IOP Conference Series: Materials Science and Engineering

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To cite this article: Randy Chiong *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **495** 012093

IOP Conf. Series: Materials Science and Engineering **495** (2019) 012093 doi:10.1088/1757-899X/495/1/012093

Effect of SMAW parameters on microstructure and mechanical properties of AISI 1018 low carbon steel joints: An experimental approach

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Abstract. Welding technologies are the fundamental application in industrial field especially for engineering, manufacturing and even medical implants. Since welding process involved in form of heat energy, it creates a property change in welded location, thus adequate control of welding parameters is essential as it determined the characteristics of welded joint. In present work, the investigation on effect of SMAW process parameters on metallographic studies and mechanical properties of AISI 1018 low carbon joints is studied throughout series of well controlled welding parameters. Steel plates with dimension of 400mm*200mm*6mm are arc welded through different set of welding currents (55A to 90A) using SMAW machine with low hydrogen stick electrode. After completion of welding process, the characteristic of welded samples were evaluated by the mean of non-destructive (NT) and destructive test (DT) in accordance to standard specifications and requirements as specified in ASTM standard and AWS D1.1 respectively. DT such as tensile, bend, impact, micro-hardness and metallographic analysis subjected to effect of thermal arc energy are interpreted and compared. Lastly, an approved welding procedure specification (WPS) supported by laboratory test results is developed.

1. Introduction

Welding is a physical and practical process that involved consolidation of materials, either similar metals or dissimilar metals through the application of thermal energy. This technique can be practiced in all industry sectors especially engineering, manufacturing and even a medical implant[7]. Welding processes can be done through adhesive and cohesive forces between metals with the present of heat energy and pressure. The metallic materials are coalescence and joined through the formation of metallic bonding [3,14]. Since the process involved in form of heat energy, an adequate control of welding parameters is essential during welding process as it determined the quality of welded joint. Without the ability to produce a strong and durable assembly between welded materials, it would be impossible to create products which are sustainable.

The metallurgy of weld is very different from the base metal. Microstructures and hardness values formed within weldment are corresponding to Fe-C Phase Diagram [12]. Technical experience showed that limitation occurred in welding due to the chemical reaction between bonding and metallurgical effect of material transformation [3]. The mechanical properties depend on dilution effect chemical elements before and after welded as well as the cooling rate induced during welding process. Wardoyo reported the mechanical properties of welded joint depend on the carbon content of material to be weld [15]. From carbon equivalent values less than 0.35CE and 0.28 Pcm, it shows good weldability with only minor hardening in HAZ of fusion welds and normally welded without special precautions and pre-heat or post-weld heat treatment [5,9,16]. The CE and P_{cm} values can be calculated using following equations:

$$C_{eq} = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}(wt\%)(1)$$

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B(2)$$

Refer to research done by Ibrahim et al., the grain size of microstructures in weld metal are different from point to point with variation of heat input [6]. Strength and toughness property of welded joint are subjected by the microstructural evaluation in weld metal [4,13]. Dendrite size and inter-dendritic spacing in HAZ reduced due to higher cooling rate. Steep thermal gradients are established in weld metal, thus promote a lesser time for the formation of martensitic [2,8]. Kumar and Shahi also noted that peak hardness was found in HAZ, between fusion boundary zone (FBZ) and coarse grain HAZ (CGHAZ)due to the present of partially unmelted grain/martensitic at FBZ.

In order to obtain a quality weld with effective strength and toughness, quality control of welding technologies is important. Hence, technical knowledge of welding methodology to the influences of microstructure of material properties are essentially important in order to provide a quality welded joint with good mechanical properties [1,11].

2. Methodology

Fig. 1 below shows the summary of experimental works in this project. All the procedures are conducted in accordance to international standard specifications and requirements as specified in ASTM standard and AWS D1.1 (Structure Welding Code – Steel) respectively.

Figure 1: Methodology Flow Chart

2.1. *Base and filler material combination*

The base metals used in present investigation is AISI 1018 low carbon steel with dimension of 400mm*200mm*6mm. The electrodes used for SMAW welding are E7016 and E7018 with diameter of 2.6mm and 3.2mm respectively.

2.2. *Welding Procedure*

In present work, single V-groove design with angle of 60° is prepared using semi-automatic gas cutting machine. Single V-groove is selected because it gives better strength and desired penetration. The plates are grinded to remove rust on the surface and cleaned with steel wire brush and compressed air to keep the surface of plates clean from impurities during the stage of welding process. To avoid moisture contamination, electrodes are baked in an oven at temperature 300 to 350˚C for 1 hour.To obtain sufficiently wide range of weld heat input, the test samples are welded through different set of welding currents (55A, 75A, 80A & 90A) using Jackle G400S SMAW machine by a certified welder. For each welded joint, surface welding is carried out with 4 weld layers (Fig. 2). All weld samples will undergo visual test (VT) and radiographic test (RT) for surface and subsurface flawsdetection after completion of weld. In accordance to acceptance criteria per section 6.12 specified in AWS.D1.1, out of four samples, only the best sample is selected. Destructive testing (DT)such chemical composition analysis, tensile, bend, impact, micro-hardness and metallographic studies are performed to determine the mechanical properties of selected weld sample.

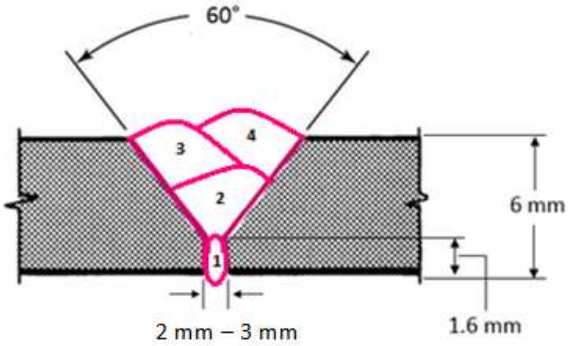

Figure 2: Single V-groove Design

3. Results and Discussion

3.1. Results:

3.1.1. Non-destructive testing:

After completion of NDT, the weld sample with 55A is selected for destructive test. Fig. 3 shows result of radiographic test for weld sample at 55A.Throughout radiographic interpretation with the kind assistance of certified ASNT Level III Inspector with Radiographic test certification, the locations of weld defects are clearly stated. The entrapments of solid particles (darkened areas) were found on the subsurface of weld sample. This is due to improper cleaning technique being employed as slag covering for each pass was not fully grinded or removed. Although slag inclusions are detected along the weld seam, it is still considered to be in the acceptable range because these small defects will not contribute to great impact to ultimate goals of present research.

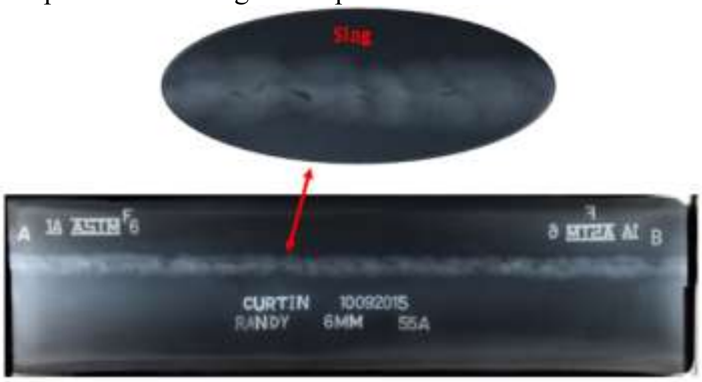

Figure 3: Radiographic Film for 55A Weld Sample

3.1.2. Destructive testing:

Since weld characteristics are essentially important to product safety, quality, reliability, strength and toughness, it could say that an effective application of welds is a key ingredient to a successful product in many industries. In order to determine the performance and integrity of completed welds in present work, destructive weld testing was conducted and the results obtained for chemical composition, tensile, bend, impact, micro-hardness and metallographic properties of welded joints are analyzed and evaluated.

i. Chemical Analysis

The chemical composition at base metal and weld metal after weld is tabulated in Table 1. As indicated in Table 1, it shows that Si, Mn and Cr had great increment in weld metal. The increases of these alloying elements will result in specific effects on the properties of weld metal.It is believed thatdilution effect of these elements will enhance the hardenability and strength of weld joint by promoting ferrite microstructure at weld metal. Besides, the additional of chromium content also help to enhance oxidation resistance of weld metal at high welding temperature.

Table 1: Chemical Composition of BM and Filler

Material	Element (wt%)								
	C	Si	P	S	Mn	Cr	Mo	Ni	Cu
BM	0.17	0.16	0.017	0.007	0.29	0.009	0.002	0.003	-
WM	0.09	0.61	0.016	0.008	1.01	0.021	0.002	0.008	0.006

ii. Tensile Test

Tensile test is performed to study the weld's strength and its ability to withstand loading throughout the bond between base metal, weld metal and heat affected zone (HAZ). Three reduced section transverse weld specimens are prepared and tested in accordance to ASTM A370 standard. The results of tensile properties are presented in Table 2.

Table 2: Results of Tensile Test

Specimen No.	T1	T2	T3	Average
Thickness (mm)	5.47	5.60	5.70	5.59
Width (mm)	20.00	20.06	20.07	20.04
Area (mm^2)	109.40	112.34	114.40	112.05
0.2% Proof Stress (MPa)	310.22	330.39	307.45	316.02
UTL (kN)	49.77	51.10	51.15	53.67
UTS (MPa)	455	455	447	452.33
Location of Failure	Broke at base metal			
Type of Failure	Ductile Failure			
Results	Acceptable			

A representative of the electronically plotted graph of force-strain curve is illustrated in Fig 4.

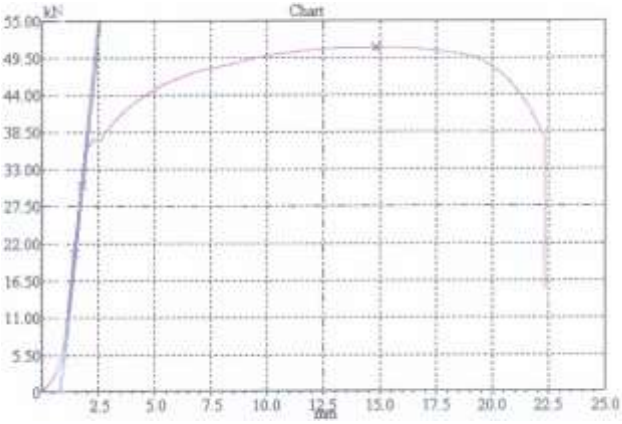

Figure 4: Force – Stress Curve

From the results obtained, it can observe the ultimate tensile stress and yield stress calculated through 0.2% proof stress for weld sample (S1) are 452.33MPa and 316.02MPa respectively. Visual observation of the fractured surface shows some fibrous surface. This shows a decrease in ductility of the specimen as seen as tensile load increases. However, all the tensile test results showed that tensile failure of welded joints are consistently occurred in the base metal. This indicates that the weld metal has better ductility as compared to base metal. This is because the carbon content at weld metal is significantly lower than base metal, which promote a better ductility and able to withstand a higher strength compare to base metal.

iii. Bend Test

The purpose of bend tests is specified as qualitative test analysis for evaluating the ductility and soundness of welded joint corresponding to weld defects. In present work, bend test was performed into two different configurations; face bend and root bend respectively. Defects such as excessive undercut or lack of sidewall fusion close to the cap can be exposed through face bend test while other defects such as lack of fusion or penetration can be observed through root bend test. Both specimens (face and root) are successfully bended to 180° convex surface with detected small open defects, 1.18mm and 1.60mm at weld for face bend and root bend, respectively. Such defect might cause my undetected porosity allocated at weld metal. However, these results are acceptable because those defects are detected under range of acceptance criteria of bend tests as specified in AWS D1.1 section 4.8.3.3.

Table 3: Result of Bend Test

Spec. No.	Remarks	Result
F1	No breakage	Accepted
	Open defect 1.18mm at weld	
R1	No breakage	Accepted
	Open defect 1.60 mm at weld	

iv. Charpy V-notch Impact Test

To evaluate the relative impact toughness of weld specimen and resistance towards a sudden load or impact,Charpy V-nothc impact test is conducted with respect to ASTM E23. The results of Charpy V-notch impact test with specimen dimension of 5*10*55 mm at 0°C are presented in Table 4.The absorbed energy at weld metal was found to be maximum at 86J and minimum of 44J. This huge variation of absorbed energy is mainly due to the imperfect of weld. The high absorbed energy indicated that test specimen 3 was defect free. On the other hand, slag inclusion may exist at test specimen 2, in turn will degrade the toughness performance (44J) at weld metal. In addition, visual observation found that all Charpy V-notch test specimens are deformed or fractured without breaking. This again proved that lower carbon content at weld metal resulted it undergoes a plastic deformation and in ductile manner.

Table 4: Result of Charpy V-notch Impact Test

Position	Spec No.	Testing Temp°C	Impact Energy, J	Remarks
At Weld Metal	1	0	54	Accepted
	2	0	44	
	3	0	86	
		Average	61	

v. Micro-hardness Test

Micro-hardness test are performed in accordance to ASTM E92to determine the hardness gradient and along a cross section of welded specimen. Fig. 5 shows the micro-hardness profile along the longitudinal direction of base metal surface with different zone of weldments. From Fig. 5, the hardness of base metal is approximately 140 HV. In addition, the measured hardness of heat affected zone (HAZ) and weld metal regions varies from 164 HV to 195 HV and 169 HV to 186 HV respectively, depending on the grain size and phases sampled from each indentation.This indicates that the hardness of HAZ region is greater than the entire region of weld metal and base metal. Meanwhile, the highest hardness values were found toward the fusion line between HAZ and weld metal due to the formation of fine grain region as a result of additional alloying elements.Moreover, the behavior of hardness properties across welded specimen can be further explained in accordance to microstructure analysis.

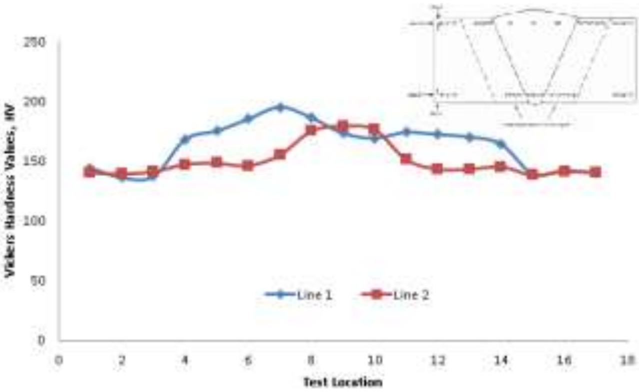

Figure 5: Micro-hardness Profile

vi. Metallographic Test

Generally, welded joint includes large amount of heterogeneity in microstructure. Microstructure distribution in the welded joint is important for mechanical discussion of the effect of intentional change of mechanical properties of weld metal.The selection of chemical composition of stick electrode and heat input process had great influences to the weld metal microstructure of fusion

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welded joints. The resulting of heterogeneity in microstructure is mainly due to the thermal variations between weld metal and base metal as well as the solidification of weld metal.

The representative weldment cross-section profiles and microstructure at different weld zones of SMAW AISI 1018 joints are shown in Fig 6. An acicular/dendrite ferrite microstructure was found in weld metal with a small amount of retained austenite and martensite. This is because multi pass of weld had been performed at the weld meta, it experienced a slow cooling rate which reduces the interfacial energy between austenite and ferrite, thus results in formation of acicular/dendrite ferrite with potentially high strength and toughness properties.

On the other hand, base metal has polygonal shape ferrite together with pearlite matrix. This area is not affected by the thermal variation during the welding process and remains as its original microstructure. Besides, base metal has the largest grain size as compared to HAZ and weld metal. This indicates that at this region, base metal is ductile but exhibits relative poor strength as compared to HAZ and weld metal.

Furthermore, due to the high intensity of SMAW process, the coarse ferrite grains with small amount of martensite were found in heat affected zone (HAZ). As compared to microstructure in weld metal and base metal, HAZ had a better and smaller grained ferrite matrix. In addition, at HAZ, the peak temperature experienced during the welding process is in between A_1 (723°C) and A_3 (910°C). As a result, phase transformation from δ-ferrite to austenite during welding process was incomplete due to the insufficient temperature from inter-critical region, producing smaller grains structure coexistence of α-ferrite and austenite. Since the austenite grain growth was limited in HAZ and due to the fast cooling rate at room temperature, the partially formed austenite were transformed back into ferrite, resulting in a microstructure at this region composed of newly formed fine ferrite surround at HAZ. Therefore, from metallurgical point of views, it is believed that HAZ is not significant influenced by mechanical deformation due to the formation of fine and course ferrite grains that contribute to good mechanical performance.

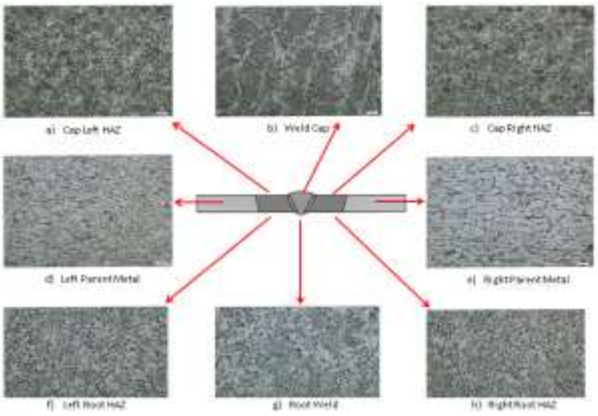

Figure 6: Microstructure Analysis

3.2. Discussion:

The mechanical properties of weld joints have direct connection to the microstructure behaviour as well as chemical composition of the weld metal and base metal. Any intentional change in microstructure of weld sample will directly influence to its mechanical performance subjected at certain circumstances, either improving or degrading.

From the interpretation of tensile strength properties of test specimens, it shows that all tensile specimens are broke at base metal. This indicates that the weld metal has higher strength than the base metal. This is to say that the selected electrodes with higher concentrations of chemical elements have indeed improved the materials strength. Furthermore, this is because at base metal, it is not affected by thermal cycle in welding process and remained as unchanged microstructure. From Fig. 6, it can be seen that the microstructure at base metal has the largest grain size and spacing, which result in relatively lower tensile strength as compared to HAZ and weld metal that is comparatively stronger. This is because the thermal variation at HAZ is consequent to high cooling rate; it leads to insufficient time for the grain to growth. As result, the microstructure at HAZ attributed to a smallest dendrite sizes and space which enhance its weld strength properties at this region. In addition, due to the filler metal additions, alloying element such as silicon, manganese and chromium are added to weld metal which in turn promoting the ferrite formation and increasing hardenability and strength at weld metal. Therefore, it proved that base metal has the lowest weld strength properties and fracture subjected to loading occurred in this region is due overmatching weld strength. This finding is agreed with the results performed by Marcelino et al [10].

In the case of Charpy V-notch impact test, it shows that the impact toughness of weld metal varies from 44J to 86J. All test specimens exhibit fracture part as 'grayish and fibrous' surface, which indicated that the weld metal is ductile manner. The nickel content in weld metal is about 3 times higher than base metal. This increment of nickel element helps to promote an austenite microstructure and generally increases the ductility and toughness characteristics of weld metal. Moreover, due to the multiple pass of welds, portion of previous weld is refined as the heat from each pass act as inter-pass temperature which tempers the weld metal below it, result in slow cooling rate with improved grain refinement (acicular/dendrite microstructure) as well as toughness properties.

In term of micro-hardness, it was observed that micro-hardness values were increasing at HAZ. However, the maximum micro-hardness was found toward the fusion boundary zone. Similar result was reported by Wichan and Loeshpahn (2013, 5) [2]. It can be seen in Figure 14, the highest micro-hardness was indicated between weld metal and HAZ. This may be due to the presence of some cementites (Fe_3C) at fusion boundary zone which lead to formation of fine grain with martensite phase during solidification stage. After reaching the highest point, the Vickers microhardness shows a decreasing trend from HAZ to base metal. This finding again agree with the microstructure shown in Fig. 6, indicating that the smaller/finer the grain size, the higher the mechanical strength and hardness.

4. Conclusions

As a conclusion, this research project can be deduced at the following criteria.

(1) Both the non-destructive tests, i.e. VT and RT are considered power inspection tools for possible surface and subsurface flaw detection.

(2) After radiography test was conducted on the different 4 test samples that were being welded using 4 different sets of welding current, all visible subsurface defects were identified, detected, analyzed and interpreted.

(3) From the chemical analysis, it was also analyzed that there were some noticeable dilution effects of chemical elements such as silicon, manganese, chromium etc promote a great improvement to harden ability and mechanical strength of welded joint.

(4) The bonding between the weld metal and the parent metal has indicated a complete fusion and revealed complete joint penetration (CJP) when using welding current of 55A coupling with stringent control of heat input of each welding pass as evident in Test Sample 1. The joint is free from crater crack, solidification cracks, overlaps, spatters etc. all along the weld seam.

(5) By looking at the microstructure of different parts of the test coupon, microstructures shown at the HAZ have finer grains and have more oriented structure compared to any other zones. Therefore, the mechanical properties such as tensile strength and micro-hardness values are having much stronger than any other zones.

In short, different material will behave differently depending to their chemical composition and thermal properties. In order to improve the mechanical performance of welded joint, a smaller/finer grain size is desired. Therefore, this finding proved that the microstructure and mechanical properties of welded joint can be improved through an adequate control of welding parameters.

References

[1] Bayraktar, E. 2014. "Introduction to Welding and Bonding Technologies."Comprehensive Materials Processing 6: 1 – 2.
[2] Chuaiphan, Wichan and LoeshpahnSrijaroenpramong. 2013. "Effect of Welding Speed on Microstructures, Mechanical Properties and Corrosion Behavior of GTA-welded AISI201 Stainless Steel Sheets." Journal of Materials ProcessingTechnology 214 (2014): 402 – 408.
[3] DeGarmoE.Paul, JT. Black and Ronald A.Kohser. 2003. Materials and Processes InManufacturing. USA: John Wiley & Sons, Inc.
[4] Ghazvinloo, H.R., A.Honarbakhsh – Raouf and N. Shadfar. 2010. "Effect of Arc Voltage, Welding Current and Welding Speed on Fatigue Life, Impact Energy and Bead Penetration of AA6061 Joints Produced by Robotic MIG Welding."Indian Journal of Science and Technology 3(2): 1 – 7.
[5] Ginzburg, Vladimir B. and Robert Ballas. 2000. Flat Rolling Fundamentals. USA: CRC Press.
[6] Ibrahim, IzzatualAini, SyarulAsrafMohamat, Amalina Amir and Abdul Ghalib. 2012. "The Effect of Gas Metal Arc Welding (GMAW) Processes on Different Welding Parameters." Procedia Engineering 41 (2012): 1502 – 1506.
[7] Karthik, G., P. Karuppuswamy and V. Amarnath. 2014. "Comparative Evaluation of Mechanical Properties and Micro Structural Characteristics of 304 Stainless SteelWeldments in TIG and SMAW Welding Process." International Journal of Current Engineering and Technology (2): 1-7.
[8] Kumar, Subodh and A.S. Shahi. 2011. "Effect of Heat Input on the Microstructure and Mechanical Properties of Gas Tungsten Arc Welded AISI 304 Stainless Steel Joints." Materials and Design 32(2011): 3617 – 3623.
[9] Kurji R. and N. Coniglio. 2014. "Towards The Establishment of Weldability Test Standards For Hydrogen-Assisted Cold Cracking." International Journal of Advance Manufacturing Technology: 1 – 17.
[10] Nascimento, Marcelino P., Herman J.C. Voorwald and Joao da C. PayaoFilho. 2011. "Fatigue Strength ofTungsten inert Gas – Repaired Weld Joints in AirplaneCritical Structures." Journal of Materials Processing Technology 211(2011):1126 – 1135.
[11] Singh, Ramesh. 2012. Applied Welding Engineering: Processes, Codes and StandardsUSA:Elsevier Inc.
[12] Tchan, IrDr Edwin Jong Nyon (2015). "Materials Engineering MCEN 2004 – Steels."PowerPointlecturenote.
[13] Wang, Q., D.L. Sun, Y.Na, Y. Zhou, X.L Han and J. Wang. 2011. "Effects of TIG Welding Parameters on Morphology and Mechanical Properties of Welded Joint of Ni – base Superalloy." Procedia Engineering 10 (2011): 37 – 41.
[14] Weld Fusion Versus Weld Penetration. 2015. The Lincoln ElectricCompany.Accessed March 23, http://www.lincolnelectric.com/en-us/support/process-andtheory/Pages/weld-fusion-weld-penetration.aspx
[15] Wardoyo, Toto Triantoro Budi, S.Izman and DenniKurniawan. 2013. "Effect of ButtJoint on Mechanical Properties of Welded Low Carbon Steel." Advanced Materials Research 845: 775 – 778
[16] Yurioka, Nobutaka. 1985. "Impact of Welding Research on Steel Composition Development." Materials and Design 5(4): 1 – 18.