Investigation into Mechanical Properties of High Strength Steel Plates Welded With Low Temperature Transformation (LTT) Electrodes

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Investigation into mechanical properties of high strength steel plates welded with low temperature transformation (LTT) electrodes

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Abstract: Controlling the amount of distortion and tensile residual stresses plays an important role during welding of high strength steels. The amount of distortion and residual stresses in high strength steel welds may be reduced and compressive residual stresses can be induced by lowering the transformation temperature with the use of low-transformation-temperature (LTT) welding electrodes.

In this study, high strength Domex 500 plates (500 mm × 300 mm × 7 mm) were welded with conventional high strength electrodes and LTT filler electrodes with a diameter of 2.5 mm. The objective of the study is to compare the mechanical and microstructural properties of high strength steel joints (i.e., Domex 500) produced using both conventional electrodes and newly-developed prototype LTT electrodes.

Keywords: distortion; residual stresses; high strength steels; M_S temperature; low-transformation-temperature; LTT.

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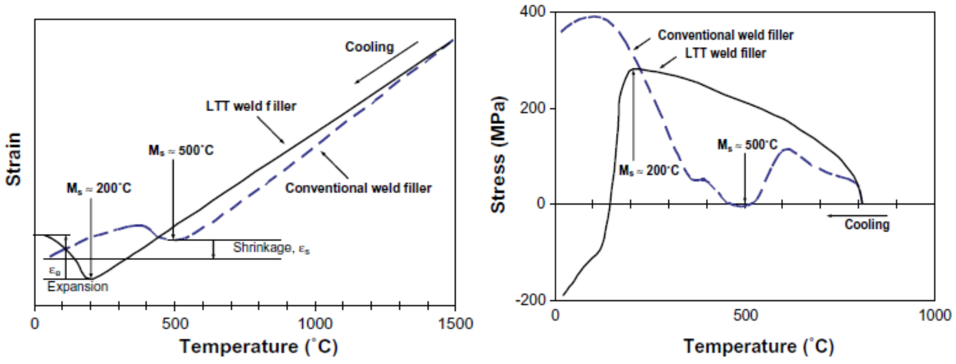
1 Introduction

In fabricating processes, welding can be considered as an essential process. Rapid heating and local high temperature zones involved in welding induce residual stresses and distortion on the structural components (Yasumasa et al., 2005). These problems can induce brittle fracture or SCC and may also shorten fatigue life of the structure. The distortion generated by welding can be decreased by using different mitigation techniques, such as shot peening, postweld heat treatment, structural modification and implementing thermal tensioning processes. From the economical point of view, however, welding distortion correction operations is usually considered as time and energy consuming processes. As an alternative, apart from constructural design and heat control, the filler material has a role on residual stress reduction concept. At this alternative approach, newly developed low-transformation-temperature (LTT) welding electrodes and wires can be used to lower the M_S temperature of the weld metal. By using LTT filler metals, volume expansion associated with the martensitic transformation can compensate the thermal shrinkage of the weld. Welding distortion and tensile residual stresses are expected to be lowered by this mechanism (Çam et al., 2010). With this phenomenon tensile residual stresses can be reduced by the martensitic transformation that occurs at lower temperatures or even compressive residual stresses are obtained on the construction. Thus, compared to conventional wires, these materials show decreased phase transformation temperatures which can work against the cooling-specific contraction. In consequence, distinct compressive residual stresses can be observed within the weld and adjacent areas. So, structures welded with lower tensile residual stresses display better properties such as fatigue life, stress corrosion cracking (SCC), resistance to cold-cracking, and service life properties (Çam et al., 2010). The strength of these fillers makes them potentially applicable to high-strength steel welding.

Figure 1 Variation of strain and stress of weld metal during cooling process, (a) strain (b) stress



(a) (b)

Source: Barsoum and Gustafsson (2009)

As seen from the Figure 1, LTT and conventional weld fillers exhibit different thermal shrinkage and residual stress profiles during cooling (Barsoum and Gustafsson, 2009). Transformation from austenite to martensite occurs at 500°C for the conventional weld filler and at about 200°C for the LTT weld filler. Amount of shrinkage is higher than the expansion if the transformation is completed at higher temperatures, so at the end of the cooling stage, conventional weld filler will have residual tensile stresses. As transformation from austenite to martensite occurs at 200°C for the LTT weld filler, the amount of expansion resulted from the transformation will be greater than the amount of shrinkage due to the cooling. So, this low temperature transformation introduces low residual tensile stresses or even compressive residual stresses in the welded components (Barsoum and Gustafsson, 2009).

Tensile residual stresses in high strength steel welds produced using conventional filler material accelerate the fatigue crack propagation and reduce fatigue life of the welded joint (Ohta et al., 2003a). On the other hand, many researchers reported that LTT weld fillers have beneficial effects on the fatigue strength improvement (Machida et al., 1999; Ohta et al., 2000, 2002, 2003a, 2003b; Eckerlid et al., 2002; Barsoum and Gustafsson, 2009). Fatigue properties of the weldments can be improved by avoiding high tensile residual stresses by using LTT fillers which lead to lower tensile residual stresses or even to compressive residual stresses in the welded components. Thus, LTT consumables lead to improved fatigue strength over conventional consumables with an increase of between 25%–90% in mean fatigue strength (Zenitani et al., 2007).

However, the fracture toughness of weldments may be reduced slightly due to the martensitic microstructure evolving in the welded components produced by using LTT consumables in contrast to these improvements. So another subject for investigation is the characterisation of mechanical properties of LTT weldments, i.e., fracture toughness.

In this work, LTT filler electrodes with varying chemical compositions were investigated. For comparison, Domex 500 MC base plates were butt welded with three different LTT electrodes and one conventional electrode. Microstructural and distortional observations, including x-ray diffraction (XRD) and scanning electron microscopy (SEM) analysis were conducted to characterise the joints obtained. Mechanical properties, such as tensile and bending behaviour, were also evaluated and compared.

2 Experimental methods

2.1 Material

The chemical compositions of the electrodes (i.e., 2.5 mm thick basic electrodes) and steel base plates used in this work are shown in Table 1. LTT electrodes with varying chemical compositions and conventional electrodes were used in the experiments for comparison. Domex 500 MC structural steel was chosen as the base material since it is a possible candidate for the application of LTT fillers due to its high strength.

Table 1 Chemical compositions of base metal and weld metals (wt. %)

Alloy	*C*	*Si*	*Mn*	*P*	*S*	*Ni*	*Cr*	*Mo*	*Nb*
LTT 1	0.05	0.56	1.50	0.01	0.004	10.84	13.27	0.05	0.00
LTT 2	0.06	0.36	0.69	0.01	0.002	10.42	9.65	0.02	0.00
LTT 3	0.06	0.36	0.72	0.01	0.001	8.28	9.43	0.03	0.00
Conventional weld	0.04	0.41	1.48	0.01	0.003	0.77	0.01	0.35	0.01
Base metal	0.06	0.04	1.32	0.00	0.002	0.09	0.00	0.01	0.03

M_S temperatures of the different weld metals are calculated theoretically using Steven-Haynes equation [i.e., $M_S = 561 - 474\ C - 33\ Mn - 17\ Cr - 17\ Ni - 21\ Mo\ (°C)$] (Çam et al., 2010). According to the calculations, LTT 1 alloy has the lowest M_S temperature value, i.e., 75°C as seen from Table 2. LTT 1 weld metal was chosen to have some retained austenite in the microstructure due to its very low MS temperature, i.e., 75°C (Table 2).

Table 2 M_S temperatures of weld metals according to the Steven-Haynes equation

Alloy	*Ms temperature (℃)*
LTT 1	75
LTT 2	168
LTT 3	208
Conventional	468
Base metal	487

2.2 Welding procedure

Test plates of 300 mm (width) × 500 mm (length) × 7 mm (thickness) were prepared for welding trials. Plates with a 60° V-shaped groove were manual arc welded using basic electrodes of both conventional and LTT electrodes with multipass (4 passes) in this study. The weld coupon and joint geometries are given in Figure 2 and Figure 3, respectively.

Figure 2 Weld coupon geometry

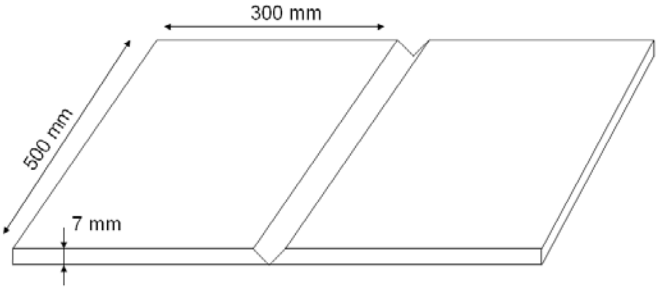
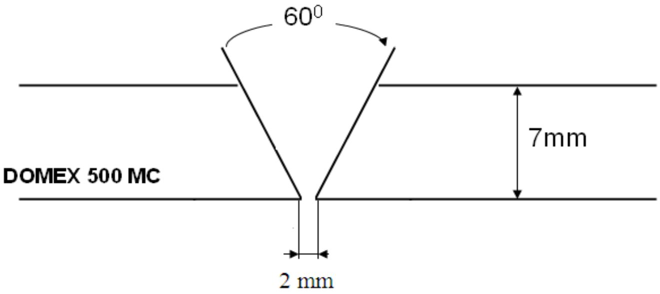


Figure 3 Joint geometry



2.3 Weld parameters

Weld parameters used in this study are shown in Table 3. Except the weld current, all the parameters are the same for all electrode types used. The reason for using different weld current is the difference between the compositions of electrodes used.

Table 3 Weld parameters

Parameter	*LTT electrodes*	*Conventional electrode*
Current	70 A	80 A
Voltage	23 V	24 V
Travel speed	3 mm/s	3 mm/s
Interpass temp.	40°C	40°C
Electrode	Basic (D: 2.5 mm)	Basic: (D: 2.5 mm)

Radiography resting (RT) were also conducted after welding to determine whether there is a lack of penetration at the root face of the weld zone.

2.4 Microstructural observations and mechanical testing

In order to carry out microstructural investigations metallographic specimens extracted from the joints produced (one specimen for each joint). The specimens were ground with SiC paper down to grit 1,200 and then polished down to 1 μm using diamond paste prior to optical microscopy. Specimens extracted from the LTT welds were etched using Viella solution whereas conventional weld specimen was etched with Nital solution. Extensive Vickers microhardness measurements were also conducted on these metallography specimens using a load of 200 g for a loading time of 15 seconds. To evaluate the joint performance values, two tensile specimens and two bending specimens (with the sizes of 260 mm × 20 mm × 7mm) were also extracted from the each joints produced. The geometry of metallographic, tensile and bending test specimens used for the characterisation of the joints are given in Figure 4.

Figure 4 Metallographic (MS), tensile (TS), and bend (BS) test specimens extracted from the welded plates (see online version for colours)

3 Results and discussion

3.1 Distortion analysis

Distortion measurements were carried out with the geometrical techniques. First, one side of the welded steel plate is fixed parallel to the floor, the displacement of the plate was measured, then the angular distortion of the plate was calculated geometrically as shown schematically in Figure 5.

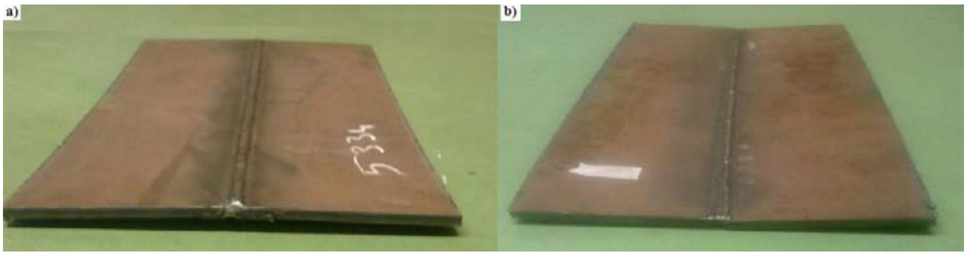
Figure 5 Measurement of angular distortion of the welded steel plates produced (see online version for colours)

According to the distortion analysis, LTT 1 weld has the smallest angular distortion. These results indicated that only LTT 1 weld which has the lowest M_S temperature exhibited the characteristic properties of LTT welds, i.e. lower distortion. As seen in Table 4, except the joint produced using LTT 1 electrode which displayed the lowest angular distortion, the joints produced using LTT 2 and LTT 3 electrodes exhibited higher angular distortion than the joint obtained with conventional electrode. Figure 6 shows clearly that the joint produced with LTT 1 filler material displayed lower angular distortion than that observed in the joint produced with the conventional electrode. This is not surprising due to the low phase transformation temperature (i.e., 75°C) of LTT 1 electrode which efficiently works against the cooling-specific contraction upon cooling.

Table 4 A summary of angular distortions of the welded steel plates obtained

Alloy	*Angular distortion (θ)*
LTT 1	4.8
LTT 2	6.6
LTT 3	11.1
Conventional	6.3

Figure 6 Angular distortions in the welded plates, (a) LTT 1 electrode (b) conventional electrode (see online version for colours)



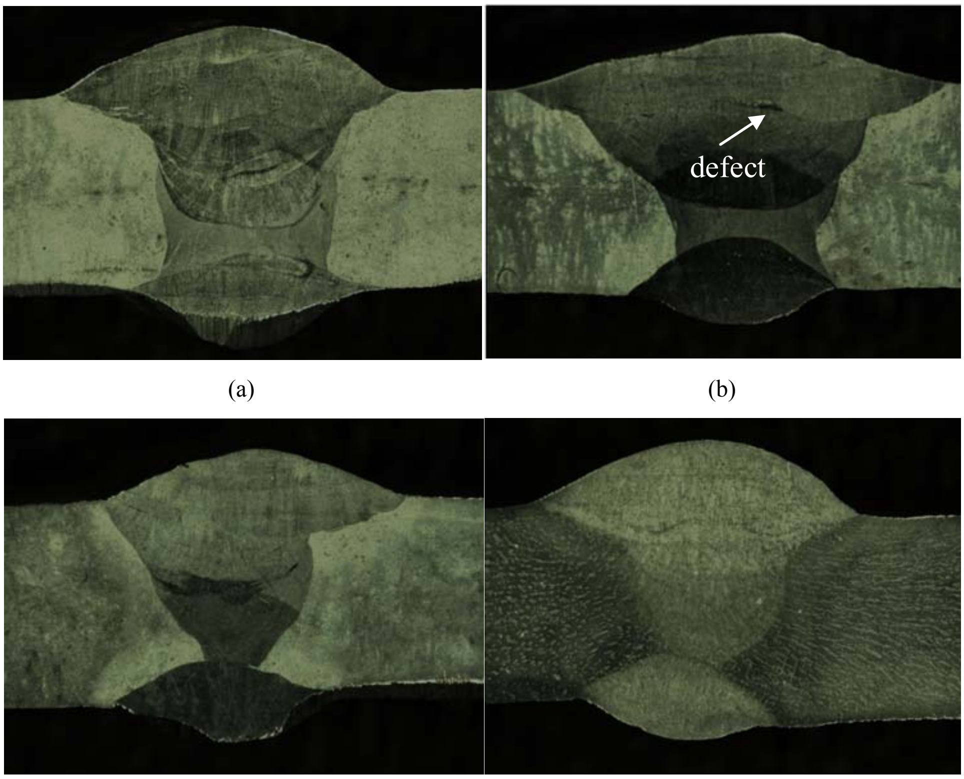
Note: Note that the joint produced with conventional electrode in b exhibiting a higher angular distortion than that of the joint produced with LTT 1 electrode in (a).

3.2 Microstructural aspects

Radiography testing – (RT) conducted after welding indicated lack of penetration at the root face of the weld zone. To mitigate this problem, a cosmetic pass is applied as repair welding after grinding the root face of the welds.

The macro-sections of all Domex 500 steel joints produced using LTT electrodes with varying chemical compositions and a conventional electrode are shown in Figure 7. As clearly seen from this figure all the welds produced were defect-free except LTT 2, Figure 7(b).

Figure 7 Macrosections showing the cross-sections of the joints, (a) LTT 1 (b) LTT 2 (c) LTT 3 (d) conventional electrodes (see online version for colours)



(a) (b)

(c) (d)

Table 5 Retained austenite amounts of weld metals

Alloy	*Retained Austenite (wt. %)*
LTT 1	41.0
LTT 2	8.0
LTT 3	3.1
Conventional	0

XRD analyses were conducted to determine the percentage of retained austenite in the microstructure of the joints produced using LTT filler materials with different compositions and conventional filler material. These analyses indicated that all the joints produced using LTT filler materials contained some retained austenite in their microstructure whereas the microstructure of the joint produced with conventional wire contained no retained austenite, Table 5. XRD patterns of the specimens were also shown in Figure 8 to Figure 11.

Figure 8 XRD pattern of LTT 1 weld metal; ferrite and austenite peaks

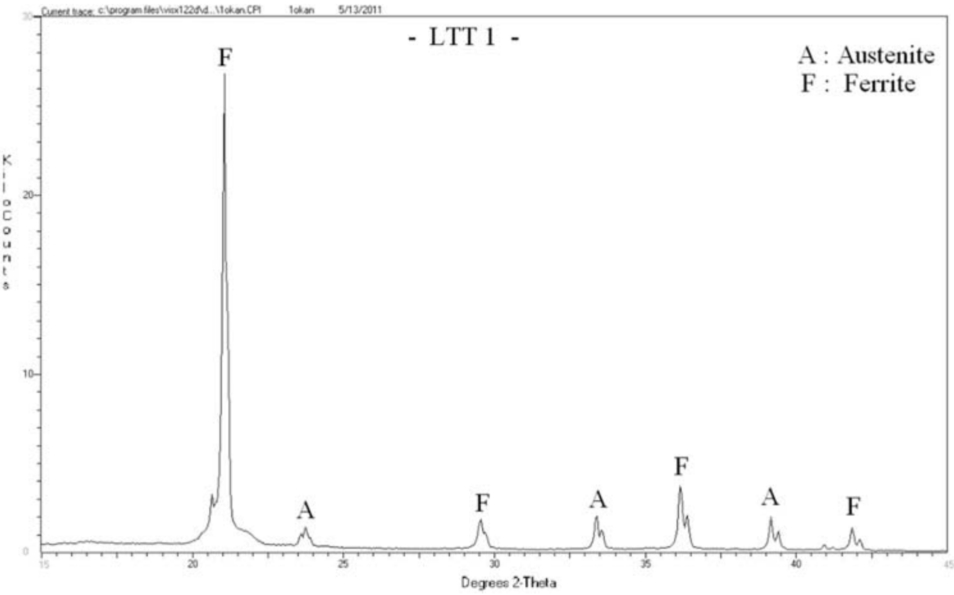


Figure 9 XRD pattern of LTT 2 weld metal; ferrite and austenite peaks

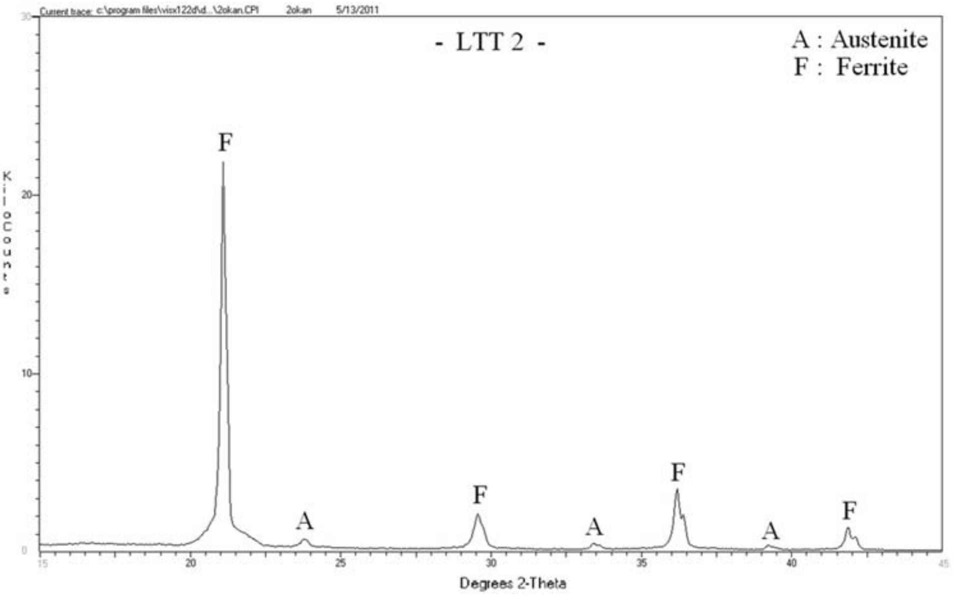


Figure 10 XRD pattern of LTT 3 weld metal; ferrite and austenite peaks

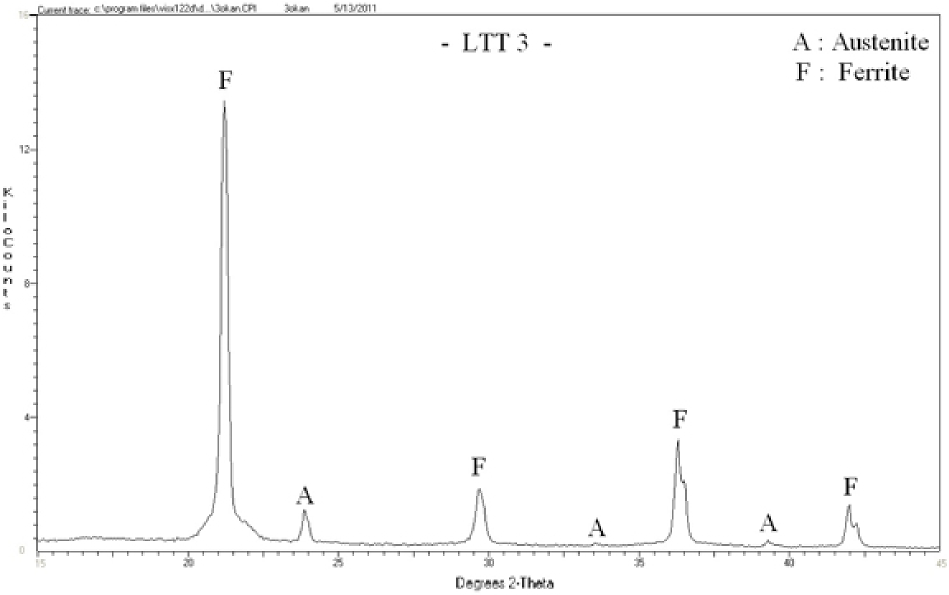
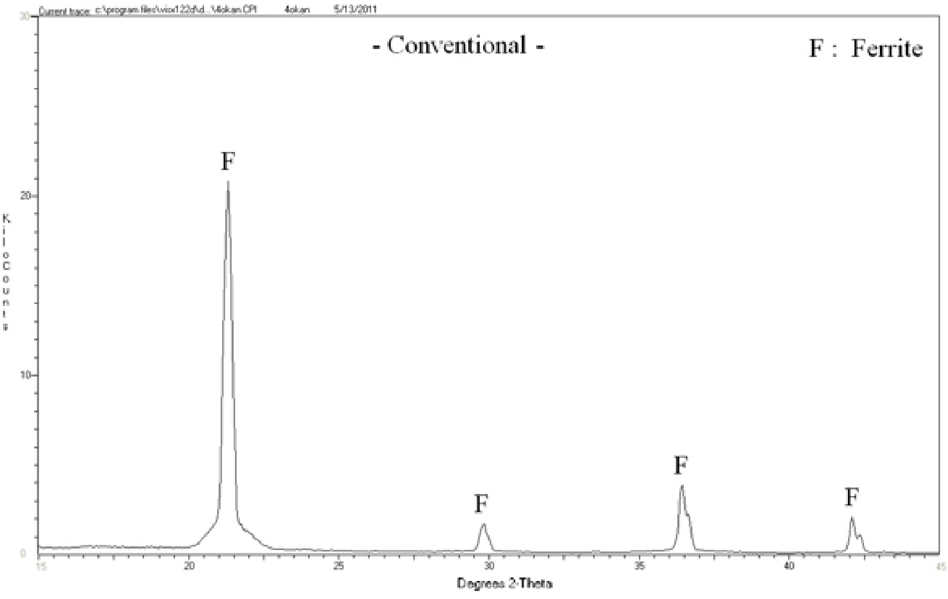


Figure 11 XRD pattern of conventional weld metal; ferrite peaks



As also seen from Figure 12 to Figure 15, which illustrate the microstructures of the joints produced in this study, only the joint produced with LTT 1 electrode showed clearly visible light-coloured segregation of Ni between martensite (retained austenite) as also reported by Kromm et al. (2007). All other joints exhibited a dominantly martensitic microstructure in the weld nugget, whereas conventional weld displays pearlitic structure as seen from Figure 15.

Figure 12 Microstructure of LTT 1 weld nugget (see online version for colours)

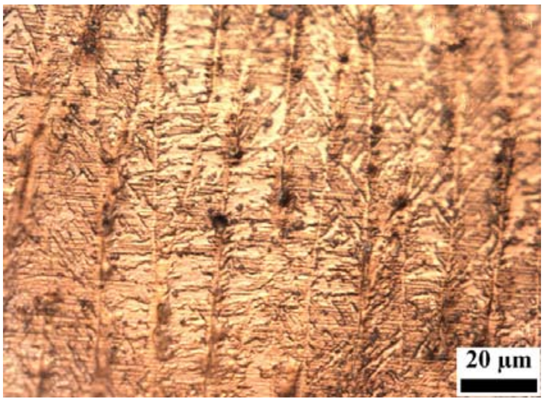


Figure 13 Microstructure of LTT 2 weld nugget (see online version for colours)

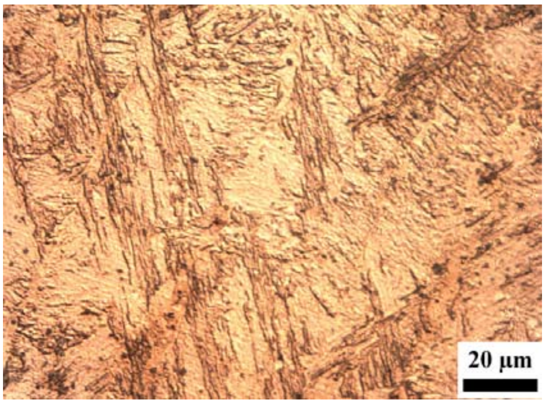


Figure 14 Microstructure of LTT 3 weld nugget (see online version for colours)

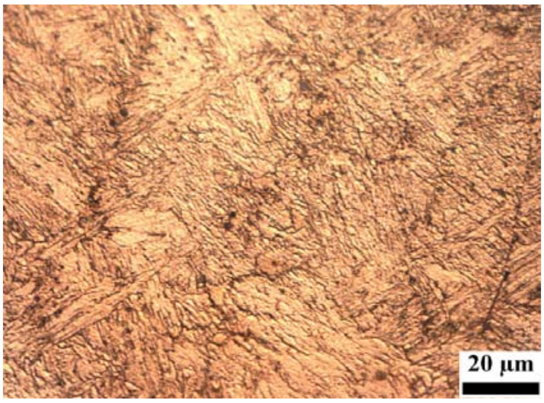
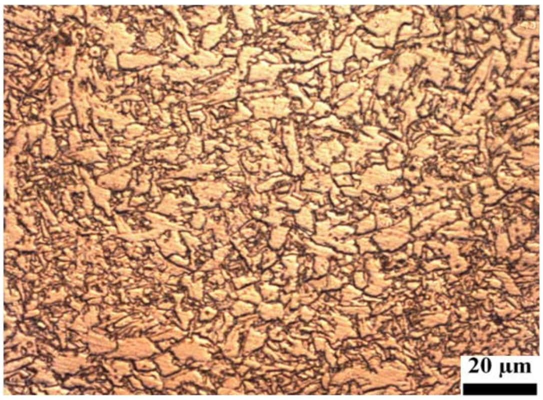
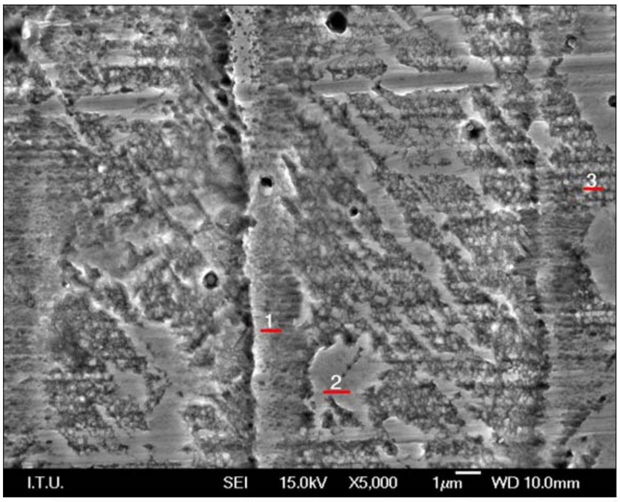


Figure 15 Microstructure of conventional weld nugget (see online version for colours)



Fusion zone (FZ) microstructures were also characterised by SEM including EDS analysis. SEM micrographs of the FZ microstructures of the joints produced are shown in Figure 16 to Figure 19. EDS analysis results indicated that the FZ microstructures of all LTT specimens contained retained austenite whereas the FZ microstructure of the conventional weld contained no retained austenite (i.e., pearlitic microstructure). Moreover, LTT1 specimen contained the highest amount of retained austenite in the FZ. Light-coloured regions in the FZ of LTT1 specimen (Figure 16, EDS spectrum 1) contained highest amount of alloying additions (i.e., Ni, Mn, Cr, Si), indicating that this phase is retained austenite. This is not surprising as LTT1 filler material has the lowest M_S temperature, leading to the presence of more retained austenite in the FZ microstructure.

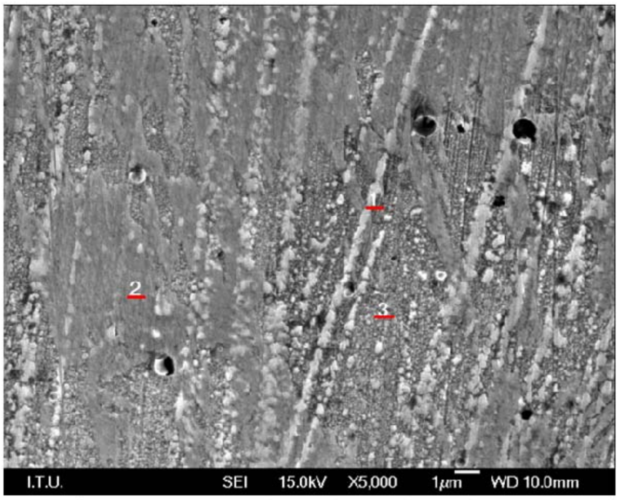
Figure 16 SEM image and EDS analysis of LTT 1 weld metal (see online version for colours)



EDS ⇨

Spectrum (wt.%)	Si	Cr	Mn	Fe	Ni
1	1.12	14.56	2.58	69.89	11.84
2	0.64	11.15	0.92	77.89	9.40
3	0.71	11.95	1.20	75.79	10.36

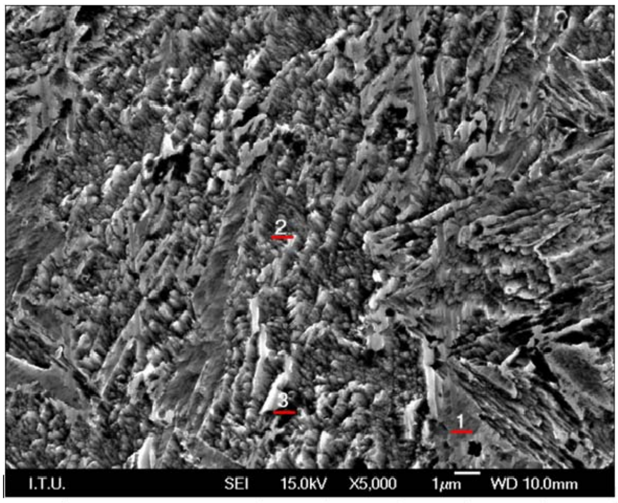
Figure 17 SEM image and EDS analysis of LTT 2 weld metal (see online version for colours)



EDS

Spectrum (wt.%)	Si	Cr	Mn	Fe	Ni
1	0.33	9.48	0.50	80.82	8.87
2	0.35	8.76	0.72	81.70	8.47
3	0.53	8.72	0.26	81.20	9.28

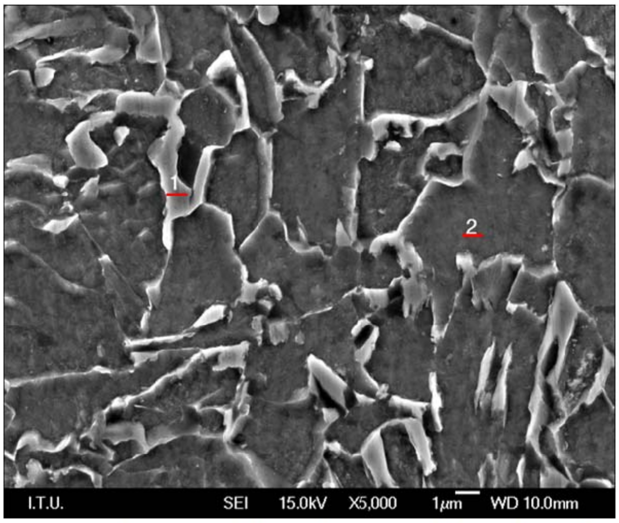
Figure 18 SEM Image and EDS analysis of LTT 3 weld metal (see online version for colours)



EDS

Spectrum (wt.%)	Si	Cr	Mn	Fe	Ni
1	0.46	9.72	1.13	80.80	7.89
2	0.47	9.36	0.23	82.11	7.84
3	0.52	9.89	0.70	79.96	8.93

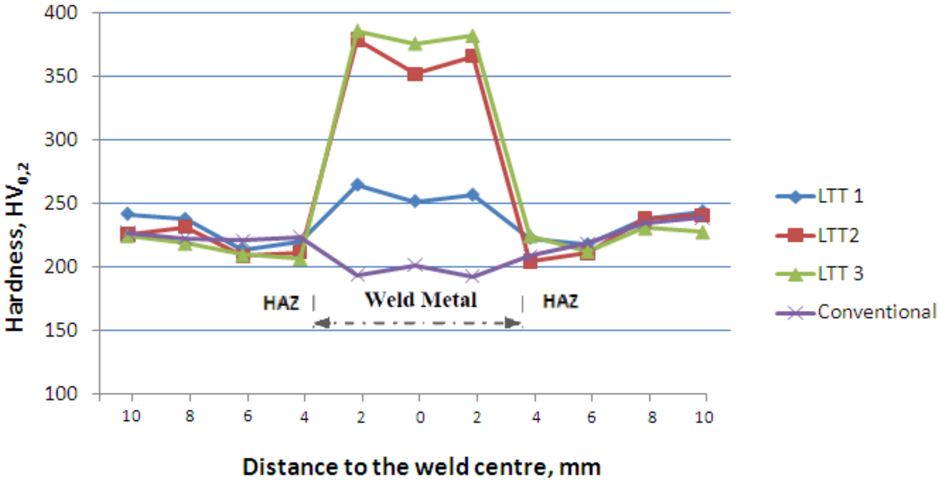
Figure 19 SEM Image and EDS analysis of conventional weld metal (see online version for colours)



EDS

Spectrum (wt.%)	Si	Cr	Mn	Fe	Ni
1	0.52	-	1.81	97.67	-
2	0.58	0.30	1.95	97.17	-

Figure 20 A comparison of hardness profiles of the joints produced using conventional and LTT electrodes (see online version for colours)



3.3 Hardness tests

A comparison of the hardness profiles of all the joints produced is given in Figure 20. According to this figure, the hardness minimum lies in the HAZ region in all the joints due to a slight grain coarsening in this region. On the other hand, the hardness of the FZ is comparable to that of the base plate in the case of the joint produced with conventional electrode whereas a hardness increase takes place in the FZs of the joints produced with LTT electrodes, indicating that a strength overmatching occurs in these joints. The joints produced using LTT 2 and LTT 3 electrodes exhibited higher hardness values in the FZ than that of the joint produced using LTT 1 electrode. This result can be attributable to the presence of retained austenite between martensite phases in the FZ of the joint produced using LTT electrode, as seen in Figure 12. Moreover, the joint produced using conventional electrode displayed the lowest hardness values in the FZ as expected.

3.4 Tensile test

Two tensile test specimens were extracted from each joint and tested. Table 6 gives the tensile test results conducted on all the joints produced in this study. As seen from the Table 6, the joints produced with LTT electrodes exhibited higher or comparable strength values to those of the base plate in contrast to the joint produced with conventional electrode which displayed a significantly lower strength value than that of the base plate. It is also clearly seen that all LTT joints exhibited higher yield and tensile strength values than those of the joint produced with conventional electrode. In other words, all the joints produced using LTT electrodes exhibited strength overmatching in the FZs whereas conventional weld displayed strength undermatching. On the other hand, all the LTT joints exhibited lower elongation values than that of the joint produced using conventional electrode. This result is not surprising since all the LTT joints have a martensitic misrostructure in the FZs. The tensile test results are also in good agreement with the hardness profiles of the joints.

Table 6 Tensile test results of the joints produced

Alloy	*Yield strength Rp0.2, (MPa)*	*Tensile strength Rm, (MPa)*	*% Elongation*	*Rupture zone*
LTT 1	600	686	12	Base metal
	608	675	13	HAZ
LTT 2	629	690	11	Weld metal
	580	640	11	HAZ
LTT 3	633	694	14	HAZ
	603	657	10	Base metal
Conventional	553	602	13	Base metal
	554	626	11	Base metal
Base metal	590	662	23	Base metal

3.5 Bending test

In order to characterise the deformation performance and to determine the existence of defects in the joints, 3-point bending tests were also carried out, two specimens for each case. As shown in Table 7, no cracking were observed for all the cases except one specimen extracted from the joint produced using LTT 2 electrode, which ruptured in the weld metal after bending agle of 60^0. This is also in agreement with the metallographic results obtained from the joints as it displayed the presence of defect in the weld region of the joint produced with LTT 2 electrode [Figure 7(b)].

Table 7 Three-point bending test results of specimens

Alloy	*Rupture zone*
LTT 1	No rupture
	No rupture
LTT 2	No rupture
	Weld metal
LTT 3	No rupture
	No rupture
Conventional	No rupture
	No rupture

4 Conclusions

All welds produced were defect-free except the joint produced using LTT 2 electrode. LTT 1 weld exhibited the smallest angular distortion among all the joints produced due to its lowest M_S temperature. The other joints produced using other LTT electrodes with higher M_S temperatures displayed higher angular distortion than that of the joint produced using conventional electrode. All the joints produced using LTT electrodes exhibited a martensitic microstructure in the weld nugget. Highest amount of retained austenite was observed in the weld nugget of the joint produced using LTT 1 electrode. The amount of retained austenite in the weld microstructure of other LTT joints is negligible.

The hardness minimum lies in the HAZ region in most of the joints due to a slight grain coarsening in this region, particularly in the joints produced with LTT 2 and LTT 3 electrodes. The hardness of the FZ is comparable to that of the base plate in the case of the joint produced with conventional electrode while a hardness increase takes place in the FZs of all the joints produced using LTT electrodes, indicating that a strength overmatching occurs in these joints. The joints produced using LTT 2 and LTT 3 electrodes exhibited higher hardness values in the FZ than that of the joint produced using LTT 1 electrode due to the presence of some retained austenite in weld nugget of this joint.

All the joints produced using LTT electrodes exhibited higher yield and tensile strength values than those of the joint produced with conventional electrode. However, they exhibited lower elongation values due to the martensitic microstructure in the weld nugget. No cracking were observed in bend specimens for all the cases except one specimen extracted from the joint produced using LTT 2 electrode, which ruptured in the weld metal.

Acknowledgements

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