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Welding of nickel free high nitrogen stainless steel: Microstructure and mechanical properties

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Abstract

High nitrogen stainless steel (HNS) is a nickel free austenitic stainless steel that is used as a structural component in defence applications for manufacturing battle tanks as a replacement of the existing armour grade steel owing to its low cost, excellent mechanical properties and better corrosion resistance. Conventional fusion welding causes problems like nitrogen desorption, solidification cracking in weld zone, liquation cracking in heat affected zone, nitrogen induced porosity and poor mechanical properties. The above problems can be overcome by proper selection and procedure of joining process. In the present work, an attempt has been made to correlate the microstructural changes with mechanical properties of fusion and solid state welds of high nitrogen steel. Shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), electron beam welding (EBW) and friction stir welding (FSW) processes were used in the present work. Optical microscopy, scanning electron microscopy and electron backscatter diffraction were used to characterize microstructural changes. Hardness, tensile and bend tests were performed to evaluate the mechanical properties of welds. The results of the present investigation established that fully austenitic dendritic structure was found in welds of SMAW. Reverted austenite pools in the martensite matrix in weld zone and unmixed zones near the fusion boundary were observed in GTA welds. Discontinuous ferrite network in austenite matrix was observed in electron beam welds. Fine recrystallized austenite grain structure was observed in the nugget zone of friction stir welds. Improved mechanical properties are obtained in friction stir welds when compared to fusion welds. This is attributed to the refined microstructure consisting of equiaxed and homogenous austenite grains.

Keywords: High nitrogen austenitic stainless steel (HNS); Shielded metal arc welding (SMAW); Gas tungsten arc welding (GTAW); Electron beam welding (EBW); Friction stir welding (FSW)

1. Introduction

High nitrogen austenitic stainless 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. Austenitic stainless steel (>0.4% N) are becoming an important engineering material with combination of strength, toughness and wear resistance [1]. Nitrogen has the following advantages: it is an effective solid solution strengthener than carbon and also enhances strengthening of grain size [2,3]. Austenitic steels can benefit from high nitrogen on several aspects: Nitrogen in a solid solution is a beneficial alloying element to increase the strength without significant loss of ductility and toughness. 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 [4]. As these steels are used for structural purposes, welding is an important consideration to join the structural components. During welding, it is very essential to avoid nitrogen losses, which result in poor 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 [5]. The nitride precipitation reduces seriously the mechanical and corrosion resistance. To alleviate the above problems, careful control of shielding gas, filler metal composition with low impurity levels (e.g., S, P) in addition to control on segregation of major alloying elements and minimizing the

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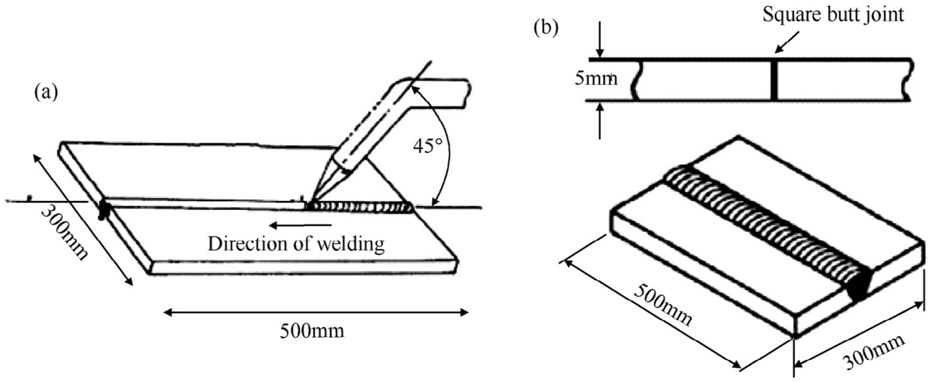

Fig. 1. Weld joint design for (a) SMAW and (b) GTAW processes.

level of intermetallic precipitates in the weld metal [6]. Defects like porosity and solidification cracking may be overcome by using a suitable filler wire, which produces the 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 contains a desired ferrite level [7]. No commercial matching filler wires are available for welding high nitrogen austenitic stainless steel [3]. Electrode with near matching composition similar to base metal resulted in improving the corrosion resistance but decreases the mechanical properties [8]. Studies on microstructure and mechanical property correlations of nickel free high nitrogen steel welds are really scarce. In view of the above problems, the present work is aimed at studying the microstructural changes in high nitrogen steel welds made using shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), electron beam welding (EBW) and friction stir welding (FSW) processes, and to correlate microstructure with observed mechanical properties of the welds.

2. Experimental details

Nickel free high nitrogen austenitic stainless steel (HNS) plates of size (500 mm × 150 mm × 5 mm) in wrought form were used in the present study. Weld joint design for SMAW and GTAW processes is shown in Fig. 1 and the welds made with various processes were shown in Fig. 2. Electrode of near matching composition of Cr–Mn–N type is used for the shielded metal arc welding process. Gas tungsten arc welding was made with standard high strength nickel based (18Ni) MDN 250 filler as no suitable fillers are available. Autogenous welds were made using electron beam welding and friction stir welding was carried out using tungsten–molybdenum (W–Mo) tool. The composition of the base metal and filler wires are given in Table 1. After having several experiments, welding parameters were optimized and we have obtained a sound weld free from defects. Optimized welding parameters of all the welding processes are given in Tables 2–5. Microstructural studies were conducted at various zones of the welds using optical microscopy and scanning electron microscopy. Orientation image mapping studies were performed with electron backscatter diffraction (EBSD) method to observe the orientation of the grains and phase analysis maps in various zones of the welds. Tensile testing is carried out using a universal testing machine at room temperature and specimens were prepared as per ASTM-E8 standard. Microhardness values were recorded towards the longitudinal directions of the weld with a load of

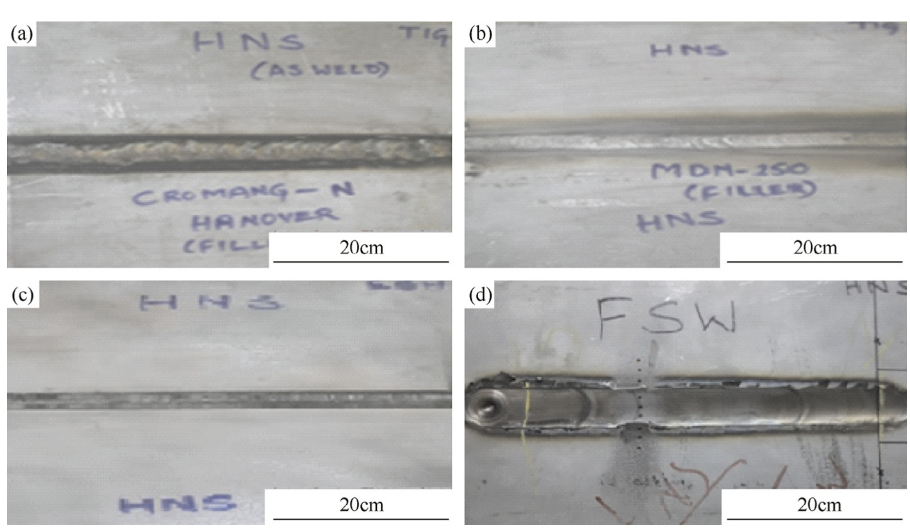

Fig. 2. Macroscopic appearance of the high nitrogen stainless steel welds (a) SMAW; (b) GTAW; (c) EBW and (d) FSW.

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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	Mo	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.

0.5 kgf for 20 seconds as per ASTM E384-09 standards using Vickers hardness tester. Face bend testing of the material was conducted to observe the crack development to know the ductile nature of the weld as per ASTM E190-92 standards.

3. Results and discussion

3.1. Microstructure

3.1.1. Base metal

Nickel free high nitrogen steel plates in cold worked condition is observed to have equiaxed fine grains of austenite and annealing twins at the grain boundaries as shown in Fig. 3. In the cold worked condition, high nitrogen steel has a concurrent twinning and slip in austenite. High nitrogen steel, in general, shows a planar slip and pronounced twinning. The twin deformation in austenite is related to the stacking fault energy of the material. In nickel containing Cr–Ni steels, the stacking fault energy does not decrease with increasing nitrogen content. However, in Ni free high nitrogen steels there is a decrease in stacking fault energy with increasing N content. In high nitrogen steel, a decrease in stacking fault energy with N enhances the 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 [9]. Grain orientation mapping and phase analysis maps of the nickel free high nitrogen steel is observed to have fine grain morphology and single phase austenite was observed and is shown in Fig. 4.

Table 2
Welding parameters using shielded metal arc welding.

Parameters	
Welding current/A	110–130
Welding speed/(mm·s^{-1})	4
Electrode diameter/mm	3.2
Electrode position/(°)	45
No. of passes	2
Root gap/mm	1.5

Table 3
Welding parameters using gas tungsten arc welding.

Parameters	
Welding current/A	130
Welding speed/(mm·s^{-1})	60
Electrode polarity	DCSP
Arc voltage/V	18–20
Filler wire diameter/mm	1.6
Electrode	2% thoriated tungsten
No. of passes	2
Shielding gas	Argon

3.1.2. Weld microstructure

Microstructural changes and solidification mode of high nitrogen austenitic stainless steel welds are determined on various factors like chemical composition of the electrode/filler and welding process. Heat input and cooling rates of the 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 [10]. Welds made with shielded metal arc welding using Cr–Mn–N type electrode have high heat input and slow cooling rate, resulting in weld metal microstructure as fully austenitic and coarse dendritic grains, as shown in Fig. 5.

Solidification mode as fully austenite structure in the weld metal of shielded metal arc welds is attributed to the high amount of chromium and manganese, which helps improve the solubility of nitrogen, enhancing the austenite phase stability. At the weld interface, along the fusion boundary towards the base metal, transition of coarse grains to fine grains was observed and is shown in Figs. 5–7.

The weld microstructure has a maximum austenite structure due to the dilution of adjacent base metal that has nitrogen, which is completely soluble in the solid solution. Scanning electron micrographs shown in Fig. 6 clearly revealed the evidence for coarsening of austenite. In Fig. 7, the grain orientation and phase analysis maps in the weld metal and weld interface of SMA weld clearly revealed coarse grain orientation at the weld zone and coarse grains to fine grain transition at the weld interface. Even though the SMAW process can be used in

Table 4
Welding parameters using electron beam welding.

Parameters	
Gun to work distance/mm	283
Gun voltage/kV	60
Beam current/mA	60
Travel speed/(m·min^{-1})	1
Energy/kW	4

Table 5
Welding parameters using friction stir welding.

Parameters	
Spindle speed/rpm	800
Travel speed/(m·min^{-1})	40
Tilt angle/(°)	2
Tool	W–Mo
Energy/kW	4

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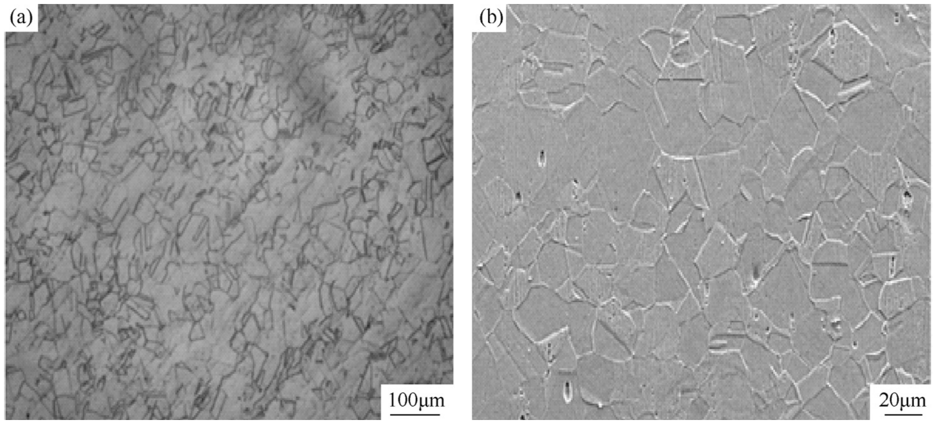

Fig. 3. Microstructure of base metal high nitrogen steel: (a) optical microscopy; (b) scanning electron microscopy.

welding most of the structural components, problems like increased width of weld zone and excess deposition rate of electrode and spattering lead to non-uniform and poor quality of the weld joint. The above problems can be overcome by using gas tungsten arc welds where control of filler metal deposition, brighter arc than SMAW and decreased width of weld zone can be achieved. GTA welds of high nitrogen steel made with high strength nickel based filler (18Ni) MDN 250 filler resulted in a continuous network of island pools of reverted austenite in the martensite matrix and clearly observed to be having elongated and coarse grains, as shown in Figs. 8–10. Weld microstructure of GTA weld is attributed to the presence of nickel and cobalt as austenite stabilizers. The rate of heating and cooling during welding affects the microstructure and composition of fusion welds of high nitrogen steel [11]. Unmixed zone formation is observed for the welds made with MDN 250 filler. This zone exists along the fusion line and between the partially melted zone and the weld metal. Unmixed zone is a boundary layer near the fusion line in which the base metals melt and re-solidify during welding without mechanically mixing with the filler wire and base metal [12]. The width of the unmixed zone depends on the local thermal conditions along the weld fusion line which can be seen in Figs. 8(c) and 9(c). In Fig. 10, grain orientation maps for the welds made with gas tungsten arc welding are observed to have an elongated coarse grain orientation. Isolated pore in the weld metal near the fusion boundary was observed due to the entrapment of nitrogen gas pores during welding. GTA welds have achieved decreased width of

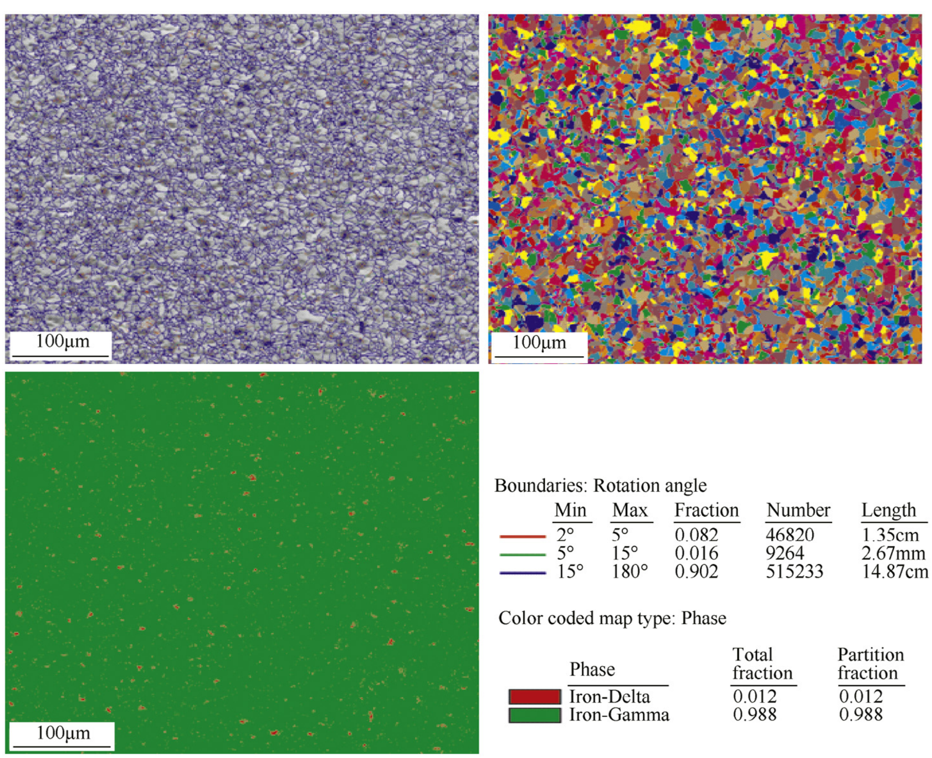

Fig. 4. Grain orientation, OIM maps and phase analysis of high nitrogen steel (base metal).

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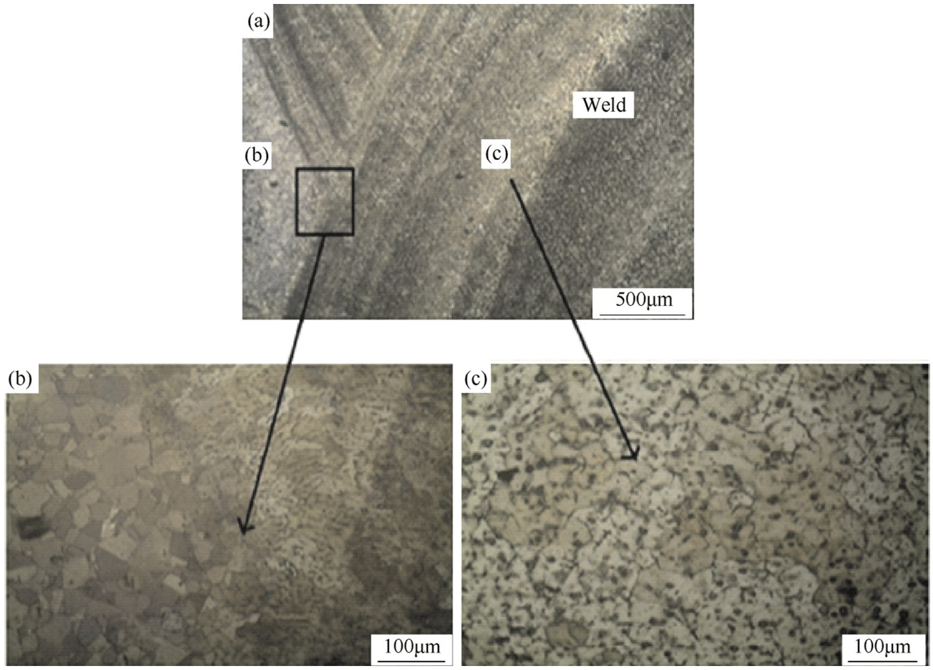

Fig. 5. Optical micrographs of high nitrogen steel SMA welds made with Cr–Mn–N electrode: (a) weld interface, (b) heat affected zone, (c) fusion zone.

weld zone due to the square butt joint when compared to SMA welds having single V joint, but due to the variation of the filler wire composition to the base metal resulted in unmixed zone along the fusion boundary adjacent to the base metal, which is not desirable for obtaining the better combination of properties. Electron beam welding is an effective autogenous welding process to produce a high precision weld joint with a 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 solidified as a mixture of austenite matrix and delta ferrite dendrites and is due to rapid cooling as shown in Figs. 11 and 12. At the weld interface of electron beam welds, formation of elongated coarse grains of austenite is observed in Figs. 11 and 12.

In Fig. 13 grain orientation maps and phase analysis maps of the high nitrogen stainless steel made with electron beam welding process have a fine grain orientation at the weld zone, and at the weld interface, formation of coarse grain heat

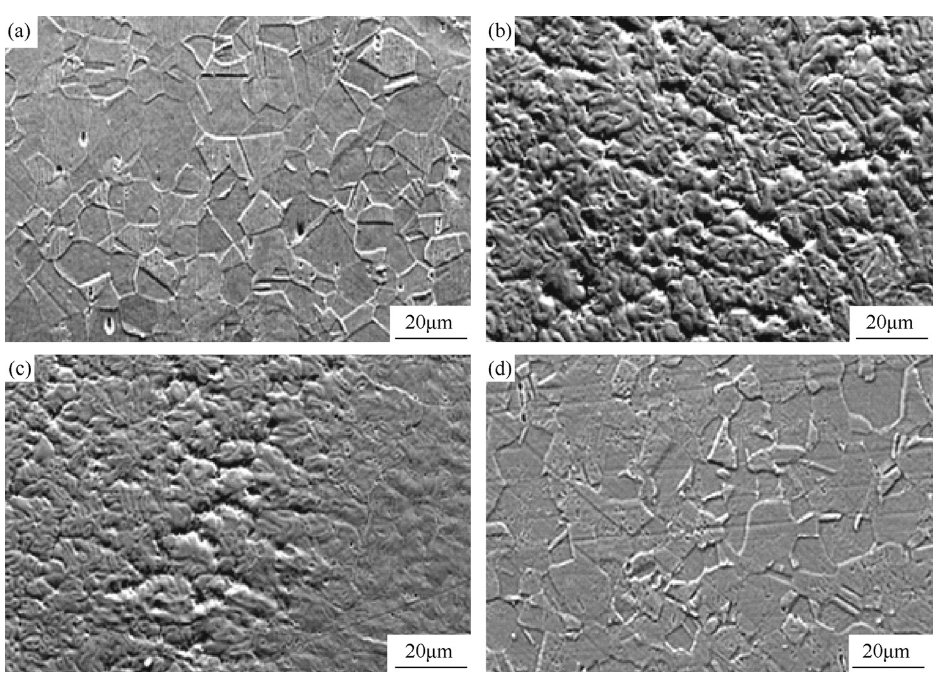

Fig. 6. SEM images of high nitrogen steel welds made with Cr–Mn–N electrode: (a) base metal, (b) fusion zone, (c) weld interface, (d) heat affected zone.

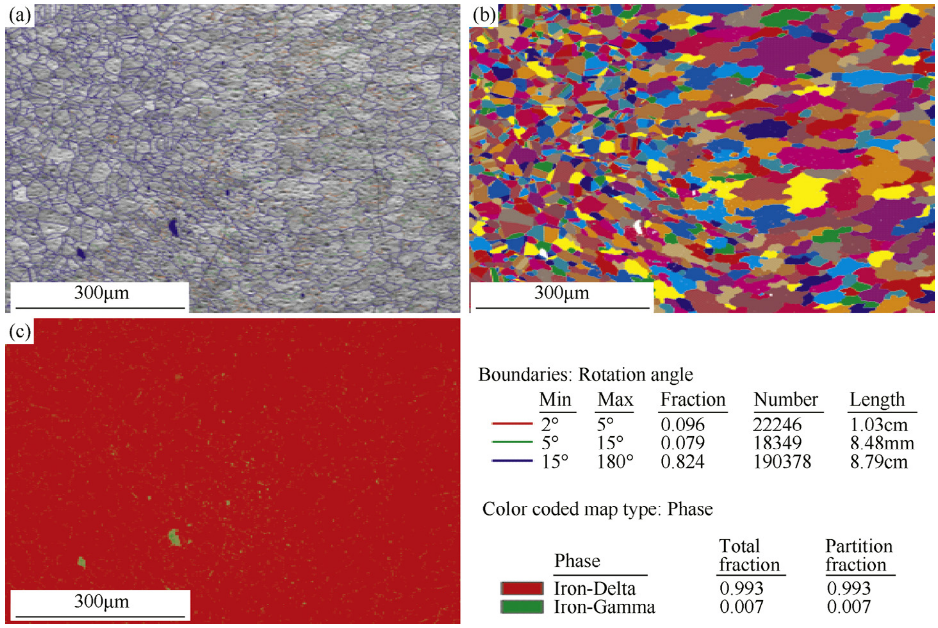

Fig. 7. Grain orientation, OIM maps and phase analysis of high nitrogen steel SMA weld.

affected zone is observed. Different phases were analysed using phase maps and recorded the percentage of delta ferrite and austenite, and also determined the distribution of the ferrite in the matrix. It can be seen in Fig. 13 that the delta ferrite is distributed as a discontinuous network of fine dispersed delta ferrite in the austenite matrix. Electron beam welds are observed as high quality weld joints with narrow width of weld joint and better compared to SMA and GTA welds, but the presence of delta ferrite prompt to affect the performance of the weld joint significantly. As discussed above, problems during fusion welding process such as nitrogen desorption, solidification cracking, liquation cracking and porosity can be avoided by the solid state joining, i.e., friction stir welding where no melting takes place and sound welds with high quality weld joint can be achieved.

Friction stir welds of high nitrogen steel made with tungsten–molybdenum (W–Mo) tool has resulted in fine recrystallized grains of austenite due to severe plastic deformation. Weld nugget microstructure of the friction stir welds has an equiaxed and homogenous austenite grain structure, as shown in Figs. 14–16. At the weld interface, relatively coarse grains were observed when compared to weld nugget, as shown in

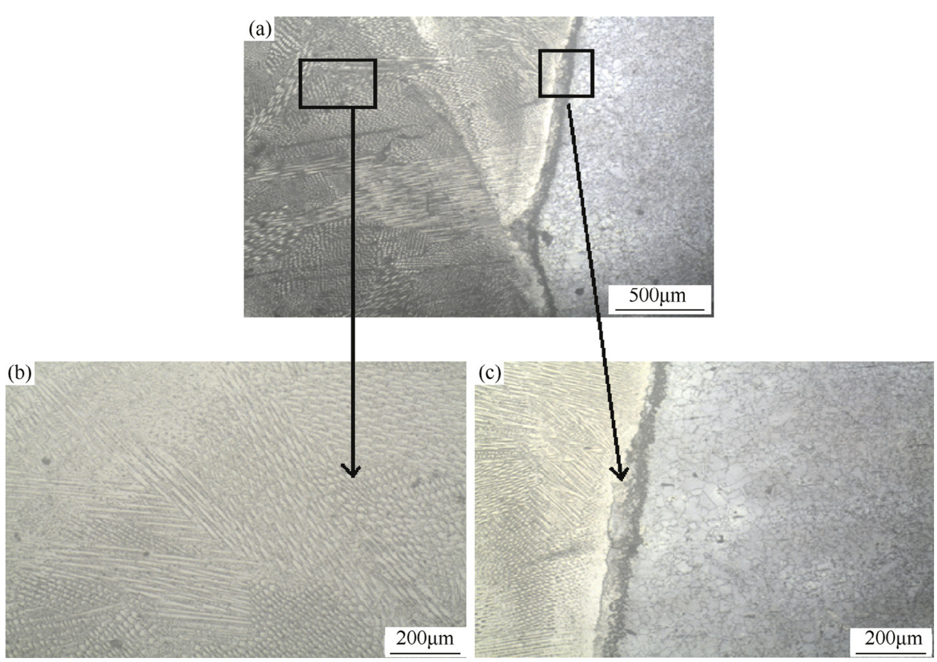

Fig. 8. Optical micrographs of high nitrogen steel GTA welds made with MDN 250 filler: (a) weld interface, (b) fusion zone, (c) heat affected zone.

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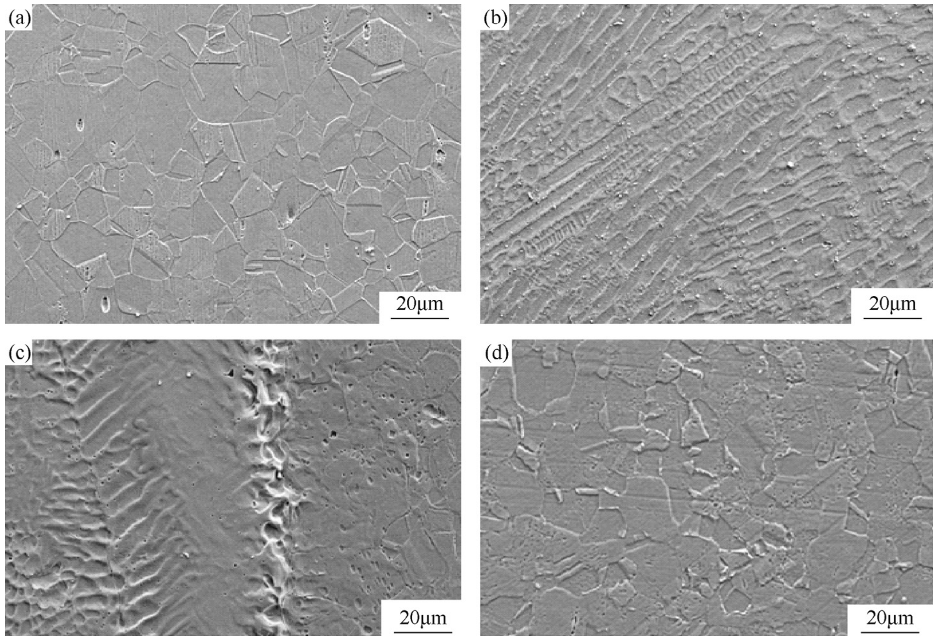

Fig. 9. SEM images of high nitrogen steel welds made with MDN 250 filler: (a) base metal, (b) fusion zone, (c) weld interface, (d) heat affected zone.

Fig. 14. In Fig. 16 grain orientation and phase analysis maps clearly revealed the formation of fine recrystallized grains and phase maps also gave evidence for single phase austenite microstructure in the weld nugget.

3.2. Mechanical properties

Strengthening has been generally observed by addition of nitrogen in steels. Nitrogen is a strong austenite stabilizer and reduces the requirement of nickel and improves microstructural stability and resistance to deformation induced martensite. Improvement in the strength of high nitrogen stainless steel is influenced by solid solution hardening and decrease in stacking fault energy [13]. In nickel free high Cr–Mn–N steels, the decrease in stacking fault energy enhances the formation of mechanical twins that enhances strength. Nitrogen containing austenitic stainless steels show high impact toughness

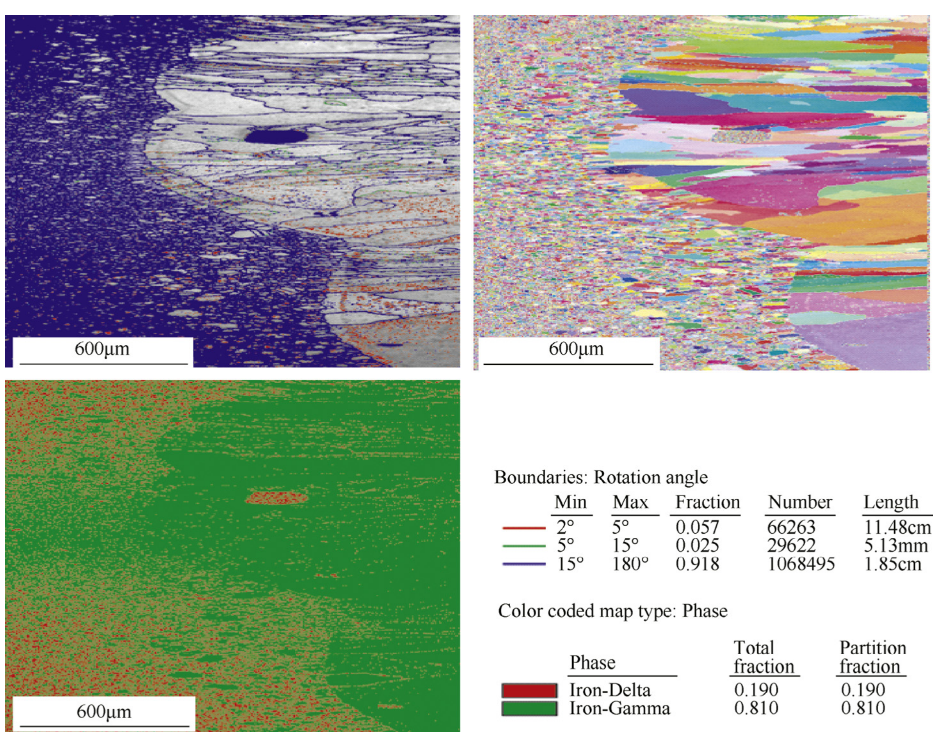

Fig. 10. Grain orientation, OIM maps and phase analysis of high nitrogen steel GTA weld.

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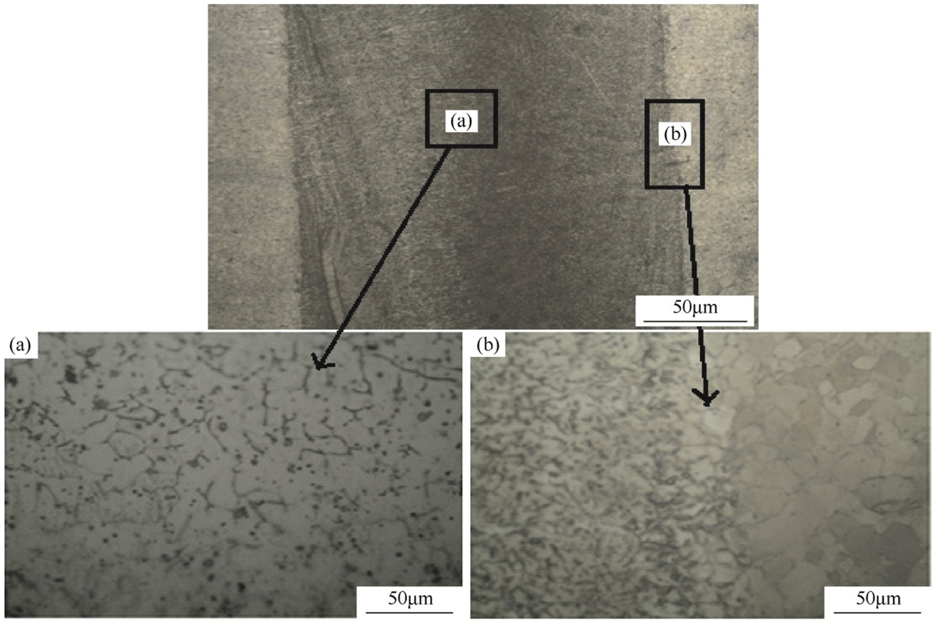

Fig. 11. Optical micrographs of high nitrogen steel EB welds: (a) macrograph, (b) fusion zone, (c) weld interface.

and this is attributed to the fact that nitrogen does not induce void nucleation sites in the steel [2]. 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. Welding process may influence the mechanical properties of high nitrogen steel significantly. Factors like heat input, cooling rate, electrode/filler wire composition lead to microstructural changes due to varying thermal cycles in the weld joints. In Fig. 17, face bend ductility tests were performed on welds and ductile joints were observed, and welds did not fail even for bending at 180° at a bend radius of 16 mm. Hardness survey is shown in Fig. 18 and it is clearly evident that friction stir welds have high strength when compared to fusion welds. Tensile tests were performed and failed specimens are shown in Fig. 19 and all the welds failed at the centre of the weld joint. Tensile properties were given in Table 6. From the observed tensile data, it is observed that shielded metal arc

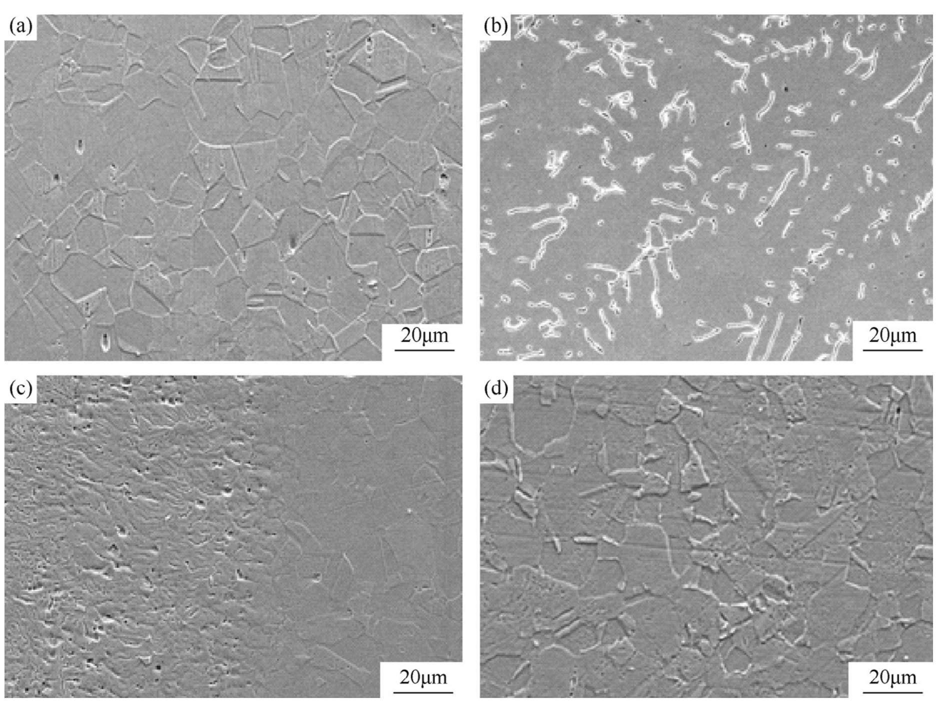

Fig. 12. SEM images of high nitrogen steel welds made with EBW: (a) base metal, (b) fusion zone, (c) weld interface, (d) heat affected zone.

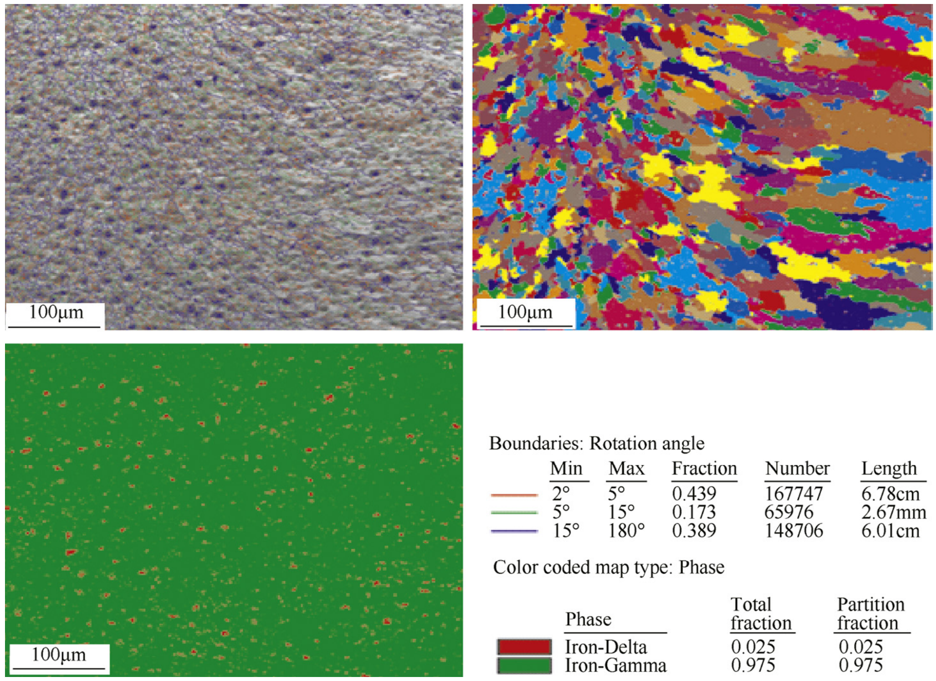

Fig. 13. Grain orientation, OIM maps and phase analysis of high nitrogen steel EB weld.

welds exhibited poor strength and it is attributed to high input during welding and coarse dendritic structure in the weld metal. Gas tungsten arc welds have recorded moderate strength but there is presence of elongated island pools, and formation of unmixed zone at the fusion boundary is having more coarse grains even though contains the chemical composition similar to base metal and not favourable for overall performance of the weld joint. Although electron beam welds have obtained maximum strength compared to other welds, ductility has been observed to be low when compared to base metal and it may

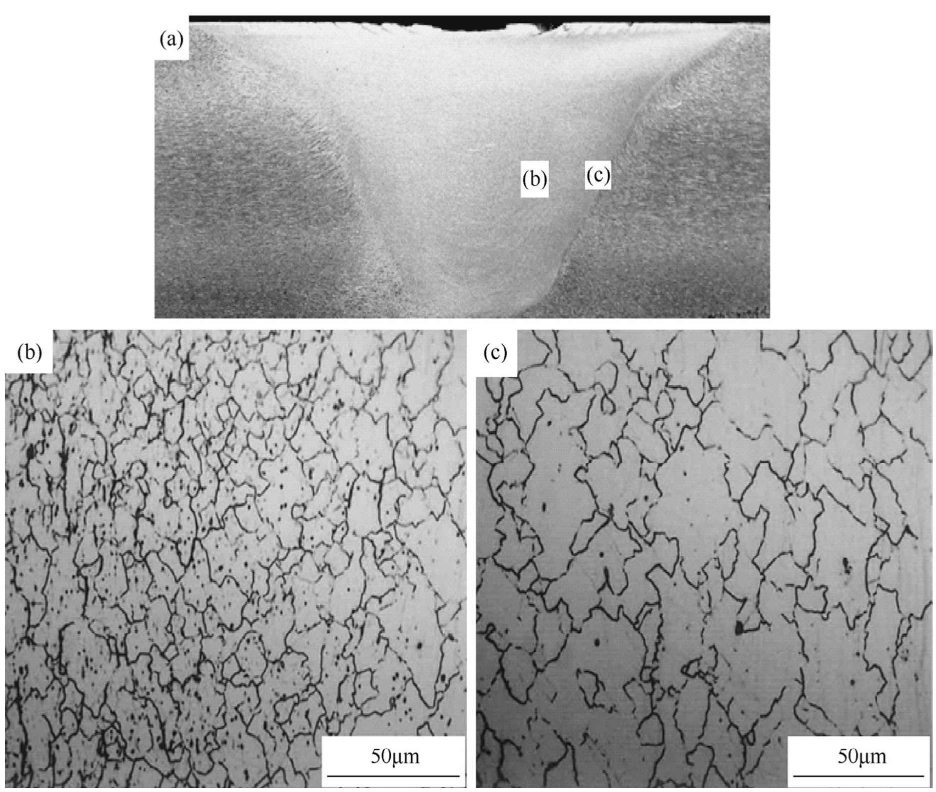

Fig. 14. Optical micrographs of high nitrogen steel FS welds made with W–Mo tool: (a) macrograph, (b) nugget zone, (c) heat affected zone.

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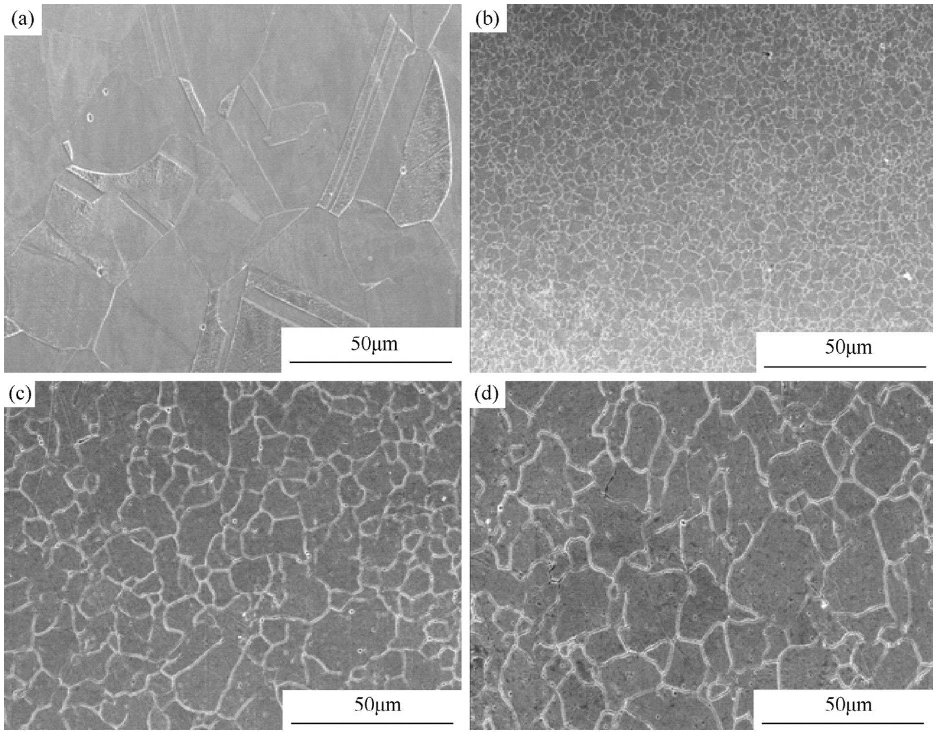

Fig. 15. SEM images of high nitrogen steel FS welds made with W–Mo tool: (a) base metal, (b) fusion zone, (c) weld interface, (d) heat affected zone.

be due to the presence of delta ferrite in the austenite matrix. In friction stir welds, the high strength and ductility were obtained and they are attributed to fine recrystallized austenite grains. Among all the welds investigated, high nitrogen steel welds made with friction stir welding exhibited high hardness, tensile strength and improvement in ductility as shown in Table 6. From Figs. 19–23, it is evident that all the fractographs of the welds were observed as ductile failure. Hence, improved mechanical properties are obtained in friction stir welds when compared to fusion welds. This is attributed to the refined

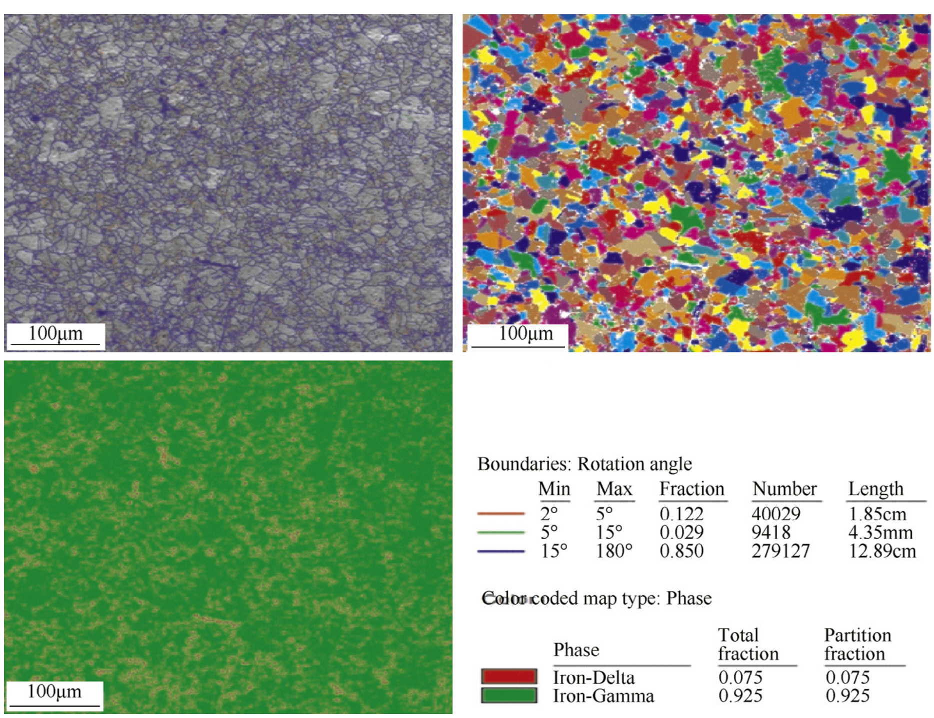

Fig. 16. Grain orientation, OIM maps and phase analysis of high nitrogen steel friction stir weld.

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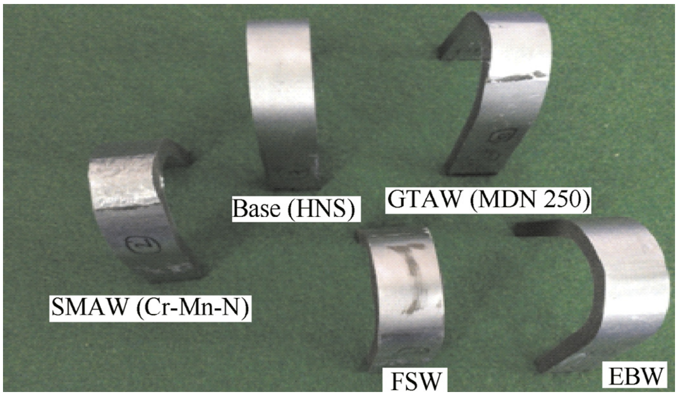

Fig. 17. Face bend specimens of nickel free high nitrogen steel welds.

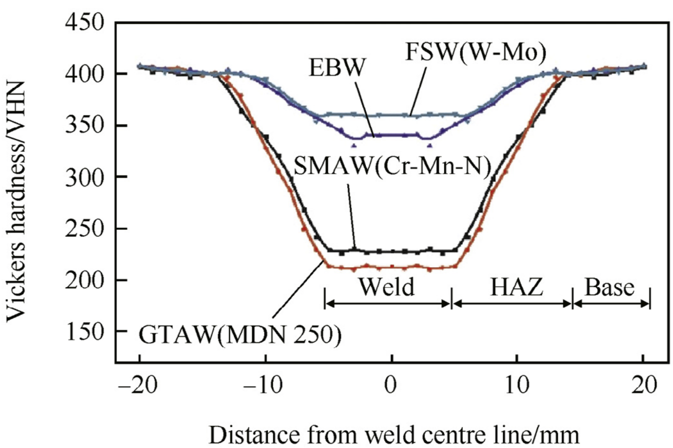

Fig. 18. Vickers hardness values of nickel free high nitrogen steel welds.

microstructure consisting of equiaxed and homogenous austenite grains.

4. Conclusions

1) SMA welds made using Cr–Mn–N electrode have a fully coarse austenite dendritic structure and are due to the presence of chromium and manganese, which help in complete solubility of nitrogen in the weld metal. SMA welds resulted in reduction in strength and ductility and it is attributed to coarse dendritic structure.
2) 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. GTA welds have moderate strength and ductility.
3) Autogenous EB welds were observed to have narrow width of weld zone and discontinuous network of delta ferrite in the austenite matrix. It has high strength and improvement in ductility.
4) Friction stir welds made with tungsten–molybdenum (W–Mo) tool resulted in high strength and ductility and it is due to recrystallized fine grain austenite structure in the weld nugget.
5) Improved mechanical properties are obtained in friction stir welding when compared to fusion welds. This is attributed to the refined microstructure consisting of equiaxed and homogenous austenite grains. Hence, friction stir welding is recommended as best welding process when compared to all fusion welding processes to achieve improved mechanical properties.

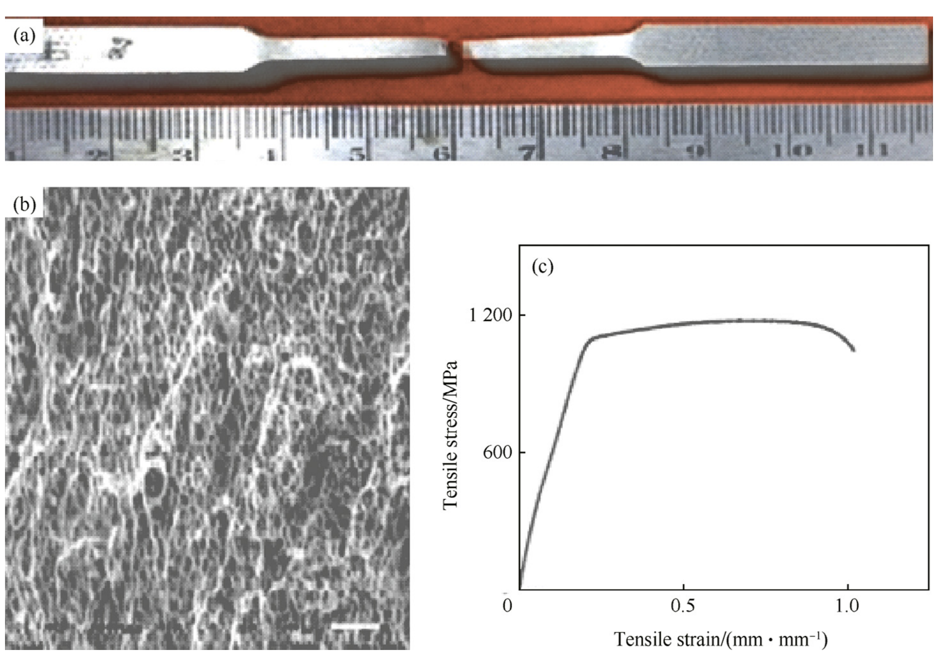

Fig. 19. Fracture features of tensile specimens of nickel free high nitrogen steel: (a) tensile failed specimen; (b) SEM fractograph and (c) stress–strain curve.

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Table 6
Tensile properties and hardness values of nickel free high nitrogen steel welds.

Material	UTS/MPa	Y S/MPa	El/%	Failure location	Hardness/VHN
HNS base	1215	1190	22	Base	410
SMAW	667	233	10	Weld	228
GTAW	655	411	9.2	Weld	211
EBW	1050	790	10.2	Weld	340
FSW	1065	811	9	Weld	364

UTS (ultimate tensile strength), Y S (yield strength), El% (elongation %) and El% of EBW is 9 and FSW is 10.2.

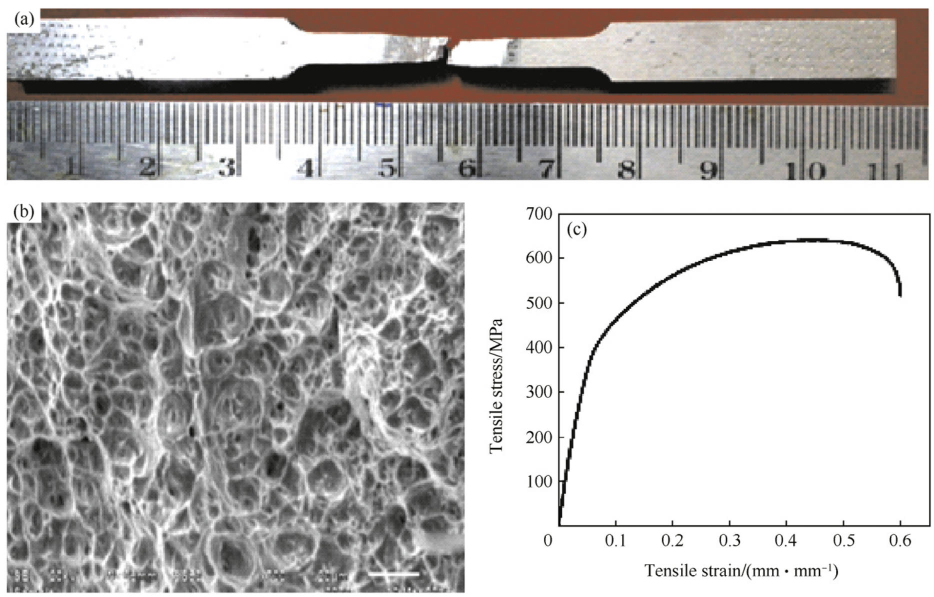

Fig. 20. Fracture features of tensile specimens of SMA welds of nickel free high nitrogen steel: (a) tensile failed specimen; (b) SEM fractograph and (c) stress–strain curve.

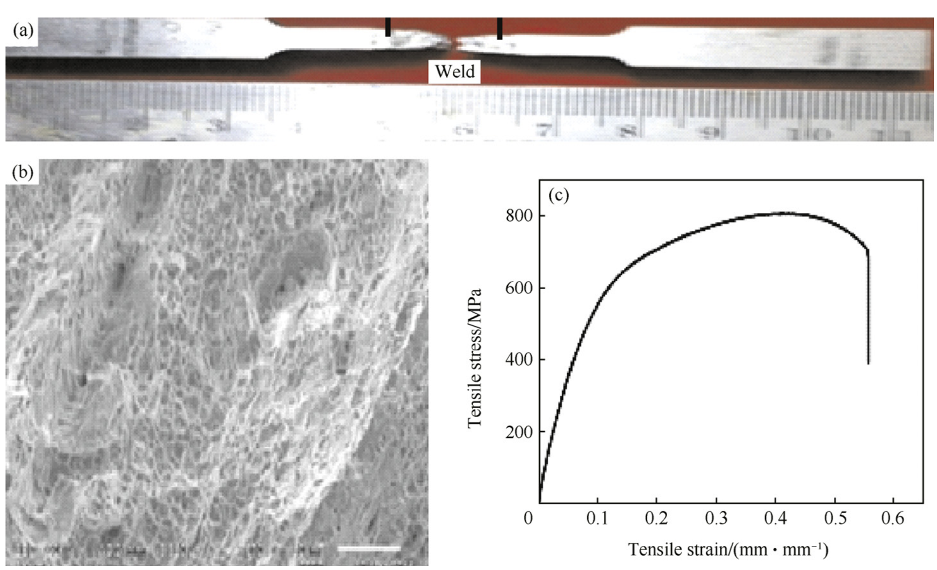

Fig. 21. Fracture features of tensile specimens of GTA welds of nickel free high nitrogen steel: (a) tensile failed specimen; (b) SEM fractograph and (c) stress–strain curve.

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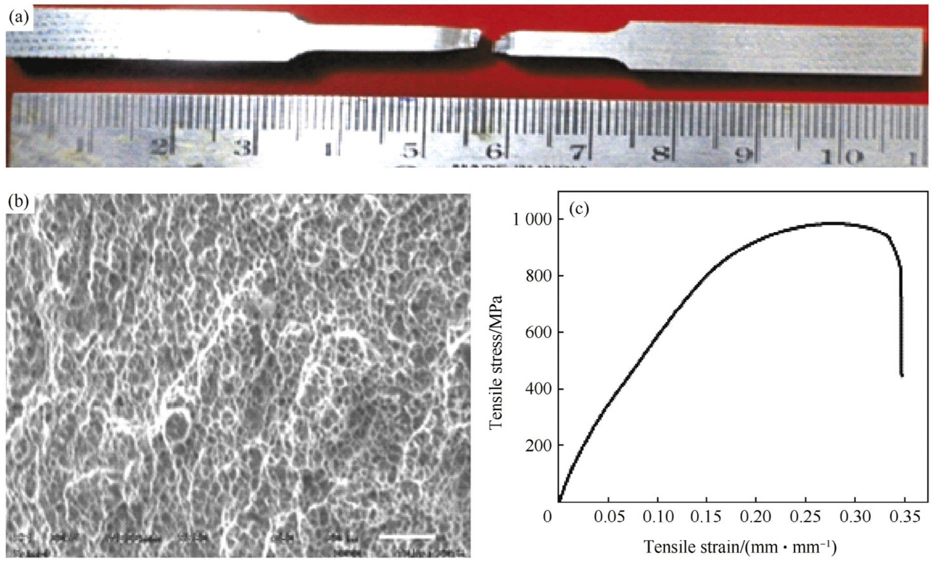

Fig. 22. Fracture features of tensile specimens of EB welds of nickel free high nitrogen steel: (a) tensile failed specimen; (b) SEM fractograph and (c) stress–strain curve.

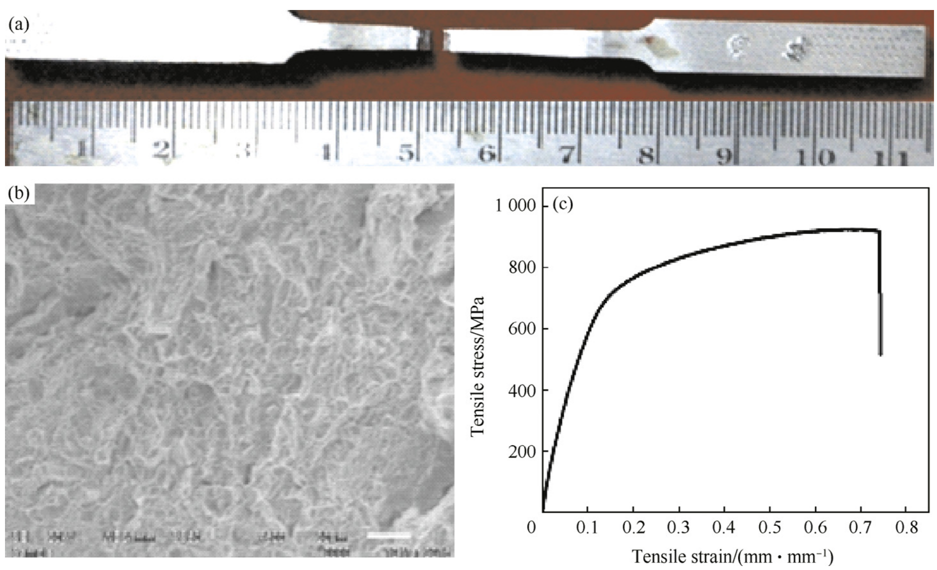

Fig. 23. Fracture features of tensile specimens of FS welds of nickel free high nitrogen steel: (a) tensile failed specimen; (b) SEM fractograph and (c) stress–strain curve.

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