

Weldability Characteristics of Shielded Metal Arc Welded High Strength Quenched and Tempered Plates

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High strength, quench and tempered (Q&T) plates having yield strength of a minimum of 670 MPa and conforming to SA 517 Gr. F specification were successfully developed at Rourkela Steel Plant in plates up to 40 mm thickness. The plates are used extensively for the fabrication of impellers, penstocks, excavators, dumpers, and raw material handling devices, where welding is an important processing step. SA 517 Gr. F plates, characterized by a relatively high carbon equivalent (CE: ~0.6) and alloyed with Ni, Cr, Mo, Cu, and V, are susceptible to a crack-sensitive microstructure and cold cracking during welding. In view of the above, the present study investigated the weldability properties of 20 mm thick plates using the shielded metal arc welding (SMAW) process. Implant and elastic restraint cracking (ERC) tests were carried out to assess the cold cracking resistance of the weld joint under different welding conditions. Preheat of 100 °C, partial or full rebake, and a heat input of 14.9 to 15.4 KJ/cm resulted in static fatigue limit (SFL) values well in excess of the minimum specified yield strength (MSYS) of 670 MPa and a critical restraint intensity (K_{cr}) value of 34,650 MPa, indicating adequate cold cracking resistance. Lamellar tear tests conducted using full thickness plates at heat input levels ranging from 9.7 to 14.4 KJ/cm and weld restraint loads (WRL) of 510 to 685 MPa showed no incidence of lamellar tear upon visual, ultrasonic, and four-section macroexamination. The weld joint, based on optimized welding parameters, exhibited adequate tensile strength (812.4 MPa) and low temperature impact toughness 88.3 and 63.4 J (9.2 and 6.6 kg-m) at −40 °C for weld metal (WM), and heat-affected zone (HAZ) properties, respectively. The crack tip opening displacement (CTOD) values of WM and HAZ (0.40 and 0.36 mm, respectively) were superior to that of the parent metal (0.29 mm), indicating adequate resistance of weld joint to brittle fracture. It was concluded that the weld joint conforms to the requirements of SA 517 Gr. F specification and ensures a high integrity of the fabricated products.

Keywords carbon equivalent, cold cracking, lamellar tear, quench and tempered, restraint intensity, shielded metal arc welding

1. Introduction

Low alloy quench and tempered (Q&T) steels containing 0.1 to 0.2% C with alloy contents, either singly or in combination, of up to 1.5% Mn, 5% Ni, 3% Cr, 1% Mo, 0.5% Cu, 0.5% V, and 0.1% Nb are extensively used for a wide range of structural applications where high strength level (500 MPa) along with good fracture toughness and weldability properties are of critical importance. This class of steel is produced through the Q&T route, where the steel is austenitized at about 900 °C followed by water or oil quench to obtain a hard martensitic or bainitic structure. The quenched steel is extremely hard and brittle, and is subjected to a subcritical heat treatment known as tempering to soften it. The tempering treatment is carried out at temperatures of 480 to 600 °C or higher, resulting in a tempered martensitic/bainitic microstructure associated with the right combination of strength, ductility, toughness, and weldability properties.

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The ability of a steel to be transformed into bainite or martensite instead of the more conventional ferrite-pearlite structure depends on an intrinsic parameter known as hardenability. Generally, the higher the alloy content, the greater the hardenability. To ensure adequate hardenability, the alloy additions must go into solid solution in the austenite and retard the diffusion-controlled transformation from austenite to ferrite-pearlite. Alloy elements can be broadly classified into two types: austenite stabilizers such as Mn, Ni, and Cu, and ferrite stabilizers such as Mo, Si, Ti, V, and Nb.[1] Ferrite stabilizers require much lower alloy additions than austenite stabilizers to achieve a given increase in hardenability. However, with many of these ferrite stabilizers the competing process of carbide precipitation in the austenite depletes the austenite of both carbon and alloy addition, thus lowering its hardenability.

The susceptibility of a steel to cold cracking is related to the carbon equivalent (CE) and its position in the Graville diagram. The CE is determined by the carbon content and the CE of alloying elements, and is given as follows:[2]

$$CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 \quad \text{(Eq 1)}$$

Graville[3] has classified a wide range of steels into different categories; namely, easy to weld, weldable, and difficult to weld, based on their carbon content and CE (Fig. 1). Steels having high carbon and high alloy content (high CE) are categorized as highly susceptible to cracking and fall under Zone

III. Steels falling under Zone II (moderate carbon level but low CE) have a lower susceptibility to cracking. A low carbon steel (<0.13%) with low CE (<0.45) falls under Zone I and ensures the highest safety to cracking under all welding conditions. Q&T steels having a carbon content of 0.1 to 0.2 and CE of 0.5 to 0.6 fall under Zone II or Zone III and are highly susceptible to cracking. Thus the welding parameters, namely, preheat temperature, heat input, weld joint design, and electrode type, need to be carefully selected for these grades of steel.

The present study was conducted to assess the resistance of an indigenously developed high-strength Q&T steel to cold cracking using the shielded metal arc welding (SMAW) process. In addition, the lamellar tear resistance of the steel under different welding conditions was evaluated. Finally, based on this work, appropriate welding consumables were identified and parameters optimized to ensure a sound weld joint.

2. Experimental

2.1 Alloy Design and Properties

The alloy chemistry (wt.%) of the steel used in the present investigation was as follows: C, 0.11; Mn, 0.85; Si, 0.35; S, 0.008; P, 0.023; Al, 0.044; Ni, 0.77; Cr, 0.50; Mo, 0.45; V, 0.05; Cu, 0.28; and B, 0.0027. A low C level (0.11%), despite a moderately high CE (~0.60), enabled the steel to fall in the transition band of Zone I and Zone III, ensuring moderate safety against cold cracking. The presence of Ni, Mo, Si, Cr, and B imparted adequate hardenability to the steel, ensuring the transformation of austenite into martensite during oil quenching. Copper was added to impart atmospheric corrosion resistance as well as precipitation hardening during tempering. The steel was made in a basic oxygen furnace (BOF), then refined in a vacuum arc degassing (VAD) unit and continuously cast into 210 mm thick slabs. The slabs were hot-rolled into 20 mm thick plates in the plate mill and heat treated in the special plate plant. The heat treatment comprised austenitization of the steel at ~900 °C and oil quenching, followed by tempering at ~600 °C. Table 1 shows the mechanical properties of 20 mm thick SA 517 Gr. F plates (The Steel Authority of India, Limited (SAIL)).

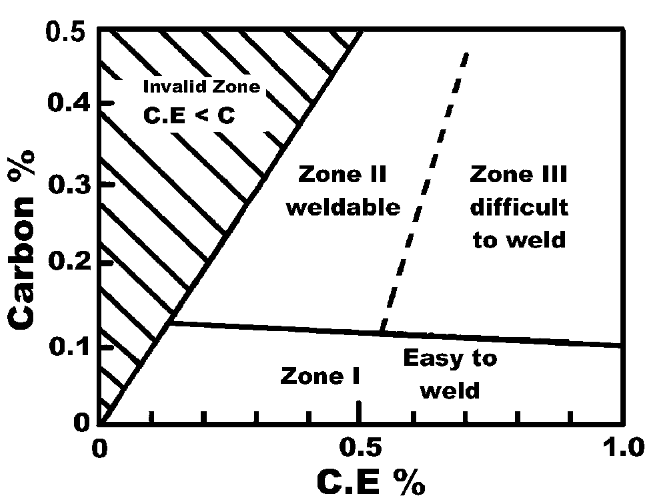

Fig. 1 Weldability assessment of steels using Graville diagram

2.2 Microscopy and Property Evaluation

Optical microscopy was carried out in a MeF_2 model microscope (Reichert, Austria). Longitudinal sections of the plates were polished and etched with 2% nital. Tensile samples were prepared per ASTM 10 (PA-370) specification and tested on a 10 ton static universal testing machine (model 1195, Instron Ltd., High Wycombe, Bucks, U.K.), at a strain rate of 6.6 × 10^{-4}/s. Standard V-notch samples were prepared and tested in the temperature range of room temperature (RT) to −40 °C for Charpy impact energy (CIE). The temperature increase during testing was within 2 °C. Crack tip opening displacement (CTOD) tests were carried out using an Instron 8502 system per the BS 7448 Part 1 (1991) specification.

2.3 Weldability Evaluation

The cold cracking susceptibility was determined by an implant test using the SMAW process. Three welding conditions involving different combinations of heat input (preheat and electrode baking temperature and time) were chosen. The test was conducted as per standard procedure outlined by the International Institute of Welding in 1973.[4] 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 the 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 certain temperature, usually 100 °C, before a static tensile load was applied to the implant specimen by a "constant loading system" until failure occurred or the lapse of 24 h, whichever was earlier. The maximum stress that the material could withstand without failure was determined by testing at different stress levels. This critical stress level for cracking is known as the static fatigue limit (SFL).

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

The lamellar tear test involved welding a cantilever to a rigid vertical test plate by depositing a multirun weld in a 45° level groove while maintaining a constant level of through

Table 1 Mechanical Properties of 20 mm Thick SAIL SA 517 Gr. F Plates

Properties	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	El (%)	RA (%)	Charpy Impact Energy (J) 0 °C	Charpy Impact Energy (J) −40 °C
Typical values	733	830	19	54	155	119
Specified	670 min	780–910	16 min	50 min	—	—

thickness stress known as the weld restraint load (WRL). The test plates were kept 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 2 presents the implant test results on a 20 mm thick plate. The welding was carried out using AWS A5.5 E11018M low-hydrogen electrodes of 3.15 and 4.0 mm diameter. SFL values obtained (710.5 and 794 MPa) using a preheat of 100 °C, heat input of 14.9 KJ/cm, and partial or full rebaking of electrodes were well in excess of the minimum specified yield strength (MSYS) of 670 MPa, indicating adequate resistance to cold cracking. Figure 2 shows the SFL plot for the steel using a preheat of 100 °C, heat input of 14.9 KJ/cm, and rebaking at 250 °C for 2 h. It may be noted that the SFL values were determined on the basis of a series of stepwise tests carried out at different stress levels.

Table 2 Static Fatigue Limit Values of SAIL SA 517 Gr. F Plates under Different Welding Conditions

Type of Electrode	Welding Conditions: Arc Voltage and Current (V/A)	Heat Input (KJ/cm)	Preheat (°C)	Rebake (°C, h)	Static Fatigue Limit (MPa)
AWS E11018M	22/110	9.7	Nil	350, 2	510.5
-do-	24/155	14.9	100	250, 1	710.5
-do-	24/155	14.9	100	350, 2	794.0

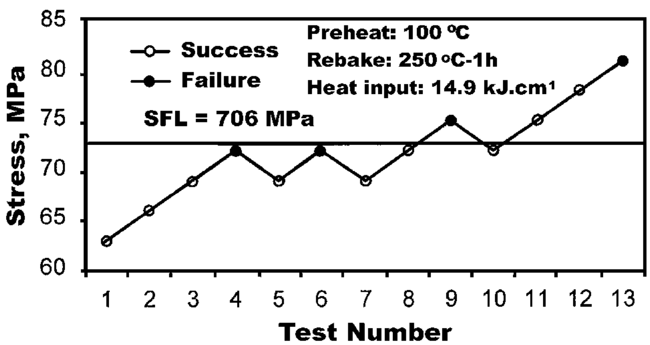

Fig. 2 SFL plot for SAIL SA 517 Gr. F steel at heat input level of 14.9 KJ/cm

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 4410 to 45,400 MPa. Figure 3(a) shows a photomacrograph of a sound weld joint specimen subjected to a restraint intensity of 31,900 MPa using a heat input of 15.4 KJ/cm, preheat of 100 °C, and fully baked electrodes. When the ERC test was repeated using a restraint intensity of 37,400 MPa, cracks were observed upon visual examination (Fig. 3b). The critical restraint intensity (K_{cr}) determined as the mean of the two values (31,900 and 37,400 MPa) was found to be 34,650 MPa in this case. The welding conditions used and K_{cr} values obtained are summarized in Table 3. It may be noted that use of higher heat input levels (15.4 KJ/cm) along with preheating and rebaking of electrodes ensured high K_{cr} values, in excess of 34,650 MPa. If one compares these values with the actual restraint intensities experienced for different structural applications (Table 4), it may be concluded that weld joints produced using the SMAW process provide adequate safety for most end-use.

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 result-

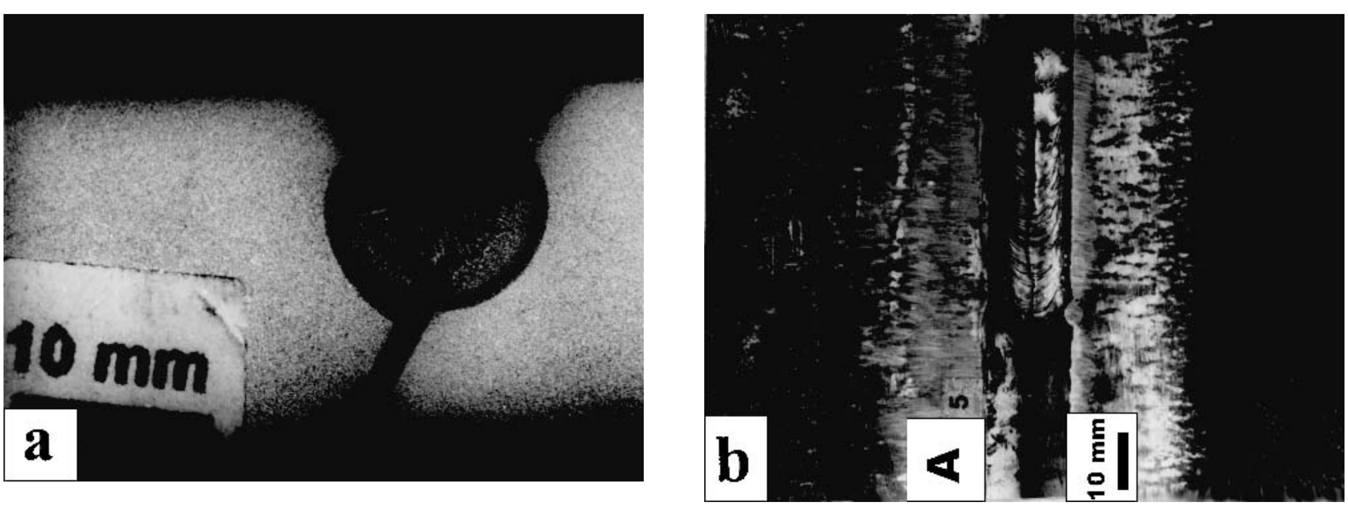

Fig. 3 Photomicrograph of (a) a sound and (b) a cracked weld joint obtained at restraint levels of 31,900 and 37,400 MPa, respectively

ing from weld contraction, high surface area of planar inclusions, high hydrogen level, and faulty weld design.

Lamellar tear tests were conducted based on a modified Lehigh technique,[5] simulating the normal conditions of fabrication involving fillet welds. Tests were conducted using 16 to 20 mm plate thickness under different conditions of welding involving no preheat/preheat at 100 °C, no rebake/rebake at 250 or 350 °C, and heat input levels varying from 8.8 to 14.7 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 decreased to around 100 °C, the weld throat thickness was measured and load corresponding to WRL ranging from 510 to 685 MPa was applied. Table 5 shows the test results. The results show no incidence of crack upon visual, ultrasonic, and macroexamination, indicating good lamellar tear resistance of the weld joint.

Centerline segregation, a common quality problem associated with concast slabs and plates,[6] adversely affects the through-thickness ductility of the steel. In view of the strong influence of centerline segregation on the susceptibility to weld cracking and HIC formation,[7,8] the lamellar tear tests were repeated using machined plate samples, so that the centerline segregated zone corresponded to the heat-affected zone (HAZ). The 20 mm thick plates were machined down to 13 mm thickness. This positioned the segregation line at a distance of 3 mm from the plate surface, corresponding to the HAZ of the weld. Out of four plate samples tested using a preheat of 100 °C, rebake of 350 °C for 2 h, heat input of 14.4 KJ/cm, and WRL varying from 510 to 780 MPa, only one sample (WRL 510 MPa) showed microlamellar tear upon macroexamination (Table 5). Figure 4 is a photomacrograph of the failed sample showing the propagation of lamellar tear in a step-wise fashion across the weld zone. The triggering of the lamellar tear was more of an exception, because the other three samples, tested under the same conditions but at higher WRL values, did not exhibit any lamellar tearing.

Table 3 Elastic Restraint Cracking Test Results for SAIL SA 517 Gr. F Plates under Different Welding Conditions

Type of Electrode	Welding Conditions: Arc Voltage and Current (V/A)	Heat Input (KJ/cm)	Preheat (°C)	Rebake (°C, h)	Critical Restraint Intensity (K_{cr}, MPa)
AWS E11018M	23/110	10.1	Nil	350, 2	4,410
-do-	24/160	15.4	65	350, 2	45,400
-do-	24/160	15.4	100	350, 2	45,400

Table 4 Restraint Intensities for Different Structural Applications

Application	Location	Thickness (mm)	Restraint Intensity, *K* (MPa)
Ship	Transverse bulk head	16	16,070
	Longitudinal bulk head	14	12,350
	Bottom shell	28	7,640
	Upper deck	32	12,540
Bridge	Diaphragm and web plate	19–38	960
	Diaphragm and flange plate	40–60	17,640
Building frame	Building column construction	28	10,680

3.4 Weld Joint Properties

On the basis of the results of the weldability tests described above, the butt welding procedure and welding parameters chosen were arc voltage 22 to 24 V; current 90 to 150 A, welding speed 10 to 12 cm/min; heat input 11.9 to 19.6 KJ/cm for 3.15/4.0 mm electrode wire diameter; interpass temperature of 135 °C max; preheat 75 °C; rebake 350 °C for 2 h; and number of passes, 11. Figure 5 shows the edge preparation and pass sequence used. Butt welding was carried out and the weld joint was subjected to microstructural examination. Figures 6(a) and (b) show an optical micrograph of the weld zone and HAZ. Although the weld metal exhibited a predominantly columnar structure of tempered martensite (Fig. 6a), the HAZ revealed a

Table 5 Lamellar Tear Test Results for Full Thickness and Machined Plates

Plate Thickness (mm)	Preheat (°C)	Rebake (°C, h)	Heat Input (KJ/cm)	WRL (MPa)	Test Result
18	Nil	NIL	9.7	588	No LT
20	Nil	350, 2	9.7	588	No LT
14	Nil	350, 2	9.7	685	No LT
14	Nil	350, 2	9.7	627	No LT
14	Nil	350, 2	9.7	588	No LT
14	Nil	350, 2	9.7	568	No LT
16	Nil	250, 2	8.8	568	No LT
16	Nil	350, 2	8.8	568	No LT
16	100	350, 2	9.7	568	No LT
16	100	350, 2	9.7	608	No LT
18	100	350, 2	9.7	550	No LT
18	100	350, 2	9.7	588	No LT
18	100	350, 2	9.7	510	LT
13	100	350, 2	14.4	510	No LT
13	100	350, 2	14.4	550	No LT
13	100	350, 2	14.4	568	No LT
13	100	350, 2	14.4	588	No LT

LT, Lamellar tear.

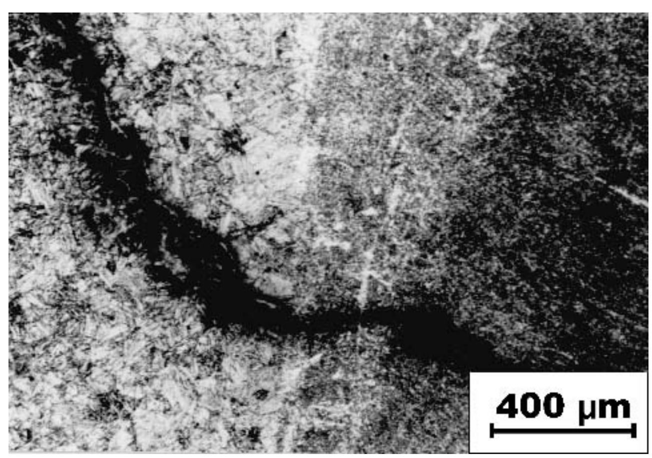

Fig. 4 Optical photomicrograph showing presence of a microlamellar tear along the weld zone

tempered martensitic structure with globular transformation product, presumably carbides, precipitated along the grain boundaries (Fig. 6b).

To characterize the weld joint properties, various tests were conducted. The transverse tensile strength of the weld joint was determined to be 812.4 MPa, which is within the specified requirement of 780 to 910 MPa. Figure 7 presents the CIEs of

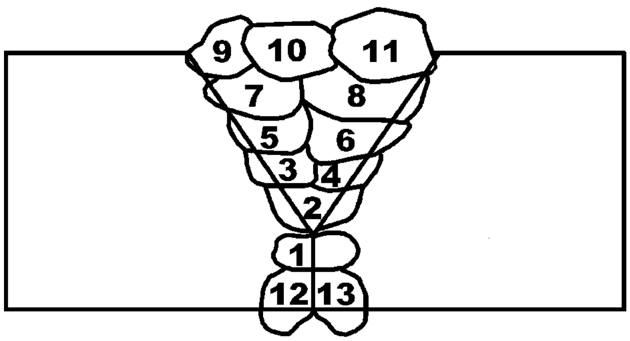

Fig. 5 Edge preparation and pass sequence for butt welding using the SMAW process

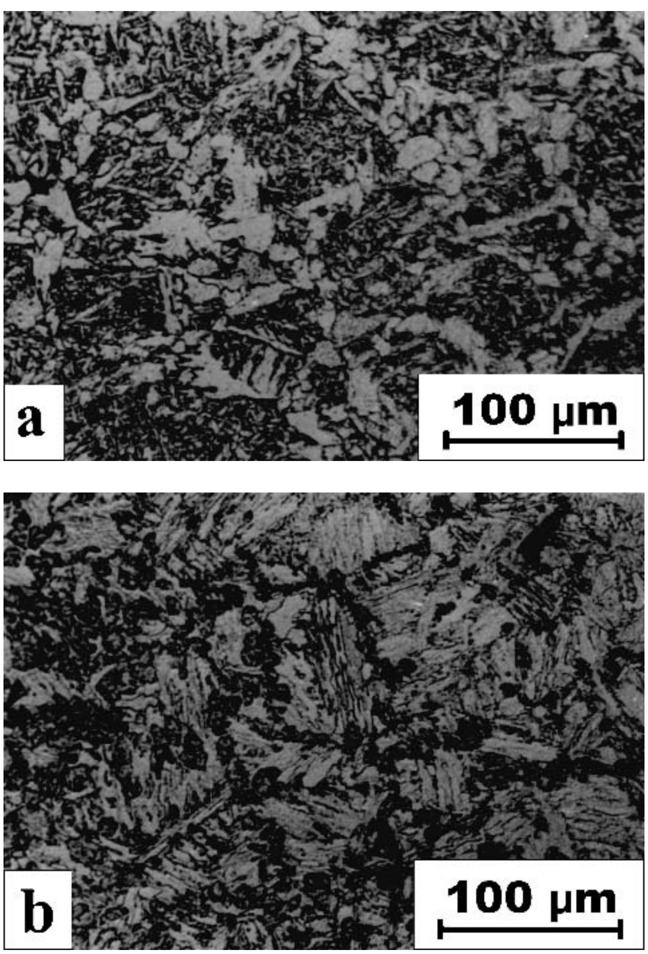

Fig. 6 Optical micrograph of (a) weld metal exhibiting columnar structure of tempered martensite, and (b) HAZ revealing a tempered martensitic structure with globular precipitates along grain boundaries

parent metal (PM), WM, and HAZ at various test temperatures ranging from 25 to −40 °C. The impact energy values of the PM were superior to those of WM and HAZ at all test temperatures. However, it may be noted that both the WM and HAZ showed excellent low temperature impact toughness values (88.3 and 63.4 J [9.2 and 6.6 kg-m]) at −40 °C, which is adequate for most end-applications. CTOD tests were carried out for the PM, WM, and HAZ, and the displacements (δ_m) determined were 0.29, 0.41, and 0.36 mm, respectively. A higher δ_m value for the WM and HAZ as compared to the PM indicates good resistance to brittle fracture and adequate protection against catastrophic failure of the weld joint. The hardness profile across the weld joint is shown in Fig. 8. The hardness values of PM, WM, and HAZ vary within the range of 274 to 281, 264 to 299, and 302 to 314 HV, respectively. The higher hardness values exhibited by the HAZ can be attributed to the presence of a higher volume fraction of tempered martensite.

3.5 Recommended Practice for Welding

On the basis of the above studies, the recommended practice for safe welding of the SAIL, SA 517 Gr. F steel was evolved. Table 6 outlines the broad process parameters required to ensure a sound weld joint conforming to SA 517 Gr. F specification. A preheat temperature of 65 °C min for <25 mm thick plates and 120 °C min for 25 to 40 mm thick plates is recommended. Post-weld heat treatment (PWHT) is not recommended for normal welding involving low to moderate restraint levels. However, for critical applications involving high restraint intensities or where post-weld rolling is involved, PWHT may be required.

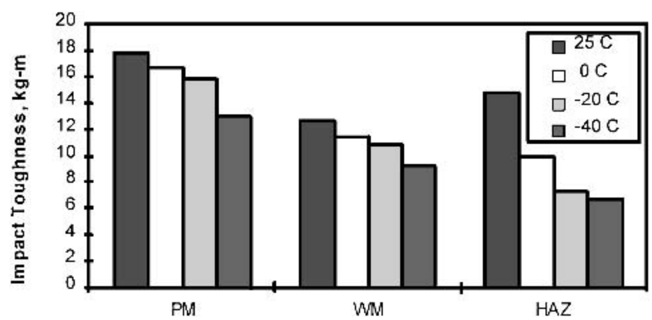

Fig. 7 Comparison of Charpy impact energies of PM, WM, and HAZ at RT, 0, −20, and −40 °C

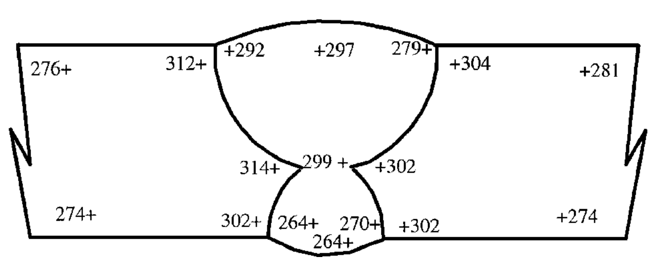

Fig. 8 Hardness profile across the weld joint

Table 6 Safe Welding Procedure for SAIL SA 517 Gr. F steel

Process	**SMAW**		
Electrode	**AWS A5.5 E11018M of 3.5 and 4 mm dia**		
Rebake	**350°C, 2 h**		
Heat input	**12–15 KJ/cm for 3.15 mm diameter and 15–18 KJ/cm for 4 mm diameter**		
Preheat	**Thickness of Plate (mm)**	**Preheat, Min (°C)**	**Interpass Temp (°C)**
	<25	65	110
	25–40	120	170

4. Conclusions

- A preheat of 100 °C, partial or full rebake, and a heat input of 14.9 KJ/cm resulted in SFL values of 710.5 and 794 MPa, well in excess of the MSYS (670 MPa), indicating good cold cracking resistance of the steel.
- The critical restraint intensities, K_{cr}, for the SMAW process under different welding conditions were found to vary between 4410 and 45,400 MPa. Preheating of the steel sample before welding, rebaking of electrodes, and a heat input level of 15.4 KJ/cm resulted in a high K_{cr} value of 34,650 MPa, indicating adequate safety for most end-applications.
- Lamellar tear tests carried out on full-thickness specimens at a WRL of 510 to 685 MPa revealed no incidence of cracks upon visual, ultrasonic, and macroexamination, indicating good lamellar tear resistance of the weld joint. Repeat tests carried out on machined specimens where the HAZ corresponded to the mid-thickness of the plate (segregated zone) revealed presence of a microlamellar tear (preheat: 100 °C; rebake: 350 °C for 2 h; WRL: 510 MPa) in one out of four samples tested.
- The weld zone revealed a columnar tempered martensitic structure, whereas the HAZ exhibited a tempered martensitic structure with globular precipitates, presumably carbides.
- The weld joint was found to possess an adequate strength (tensile strength 812.4 MPa) level. The impact toughness of the PM was found to be superior to that of the WM and HAZ at all test temperatures. However, the impact energy values of WM and HAZ even at −40 °C were found to be adequate, being 88.3 and 64.4 J, respectively.
- The CTOD values of the WM and HAZ were found to be higher (δ_m: 0.41 and 0.36 mm, respectively) than that of the PM (0.29 mm), indicating adequate resistance of the weld joint to brittle fracture.
- The safe welding procedure for SAIL SA 517 Gr. F steel using the SMAW process was evolved. The properties obtained in the weld joint were found to meet stipulated requirements.

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