63rd Annual Assembly & International Conference of the International Institute of Welding
11-17 July 2010, Istanbul, Turkey

AWST-10/35

Progress in Low Transformation Temperature (LTT) Filler Wires: Review

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Abstract

Excessive tensile residual stresses and distortion may develop in welding of steels depending on the phase transformation temperature as it plays an important role on their formation during welding. The development of distortion in the welded steel structures lead to time-energy consuming and environmentally detrimental correction operations whereas the presence of tensile residual stresses may intolerably dagrade the fatigue properties of the welded components. The amount of distortion developed in steel welds may be reduced and compressive residual stresses can be induced without any preheating or postweld treatment by lowering the transformation temperature with the use of proper filler wire, i.e. so-called low-transformation-temperature (LTT) welding wire. Thus, the welded structures with compressive residual stresses display better properties such as fatigue life, stress corrosion cracking (SCC), resistance to cold-cracking, and service life properties. However, the fracture toughness may be reduced slightly.

The residual stresses and distortion developed in high stregth steel welded structures play an important role on the reliability and cost efficiency of these joints. In this study, the state-of-art of the low transformation temperature filler wires, which is recently developed by tailoring its chemical composition to lower the M_S temperature, and their effects on the residual stress formation, fatigue life, and cold-cracking are discussed in detail.

Keywords: *Steels, Joining, Distortion, Residual stresses, Fatigue, Phase transformation, Filler wire, Consumables, Fracture toughness, Cold-cracking*

1. Introduction

Residual stresses induced during joining are major contributers to the overall stress state of the welded structural components [1]. They can induce SCC and brittle failure in addition to distortion, and may lead to the deterioration of fatigue life. The development of distortion in the welded steel structures may also lead to costly correction operations. In order to improve the structural performance of the welded structures a number of mitigation techniques have been proposed, e.g. postweld stress relief heat treatment, shot peening, modification of the structural configuration and implementation of the thermal tensioning technique [1-3]. There are, however, some limitations in implementation of these techniques due to the technical complexity and/or the high costs.

An alternative approach to overcome the residual stress problem in steel weldments is to lower the M_S temperature by the use of LTT filler wires. These consumables are typically alloys with 0−15 wt.-% Ni, 0−15 wt.-% Cr and exhibit displacive transformation mechanism at a low temperature [1]. It was first suggested by Jones and Alberry in the late 1970s [4] that tensile residual stresses are best avoided by suppressing the M_S temperature such that the phase change can continue to compensate for the accumulation of contraction strains down to room temperature. Indeed, recent work in Japan has shown that by using LTT consumables it is possible not only to reduce the residual tensile stresses developed in the steel weldments, but also to induce residual compressive stresses into the weld region with consequential improvements in fatigue life [5-7].

The reduction in tensile welding residual stresses due to low phase transformation temperature can be explained as follows. By proper adjustment of Mn, Cr and Ni contents of the welding wire, a martensitic microstructure within the fusion zone can be achieved. If the transformation of austenite to martensite begins at a temperature below that at which the thermal contraction cannot negate the phase-induced volumetric expansion, i.e. lower than 550 ^oC, a compressive residual stress in the fusion zone is developed. It was also proposed by Murakawa et al. [1] that the decreasing M_S temperature down to 200 ^oC increases the magnitude of the compressive stresses generated and a futher decrease in the M_S temperature below that results in no additional benefit. The martensitic transformation should also end above room temperature to ensure the maximum volumetric expansion [8].

The development of compressive residual stresses within the weld metal by lowering the M_s temperature, thus, leads to beneficial effects on fatigue life [5-7, 9, 10] and distortion [11]. Although compressive stresses are developed within weld metal by lowering the M_S temperature with the use of low transformation temperature welding consumables which leads to benefial effects on fatigue strength and distortion the fracture toughness may deteriorate. However, the fracture toughness of the recently developed LTT filler alloy has been found satisfactory [12].

2. Martensitic transformation start (M_S) temperature

Martensite is of the greatest technological importance in steels where it can lead to an outstanding combination of strength (> 3500 MPa) and toughness (> 200 MPa.$m^{1/2}$). The temperature at which martensitic transformation, frequently also called a shear or displacive transformation, takes place depends on the chemical composition of the steel.

Austenite stabilizing elements, such as C, Mn, Ni and N, retard the transition from austenite to martensite. Out of all the carbon content strongly affects the martensite start (M_S) temperature. Although Cr is a alpha stabilizer it also acts like an austenite stabilizer when added together with Ni as the case in austenitic stainless steels. Since C is not desired for improved toughness as well as Mn, the M_S temperature can be lowered by adding Ni and Cr to the filler wire with small amounts of other alloying additions, e.g. Mo. The M_S temperature can approximately be calculated using the Equation 1 [13].

$$M_S = 561 - 474C - 33Mn - 17Cr - 17Ni - 21Mo\ (^oC) \qquad (1)$$

This equation provides reasonably good agreement also with minor variations of the chemical composition. Thus, the temperature at which martensitic transfomation occurs in welding of structural steels can be controlled by tailoring the chemical composition of the filler wire, i.e. the low M_S temperature [5]. A fully martensitic structure within the fusion zone can be developed if both the M_S and M_F temperatures are above the room temperature, whereas a small amount of retained austenite remains provided that the M_F temperature lies below the room temperature.

Table 1.M_S temperatures and chemical compositions of some conventional and newly developed LTT filler wires

Filler wire	Main alloying additions in filler wire (wt.%)						M_s temp., (^{o}C)	M_f temp., (^{o}C)	Ref.
	C	Ni	Cr	Mn	Si	Mo			
Conventional wires									
MGS-63B	0.03	--	0.42	1.09	0.50	0.29	500	--	5-7
OK Autrod 12.51	0.10	--	--	1.10	0.70	--	500	--	10
Mn1	--	0.08	12.3	1.76	--	--	533	400	16
Cr1	--	0.10	10.5	0.09	--	--	537	486	16
LTT wires									
10Cr-10Ni	0.025	10.0	10.0	0.70	0.32	0.13	180	--	5-7
OK Tubrod 15.55	0.01	6.7	12.5	1.80	0.40	2.50	200	--	10
--	0.02	10.14	9.76	0.19	0.39	0.17	205	< 0	17
--	0.076	6.13	6.14	0.55	0.43	0.10	380	130	17
	0.04	6.0	8.0	0.70	0.40	--	281	--	15
	0.04	8.0	10.0	0.70	0.40	--	213		15
	0.04	10.0	10.0	0.70	0.40	--	179		15
	0.04	12.0	10.0	0.70	0.40	--	145	--	15
	0.04	8.0	8.0	0.70	1.60	--	247	--	15
	0.04	10.0	10.0	0.70	1.60	--	179	--	15
	0.03	10.0	10.0	0.70	0.32	--	180	--	15
Ni1	--	3.41	11.0	0.20	--	--	293	147	16
Ni3	--	9.99	12.0	0.28	--	--	170	135	16

Recently, several studies have been conducted to produce low transformation temperature (LTT) filler wires in order to decrease the tensile resiadual stresses developed in the weld zone, even to produce compressional residual stresses [5-7, 9, 10]. Table 1 gives the M_S temperatures and chemical compositions of some conventional and newly developed LTT filler wires.

However, the chemical composition of the fusion zone is a mixture of those of the filler wire and the steel plates welded. This dilution should be taken into account for the actual M_S temperature of the weld metal. The transformation temperatures can be determined during welding by temperature measurement techniques, such as the SS-DTA method (Sensor Differential Thermal Analysis) [14, 15]. In this technique, type C (W-Re) thermocouples should be immersed into the liquid weld metal, instead of type K (Ni-CrNi) in order to avoid the reaction, and the measured cooling curve is then plotted. The deviations in the curve reveal the start and end of solid state transformations [15]. The M_S temperatures determined during welding of S690Q steel plates using LTT-wires were quite different than those of the LTT wires used due to the dilution effect [15].

3. Residual stresses and distortion

Residual stresses or **'locked-in'** stresses are defined as those stresses existing within a body in the absence of external loading or thermal gradients. Factors that cause residual stresses:

- Volumetric changes occurring during solidification,
- Solid state transformations**,**
- Differences in the coefficient of thermal expansion**,**
- Localized yielding of material,
- Mechanical constraints

During the welding, rapid and local heating to high temperature generates non-uniform strain distribution and thermal expansion. Contraction upon cooling causes distortion of structural components. The amount of distortion developed in steel welds may be reduced by lowering the transformation temperature with the use of proper filler wire as shown in Figure 1. The lowering of M_S temperature can be achieved by controlling the amounts of Cr and Ni contents of the filler wire. By doing this a martensite start (M_S) temperature of about 260 ^{o}C can be achieved [15]. Figure 2. also shows a comparison of various amounts of residual angular distortion obtained in T-joints welded with various filler wires with different martensitic transformation temperatures. Figure 3 illustrates the microstructures of two-layer welds in S690 Q steel produced with a LTT (10% Ni-10% Cr) filler.

The lowering of transformation temperature also reduces the residual stresses developed within the welded joints due to the expansion of martensite, which is hindered by carbon atoms. Classical X-ray diffraction (using X-ray radiation) as well as diffraction methods using high energy synchroton radiation can be used for resial stress measurements of weldments [15].

Recent studies have revealed that compressional residual stresses within the weld region can be obtained by using LTT filler wires. Figure 4. shows how compressional residual stresses are produced within the weld zone using LTT filler wires whereas tensile residual stresses are formed if conventional filler wires with higher M_S temperatures are employed. This can be explained as follows. The martensitic transformation occurs at the latest stage of the cooling so the thermal contraction effect due to cooling is lower than the volumetric expansion due to the phase transformation if the M_S temperature is sufficiently low. That is the thermal contraction effect is minimized. If the martensitic transformation ends well above the room temperature it insures the maximum possible formation of martensite whereas some retained austenite remains if the M_F temperature is below the room temperature. Figure 4.a. shows difference of dilatation in cooling between conventional and LTT filler wires [5, 6, 10, 18].

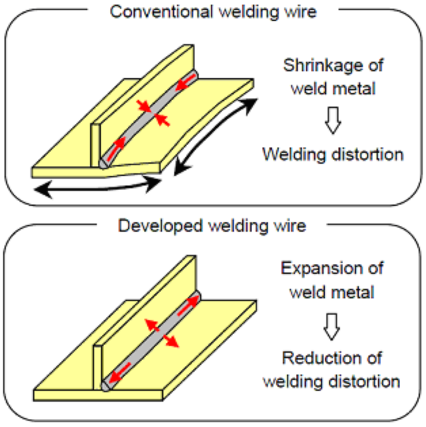


Figure 1. Deformation of mild steel plates joined with a single pass weld using two types of consumables [19]

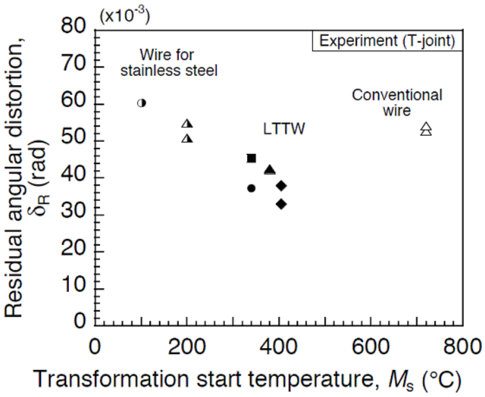


Figure 2. Relationship between M_S temperature and angular distortion [17]

The lower transformation temperature of filler weld metal results in considerably lower residual stresses as shown clearly in Figure 5. Moreover, LTT filler wires may introduce significant longitudinal compressive residual stresses within the fusion zone [20]. Similarly, numerous recent works conducted to investigate the effect of M_S temperature of the filler wire on the residual stresses developed within the weld region of high strength steels [1, 8, 15, 17, 18, 20, 21] also indicate that the amount of distortion developed may be reduced and even compressive residual stresses can be induced with the use of these newly developed LTT filler materials.

It is thus clear that weld metals with intermediate C contents (i.e. sufficient weldability) has a better chance to benefit from martensite expansion. Thus, it can be said that alloyed weld metals (low M_S temperature) with an intermediate carbon content (decrease of the stresses due to martensite expansion and good weldability) yield low residual stresses and distortion.

The welded structures with lower residual stresses also display better properties such as fatigue life [5-7, 9, 10] and cold cracking [22] with some degradation in fracture toughness [23]. However, as pointed out earlier, the fracture toughness of the recently developed LTT filler alloy has been found satisfactory [12]. Futhermore, several workers [11, 17] have studied the effect of the martensitic transformation expansion of weld metals on welding distortion and reported that the welds produced using LTT filler wires exhibit lower distortion compared to those experienced using conventional filler wires.

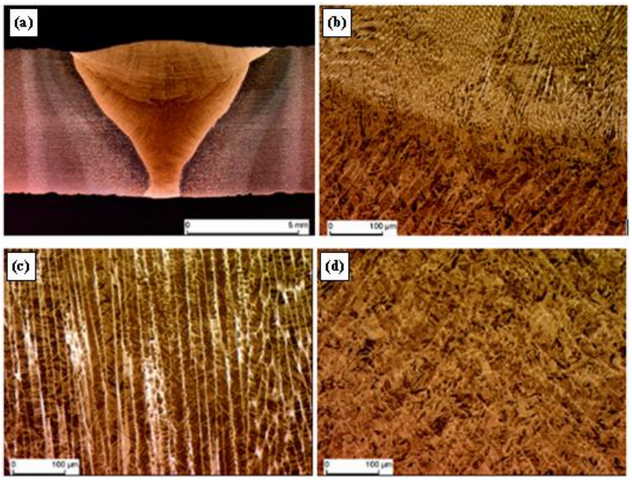


Figure 3. Microstructures of two-layer welds in S690 Q steel produced with a LTT (10% Ni-10% Cr) filler: a) macro-section, b) transition between root and final pass, c) light coloured segregation of Ni (retained austenite) between martensite in final pass, and d) martensitic structure in root pass [15]

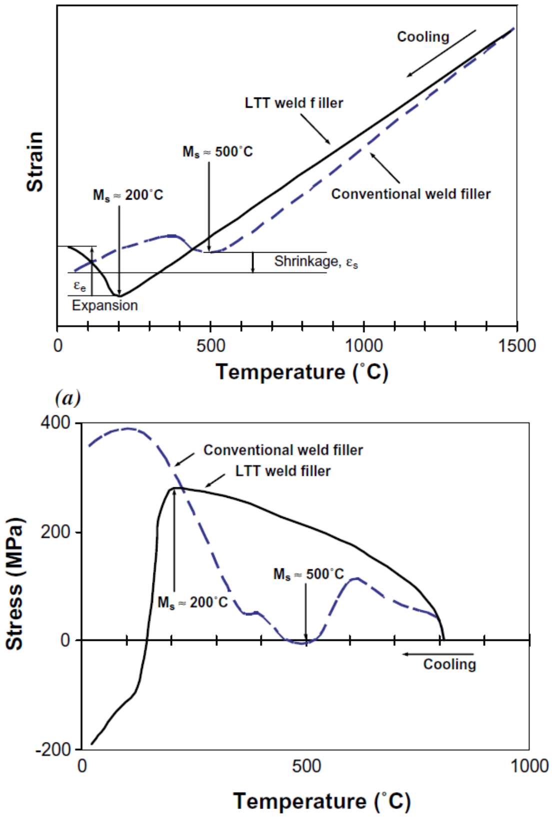


Figure 4. Variation of residual stress and strain developed during cooling using conventional and LTT filler wires: a) strain and b) stress [10]

4. Fatigue properties

High tensile residual stresses forming in high strength steel welds accelerate the fatigue crack propagation and reduce fatigue life of the weldment [7]. Another reason for reduced fatigue strength of weldments is the stress concentration [24]. The basic approach for improved fatigue strength in high strength steel welds is to avoid the joining in highly stressed areas. When this is not possible then the following measures are usually taken [7, 25]:

- reducing stress concentration by improved structural design,
- improving weld quality (e.g. geometry or introduction of compressive residual stresses) by post-weld treatment of critical welds, such as grinding of weld toe, hammer peening and shot blasting,
- replacing welded connections by mechanical fastening methods, for instance bolted connections.

However, all of these methods increase the production time and cost. Another way of reducing tensile residual stresses or even introducing compressive residual stresses is the use of newly developed low transformation temperature (LTT) filler materials as earlier mentioned.

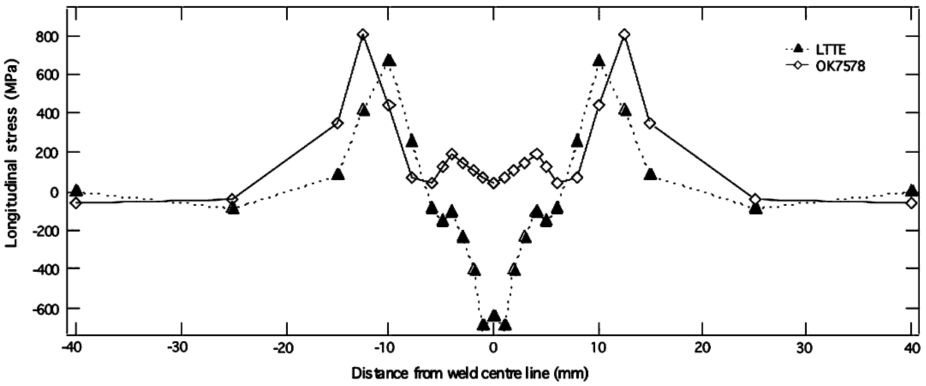


Figure 5. Comparison of longitudinal stresses measured in the joints produced using conventional and LTT wires by neutron diffraction [21]

Recently, numerous studies have been conducted to investigate the effect of using LTT filler wires on fatigue behaviour of steel weldments [5-7, 10, 25, 26, 27]. Figure 6 shows a comparison of fatigue performances of steel welds produced with conventional and LTT welding consumables [7]. As seen from this figure, LTT consumables lead to improved fatigue strength over conventional consumables, i.e. an increase of between 25-90% in mean fatigue strength. In addition to that, it also reduces deformation and decreases the risk of cold cracking [22].

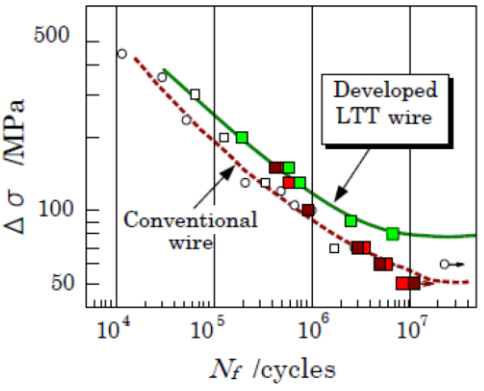


Figure 6. Comparison of fatigue performance of steel welds produced with conventional and LTT welding consumables [18].

The fatigue crack growth properties of joints welded with low transformation temperature welding wire are also shown in Figure 7. with the fatigue crack growth behavior of conventional welded joints indicated by bands. The plot for the joints welded with low transformation temperature welding wire moves to the right side of these bands, indicating a higher fatigue performance. The fatigue threshold of joint which is welded with LTT is about twice that for conventional welded joints [5].

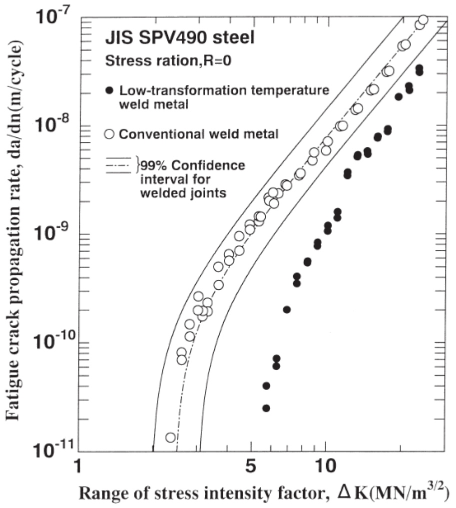


Figure 7. Comparison of the fatigue crack growth properties of weld joints produced with conventional and LTT welding consumables [5].

5. Cold cracking

Cold cracks are defects that results from the contamination of microstructure by hydrogen and occurs between -50 ^{0}C and 150 ^{0}C. This type of cracking can be seen after weeks or even months after welding [28]. Such cracking is associated with the combined presence of three factors; susceptible microstructure, diffusible hydrogen and residual stress [23]. Result of the diffusion of elemental hydrogen is that after migration to dislocations, hydrogen forms pockets and creates pressure to expand the defect and thus results in a crack. For cracking, conductive microstructure to crack growth is also required. This type of crack is mostly seen as transgranular [29]. The toughness of the alloy will be improved as a result of presence of stable dispersed austenite films in low carbon martensitic stainless steels. Considering cracking phenomena, as retained austenite is present near a propogating crack, concentrated strain field at the crack tip induces transformation into martensite. This transformation will absorb energy and acts like a toughening mechanism. Volumetric expansion resulted from the martensitic transformation, would lead to close the crack and relieve stresses at crack tip. This mechanism will absorb the strain energy and limit crack extension. Also, austenite has higher solubility for hydrogen than martensite, and thus it will absorb hydrogen from martensite. This will, in turn, help to lower hydrogen concentration in martensite [30].

Experiments on the welds produced with different LTT weld consumables [31] show that cold cracking can be avoided when appropriate contents of retained austenite are existent as seen from Table 2 and Figures 8. and 9 It was demonstrated that the joint produced with LTT weld consumables, i.e. 12% Ni, yielded in a microstructure containing some retained austenite due to its low M_S temperature, i.e. 40 ^oC, and showed the highest crack resistance, Figure 8. It was reported that as the nickel content in the filler wire increases the transformation temperature and thus the crack ratio decreases. The crack ratio decreases down to about 30% at a Ni-content of 10% and crack-free welds are obtained with the use of weld consumables containing 12% Ni. This can be attributed to the presence of compressive residual stresses in the joint and of retained austenite in the microstructure [31]. These results indicate that LTT filler wires may be succesfully used to avoid cold cracking.

Similarly, Shiga et al. [18] reported that LTT welding consumables with a M_S temperature of 100 ^oC, resulting in a dual phase microstructure consisting of martensite and austenite, completely suppresses cold cracking without preheating, Figure 10. However, to what extent the M_S temperature (thus the presence of retained austenite) and residual stresses are responsible for the suppression of cold cracking have not yet been determined [18].

Table 2. Crack ratios and hardness values obtained with various LTT consumables in Tekken test

LTT Alloy	Hardness HV10	Surface crack ratio in %	Section crack ratio in %
8%Ni	417	70	60
10%Ni	401	0	30
12%Ni	394	0	0

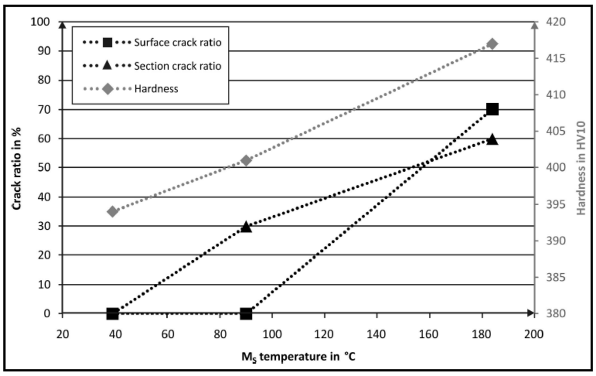
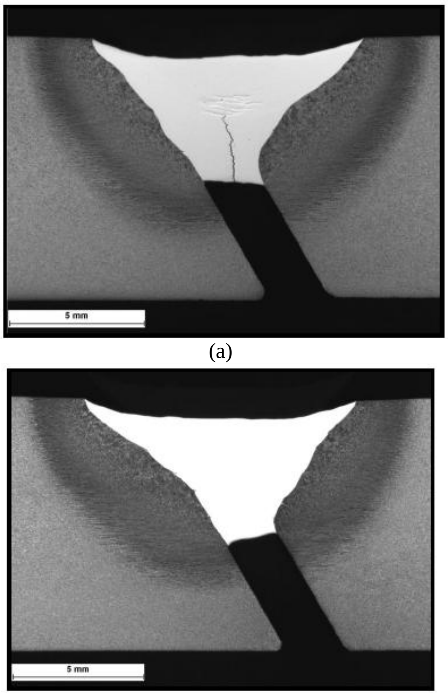


Figure 9. Variation of crack ratios and hardness values with M_S temperatures obtained with various LTT consumables in Tekken test [31]



(b)

Figure 8. Cross sections of the joints produced with LTT consumables with varying Ni-contents after Tekken test: a) %10 Ni and b) %12 Ni [31]

6. General remarks

Recent studies have clearly demonstrated that LTT welding consumables produces fully martensitic structure or martensitic structure containing some retained beta. Residual tensile stresses are lowered or compressive residual stresses are generated within the weld region due to martensitic expansion when the transformation takes place at lower temperatures. Thus, weld properties such as fatigue strength and cold cracking resistance are increased without any costly post-weld treatment.

However, some issues concerning LTT consumables such as effects of multipass welding and dilution with parent plate are to be clarified throughly before it can be concluded that the use of these new consumables is a practical approach of increasing fatigue performance and minimizing welding induced deformation. It also remains to develop suitable LTT consumables, which do not only modify the stress distribution, but also provide acceptable static strength and impact toughness. Another issue to be clarified is hot cracking since the main alloying addition in these consumables for suppressing M_S temperature is Ni, which maight shift the weld metal into austenitic solidification. Alternative alloying concepts should therefore be investigated for the sake of safety from the practical point of view.

Nevertheless, the studies conducted up to date clearly demonstrate that the use of LTT consumables is a promising approach for reducing the risk of welded component fatigue failure without any post-weld treatment such as PWHT or shot peening. Large scale fatigue testing identical to real life applications is still lacking. The use of LTT consumables with sufficiently low M_S temperatures also avoids cold-cracking. However, to what extent the M_S temperature (thus the presence of retained austenite) and residual stresses are responsible for the suppression of cold cracking has not yet been determined. These points have to be clarified prior to its practical use.

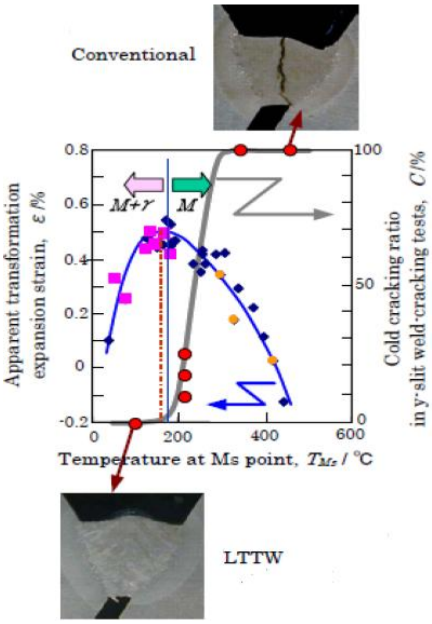


Figure 10. Effect of M_S temperature, and thus microstructure, on the dilatation strain and crack ratio obtained in Y-groove weld cracking tests [18]

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