, D. (2011). Hardness and microstructural gradients in the heat affected zone of welded low-carbon quenched and tempered steels. Australasian Welding Journal, 56(2), 36-48.
[18] G.E. Linnert (1985). Welding metallurgy of carbon and alloy steels, Volume 1, American Welding Society.
[19] R. Blondeau, (2001). Metallurgy and Mechanics of Welding, John Wiley and Son Ltd.
[20] E. G. Signes (1972). A simplified method for calculating cooling rates in mild and low alloy weld metals.
[21] T. Kasuya, N. Yurioka, and M. Okumura (1995). Methods for predicting maximum hardness of heat-affected zone and selecting necessary preheat temperature for steel welding. Nippon Steel Journal, UDC621.791.011/.02
[22] Retrieved on (2014, Jan 8). Arc welding. Retrieved from www.energymanagertraining.com/Journal/02112007/ArcWelding.pdf
[23] R.C. Hibbeler. (2008). Mechanics of materials 7th Edition. Mechanical properties of materials, pp 85: Prentice Hall.
[24] Zakaria Boumerzoug, Chemseddine Derfouf and Thierry Baudin (2010). Effect of welding on microstructure and mechanical properties of industrial low carbon steel. Journal of Engineering, 2010, 2, 502-506.