MICROSTRUCTURE AND MECHANICAL PROPERTIES EVALUATIONS OF HEAT TREATED DISSIMILAR METAL JOINT WELDMENT BETWEEN API 5CT C90 AND ASTM A182 F22

By

MOHD HAFIZ BIN OTHMAN

FINAL PROJECT REPORT

Submitted to the Mechanical Engineering Programme
in Partial Fulfilment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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(Dr. Mokhtar Awang)

Project's Supervisor.

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(Mohd Hafiz bin Othman)

ABSTRACT

In this research, dissimilar metal welding of API 5CT C90 and ASTM A182 F22 is used to connect between the upset riser pipe and the riser connector of a marine riser. API 5CT C90 material is the material have high carbon content that lead to its high hardness and low weldability. Proper welding parameters need to be qualified so that the welding process will give desired mechanical properties, less costly and consume less time. Therefore, post-weld heat treatment (PWHT) is needed to reduce the hardness and increase the impact energy of the weldment as the intermixture zone at fusion line between the base metal and weld metal has potential of having high hardness due to residual stress in the intermixed microstructure after high temperature welding. The main objective of this research is to get the most suitable PWHT temperature that will give the desired hardness and impact energy values in accordance of NACE MR0175/ISO15156**.** All the testing and examinations were conducted on the fusion line area of API 5CT C90 as this area is the most crucial part of weldment. Specimens from the dissimilar metal joint have been prepared in 5 different PWHT temperatures. Then, the change in grain size, the hardness value and the impact energy of each PWHT temperature were examined and evaluated. It can be concluded that when PWHT temperature increase, hardness of the weldment decreases and impact energy increases while the grains size increases (enlarge). These findings confirms to the research done by Olabi et al. [25].

Keywords: Post-weld heat treatment (PWHT), Residual stress, Microstructure examination, Hardness Test, Charpy impact test, Dissimilar metal welding.

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1.0 INTRODUCTION

1.1 Project Background

Dissimilar metal joint welding between API 5CT C90 and ASTM A182 F22 is applied to connect between the riser upset pipe and the riser connector as shown in figure 3. A marine riser as shown in figure 1 and figure 2, is a system that provides a fluid conduit to and from the wellbore, that is, it extends the wellbore from the subsea Blow-out Preventer (BOP) to the drilling rig. It also supports auxiliary lines, such as high-pressure choke and kill lines, mud booster lines, and hydraulic conduits. Further, the marine riser system guides the drill stem and other tools from the drilling rig to the wellhead on the seabed. Finally, it provides a means of running and retrieving the BOP assembly on the seafloor **[2].**

Figure 1: A section of a marine riser

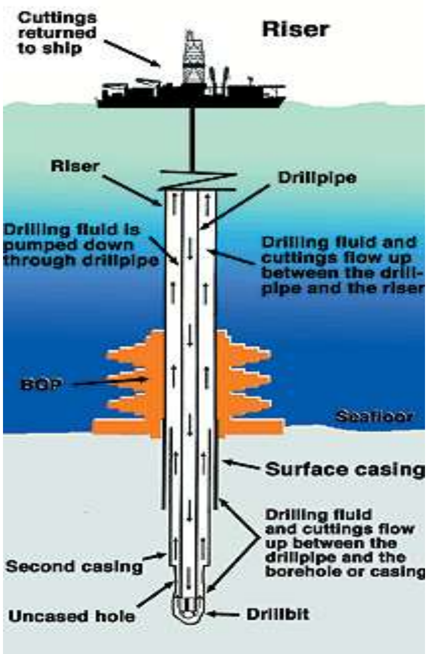


Figure 2: Application of a marine riser

Marine riser systems are critical equipment, therefore if a system fails, catastrophic losses can result. Consequently, the overall design of the system is of paramount importance. This includes the involvement of welding between the pipe body and the connector of a marine riser. A marine riser must be able to withstand a variety of forces **[2]**;

- Dynamic and axial loads while running and retrieving the riser system and BOP assembly
- Lateral forces from currents and vessel offset
- Cyclic forces from currents and vessel motion
- Axial loads created by the weight of the riser system itself, the weight of the drilling fluid inside the riser, and the additional weight of freestanding pipe within the riser
- Axial tension from the tensioning system at the surface

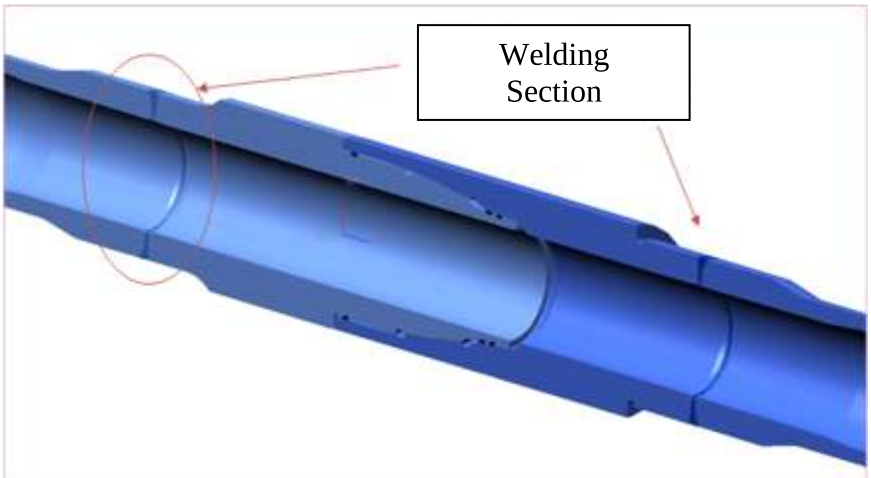


Figure 3: Welding section of a marine riser

API 5CT C90 is an ultra high strength material that belongs to medium carbon steel group with 0.35% carbon **[2]**. Riser upset pipe material that is used in this project is a modified C90 that have high strength pipe section up to 90ksi yield and also upset end to increase weld area. This property is suitable resisting wear inside the marine riser caused by the drilling pipe and tools going up and down. API 5CT C90 also has balanced ductility and strength to withstand all the forces mentioned before **[3]**. Table 1 and 2 shows the material composition of API 5CT C90 and ASTM A182 F22.

Table 1: Material composition of original API 5CT C90

Group	Grade	Type	C		Mn		Mo		Cr		Ni	Cu	P	S	Si
			min.	max.	min.	max.	min.	max.	min.	max.	max.	max.	max.	max.	max.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	C90	1	—	0.35	—	1.20	0.25 [b]	0.85	—	1.50	0.99	—	0.020	0.010	—

Table 2: Material composition of ASTM 182 F22

ASTM A182, Grade F22, Class 3 – 2 1/4% Chromium 1% Molybdenum Where elevated temperature, surface stability, and greater strength than F11 are needed.		
C 0.15 Max. Mn 0.30 - 0.60 P .040 Max. S 0.015 - 0.035 Si 0.50 Max Cr 2.00 - 2.50 Mo 0.87 - 1.13	TS Min. psi(MPa) YS Min. psi(MPa) EL (2" Min.) RA Min. Hardness, Bhn	75,000(515) 40,000(310) 20% 30% 156-207

The weldability of both modified C90 and F22 steel are as known weak. The modified C90 steel has a low weldability which is linked with the high carbon content of 0.28%. With 1.05% Chromium and 0.82% Molybdenum, this gives a carbon equivalent (CE IIW) value of 0.726. this hardenability is sufficient to cause martensite formation; a form of steel that possesses a super-saturated carbon content in a deformed body-centered cubic (BCC) crystalline structure, properly termed body-centered tetragonal (BCT), with much internal stress, during welding with resulting high hardness (500-550 KG/mm²). International Institute of Welding, IIW recommend a maximum carbon content of 0.15% and a carbon equivalent of Max. 0.4 for weldable steels.

Although the F22 steel has a higher carbon equivalent of 0.975, its carbon content is only half of the content in C90 steel, which will give much lower hardness and higher toughness and the welding wire that is used has a low carbon content (0.09%) but are also alloyed with Cr and Mo with carbon equivalent result of 0.932 **[4][5]**. API 5CT C90 material which have high carbon content also might pull the Chromium content from the F22 and lead to the precipitation of Chromium Carbide that result in relatively poor corrosion resistance along the grain boundary areas of the depleted region.

Post-weld Heat Treatment (PWHT) is needed after the welding process of API 5CT C90 material. This is to relieve the residual stress caused by the intermixture of microstructures between API 5CT C90 and the weld metal **[6]** and also to re-dissolve the carbides. There are requirements according to NACE MR0175/ISO15156 – Material Use for H2S containing environments, contain guidelines on suitable material hardness and fracture toughness which are, hardness values below 275Hv10 at cap, below 250Hv10 at root and 30J single value, 42J average value at -20 °C for charpy impact test [**1]**. FMC Wellhead Equipments have tried qualifying a welding procedure of API 5CT C90 to ASTM A182 F22 using Gas Tungsten Arc Welding (GTAW) welding process with bevel angle of 5° on API 5CT C90 and 5° on ASTM 182 F22 but failed. These bevel angles of 5° on both sides will reduce welding time and filler metal needed to join them thus greatly reducing the overall cost of the welding process of the riser.

Bevel angle of 5° on both side of the riser upset pipe and the riser connector will greatly reduce the overall cost of welding the pipes. By using bevel small bevel angle such as 5° on both side of the pipe, the amount of weld metal needed to fill the gap during welding will be less. This means lower cost spent for the weld metal. Plus, the duration of the welding process will also be decreased. Meaning, the power supply for the welding machine and the labor hours for welding one joint will be decreased, decreasing the overall cost. A welding procedure of this welding process for joining upset riser pipe and riser connector have been qualified y FMC Wellhead Equipments Sdn. Bhd. but with larger bevel angle that is 35° on one side and 5° on the other side. This cost the company about 8 hours to complete one joint. Even so, lower bevel caused the weldment having lower impact energy as the contribution of the weld metal to the weldment during charpy impact test is low. Higher bevel angle have more weld metal at the point of impact during charpy impact test, thus leading to higher impact energy. A solution is needed to improve the weldment mechanical properties of 5° bevel angle on both side.

The welded pipe joint of API 5CT C90 to ASTM A182 F22, was prepared by FMC Wellhead Equipments Sdn. Bhd. that is situated in Gelang Patah, Johor Darul Takzim, Malaysia. The pipes length is about 4 inch each, the outside diameter is 200mm each and the pipe thickness is 32mm each as shown in figure 5. The pipes was welded by and AMI M52 Welding Head as shown in figure 6 and 7, using ER90S-G BØHLER CM 2-IG filler metal. The joint design is U-groove, with bevel angle of 5° on API 5CT C90 and 5° on ASTM 182 F22. The welding wire that is used has a low carbon content (0.09%) but are also alloyed with Cr and Mo with carbon equivalent result of 0.932 .The initial cleaning of the joint before welding are grinding the surface, brushing using stainless steel wire brush and chemically cleaned as needed. Figure 4 shows the picture of the pipe.

Figure 4: actual welded pipe from FMC Wellhead Equipment Sdn. Bhd.

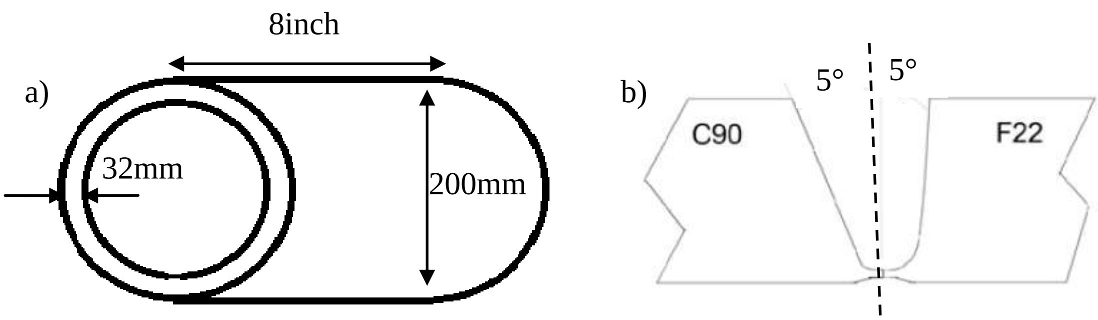


Figure 5: Schematic diagrams of a) dimensions of each pipe and b) joint design

Figure 6: AMI M52 Welding Head

Figure 7: during welding of riser

1.2 Problem Statement

API 5CT C90 is an ultra high strength material and characterized as having low weldability because of having high carbon equivalent. Moreover, the intermixture zone at fusion line between the base metal and weld metal has potential of having high hardness due to residual stress in the intermixed microstructure after high temperature welding. This will also leads to low impact toughness of the weldment. Of course, this is something that we must overcome as welding is a major joining method in industrial applications and we don't want any of these especially in oil and gas industry **[7]**.

Thus, PWHT is required to be performed on the weldment to return the grain sizes of the weldment back to the original sizes and to relieve the residual stress and lower the hardness after welding. By lowering the hardness, the impact toughness of the weldment will also be increased. The challenge is to determine the suitable PWHT holding temperature to lower the high hardness at heat affected zone (HAZ) and increase fracture toughness at fusion line of weldment. The cost for performing a PWHT is so expensive and this project will be a cost reducing information for engineers to know the effect of PWHT temperatures and use the right temperature the first time to acquire the desired weld properties.

1.3 Objectives and Scope of Study

Objective

The main objective is to determine the effect of varying the PWHT temperatures at the fusion line of dissimilar metal joint weldment between API 5CT C90 and ASTM A182 and to determine suitable PWHT temperatures giving hardness values and impact energies that complies with NACE MR0175/ISO15156 for riser application. To achieve this objective, the goals are:

a) To observe and evaluate the changes of microstructure between the heat treated weldments and the original weldment using Optical Microscope.
b) To obtain the hardness value (Hv10) of the heat treated weldments and the original weldment by performing hardness test.
c) To obtain the impact energy of the heat treated weldments and the original weldment by performing charpy impact test.

Scope of Study

The project of determining the effect of varying the PWHT temperatures at the fusion line of dissimilar metal joint weldment between API 5CT C90 and ASTM A182 will be focusing on three areas that are microstructure characteristics, hardness value and toughness value. PWHT in the context described here refers to the process of reheating a weld to below the lower transformation temperature at a controlled rate, holding for a specific time and cooling at a controlled rate. All the evaluation will be made on the fusion line area of API 5CT C90 side. The welded pipe joint will first be cut into six sections for six PWHT temperatures and further be cut for microstructure evaluation and mechanical testing.

To examine the microstructure characteristics of the weldments at different conditions (non-heat treated and different PWHT temperatures), Scanning Electron Microscope will be used to observe and evaluate the microstructures. In addition, Optical Microscope will also be used to perform micro-examination, which is to observe and evaluate the grain size of the weldments. Then, hardness test will be performed on all the different conditions of weldments. The hardness test of Hv 10 macro-hardness scale will be performed as close as possible to the fusion line of API

5CT C90 side. The area as close as possible to the fusion line will be divided into three; top, middle and below. Next, charpy impact test will be performed -20°C (below service temperature) on all different conditions of weldments to obtain the fracture toughness value. The temperature reducing substance is liquid nitrogen **[8][9][10][11]**.

2.0 LITERATURE REVIEW

Several researches have been done to determine the effect of Post-Weld Heat Treatment (PWHT) on weldment mechanical properties and also evaluation of the heat treated microstructures. Some of them were Yajiang et al **[12]**, 2000, Microstructure in the Weld Metal of Austenitic-Pearlitic Dissimilar Steels and Diffusion of Element, Departments of Materials Engineering, Shandong University, Jinan 250061, China, Feng et al. **[13]**, determining the effects of post-weld heat treatment on microstructure and mechanical properties of friction stir welded joints of 2219-O aluminium alloy and also Ravindra and Dwarakadasa **[14]**, determining the effect of post-weld heat treatment on mechanical properties of gas-tungsten arc welds of Al-Li 8090. The information from these researchers are very useful in proceeding in the project of microstructure and strength evaluation at fusion line of heat treated dissimilar metal joint weldment between API 5CT C90 and ASTM A182 F22.

Welding of Dissimilar Metals

A successful weld between dissimilar metals is one that is as strong as the weaker of the two metals being joined, i.e., possessing sufficient tensile strength and ductility so that the joint will not fail in the weld. Such joints can be accomplished in a variety of different metals and by a number of the welding processes. The problem of making welds between dissimilar metals relates to the transition zone between the metals and the intermetallic compounds formed in this transition zone. According to P. Seliger1 and A. Thomas **[15]**, the observed carbide depletion in the P22 weld metal adjacent to the fusion line of P91-P22 dissimilar welds and its effect on the weld strength reduction have to be taken into account. For the fusion type welding processes it is important to investigate the phase diagram of the two metals involved. If there is mutual solubility of the two metals the dissimilar joints can be made successfully. If there is little or no solubility between the two metals to be joined the weld joint will not be successful **[16]**. The intermetallic compounds that are formed, between the dissimilar metals, must be investigated to determine their crack sensitivity, ductility, susceptibility to corrosion, etc. Yajiang et al. **[12]** states that in welding dissimilar steels, it is inevitable for the fusion zone to produce a transition zone which the chemical composition lies between that of the base metal and the weld filler metal and the fusion zone is divided into base metal fusion zone and weld metal fusion zone, whose interfaces can be clearly displayed by etchant. Further by Jounghoon Lee et al. **[17]**, the distinctive region of dissimilar metal welds, such as SA508 Gr.3 base (a), buttering (b), inconel 82/182 welding region (b, c, e), and TP316 base (d) are clearly visible after proper etching application. Microstructure of the intermetallic compound is extremely important. In some cases, it is necessary to use a third metal that is soluble with each metal in order to produce a successful joint. Another factor involved in predicting a successful service life for dissimilar metals joint relates to the coefficient of thermal expansion of both materials. If these are widely different, there will be internal stresses set up in the intermetallic zone during any temperature change of the weldment. A. Celik et al **[18]** states that large thermal stresses can occur in dissimilar joints due to the difference in thermal expansion during temperature fluctuations. If the intermetallic zone is extremely brittle service failure may soon occur. The difference in melting temperatures of the two metals that are to be joined must also be considered. This is of primary interest when a welding process utilizing heat is involved since one metal will be molten long before the other when subjected to the same heat source. When metals of different melting temperatures and thermal expansion rates are to be joined the welding process with a high heat input that will make the weld quickly has an advantage. The difference of the metals on the electrochemical scale is an indication of their susceptibility to corrosion at the intermetallic zone. If they are far apart on the scale, corrosion can be a serious problem **[16]**.

In certain situations, the only way to make a successful joint is to use a transition material between the two dissimilar metals. An example of this is the attempt to weld copper to steel. The two metals are not mutually soluble, but nickel is soluble with both of them. Therefore, by using nickel as an intermediary metal the joint can be made. Two methods are used either by using a piece of nickel, or deposit several layers of nickel alloy on the steel, i.e., buttering or surfacing the steel with a nickel weld metal deposit **[19]**. The nickel or nickel deposit can be welded to the copper alloy using a nickel filler metal. Such a joint will provide satisfactory properties and will be successful. Another method of joining dissimilar metals is the use of a composite insert between the two metals at the weld joint.

The composite insert consists of a transition joint between dissimilar metals made by a welding process that does not involve heating. By selecting the proper materials for the composite insert like metals can be welded to like metals in making the fusion weld joint **[16]**.

The fusion zone is the result of melting which fuses the base metal and filler metal to produce a zone with a composition that is most often different from that of the base metal. This compositional difference produces a galvanic couple, which can influence the corrosion process in the vicinity of the weld. This dissimilar-metal couple can produce macroscopic galvanic corrosion. The fusion zone itself offers a microscopic galvanic effect due to microstructural segregation resulting from solidification. The fusion zone also has a thin region adjacent to the fusion line, known as the unmixed (chilled) region, where the base metal is melted and then quickly solidified to produce a composition similar to the base metal. For example, when type 304 stainless steel is welded using a filler metal with high chromium-nickel content, steep concentration gradients of chromium and nickel are found in the fusion zone, whereas the unmixed zone has a composition similar to the base metal as shown in figure 8 **[20]**.

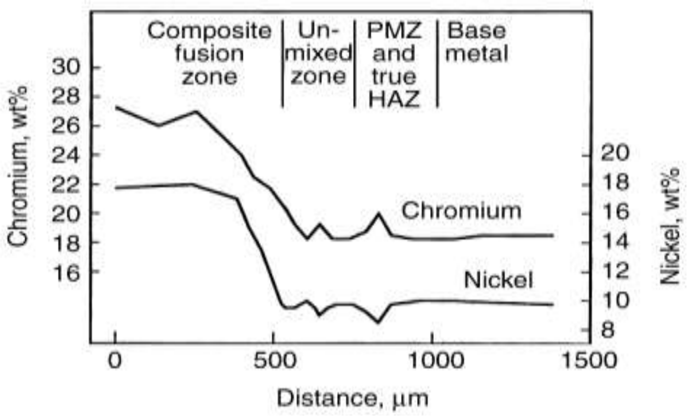


Figure 8: Concentration profile of chromium and nickel across the weld fusion boundary region of type 304 stainless steel

In the fusion zone of dissimilar steels, diffusion of some alloying elements, especially carbon element, results in the formation of a diffusion layer in the fusion zone. Under the condition of long time work at high temperature, a layer of decarburized ferrite is easily formed in the pearlitic base metal near the fusion zone; and a carbon enriched layer which has high hardness is formed in the fusion zone near the austenitic weld metal.

Welded joint specimens of dissimilar metals treated at 600°C for 100 hours were analyzed by optical microscope and the experimental results can be observed in figure 8. Because of the formation of the carburization layer and carbon enriched layer nearby fusion zone, some changes in performance in the welding zone occur **[12]**.

Welding dissimilar metals often introduces new difficulties to GTAW welding, because most materials do not easily fuse to form a strong bond. However, welds of dissimilar materials have numerous applications in manufacturing, repair work, and the prevention of corrosion and oxidation. In some joints, a compatible filler metal is chosen to help form the bond, and this filler metal can be the same as one of the base materials (for example, using a stainless steel filler metal with stainless steel and carbon steel as base materials), or a different metal (such as the use of a nickel filler metal for joining steel and cast iron). Very different materials may be coated or "buttered" with a material compatible with a particular filler metal, and then welded. In addition, GTAW can be used in cladding or overlaying dissimilar materials.

Minnick et al. **[21]** states that when welding dissimilar metals, the joint must have an accurate fit, with proper gap dimensions and bevel angles. Care should be taken to avoid melting excessive base material. Pulsed current is particularly useful for these applications, as it helps limit the heat input. The filler metal should be added quickly, and a large weld pool should be avoided to prevent dilution of the base materials

Heat Treatment of Steel

Because of the solid-state structural changes which take place in suitable alloys, steels are among the relatively few engineering alloys which can be usefully heat-treated in order to vary their mechanical properties. Kumar et al. **[22]** states that the functions of a PWHT are to reduce the hardness and increase the toughness, and to decrease residual stresses associated with welding. Feng et al**.** **[13]** did an the experiment on 2219-O aluminium alloy, with the O-condition stating that the post-weld heat treatment can restore the mechanical properties of the joints successfully. This statement refers, of course, to heat-treatments other than simple stress-relief annealing processes. Heat-treatments can be applied to steel not only to harden it but also to improve its strength, toughness or ductility. In all of these processes the steel is heated fairly slowly to some predetermined temperature, and then cooled, and it is the rate of cooling which determines the resultant structure of the steel and, hence, the mechanical properties associated with it.

According to Ravindra and Dwarakadasa **[14]** the joint efficiency of the welds before heat treatment is very low and PWHT comprising solutionizing and ageing increases the joint strength. According to Higgins et al. **[23],** the final structure will be independent of the rate of heating, provided this has been slow enough for the steel to reach structural equilibrium at its maximum temperature. The subsequent rate of cooling, which determines the nature of the final structure, may vary between a drastic water-quench and slow cooling in the furnace.

Higgins et al. **[23]** further states that hydrogen ions dissolve interstitially in solid steel and are thus able to migrate within the metal, resulting in embrittlement as shown by a loss in ductility. This hydrogen may be dissolved during the steel-making process but is more likely to be introduced from moisture in the flux coating of electrodes during welding, or released at the surface during an electroplating or acid-pickling operation. Hydrogen ions released during surface corrosion may also be absorbed. The presence of hydrogen in steels can result in so-called 'delayed fracture', that is fracture under a static load during the passage of time. The effect is very dependent on the strain rate so that whilst ductility is considerably impaired during slow tensile tests, charpy impact values are little affected. Much of this dissolved hydrogen can be dispersed during a low-temperature annealing process in a hydrogen-free atmosphere. The term 'annealing' describes a number of different thermal treatments which are applied to metals and alloys. Prolonged annealing may in fact cause deterioration in properties, since although ductility may increase further, there will be a loss in strength.

Whilst the tensile strength is not greatly affected by heat treatment, both toughness and ductility are improved as shown by the following values for cast carbon steel in table 3.

Table 3: Higgins et al. **[23].** Tensile strength values for specimens with and

Condition	Tensile strength	Percentage elongation	Bend test
Specimen 'as cast'.	470 N/mm^2	18	40°
Specimen annealed.	476 N/mm^2	34	180° (without fracture)

Kozuh et al. **[24]** stated that hardness values are lower at base metal after PWHT but with no fixed trend as shown in table 4. Feng et al. **[13]** stated that tensile strength of heat treated joints increases with increasing PWHT temperature. Results of hardness test were not stable. Kozuh et al. **[24]** and Ravindra **[14]** stated that there are ductile and cleavage fractures at fracture locations of Charpy impact test specimens.

Table 4: Kozuh et al. **[14].**Hardness values at AISI 316L and weld metal

	Hardness, HV_{30}				
	Before annealing	Temperature of annealing [°C]			
		600	700	800	900
Base metal	167.3	164.3	155.6	152.3	153.3
Weld metal	224.2	240.9	233.7	241.5	232.2

Olabi et al. **[25]** in his two researches involving MIG welding of AISI 1020 found out that residual stress and hardness value decreases with increasing PWHT temperature but impact energy increase with increasing PHWT temperature as shown in figure 9, figure 10 and table 5.

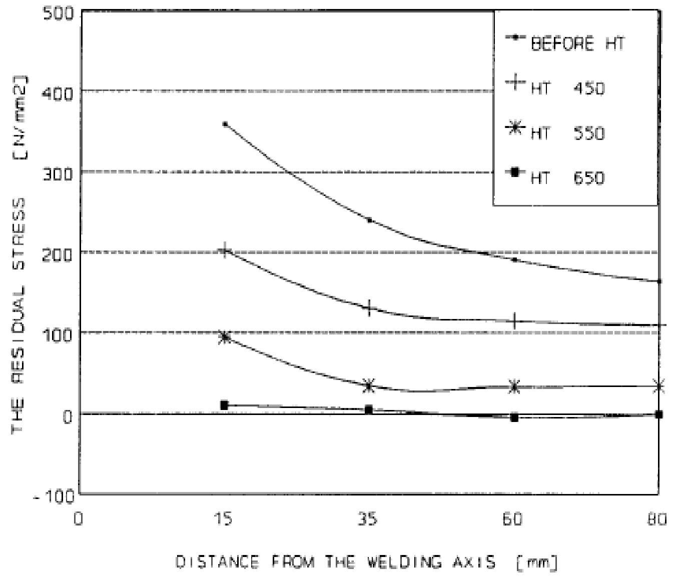


Figure 9: Olabi et al. **[25].** Residual stress of different PWHT temperatures

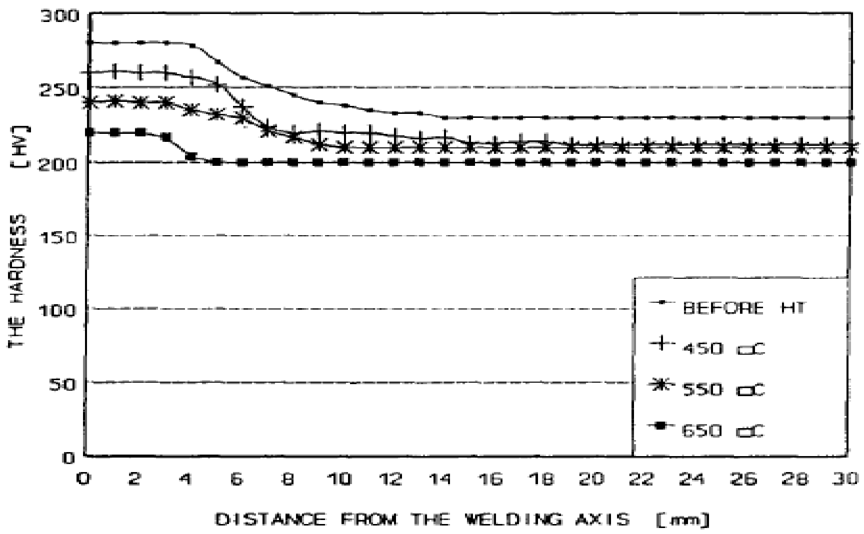


Figure 10: Olabi et al. **[25].** Hardness values of different PWHT temperatures for AISI 1020

Table 5: Olabi et al. **[25].** Impact energy of different PWHT temperatures for AISI 1020

Heat treatment schemes	Description	Tensile strength [N/mm²]	Impact energy [J]
Before PWHT		420	54
PWHT 1	S.T. = 450°C	432	70
PWHT 2	S.T. = 550°C	445	73
PWHT 3	S.T. = 650°C	458	80

Accurate PWHT procedure will lead the research to desired and expected results. In other words, the range of PWHT temperatures selected for the research must be appropriate to so that desired changes of microstructures and mechanical properties can be observed. Too low PWHT temperatures maybe will not affect the material in term of microstructure characteristics and too high PWHT temperature may caused the material to deform or having very low strength. Khaleel Ahmed **[26]** states in his research that the temperatures recommended for stress relieving low carbon steels are 595-675°C. This means stress relieving temperature for medium carbon steel is higher than range for low carbon steel. Scott **[27]** in his research states that the properties of quenched and tempered alloy steels, for instance, can be adversely affected by PWHT if the temperature exceeds the tempering temperature of the base metal. Such as, Stress relief cracking can occur.

Mechanical Test and Microstructure Evaluation

Proper mechanical tests should be selected in order to evaluate the desired mechanical properties. These properties usually are the properties that lacks. Most researchers aimed to study the effects of PWHT on microstructure and mechanical properties and their problem statements whether about the material weakness or limited information of material weldability so they experiment on the effect of PWHT and research on their mechanical properties. So, they performed most of the mechanical tests. Kozuh et al. **[24]** performed tensile test, hardness test and charpy impact test as the aim is to find out how mechanical properties and impact energy are affected by sigma phase (material weakness). For API 5CT C90, problems associated with excessive weld heat affected zone (HAZ) hardness and brittle course grain HAZ are detected after welding. So, hardness test and charpy impact test are sufficient **[26].**

For microstructure examination, Kozuh et al. **[24]** and Ravindra **[14]** presented their results almost the same way. They show the pictures from optical microscope and SEM. Kozuh et al. **[24]** discussed about grain size, austenite and ferrite phase after observation by optical microscope as shown in figure 11 and includes elements Intensity vs. Energy graph from SEM as shown in figure 13. Kozuh et al. **[24]** and Ravindra **[14]** also include SEM evaluation at fracture cross section after charpy impact test and transverse tensile test as shown in figure 12.

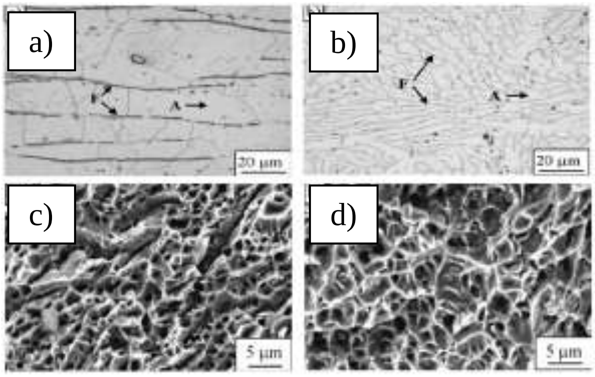


Figure 11: Kozuh et al**. [24].** Optical micrograph at (a) AISI 316L stainless steel (b) weld metal. SEM microfractograph of AISI 316L weld metal after (c) tensile test (d) Charpy test

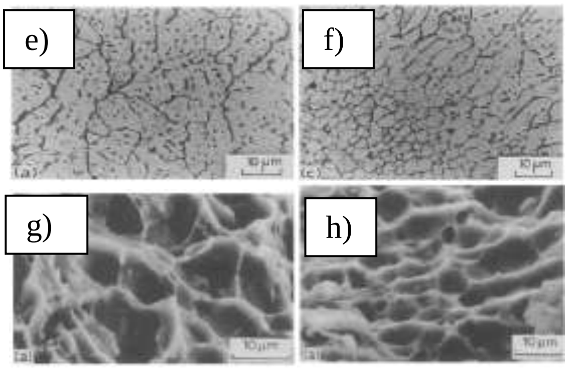
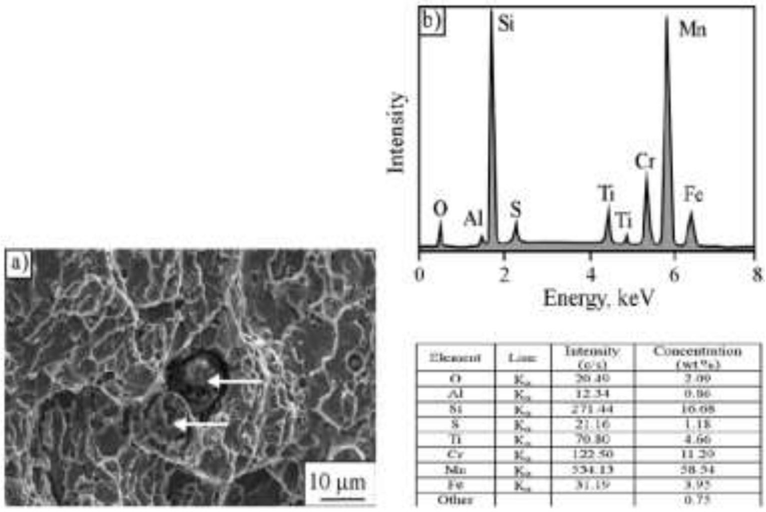


Figure 12: Ravindra **[12]**. Optical micrograph at (e) weld metal (f) fusion line. SEM microfractograph of tensile fracture show dimple features (g) as-welded (h) after PWHT



Element	Line	Intensity (c/s)	Concentration (wt %)
O	K_α	20.40	2.00
Al	K_α	12.34	0.86
Si	K_α	271.44	16.08
S	K_α	21.16	1.18
Ti	K_α	70.80	4.66
Cr	K_α	122.50	11.20
Mn	K_α	534.13	58.54
Fe	K_α	31.19	3.95
Other			0.75

Figure 13: Kozuh et al. **[12]**. SEM microfractograph of AISI 316L steel weld metal after Charpy impact testing (a) with the corresponding EDX particle spectrum (b). Specimens annealed at 900 °C

3.0 METHODOLOGY

3.1 Process Flow*

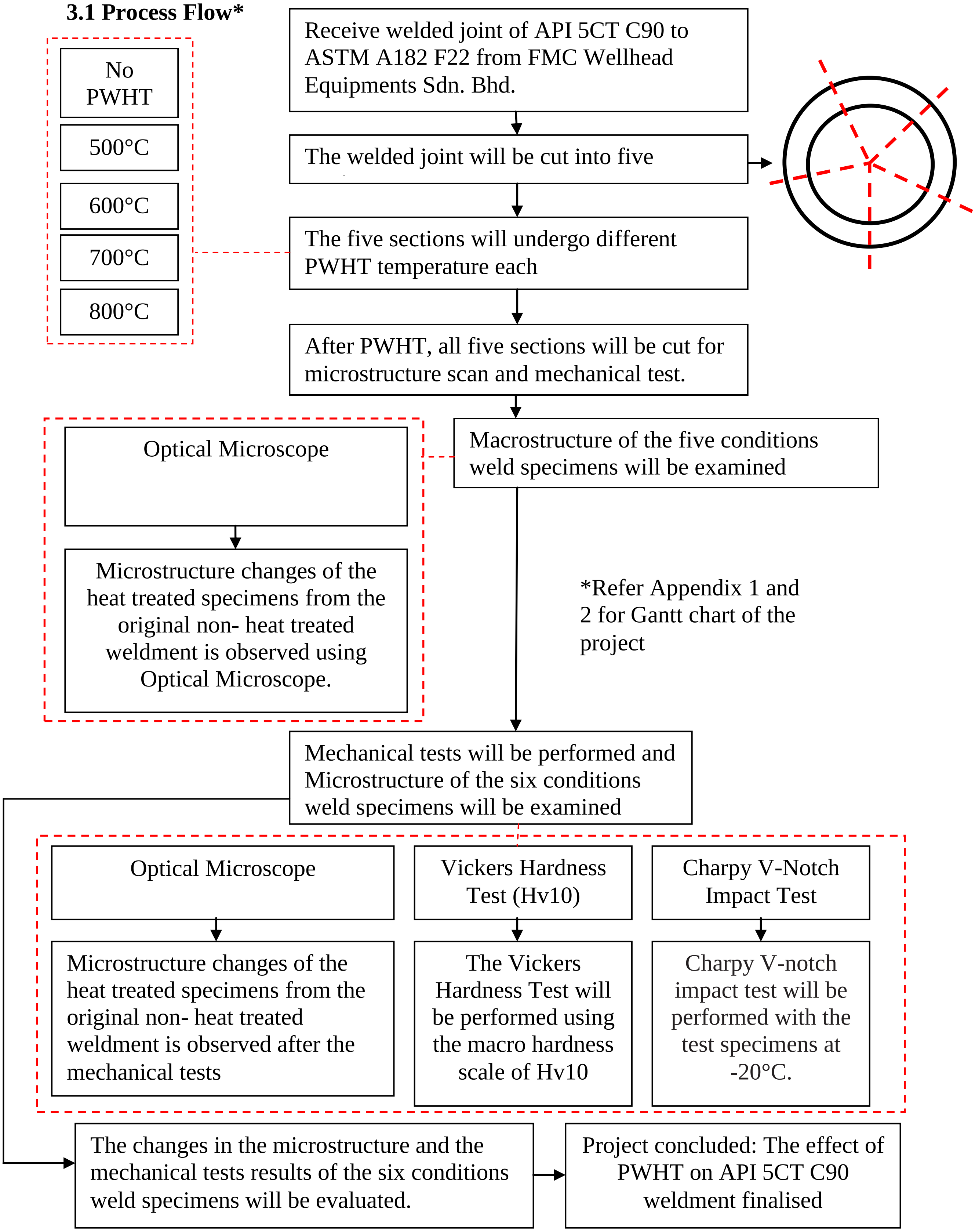


Figure 14: Project Flow Chart

3.2 Specimens Preparation

Post Weld Heat Treatment

The welded pipe received from FMC Wellhead Equipments Sdn. Bhd. is cut down into five same sized pieces before heat treated. These five specimens are for four different PWHT temperatures and one specimen without PWHT as base reference. Measurement and marking are done by protractor and permanent marker. The cutting process is done by a linear hack band saw. Below are some pictures during the cutting process in figure 15, 16 and 17:

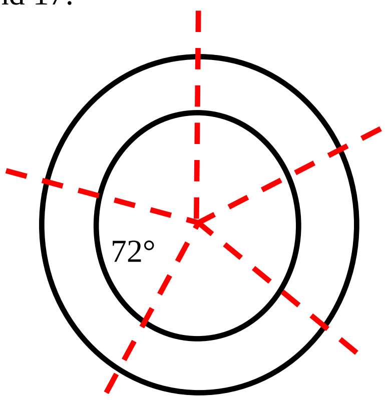


Figure 15: The pipe is divided into five pieces, about 72° each

Figure 16: Cutting the pipe into 5 pieces using a linear hack band saw

Figure 17: Specimens for PWHT

Hardness Test

After PWHT, one section from each piece is cut using a linear hack band saw. The pieces are then milled and grinded to a flat and smooth surface on both sides to a thickness of 10 to 15mm.

Specimens for hardness test will be cut to obtain flat and parallel surfaces as shown in figure 19, figure 20 and figure 21. This will make the force applied during hardness test will be distributed uniformly and the size of the indentation will be accurate. This will result in accurate hardness reading. The size of the specimens is as figure 18 below:

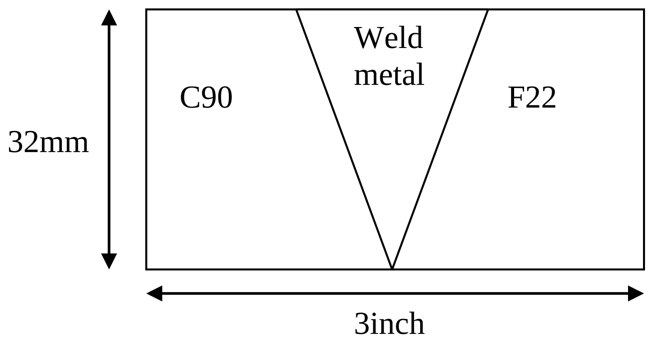


Figure 18: Size of specimen for hardness test

The specimens will be macro-etched to differentiate the weld metal, fusion line and heat-affected zone to determine the points of hardness test and the location for microstructure examination. Before macro-etching, the surface of the specimens must be very smooth. This type of surface will be obtained by grinding as shown in figure 22. The grinding technique is by using a rougher grit grinding disc at first and further uses grinding discs of decreasing roughness until the desired smooth surface finish is obtained. After that, macro-etching will be done where etchant is applied on the mirror finished surface as shown in figure 23 and 24. Etchant that will be used is nitric acid diluted in water and the ratio of nitric acid to water is 1:6 **[29]**.

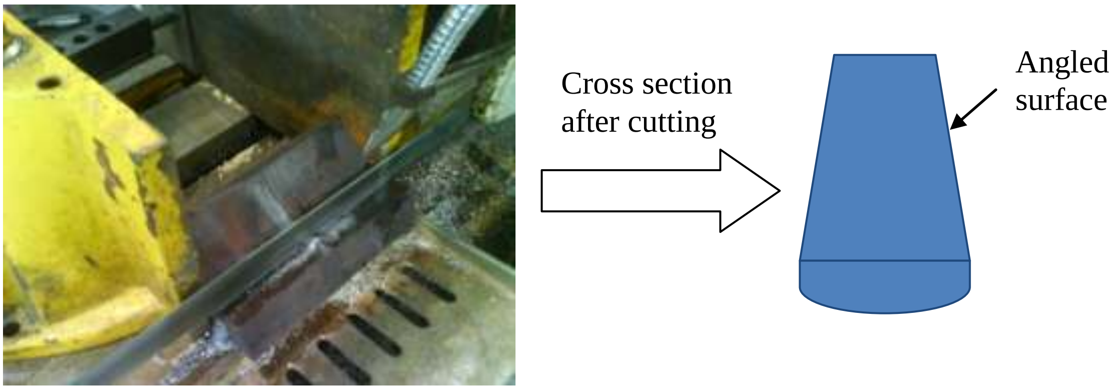


Figure 19: Cutting a section from the heat treated specimen and cross section after cutting

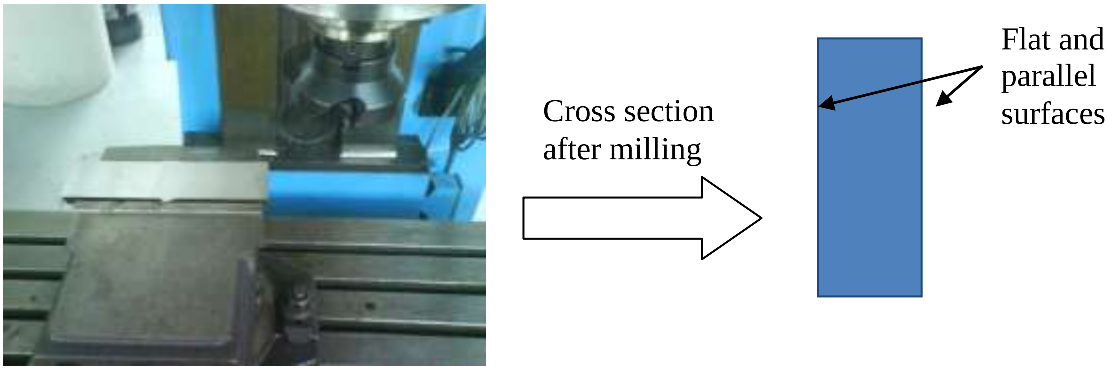


Figure 20: Milling to obtain parallel surface

Figure 21: Specimens for hardness test after cutting with linear hack saw machine (top specimen)

Figure 22: Grinding machine to obtain a smooth and mirror finished surface

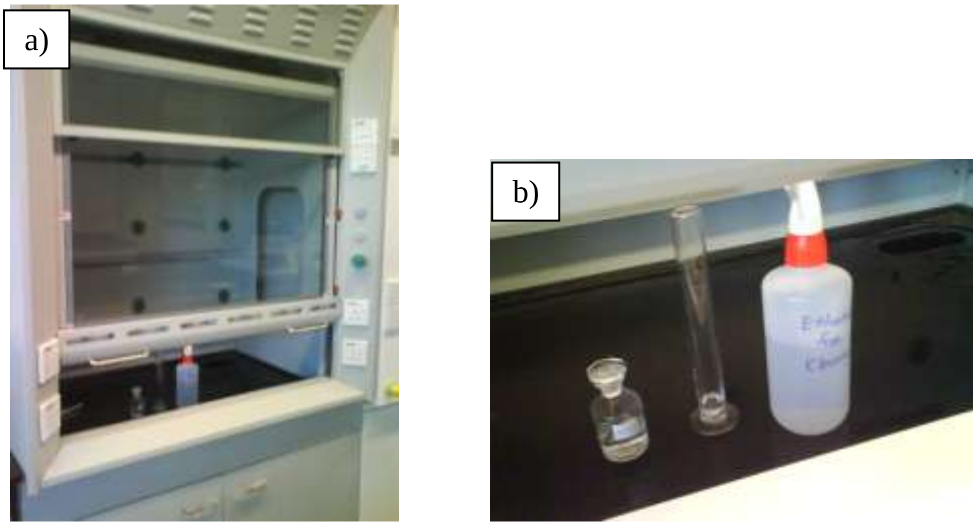


Figure 23: a) Macro-etching lab and b) etchant (diluted nitric acid)

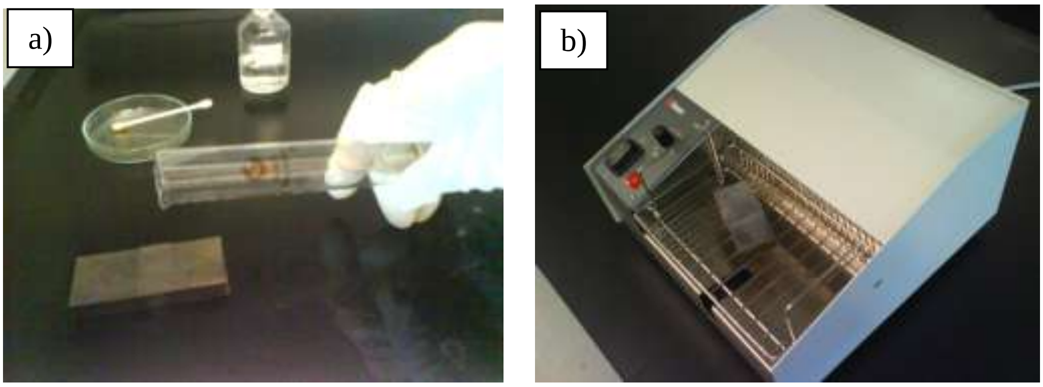


Figure 24: a) Applying etchant to specimen b) drying the specimen after etching

<u>Charpy Impact Test Microstructure Examination</u>

Microstructure examination will be performed on the charpy impact test specimens before they are tested as grinding and polishing equipments available only allows small sized specimens to be much easier prepared and time saving. So, microstructure examination and charpy impact test are using the same specimens. One section of weldment are cut from each of the 5 different PWHT conditions and then milled and grinded to a flat and smooth surface on both sides and the thickness is 10mm. The surface is then macro-etched to differentiate the weld metal, fusion line and heat-affected zone using nitric acid diluted in water and the ratio of nitric acid to water is 1:6 **[29]**. Then, the cutting section for the charpy impact test specimens is marked on the flat surface of the 5 pieces as shown in figure 25. The size of the marking is the same as the size for charpy impact test specimen that is 55m x 10mm x10mm as shown in figure 26.

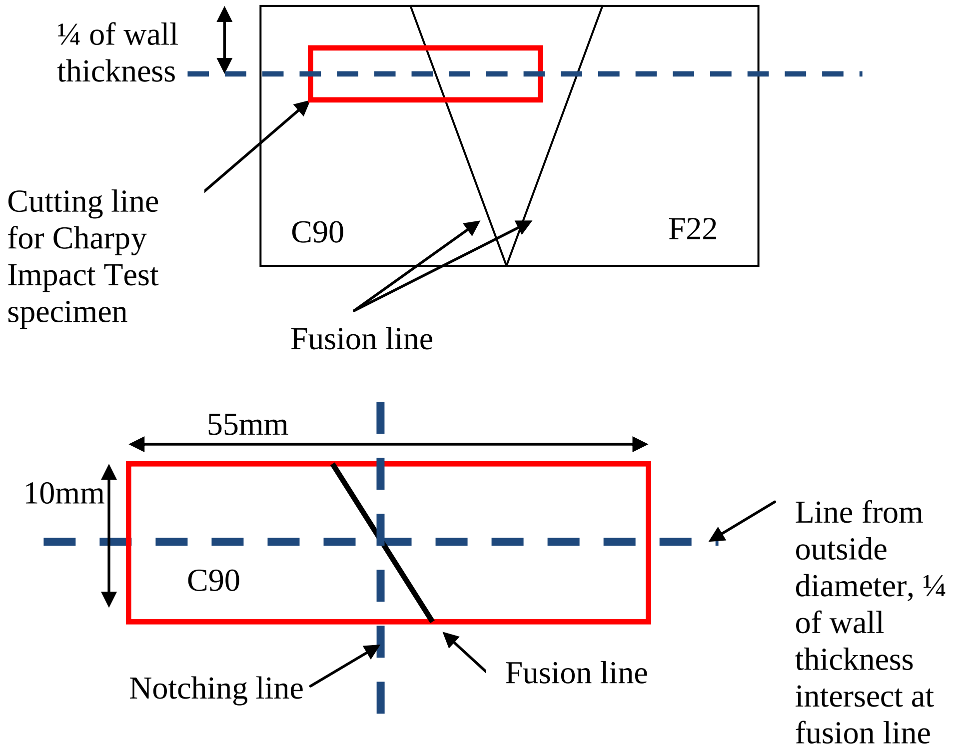


Figure 25: Charpy Impact Test location

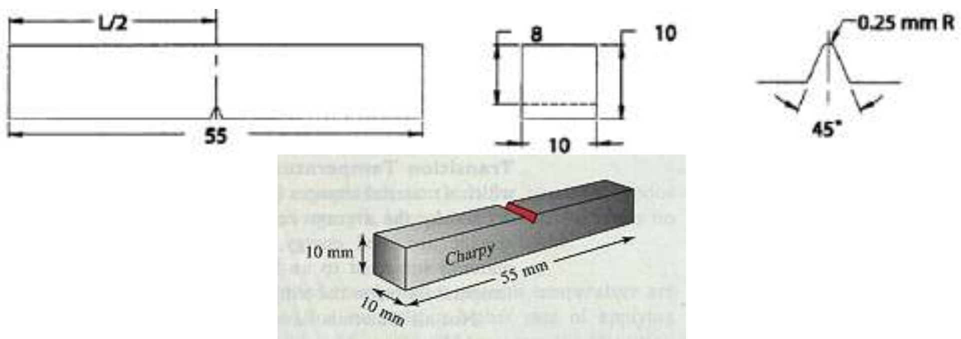


Figure 26: Charpy Impact Test specimen dimension

After marking the cutting location on the flat surface of weldment **(Figure 24)**, cutting process will be done. This can be done by EDM Wire cut machine or by using conventional method. By using conventional method, the weldment is cut 2mm outside of the marked cutting location for charpy impact test specimen using a linear hack band saw and then milled and grinded to obtain a smooth surface until the desired size at marked cutting line as shown in figure 27.

By using EDM Wire cut machine, the specimen design (using AUTOCAD 2004) is transferred into the machine and the EDM Wire cut machine will cut the specimen according to the design. Then, a notch will be made at the marked line for notching as shown in figure 25 by using an EDM cutting machine. The size of the notch is 2mm deep and an angle of 45° as shown in figure 26.

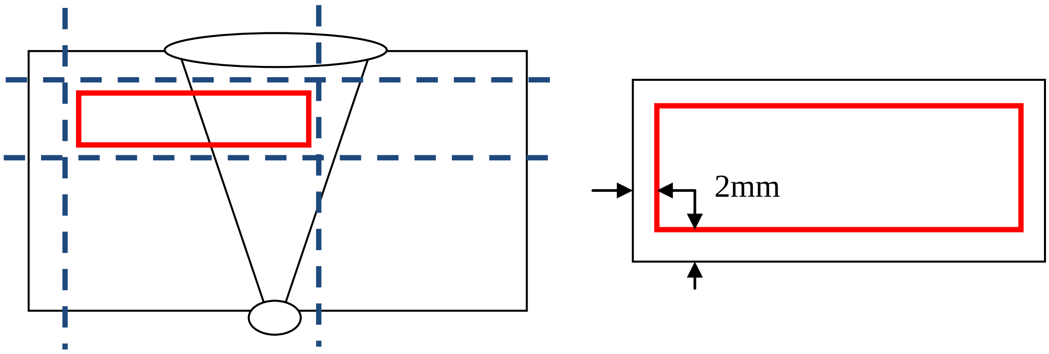


Figure 27: a) cutting line of 2mm outside marked line of charpy impact test specimen size.
b) Size of specimen after cutting 2mm outside marked line for charpy impact test specimen

Before performing the Charpy V-notch impact test, the charpy specimens is grinded and polished until a mirror finished surface is obtained for microstructure examination using optical micrograph. The microstructure examination will be done on the fusion line of C90 at capping area, middle section and root of the weldment. Below in figure 28 are the specimens for charpy impact test.

a) No PWHT

b) 500°C

c) 600°C

d) 700°C

e) 800°C

Figure 28: Charpy Impact Test specimens a) No PWHT b) 500°C c) 600°C d) 700°C e) 800°C

3.3 Post-Weld Heat Treatment

The welded pipe that was cut into five pieces will be sent for PWHT. Each piece as shown in figure 30 will undergo different PWHT temperatures where one piece will not undergo PWHT. The temperatures are 500°C, 600°C, 700°C and 800°C. The heat increment and decrement (heating and cooling) is fixed at 150°C/hour. Before a specimen is being put into the PWHT furnace, all the parameters are being set on the digital control panel of the furnace as shown in figure 29, such as heating rate, cooling rate, holding temperature and holding time.

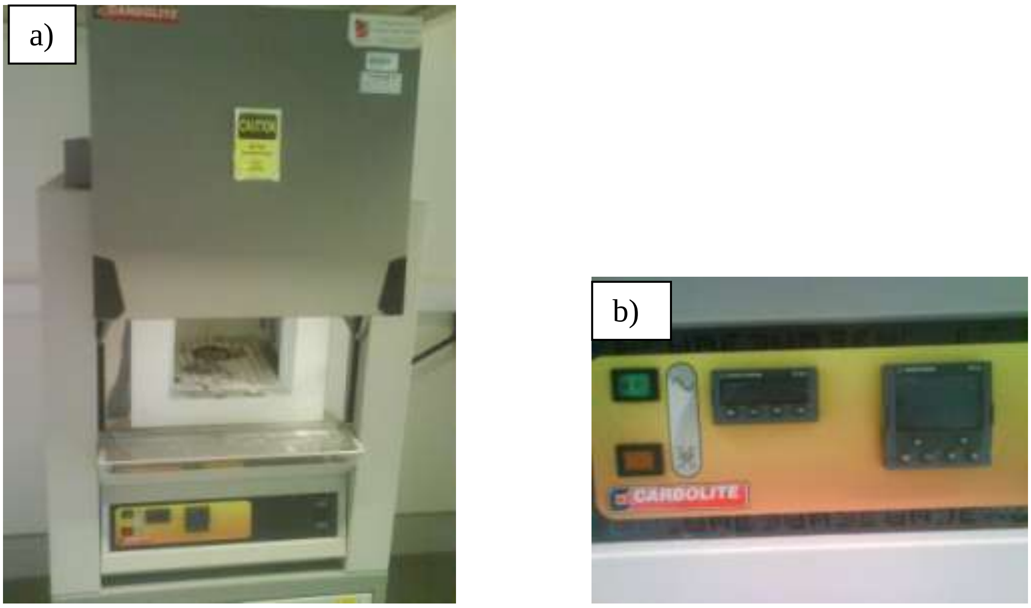


Figure 29: a) Carbollite PWHT furnace b) Control panel of the Carbollite PWHT furnace

Figure 30: PWHT specimens

3.4 Microstructure Examination

As discussed before, the specimen for microstructure examination will be done on the charpy impact test specimens that was prepared to have a mirror finished surface and being etched to reveal the fusion line and heat affected zone as shown in figure 33. This microstructure examination will be done using an optical micrograph where the grains size will be observed as shown in figure 32. Each of the non-heat treated, 500°C, 600°C, 700°C and 800°C heat treated specimens will be examined. The grains in the HAZ as close as possible to the fusion line will be examined and compared between each heat treated and non-heat treated specimens as shown in figure 31 below. The picture of how the grains look will be shown on the computer's monitor attached to the optical micrograph and will be recorded and evaluated.

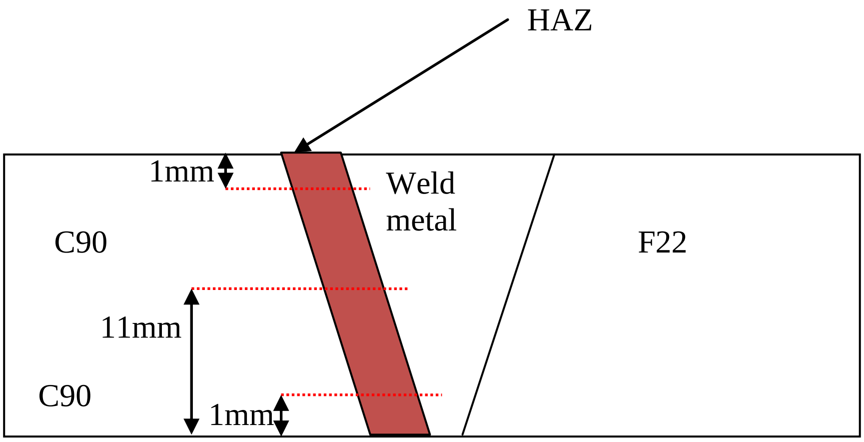


Figure 31: Locations where grain size will be observed using optical microscope (red)

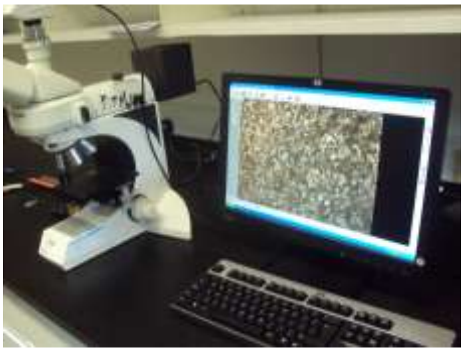


Figure 32: Optical Microscope

Figure 33: Mirror finished samples

3.5 Hardness Test

Hardness values will be evaluated only on the API 5CT C90 side using macro-hardness scale of Hv10 as shown in figure 34. After etched, the points of hardness test locations are marked on the specimen **(Figure 31)**. Points of hardness test in the HAZ region starts from as close as possible to the fusion line and the hardness values will be recorded in hardness test value form (appendix3).

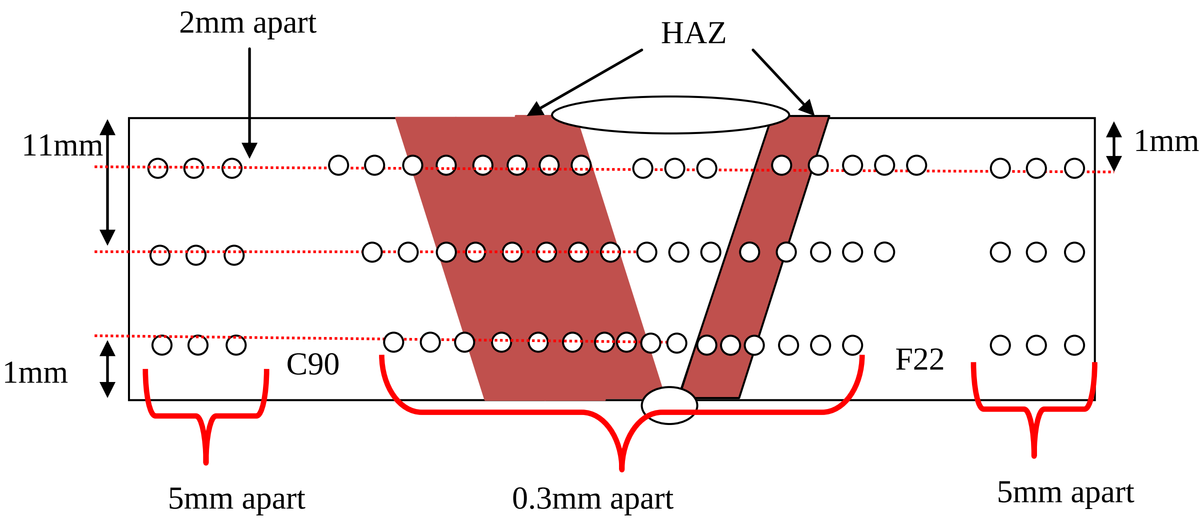


Figure 34: Hardness test locations

3.6 Charpy Impact Test

Charpy impact test will be performed by specimens' temperature at -20°C as this is below the service temperature of risers that is expected to be 0°C. -20°C below the expected temperature is chosen as a safety factor so that the charpy values is actually higher than those obtained from the charpy impact test and the desired charpy values is referred to NACE MR0175/ISO15156 [1] where the charpy values should be 30J single value, 42J average value at -20°C. They will be 3 test specimens for each of the conditions (non-heat treated, 500°C, 600°C, 700°C and 800°C PWHT temperatures). Temperature of -20°C will be achieved by using ethanol with some dry ice solution as shown in figure 36. The specimens for charpy impact test will be hold in the solution for about 5 to 10 minutes until the temperature stabilizes. An electronic thermometer will be used to monitor the temperature **[29]**. The charpy values will be recorded in charpy impact test value form (appendix 2). Below in figure 35 is the dimension of the striking edge and the impact testing machine and charpy specimens in figure 37.

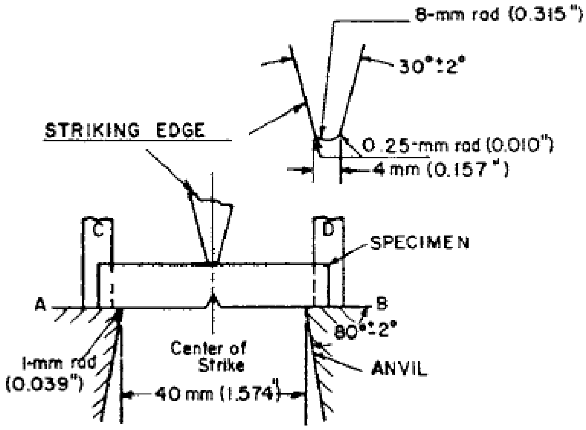


Figure 35: Charpy striker

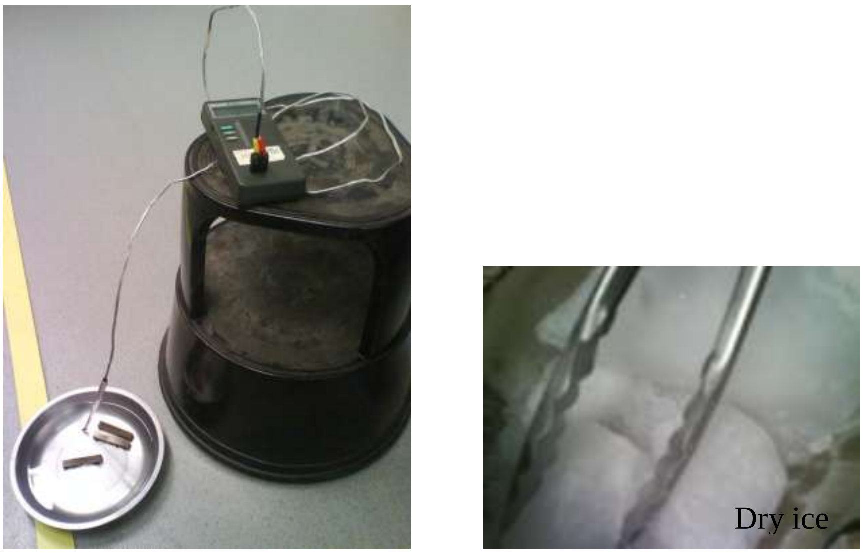


Figure 36: Temperature control of specimens by holding specimens in mixed ethanol and dry ice solution

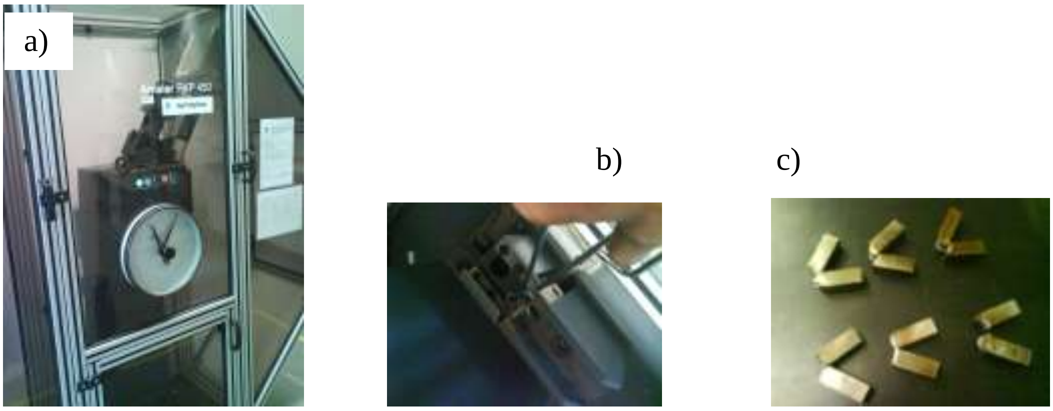


Figure 37: a) Impact testing machine and b) positioning charpy specimens on the impact testing machine c) fractured specimens

4.0 RESULTS AND DISCUSSION

4.1 Post-weld heat treatment

Four sections of the pipe that have been cut were sent for PWHT and the holding temperatures are 500°C, 600°C, 700°C and 800°C. The conditions of the specimens are as below in figure 38:

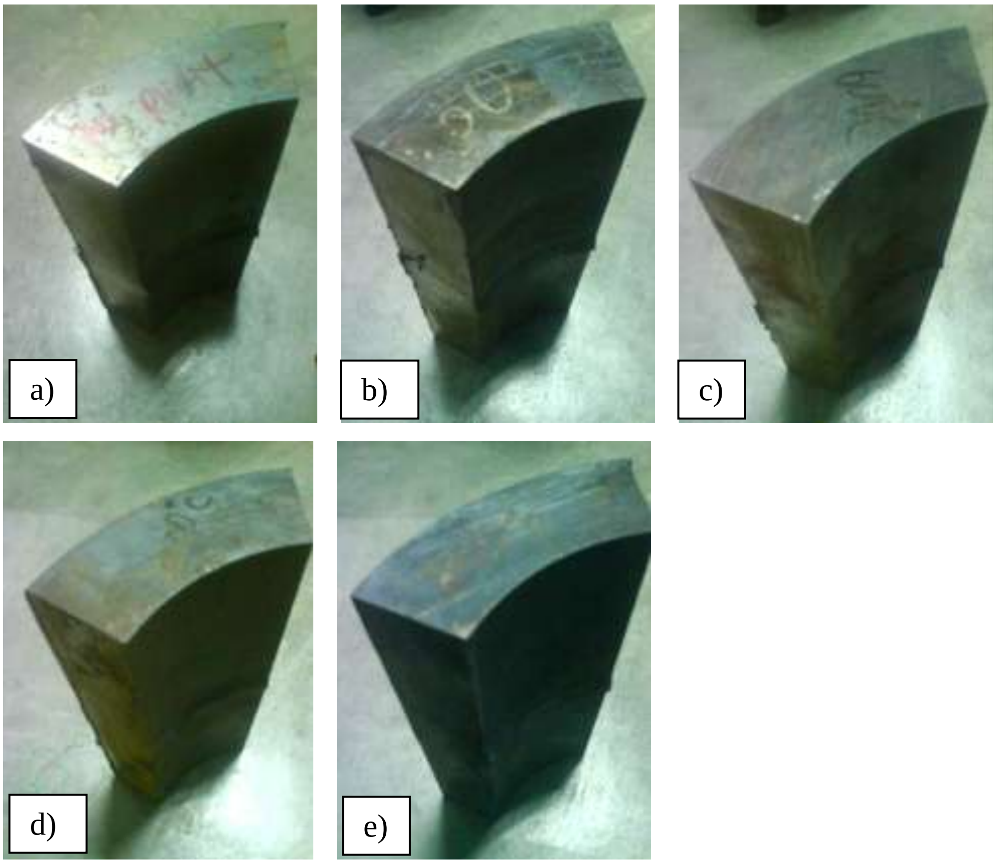


Figure 38: PWHT specimens at a) no PWHT b) 500°C c) 600°C d) 700°C e) 800°C

Visually, the heat treated specimens are darker at higher PWHT holding temperatures. This can be seen clearly between the non heat treated specimen and the specimen for 800°C PWHT temperature. This might be caused by the forming of oxide layer during PWHT that more oxide layers are formed at higher PWHT temperatures.

4.2 Macro-etching

Macro-etching was done where etchant is applied on the specimens' surface to reveal the weld metal, fusion line and heat-affected zone using nitric acid diluted in water and the ratio of nitric acid to water is 1:6 **[29]**. The macro-etched specimens below in figure 39 were used for hardness testing so that hardness value can be taken at the base metals, heat –affected zones and weld metal:

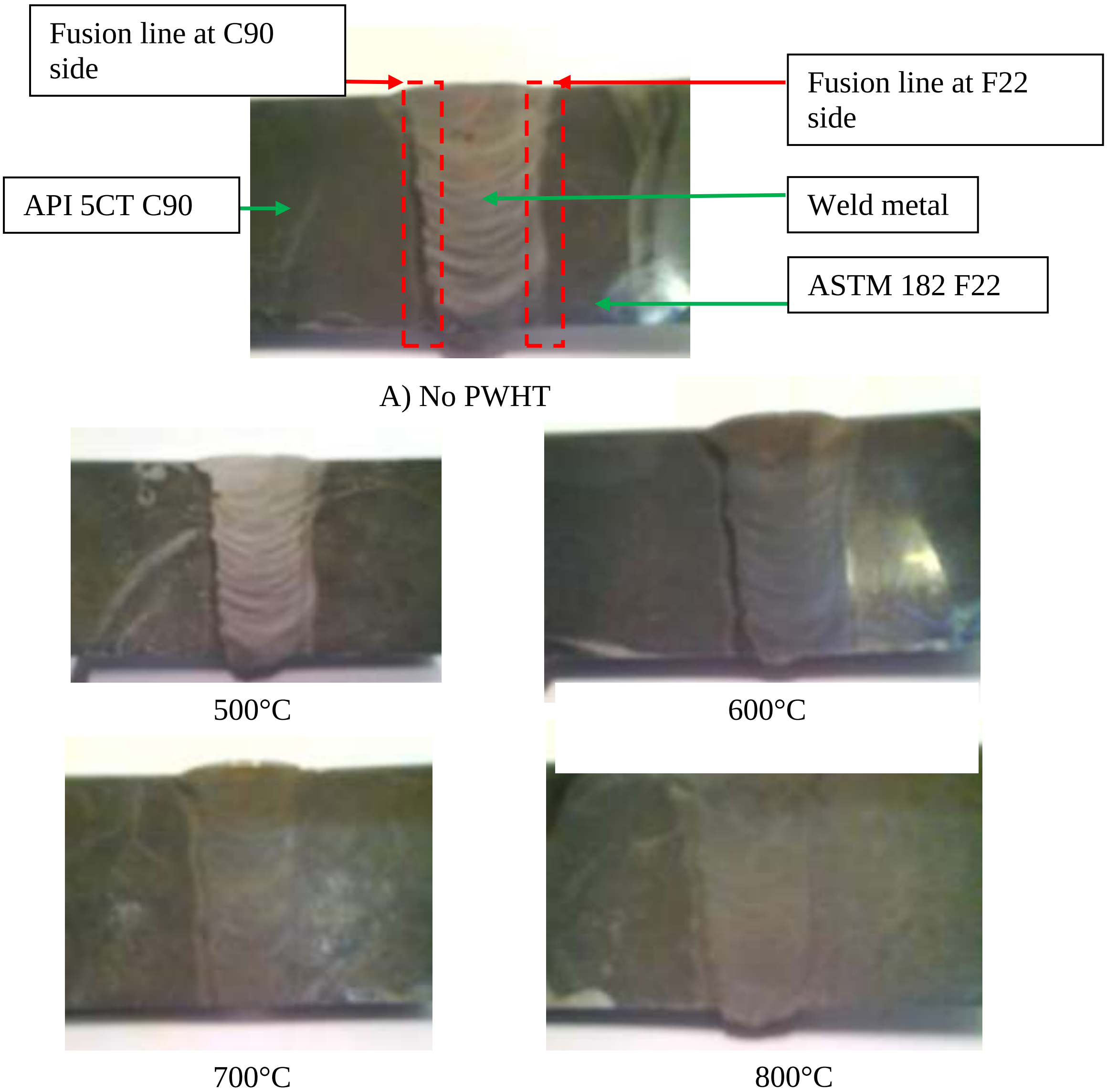


Figure 39: Macro-etching of PWHT specimen with areas of interest on the weldment a) No PWHT b) 500°C c) 600°C d) 700°C e) 800°C

As we can see in figure 39 above, some specimens show clear differentiation of the base metals, heat-affected zones and the weld metal and some are not. This is due to quality of the surface finish of the specimens. For hardness testing, the specimens should at least show the different areas (base metals, heat-affected zones and the weld metal) so that hardness value can be taken at each of the area. So, blur image of the areas revealed after macro-etching is not a problem as long as the heat-affected zone and weld metal can be seen.

4.3 Microstructure Examination

Microstructure examination was done using optical microscope with magnification of 150x. The location of the microstructure examination was on the fusion line of C90 side. By carefully examine the micrograph at some parts, we can clearly see the grain boundaries and compare the grain size between the PWHT conditions. Referring to figure below, we can see that as the PWHT temperature increases, the grains size also seems larger. The grains enlargement is more significant at PWHT of 800 ºC, where we can see clearly the grains size increased compared to other PWHT temperatures.

The change in grain size (grain size increase) will affect the mechanical properties of the weldment. In this project, the mechanical properties at the fusion line of C90 side will change. Increase in grain size at the fusion line shows that the residual stress of between the intermixed microstructure has been decreased. After welding, the grains intermixture of the weld metal and base metal at the fusion line are in high residual stress as the intermixed grains tend to return back to their original size. After PWHT, the grains are given thermal energy so that the grain size will increase and returning back to their original size and thus the residual stress is decreased. Figure 40 below shows the illustration of how residual stress is formed in the weldment microstructures after welding.

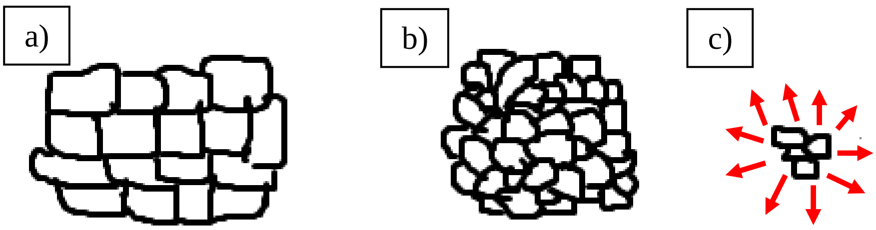


Figure 40: Illustration of how residual stress formed in the grains at fusion line of C90 side; a) microstructure before welding b) microstructure after welding c) Residual stress formed as grains tend to return to original size

Microstructure examination by optical microscope in this project as shown in figure 41 shows that the grains are larger at higher PWHT temperature and it is expected that the mechanical properties are better at higher PWHT temperature **[25]**. It is expected that the hardness decrease and the impact energy increases with increasing PWHT temperature **[25]**.

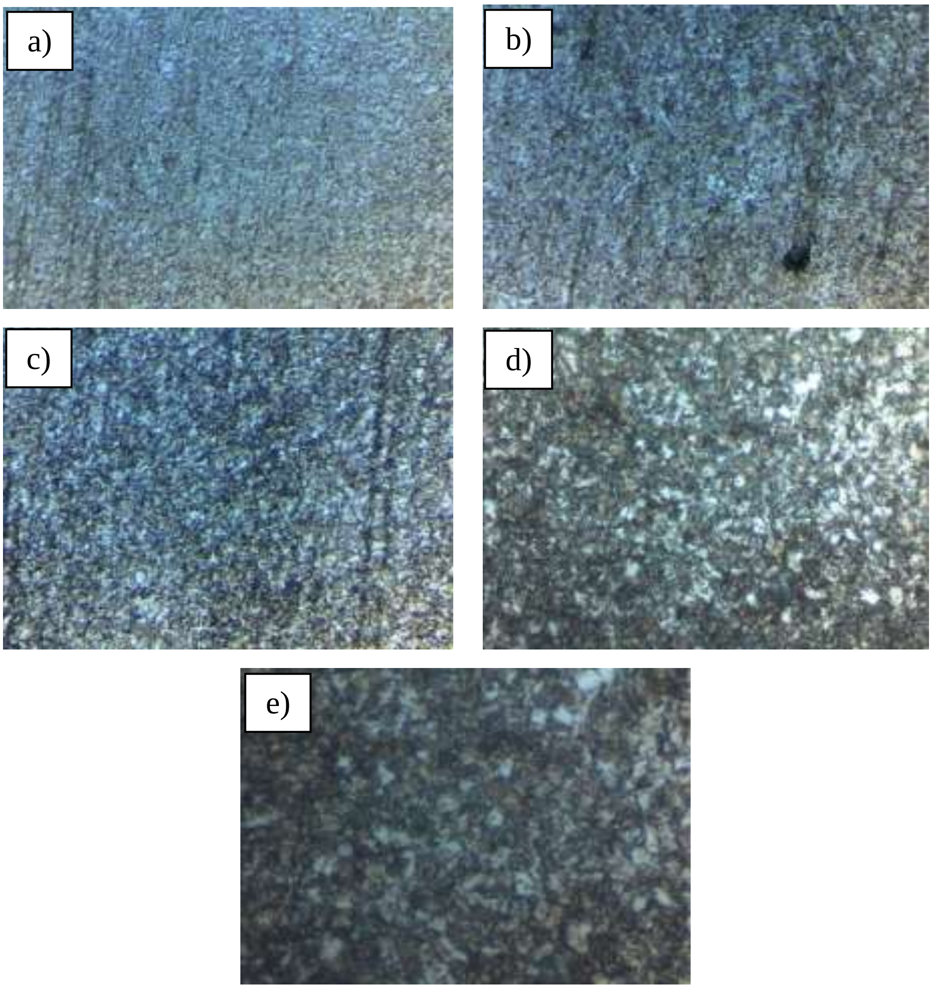


Figure 41: Microstructure at fusion line of C90 side of heat treated specimens using optical microscope with 150x magnification: a) no PWHT b) 500ºC c) 600 ºC d) 700 ºC e) 800 ºC

4.4 Hardness Test

The specimens for hardness test been started to be prepared and the hardness testing was completed using Vickers hardness scale of Hv10. Five specimens (one for each PWHT conditions) with a smooth surface have been prepared and macro-etched to reveal the base metals, heat-affected zones and the weld metal as shown in figure 39. The specimens' thicknesses are between 10mm to 15mm and they have a parallel surface of both sides. The hardness test have been performed on each of the specimen on 5 areas which are at the C90 metal, fusion line of C90 side, weld metal, fusion line of F22 side and at F22 metal. Below are the hardness test locations in figure 42 and table 6 and results and the details of the hardness values are included in Appendix 5:

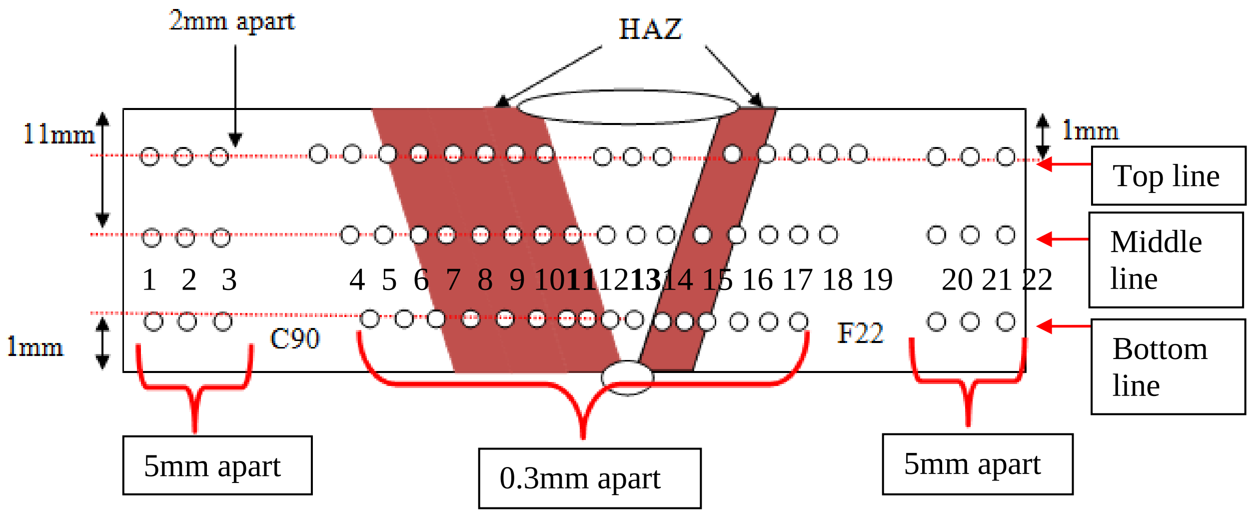


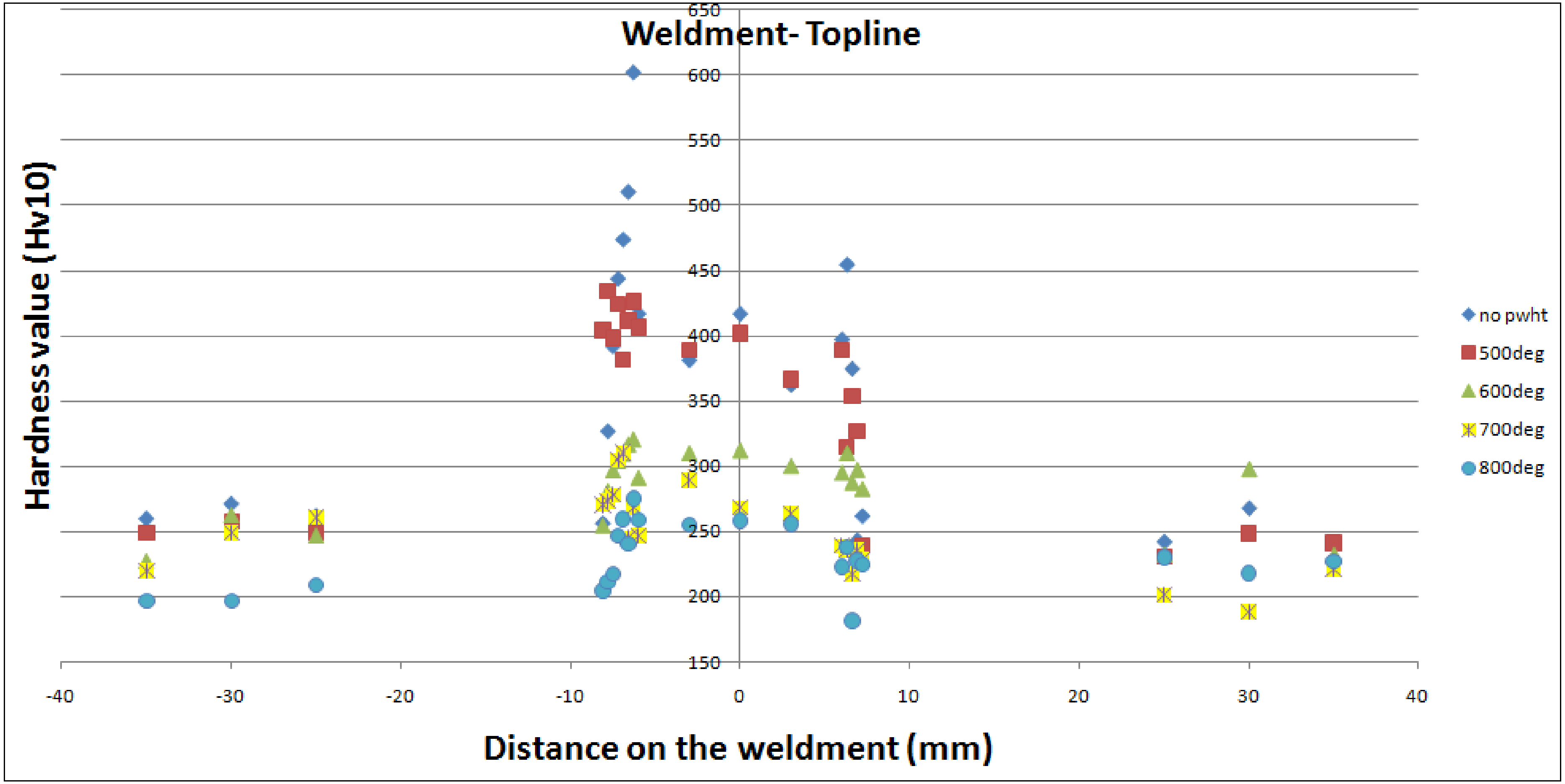
Figure 42: Hardness test locations

Table 6: Hardness test locations and distance from centre of weldment

Hardness test Locations	1	2	3	4	5	6	7	8	9	10	11
Distance from centre of weldment (mm)	-35	-30	-25	-8.1	-7.8	-7.5	-7.2	-6.9	-6.6	-6.3	-6

Hardness test Locations	12	13	14	15	16	17	18	19	20	21	22
Distance from centre of weldment (mm)	-3	0	3	6	6.3	6.6	6.9	7.2	25	30	35

Hardness Test Locations:
1-3 : C90
4-11 : HAZ at C90
12-14 : Weld metal
15-19 : HAZ at F22
20-22 : F22



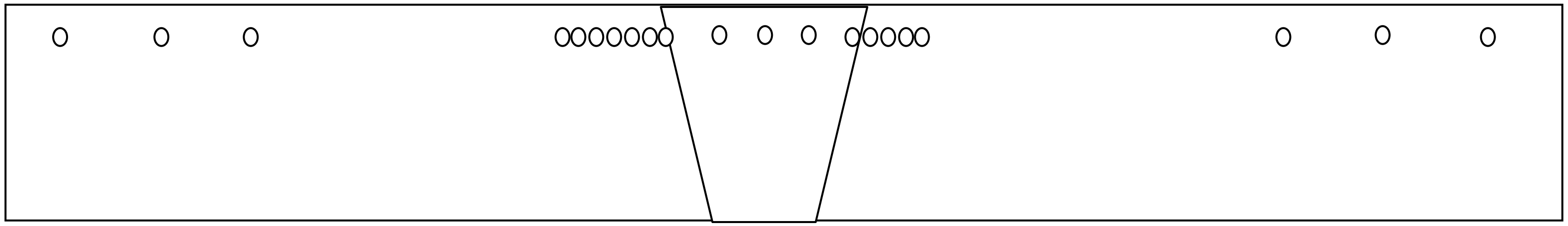


Figure 43: Hardness value vs. Hardness test locations graph for all PWHT conditions at the top line

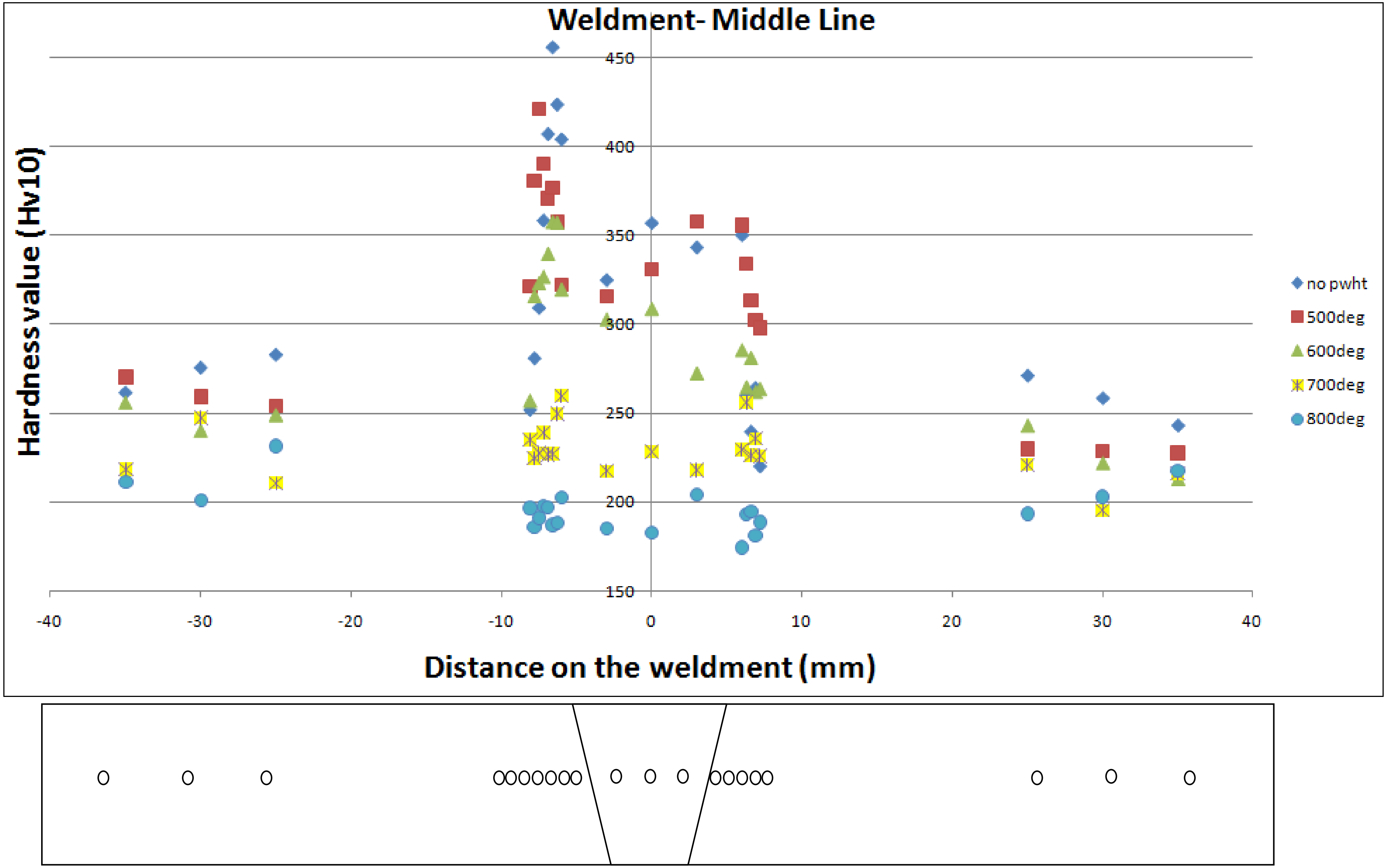


Figure 44: Hardness value vs. Hardness test locations graph for all PWHT conditions at the middle line

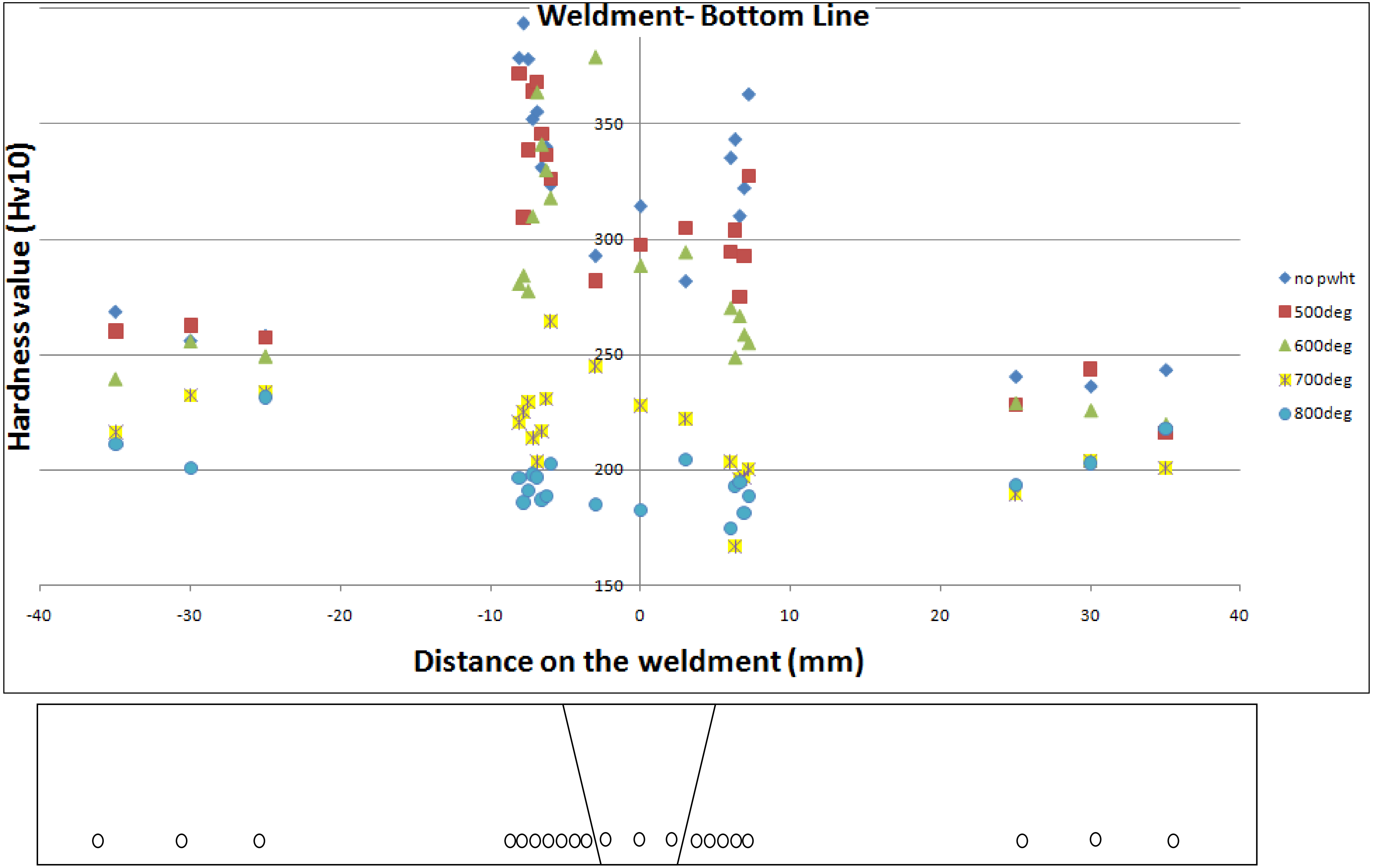


Figure 45: Hardness value vs. Hardness test locations graph for all PWHT conditions at the bottom line

Figure 43, 44 and 45 shows the hardness test results at top, middle and root of weldment. By comparing the hardness values of specimen from each PWHT temperatures, we can see that the hardness values are scattered in a particular hardness range depending on the PWHT temperature performed on the specimens. Arranging from the highest hardness values to the lowest hardness values:- without PWHT specimens, 500°C, 600°C, 700°C and 800°C. Highest hardness value for each PWHT temperatures is located at fusion line of C90 (location 4 -11). The range of hardness values is highest at top line of specimen.

This hardness behaviour can be related to the different physical appearance of the specimens after performing PWHT as shown in figure 38 where the specimens were having different colour (increasing PWHT temperature specimens are darker) and the early assumption made was the mechanical properties of the heat treated specimens may have changed. The hardness test results above showed that the mechanical properties of the heat treated specimens have changed where increasing PWHT temperature lowers the specimens' hardness. The hardness values for each PWHT temperature are scattered in a range of hardness values and this clearly shows the range of hardness for each PWHT temperature. For example, most of the hardness values for specimen without PWHT are larger than other specimens with PWHT while most hardness values for specimen heat treated with 800°C holding temperature are lowest. By comparing these two PWHT temperatures, we can observe that hardness decreases with increasing PWHT temperatures.

Regarding the mechanical properties (hardness value and impact energy) of the weldment in compliance with NACE MR0175/ISO15156 for riser application, none of the PWHT temperatures give hardness values that complies with NACE MR0175/ISO15156, <250Hv10 (root) and <275Hv10 (cap). Specimens of 800°C PWHT temperature gives the closest hardness values to the standard but some test locations at the capping line (top line) slightly exceed.

The parameters of the PWHT might need to be changed in the future research of this project such as, need slightly higher PWHT temperature or change other PWHT parameters such as heating and cooling rate and holding time but still need to consider the toughness when evaluating the mechanical properties. It is also proven that the highest hardness values located at fusion line of C90 side.

PWHT in this project is mainly to relieve the residual stress in the specimens. The residual stress is caused by intermixed microstructure at the fusion line of the weldment after high temperature welding. These intermixed microstructures contain residual stress as they tend to return to their original size and this lead to the high hardness at those areas. With the holding time of the PWHT is fixed for each PWHT temperatures, the hardness test results above shows the effect by having different PWHT temperatures. We can conclude that higher PWHT temperatures lower the hardness of the weldment but when reaching certain temperature; the decrement of the hardness is not that obvious. This can be proven by the graphs above where the scattered hardness values for 700°C and 800°C is much closer compared to the hardness values between 500°C and 600°C. This hardness decrement rate is possibly as a result that the intermixed microstructures have returned to their original sizes.

The hardness values are scattered but within a particular hardness range are possibly caused by a few reasons. Firstly, the surface finish of the hardness test specimens might be insufficiently smooth. Secondly, there might be contaminants such as dust or debris that lies between the hardness test indenter and the specimen. Lastly, the inaccuracy of measuring D1 and D2 of the indent during the hardness test as shown in figure 46 **[45]**.

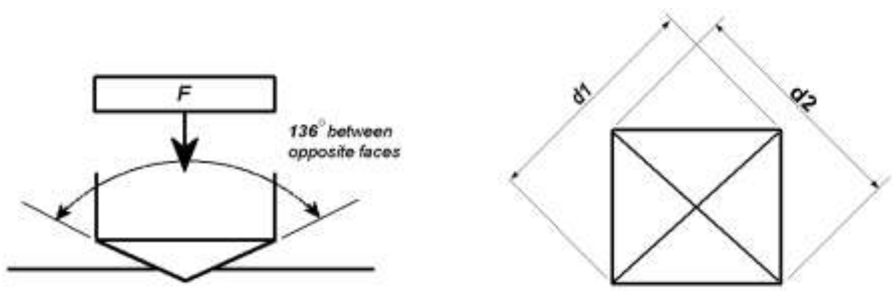


Figure 46: Indentation of the hardness test

4.5 Charpy Impact Test

Charpy impact test was done at the temperature of -20ºC. The specimen was cooled to -20ºC by sinking the specimens in a mixture of ethanol and dry ice. The temperature was monitored using an electronic thermocouple. Three specimens were prepared for each PWHT conditions and the impact energy values were averaged.

By referring to table 7 below, we can see that the impact energy values for each specimen is scattered. By averaging them, we can see the pattern of how the impact energies changes with the PWHT temperature. Impact energy of the weldment at the fusion line of C90 side increased with increasing PWHT temperature. From lowest to highest impact energy; No PWHT, 500 ºC ,600 ºC , 700 ºC and 800 ºC .Although the impact energy average values between 500 ºC and 600 ºC did not follow the pattern, but their values did not vary much from each other and are still higher than average value of the specimen without PWHT. There might have been some errors during the charpy impact test of these two PWHT conditions (500 ºC and 600 ºC) such as excess test temperature (e.g. -25ºC) that led to the impact energy inaccuracy.

From the impact energy values, it is clear that the brittleness of the specimens decreased with increasing PWHT temperatures. Lower impact energy means that the specimen is much easier to fracture, in other words the specimen is more brittle. Relating the impact energy to the residual stress within the intermixed microstructure at the fusion line of C90 side, higher residual stress caused the specimen having lower impact energy. So, from this charpy impact test, we can see that impact energy increased with increasing PWHT temperatures, proving that the residual stress are getting lower and so do the brittleness of the specimen.

Impact energies of 600ºC, 700ºC and 800ºC PWHT temperature specimens complies with NACE MR0175/ISO15156 for riser application (30J single value, 42J average value at -20 °C). In the other hand, specimens with no PWHT and 500ºC PWHT temperature did not meet the standard where one of their impact energies was below 30J although the average impact energy is above 42J.

Table 7: Impact energy values of different PWHT temperatures

PWHT temperature	impact energy (J)	Average
No PWHT	33.6	52.2
	93.7	
	29.4	
500ºC	113.7	62.1
	54.5	
	18	
600ºC	59.4	60.2
	74	
	47.3	
700ºC	116.7	79.8
	62	
	60.6	
800ºC	155.8	96.1
	64.5	
	68.1	

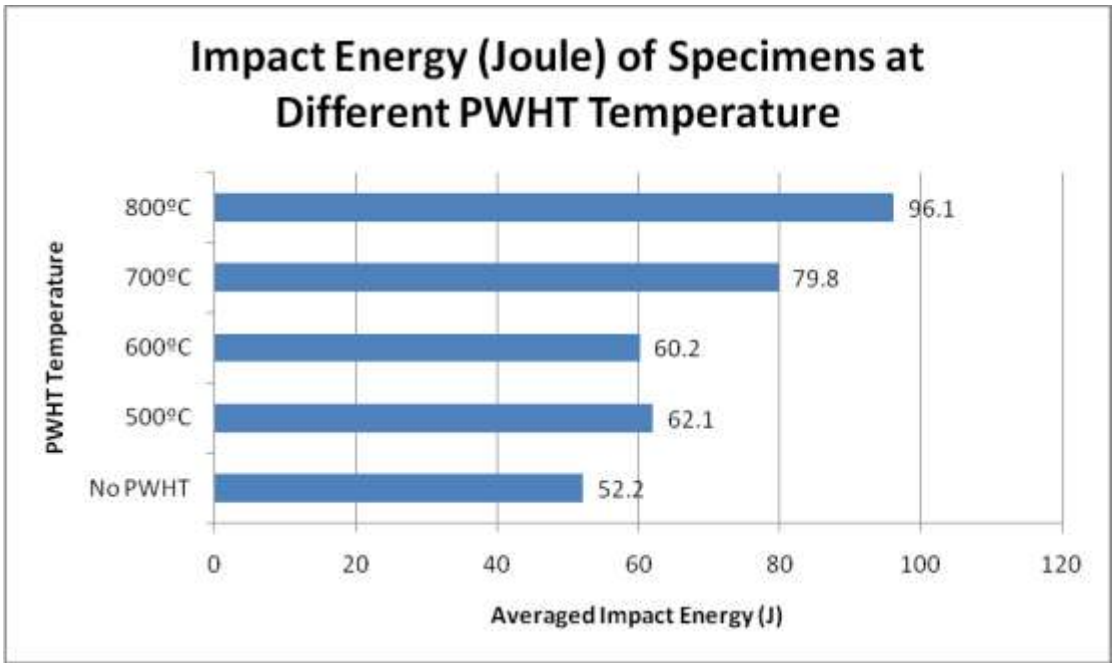


Figure 47: Averaged impact energy of 3 specimens for each PWHT temperature

5.0 CONCLUSION AND RECOMMENDATION

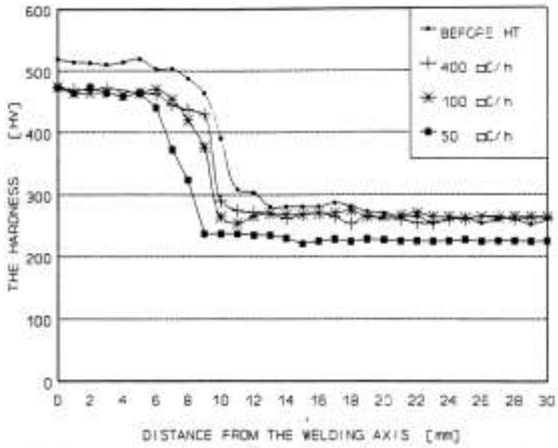
In this project, residual stress that was formed after the high temperature welding process has been relieved and this is proved by the hardness values is decreasing while impact energy at the fusion line of C90 side is increasing with increasing PWHT temperature. These results have proven the literature reviewed earlier. In the duration of 3 hours PWHT holding time, 150°C/h heating and cooling rate, higher PWHT temperature gives more energy for the grains to return to their original size. Arranging from the highest hardness values to the lowest hardness values:- without PWHT specimens, 500°C, 600°C, 700°C and 800°C and arranging from lowest to highest impact energy values:- without PWHT specimens, 500°C, 600°C, 700°C and 800°C.

None of the PWHT temperatures gives weldment with hardness together with impact energy values that complies to NACE MR0175/ISO15156, <250Hv10 (root) and <275Hv10 (cap) for hardness and 30J single value, 42J average value at -20 °C for impact energy. For hardness test, none of the PWHT temperature gives the required temperature and the best PWHT temperature that with the least hardness location exceeding the acceptance range is PWHT of 800ºC. For impact energy, 600ºC, 700 ºC and 800 ºC PWHT temperature gives a weldment with impact energies that accepted by the standard while weldment with no PWHT and 500 ºC PWHT temperature did not achieve impact energies in acceptance of the standard.

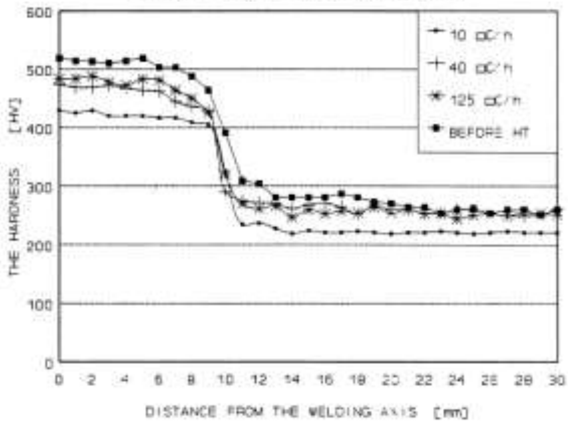
By observing the hardness test and charpy impact test results, PWHT temperature specimens with higher hardness value will give lower impact energy value. This shows that higher hardness specimens are more brittle and easier to fracture. As PWHT temperature increases, the specimens hardness value decreases and they are more difficult to fracture and this is showed by their impact energies which are higher and it shows that the specimen are becoming less brittle. So, by increasing the PWHT temperatures, the residual stress decreases, the hardness decreases and the impact energy increase at the fusion line of API 5CT C90 side.

Recommendations for future research of this project for mechanical properties of weldment (hardness value and charpy impact energy) compliance with NACE MR0175/ISO15156 for riser application:

1. Use slightly higher PWHT temperatures
2. Research the effects of heating rate and cooling rate on the weldment and decide on the best heating and cooling rate as shown in figure 47:



a)



b)

Figure 48: Olabi et al. **[25]** a) hardness values at different heating rates b) hardness values at different cooling rate

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APPENDIX

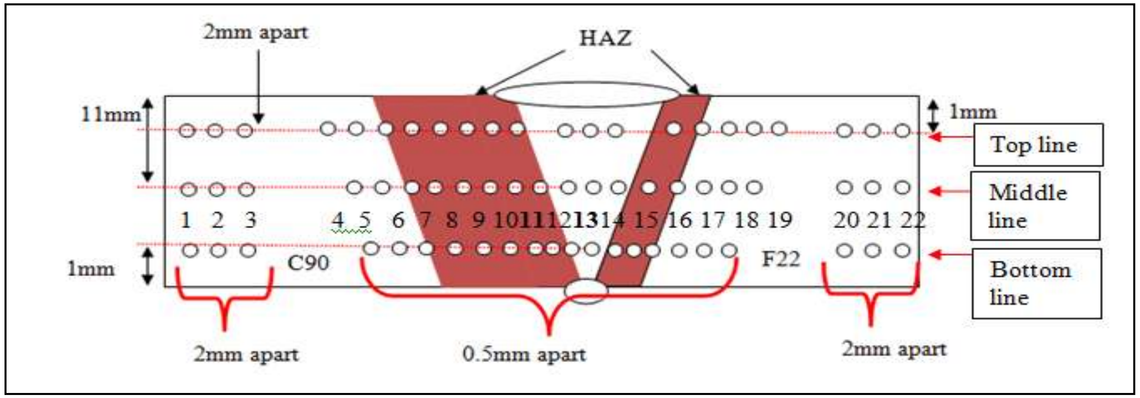
FYP 1 Gantt Chart

No	Details	Jan 2010				Feb 2010				Mar 2010				Apr 2010				May 2010			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	• Survey the availability of PWHT, microstructure evaluation and mechanical tests equipments in UTP • Review literatures on similar researches																				
2	Received welded pipe joint from FMC Technologies																				
	Submission of Progress Report I																				
3	Seminar																				
4	Project work begin • Specimen preparation for PWHT • PWHT (500ºC, 600 ºC, 700 ºC, 800 ºC)																				
5	Finished cutting pipe for PWHT																				
6	Finished PWHT																				
8	Specimen preparation for hardness test																				
11	Submission of Interim Report Final Draft																				
12	Oral Presentation												During study week								

FYP 2 Gantt Chart

No	Details	July 2010				Aug 2010				Sep 2010				Oct 2010				Nov 2010			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Project work continues from FYP I • Specimen preparation for hardness testing (cut) • Grinding specimens • Etching • Hardness Testing	■	■	■	■	■	■	■	■												
2	Complete hardness test								●												
3	Submission of Progress Report I						●														
4	Project work continues • Specimen preparation for charpy impact test (cut)									■	■	■									
5	Complete cutting charpy specimens											●									
6	Submission of Progress Report II											●									
7	Seminar												●								
8	Project work continues • Grinding and polishing charpy specimens • Etching • Optical Microscope • Charpy impact test												■	■							
9	Complete charpy impact test													●							
10	Poster Exhibition														●						
11	Submission of Dissertation Final Draft																	●			
12	Oral Presentation												During study week								
13	Submission of Dissertation (hard bound)												7 days after oral presentation								

1. Hardness Test values form



PHWT Temperature/Area		C90			Fusion Line at C90 side								Weld Metal			Fusion Line at F22 side					F22		
	TOP																						
	MIDDLE																						
	BOTTOM																						

2. Charpy Impact Test values Form

PWHT temperature	Specimens	Impact energy (J)	Average = [1+2+3]/3
No PWHT	1		
	2		
	3		

PWHT temperature	Specimens	Impact energy (J)	Average = [1+2+3]/3
500°C	1		
	2		
	3		

PWHT temperature	Specimens	Impact energy (J)	Average = [1+2+3]/3
600°C	1		
	2		
	3		

PWHT temperature	Specimens	Impact energy (J)	Average = [1+2+3]/3
700°C	1		
	2		
	3		

PWHT temperature	Specimens	Impact energy (J)	Average = [1+2+3]/3
800°C	1		
	2		
	3		

3. Hardness Test results

PHWT Temperature/Area		C90			Fusion Line at C90 side								Weld Metal			Fusion Line at F22 side					F22		
NO PWHT	TOP	260.4	271.8	262.6	256.8	327.4	392.5	444.3	474.3	510.9	602.4	417.5	381.9	417.4	362.9	397.7	455.1	375.3	243.8	262.4	242.7	268.4	240.1
	MIDDLE	261.3	275.4	282.7	251.6	280.7	309.1	358.4	407.1	456	423.7	404.1	324.8	356.9	343.2	350.1	259.9	239.3	263.9	219.8	270.9	258.2	242.8
	BOTTOM	268.6	256	258.2	378.4	393.4	377.9	351.9	355.1	331.1	339.9	323.6	292.8	314.3	281.8	335.2	343.2	310	322.1	362.7	240.5	236.3	243.4

PHWT Temperature/Area		C90			Fusion Line at C90 side								Weld Metal			Fusion Line at F22 side					F22		
500°C	TOP	249.5	257.3	249	404.2	434	398.3	424.4	381.7	411.6	426.5	407	388.9	402	366.5	389.3	314.6	354.1	326.7	239.7	230.5	248.7	241.4
	MIDDLE	270.3	259.1	253.8	321.3	380.6	421.1	390.2	370.7	376.9	357.4	322.3	315.7	330.6	357.7	355.8	333.7	313.3	302.5	297.9	229.9	228.5	227.5
	BOTTOM	260.1	262.6	257.6	371.7	309.5	338.6	364.2	368.1	345.5	336.5	326.4	282.1	297.6	304.8	294.7	303.9	275.2	292.7	327.3	228.3	243.8	216.1

PHWT Temperature/Area		C90			Fusion Line at C90 side								Weld Metal			Fusion Line at F22 side					F22		
600°C	TOP	227.6	262.9	247.1	254.7	281.2	296.9	304.1	309.6	316.7	320.6	291.2	310.2	312.2	300.4	295	310.2	287.6	297.2	282.6	232.5	297.9	232.4
	MIDDLE	255.9	240.1	248.9	257	315.9	323.1	326.7	339.7	357.6	357.2	319.6	302.7	308.7	272.4	285.5	264.6	281.1	261.9	263.5	242.9	221.9	212.9
	BOTTOM	239.2	255.5	249	280.4	284	277.3	309.7	363.5	340.9	329.8	317.7	378.8	288.3	294.2	269.9	248.5	266.4	258.4	254.7	228.7	225.5	219.5

PHWT Temperature/Area		C90			Fusion Line at C90 side								Weld Metal			Fusion Line at F22 side					F22		
700°C	TOP	219.8	249.1	260.8	270.3	273.4	278.1	304.8	268.3	245.2	268.5	246.6	289.2	310.7	263.9	239.1	235.5	217.6	236.1	228.8	201.3	188.1	221.3
	MIDDLE	218.5	247.4	210.7	235.1	224.8	227.4	239	226.7	227.2	249.7	259.7	217.4	228.4	218	229.4	255.9	226.4	235.6	225.9	220.9	195.2	215.8
	BOTTOM	216.4	232.3	233.6	220.6	225.1	229.3	213.9	203.6	216.8	230.8	264.4	244.9	227.8	222.1	203.5	166.8	195.9	196.9	200.3	189.6	203.9	200.8

PHWT Temperature/Area		C90			Fusion Line at C90 side								Weld Metal			Fusion Line at F22 side					F22		
800°C	TOP	197.1	196.9	209.2	204.7	211.4	217.5	247	259.6	240.6	258.4	258.5	255.4	275.5	256	222.9	238	181.4	227.9	224.9	230.2	218	227.2
	MIDDLE	222	211.2	199.9	233.5	202.8	208.7	192.4	183.7	200.9	209.6	192	230.1	210.3	217.6	224.3	222.9	216.9	185.5	159.8	201.2	209.2	210.1
	BOTTOM	211.3	200.8	231.5	196.6	185.8	191	198	196.9	187	188.4	202.8	184.9	182.7	204.3	174.4	192.9	194.5	181.4	188.7	193.5	203	217.7