CHAPTER 5
RESULTS AND DISCUSSION

5.1 BASE MATERIAL

5.1.1 Chemical Composition

The chemical composition of the base material used in this study is given in Table 5.1. The values presented in the table are averages of a minimum of three investigations using the optical emission spectroscopy. As can be seen from the table the major alloying elements in 304B4 are Cr and Ni. The composition is similar to austenitic stainless steels with the main exception of high boron content. However, the increase in nickel is intended to compensate the effects of boron on the properties.

Table 5.1 Chemical composition of base metal, weight %

<table>
<thead>
<tr>
<th>Material</th>
<th>Cr</th>
<th>Ni</th>
<th>Mn</th>
<th>B</th>
<th>Si</th>
<th>P</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSS 304B4</td>
<td>18.1±1</td>
<td>12.5±1</td>
<td>1.3±1</td>
<td>1.05±1</td>
<td>0.74±1</td>
<td>0.02±1</td>
<td>0.02±1</td>
</tr>
</tbody>
</table>

5.1.2 Microstructure

The microstructure of the borated stainless steel is shown in Figure 5.1a. As it can be noticed, irregular boride particles of (Fe, Cr)_2B seen as dark phase dispersed in austenitic matrix (white) (Robino et al 1995). The Scanning Electron Microscopy (SEM) micrograph shown in Figure 5.1b and weight percentage of elements in EDS analysis is presented in Table 5.2 also reveals that the boride particles are irregular in size and shape and not distributed homogenously in the austenite matrix as also described by Dilip et al (1999).
Figure 5.1 Microstructures of base materials showing the boride network in an austenitic matrix: (a) Optical microstructure; (b) SEM micrograph
Table 5.2 EDS spectrum elements obtained on boride particle.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Element</th>
<th>AN</th>
<th>Wt% of element</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fe</td>
<td>26</td>
<td>63.40</td>
<td>1.93</td>
</tr>
<tr>
<td>2</td>
<td>Cr</td>
<td>24</td>
<td>20.77</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>Ni</td>
<td>28</td>
<td>10.33</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>Mn</td>
<td>25</td>
<td>2.69</td>
<td>0.19</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>5</td>
<td>1.5</td>
<td>1</td>
</tr>
</tbody>
</table>

The particles were found to be rich in Cr and Fe during EDS analysis. It has been reported by Goldschimdt (1967) that boride structure and stoichiometry are chiefly controlled by the size of boron atoms. He also observed that the Fe$_2$B and Cr$_2$B phases can exist in boron containing stainless steels and they are essentially polymorphs of one another and their structures are very similar. As Fe$_2$B can dissolve Cr, Cr$_2$B can dissolve Fe, and both can dissolve Ni, it is difficult to identify the two distinct borides at the room temperature (Robino et al 1995). Boron is insoluble in austenite virtually at all temperatures. The insolubility is more significant in case of the steels having high boron levels, which in turn results in a continuous network of boride eutectics such as Fe$_2$B and Cr$_2$B in austenitic matrix.

The dispersion of (Fe,Cr)$_2$B boride precipitates in this material strengthen the austenite matrix but adversely affect the toughness and ductility of these steels. Furthermore, the shape of these eutectic phases is also one of the factors affecting the mechanical behaviour of the welds (Robino et al 1997).

5.1.3 Mechanical properties

Mechanical properties of the base material are given in the Table 5.3. The values presented in the table are averages of a minimum of three investigations. All tests were conducted on the same calibrated machine under identical conditions. It can be noticed from the above table that borated
stainless steels exhibit poor ductility and toughness at ambient temperatures compared to that of the austenitic stainless steel (304). Limited solubility of B in γ phase results in the formation of (Fe, Cr)₂B borides which in turn affect ductility and toughness dramatically at ambient and high temperatures (Park et al 1997).

Table 5.3 Mechanical properties of the base material

<table>
<thead>
<tr>
<th>Base metal</th>
<th>Yield Strength 0.2% Proof (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>% Elongation</th>
<th>Micro Hardness (HV)</th>
<th>Impact toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSS 304B4</td>
<td>384±5</td>
<td>576±3</td>
<td>12</td>
<td>230</td>
<td>7±1</td>
</tr>
<tr>
<td>SS 304</td>
<td>205±5</td>
<td>515±3</td>
<td>40</td>
<td>-</td>
<td>200±5</td>
</tr>
</tbody>
</table>

5.2 GTA WELDS

5.2.1 Conventional GTA Welds

5.2.1.1 Bead geometry

Figure 5.2 Macrographs of autogenous GTA welds produced in different passes: (a) Single pass; (b) Double pass

Macrostructures of single pass and multi pass GTA welds are shown in Figure 5.2. In order to have full penetration welds for microstructural studies and evaluation of mechanical properties, welds were
made using two passes. The cross sectional area of FZ was calculated using imageJ software and it is found to be 73 mm$^2$ per pass. Furthermore, the depth of penetration in single pass GTAW was found to be 5 to 6 mm and the aspect ratio (depth to width) was 0.4. Total average heat input was observed to be 4.12 KJ/mm resulting in larger weld metal. It has been subsequently found that the total heat input or the weld pool size affects the location of failure during 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 (Apblett 1954; Borland 1960). 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 hot cracking in either partial or full penetration welds, which is evident from the macrostructures presented. In comparison to the welding of austenitic stainless steel, no significant processing adjustments were required for the borated stainless steel.

5.2.1.2 Metallographic Characterization

Metallographic observation of welds revealed three distinct regions namely Fusion Zone (FZ), Partially Melted Zone (PMZ) and Heat Affected Zone (HAZ). The microstructures of various zones are presented in Figure 5.3. Welds made using constant current result in equiaxed dendritic structure in the fusion zone as shown in Figure 5.3a.

The FZ is a solidification microstructure which consists of primary austenite dendrites with boride eutectics in the interdendritic regions (Robino et al 1997). As it can be seen from the Figure 5.3a the FZ of GTA weld consists of the eutectic constituents of irregular nature. The PMZ of GTA weld shown in Figure 5.3b consists of austenite islands that remain solid during welding, surrounded by irregular and larger boride eutectics similar to
those in FZ. The microstructure of HAZ region does not appear to result in distinguishable feature and as this region is heated to temperatures near solidus, microstructure remains unchanged by the weld thermal cycle and it seems to be same as that of base metal microstructure.

Figure 5.3  Microstructures of GTA welds: (a) Fusion Zone (b) Partially Melted Zone and Heat Affected Zone
5.2.1.3 Microhardness Profile

The microhardness survey carried out across the weld is presented in Figure 5.4, where the different weld zones of interest namely FZ, PMZ, HAZ and Base metal (BM) are marked. The fusion zone of GTAW exhibited higher hardness than that of the other zones. The increase in hardness of FZ is attributed to the presence of equiaxed dendritic microstructure with boride eutectics at the interdendritic regions (Figure 5.3a).

![Microhardness Survey Graph]

**Figure 5.4** Vickers microhardness survey conducted at the mid thickness of the weld

It can be noticed that there is a sudden fall of hardness in the PMZ and the significant reduction in PMZ hardness is attributed to the difference in cooling rates which results in variation in size, shape and distribution of eutectic borides formed in PMZ as can be seen from the microstructure shown in the Figure 5.3b.
It suggests that the welds are prone to fracture in this zone during tensile test. It is shown in the next section that the strength values also vary in accordance with the hardness profiles of the welds. As mentioned earlier, HAZ is heated to temperatures near the solidus and the microstructure of this region is eventually unchanged by the weld thermal cycle. Thus, the hardness in HAZ also was found to be same as that of BM.

5.2.1.4 Tensile Properties

The tensile test results of GTA welds are summarised in Table 5.4. The various tensile properties such as yield strength (YS), tensile strength (UTS) and percentage elongation were determined and compared with that of base metal. The joint efficiency (based on ultimate tensile strength) of 95% was measured and fracture occurs at PMZ as shown in Figure 5.5, the region where the lowest hardness values were found to notice due to irregular distribution of boride eutectics. The PMZ damage is mainly because of the high heat input (4.12 KJ/mm) employed per pass during GTA Welding process.

### Table 5.4 Results of tensile and impact testing of 304B4 GTA weld

<table>
<thead>
<tr>
<th>Material</th>
<th>Proof Stress (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>% Elongation</th>
<th>Location of fracture</th>
<th>Joint efficiency in terms of UTS</th>
<th>Impact toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>384±5</td>
<td>576±3</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>7±1</td>
</tr>
<tr>
<td>GTAW</td>
<td>379±5</td>
<td>545±3</td>
<td>10</td>
<td>PMZ</td>
<td>94.63%</td>
<td>7±1</td>
</tr>
</tbody>
</table>
Figure 5.5  Tensile tested GTA welds: (a) cross section of a fracture surface (b) failed specimens (arrow shows failure location) (c) SEM fractograph of the tensile specimen
The SEM fractograph of tensile tested samples is shown in Figure 5.5c. Ductile, dimpled rupture features with occasional boride decohesion and cracking can be observed from SEM micrograph. The fracture modes were observed to be in agreement with the results reported earlier by Park et al (1997).

5.2.1.5 Impact toughness

The results of Charpy impact test are presented in Table 5.4 and the tested samples are shown in Figure 5.6. The GTA weld exhibited a toughness value of 7 J at room temperature similar to that of the base metal. The low value of impact strength is due to the dendritic network of eutectic phases present in the FZ. The physical observation of fracture appearance for a center line notched GTA weld is completely brittle as that of the base material.

5.2.2 Activated Flux Gas Tungsten Arc Welds

5.2.2.1 Effect of process parameters on weld bead geometry

Cross sections of the various weld trials made using activated flux GTA welding process are presented in Table 5.5, along with the bead profile
parameters and corresponding welding parameters used. A substantial increase in both depth of penetration and weld aspect ratio (depth to width) can be seen in activated flux GTA welding. It has been observed in this study that bead shape becomes narrow and deeper with the increase in welding current.

Table 5.5 Macrostructure of GTA weld trials made using Activated flux and bead profile parameters

<table>
<thead>
<tr>
<th>Welding parameters</th>
<th>Macrostructure</th>
<th>Bead profile parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld current: 215 A Arc Voltage: 17V Travel Speed: 120 mm/min Gas flow rate: 15 lpm</td>
<td><img src="image1" alt="Macrostructure Image" /></td>
<td>Depth of penetration: 6.6 mm Aspect ratio: 0.56</td>
</tr>
<tr>
<td>Weld current: 230 A Arc Voltage: 17V Travel Speed: 120 mm/min Gas flow rate: 15 lpm</td>
<td><img src="image2" alt="Macrostructure Image" /></td>
<td>Depth of penetration: 8.9 mm Aspect ratio: 0.76</td>
</tr>
<tr>
<td>Weld current: 235 A Arc Voltage: 17V Travel Speed: 120 mm/min Gas flow rate: 15 lpm</td>
<td><img src="image3" alt="Macrostructure Image" /></td>
<td>Depth of penetration: 10 mm Aspect ratio: 0.8</td>
</tr>
</tbody>
</table>

Generally, the surface tension (σ) on the pool surface, formed by cohesive forces of liquid metal, decreases with increase in temperature. Thus, temperature gradient becomes negative i.e. dσ/dT < 0 which in turn generates centrifugal marangoni convection in molten pool as shown in Figure 5.7a. This constitutes one of the main reasons for shallow penetration and lower aspect ratio in conventional GTA welding. However, in case of activated
GTA welds, the presence of activated flux changes the temperature gradient to positive value i.e. \( \frac{d\sigma}{dT} > 0 \). This positive temperature gradient presents centripetal marangoni convection which in turn directs the flow toward pool center resulting in deeper and narrow weld pool (Figure 5.7 b)

Furthermore, the aspect ratio was increased due to the variation in temperature gradient. The same was also reported by Lu et al. (2003) and Fuji et al. (2008). By and large, it can be stated that the activated flux beneficially influences the Marangoni convection mode by changing the temperature gradient.

![Figure 5.7](image-url)  
**Figure 5.7** Marangoni convection mode in molten weld pool in activated flux GTA welding (a) \( \frac{d\sigma}{dT} < 0 \) (b) \( \frac{d\sigma}{dT} > 0 \) (Fujii et al. 2008)
5.2.2.2 Weld Metal microstructure

The microstructures of FZ and PMZ for the welds made using activated GTA welding process are presented in Figure 5.8.

**Figure 5.8** Microstructures of activated flux GTA weld (a) Fusion Zone (b) Partially Melted Zone & Heat Affected Zone
Activated flux GTA welding has a high energy density heat source, which is characterized by a low heat input and consequently rapid cooling rate, thereby affecting metallurgical structures. The fusion zone of activated flux GTA weld was characterized by columnar austenite dendritic structure with eutectic borides solidified in the interdendritic regions as shown in Figure 5.8a.

The typical appearance of the PMZ is shown in Figure 5.8b. As it can be noticed, the representative PMZ consists of localized regions of austenite that remain solid during welding, surrounded by irregular boride eutectics. Furthermore, the width of PMZ was found to be narrower than that of GTA welds. This is attributed to rapid cooling rates associated with low heat inputs prevail in activated flux GTA welding process. As in case of GTA welds, the microstructure of HAZ region was found to be unchanged by the weld thermal cycle and it seems to be same as that of base metal.

### 5.2.2.3 Effect of Activated Flux on Mechanical Properties

Microhardness survey carried out, across the various zones such as FZ, PMZ, HAZ and BM of different welds is shown in Figure 5.9. Hardness profile revealed that FZ exhibits higher hardness values. The increase in hardness of FZ is attributed to the presence of dendritic microstructure with boride eutectics in the interdendritic regions (Figure 5.8a). Furthermore, the hardness minimum was found to observe in the heat affected zone, indicating that FZ and PMZ regions show better hardness values than that of base metal. It is shown in the next section that the tensile fractures are in accordance with the hardness profiles, as the failures take place in the base metal.

The results of tensile tests are presented in Table 5.6. The various tensile properties such as yield strength (YS), ultimate tensile strength (UTS) and total elongation were determined and compared with that of base metal.
The joint efficiency (based on ultimate tensile strength) of the welds was found to be 98%. The fracture locations during tensile tests were found to occur in the heat affected zone, far away from the weld centre (Figure 5.10b). This suggests that the welds are stronger than base metal. This is mainly because of the low heat input welding process.

The results of Charpy impact test are presented in Table 5.6. The activated GTA weld exhibited a toughness value of 7 J at room temperature as that of the base metal. The low value of impact strength is due to the dendritic network of eutectic phases present in the FZ. Activated flux was found to show no affect on the impact toughness of the welds as significant changes in the microstructure of FZ were not observed when compared to that of GTA welds.

![Vickers microhardness survey for activated GTA weld](image)

**Figure 5.9 Vickers microhardness survey for activated GTA weld**
Table 5.6 Results of tensile and impact testing of 304B4 activated flux GTA welds

<table>
<thead>
<tr>
<th>Process</th>
<th>Proof Stress (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>% Elongation</th>
<th>Location of fracture</th>
<th>Joint efficiency in terms of UTS</th>
<th>Impact toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>384±5</td>
<td>576±3</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>7±1</td>
</tr>
<tr>
<td>Activated flux GTAW</td>
<td>400±5</td>
<td>569±3</td>
<td>14</td>
<td>HAZ</td>
<td>98.78%</td>
<td>7 ±1</td>
</tr>
</tbody>
</table>

Figure 5.10  Tensile tested activated GTA welds: (a) failed specimens; (b) cross section of a fracture surface (arrow shows failure location)
5.2.3 Influence of Nitrogen

The addition of nitrogen in welding of austenitic stainless steels is said to be beneficial for several reasons and is generally employed in the form of shielding gas. Nitrogen addition to stainless steel has been shown to increase its resistance to sensitization but the extent of beneficial effect varies in type 304L and 316L stainless steels (Beneke et al 1989 & Mozhi et al 1987). It has also been reported that nitrogen addition up to 0.16 wt.% reduces susceptibility to Intergranular Stress Corrosion Cracking in sensitised type 304 stainless steel in sodium sulphate added water at 250 °C (Mozhi et al 1985). Nitrogen is used as the backing gas to improve corrosion resistance at the root in stainless steel pipe welding. The addition/absorption of nitrogen in the weld metal and the consequent improvement in mechanical and corrosion properties of austenitic stainless steels and duplex stainless steels have been reported previously (Sedriks 1988).

In the current research work, controlled addition of nitrogen to the autogenous gas tungsten-arc weld metal was made using shielding gas mixtures of argon + 2%, 4% and 6% (volume) nitrogen. The influence of nitrogen on the microstructure and mechanical properties of Borated stainless steel welds was studied.

5.2.3.1 Macrostructure

The cross sections of welds produced with autogenous GTA welding using different levels of nitrogen viz. 0%, 2%, 4%, 6% (volume) in the argon and nitrogen shielding gas mixtures are shown in Figure 5.11.
Figure 5.11 Macrographs showing the effect of nitrogen on depth of penetration

As it can be seen from the Figure 5.11, the addition of nitrogen in shielding gas mixture improves depth of penetration for the same heat input. However, the increase is found to be significant at particular level of nitrogen (2%). The maximum depth of penetration of 6.7 mm is observed for 2% nitrogen. The increase in depth of penetration can be attributed to the change in the surface tension and other forces acting in the nitrogen added molten metal.

As the depth of penetration is found to be maximum at 2% nitrogen in shielding gas mixture, nitrogen added autogenous GTA welds were made
only using 2% nitrogen. In order to achieve full penetration welds were made using two passes as shown in Figure 5.12.

![Cross section of double pass GTA weld made using argon plus 2% nitrogen shielding gas](image-url)

**Figure 5.12** Cross section of double pass GTA weld made using argon plus 2% nitrogen shielding gas

5.2.3.2 Influence of nitrogen on weld metal microstructure

The optical micrographs showing the microstructural features of nitrogen added GTA welds are given in Figure 5.13. Metallographic observation of welds revealed three distinct regions such as FZ, PMZ and HAZ.

The fusion zone of nitrogen added GTA welds exhibited both equiaxed and columnar dendritic structure with eutectic borides in the interdendritic regions as shown in Figure 5.13a. No major changes could be observed in terms of dendritic structure in the fusion zone by the addition of nitrogen in shielding gas.
As it can be seen from the Figure 5.13b, the microstructure reveals the partially melted zone formed adjacent to the fusion zone. As in case of GTA welds, PMZ in nitrogen added GTA welds also characterized by
austenite islands that remain solid during welding, surrounded by irregular boride eutectics similar to those in FZ. The microstructure of HAZ region was not found to exhibit significant variations compared to base metal. As this region is heated to temperatures near solidus, microstructure remains unchanged by the weld thermal cycle and it seems to be same as that of base metal microstructure.

5.2.3.3 Effect of nitrogen on mechanical properties

The microhardness survey conducted across the welds is presented in Figure 5.14. Hardness minimum was found to occur in PMZ region of the weld. The significant reduction in PMZ hardness is attributed to the difference in cooling rates which results in variation in size and shape of eutectic borides formed in PMZ as can be seen from the microstructure shown in the Figure 5.13b. It suggests that the welds are prone to fracture in this zone during tensile test. It is shown in the next section that the strength values also vary in accordance with the hardness profiles of the welds. The fusion zone of nitrogen added GTAW exhibited significantly higher hardness values than that of the welds made using other welding processes. The increase in hardness of FZ is attributed to the presence of nitrogen in shielding gas mixture.

The tensile test results of nitrogen added GTA welds are summarised in Table 5.7. 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 the welds was found to be 96%. The fracture locations during tensile tests were found to occur in the PMZ (Figure 5.15b), the region where the lowest hardness values were found to notice due to irregular distribution of boride eutectics. The PMZ damage is mainly because of the high heat input employed during the welding process.
Figure 5.14 Vickers microhardness survey for nitrogen added GTA weld

Figure 5.15 Tensile-tested nitrogen added GTA welds: (a) cross section of a fracture surface (b) failed specimens (arrow shows failure location)
The results of Charpy impact test are presented in Table 5.7. The nitrogen added GTA welds exhibited a toughness value of 8 J at room temperature. Nitrogen addition in shielding gas seemingly has no effect on the impact toughness as the test results show similar values as that of the conventional GTA welds.

**Table 5.7 Results of tensile and impact testing of nitrogen added GTA weld**

<table>
<thead>
<tr>
<th>Process</th>
<th>Proof Stress (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>% Elongation</th>
<th>Location of fracture</th>
<th>Joint efficiency in terms of UTS</th>
<th>Impact toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>384±5</td>
<td>576±3</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>7±1</td>
</tr>
<tr>
<td>Nitrogen added GTAW</td>
<td>390±5</td>
<td>550±3</td>
<td>11</td>
<td>PMZ</td>
<td>96.32%</td>
<td>8±1</td>
</tr>
</tbody>
</table>

**5.2.4 Pulsed Gas Tungsten Arc Welds**

Significant refinement of the solidification structure has been reported in austenitic stainless steels (Gokhale et al 1983; Ravi Vishnu, 1995; Shinoda et al 1990), titanium alloys (Mohandas & Madhusudhan Reddy 1996; Sundaresan et al 1999b) and tantalum (Grill 1981). The observed refinement was attributed to the effects of current pulsing on weld pool shape, fluid flow and thermal gradients.

The influence of pulsing current during the welding of borated stainless steels has not been demonstrated and its effect seems to be still unknown. To understand the effect of pulsing current on microstructure and
mechanical properties of borated stainless steel GTA welds, an attempt was made to investigate the pulsed GTA welding of borated stainless steels.

### 5.2.4.1 Bead geometry

![Macrograph of autogenous pulsed GTA weld produced in double pass](image)

**Figure 5.16 Macrograph of autogenous pulsed GTA weld produced in double pass**

The macrostructure of pulsed GTA welding is shown in Figure 5.16. In order to have full penetration, welds were made using two passes. The base and peak currents during pulsed GTA welding were employed in such a way that the heat input is same as that of constant current GTA welding. Full penetration defect free welds were obtained and it is evident from the macrostructures that no cracks were observed. The cross sectional area of FZ was calculated using imageJ software and it is found to be 92 mm².

### 5.2.4.2 Metallographic characterization

The optical micrographs of pulsed GTA welds are presented in the Figure 5.17. Metallographic observation of welds revealed three distinct regions such as Fusion Zone (FZ), Partially Melted Zone (PMZ) and Heat Affected Zone (HAZ). The GTA welds made using pulsing current result in columnar dendritic structure in the fusion zone as shown in Figure 5.17a.
Figure 5.17 Microstructures of pulsed GTA weld (a) Fusion Zone (b) Partially Melted Zone and Heat Affected Zone
The primary austenite dendrites are solidified as columnar structure in the fusion zone and the boride eutectics are placed in the interdendritic regions. The eutectic boride phase is distributed in the form of continuous network in the FZ.

The typical appearance of the PMZ is shown in Figure 5.17b. As it can be noticed, the representative PMZ consists of localized regions of austenite that remain solid during welding, surrounded by irregular boride eutectics. Furthermore, the width of PMZ was found to be narrower than that of GTA welds. This is attributed to rapid cooling rates associated with low heat inputs prevail in pulsed GTA welding process. As in case of GTA welds, the microstructure of HAZ region was found to be unchanged by the weld thermal cycle and it seems to be same as that of base metal.

5.2.4.3 Hardness profile across the weld

Microhardness survey carried out, across the various zones such as FZ, PMZ, HAZ and BM of different welds is shown in Figure 5.18. Hardness profile revealed that FZ exhibits higher hardness values (280±5 HV). The increase in hardness of FZ is attributed to the presence of dendritic microstructure with boride eutectics in the interdendritic regions (Figure 5.17a). Furthermore, the hardness minimum was found to observe in the heat affected zone, indicating that FZ and PMZ regions show better hardness values than that of base metal. It is shown in the next section that the tensile fractures are in accordance with the hardness profiles, as the failures take place in the base metal.
5.2.4.4 Tensile and Impact properties

The results of tensile tests are presented in Table 5.8. The various tensile properties such as YS, UTS and total elongation were determined and compared with that of base metal. The joint efficiency (based on ultimate tensile strength) of the welds was found to be 97%. The fracture locations during tensile tests were found to occur in the heat affected zone, far away from the weld centre (Figure 5.19). This suggests that the welds are stronger than base metal. This is mainly because of the low heat inputs employed during the welding.
Figure 5.19 Tensile-tested pulsed GTA welds: (a) failed specimens (b) cross section of a fracture surface (arrow shows failure location)

Table 5.8 Results of tensile and impact testing of 304B4 pulsed GTA weld

<table>
<thead>
<tr>
<th>Process</th>
<th>Proof Stress (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>% Elongation</th>
<th>Location of fracture</th>
<th>Joint efficiency in terms of UTS</th>
<th>Impact toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>384±5</td>
<td>576±3</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>7±1</td>
</tr>
<tr>
<td>Pulsed GTAW</td>
<td>380±5</td>
<td>561±3</td>
<td>11</td>
<td>HAZ</td>
<td>97.39 %</td>
<td>7±1</td>
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</tbody>
</table>
The results of Charpy impact test are presented in Table 5.8. The pulsed GTA weld exhibited a toughness value of 7 J at room temperature as that of the base metal. The low value of impact strength is due to the dendritic network of eutectic phases present in the FZ. The use of pulsing current was found to show no effect on the impact toughness of the welds as significant changes in the microstructure of FZ were not observed when compared to that of GTA welds.

5.3 SHIELDED METAL ARC WELDS WITH 308 FILLER

SMA Welding of borated stainless steels was investigated using 308 filler to understand weldability, variations in microstructures and mechanical properties of the welded joints.

5.3.1 Macrostructure

Macrostructure of multi pass SMA welds made using 308 filler is shown in Figure 5.20. The joints were made in 9 passes and the total average heat input has been 3.15 KJ/mm. The full penetration defect free welds were obtained and it is evident from the macrostructure that no cracks were observed. The cross sectional area of FZ was calculated using image analysis software and it is found to be 71 mm$^2$.

Figure 5.20  Macrostructure of multi pass SMA weld produced using 308 filler
5.3.2 Weld metal Microstructure

The optical micrographs of the welds are presented in the Figure 5.21.

Figure 5.21 Microstructures of SMA weld (a) Fusion Zone (b) Partially Melted Zone
Metallographic observation of welds reveals two distinct regions such as Fusion Zone (FZ), Partially Melted Zone (PMZ). As it can be seen from the Figure 5.21a, the FZ of SMA weld exhibits skeletal (vermicular) ferrite microstructure in an austenite matrix. This phenomenon is attributed to the advance of the austenite consuming the ferrite until the ferrite is sufficiently enriched in austenite promoting elements (nickel) that it is stable at lower temperatures where diffusion is limited. This is the common feature of FZ for SMA welds when 308 filler is used, as the same has also been reported by Andres et al (2011). The typical microstructure of PMZ for SMA weld is shown in Figure 5.21b. It was observed that the PMZ in case of SMA weld contains lesser boron eutectics compared to that of GTA welds and it is mainly due to the dilution that happens between molten base material and the 308 filler.

5.3.3 Mechanical Properties

Microhardness survey carried out across the welds made on shielded metal arc welding is shown in Figure 5.22. Hardness profile revealed that FZ exhibits higher hardness values. The increase in hardness of FZ is attributed to the presence of duplex structure of about 10% ferrite in austenite matrix (Figure 5.21a). Furthermore, the hardness minimum was observed in the base metal, indicating that FZ and PMZ regions show better hardness values than that of base metal. It is shown in the next section that the tensile fractures are in accordance with the hardness profiles, as the failures take place in the base metal.
The results of tensile tests are given in Table 5.9. The joint efficiency (based on ultimate tensile strength) of the welds was found to be 98%. The fracture locations during tensile tests were found to occur in the base metal, far away from the weld centre (Figure 5.23). This suggests that the welds are stronger than base metal. This is mainly because of the low heat inputs (3.15 kJ/mm) employed during the welding. The SEM fractograph of tensile tested samples is shown in Figure 5.23c. As it can be seen SEM micrograph, the fracture mode was found to be brittle since the fracture occurred in base metal which contains a continuous boron eutectic network.

Figure 5.22 Vickers microhardness survey for SMA weld
Figure 5.23  Tensile-tested SMA welds: (a) cross section of a fracture surface (b) failed specimens (arrow shows failure location) (c) SEM fractograph of the tensile specimen
The results of Charpy impact test are presented in Table 5.9. The SMA welds exhibited a toughness value of 37 J at room temperature. It is observed that 308 filler has significantly improved the impact strength of SMA welds. As the weld region does not contain 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.

Table 5.9 Results of tensile and impact testing of 304B4 SMA weld

<table>
<thead>
<tr>
<th>Process</th>
<th>Proof Stress (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>% Elongation</th>
<th>Location of fracture</th>
<th>Joint efficiency in terms of UTS</th>
<th>Impact toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>384±5</td>
<td>576±3</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>7±1</td>
</tr>
<tr>
<td>SMAW</td>
<td>385±5</td>
<td>572±3</td>
<td>12</td>
<td>BM</td>
<td>98%</td>
<td>36.7±1</td>
</tr>
</tbody>
</table>

5.4 ELECTRON BEAM WELDS

The electron beam welding (EBW) process grouped under power beam processes, offers many advantages such as high productivity, absence of contamination, a high depth-width ratio, reduced residual stress and distortion and the possibility of automation. The rapid cooling rate is one of the characteristics of electron beam welding process.
Furthermore, beam oscillation technique in EBW is an effective method which improves the quality of the welds by beneficially affecting the fusion and solidification processes. Electron beam oscillation in various shapes such as triangular, rectangular and circular improves the weld quality and penetration efficiency (Kautz et al 1991 and Fu et al 2014). The beam oscillation also widens the width of fusion zone and allows gas porosity to rise and escape from weld pool (Schultz 2003). However, the influence of beam oscillation during EB welding of borated stainless steels on microstructures and mechanical properties has not been investigated in detail. In view of the above, an attempt was made to investigate the effect of beam oscillation on EB welding of borated stainless steels.

5.4.1 Bead Geometry

The cross sections of the welds made using EB welding with and without beam oscillation are shown in Figure 5.24. As it can be seen full penetration defect free welds were obtained. The cross sectional areas of fusion zone were calculated using image analysis software and they were found to be 13-15 mm$^2$.

A significant surge was found to occur in aspect ratio (4 to 6) of the EB welds compared to that of other welding processes. The substantial increase in aspect ratio is attributed to high power beam density of EB welding. The huge difference in fusion areas between EBW and other welding processes is due to variation in heat inputs used. It can be seen that no appreciable change in keyhole width with the variation of beam oscillation in EB welding.
(a) Conventional EBW
  Toe width : 2 mm
  Keyhole width: 1.31 mm
  FZ Area : 13.18 mm²
  Aspect ratio: 6.06

(b) Triangular beam oscillation EBW
  Toe width : 3.12 mm
  Keyhole width: 1.45 mm
  FZ Area: 15.18 mm²
  Aspect ratio: 4.38

(c) Elliptical beam oscillation EBW
  Toe width : 3.65 mm
  Keyhole width: 1.46 mm
  FZ Area: 15.16 mm²
  Aspect ratio: 3.92

Figure 5.24 Macrographs of different EB welds produced in single pass

5.4.2 Effect of Beam Oscillation on weld microstructures

The microstructures of the FZ and Interface for the welds made using EB welding with and without beam oscillation are shown in Figure
5.25. Electron beam welds exhibited finer dendritic structure due to the low heat input and rapid cooling rate.

Figure 5.25 Microstructures of FZ and Interface of various EB welds: Conventional-(a) FZ, (b) Interface; Triangular- (c) FZ, (d) Interface; Elliptical-(e) FZ, (f) Interface
Fusion zone of EB welds was found to exhibit a solidification microstructure (Figures 5.25a, c and d) which consists of primary austenite dendrites with boride eutectics in the interdendritic regions.

Low heat input associated with high cooling rates almost eliminated the PMZ in electron beam welding and no localized region of austenite was noticed in Figures 5.25d and f.

Beam oscillation technique almost eliminated partially melted eutectic borides formed in PMZ and no localized region of austenite was noticed as it can be seen in the Figures 5.25d and f. However, the partially melted eutectics in conventional EB welding differ in size and shape compared to that of EB welding with beam oscillation. This could be attributed to the further rapid cooling rates offered by beam oscillation in EB welding.

5.4.3 Effect of Beam Oscillation on Hardness Profile

The microhardness profiles measured across the various weld zones such as FZ and BM of EB welds are presented in Figure 5.26. Hardness profiles revealed that FZ in EB welds exhibited higher hardness about 350-370 HV compared to that of all other welds. This could be due to very fine dendritic microstructure with boride eutectics in the interdendritic regions in fusion zone as shown in Figure 5.25a, c and e.
Furthermore, the hardness minimum was found to observe in the base metal, indicating that FZ region show better hardness values than that of base metal. It is shown in the next section that the tensile fractures are in accordance with the hardness profiles, as the failures take place in the base metal.

5.4.4 Effect of beam oscillation on Tensile Properties

The tensile test results of EB welds are summarised in Table 5.10. The various tensile properties such as yield strength (YS), tensile strength (UTS) and percentage elongation were determined and compared with that of base metal. The joint efficiency of about 97-99% was measured in EB welds and fracture occurs far away from FZ as shown in Figure 5.27. This could be attributed to the rapid cooling rates offered by EB welding.
Table 5.10 Results of tensile and impact testing of 304B4 EB weld with different beam oscillations

<table>
<thead>
<tr>
<th>Process</th>
<th>Proof Stress (MPa)</th>
<th>Ultimate Tensile Strength (Mpa)</th>
<th>% Elongation</th>
<th>Location of fracture</th>
<th>Joint efficiency in terms of UTS</th>
<th>Impact toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>384±5</td>
<td>576±3</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>7±1</td>
</tr>
<tr>
<td>EBW – C</td>
<td>340±5</td>
<td>560±3</td>
<td>10</td>
<td>BM</td>
<td>97.22%</td>
<td>7±1</td>
</tr>
<tr>
<td>EBW – T</td>
<td>415±5</td>
<td>570±3</td>
<td>12</td>
<td>BM</td>
<td>98.95</td>
<td>10±1</td>
</tr>
<tr>
<td>EBW – E</td>
<td>376±5</td>
<td>561±3</td>
<td>10</td>
<td>BM</td>
<td>97.39%</td>
<td>7±1</td>
</tr>
</tbody>
</table>

Figure 5.27 Tensile-tested EB welds: (a) failed specimens (b) cross section of a fracture surface (arrow shows failure location)
5.4.5 Effect of beam oscillation on Impact strength

The results of Charpy impact test are presented in Table 5.10. The EB welds exhibited a toughness value of about 7-10 J at room temperature. It was observed that the welds exhibit almost same toughness as that of BM irrespective of welding process employed. Beam oscillation method did not substantially affect the toughness of the welds. Lower toughness of BM and FZ is mainly due to brittle (Cr, Fe)$_2$B borides (Robino et al 1995).

5.5 COMPARISON OF WELDS MADE USING DIFFERENT WELDING PROCESSES

5.5.1 Bead Geometry

Cross sections of the welds made using different welding processes are presented in Figure 5.28, along with the bead profile parameters and corresponding welding parameters used. Full penetration defect free welds were obtained and it is evident from the macrostructures that no cracks were observed.

The cross sectional areas of FZ for both GTAW and SMAW were calculated using image analysis software and they were found to be 146 mm$^2$ (2 passes) and 71 mm$^2$ (9 passes) respectively. The difference in areas is due to the difference in number of passes employed and the corresponding heat inputs. It has been subsequently found that the total heat input or the weld pool size affects the location of failure during a tensile test.
Figure 5.28 Cross sections of the welds made using different welding processes.
It has been observed in this study that bead shape becomes relatively wider and shallow with the increase in welding current in case of both GTA and nitrogen added GTA welding. However, the effect of activated flux on the bead geometry is much more significant and a full penetration of 10 mm in single pass could be observed. It can also be seen from the macrograph presented in the Figure 5.28 that activated flux also causes the aspect ratio of the weld bead to increase to 0.8 which is a significant change. It was noticed that the activated flux has beneficially influenced the Marangoni convection mode by changing the temperature gradient. Electron beam welds exhibited a keyhole type of bead geometry and full penetration could be achieved using far lesser heat input of 0.36 kJ/mm showing the process to be a class apart.

5.5.2 Microstructure

The typical microstructures of the FZ for the welds made using various welding processes are shown in Figure 5.29 a-f. The FZ is a solidification microstructure which consists of primary austenite dendrites with boride eutectics in the interdendritic regions. The fusion zone of activated flux GTA and pulsed GTA welds was characterized by columnar austenite dendritic structure with eutectic borides solidified in the interdendritic regions (Figure 5.29b and d). However, GTA and nitrogen added GTA welds exhibited both equiaxed and columnar dendritic structure. Short interaction span with high energy density causes low heat input in EBW. As a result, FZ in EBW cools faster resulting in finer equiaxed dendritic structure (Figure 5.29f).

In case of SMA welds, FZ exhibits skeletal (vermicular) ferrite microstructure in an austenite matrix as shown in Figure 5.29e. This is the common feature of FZ for SMA welds when 308 filler is used.
Figure 5.29 Microstructures of the Fusion Zone in (a) GTA (b) Activated flux GTA (c) nitrogen added GTA (d) pulsed GTA (e) SMA (f) EB welding processes
The typical appearances of the PMZ for various weld types are presented in Figure 5.30a-f.

Figure 5.30 Microstructures of the weldments of various welding processes (a) GTAW (b) Activated GTAW (c) nitrogen added GTAW (d) Pulsed GTW (e) SMAW (f) EBW
As it can be noticed, the representative PMZ consists of austenite islands that remain solid during welding, surrounded by irregular boride eutectics. However, the width of PMZ was found to be more in case of GTA and nitrogen added GTA welds than that of activated flux GTA and Pulsed GTA welds. This is attributed to slow cooling rates associated with high heat inputs prevailing in GTA and nitrogen added GTA welds. Low heat input associated with high cooling rates almost eliminated the PMZ in electron beam welding and no austenite islands were noticed in Figure 5.30f. It can be observed that the PMZ in case of SMA weld (Figure 5.30e) 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.

5.5.3 Hardness Profiles

Microhardness surveys carried out, across the various weld zones such as FZ, PMZ and BM of different welds and their failure locations are shown in Figure 5.31 and 5.32. Hardness profiles revealed that FZ exhibited higher hardness for all the welds. The increase in hardness of FZ is attributed to the presence of dendritic microstructure with boride eutectics in the interdendritic regions.

It was observed that the nitrogen addition in GTA welds significantly enhances FZ hardness. It was also noticed that there is a sudden fall in hardness of the PMZ in case of both GTA and nitrogen added GTA welds while there exists no such trend in activated GTA, pulsed GTA, SMA and EB welding. The significant reduction in PMZ hardness is attributed to the difference in cooling rates which results in variation in size and shape of eutectic borides formed in PMZ as can be seen from Figure 5.30a and c. It can be seen from Figure 5.31b that the fracture during tensile test in case of GTA and nitrogen added GTA welds, occurs in PMZ whereas in case of other welds fracture occurs in the Heat Affected Zone (Figure 5.32b).
5.5.4 Tensile Properties

The tensile properties have been presented in Table 5.11, for the different welds considered in present study. Though there is no significant variation in joint efficiencies of the welds, a marginal improvement in yield strength for electron beam (triangular) and activated GTA welds was noticed due to the variation in the microstructural features.

![Figure 5.31](image)

**Figure 5.31** Hardness profiles and failure locations of various welds: (a) Hardness profiles (b) failure locations occurred in PMZ

The GTA and nitrogen added GTA welds were found to fracture at PMZ, the region where the loss of hardness can be clearly noticed due to larger boride eutectics. It was also observed that activated GTA, pulsed GTA, and SMA welds failed in HAZ far away from the weld metal. Low heat input welding processes exhibited significant improvement in tensile strength compared to high heat input welding process.
Figure 5.32  Hardness profiles and failure locations of the welds made using different welding processes : (a) Hardness profiles  (b) failure locations
The surfaces as observed in the SEM for tensile tested samples of welds produced by GTA welding revealed that ductile, dimpled rupture features with occasional boride decohesion and cracking as it can be seen from 5.33a. Examination of the tensile fracture surfaces of SMA weld showed the brittle fracture mode as it happens in the base material containing boron eutectic network (Figure 5.33b).

Figure 5.33  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

5.5.5  Impact Toughness

The results of Charpy impact test conducted at room temperature for the welds produced using various welding processes are presented in Table 5.11. It was observed that the almost of all the welds exhibit the same toughness as that of BM except SMA welding processes. Lower toughness of BM and FZ is mainly due to brittle (Cr,Fe)$_2$B borides. The SMA weld exhibited good toughness value of 37 J at room temperature. It is observed that 308 filler has significantly improved the impact strength of SMA welds. As the weld region does not contain 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.

Table 5.11 The mechanical properties of 304B Stainless Steels welds made by various welding processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Proof Strength</th>
<th>Ultimate Tensile Strength</th>
<th>% Elongation</th>
<th>Joint Efficiency in terms of tensile strength</th>
<th>Failure Location</th>
<th>Impact toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>384± 5</td>
<td>576± 3</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>GTAW</td>
<td>379± 5</td>
<td>545±3</td>
<td>10</td>
<td>94.62</td>
<td>PMZ</td>
<td>7</td>
</tr>
<tr>
<td>AGTAW</td>
<td>400± 5</td>
<td>569± 3</td>
<td>14</td>
<td>98.78</td>
<td>HAZ</td>
<td>7</td>
</tr>
<tr>
<td>N-GTAW</td>
<td>390± 5</td>
<td>550± 3</td>
<td>11</td>
<td>96.32</td>
<td>PMZ</td>
<td>8</td>
</tr>
<tr>
<td>Pulsed-GTAW</td>
<td>380± 5</td>
<td>561± 3</td>
<td>11</td>
<td>97.39</td>
<td>HAZ</td>
<td>7</td>
</tr>
<tr>
<td>SMAW</td>
<td>385± 5</td>
<td>572± 3</td>
<td>12.1</td>
<td>98</td>
<td>BM</td>
<td>36.7</td>
</tr>
<tr>
<td>EBW –C</td>
<td>340± 5</td>
<td>560± 3</td>
<td>10</td>
<td>97.22</td>
<td>BM</td>
<td>7</td>
</tr>
<tr>
<td>EBW –Triangular</td>
<td>415± 5</td>
<td>570± 3</td>
<td>12</td>
<td>98.95</td>
<td>BM</td>
<td>10</td>
</tr>
<tr>
<td>EBW –Elliptical</td>
<td>376± 5</td>
<td>561± 3</td>
<td>10</td>
<td>97.39</td>
<td>BM</td>
<td>7</td>
</tr>
</tbody>
</table>

5.6 CORROSION BEHAVIOUR

5.6.1 Potentiodynamic Polarization Test in NaCl Solution

The corrosion behaviour of the borated stainless steel base material and GTA weld was first evaluated in pure 1M NaCl solution and their curves are shown in Figure 5.34.
The electrochemical data obtained from the studies in chloride media are presented in Table 5.12.

**Table 5.12 Electrochemical data for the 304B welds in 1M NaCl solution**

<table>
<thead>
<tr>
<th>Weld metal</th>
<th>Corrosion Potential, $E_{\text{corr}}$ (mV)</th>
<th>Corrosion Current Density, $I_{\text{corr}}$ ($\mu$A/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIG</td>
<td>-89</td>
<td>4.259e-08</td>
</tr>
<tr>
<td>Base Metal</td>
<td>10</td>
<td>3.339e-09</td>
</tr>
</tbody>
</table>

The comparison of polarisation behaviours of base metal and fusion zone in 1 M NaCl is presented in Figure 5.34. As it can be clearly noticed that fusion zone exhibits the inferior corrosion resistance than that of base metal.
But on the other hand, no pitting i.e., no breakdown in the passive region was observed in both base metal and the weld, which in turn shows that eutectic borides and primary austenite resist pitting strongly in sodium chloride solution.

5.6.2 Potentiodynamic Polarization test in NaCl+H₂SO₄ Solution

The corrosion behaviour of fusion zone for the welds made using various welding processes such as GTA, Activated GTA, SMA and EB welding was evaluated in NaCl+H₂SO₄ solution and the polarization curves are shown in Figure 5.35.

![Data Graph](image)

**Figure 5.35** Polarisation behaviour of Fusion Zone for various Borated Stainless Steel base metal and welds in NaCl+H₂SO₄ solution

The potentiodynamic polarization curves revealed that the welds made using GTA, SMA and EB welding processes exhibited superior
corrosion resistance in NaCl + H₂SO₄ solution compared to that of base material. However, activated GTA welds were found to show inferior corrosion resistance than that of base metal. The macro and microstructures showing clear appearance of pit formation are presented in Figures 5.36 and 5.37 respectively.

Table 5.13  Electrochemical data of the Fusion Zone for various 304B welds in NaCl+H₂SO₄ solution.

<table>
<thead>
<tr>
<th>Weld metal</th>
<th>Corrosion Potential, E_corr (mV)</th>
<th>Corrosion Current Density, I_corr (µA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIG</td>
<td>-123</td>
<td>2.731e-8</td>
</tr>
<tr>
<td>ATIG</td>
<td>-394</td>
<td>0.0218883</td>
</tr>
<tr>
<td>SMAW</td>
<td>-303</td>
<td>0.0001025</td>
</tr>
<tr>
<td>EBW</td>
<td>-324</td>
<td>0.005964</td>
</tr>
<tr>
<td>Base Metal</td>
<td>-385</td>
<td>0.0008413</td>
</tr>
</tbody>
</table>

From the electrochemical data presented in Table 5.13, it is evident that the GTA welds exhibit significantly better corrosion resistance, as the corresponding polarization curve shifts very much towards the positive side at about corrosion potential (E_corr) of -123mV (Figure 5.35). The corrosion current density for the welds made using GTA Welding was found to be the lowest, again indicating its superior resistance to corrosion in NaCl + H₂SO₄ medium. The weld metal of GTAW did not show any sign of pitting as can be seen from macro and microstructures shown in Figure 5.36a and Figure 5.37a respectively. The superior corrosion resistance of GTA welds is possibly on the account of either its equiaxed dendritic structure in FZ.
Figure 5.36 Macrographs of various 304B welds and base metal after the corrosion test (a) GTAW (b) AGTAW (c) SMAW (d) EBW (e) Base Metal

The corrosion potential ($E_{corr}$) in case of activated GTA welds shifts towards the active side at about -394 mV and the current density is also higher, showing inferior resistance to corrosion in the test medium. The pits have been clearly noticed in the FZ of activated GTA welds as can be seen from the macrograph shown in Figure 5.36b. The reduction in corrosion
resistance is attributed to the presence of columnar microstructure in the FZ of activated GTA welding as shown in the Figure 5.37b.

Figure 5.37  Microstructures of various 304B welds and base metal after the corrosion test (a) GTAW (b) AGTAW (c) SMAW (d) EBW (e) Base Metal
The polarisation behaviour of PMZ for the welds made using various welding processes such as GTA, Activated GTA, and SMA evaluated in NaCl+H₂SO₄ solution and the polarization curves are shown in Figure 5.38.

![Figure 5.38](image)

**Figure 5.38** Polarisation behaviour of PMZ of various Borated Stainless Steel welds in NaCl+H₂SO₄ solution

The corrosion behaviour of PMZ for various welds was also found to exhibit the same trend as that of FZ. The corresponding $E_{\text{corr}}$ and $I_{\text{corr}}$ values are presented in Table 5.14.

**Table 5.14** Electrochemical data for the Partially Melted Zone of various 304B welds in NaCl+H₂SO₄ solution.

<table>
<thead>
<tr>
<th>Weld metal</th>
<th>Corrosion Potential, $E_{\text{corr}}$ (mV)</th>
<th>Corrosion Current Density, $I_{\text{corr}}$ (μA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIG</td>
<td>-213</td>
<td>1.231e-05</td>
</tr>
<tr>
<td>ATIG</td>
<td>-332</td>
<td>0.0011996</td>
</tr>
<tr>
<td>SMAW</td>
<td>-360</td>
<td>0.0015253</td>
</tr>
<tr>
<td>EBW</td>
<td>-364</td>
<td>0.0013805</td>
</tr>
</tbody>
</table>