Studies on Fusion Welding of High Nitrogen Stainless Steel: Microstructure, Mechanical and corrosion Behaviour

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Abstract. An attempt has been made in the present investigation to weld high nitrogen steel of 5mm thick plates using various process i.e., shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW) and autogenous electron beam welding (EBW) process. Present work is aimed at studying the microstructural changes and its effects on mechanical properties and corrosion resistance. Microstructure is characterized by optical, scanning electron microscopy and electron back scattered diffraction technique. Vickers hardness, tensile properties, impact toughness and face bend ductility testing of the welds was carried out. Pitting corrosion resistance of welds was determined using potentio-dynamic polarization testing in 3.5%NaCl solution. Results of the present investigation established that SMA welds made using Cr-Mn-N electrode were observed to have a austenite dendritic grain structure in the weld metal and is having poor mechanical properties but good corrosion resistance. GTA welds made using 18Ni (MDN 250) filler wire were observed to have a reverted austenite in martensite matrix of the weld metal and formation of unmixed zone at the fusion boundary which resulted in better mechanical properties and poor corrosion resistance. Fine grains and uniform distribution of delta ferrite in the austenite matrix and narrow width of weld zone are observed in autogeneous electron beam welds. A good combination of mechanical properties and corrosion resistance was achieved for electron beam welds of high nitrogen steel when compared to SMA and GTA welds.

1. Introduction

Austenitic stainless steels (ASS) are known for structural application because of better combination of formability, strength and corrosion resistance. Typically austenitic stainless steel requires a combination of 8% Nickel (Ni) and 18% Chromium (Cr) to achieve required strength and corrosion resistance [1].Even though conventional stainless steels are fully austenitic, they are generally not considered because of higher cost associated with high Ni content. However, replacing carbon (C) in SS with nitrogen (N) became favourable since N is a strong austenite stabilizer, and has greater solubility than C [2]. An austenitic material generally is considered high-N if it contains > 0.4 wt% N [3]. High nitrogen steels have much higher yield strengths than the 300 series SS such as types 304 SS and 316 SS [4-7].High nitrogen steel is a nickel free high Cr-Mn-N steel having a wide scope in defence sector for manufacturing battle tanks by replacing the existing armour steel are becoming an important engineering materials [8]. Nitrogen not only an effective solid solution strengthener than carbon but also enhances grain size strengthening [9,10]. Nitrogen is a strong austenite stabilizer, thereby reducing the amount of nickel required for austenite stabilization. Nitrogen remarkably improves resistance to intergranular, pitting, crevice and stress corrosion cracking [11]. Even though

base metal exhibits better combination of properties, welding results in significant loss of mechanical properties and corrosion resistance. In conventional fusion welding process, it leads to several problems like formation of nitrogen pores, solidification cracking in the weld zone, lowering the dissolved nitrogen for solute strengthening and precipitation of Cr-nitrides in the heat affected zone [12]. The nitride precipitation reduces seriously the mechanical and corrosion resistance. Proper selection of filler metal is important to overcome the above problems and should be aimed at low impurity levels and good control on segregation of alloying elements [13]. Defects like porosity and solidification cracking may be overcome by the use of similar composition of matching filler wire or by choosing a filler wire which produces required amount of delta ferrite in fusion welds. Based on service conditions, delta ferrite requirement in austenitic stainless steel welds is often specified to ensure that weld metal to alleviate the cracking tendency [14]. High nitrogen steel welds made with near matching composition similar to base metal resulted in improved corrosion resistance but inferior in strength [15]. Presently as no matching filler wires are commercially available for welding high nitrogen austenitic stainless steel [16].Keeping in view of the above factors, an attempt has been made to weld high nitrogen steels of 5mm thick plates using various welding process i.e., shielded metal arc welding (SMAW) with near matching Cr-Mn-N electrode, gas tungsten arc welding (GTAW) with high strength (18Ni) maraging steel and autogeneous welds made with electron beam welding (EBW) process. Present work is aimed at studying the microstructural changes during welding of high nitrogen steel and to correlate with observed mechanical properties and pitting corrosion resistance.

2. Experimental Details

Shielded metal arc welding with Cr-Mn-N electrode, gas tungsten arc welding with high strength (18Ni) MDN 250 filler and electron beam welding were used to join high nitrogen stainless steel plates of 5mm thick plates. Base metal and filler wires compositions are given in the Table 1. Optimized welding parameters of all the welding processes are given in the Table 2, 3 and 4. Welded plates of high nitrogen steel using shielded metal arc welding, gas tungsten arc welding and autogeneous electron beam welding are shown in Fig. 1. X-ray radiography of welds observed to be a sound weld for all the welding process. Microstructural changes in various zones of the welds were studied using optical microscopy, scanning electron microscopy and grain orientation studies were carried out with electron back scattered diffraction method at various zones of the welds. Tensile testing is carried out using 40Tuniversal testing machine to determine ultimate tensile strength, yield strength and % elongation. Vickers hardness values were recorded in the longitudinal directions of the weld with a load of1kgf. Face bend ductility was observed at the weld as per ASTM E190-92 standard. Charpy impact testing was done on the sub size specimen to determine the toughness of the welds. Pitting corrosion resistance of welds are carried out using potentio-dynamic polarization testing in 3.5% NaCl solution. The exposure area for these experiments was 1 cm^2.

Table 1 Composition of the base metal (HNS), Electrode (Cr-Mn-N) and filler (MDN 250)

Material	C	Mn	Cr	N	S	P	Ni	Co	Si	Fe
Base metal (HNS)	0.076	19.78	17.96	0.543	0.007	0.051	-	-	0.34	Bal.
Electrode (Cr-Mn-N)	0.066	17.36	17.33	0.366	0.017	0.047	0.09	-	0.522	Bal.
Filler (MDN 250)	0.03	0.10	0.50	-	0.10	0.01	18	8	0.10	Bal.

Table 2 Welding parameters using Shielded Metal Arc Welding

Welding Current	110-130A
Welding Speed	4mm/sec
Electrode Diameter	3.2mm
Electrode position	45^0
No. of passes	3
Root gap	1.5mm

Table 3 Welding parameters using Gas Tungsten Arc Welding

Welding Current	130A
Welding Speed	60mm/min
Electrode polarity	DCSP
Arc voltage	18-20V
Filler wire diameter	1.6mm
Electrode	2% thoriated tungsten
No. of passes	2
Shielding gas	Argon

Table 4 Welding parameters using Electron Beam Welding

Gun to work distance	283 mm
Gun voltage	60 kv
Beam Current	60mA
Travel Speed	1m/min
Energy	4kW
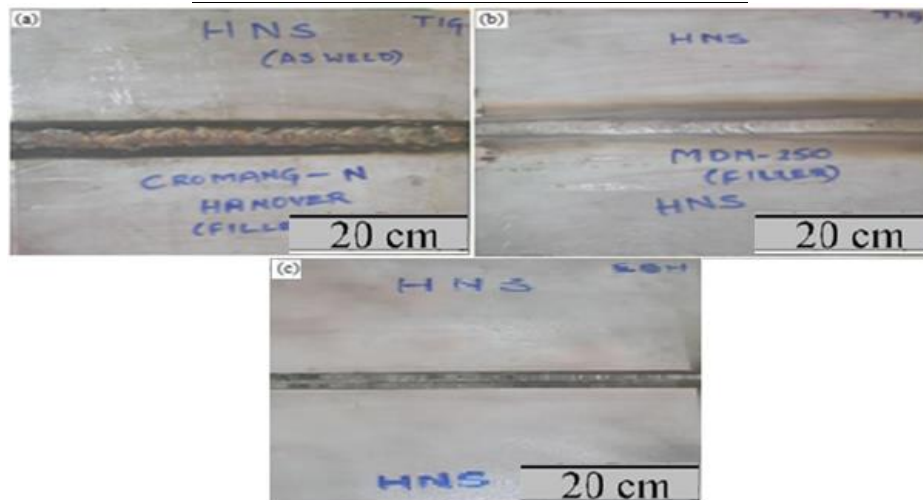
Fig.1 Macroscopic appearance of the high nitrogen stainless steel welds (a). SMAW (Cr-Mn-N);
(b). GTAW (MDN 250) and (c). EBW

3 Results and Discussions

3.1. Microstructure

3.1.1. Base Metal. In the cold worked condition, high nitrogen steel is having a concurrent twinning and slip in austenite. High nitrogen steel in general, show planar slip and pronounced twinning. The twin deformation in austenite is related to the stacking fault energy of the material. In nickel containing Cr-Mn and Cr-Ni steels, the stacking fault energy does not decrease with increasing nitrogen content. However, in nickel free high nitrogen steels it is observed a decrease in stacking fault energy with increasing nitrogen content. In high nitrogen steel, a decrease in stacking fault

energy with nitrogen enhances formation of deformed band structure. These bands have high dislocation density and do not undergo dynamic recovery. Hence, nitrogen gives more strengthening to Ni free Cr-Mn steel than Ni containing steels [17]. Grain orientation mapping and phase analysis maps of the nickel free high nitrogen steel is observed to have fine grain morphology and single phase of austenite were observed as shown in Fig.3.
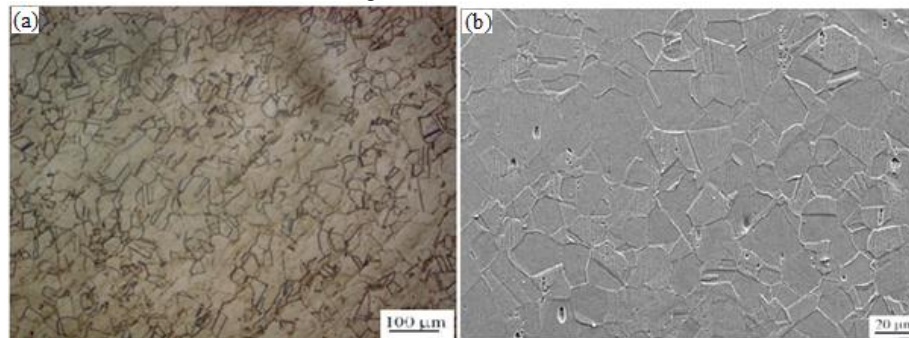

Fig.2 Optical Microstructure of base metal nickel free high Cr-Mn-N steel (HNS) (a).Optical (b).Scanning electron microscopy
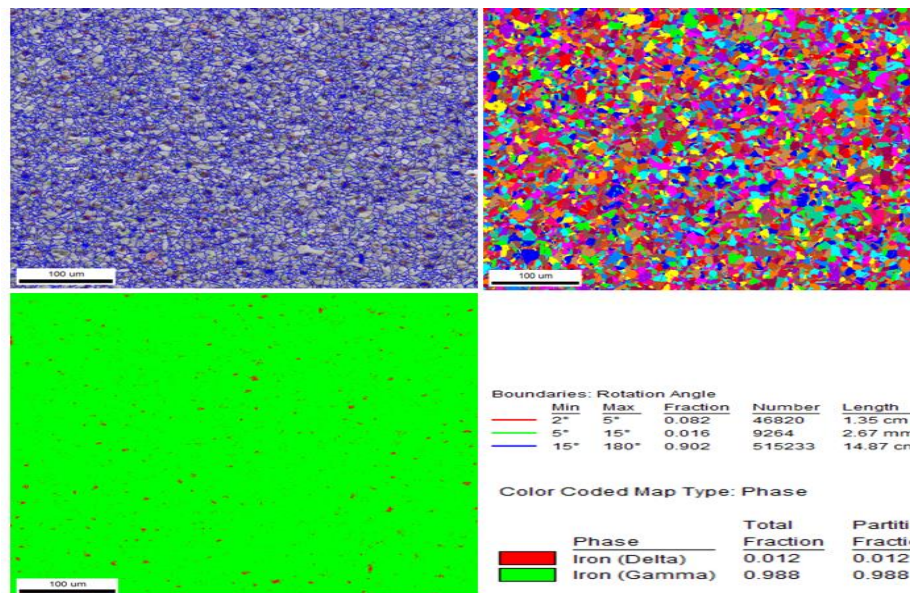
Fig.3 Grain orientation, OIM maps and phase analysis of nickel free high Cr-Mn-N steel

3.1.2. Weld Microstructure. Microstructural changes and solidification mode of high nitrogen austenitic stainless steel welds is determined on various factors like chemical composition of the electrode/filler and welding process. Heat input and cooling rates of welding process may influence the dilution of the weld. Based on cooling rates, the extent of dilution also varies in the welds. Filler wire which differs from base metal composition also alters the solidification mode and extent of dilution [18].Shielded metal arc welding using Cr-Mn-N type electrode is having high heat input and slow cooling rate resulted in weld metal microstructure as fully austenitic and consists of coarse dendritic austenite grains.
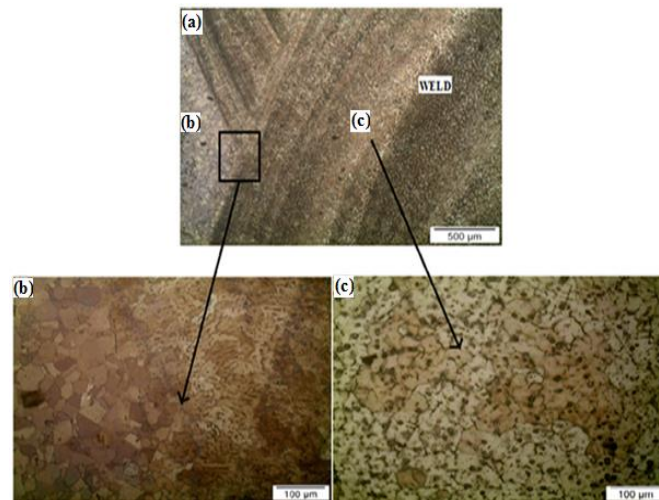
Fig.4 Optical micrographs of nickel free high Cr-Mn-N steel SMA weldsl (a) Weld interface (b) Heat affected zone (c) Fusion zone
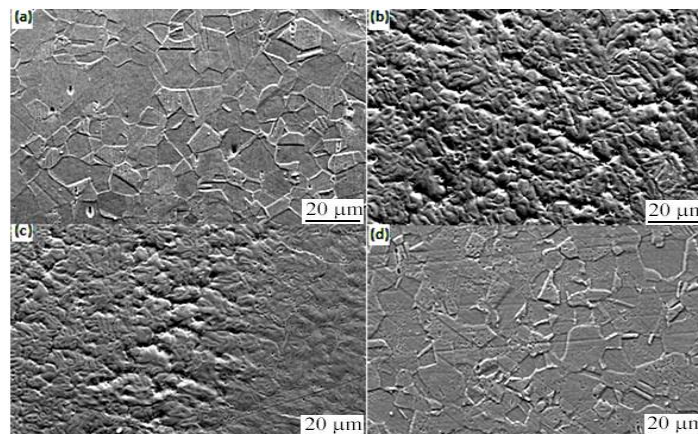

Fig.5 SEM images of nickel free high Cr-Mn-N steel SMA welds (a) Base metal (b) Fusion zone (c) Weld interface (d) Heat Affected zone

Fully austenite structure in the weld metal is attributed to the high amount of chromium and manganese which helps to improve the solubility of nitrogen. At the weld interface, along the fusion boundary towards the base metal transition of coarse grains to fine grains were observed and is shown in Fig.4.Microstructure is having maximum austenite structure due to the dilution of adjacent base metal which is having nitrogen which is completely soluble in the solid solution. Scanning electron micrographs shown in Fig.4 clearly reveals the coarse grains of austenite.

In Fig. 6, from the grain orientation and phase analysis maps at the weld metal and weld interface of SMA weld is having coarse grains orientation at the weld zone and at weld interface, it is observed to have coarse grains to fine grains transition from fusion zone to base metal. However, high nitrogen steel weld made with high strength (18Ni) MDN 250 filler resulted in continuous network of island pools of reverted austenite in the martensite matrix and observed to be having elongated and coarse grains and as shown in Figs. 7 and 8. Heating and cooling rates during welding affects the microstructure and surface composition of fusion welds of high nitrogen steel [19]. Unmixed zone is observed at the fusion boundary of welds made with MDN 250 filler and is attributed to the melting of base metal and re-solidifies during welding without mechanically mixing with the filler wire and base metal [20]and can be seen in Figs. 7c and 8c.
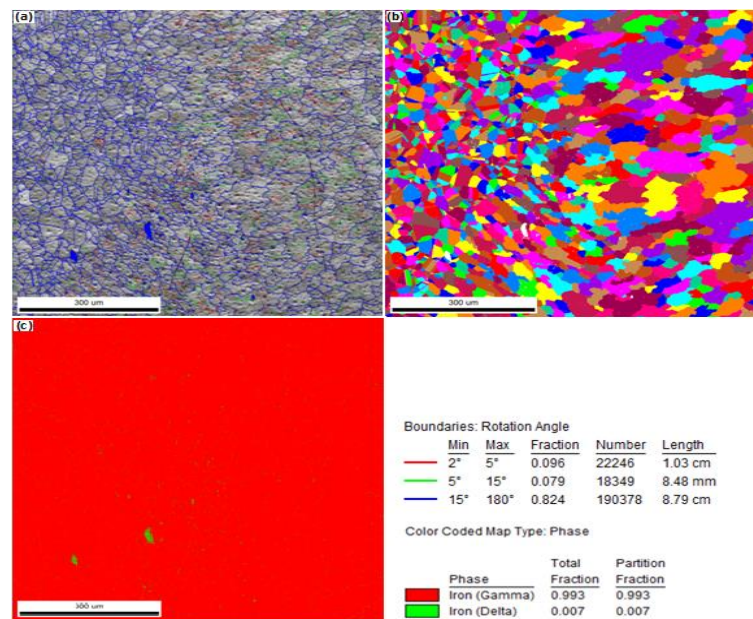
Fig. 6 Grain orientation, OIM maps and phase analysis of nickel free high Cr-Mn-N steel SMA Weld
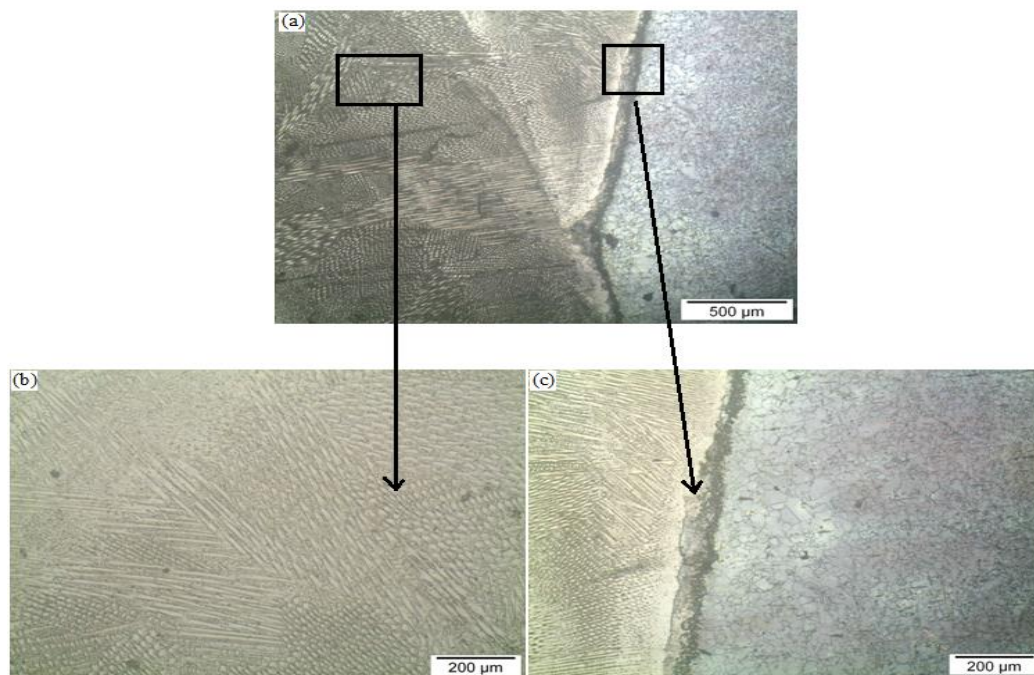

Fig.7 Optical micrographs of nickel free high Cr-Mn-N steel GTA welds made with MDN 250 filler:
(a) Weld interface (b) Fusion zone (c) Heat affected zone

In Fig. 9, grain orientation maps for the welds made with gas tungsten arc welding is observed to have an elongated coarse grain orientation. Isolated pore in the weld metal near to fusion boundary. Unmixed zone is clearly visible along the fusion boundary adjacent to the base metal due to non matching filler composition to base metal.
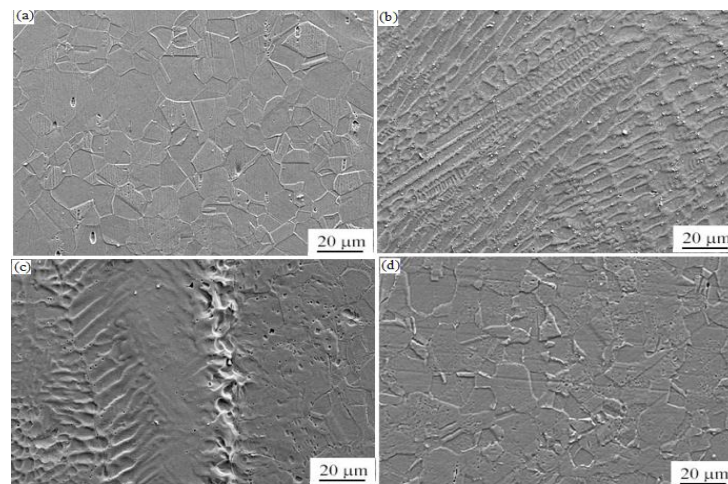
Fig.8 SEM images of nickel free high Cr-Mn-N steel welds made with MDN 250 filler: (a) Base metal (b) Fusion zone (c) Weld interface (d) Heat Affected zone
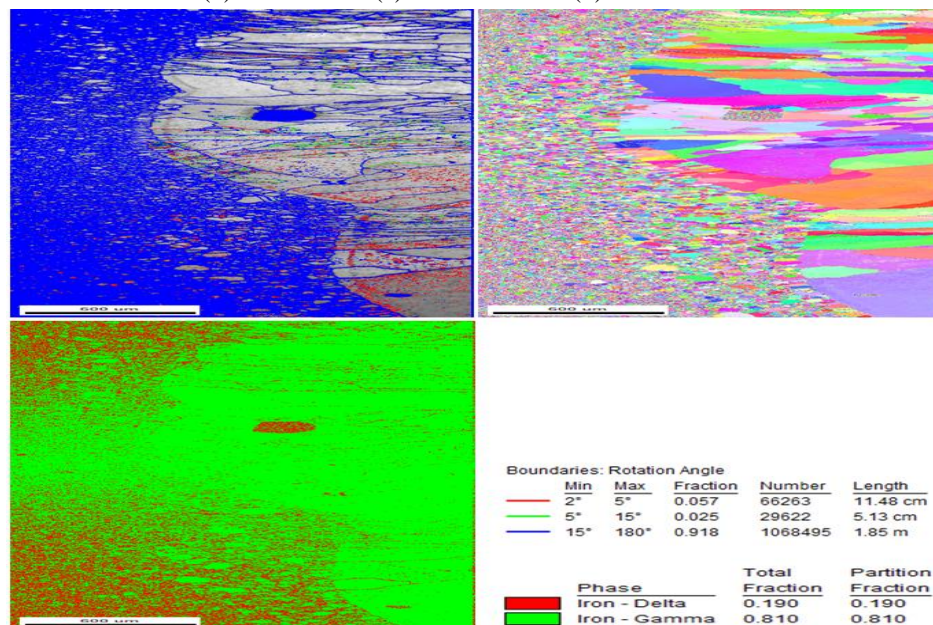

Fig.9 Grain orientation, OIM maps and phase analysis of nickel free high Cr-Mn-N steel GTA weld (weld interface)

Whereas the electron beam welds of high nitrogen steel resulted in narrow width of the weld zone and is attributed to low heat input and faster cooling rates. Weld metal microstructure of the electron beam welds is having a mixture of austenite matrix and delta ferrite dendrites due to rapid cooling as shown in Figs.10 and 11. At the weld interface of electron beam welds, formation of elongated coarse grains of austenite is observed in Figs. 10 and 11.In Fig. 12 grain orientation maps and phase analysis maps of the high nitrogen steel made with electron beam welding process is having a fine grain orientation at the weld zone and at the weld interface formation of coarse grain heat affected zone is observed. Different phases were analysed using phase maps and recorded the percentage of delta ferrite, austenite and also determined the distribution of the ferrite in the matrix. It can be seen in Fig.12 that the delta ferrite is distributed as discontinuous network in the austenite matrix.
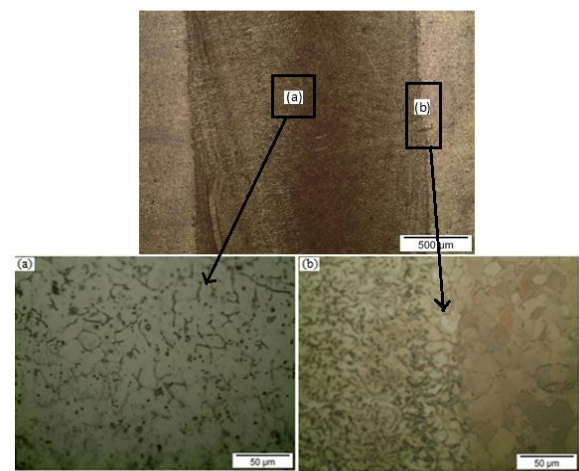
Fig.10 Optical micrographs of nickel free high Cr-Mn-N steel GTA welds made with electron beam welding: (a) Weld interface (b) Fusion zone (c) Heat affected zone
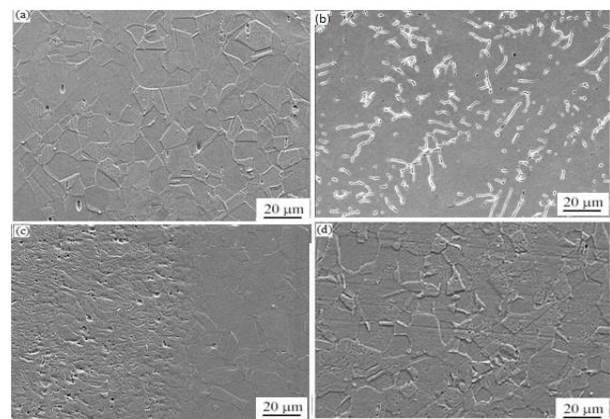

Fig.11 SEM images of nickel free high Cr-Mn-N steel welds made with electron beam welding: (a) Base metal (b) Fusion zone (c) Weld interface (d) Heat Affected zone
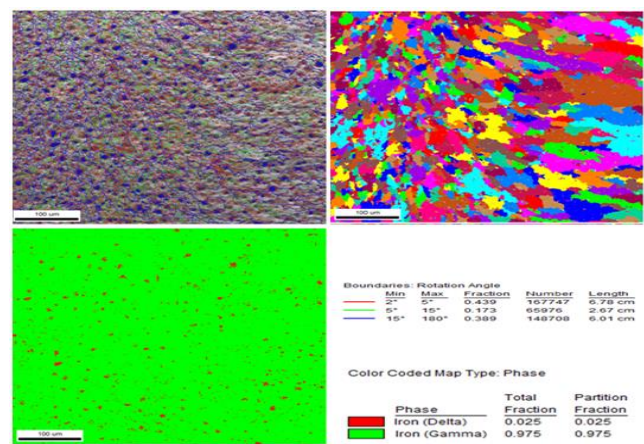

Fig.12 Grain orientation, OIM maps and phase analysis of nickel free high Cr-Mn-N steel electron beam welds (weld interface)

3.2. Mechanical studies

Mechanical properties of high nitrogen steel were studied using Vickers hardness, tensile properties, impact toughness and face bend ductility are compared with welds obtained using various welding process. Higher strength in high nitrogen steel could be attributed to solid solution and grain boundary strengthening mechanisms. Strengthening has been generally observed by addition of nitrogen in steels. Improved strength in high nitrogen steel is influenced by solid solution hardening and decrease in stacking fault energy [21].In nickel free high Cr-Mn-N steels, the decrease in stacking fault energy enhances formation of mechanical twins that enhances strength. Nitrogen containing austenitic stainless steels show high impact toughness and is attributed to the fact that nitrogen does not induce void nucleation sites in the steel [22]. However, increasing nitrogen content enhances strength and retains impact toughness. Hence, nickel free high nitrogen austenitic stainless steels have the optimum combination of strength, ductility and toughness. Whereas welding process, filler/composition of filler and heat input may influence the mechanical properties of high nitrogen steel welds. Tensile testing for all nickel free high nitrogen steel welds are observed to fail at the weld zone and it can be seen in Fig.13 and given in Table 5. Impact studies to determine the energy absorbed is recorded using charpy impact testing and resulted in high impact toughness for welds made with electron beam welds and is given in Table 6 and shown in Fig. 14. Face bend test results shows the ductility and free from cracks or fissures as shown in Fig. 15. Hence, Welds made with electron beam welding has resulted in achieving mechanical properties similar to that of base metal and superior to that of welds made with shielded metal arc welding and gas tungsten arc welding.
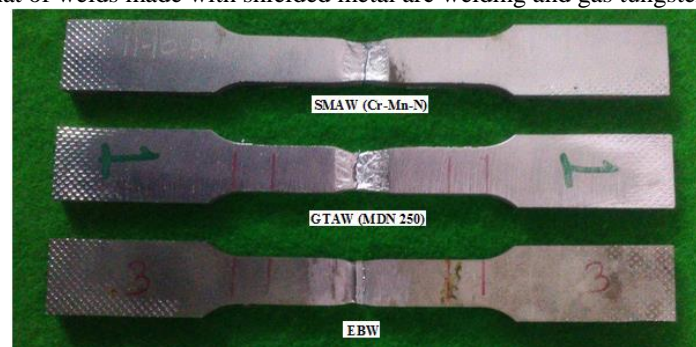

Fig. 13 Tensile failed specimens of nickel free high Cr-Mn-N steel welds

Table 5 Tensile values of nickel free high Cr-Mn-N steel welds

Material	UTS (MPa)	Y S (MPa)	% El	Location of Failure
HNS Base	1215	1190	22	Base
SMAW (Cr-Mn-N)	667	233	10	Weld
GTAW (MDN 250)	919	644	9.2	Weld
EBW	1065	811	5.8	Weld

Table 6 Hardness and charpy impact values of nickel free high Cr-Mn-N steel welds

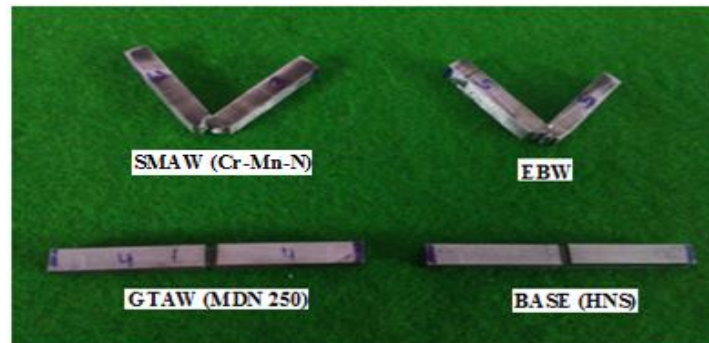| Material	Hardness (VHN)	Impact Strength (J)	Location of Failure
HNS Base	353	30	Base
SMAW (Cr-Mn-N)	251	40	Weld
GTAW (MDN 250)	211	18	Weld
EBW	310	44	Weld

Fig. 14 Impact failed specimens of nickel free high Cr-Mn-N steel welds

Fig. 15 Face Bend Specimens of nickel free high Cr-Mn-N steel welds

3.3. Pitting Corrosion

High nitrogen stainless steel generally exhibits better localized corrosion resistance in alkaline solution but only varies with cold work level. [23, 24]. High nitrogen steel tested using GillAC electrochemical system with an exposed area of $1cm^2$. As the morphology of the base metal is homogenous and fine, compact passive film is easy to form and makes difficult for chloride ion to pass through the surface and thus improves the corrosion resistance. Potentiodynamic polarization curves are shown in the Fig.16 respectively for the cold worked HNS base metal and welds in 3.5% NaCl solution. The pitting potential of the base metal high nitrogen stainless steel in cold worked condition is observed as 130mV. In general, localized corrosion resistance of welds is affected by microstructural changes. Nickel free high stainless steel enhances the pitting corrosion resistance and the welds may cause the inferior corrosion resistance due to nitrogen loss. Surface passive film formation may be influenced by the heat input during welding, grain size and microstructure of the weld metal. SMA welds made using near matching Cr-Mn-N type electrode resulted in higher pitting potential due to the presence of chromium and nitrogen as alloying elements and are due to homogenous grains it is observed as 270mV. In GTA welds made using MDN 250 filler is observed to have lower pitting potential and is attributed to the grain coarsening and absence of chromium in the weld metal which helps in formation of the surface passive film and pitting potential is observed as -20mV. Whereas electron beam welds is affected by low heat input and faster cooling rates helps in fine grains in the weld metal. Faster cooling rates resulted in distribution of delta ferrite in austenite matrix in the weld metal. Electron beam welds are having a moderate pitting potential and is observed as 170mV when compared to base metal and is attributed to the austenite/delta ferrite interface. Hence, welds made with electron beam welding is having pitting potential as uniform when compared to base metal and observed as higher corrosion resistant when compared to SMA and GTA welds.
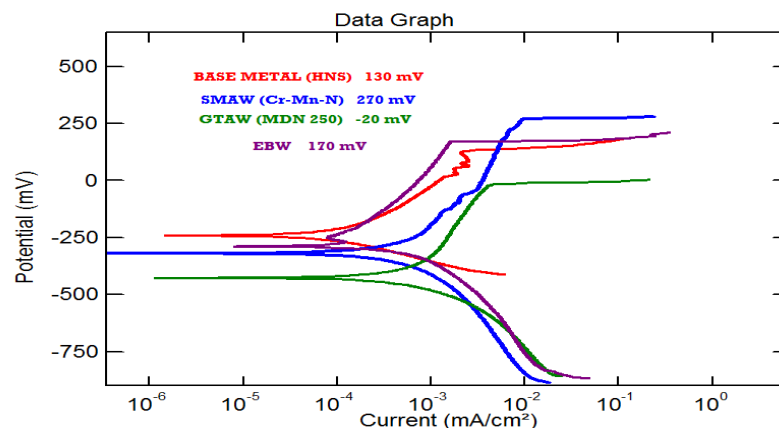
Fig. 16 Potentio-dynamic polarization curves of nickel free high Cr-Mn-N steel welds

4. Conclusions

1. High nitrogen steels are observed as equiaxed austenite fine grain structure with annealing twins at grain boundaries.

2. SMA welds made using Cr-Mn-N electrode is having a fully coarse austenite dendritic structure and is due to the presence of chromium and manganese which helps in complete solubility of nitrogen in the weld metal and resulted in superior pitting corrosion resistance but inferior mechanical properties.

3. GTA welds made using MDN 250 filler has resulted in reverted austenite island pools in the martensite matrix. Unmixed zone is formed adjacent to the weld metal due the variation in base metal and filler wire composition. In these welds, mechanical properties are observed to be superior but poor in pitting corrosion resistance.

4. Autogeneous EB welds revealed a delta ferrite discontinuous network in the austenite matrix resulted in having better mechanical properties and pitting corrosion resistance.

5. Hence, electron beam welding of high nitrogen steel with narrow width of weld zone is achieved in having a high quality weld joint and having better combination of mechanical properties and pitting corrosion resistance when compared to shielded metal arc welds and gas tungsten arc welds.

References

[1] R.P. Reed, J. Metals 3 (1989) 16

[2] M.O. Speidel, "Properties and Applications of High-Nitrogen Steels," Proc. Int. Conf. High-Nitrogen Steels, HNS 88, held in Lille, France, May 1988, eds. J. Foct, A. Hendry (London, England: The Institute of Metals, 1989) 92

[3] M.L. Byrnes, M. Grujicic, W.S. Owen, Acta Metall. 35, 7 (1987) 1,853

[4] J. Menzel, G. Stein, P. Dahlmann, "Massively Nitrogen-Alloyed Austenitic Bolt Materials for High-Strength and High-Temperature Applications," Proc. Int. Conf. High-Nitrogen Steels, HNS 88, held in Lille, France, May 1988, eds. J. Foct, A. Hendry (London, England: The Institute of Metals, 1989) 147

[5] J.C. Rawers, J.S. Dunning, G. Asai, R.P. Reed, *Metall. T-A* 23A (1992) 2,061

[6] J.C. Rawers, G. Asai, R. Doan, J.S. Dunning, *J. Mater. Res*. 7, 5 (1992) 1,083

[7] M.O.Speidel, Uggowitzer P.J., Stickstofflegierte Stahle, Ergebnisse der Werkstoff Forschung Band 4, Thubal-Kain, Zurich, 1991.

[8] M.L.G. Byrnes, M. Grujicic and W.S. Owen, *Acta Metall*., 35 (1987) 1853.

[9] E. Werner, *Mater. Sci. Eng. A,* 101 (1988)93.

[10] M. Du Toitand, P.C. Pistorius**,** *welding journal* (2003) 219-222-S.

[11] WooInsuand KikuchiYasushi,*Trans.JWRI*, Vol.31,2, (2002)129.

[12] Mrityunjoy Hazra, Kotipalli SrinivasaRao, Gankidi Madhusudhan Reddy, J. *of Materials Research and Technology.* (2014) 90.

[13] Baldev Raj, P.Shankar and T Jayakumar, *Advances in Stainless Steel.*, (2010) 342.

[14] Madeleine du toit, *Journal of materials engineering and performance.*, 11 (2002) 312.

[15] Deepashri D. Nage, V.S. Raja, Journal of Material Science, 41 (2006) 2097.

[16] Raffi Mohammed, G. Madhusudhan Reddy and K. Srinivasa Rao, Defence Technology, *Special Issue on Materials Joining*, 11, 3 (2015) 237.

[17] Gavriljuk.V.G and Berns.H, High Nitrogen Steels, Springer, (1999) 82.

[18] Corrosion of weldments, ASM International.,(2006) 01.

[19] Edward Ghali, V.S.Sastri, M. Elboujdaini, Corrosion prevention and protection: practical solutions., Wiley (2009) 380.

[20] Alierza Namjou, Reza Dehmoloei, Ali ashrafi., *Int. J. of natural and engineering sciences.*, (2014) 22-28.

[21] M.D Mathew, V.S. Srinivasan, Mechanical properties of nitrogen bearing steels, (2006) 182.

[22] Speidel M.O, proc. Of Intnl. Conf. On high nitrogen steels, HNS 88 (1989) 92.

[23] N. Parvathavarthini, R.K. Dayal, S.K.Seshadri, J.B.Gnanamoorthy, *J.Nucl.Mater.* (1989)83.

[24] Yao Fu, Xinqiang Wu, En-Hou Han, Wei Ke, Ke Yang, Zhouhua Jiang, *J. Electrochemical Acta.* (2009) 1618.