Microstructure and Mechanical properties of Borated Stainless Steel (304B) GTA and SMA welds

G. RajaKumar, G. D. J. Ram, S. R. K. Rao

Borated stainless steels are used in nuclear power plants due to their high capacity to absorb thermal neutrons. Borated Stainless Steels are being used to control neutron criticality in reactors as control rods, shielding material, spent fuel storage racks and transportation casks. In the present study, an attempt has been made to investigate the microstructural and mechanical properties of the borated stainless steel welds made on 10 mm thick plates, using SMAW and GTAW welding processes. Microstructural investigations revealed that the fusion zone in GTAW exhibited dendritic structure with eutectic constituents in interdendritic regions. GTA welds failed in the partially melted zones formed (PMZ) immediately adjacent to the fusion zone, while the SMA welds failed in the base metal because of the high heat input used per pass in GTAW process resulting in larger PMZ. The heat input in GTAW was very high compared to the SMAW while both the welds exhibited high joint efficiencies, SMA welds were found to be superior. Impact testing revealed that welds made using SMA exhibited significantly higher toughness as the filler does not contain boron. It has been concluded that high efficiency welded joints can be made on 304B plates using both the processes.

Keywords: Borated Stainless Steels - 304B - SMAW - GTAW - Mechanical Properties - 308-16

INTRODUCTION

In recent years, the demand for various neutron absorption materials has been increasing in nuclear industry to ensure safety in disposal of spent fuel. Out of various neutron absorption materials, Boron (^{10}B) containing materials are more preferred in nuclear industry due to their low cost and very high thermal absorption. Austenitic stainless steels naturally added with 0.5-2% boron are known as Borated stainless steels (BSS) and are designated as 304B.
Borated stainless steels are covered by ASTM specification A887-89, which includes eight boron levels and two grades per type. For each of the eight types, specification A887 describes two grades, A and B, based on mechanical property requirements [1]. Borated SS have been widely used in nuclear industry for control rods, spent fuel storage racks, transportation casks and shielding to control the reactivity of spent nuclear fuel [2, 3]. Borated stainless steels solidify as primary austenite with a terminal eutectic constituent in the form of Fe_2B, Cr_2B dependent upon the boron level [4]. The dispersion of Cr_2B- type precipitates due to the presence of the ^{10}B isotope results in higher thermal neutron absorption [5]. Owing to this, Borated Stainless steels are used as the candidate materials in fabricating the Vacuum Vessel In-wall Shield (VV-IWS) blocks of International Thermo-nuclear Experimental Reactor (ITER). Due to the higher capacity for neutron absorption, borated stainless steel racks have replaced the austenitic stainless steel (AISI304) racks used in nuclear applications [6]. Borated SS racks can store 1.4 to 3 times more neutrons compared with austenitic stainless steels [7].
During early stage, fabrication of structures with Borated SS was done using riveting process, but this process was slow and could not be automated, contributing to higher fabrication cost. Several efforts have been made to use an automated process for the joining of borated stainless steels. Robino et al [8] reported that the borated stainless steels behave in a manner similar to binary irregular eutectic alloys such as Fe-C and Al-Si. The same author [9] also investigated the weldability of borated stainless steels 304A type and concluded that they were not substantially different from that of conventional austenitic stainless steels. Shinoda et al [10] investigated that hot cracking is not likely to occur if boron additions of >0·6% are made to

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Material	Cr	Ni	Mn	B	Si	P	C
304B4	18.1	12.5	1.3	1.15	0.57	0.02	0.02
308L filler	19	10	1.8	-	0.65	0.5	0.03

Table 1 - Chemical composition of the base metaland filler

Process	Welding Current (A)	Voltage (V)	Welding Speed	Heat Input/ Pass
SMAW (9 Passes)	60 A	21 V	3.5 mm/ sec	0.35 KJ/mm
GTAW (2 Passes)	250 A	17 V	2 mm/ sec	2.04 KJ/mm

Table 2 - Welding Parameters

AISI 304 stainless steel. It was reported by Arivazhagan et al.[11] that there was complete absence of liquation cracks in weldments because of the increase in eutectic boride phase content with the increase in heat input. Though austenite matrix is ductile in borated SS, the brittle nature of dispersed secondary phase resulted in adverse influences on the mechanical properties such as ductility and impact toughness at ambient and high temperatures [12]. Matsumoto et al.[13] concluded that the lower solidification cracking susceptibility of high boron steel is mainly due to the healing of cracks by the abundant amounts of low melting point eutectic liquid of $(Cr, Fe)_2B$ and γ-Fe. However, the microstructural and mechanical properties of borated SS welded with filler have been seldom reported. Different researchers have also studied corrosion behaviour of this material like general, localized corrosion [14, 15].
From the literature reviewed on the material 304B SS, several researchers have reported their investigations on weldability of this material but no particular studies on if we can use austenitic filler to make a multi pass welds. Therefore, the objective of the present study has been to investigate GTAW and SMAW with 308 filler to understand weldability, micro and macrostructural changes and to evaluate mechanical properties of the welded joints.

EXPERIMENTAL PROCEDURE

Welding Procedure

Two different processes viz automatic GTAW and SMAW with 308 SS filler have been investigated.
Gas Tungsten Arc Welding: The base material used in this study was 10mm thick plates of Borated Stainless Steel (BSS) 304B4 Grade B and its chemical composition is shown in Table 1. As received rolled plates of 40 mm thick were sliced using EDM wire cutting into plates of size 300mm ×110 × 10mm. Prior to welding, these plates were ground using silicon carbide paper and cleaned with the acetone to remove surface contamination. The bead-on-plate weld trials were made using gas tungsten arc welding (GTAW) machine employing 2% thoriated tungsten (EW-Th2) electrode of diameter 3.2 mm. The GTAW was carried out in two passes one from each side with the polarity DC electrode negative (EN). The shielding gas of pure argon with 15 L/min flow rate was maintained during welding. The welding parameters are presented in Table.2.

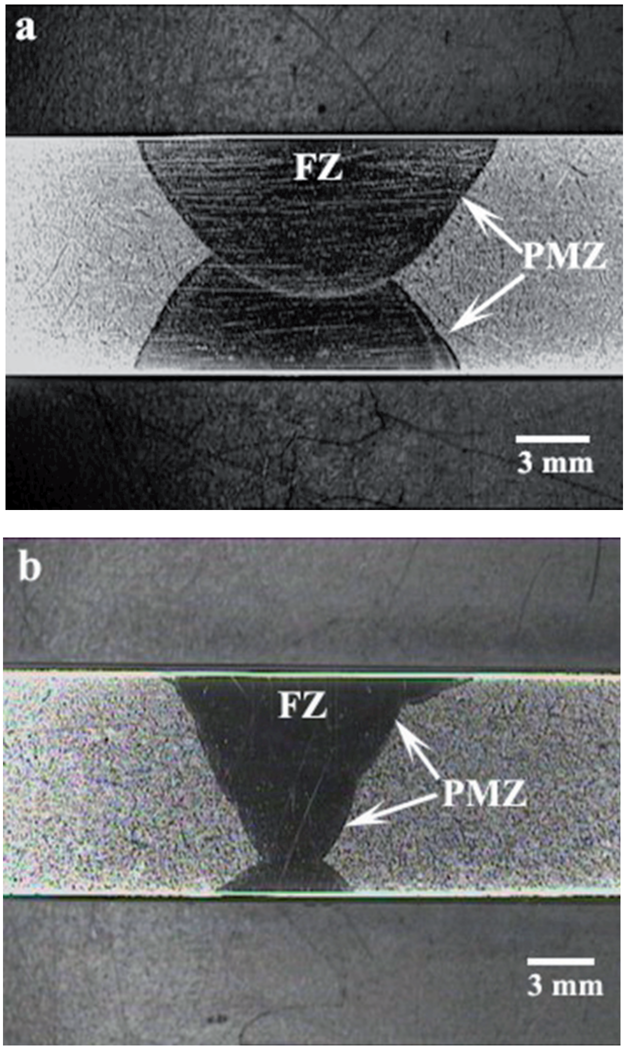

Fig.1 - Macrostructures of (a) GTAW (2 Passes) (b) SMAW (9 Passes)

Shielded Metal Arc welding: The base metal plates of 304B4 were cut and machined to the size of 300 mm × 70 mm × 10 mm by EDM wire cutting and grinding processes. The edge preparation of the plates was done accurately by CNC cutting to make a single V groove butt joint configuration with 60^0 groove angle with 2 mm root gap and 1mm root face as shown in Fig.1. An AWS E308L-16 type of electrode 2.5 mm in diameter and length 300mm was employed in the welding process. The chemical composition of the electrode is provided in the Table 1. Using the Shielded Metal Arc Welding (SMAW) process, the plates were welded in nine passes including one root pass. The corresponding welding parameters are given in Table 2.

Metallography

The specimens for metallographic studies were taken from weld pad and then polished using various grades of SiC paper up to 1200 grit followed by cloth polishing using 1 μm diamond paste. Then these polished specimens were chemically etched in Kalling's 1 solution containing 5 g cupric chloride, 100 ml hydrochloric acid and 100 ml ethanol. The microstructures of different zones of interest like Fusion Zone (FZ), Fusion boundary, Partially Melted Zone (PMZ) were captured with an optical microscope. The macrostructures of the welds were also obtained using a stereo microscope and analyzed with the help of image analysis software.

Mechanical Testing

Micro-hardness survey **w**as carried out across the weld using a Vickers micro-hardness tester. A load of 500 g was applied with a dwell time of 10 sec at indent spacing of 0.5mm. Measurements covered base metal, partially melted zone (PMZ) and weld metal (WM).

Tensile tests and Charpy impact tests were also carried out at room temperature. Specimens were sliced by Electrical Discharge Machining as per ASTM E8 [16] guidelines keeping fusion zone as center. The fractured specimens brought together carefully and mounted for microstructural studies to identify fracture location. The fracture morphology of the specimens was analyzed using scanning electron microscopy (SEM). Charpy impact specimens were prepared measuring 5mm × 10mm × 55mm with a 1 mm deep 45^0 angle V-Notch and a 0.25 mm root radius in accordance with ASTM E23[17]. The identical V-notch was machined on three specimens at the weld center using a broaching machine. Impact Testing was conducted at room temperature using a pendulum type machine with a maximum capacity of 300 J.

RESULTS AND DISCUSSIONS

Macrostructure

Macrostructures of the 304B stainless steel GTA and SMA welds are presented in Fig. 2. Two distinct regions, Fusion Zone (FZ) and Partially Melted Zone (PMZ) can be clearly observed. The cross sectional areas of FZ for both GTAW and SMAW were calculated using image analysis software and they were found to be 73 mm^2 and 41 mm^2 respectively. The difference in areas is due to the difference in number of passes (for GTAW- 2 passes and for SMAW- 9 passes) employed in welding processes and the corresponding heat inputs. Total average heat input in case of GTAW (2 passes) has been 4.08 KJ/mm and for SMAW (9 passes) it is 3.15 KJ/mm resulting in larger weld metal in GTA welds. It has been subsequently found that the total heat input or the weld pool size affects the location of failure during a tensile test. Full penetration defect free welds were obtained and it is evident from the macrostructures that no cracks were observed. If the amount of boron content exceeds 0.5 wt%, a crack healing phenomenon occurs in borated stainless steels which in turn reduces the crack susceptibility [18, 19]. As the material used in the present study contains about 1% boron, cracks are refilled by low melting eutectic phases. Thus, the welds were found to be free from cracks, which is evident from the macrostructures presented.

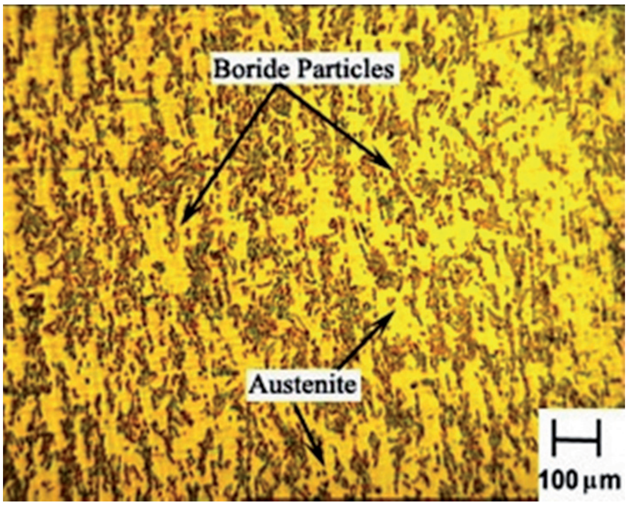

Fig. 2 - Microstructure of base metal 304B4

Microstructure

The microstructure of base metal is shown in Fig. 2. As it can be observed, irregular boride particles $(Fe,Cr)_2B$ seen as dark phase, are dispersed in austenitic matrix. Boron is essentially insoluble in austenite virtually at all temperatures, particularly in case of the steels having high boron levels the insolubility is profuse, which results in continuous network of boride eutectics such as Fe_2B and Cr_2B in austenitic matrix as shown by Goldschmidt[20]. Furthermore, he reported that these eutectic phases can exist in borated stainless steels and their composition will be similar and polymorphs of one another because Fe_2B can dissolve Cr, and Cr_2B can dissolve Fe.

The FZ and PMZ microstructures of GTAW and SMAW are shown in Fig.3.The FZ is a solidification microstructure which consists of primary austenite dendrites with boride eutectics in the interdendritic regions. As it can be seen from the Fig.3a the FZ of GTA weld consists of the eutectic constituents of irregular nature and these irregular eutectics could be noticed by their highly angular nature. The PMZ of GTA weld consists of irregular boride eutectics (Fig.3b) similar to those in FZ, which are looking to be placed in the localized regions of austenite which does not melt during welding process. The same has also been reported by Robino and Cieslak [3].

The FZ of SMA weld exhibits skeletal (vermicular) ferrite microstructure in an austenite matrix as shown in Fig.3c. This phenomenon is attributed to the advance of the austenite consuming the ferrite until the ferrite is sufficiently enriched in ferrite promoting elements (nickel) that it is stable at lower temperatures where diffusion is limited.

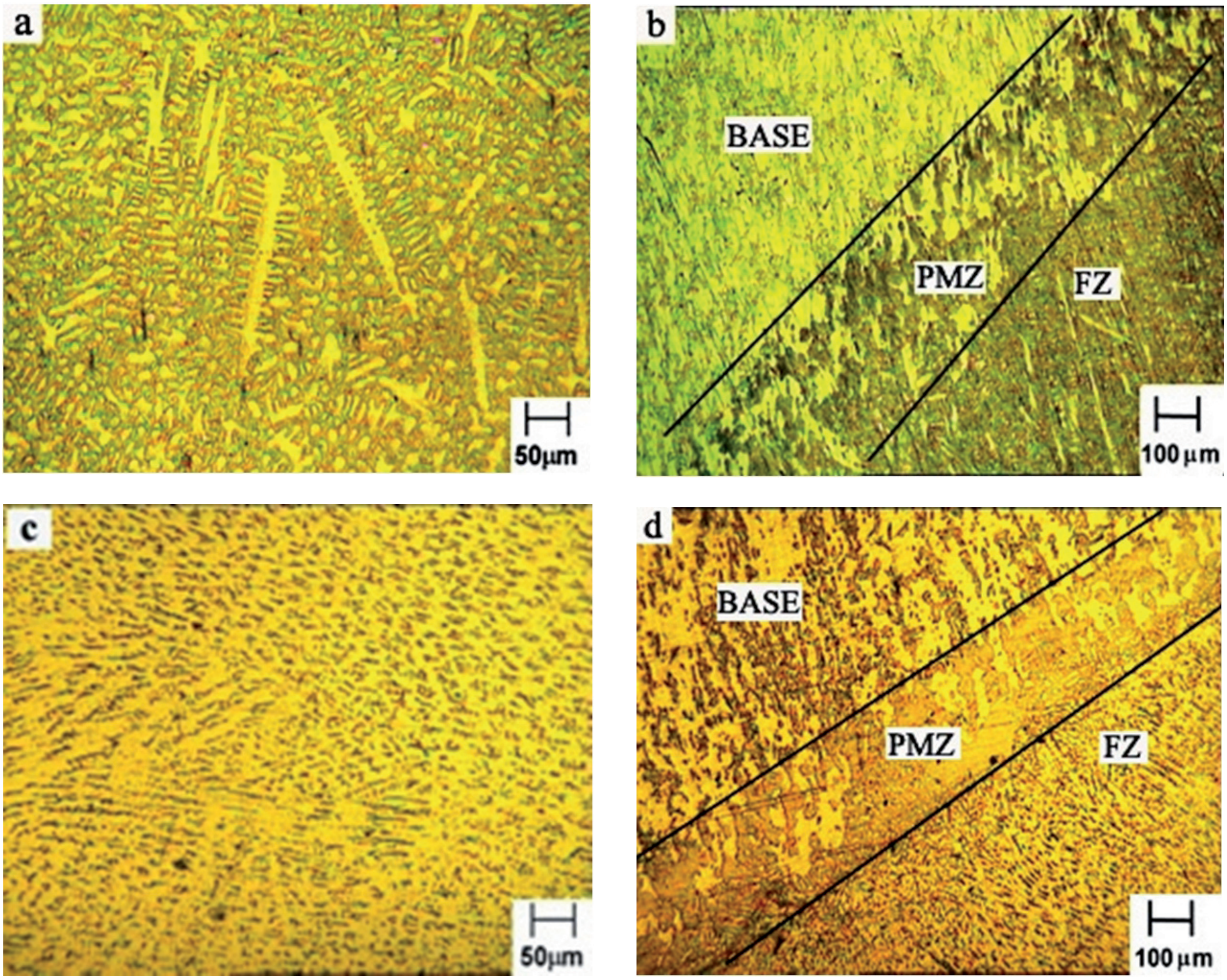

Fig. 3 - Microstructures of GTA weld (a) Fusion Zone (b) Partially Melted Zone and of SMA weld at (c) Fusion Zone (d) Partially Melted Zone

This is the common feature of FZ for SMA welds when 308 filler is used, as the same has also been reported by Galvis and Hormaza [21]. The typical microstructure of PMZ for SMA weld is shown in Fig.3d. It can be observed that the PMZ in case of SMA weld contains less of boron eutectics compared to that of GTA welds. This is mainly due to the dilution that happens between molten base material and the 308 filler.

Microhardness

The microhardness profiles measured on both GTA and SMA welds are presented in Fig.4, where the different weld zones of interest FZ, PMZ and Base metal (BM) are marked. The fusion zone of GTAW exhibited higher hardness than that of the base metal & PMZ. In both the welds, the increase in hardness of FZ is attributed to the presence of fine dendritic microstructure with boride eutectics at the interdendritic regions (Fig.3a) in case of GTA welds and to the duplex structure of about 10% ferrite in austenite matrix in case of SMA welds. The hardness in PMZ of GTA welds was found to be lower compared to FZ and BM since the formation of eutectic borides which are irregularly di-

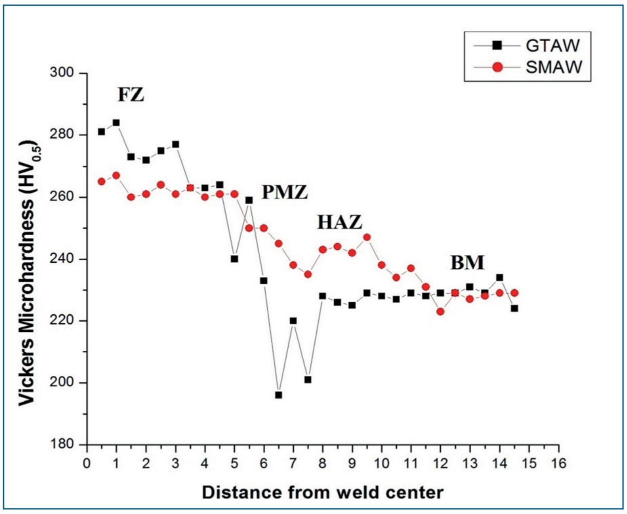

Fig. 4 - Vickers microhardness survey for GTA and SMA welds

Material	Proof Strength (MPa)	Ultimate Tensile Strength(MPa)	% elongation	Location of Fracture	Joint efficiency	Impact Toughness (J)
Base Metal	384	576	11.7	-	-	7
SMAW	385	572	12.1	Base Metal	98	36.7
GTAW	379	545	10	PMZ	94.61	7

Table 3 - Results of transverse tensile and impact testing (average of three tests)

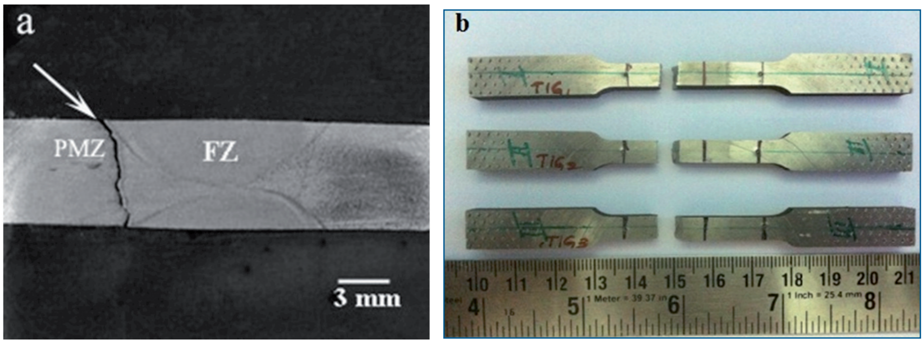

Fig. 5 - Tensile-tested GTA welds: (a) cross section of a fracture surface, (b) failed specimens (arrow shows failure location)

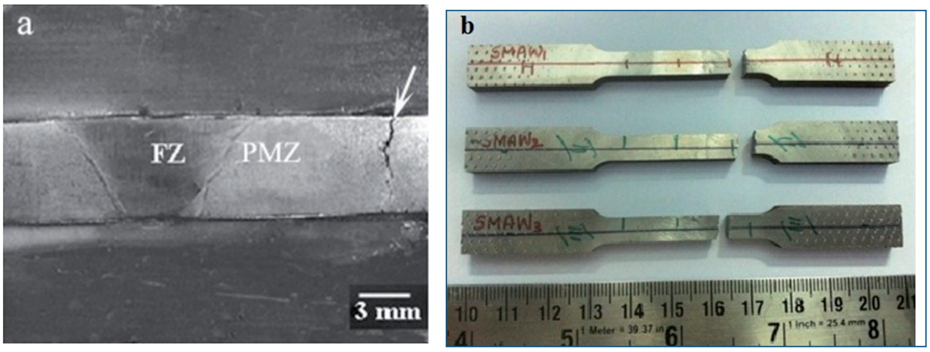

Fig. 6 - Tensile-tested SMA welds: (a) cross section of a fracture surface,(b) failed specimens (arrow shows failure location)

stributed (Fig.3b) in austenite. It suggests that the tensile specimens are prone to fracture in this zone. It is shown in the next section that the strength values also vary in accordance with the hardness profiles of the welds. The FZ hardness in case of GTA Weld is found to be marginally higher than that noticed in SMA weld. This can be easily understood as the FZ of SMA weld does not contain any boron and is made up of 308 filler.

Tensile Properties

The tensile test results of GTA and SMA welds are summarised in Table 3. The various tensile properties such as yield strength (YS), tensile strength (UTS) and total elongation were determined and compared with that of base metal. The joint efficiency (based on ultimate tensile strength) of 94.61% was measured in GTA welds and fracture occurs at PMZ as shown in Fig.5, the region where the loss of hardness can be clearly noticed due to irregular distribution of boride eutectics. GTA welds failed in the partially melted zones formed immediately adjacent to the fusion zone, while the SMAW welds failed in the base metal far away from the weld metal as shown in Fig.5 and 6. This was mainly because of the high heat input used per pass in GTA process. The heat input in GTAW (2.06 KJ/mm per pass) was very high compared to the SMAW (0.36KJ/mm per pass with 308 filler). SMA and GTA welds exhibited the joint efficiency of 98% and 94.61%. This can be correlated to the microhardness survey presented in Fig.4

The surfaces as observed in the SEM for tensile tested samples of welds produced by GTA and SMA welding processes are shown in Fig. 7a and b respectively. Ductile, dimpled rupture features with occasional boride decohesion and cracking can be observed from Fig.7a. Examination of the tensile fracture surfaces of SMA weld revealed brittle fracture mode as it happens in the base material containing boron eutectic network (Fig.7b). The fracture modes observed were as expected in this material and is in agreement with the results reported earlier by Park et al [22].

Impact Properties

The Charpy impact toughness test data for the weld joints made by GTA and SMA welding processes are shown in Table 3. The SMA weld exhibited good toughness value of 37 J at room temperature. The GTA weld exhibited a toughness value of 7 J which is equal to that exhibited by the base metal. The low value of impact strength is due to the continuous network of eutectic phases present. It is observed that 308 filler has significantly improved the impact strength of SMA welds. As the weld region does not con-

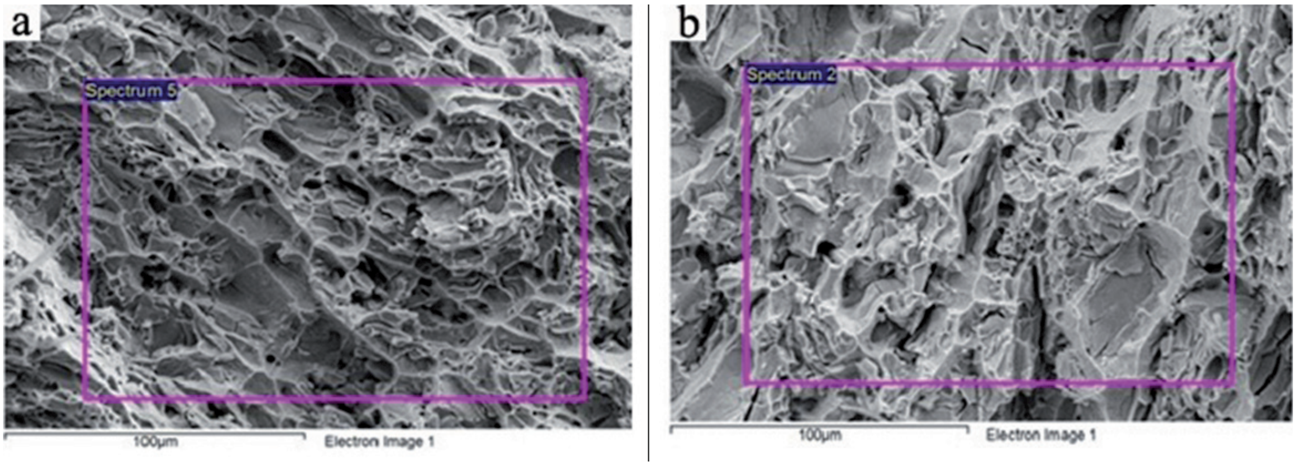

Fig. 7 - SEM fractograph of the tensile specimen of (a) GTA weld showing dimple ruptured surface with occasional boride cracking (b) SMA weld showing brittle fracture mode

tain boron, it is not recommended to use for the applications where neutron absorption is required. However, the better tensile and impact properties offered by 308 filler SMA welding and can be advantageously utilized in fillet welds and lap joints where the positioning of base plates is such that leakage of neutrons through weld metal does not happen.

CONCLUSIONS

- Defect free full penetration welds of 304B4 Borated stainless steels can be easily made using SMA (308L filler) and GTA welding processes.
- The fusion zone microstructure of GTAW reveals primary austenite dendrites with boride eutectics (Fe_2B and Cr_2B) of irregular nature and these irregular eutectics could be noticed by their highly angular nature in the interdendritic regions.
- The fusion zone of GTAW exhibited higher hardness. The hardness in partially melted zone (PMZ) of GTA welds was found to be lower compared to FZ and BM. The irregular distribution of eutectic phases in austenite is chiefly responsible for the loss in hardness of PMZ
- The joint efficiency in case of GTA welds is found to be 94.61% and 98% for SMA welds. Welds made using SMA welding process exhibit superior tensile properties compared to those made GTA welding process.
- Lap joints and fillet welds with better tensile and impact properties can be made using SMAW with 308L filler.

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