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A study on cold cracking of high strength steel butt weld joints

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ABSTRACT

Welding of high strength steels has a great risk for forming cold cracking particularly, in case of thick products and preheating is of great importance for avoiding this type of cracking. This research work focused on effect of welding process type, joint thickness, and joint size on preheating level required to avoid cold cracking of high strength steel St. 52. Both manual metal arc ((MMA) and semi-automatic metal active gas (MAG) welding processes were used. It is found that for small size (laboratory scale) joint, cold cracking has been avoided for joint thickness up to 30mm regardless of type of welding process. For thicker and/or larger joint, preheating of about 150^{o}C is necessary for avoiding cold cracking. In both cases, the recommended low hydrogen type welding electrode has been used. Cold cracking susceptibility of high strength steel is primarily related to the microstructure of the HAZ which, in turn, is related to the preheating temperature. A lower preheating level, which resulted in harder microstructure, led to increased susceptibility. Suitable preheating temperature required to prevent cold cracking increased with the increase in joint thickness and/or size. Avoiding or minimizing preheating level is of considerable importance since it will result in reducing welding costs.

KEYWORDS

High strength steels;
Cold cracking;
Preheating temperature;
Welding process;
Joint thickness;
Small- and large-size joint.

INTRODUCTION

Structural steels are widely used in different critical applications such as building, bridges, pressure vessels, and machinery equipment for both military and civil applications. The main risk in welding structural steels is the occurrence of cold cracking in the HAZ zone. This is related mainly to high strength level and high carbon equivalent. Cold cracking of high strength steels is one of the most serious problems that are encountered during welding performance. The cold cracking behaviour of their weld joints is determined by numerous influencing factors that, to some extent, interact with one another. There are any reports[1-6] which deal with cold cracking in relation to alloying elements, microstructure, weld heat input, diffusible hydrogen content and restraint stress. However, it has so far not been possible to determine the effect of all influencing factors to the desired extent. Therefore, there is still no generally accepted concept concerning the material-oriented determination of minimum preheating temperature to prevent cold cracking that takes into account in detail the existing production conditions.

A self-restraint test[7-9] simulates cold cracking in weld more accurately than does an external restraint test[10-12]. The self-restraint test provides, in general, the critical preheating temperature at which cracking is prevented. Cold cracking occurring in a single-pass butt weld has been widely examined using Y-groove restraint test[13, 14]. Cold cracking occurring in a single-pass fillet weld has been researched using controlled thermal severity test which simulates the conditions in a single-pass fillet welding[15, 16]. However, cold cracking occurring in a multi-pass butt weld in large size actual applications has not been extensively researched.

Therefore, in this study, multi-pass butt welds were carried out on both small-size laboratory and large-size actual applications to determine the suitable minimum preheating temperature for cold-crack-free weld of steel 52. The effect of welding process, joint thickness and size was studied.

EXPERIMENTAL PROCEDURE

The material used in this investigation was 10-30 mm thick plates of DIN St. 52 steel which is used as structural steel in many applications including bridges and shipbuilding. The chemical composition and mechanical properties of this steel is shown in TABLE 1.

Welded joints were produced using both manual metal arc (MMA) and semi-automatic metal active gas (MAG) welding processes. Dimensions of butt joint used for MMA and MAG welding are shown in Figure 1. MMA welding was carried out using a low-hydrogen type electrode (E7018) with two different sizes, i.e. 4 and 3.2 mm in diameter. MAG welding was carried out using ER70S filler wire with 1.0 mm diameter. Shielding gas for MAG welding was argon-25%CO_2. The actual welding parameters used are given in TABLE 2. Three different levels of preheats; 25, 75 and 150°C, were utilized for the test. The test was repeated three times for each preheating temperature.

Welded joints were evaluated using different non-destructive and destructive tests. Non-destructive tests included both visual and radiographic investigations while destructive tests included tensile, bending, and impact tests, hardness measurements and metallographic investigation.

Each test piece was transversely cut into three sections after 72 h had passed since completion of the welding. Susceptibility to cracking is determined through both visual examination with a magnifying glass and microscopic examinations using a profile projector. The preheat level at which the three tests remain crack free is designated as preheat required to prevent cracking.

Both microscopic investigations and microhardness measurements were made in base metal, HAZ and weld metal. Five indentations close to the fusion boundary in the HAZ and three in both weld metal and base metal were made using 200 g load. The maximum value of the five indentations of HAZ was taken as the maximum HAZ hardness. The maximum hardness values of the five sections were thus averaged to give a good estimate of the maximum hardness of HAZ.

TABLE 1 : Chemical composition and mechanical properties of the used steel.

Chemical composition (mass %)				
C	**Si**	**S**	**P**	**Mn**
0.11	0.50	0.02	0.03	1.30
Mechanical properties				
Yield strength, MPa	**Tensile strength, MPa**	**Elongation, %**	**Hardness, Hv-10 kgf**	**Impact value, J at - 20 °C**
375	593	25	207	39

TABLE 2 : Welding conditions used.

MMA welding				
Electrode type /diameter (mm)	**Welding variables**			**heat input kJ/mm**
	current A	**arc voltage V**	**welding speed mm/min**	
E7018 / 4.0	137	28	130	1.770
E7018 / 3.2	111	26	130	1.332
MAG welding				
Electrode type /diameter (mm)	**welding variables**			**heat input kJ/mm**
	current A	**arc voltage V**	**welding speed mm/min**	
ER70S / 1.0	280	29	250	1.949

RESULTS AND DISCUSSION

Effect of joint thickness

Cold cracking is a function of microstructure, diffusible hydrogen content of weld metal and tensile strength level of base metal. In order to clarify the effect of microstructure as a function of preheating temperature, both diffusible hydrogen contents of weld metal and tensile strength level of base metal were kept constant. Cross sections of 10 and 30mm thick joints welded using MAG welding process with 25°C preheating are show in Figures 2 and 3 respectively. It can be noticed that crack was initiated and propagated at root of both 10 and 30mm thick joints produced wit such low preheating level. It should be reported that no crack was found in joints produced using either MAG or MMA welding process after preheating it at or higher than 75°C as shown in Figures 4 and 5. Every time a crack propagates, an incubation period of hydrogen accumulation from the surrounding area is necessary. Toe cracking was not observed in this investigation. This has been confirmed by optical microscopic observation of all welded joint cross-sections, where only root cracking was observed. The root crack was initiated and propagated in the coarse grain region of HAZ. The grain coarsened HAZ is the region with the greatest susceptibility to cold cracking since it experiences the fastest cooling rate and also possesses a high hardenability. The crack was terminated at weld metal, where cold cracking eventually stops as it passes the site of critical hydrogen concentration.

For MMA welding, root cracking was more severe in welds on using a 3.2 mm diameter electrode

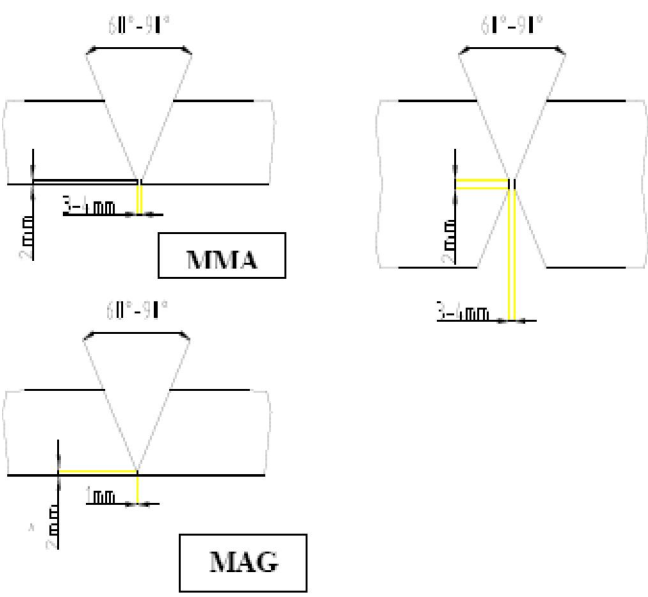

Figure 1 : Dimensions of butt joints used for MMA and MAG welding.

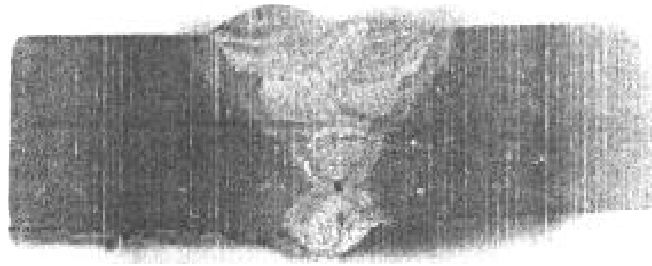

Figure 2 : Macrograph of 10mm thick joint welded using MAG welding process and 25°C preheating.

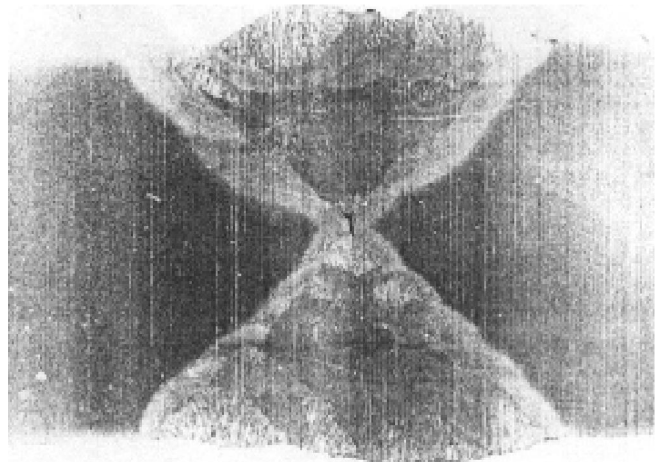

Figure 3 : Macrograph of 30mm thick joint welded using MAG welding process and 25 °C preheating.

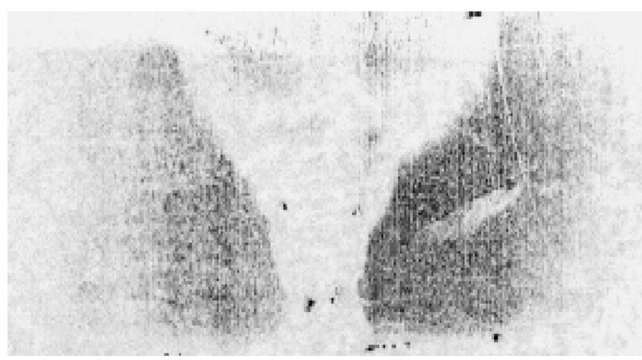

Figure 4 : Macrograph of 20mm thick joint welded using MAG welding process and 75 °C preheating.

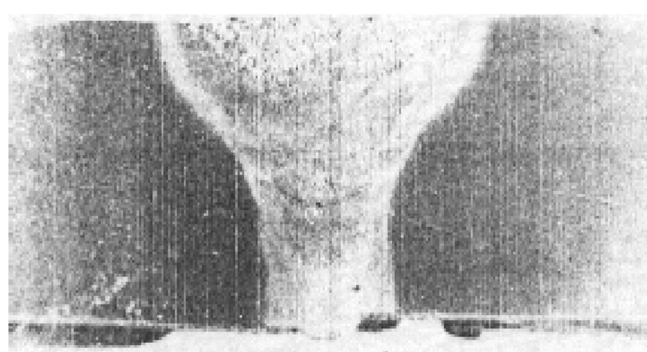

Figure 5 : Macrograph of 20mm thick joint welded using MAG welding process and 75 °C preheating

compared with welds made using 4 mm diameter electrode. This could be attributed to the higher cooling rate on using a 3.2 mm diameter electrode, due to lower heat input (1.332 kJ/mm) in comparison with 1.770 kJ/mm in the case of the 4 mm diameter electrode.

Generally, degree of distortion is largely affected by the angle of the groove where increasing groove angle from 60 to 90 has resulted in unacceptable degree of distortion particularly with thickness equal to or larger than 20mm. Double V joint resulted in less distortion than single V joint that helped in obtaining sound welded joint free from cold cracking for both MMA and MAG welding processes.

Effect of preheating temperature

In order to explain the preheating temperature in dependence of cold crack, both micro-hardness measurements and microstructural investigations were carried out for base metal, HAZ, and weld metal. The micro-hardness profiles across weld metal, HAZ and base metal of both as-welded and 75°C preheated MMA and MAG welded joints are shown in Figure 6. Hardness was measured at three positions (face, mid, & root) on cross section of welded joints. No significant discrepancy between the three test positions could be found. For preheating levels up to 25°C, the hardness value of HAZ was much higher than that of both base and weld metals. This large difference in hardness values of HAZ, base metal and weld metal decreased sharply with increasing preheating temperatures to 75°C. The HAZ maximum hardness decreased from 419 HV at 25°C preheating temperature (as-welded) to 250 HV at 75°C preheating temperature.

The obtained hardness profile corresponds to the change in the microstructure. In other words, the increase in hardness in heat affected zone is attributed to its microstructural change. Martensitic transformed microstructures in HAZ has the highest degree of hardness. Generally, the HAZ hardness is regarded as a rough index describing the susceptibility to cold cracking. The value of 350 HV is often-specified as the maximum allowable HAZ hardness for avoiding cold cracking[17]. However, this maximum HAZ hardness depends on both type of cold cracking test and steel grade. HAZ cracking may initiate at a hardness of less than 300 HV in the Y-groove restraint test and may not occur even at 500 HV in bead-on-plate underbead testing if a low-hydrogen electrode is used. Line pipe steels and pressure vessel steels for sour gas service, where ASTM A 516-70 steel is used, are required to satisfy a HAZ hardness of about 250 HV, primarily to avoid hydrogen induced stress corrosion cracking in service[18]. In this study, the maximum allowable HAZ hardness was obtained at preheating temperature of 75°C.

Two bend and two tensile test specimens were machined for checking bending and tensile properties. Results of bend test showed high degree of soundness and ductility of welded joints since no indication of welding defects was observed after U-bends were made, for both MMA and MAG welded joints produced with 75°C preheating. The results of the transverse tensile test for welded joints produced using MMA and MAG welding processes and 75°C preheating are summarized in TABLE 3 and Figure 7 and 8. It can be seen that acceptable tensile strength was obtained for welded joints produced using both MMA and MAG welding processes and 75°C preheating, compared with

TABLE 3 : Results of tensile test of as-welded joints.

Process / Ø / t	Tensile strength, MPa	Fracture feature / location
MMA-4.0 /10	690.5	Ductile / base metal
MMA-3.2 /10	605.5	Ductile / base metal
MMA-4.0 /20	591.7	Ductile / base metal
MMA-3.2 /20	606.6	Ductile / base metal
MMA-4.0 /30	599.7	Ductile / base metal
MMA-3.2 /30	607.3	Ductile / base metal
MAG-1.0 / 10	575.3	Ductile / base metal
MAG-1.0 / 20	590.7	Ductile / base metal
MAG-1.0 / 30	597.4	Ductile / base metal

Process / Ø / t : welding process / electrode diameter / joint thickness

TABLE 4 : Results of Charpy impact test of as-welded joints.

Process / Ø / t	Absorbed energy, J at -25 °C
MMA-4.0 /10	20
MMA-3.2 /10	19
MMA-4.0 /20	20
MMA-3.2 /20	18
MMA-4.0 /30	18
MMA-3.2 /30	17
MAG-1.0 / 10	22
MAG-1.0 / 20	21
MAG-1.0 / 30	19

Process / Ø / t : welding process / electrode diameter / joint thickness

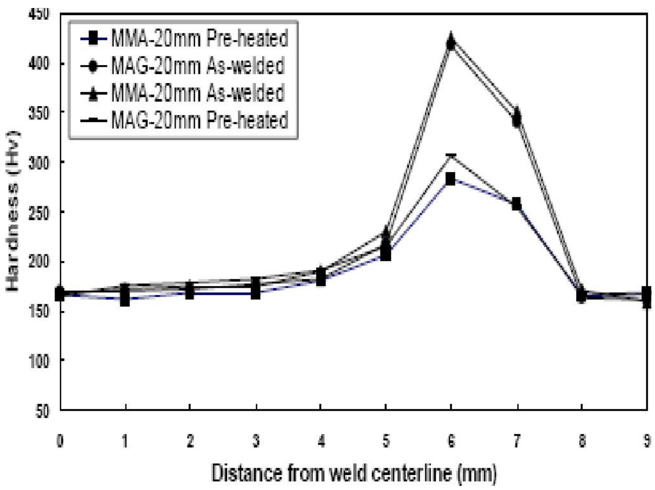

Figure 6 : Micro-hardness profiles across weld metal, HAZ and base metal of both as-welded and 75 °C preheated MMA (4mm electrode diameter) and MAG welded joints.

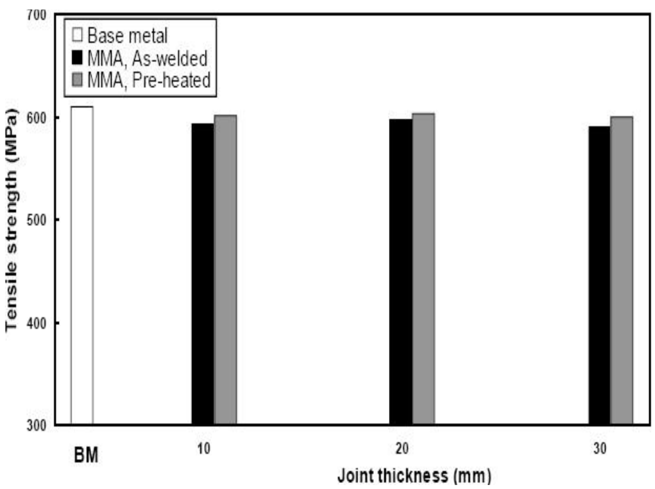

Figure 7 : Results of tensile test for joints produced using MMA welding process (4mm electrode diameter) with 75 °C and without preheating.

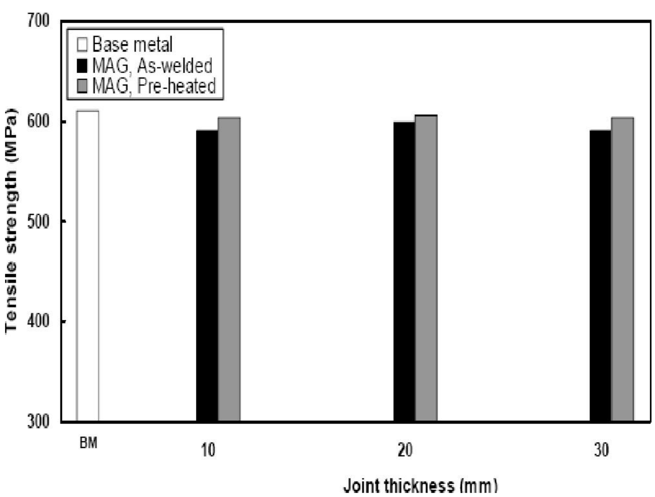

Figure 8 : Results of tensile test for joints produced using MAG welding process, with 75 °C and without preheating.

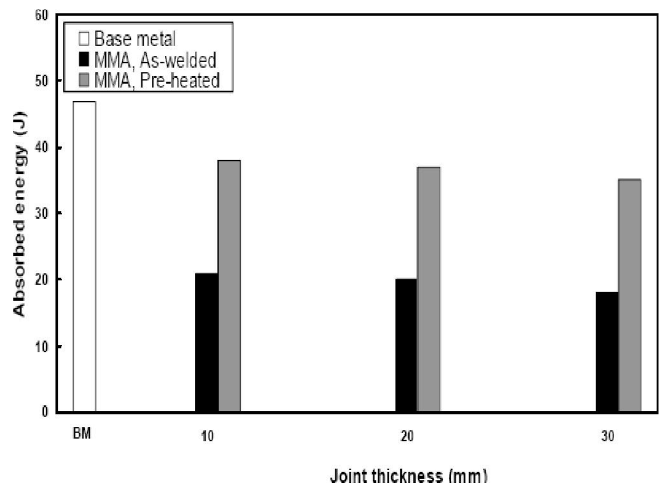

Figure 9 : Results of Charpy V-notch impact test, at room temperature, for joints produced using MMA welding process (4mm electrode diameter), with 75 °C and without preheating.

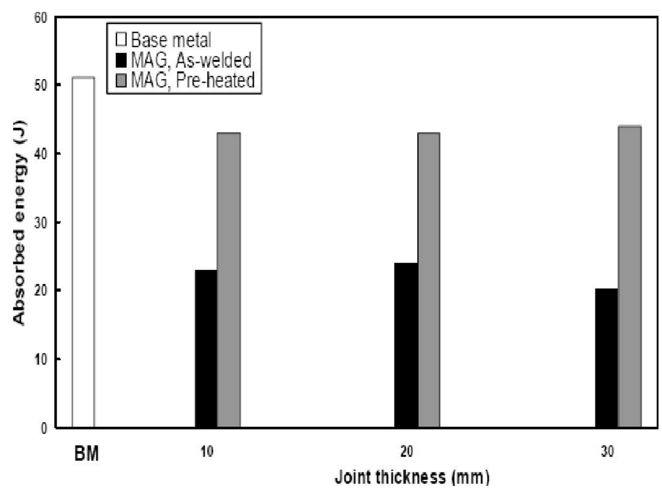

Figure 10 : Results of Charpy V-notch impact test, at room temperature, for joints produced using MAG welding process, with 75 °C and without preheating.

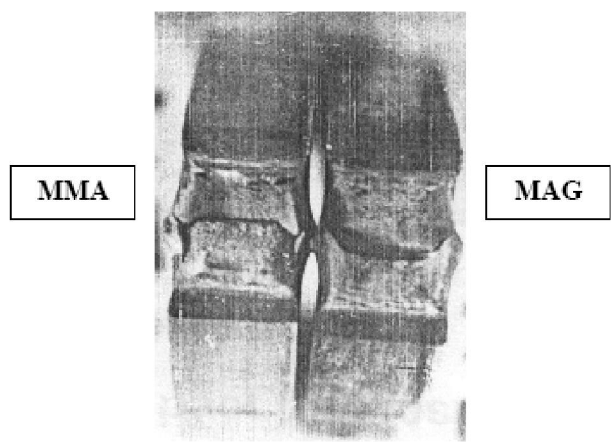

Figure 11 : Macrograph of fracture surface of impact tested joints produced using MMA (4mm electrode diameter) and MAG welding processes.

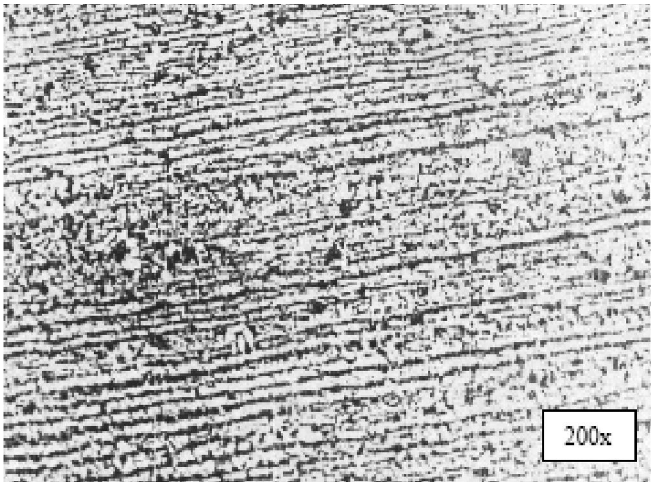

Figure 12 : Optical microstructure of the used base metal.

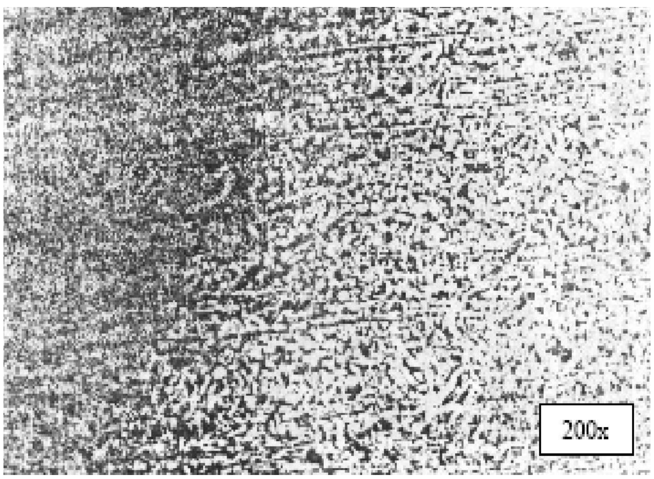

Figure 13 : Optical microstructure of fine grain HAZ of 75°C preheated joint produced using MAG welding process.

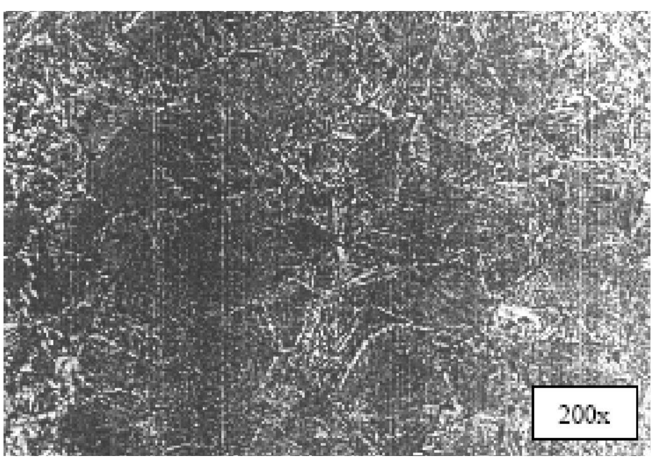

Figure 14 : Optical microstructure of coarse grain HAZ of 75°CV preheated joint produced using MAG welding process.

that of base metal. However, there was a considerable decrease in the elongation of welded joints. The low ductility of welded joints is caused by phase transfor-

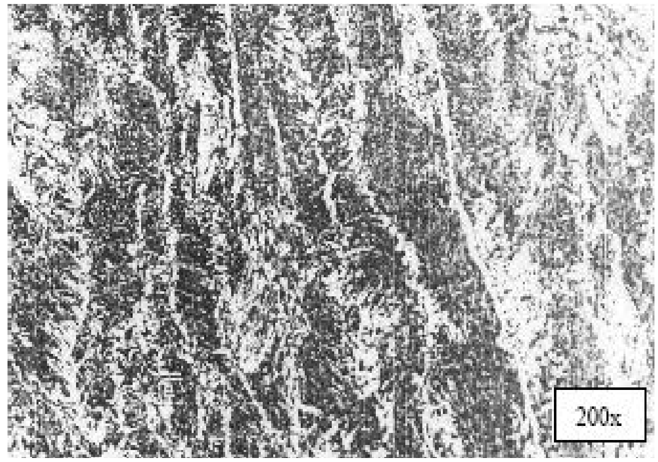

Figure 15 : Optical microstructures of weld metal of 75°C preheated joint produced using MAG welding process.

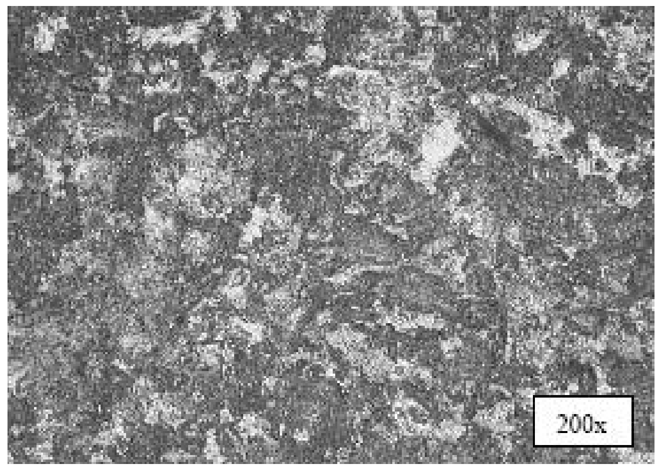

Figure 16 : Optical microstructure of coarse HAZ of 25°C preheated joint produced using MAG welding process

mation in HAZ that caused strength overmatch.

The failures of tensile tested joints occurred in base metal outside of the fusion zone. The predominantly martensite produced in the HAZ exhibit hardness and strength levels higher than those of the unaffected base metal. Results of Charpy V-notch impact test, at room temperature, for joints produced using MMA and MAG welding processes with 75°C and without preheating are shown in Figures 9 and 10. It is clean that impact absorbed energy of preheated joints is much higher than that of non-preheated ones where values close to that of base metal were obtained. Visual and macroscopic examination of fracture surface of impact tested MMA and MAG joints showed ductile fracture surface of the preheated weld joints (Figure 11).

In comparison with MMA welding, MAG welding results in relatively narrow weld bead width in addition to better mechanical properties. This is attributed to relatively lower cooling rate as a result of higher heat input. MAG welding process has also the advantage of higher welding speed that mean higher productivity than MMA welding process.

Regarding microstructural investigations, Figure 12 shows optical microstructure of the used base metal. This microstructure consists of ferrite-pearlite bands with pearlite lamellar morphology. Optical microstructures of fine and coarse grain HAZ are shown in Figures 13 and 14 while that of weld metal of joint produced using MAG welding and 75 °C preheating are shown in Figure 15. It is worthy to note that cracking was not obtained at this preheating level where HAZ had a bainitic structure. In other words, the microstructure of HAZ is free from martensite phase. The microstructure of weld metal showed isolated regions of polygonal ferrite (PF) in a matrix of acicular ferrite.

From the foregoing, it can be deduced that occurrence of cold cracking in HAZ rather than weld metal is attributed to higher hardness values, due to forming of harder martensitic microstructure as shown in Figure 16. The most important factor which influence HAZ microstructure or hardness and thus the susceptibility to cold cracking is the preheat level. Preheating reduces the maximum cooling rate, which occurs in the heat-affected zone during welding. This could result in softer structures being produced in the HAZ. The other effect of preheat is to maintain temperatures in the heat affected zone above a critical temperature long enough to permit hydrogen to diffuse out of that zone during cooling. Consequently, both HAZ softer structure and lower hydrogen content in HAZ will help in the prevention of cold cracking.

In general, preheating temperature depends on carbon equivalent, joint thickness and diffusible hydrogen content of weld metal. The higher carbon equivalent and/or the thicker joint thickness, is the higher preheating temperature. In order to reduce the minimum preheating temperature required to prevent cold cracking, the low hydrogen electrodes must be properly stored and kept dry away from a humid atmosphere.

CONCLUSIONS

In view of the results achieved in this study the following conclusions can be drawn:

- Cold cracking of high strength steel St. 52 was sited at HAZ only due to higher hardness than that of weld metal particularly, for 20 and 30mm thick joints.

- The susceptibility of this type of steel to cold cracking decreased with increasing preheating temperatures where higher preheating temperatures produced softer microstructures, which helped in depression of cold cracking;

- Minimum preheating temperature of 75 °C was suitable to prevent cold cracking in the case of MMA and MAG welding. This preheating level resulted in hardness values less than the maximum allowable HAZ hardness to avoid cold cracking. However, higher preheating level is necessary for larger joint size.

- Degree of distortion is largely affected by the angle of the groove, increasing groove angle from 60 to 90 has resulted in unacceptable degree of distortion particularly with thickness equal to or larger than 20mm.

- Double V joint resulted in less distortion than single V joint that helped in obtaining sound welded joint free from cold cracking for the used high strength steel (St 52).

- In comparison with MMA welding, MAG welding has the advantage of high welding speed and relatively narrow weld bead width in addition to better mechanical properties. This is attributed to relatively lower cooling rate as a result of higher heat input.

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