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Comparison of Microstructure and Properties of Modified 9Cr-1Mo Welds Produced by Narrow Gap Hot Wire and Cold Wire Gas Tungsten Arc Welding Processes

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Abstract

Modified 9Cr-1Mo material is used as principal material of construction of Steam Generators (SG) for India's first of its kind 500MWe Prototype Fast Breeder Reactor (PFBR).The fabrication of Steam Generators is carried out by combination of hot wire and cold wire Gas Tungsten Arc Welding (GTAW) processes. Eventhough welds were meeting the specification requirements, limited information available on hot wire GTAW process in open literature motivated authors for characterization of welds produced using this specialized technique. The impact properties at 0^0Cof modified 9Cr-1Mo welds produced by hot wire GTAW processis found inferior compared to welds produced by cold wire GTAW process. The properties such as tensile strength, hardness, impact toughness at $+18^0$C were found almost comparable for the welds produced by both the welding processes. This paper characterizes the microstructure and various mechanical properties of modified 9Cr-1Mo welds produced by narrow gap hot wire and cold wire GTAWprocesses.

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1. Introduction

Ferritic steel of type modified 9Cr-1Mo (grade 91) has been selected for PFBR Steam Generators, as this material possesses high resistance to stress corrosion cracking in caustic environment and has excellent high temperature mechanical properties. One of the major problems associated with welding of Modified 9Cr-1Mo steel is poor toughness of weld metal produced from any of the processes that involves the use of flux. S.K.Albert et al. indicated that the impact properties of weld metal produced by the processes that involves the use of flux is far inferior (in the range of 40–100J) while that of the weld metal produced by Gas Tungsten Arc Welding (GTAW) process. This problem exists even for the weld metals of more advanced ferritic steels, like grade 92, grade 911 etc. Since, these steels are essentially meant for high temperature applications, good toughness at ambient temperature is not a critical requirement for the service. However, toughness is an important consideration during hydro testing of components fabricated using these materials.

Fig. 1: Hot wire GTAW System and PFBR Steam Generators

As per PFBR Steam Generator specification, hydro-testing is a mandatory requirement at various manufacturing stages and these tests has to be conducted preferably at ambient temperature. This requires both weld and base metal must possess adequate toughness at ambient temperature to ensure that no unexpected failures take place during hydro-test. Accordingly, upper limit for RTNDT (Reference Temperature – Nil Ductility Transition) has been specified to be -15ºC for both base metal and welding consumables used for fabrication of PFBR Steam Generators. The specified upper limit for RTNDT would ensure that there is no risk of fast fracture in the component during hydro test at ambient temperature.

Gas Tungsten Arc Welding (GTAW) process is widely used as a fabrication tool in many industries as it allows excellent control of root pass weld penetration and possesses various advantages such as low-distortion during fabrication associated with production of high quality welds. The major disadvantage of this welding process is low deposition rate which makes it highly uneconomical for welding component with large section thickness. Hot wire GTAW is a relatively new process and limited machines/facilities are available in India for welding with this specialized technique. The most important benefit from the use of a hot wire GTAW system is high weld deposition rate due to preheating of the filler wire and excellent profile of the weld with reduced dilution and porosities from the weld deposits.

The manufacturing of PFBR Steam Generator components involves welding of shells, reducers, cones etc. and GTAW process is chosen for this purpose. Manual cold wire GTAW, automatic cold wire GTAW and automatic hot wire GTAW processes were employed during fabrication based on the practical feasibility. Eventhough welds were meeting the specification requirements during welding procedure qualification, limited information available on hot wire GTAW process in open literature motivated authors for characterization of welds produced by this specialized technique.During manufacture, it is a mandatory requirement to weld one test coupon for every 20 meters of weld length on the actual job for ascertaining the properties during fabrication. During welding procedure qualification, it was found that impact test results (at 0^0C) of weld metal produced by cold wire GTAW process is superior than the weld metal produced by hot wire GTAW process. In light of this, further studies have been conducted to find out the trends of mechanical properties in various production test coupons during manufacture. In this paper, the microstructure and results of various mechanical properties of modified 9Cr-1Mo welds produced by narrow gap hot wire and cold wire GTAW processes are discussed in detail.

Nomenclature

PFBR	Prototype Fast Breeder Reactor	GTAW	Gas Tungsten Arc Welding
SG	Steam Generator	SMAW	Shielded Metal Arc Welding

2. Fabrication of PFBR Steam Generators and welding related issues

The PFBR Steam Generator manufacture involves welding of 12mm, 30mm and 90mm thick modified 9Cr-1Mo components. The typical % by weight of chemical composition of modified 9Cr-1Mo plates used for fabrication are C-0.08 to 0.12, Cr-8 to 9.5, Mo-0.85 to 1.05, Si-0.2 to 0.5, Mn-0.3 to 0.6, V-0.18 – 0.25, N-0.03 to 0.07, Nb-0.06 to 0.1, S-0.01 max, P-0.02 max, Ni-0.4 max, Al-0.04 max., Iron-balance. Modified 9Cr-1Mo plates are procured as per PFBR specification with very stringent acceptance criteria. During material procurement, all the plates were subjected to thorough Visual Examination/Liquid Penetrant Examination (LPE) and 100% Ultrasonic Examination (UE) with each scan overlapping at least 10% of the previous scan to ensure the soundness of plate. High temperature tensile test (525^{0}C) is carried out in addition to tensile test at ambient temperature on the specimens of plates to evaluate and ascertain the properties for service conditions. In addition, the plates were procured with simulated heat treated and tested condition meeting mechanical properties with additional soaking hours during heat treatment.

Even though Shielded Metal Arc Welding (SMAW) process is permitted as per PFBR specification, 100% GTAW process alone is adapted during fabrication to meet the impact properties of welds. Combination of hot wire and cold wire GTAW process is chosen for fabrication based on the practical possibility and feasibility. The 12mm thick shell welding around the tube bundle is carried out by 100% cold wire GTAW process. The 30mm thick component welding is carried out by combination of automatic cold wire and hot wire GTAW process and 90mm thick components welding are carried out only by automatic hot wire GTAW process, as the amount of weld metal to be deposited during fabrication is high. ER 90SB9 filler wire is used during GTAW process in all the above processes. The typical % by weight of chemical composition of ER 90SB9 filler wire (as per PFBR specification) used for welding are C-0.08 to 0.12, Cr-8 to 9.5, Mo-0.85 to 1.05, Si-0.2 to 0.4, Mn-0.5 to 1.2, V-0.15 to 0.22, N-0.03 to 0.07, Nb- 0.04 to 0.07, S-0.01 max, P-0.015 max, Ni-0.6 to 1, Iron-balance. As shell assemblies of Steam Generators are insitu welded around the tube bundle in horizontal condition, the welding is carried out only from outside, as there is no access to carry out welding from the tube bundle side. Due to this limitation, the shell joint Weld Edge Preparation (WEP) has only single V or J type WEP. After fabrication, entire 26 meters length Steam Generator is subjected to Post Weld Heat Treatment (PWHT) in a single charge at 760±10^{0}C for 4 hours soaking time to relieve the welding stresses and to get homogenous tempered martensite structure.

3. Welding for procedure qualification and production test coupons

The welding procedure qualification is carried out on 12mm, 30mm and 62mm thick test coupons using GTAW processes. The following paragraph explains the typical welding process parameters used during procedure qualification and production test coupons.

2.4mm, 3.0mm and 3.2mm diameter 2% thoriated non-consumable tungsten electrode (2% EWTh-2) is employed for GTAW process. The welding system having direct current with straight polarity (DCEN) is used during GTAW process. The 1.2mm and 2.4mm diameter welding consumable ER 90SB9 filler wire (as per PFBR specification) is used for welding. The 1.2mm diameter filler wire is used for root pass & subsequent one pass and 2.4mm diameter filler wire is used for welding of remaining all the passes. All modified 9Cr-1Mo weld joints are preheated at 200-250^{0}C and interpass temperature is maintained at 200-250^{0}C. After welding, post heating is carried out at 200^{0}C for 2 hours. The shielding rate and purging rate of argon gas is maintained at 20 LPM and 10 LPM respectively for the 30mm thick test coupons. Subsequently, the test coupons were subjected to Post Weld Heat Treatment (PWHT) at

760±10^{0}C for 4 hours soaking time. The heating rate and cooling rate during PWHT is controlled at the rate of 20^0 to 25^{0}C/hour to avoid thermal shock and distortion.

The welding procedure is qualified with stringent destructive and non-destructive examinations & testing before executing welding on the actual job. The qualification test coupons were subjected to all the non-destructive examinations applied in fabrication of actual job. During procedure qualification, weld joints were subjected to thorough visual examination, Liquid Penetrant Examination (LPE), Radiography Examination (RE), Longitudinal and transverse tensile test at ambient temperature as well at high temperature (525^{0}C), bend tests, RTNDT, Charpy V notch impact test, hardness survey and metallographic examination at 200X magnification for the complete transverse section of the weld.

Production Test Coupons (PTCs) were welded for every 20m of production weld length adapting same welding process parameters of procedure qualification and job welds to ascertain and control the quality of welds during production. The PTCs were subjected to all the destructive and non-destructive examinations & testing carried out during welding procedure qualification. 3 sets of production test coupons were welded using cold wire GTAW process on the 30mm thick test coupons. Totally 15 numbers of production test coupons were welded using hot wire GTAW process on 30mm thick test coupons, as most of the welding of 30mm thick components of Steam Generators were carried out using hot wire GTAW process.

4. Testing procedure of qualification test coupons

The following paragraph discusses the procedure adapted during testing of qualification test coupons.

4.1Tensile Test

After completion of satisfactory non-destructive examinations of the qualification test coupons, the tensile testing is carried out as per the conventional procedure as per ASTM E8 and ASTM E21. The longitudinal and transverse tensile tests were carried out at room temperature as well at high temperature (525^{0}C). The tensile test specimens from the qualification coupons were taken from different zones to check the consistency and uniformity of the properties.

4.2 Micro Hardness Test

The micro-hardness testing was carried out as per ASTME-384 using Vickers hardness testing machine. Diamond indenter (pyramid) with face angle of 136° is used. For testing, sample was prepared upto mirror finish and etched with Villella’s reagent to identify the weld, Heat Affected Zone (HAZ) and base metal. During testing, load of 1 kg is applied on sample with dwell time of 15 seconds. After putting indentation, both the diagonals of pyramid indenter (d1 and d2) are measured with microscope at magnification of 500X.

4.3 Reference Temperature – Nil Ductility Transition (RTNDT) Test

The upper limit for RTNDT test has been specified to be -15ºC. The RTNDT test is carried out by drop weight test as per ASTM E208 during which P2 type specimens were selected. Approximately 50mm wide crack-starter weld is deposited on the tension surface of drop weight specimen using 5mm diameter UTP 350 electrodes with minimum 350 BHN hardness. At the centre of the bead length, a notch is cut as per ASTM E208. The specimen is oriented so that the longitudinal axis is transverse to the weld seam with the notch in the centerline of the weld face so that the crack propagates in the direction of the weld root. The specimen positioned in the anvil is deflected by a free falling weight with an adequate energy, which is dependent on the yield strength of the material to be tested. The specimen is considered broken if the crack starting from the notch of the weld bead propagates to one or both edges of the tension surface. Subsequently impact test is carried out at 33K above TNDT and impact energy = 68 joules (minimum) and lateral expansion= 0.9 mm (above)have been met as per the specification requirement.

4.4 Charpy V notch Impact Test

Charpy-V notch impact test specimens of 10 mm x 10 mm section having a 2 mm deep V notch at an angle of 45°, with a root radius of 0.25 mm is machined. The orientation of specimen for welded joints is transverse to the weld and the base of the notch shall always be perpendicular to the welded surface (in the direction of weld). Impact test specimens were taken transverse to the weld from top and bottom portion of weld. The top weld specimen is located as close as possible to that surface of the weld joint where the last heavy bead has been deposited (but not more than 3 mm from surface). The test specimens were immersed in the liquid bath maintaining at test temperature for at least 5 minutes period. Specimens were broken within 5 seconds from the time of removal from the bath.

4.5 Metallographic Examination

Metallographic examination of weld metal is carried out to evaluate the structure by means of a light optical microscope (Model No. OLYMPUS -GX-51 F, Serial No. 7B 18867). The surface to be examined for metallography is prepared initially by milling and grinding.Subsequently sample surface is polished using emery at 120,220,320,400 and 600 grit papers as per ASTM E3. After emery polishing, diamond polishing is done to obtain the mirror finished surface which is free from scratches. Prepared sample is etched to reveal the structure using Vilella's reagent etchant (1gm picric acid+5ml HCl+100ml methanol). After etching, sample is cleaned in running water and subsequently with acetone and dried. The sample is examined under the optical microscope at 500X magnifications.

5. Results and discussion

5.1 Results and observations of welds during welding procedure qualification

Systematic evaluation is carried out for mechanical properties of 12mm, 30mm and 62mm thick modified 9Cr-1Mo welds produced by hot wire GTAW and cold wire GTAW processes during welding procedure qualification. It is noted that weld metal has qualified all the destructive testing/mechanical properties and non-destructive examinations as per specification requirements irrespective of welding process. i.e. Cold wire GTAW process or Hot wire GTAW process.

However, during impact testing at 0^0C, it was found that the toughness of weld metal produced by cold wire GTAW process is superior than the weld metal produced by hot wire GTAW process. The impact toughness value observed at 0^0C for 30mm thick qualification test coupon welded using cold wire GTAW process is 205 Joules. The impact toughness value observed at 0^0C for 30mm thick qualification test coupon welded using hot wire GTAW process was 108 Joules, which is nearly half the impact toughness value of cold wire GTAW process. Hot wire GTAW process qualification test coupon welded in 62mm thickness has further reduced the impact properties to 54 Joules. The impact toughness value observed at 0^0C on different 12mm thick qualification test coupons welded using cold wire GTAW process found to be equal and greater than 150 Joules. However, there were no recordable variations observed in tensile properties at ambient temperature as well at high temperature (525^0C) for the welds produced using both the processes. As welded hardness and heat treated hardness values were also found almost comparable for both the processes.

5.2 Results and observations of welds in 30mm thick production test coupons

Based on the observations during welding procedure qualification, further studies have been carried out to find out the trends of mechanical properties in various production test coupons during manufacture. In hot wire GTAW process, the welding of 30mm thick production test coupons was carried out with average 23 numbers of weld layers. The average number of weld layers during welding of 30mm thick production test coupons using cold wire GTAW process was 34. In both the above processes, 1.2mm diameter filler wire was used for root pass &subsequent

one pass and 2.4mm diameter filler wire was used for remaining all the passes. During the course of manufacture, weld metal in the production test coupons have qualified all the destructive testing/mechanical properties and non-destructive examinations as per the specification requirements irrespective of welding process. i.e. Cold wire GTAW process or Hot wire GTAW process. The following paragraph explains the various test results of welds made on the 30mm thick production test coupons using cold wire GTAW process and hot wire GTAW process.

Figure 2 : Hardness values after heat treatment for the 30mm thick weld coupons produced by coldwire GTAW process

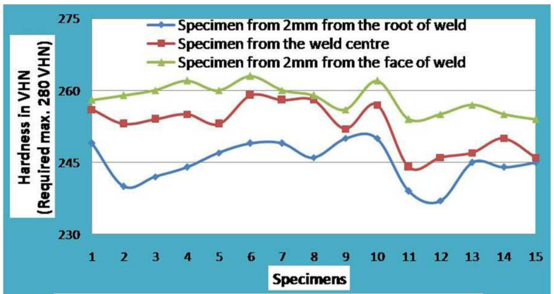


Figure 3: Hardness values after heat treatment for the 30mm thick weld coupons produced by hot wire GTAW process

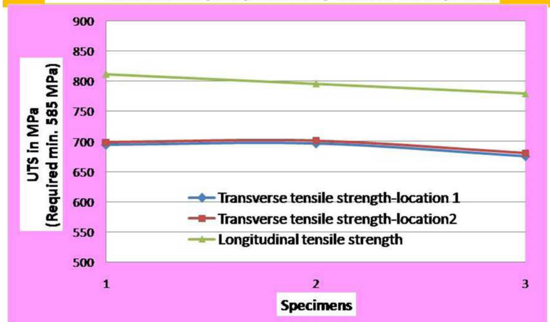


Figure 4: Room temperature tensile strength for the 30mm thick weld coupons produced by cold wire GTAW process

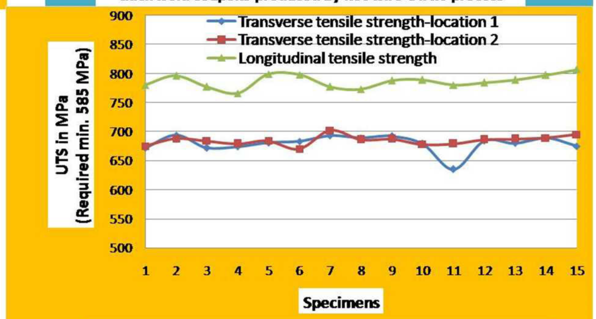


Figure 5: Room temperature tensile strength for the 30mm thick weld coupons produced by hot wire GTAW process

Figure-2 and Figure-3 shows the distribution of heat treated hardness values of the weld specimens taken from cold wire GTAW process and hot wire GTAW process. It is noted that heat treated hardness values for the specimens of 2mm from the root of the weld, centre of the weld and 2mm from face of the welds were found almost comparable for both cold wire GTAW process and hot wire GTAW processes. However, there is uniform trend in reduced hardness values were noticed on the weld specimens taken 2mm from root of the weld in both the processes. The hardness values of the weld metal specimen taken 2mm from top of the weld were found higher than the hardness values of the weld specimens from bottom portion in both the processes. The hardness values observed on the weld specimens taken from the centre of the weld is found in-between the hardness values of top and bottom layer of welds in both the welding processes viz. Cold wire GTAW process or hot wire GTAW process. The trend of decrease in hardness value of weld from the face of the weld to the root of weld is due to tempering effect of the each weld bead by the subsequent weld bead during welding.

There were no recordable variations observed in tensile properties at ambient temperature as well at high temperature (525^0C) for the welds produced using cold wire GTAW and hot wire GTAW processes. Figure-4 and Figure-5 shows the results of room temperature tensile test carried out on the weld specimens taken from cold wire GTAW process and hot wire GTAW process. It is noted that room temperature tensile strength of the welds were found almost comparable for both the GTAW processes. However, the tensile strength values of the weld specimens taken along the length (Longitudinal specimens) were found higher than the tensile strength values of specimens taken along the transverse direction (Transverse specimens) in both the processes.

Figure-6 and Figure-7 shows the results of high temperature tensile test (525^{0}C) carried out on the weld specimens taken from cold wire GTAW process and hot wire GTAW process. It is noted that high temperature tensile strength of the welds were also found almost comparable for both the processes. However, the tensile strength values of the weld specimens taken along the length (Longitudinal specimens) were found higher than the tensile strength values of the weld specimens taken along the transverse direction (Transverse specimens) in both the cases.

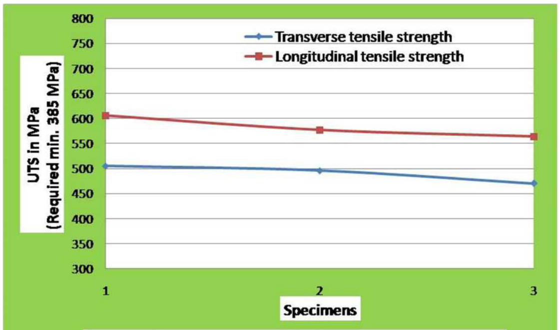


Figure 6: High temperature (525^{0}C) tensile strength for 30mm thick weld coupon produced by cold wire GTAW process

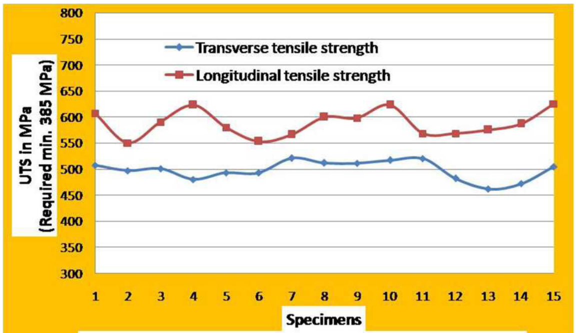


Figure 7: High temperature (525^{0}C) tensile strength for the 30mm thick weld coupons produced by hot wire GTAW process

Figure-8 and figure-9 shows the results of V notch impact test carried out at +18^{0}C on the specimens taken from ¼th thickness from top of the welds of cold wire GTAW process and hot wire GTAW process. During impact testing at +18^{0}C, it was found that the toughness of weld metal produced by cold wire GTAW process and hot wire GTAW process are comparable, eventhough there were scattered values exist on the impact strength. Figure-10 and figure-11 shows the results of V notch impact test carried out at 0^{0}C on the weld specimens taken from cold wire GTAW process and hot wire GTAW process. During impact testing at 0^{0}C, it was found that the toughness of weld metal produced by cold wire GTAW process is superior than the weld metal produced by hot wire GTAW process.

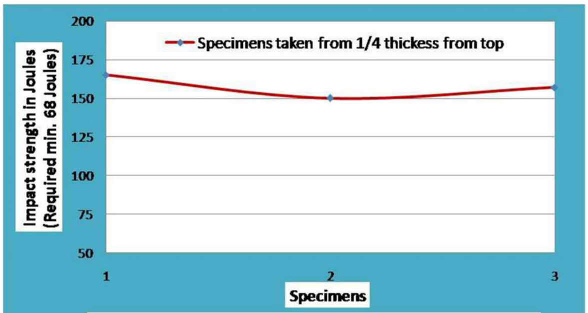


Figure 8: Toughness at +18^{0}C for the 30mm thick weld coupons produced by cold wire GTAW process

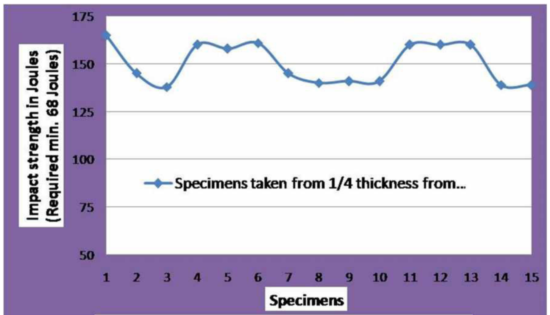


Figure 9: Toughness at +18^{0}C for the 30mm thick weld coupons produced by hot wire GTAW process

The impact toughness value observed at 0^{0}C for 30mm thick production test coupons welded using cold wire GTAW process was in the range of 198 to 205 joules for the specimens taken from root of the welds. The impact toughness value observed at 0^{0}C for 30mm thick production test coupon welded using hot wire GTAW process was in the range of 125 to 185 joules for the specimens taken from root of the welds, which indicates the reduction in impact properties for the welds produced using hot wire GTAW process. The impact toughness value observed at 0^{0}C using cold wire GTAW process for the specimens taken 2mm from top of the welds was in the range of 140 to 157 joules. The impact toughness value observed at 0^{0}C using hot wire GTAW process was in the range of 73 to 135 joules for the specimens taken 2mm from top of the welds. When impact toughness properties at 0^{0}C were compared for the weld specimens produced by cold wire and hot wire GTAW processes, it is obvious from figure-10 and figure-11 that recordable variations were found on the impact strength at 0^{0}C for the specimens taken 2mm from top of the welds as well as root of the weld. Irrespective of location of the weld, it was found that impact properties at 0^0C are inferior for the weld specimens produced by hot wire GTAW process, eventhough requirements as per specification are met.

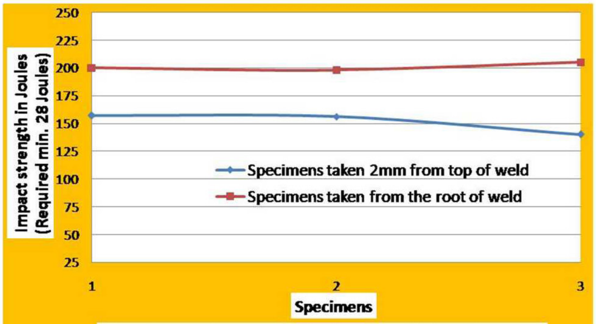


Figure 10: Toughness at 0°C for the 30mm thick weld coupons produced by cold wire GTAW process

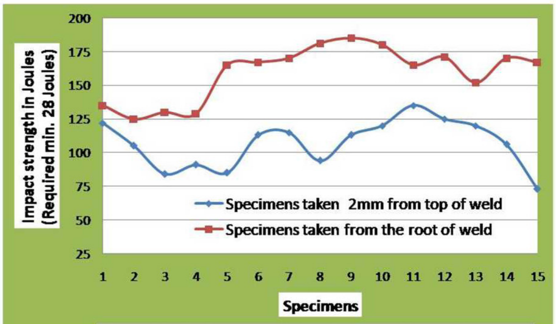
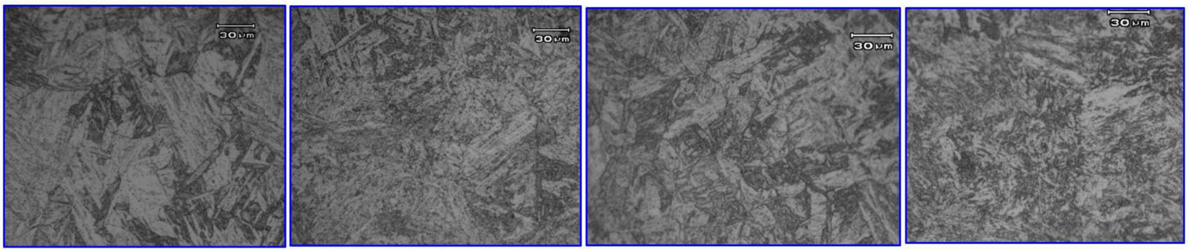


Figure 11: Toughness at 0°C for the 30mm thick weld coupons produced by hot wire GTAW process

During welding of production test coupons, higher deposition efficiency was achieved in hot wire GTAW process than cold wire GTAW process. During hot wire GTAW process, reduced welding speed resulted in reduced number of weld layers with higher thickness of each layer causing higher heat input to the weld. Higher welding speed with higher number of weld layers and reduced thickness of each weld layer in cold wire GTAW process has facilitated effective tempering of the weld beads, which in turn caused for improving the impact properties of the welds. In addition, the hot wire GTAW process is carried out by weaving method, during which each layer is tempered with only one previous weld layer. In cold wire GTAW process, each weld layer is overlapped with two subsequent layers to cover the complete groove width, which might have helped for repeated tempering of previous weld layer for improving the impact properties.



(a) (b) (c) (d)

Figure 12: Micro structure of welds at 500X magnification (a) Hot wire GTAW weld specimen taken from top layer, (b) Hot wire GTAW weld specimen taken from bottom layer, (c) Cold wire GTAW weld specimen taken from top layer, (d) Cold wire GTAW weld specimen taken from bottom layer

In light of all these observations, detailed microstructural analysis is carried out to evaluate the structure at 500X using light optical microscope. Figure12 (a) and 12 (b) shows the tempered martensite structure of weld produced by hot wire GTAW process at 500X magnification on the specimens from top and bottom weld layers respectively. During metallography examination, coarse grains structure is observed on the weld specimens of hot wire GTAW process. Higher heat input to the welds during hot wire GTAW process caused grain growth which in turn reduced the impact property. In addition, relatively more coarse grain structure on the top weld layer is observed compared to the bottom weld layer due to which the impact properties at 0^0C are varied at the top portion as well as bottom portion of the weld (Refer figure-11). More carbide precipitation is seen in the micrographs, which could also be the reason for poor toughness of the welds produced by hot wire GTAW process.

Figure 12 (c) and 12 (d) shows the tempered martensite structure of weld produced by cold wire GTAW process at 500X magnification on the specimens from top and bottom weld layers respectively. During metallography examination, relatively fine grains structure is observed on the weld specimens of cold wire GTAW process compared to weld structure of hot wire GTAW process. Lower heat input to the welds during cold wire GTAW process has caused fine grains structure which in turn improved the impact property. In addition, relatively more fine grain structure on the bottom weld layer is observed compared to the top weld layer due to tempering phenomenon as explained earlier, due to which the impact properties at 0^0C are varied at the bottom portion as well as top portion of the weld (Refer figure-10). Significant carbide precipitation is not seen in the micrographs, which could also be the reason for improved toughness of the welds produced by cold wire GTAW process.

6. Statistical analysis of properties of welds produced by cold wire GTAW and hot wire GTAW process

During impact testing of hot wire GTAW weld specimens, scattered test values were observed and it was not the right choice to conclude the observations based on trends of test values and micro-structure. As there were scattered values of few of other weld properties too, it was decided to evaluate the observations of various test results by mathematical co-relation. Therefore, statistical analysis is carried out using student's t-test for the properties of welds produced by cold wire GTAW process and hot wire GTAW process. The primary objective of this t-test is to compare and evaluate whether the observations of various obtained test results of cold wire GTAW process and hot wire GTAW process are guanine or by chance. A two-sided t-test was chosen for this analysis. The t-value for the test results of each property is estimated using the following equation.

$$t_{estimated} = \frac{x_c - x_h}{\sqrt{\frac{S^2_c}{N_c} + \frac{S^2_h}{N_h}}}$$

Where, X_c and X_h = Means of weld properties of specimens produced by cold wire and hot wire GTAW process, S_c and S_h =Standard deviations of weld properties of specimens produced by cold wire and hot wire GTAW process, N_c and N_h = Number of tests carried out on the weld specimens produced by cold wire and hot wire GTAW process.

Table 1 Results of t-test for the weld properties of hot wire and cold wire GTAW process

Tests	Average test values		Standard deviation of test values		t-value	
	Cold wire GTAW process	Hot wire GTAW process	Cold wire GTAW process	Hot wire GTAW process	$t_{estimated}$	$t_{statistical}$
Impact strength at 0^0C (2mm from top of weld) in Joules	151	107	10	18	+5.9363	±2.63
Impact strength at 0^0C(Root of the weld) in Joules	201	159	4	20	+7.4244	
Impact strength at $+18^0$C (¼ thickness from top of weld) in Joules	157	150	8	10	+1.3227	
Hardness (Specimen taken 2mm from the root of weld) in VHN	248	245	3	4	+1.4877	
Hardness (Specimen taken from centre of the weld) in VHN	256	253	3	5	+1.3887	
Hardness (Specimen taken 2mm from face of the weld) in VHN	258	258	3	3	0.00	
Transverse tensile strength at room temperature (location-1) in MPa	689	679	12	14	+1.2796	
Transverse tensile strength at room temperature (location-2) in MPa	694	685	11	8	+1.3475	
Longitudinal tensile strength at room temperature in MPa	796	787	16	11	+0.0964	
Transverse tensile strength at high temperature (525^0C) in MPa	490	498	18	18	-0.7027	
Longitudinal tensile strength at high temperature (525^0C) in MPa	582	588	22	25	-0.4211	

The properties such as impact strength, hardness, tensile strength were compared from the t-table of statistics at 95% confidence level. A confidence level of 95% corresponds to a probability of finding significant difference between the means of the properties of welds produced by cold wire GTAW and hot wire GTAW process. If $t_{estimated}$falls within the range of $t_{statistical}$, then, it can be said that there is no difference exist for the weld properties of cold wire GTAW and hot wire GTAW process at 95% confidence level. Accordingly, the weld properties of both cold wire GTAW and hot wire GTAW process are said to be reliable and the results are accurate.

It is obvious from the table-1 that all the properties fall within the interval of tabulated value of ±2.63 at a confidence level of 95% except the impact properties at 0^0C for the specimens taken from the root as well as face of the weld. Therefore, with more than 95% confidence level, it can be said that there are genuine difference in the impact properties of the welds produced by hot wire GTAW process and cold wire GTAW process at 0^0C and this is not by chance. Similarly, with more than 95% confidence level from the table-1, it can be said that there are no systematic difference between the welds produced by hot wire GTAW process and cold wire GTAW process in terms of properties such as Hardness, Tensile strength and Impact strength at $+18^0$C. The differences in the means of properties (Hardness, Tensile strength and Impact strength at $+18^0$C) are only due to random errors and not due to any systematic errors except for the impact properties at 0^0C.

Based on statistical analysis, mathematically it can be said that the impact properties (at 0^0C) of welds produced by hot wire GTAW is inferior compared to the welds produced by cold wire GTAW process. Using students t-test, it is proved that various properties obtained from various tests of welds of cold wire and hot wire GTAW process are genuine and are not by chance,as per the comparative observations made in the earlier paragraphs.

7. Conclusion

Impact properties at 0^0C for the modified 9Cr-1Mo welds produced by hot wire GTAW process is inferior compared to welds produced by cold wire GTAW process, eventhough toughness is meeting the specification requirements. During impact testing at $+18^0$C, it was found that the toughness of weld metal produced by cold wire GTAW process and hot wire GTAW process are nearly comparable, eventhough there are scattered values exist on the impact strength. However, there were no recordable variations observed in tensile properties (longitudinal and transverse tensile strength) at ambient temperature as well at high temperature (525^0C) for the welds produced using both the processes. Hardness values were also found almost comparable for both the processes.

With more than 95% confidence level, it was proved by the statistical analysis (t-test) that there are difference in the impact properties (at 0^0C) of the welds produced by hot wire GTAW process and cold wire GTAW process and this is genuine and not by chance. Heat input is a key parameter which shall be controlled during welding process to get the desired impact properties. Grains coarsening during hot wire GTAW process perhaps the major cause for the poor toughness of welds. The modified 9Cr-1Mo welds produced by hot wire GTAW process with higher welding speed & many number of weld layers with reduced thickness of each weld layer may reduce the heat input which inturn improve the toughness of welds. In addition, welding engineers can explore, analyze and characterize the impact properties by overlapping of weld layers instead of weaving of welds during hot wire GTAW process. Better optimization of the process parameters such as current, voltage and welding speed in hot wire GTAW process would certainly improve the impact properties.

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