Weldability Evaluation of High Tensile Plates Using GMAW Process

R. Datta, D. Mukerjee, K.L. Rohira, and R. Veeraraghavan

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High tensile plates, SAILMA-450 high impact (HI) (yield strength, 45 kg/mm^2 minimum; ultimate tensile strength, 57 kg/mm^2 minimum; elongation, 19% minimum; Charpy impact energy 2.0 kg.m at –20 °C minimum) were successfully developed at the Steel Authority of India Ltd., up to 32 mm plate thickness. Since then the steel has been extensively used for the fabrication of impellers, bridges, excavators, and mining machineries, where welding is an important processing step.

The present study deals with the weldability properties of SAILMA-450 HI plates employing the gas metal arc welding process and carbon dioxide gas. Implant and elastic restraint cracking tests were conducted to assess the cold cracking resistance of the weld joint under different welding conditions. The static fatigue limit values were found to be in excess of minimum specified yield strength at higher heat input levels (9.4 and 13.0 kJ/cm), indicating adequate cold cracking resistance. The critical restraint intensities, K_{cr}, were found to vary between 720 and 1280 kg/mm^2, indicating that the process can be utilized for fabrication of structures involving moderate to low restraint intensities (200 to 1000 kg/mm^2). Lamellar tear tests conducted using full thickness plates at heat input levels ranging from 10 to 27 kJ/cm showed no incidence of lamellar tear upon visual, ultrasonic, and four-section macroexamination. These tests were repeated using machined plates, such that the midthickness of the plates (segregated zone) corresponded to the heat affected zone of the weld. No cracks were observed, indicating good lamellar tear resistance of the weld joint. Optimized welding conditions were formulated based on these tests. The weld joint was subjected to extensive tests to assess the physical properties and soundness of the weld joint. The weld joint exhibited good strength (64.7 kg/mm^2) and impact toughness (5.7 and 3.5 kg.m at –20 °C for weld metal and heat affected zone properties. Crack tip opening displacement (CTOD) tests carried out for parent metal, heat-affected zone, and weld metal resulted in δm values of 0.41, 0.40, and 0.34 mm, respectively, which indicates adequate resistance to cleavage fracture. It was concluded that the weld joint conforms to the requirements of SAILMA-450 HI specification and ensures a high integrity of the fabricated products.

Keywords cold cracking, gas metal arc welding, impact toughness, lamellar tear, restraint intensity, thermomechanical controlled processing

1. Introduction

Increasing emphasis by designers and builders on lighter, cost effective materials has provided impetus for the development of high tensile steels with superior performance capabilities. The introduction of thermomechanical controlled processing (TMCP) has paved the way toward the development of a new generation of high strength steels (yield strength, 350 to 550 MPa) through controlled processing of austenite, leading to a fine ferrite grain size upon cooling. The addition of microalloying elements such as niobium, titanium, and vanadium facilitates the austenite conditioning process (Ref 1-3), lowers the transformation temperature (Ref 4), and also induces some amount of precipitation hardening of the ferrite (Ref 5). Exhaustive research in this area has shown that the effectiveness of austenite conditioning can be quantified through the parameter, S_v, the total interfacial area of near planar crystalline defects that can exist in a polycrystalline aggregate (Ref 6-8). Because these defects act as nucleation sites for ferrite during transformation, larger values of S_v are associated with finer ferrite grain size, leading to a concomitant enhancement of strength, ductility, and impact toughness properties (Ref 9-10).

The development of microalloyed steel plates in SAIL was initiated by its Research and Development Centre in 1975, using the microalloying elements niobium and vanadium, singly or in combination (Ref 11). Initially two grades under the trade name SAILMA 300 and 350 (yield strength, 30 and 35 kg/mm^2 minimum) were produced. Later these grades were upgraded to a high impact (HI) variety by controlling the steel chemistry to lower levels of carbon equivalent and hot rolling parameters to induce a finer ferrite grain size. Subsequently, SAILMA-410 HI (yield strength, 41 kg/mm^2 minimum), and very recently, SAILMA-450 HI (yield strength, 45 kg/mm^2 minimum) (Ref 12) were developed and commercialized using TMCP technology.

The resistance of a steel to two basic types of weld cracking, cold and hot cracking, forms the basis of weldability assessment (Ref 13-15). Cold cracking, also referred to as hydrogen induced cracking (HIC), is related to the entrapment of hydrogen atoms in the weld pool during welding. These hydrogen

R. Datta and **D. Mukerjee,** Research and Development Centre for Iron and Steel, Steel Authority of India Limited, Ranchi 834002, India; **K.L. Rohira** and **R. Veeraraghavan,** Welding Research Institute, BHEL, Tiruchirapalli 620014, India. Contact e-mail: dm@rdcis.bih.nic.in.

ions diffuse to the defect sites, such as grain boundary, dislocations, and inclusions, and combine together forming hydrogen molecules, which are incapable of further migration. A buildup of hydrogen molecules at such trap sites leads to high internal pressure and induces cracking. In addition to hydrogen content, the carbon equivalent (CE) and the microstructure of the weld metal (WM) and heat affected zone (HAZ) strongly influences the cold cracking susceptibility. A martensitic structure has the highest susceptibility to HIC, followed by bainite, acicular ferrite, and ferrite-pearlite structures.

A comprehensive study was conducted to assess the resistance of SAILMA-450 HI steel to cold cracking using the gas metal arc welding (GMAW) process. Additionally, the lamellar tear resistance of the steel under different welding conditions was evaluated. A comparative analysis of weldability properties for the GMAW and the shielded metal arc welding (SMAW) processes was attempted. Finally, based on this work, appropriate welding consumables were identified and parameters optimized to ensure a high integrity of the weld joint.

Table 1 Chemical composition (wt%) of 12 mm thick SAILMA-450 high impact grade plate

C	Mn	Si	Al, min	S, max	P, max	Nb + V, max
0.10-0.12	1.30-1.35	0.30-0.40	0.02	0.01	0.02	0.10

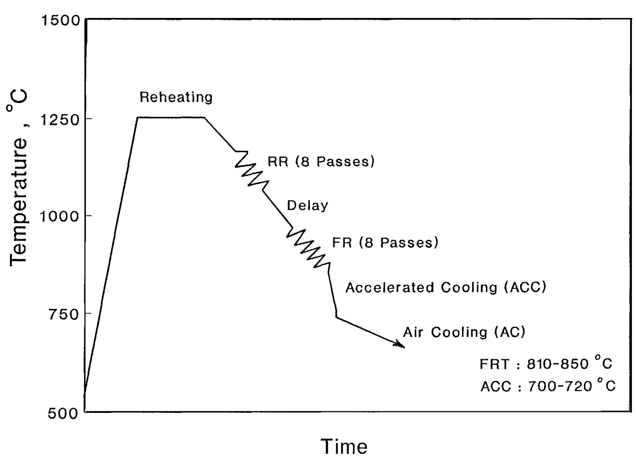


Fig. 1 Thermomechanical controlled processing schedule for processing of SAILMA-450 high impact plates

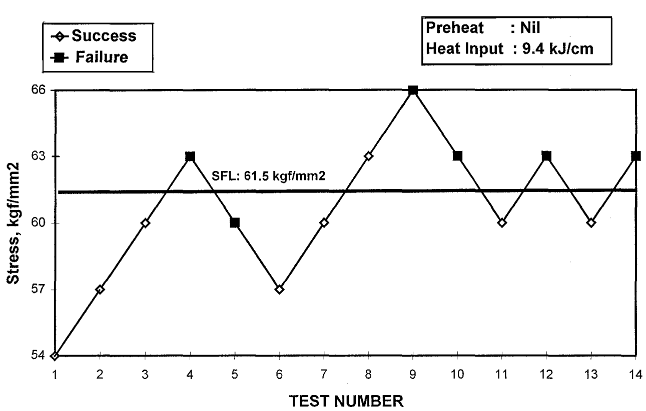


Fig. 2 Static fatigue limit plot for SAILMA-450 high impact steel at a heat input level of 9.4 kJ/cm

2. Experimental

2.1 Alloy Design

Two alloy chemistries were designed for the production of SAILMA-450 HI plates: niobium-vanadium for plates less than 20 mm thickness and niobium-titanium combination for 20 to 32 mm plate thickness. The addition of titanium ensures a finer austenite starting grain size after reheating and also restricts the degree of grain coarsening in the HAZ during welding (Ref 16). A carbon level of 0.10 to 0.14% and a manganese level of 1.30 to 1.35% ensured restriction of CE to 0.35 maximum. Typical values of microalloying elements, such as niobium, vanadium, and titanium that were added were 0.03, 0.05, and 0.02%, respectively.

2.2 Steelmaking and Rolling

Heats of the previous chemistry were made in a 130 T basic oxygen furnace (BOF) and argon purged for 3 to 7 min at a flow rate of 35 to 45 m^3/h to ensure homogenization and uniformity of metal temperature in the ladle. The steel was next treated in 110 T vacuum arc degassing (VAD) unit. In addition to enhancing the cleanliness level through reduction of oxygen, nitrogen, and hydrogen levels, it also facilitated effective desulfurization (<0.01%) and fine tuning of composition. The steel was cast into 200 by 1500 mm and 250 by 1500 mm slab casters, depending on the final plate thickness.

The slabs were reheated to 1220 ± 10 °C and control rolled in a 3600 mm plate mill. A TMCP schedule outlining the temperature-deformation scheme for conditioning of the austenite, followed by accelerated cooling, is shown in Fig. 1. The plate entry temperature in the finishing stand was maintained at 950 to 970 °C, which ensured deformation in the austenite nonrecrystallization region. A reduction of 60 to 65% in this zone facilitated elongation of the austenite grains leading to a higher S_v and thereby a finer ferrite grain size on cooling (Ref 17). The finish rolling temperature (FRT) was controlled within 810 to 850 °C followed by spray cooling of the plates to a temperature of approximately 710 ± 10 °C. Strict control over steelmaking and TMCP parameters not only facilitated conformance of mechanical properties (yield strength, ultimate tensile strength, and percent elongation) as per stipulated specifications, it also ensured that the properties were restricted within a very narrow band. Tables 1 and 2 show the chemical composition and properties of SAILMA-450 HI plates.

2.3 Microscopy and Property Evaluation

Optical microscopy was carried out in a MeF_2 model microscope (Reichet, Austria). Longitudinal sections of the plates were polished and etched with 2% nital. The volume fraction of pearlite was determined using a texture analysis system (TAS) quantitative image analyzer (Leitz, Germany).

Tensile samples were prepared per ASTM 10 (PA-370) specification and tested on a 10 ton static universal testing machine (Instron-1195 model, Instron Ltd., High Wycombe, Bucks, UK), at a strain rate of 6.6×10^{-4}/s. Standard Charpy V-notch samples were prepared and tested at room temperature (0 and –20 °C) for Charpy impact energy (CIE). The temperature rise during testing was within 2 °C. Crack tip opening displacement (CTOD) tests were carried out using an Instron-8502 system (Instron Ltd., High Wycombe, Bucks, UK) per the BS 7448 Part 1 (1991) specification.

2.4 Weldability Evaluation

The cold cracking susceptibility of the weld joint was determined by the implant test using the GMAW (CO_2) process. The CO_2 gas used was of welding quality with a low moisture and condensable impurity content (dew point less than –40 °C). Three heat input levels were chosen, namely, 6.7, 9.4, and 13.0 kJ/cm. Standard procedure for conducting the test was outlined by the International Institute of Welding in 1973 (Ref 18). In this study one end of a 6 mm diameter cylindrical specimen was inserted with a sliding fit into a hole bored in a plate called the "host plate." The other end of the specimen was threaded to facilitate application of load through a loading bar. A weld bead was laid under conditions of investigation on the host plate across the implant specimen. The setup was allowed to cool to a temperature, usually 100 °C, before a static tensile load was applied to the implant specimen by a "constant loading system" until failure occurs or there is a time lapse of 24 h, whichever is earlier. The maximum stress that the material could withstand without failure for 24 h was determined by testing at different stress levels. This critical stress level for cracking is known as the static fatigue limit (SFL).

Table 2 Mechanical properties of 12 mm thick SAILMA-450 high impact grade plate

Yield strength, kg/mm^2	Ultimate tensile strength, kg/mm^2	Elongation, %	Charpy impact energy at –20 °C, kg · m
47-51	57-62	22-27	5-11

In the elastic restraint cracking (ERC) test, a two-part plate specimen was clamped rigidly into the clamping frame with high strength bolts. The material and geometry of the frame was chosen because it behaves elastically at all levels of reaction stress. In the test, different levels of restraint intensities were generated depending on the restraining frames and welding conditions. Weld cracking occurred when the restraint intensity, K, imposed was higher than a critical level, known as the critical restraint intensity, K_{cr}. The K_{cr} value was determined under different welding conditions.

The lamellar tear test involved welding a cantilever to a rigid vertical test plate by depositing a multirun weld in a 45 °C bevel groove while maintaining a constant level of through-thickness stress called the weld restraint load (WRL). The test plates were allowed to be under load for 24 h to allow hydrogen-induced cracks (HIC) to initiate and trigger lamellar tear.

3. Results and Discussion

3.1 Implant Test

Table 3 presents the implant test results on a 12 mm thick plate. The welding was carried out using AWS 5.28 ER SG (Kobe MGW 588; under tradename KOBELCO by Kobe Steel Ltd., Japan) electrode wire of 1.2 mm diameter. The SFL values obtained for the three heat input conditions (6.7, 9.4, and 13.0 kJ/cm) were 44.4, 61.5, and 71.5 kg/mm^2. The SFL values, except for those obtained using a heat input level of 6.7 kJ/cm (44.4 kg/mm^2), were well in excess of the minimum specified yield strength (MSYS) of 45 kg/mm^2, indicating adequate resistance to cold cracking. Figure 2 shows the SFL plot for the steel using a heat input of 9.4 kJ/cm. It can be noted that SFL values were determined on the basis of a series of stepwise tests carried out at different stress levels.

The type of heat flow and corresponding cooling time from 800 to 500 °C ($\Delta t_{8/5}$) for implant tests at three heat input levels (6.7, 9.4, and 13.0 kJ/cm) as well as for the butt welding test using GMAW (CO_2) process are shown in Table 4. The cooling times for the implant and butt weld tests match reasonably well, especially at lower heat input levels (6.7 and 9.4 kJ/cm), indicating that the welding thermal cycles for the two

Table 3 Static fatigue limit values of SAILMA-450 high impact plates under different welding conditions

Type of electrode	Welding conditions: Arc voltage, V	Current, A	Heat input, kJ/cm	Static fatigue limit, kg/mm^2
AWS 5.28 ER 80 SG	23	170	6.7	44.4
	23	170	9.4	61.5
	27	200	13.0	71.5

Table 4 Type of heat flow and cooling time ($\Delta t_{8/5}$) for implant and butt welding tests

Welding process	Heat input, kJ/cm	$\Delta t_{8.5}$ for implant, s	$\Delta t_{8/5}$ for butt welding, s	Heat flow type, butt weld
Gas metal arc welding	6.7	3.1	2.8	3D
	9.4	4.3	4.7	2D
	13.0	6.0	9.0	2D

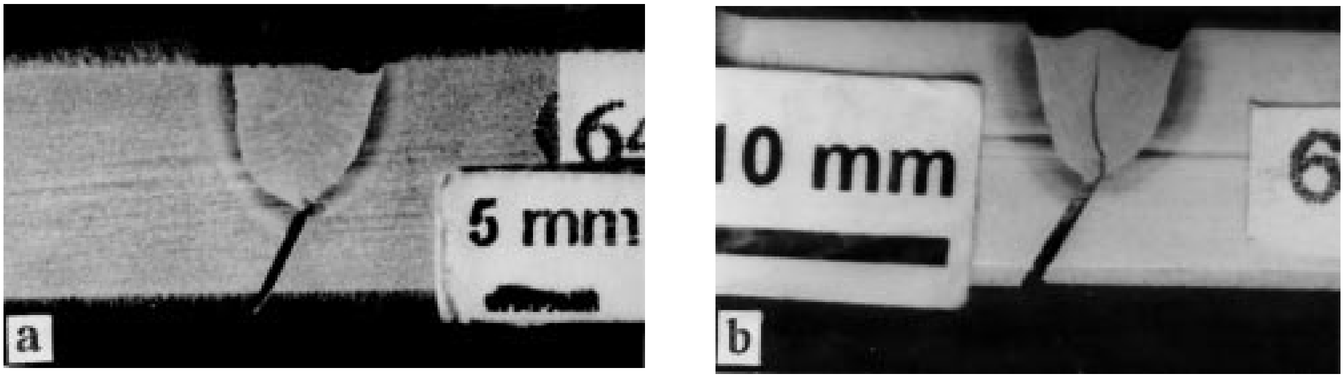


Fig. 3 Macrophotographs of (a) a sound and (b) a cracked weld joint obtained at restraint levels of 630 and 2560 kg/mm^2, respectively

Table 5 Elastic restraint cracking test results for SAILMA-450 high impact plates under different welding conditions

Electrode type	Welding conditions: Root gap, mm	Preheat, °C	Heat input, kJ/cm	Critical restraint intensity, K_{cr}, kg/mm^2
AWS 5.28 ER 80 SG	Nil	Nil	6.7	1280
	Nil	Nil	9.3	1170
	0.6	Nil	12.9	720

Table 6 Restraint intensities for different structural applications

Applications	Location	Thickness, mm	Restraint intensity, K, kg/mm^2
Ship	Transverse bulk head	16	1640
	Longitudinal bulk head	14	1260
	Bottom shell	28	780
	Upper deck	32	1280
Bridge	Diaphragm and web plate	19-38	200
	Diaphragm and flange plate	40-60	1800
Building frame	Building column construction	28	1090

tests are similar. With an increase in the heat input level, the cooling time progressively increased from 3.1 to 6.0 s for the implant test and 2.8 to 9.0 s for the butt welding test. This resulted in a corresponding decrease in the cooling rate and minimized the chances of formation of a hard and brittle structure at the weld joint. Further, a slower cooling rate below 500 °C, especially in the temperature range of 300 to 100 °C facilitated diffusion of hydrogen from the weld joint and the combination of these two factors, lead to a higher SFL value (71.5 kg/mm^2) at a heat input level of 13.0 kJ/cm.

3.2 Elastic Restraint Cracking

The sensitivity of cracking of the root layer in butt welding was tested by imposing different levels of restraint intensities, varying from 630 to 4630 kg/mm^2. Oblique Y grooves were machined for the test joints. Table 5 shows the welding conditions used and the K_{cr} values determined. Figures 3(a) and (b) show the macrophotographs of a sound and a cracked weld joint subjected to restraint intensities of 630 and 2560 kg/mm^2, respectively. The crack appears to initiate at the root and propagate through the weld metal leading to failure. The K_{cr} values obtained were quite low, (720 to 1280 kg/mm^2) under all welding conditions. If these values are compared with the actual restraint intensities experienced for different structural applications (Table 6), it can be concluded that the GMAW process is suitable only for structures involving low to moderate restraint intensities (<1000 kg/mm^2).

3.3 Lamellar Tear Resistance

Lamellar tears are separations lying beneath the weld and parallel to the plane of the plate. These separations are caused by stresses generated in the through-thickness direction resulting from weld contraction, high surface area of planar inclusions, high hydrogen level, and faulty weld joint design.

Lamellar tear tests were conducted simulating the normal conditions of fabrication involving fillet welds. Tests were conducted using full thickness specimens, no preheat, and heat inputs ranging from 10 to 27 kJ/cm. A multirun weld was applied, starting from the same side for all the passes. After each pass was deposited and the bead temperature dropped to around 100 °C, the weld throat thickness was measured and the load corresponding to a WRL of 42 kg/mm^2 was applied. Table 7 shows the test results. The results show no incidence of crack upon visual, ultrasonic (nondestructive testing), and macroexamination, indicating good lamellar tear resistance of the weld joint.

To detect the lamellar tear susceptibility of the material under specific conditions when the weld thermal cycle imposed reaches the midthickness of the plate (zone of center-line segregation) coupled with weld restraint loads, the tests were repeated using a modified procedure. The 12 mm thick plate was machined down to 9 mm thickness. This positions the segregated zone at a distance of 3 mm from the plate surface

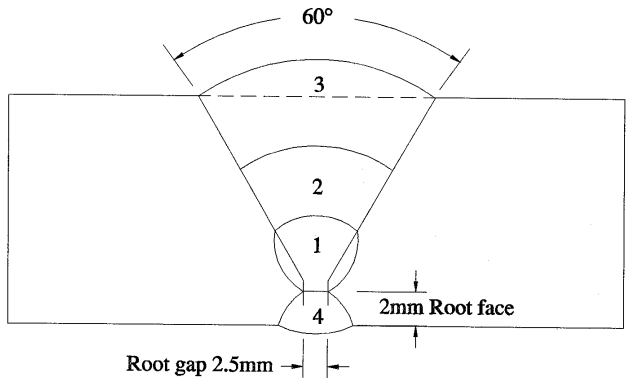


Fig. 4 Edge preparation and pass sequence for butt welding using the gas metal arc welding process

corresponding to the HAZ of the weld. The five plate specimens tested under different heat input conditions (9 to 20 kJ/cm) did not reveal any lamellar tear upon visual, ultrasonic, and macroexamination.

3.4 Comparative Analysis of Gas Metal Arc Welding and Shielded Metal Arc Welding Processes

The weldability properties of SAILMA-450 HI plates using the SMAW process have been reported elsewhere (Ref 19). The SFL values obtained under three welding conditions, no rebake, partial rebake, and full rebake, were 41.9, 47.8, and 52 kg/mm^2. These values are appreciably lower than the SFL values obtained using the GMAW process (44.4, 61.5, and 71.5 kg/mm^2), indicating that the resistance to cold cracking is superior for welded joints using the GMAW process. This is expected because among the arc welding processes, the GMAW process has the lowest level of diffusible hydrogen (0 to 10 mL/100 g) in welds.

Elastic restraint cracking tests conducted using the SMAW process under different welding conditions (no rebake, partial rebake, and full rebake) resulted in K_{cr} values of 990, 3540, and 3540 kg/mm^2, respectively. The K_{cr} values obtained under partial and full rebake conditions (3540 kg/mm^2) were significantly higher than the corresponding values obtained using the GMAW process (720 to 1280 kg/mm^2). The previous results indicate that while the SMAW process is suitable for structures with high restraint intensities, the GMAW process can be used only for applications involving low to moderate restraint levels (200 to 1000 kg/mm^2).

3.5 Weld Joint Properties

Based on the results of the weldability tests described previously, the butt welding procedure and welding parameters chosen were arc voltage, 20 to 22 V; current, 170 to 190 A; welding speed, 20 to 25 cm/min; heat input, 8 to 12 kJ/cm for 1.2 mm wire diameter; interpass temperature, 250 °C maximum; and number of passes, 4. Figure 4 shows the edge preparation and pass sequence. Butt welding was carried out, and the weld was subjected to microstructural examination. Figures 5(a) and (b) show optical micrographs of the weld metal (WM) and HAZ. The WM revealed a predominantly acicular ferritic microstructure (Fig. 5a) with a network of proeutectoid ferrite

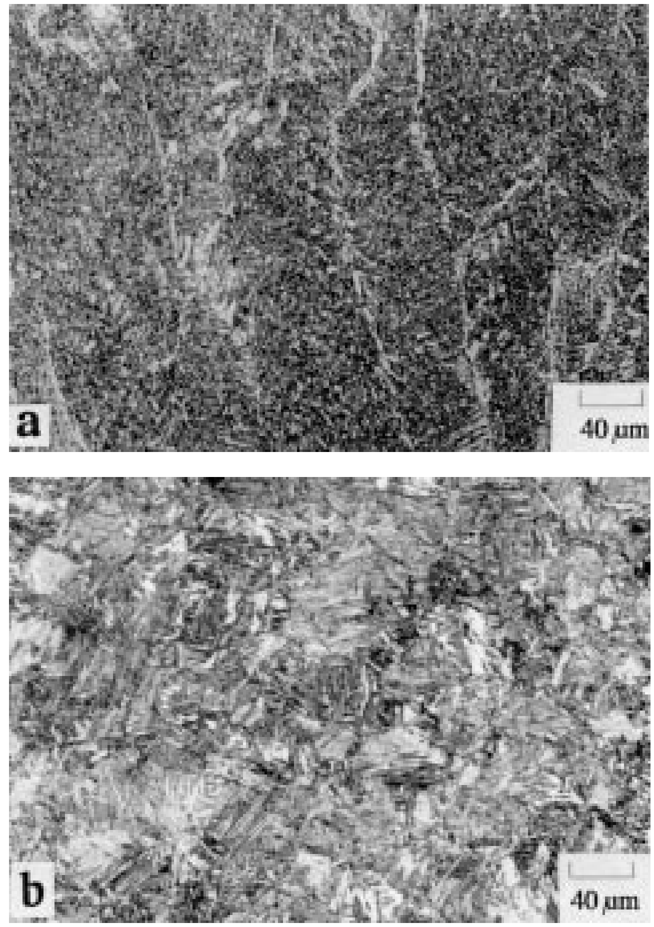


Fig. 5 Optical micrograph of (a) weld metal and (b) heat affected zone exhibiting acicular ferrite and bainite microstructures, respectively

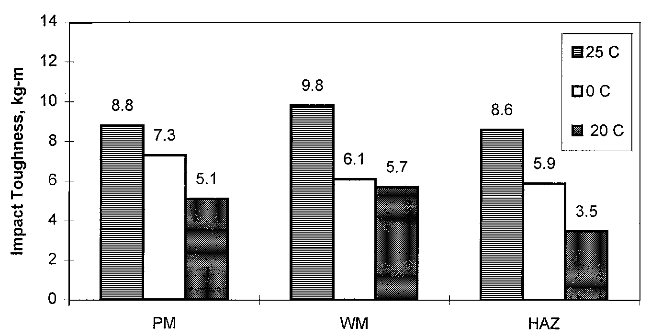


Fig. 6 Comparison of Charpy impact energies of parent metal, weld metal, and heat-affected zone

at the prior austenite grain boundaries. The HAZ microstructure, conversely, exhibited a typical bainitic structure (Fig. 5b).

To characterize the weld joint properties, various tests were conducted. The transverse tensile strength of the weld joint was determined to be 64.7 kg/mm^2, which is significantly higher than the minimum specified tensile strength of (MSTS) 57 kg/mm^2. Figure 6 presents the Charpy impact energies of parent metal (PM), WM, and HAZ at various test temperatures. The impact energy values for PM, WM, and HAZ at –20 °C were 5.1, 5.7, and 3.5 kg · m, respectively, and were significantly higher than the minimum specified level of 2 kg · m at –20 °C. However, it can be noted that the HAZ exhibited lower toughness properties, especially at –20 °C (3.5 kg · m) making it the likely zone for crack initiation and propagation. Crack tip opening displacement tests were carried out for the PM, WM, and HAZ, and the displacement, δ_m, values determined were 0.41, 0.40, and 0.34 mm, respectively. It can be concluded that the WM and HAZ possess adequate resistance to brittle fracture, that is, good toughness property. Figure 7 depicts the hardness profile across the weld joint. The hardness varied within a range of 186 to 373 HV. The hardness range of PM, WM, and HAZ were PM, 186 to 192 HV; WM, 200 to 264 HV; and HAZ, 211 to 373 HV. A higher hardness level in the HAZ reflects the presence of a hard microstructure, which is

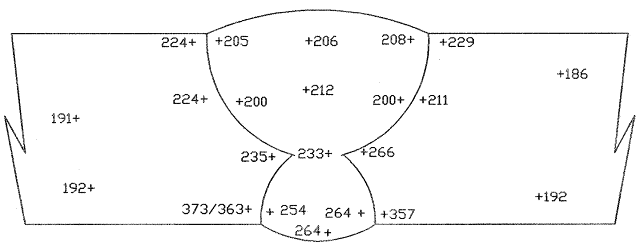


Fig. 7 Hardness profile across the weld joint

bainite in the present case. It also indicates a lower impact toughness and CTOD value for the HAZ as compared to the PM and WM. This agrees very well with the results reported earlier.

3.6 Weld Joint Configurations

Welding of SAILMA-450 HI plates for various end uses, such as impellers, bridges, earth movers, mining equipment, and so on, necessitates the use of different welding configurations depending on the thickness and welding process employed. Five weld joint configurations, namely, single lap, double lap, angular butt joint, and cruciform fillet joints with and without edge preparation, were tested. Table 8 gives the welding parameters used for the different joint shapes. The photographs of various joints are shown in the following figures: double lap joint (Fig. 8a), angular butt joint (Fig. 8b), and cruciform fillet joint with edge preparation (Fig. 8c). The tensile shear strengths of the five joints were determined and are presented in Table 8. All five weld joints meet the MSTS level of 57 kg/mm^2.

4. Conclusions

The following conclusions can be drawn:

- The SAILMA-450 HI grade steel plates in the thickness range of 8 to 32 mm were developed through the BOF-concast-TMCP process. The plates possess a good combination

Table 7 Lamellar tear test results of unmachined and machined SAILMA-450 high impact plates under different welding conditions

Arc voltage, V	Current, A	Heat input, kJ/cm	WRL, kg/mm	Lamellar tear detection test results: Visual	Nondestructive test	Macro (four section)
Unmachined plates						
23	170	17.4	42	No crack	No LT	No LT
23	170	19.6	42	No crack	No LT	No LT
27	200	25.1	42	No crack	No LT	No LT
27	200	24.0	42	No crack	No LT	No LT
27	200	27.0	42	No crack	No LT	No LT
Machined plates						
23	170	18.2	42	No crack	No LT	No LT
23	170	20.1	42	No crack	No LT	No LT
27	200	9.0	42	No crack	No LT	No LT
27	200	10.0	42	No crack	No LT	No LT
27	200	11.0	42	No crack	No LT	No LT

LT, lamellar tear

Table 8 Welding parameters and tensile shear strength for five weld joint configurations

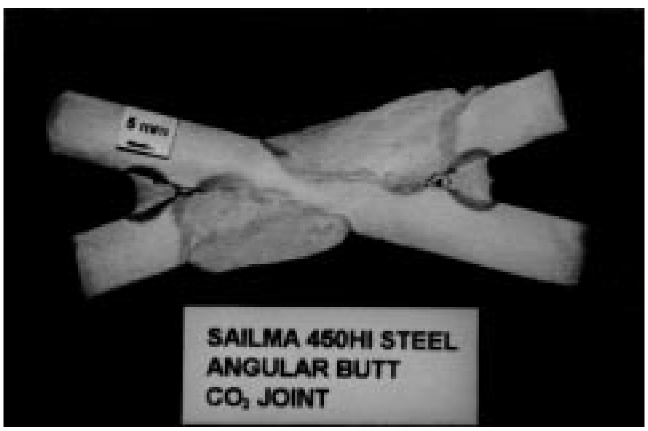
Type of joint	Welding parameters: No. of passes	Arc voltage, V	Current, A	Welding speed, cm/min	Tensile shear strength, kg/mm^2	Position of fracture
Single lap	6	23	170	25	59.0	PM
Double lap	12	23	170	25	59.0	PM
Angular butt joint	10	23	170	20-25	58.5	PM
Cruciform fillet with prepared edge	8	23	170	23-27	58.2	PM
Cruciform fillet without prepared edge	8	23	170	22-25	58.2	PM

PM, parent metal

of strength-ductility-toughness properties (yield strength, 47 to 51 kg/mm^2; tensile strength, 57 to 62 kg/mm^2; elongation, 22 to 27%; CIE, 5 to 11 kg · m at –20 °C; and CTOD, 0.41 mm).

- Implant tests carried out for GMAW process under different welding conditions, that is, heat input of 6.7, 9.4, and 13 kJ/cm, yielded SFL values of 44.4, 61.5, and 71.5 kg/mm^2, respectively, indicating good resistance to cold cracking, especially at higher heat input levels. The SFL values were found to be higher for the GMAW process as compared to the SMAW process. However, both the processes exhibited SFL values higher than the MSYS, indicating adequate cold cracking resistance of the weld joint.

(a)



(b)

(c)

Fig. 8 Photographs of different weld joint configurations. (a) Double lap joint. (b) Angular butt joint. (c) Cruciform fillet joint with edge preparation

- The critical restraint intensities, K_{cr}, for GMAW process under different welding conditions were found to range between 720 and 1280 kg/mm^2. The K_{cr} values were found to be distinctly lower for the GMAW process as compared to the SMAW process. Thus while the SMAW process is suitable at all restraint intensity levels, the GMAW process can be used only for applications involving low to moderate restraints (200 to 1000 kg/mm^2).
- Lamellar tear tests carried out on full thickness specimens at a WRL of 42 kg/mm^2 revealed no incidence of cracks, indicating good lamellar tear resistance of the weld joint. Repeat tests carried out on machined plate specimens where the HAZ corresponded to the midthickness of the plate (segregated zone) also revealed no evidence of cracks or lamellar tear, indicating excellent lamellar tear resistance of the weld joint.
- The weld zone revealed an acicular ferrite structure with dispersed islands of proeutectoid ferrite at prior austenite grain boundaries. The HAZ exhibited a typical bainitic structure.
- The weld joint was found to possess adequate strength (tensile strength, 64.7 kg/mm^2) and impact toughness (CIE, 5.7 and 3.5 kg · m at –20 °C for WM and HAZ, respectively) properties. The CTOD values for the WM and HAZ were 0.40 and 0.34 mm, respectively, indicating adequate resistance to brittle fracture.
- Tensile shear tests were conducted on five commonly used joint configurations. The tensile shear strength of the weld joints was found to be in excess of MSTS (57 kg/mm^2).

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