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Fatigue strength improvement of welded structures using new low transformation temperature filler materials

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Abstract

The results reported in this research study are part of a larger EU RFCS (Research Fund for Coal and Steel) project where the aim is to study the fatigue behavior of improved welds in high strength steels by utilizing different improvement techniques. In this particular study LTT (Low Transformation Temperature) weld filler material have been investigated and their possibility to improve the fatigue strength. The characteristic of these filler material is that they undergo phase transformation at temperature close to room temperature which will reduce the tensile residual stress in the weld and in some cases result in compressive residual stresses. Two different LTT alloy compositions have been developed, with different Ms (Martensite Start) temperatures in order to study the amount of tensile/compressive residual stresses produced by these wires. Welding residual stress measurements were carried out by X-ray diffraction technique. Plates with welded longitudinal attachments were fabricated in 700 MPa and 960 MPa steel grades using different LTT filler materials. These specimens were fatigue tested in constant and variable amplitude loading and the fatigue test results were compared with results from specimen welded with conventional weld filler material.

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Keywords: Residual stresses; LTT; Welded joints; Fatigue testing;

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1. Introduction

The fatigue strength of a welded joint is less than virgin base material and also, it does not increase with the increase in the yield strength of the base material. It is because of high tensile welding residual stresses due to the thermal shrinkage of the weld metal, weld toe/root defects and small notch radii at local weld toe geometry. The weld toe/root defects can be controlled to large extent by optimizing the welding process specifications. The local weld toe geometry can be improved by different post-weld treatments, including TIG dressing, laser re-melting and burr grinding etc. And, the tensile welding residual stresses which are considered as detrimental for fatigue loaded structures since they combine with applied loading conditions and increase the mean loading stresses can be reduced or even modified into beneficial compressive residual stresses by using HFMI (High Frequency Mechanical Impact) treatment. HFMI treatment not only induces the compressive residual stresses but also it improves the local weld toe geometry. But, being a post weld treatment is its only disadvantage as it will increase the production cost of the component. Moreover, the significant reduction in the tensile welding residual stresses can also be achieved by using LTT (Low Transformation Temperature) filler wires instead of the conventional ones.

Phase transformation plays a prominent part in the formation of welding residual stresses in high-strength steels. During welding, phase transformations are affected by the chemical composition and the cooling rate in regions that are being austenized during the heat cycle. And depending on these two variables different transformation temperatures are yielded. The characteristic of LTT filler material is that it undergoes austenite to martensite phase transformation at temperature close to room temperature which will reduce the tensile residual stress in the weld and in some cases result in compressive residual stresses. Up to now different approaches of alloys with special adjusted martensite start temperatures have been published. The research group around Ohta et al [1] has introduced an iron-based alloy using chromium and nickel as main alloying elements. Martinez-Diez [2] has published an alternative composition substituting nickel by manganese. Another approach with only nickel serving as main alloying element was recently proposed in [3].

Many publications have reported the significant reduction in tensile welding residual stresses and improvement in fatigue strength by using LTT filler material as compared to the joints welded with conventional filler wires [4-9]. Barsoum et al [10] has reported compressive residual stresses at the weld toe of out of plane gusset fillet joint when welded with LTT filler wires. Furthermore, significant improvement in mean fatigue strength is obtained under constant amplitude loading. And, less significant improvement in mean fatigue strength is achieved under variable amplitude loadings due to stress relaxations. Eckerlid et al [11] has shown an improvement in mean fatigue strength of the joint welded with LTT filler wires by 20-95% at 2 million cycles when tested under constant amplitude loadings. Machida et al [12] carried out constant amplitude fatigue testing on box welds and an improvement of 12% in fatigue strength at 2 million cycles is achieved when compared with the joints welded with conventional filler wires. Ohta et al [13] carried out additional welds around horizontal gusset of box weld specimen which was already welded with conventional filler wire and found compressive residual stresses near the weld toe and also observed 2 times increase in the fatigue strength.

In the present study two different LTT alloy compositions have been developed, with different Martensite Start (Ms) temperature. The main aim is to study the amount of tensile/compressive residual stresses produced by these wires and also their effect on the fatigue strength of the joint under constant amplitude loadings at R-ratio (minimum stress/maximum stress) 0.1 and 0.5 and also under variable amplitude loadings.

2. Development of LTT filler wires

In order to investigate the influence of weld filler properties on the enhancement of the fatigue strength of the welded joint, two LTT- filler metals have been designed in a few iterating steps based on theoretical as well as practical considerations. In a first step chemical compositions leading to appropriate Ms-temperatures are identified from literature. Possible candidates are selected and manufactured in form of metal cored wires with a diameter of 1.6 mm. Additional to Ms the overall cracking behavior comprising cold as well as solidification cracking is evaluated due to numerous welding tests. The application of LTT for welding high strength steels calls for appropriate strength and toughness. Tensile as well as charpy impact tests revealed that LTT fillers may fulfill these requirements. After evaluation of possible LTT concepts the final compositions have been selected. They are manufactured as metal cored wires with a diameter of 1.2 mm. The wires are both iron based showing on the one hand a modified chromium nickel ratio leading to Ms below 250°C. On the other hand a chemical composition was designed showing chromium and manganese as main alloying elements. Ms of the latter is situated below 150°C.

In the present study the chromium nickel based filler wire is identified as 'S' and chromium manganese based wire is named as 'C'.

3. Experimental Details

3.1. Specimen

Steel grades having minimum yield strength of 700MPa and 960MPa are used as the parent material for the fabrication of longitudinal stiffener fillet welded joints. The base plate and stiffener have the same thicknesses and the specimens are prepared in 5mm and 10mm thicknesses. The complete design and dimensions of the joint with base plate and stiffener having thickness 5mm is shown in figure 1.

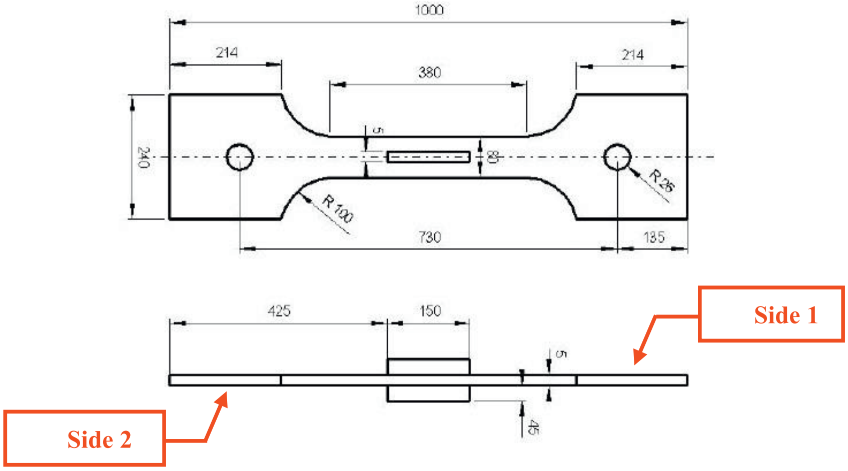

Fig. 1. Design and dimensions of longitudinal stiffener fillet welded joint

3.2. Welding setup

Conventional as well as newly developed LTT filler wires are used for welding of longitudinal stiffener joint by means of a welding robot. Identical welding process is utilized for the preparation of the specimens using all weld filler wires, but with different welding parameters. The welding of joint is carried out in such a way that, firstly, the stiffener on side 1 is welded to the base plate and cooled down to ambient room temperature. Then, the stiffener on side 2 is welded to the base plate and joint is then again cooled down to ambient room temperature. The welding direction and start/stop location used during the welding of longitudinal stiffener joint is shown in figure 2.

Table 1. Welding parameters

Weld filler wire	Steel grade	Thickness (*mm*)	Current (*A*)	Voltage (*V*)	Welding speed (*mm/min*)
LTT C	S960MC and S700MC	5	165	27.2	247
LTT S	S960MC and S700MC	5	179	26.9	247
Conventional	S700MC	5	185	26.5	295

Different trails of welding experiments are carried out to attain the optimized welding parameters which result in acceptable weld quality and full root penetrated joint. The final parameters used for the welding of some of the longitudinal stiffener joints of thicknesses 5mm using different filler wires are shown in table 1. These parameters are an average value over the single completed weld.

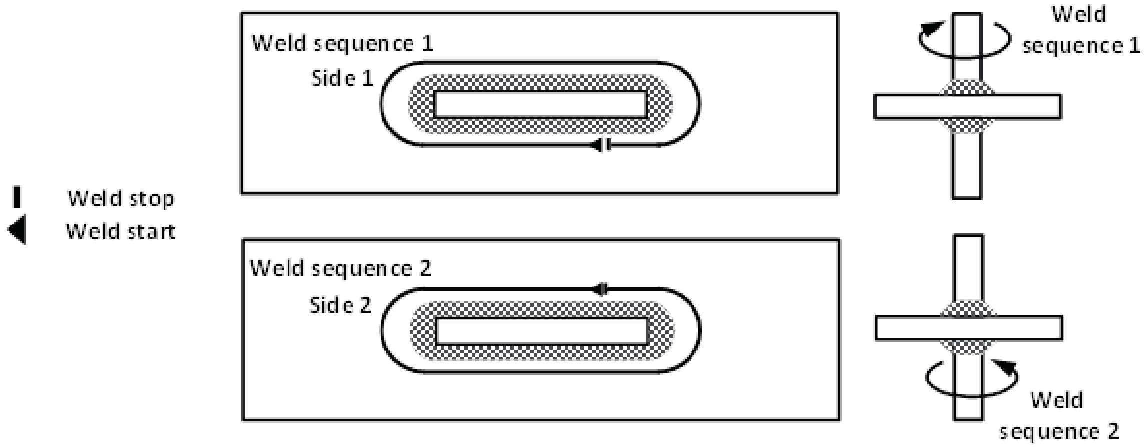

Fig. 2. Welding start/stop location, direction and sequences for the joint

3.3. Residual stress measurements

In order to study the influence of the welding residual stress on the fatigue strength of the longitudinal stiffener joint welded with different filler wires, X-ray diffraction method is used to measure longitudinal residual stresses along four different paths (A-D) on a few specimens.

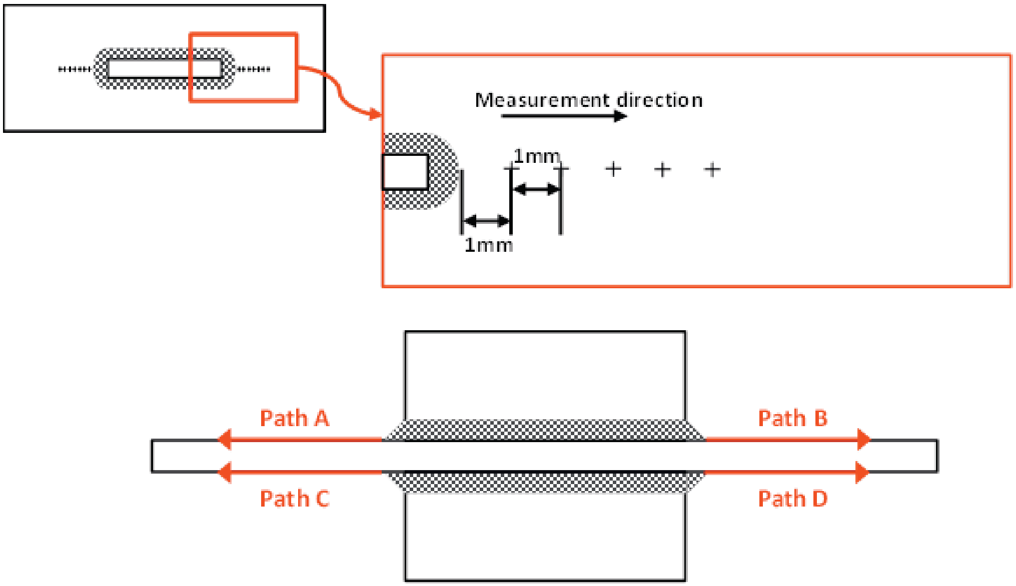

Fig. 3.Residual stress measurement points along four different paths (A-D)

The diameter of collimator used in the measurements is 2mm and, standard Cr-Ka radiation is used to measure the ferrite interference line (211). In order to avoid the collision of the X-ray detectors with the stiffener the first measurement point is measured at a distance of 1mm from the weld toe of the joint and the subsequent measurement points are 1mm apart as shown in figure 3. In case of the joint welded with conventional filler wire the first two measurement points are 1mm and the subsequent measurement points are 2mm apart.

A comparison of measured welding residual stresses along all four paths (A-D) in S700MC 5mm joint welded with LTT C and conventional filler wire is shown in figure 4. Moreover, the comparison of measured welding residual stresses along all four paths (A-D) in S960MC 5mm joint welded with LTT C and S filler wires is shown in figure 5.

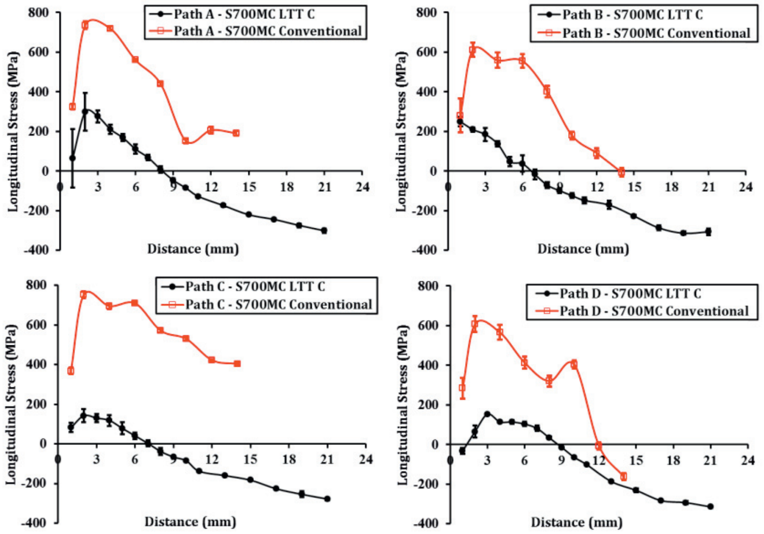

Fig. 4.Distribution of residual stresses in S700MC steel along four different paths (A-D) welded with LTT C and conventional filler

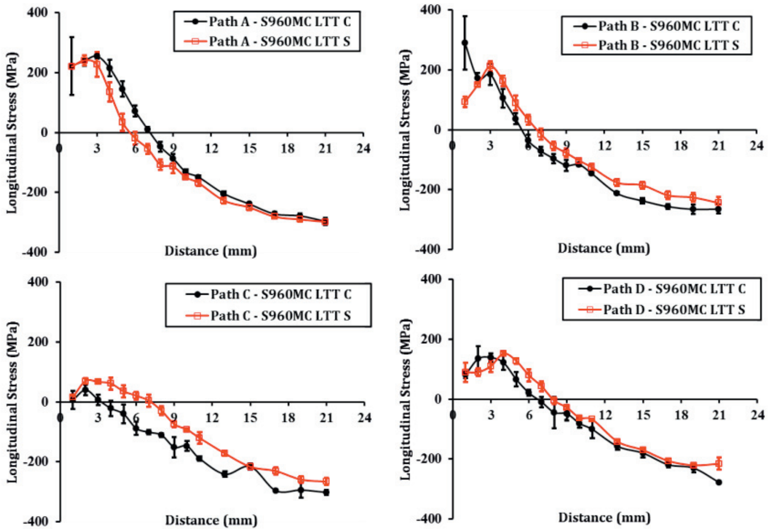

Fig. 5. Distribution of residual stresses in S960MC steel along four different paths (A-D) welded with LTT C and LTT S filler wires

3.4. Fatigue testing

The fatigue testing is performed at CAL (Constant Amplitude Loading) as well as at VAL (Variable Amplitude Loading). Under CAL the specimen are tested at two different *R*-ratios i.e. at *R*=0.1 and *R*=0.5. The maximum stress level is 388.8*MPa* for *R*=0.1 and 700*MPa* for *R*=0.5. The spectrum for VAL consists of random sequences within a block of 100000 cycles. This spectrum is a tension/compression spectrum i.e. the mean stress is zero as shown in figure 6. The maximum stress level used in VAL is 624*MPa*. The equivalent stress range σ_{eqv} is calculated as reported by [10] see table 3.

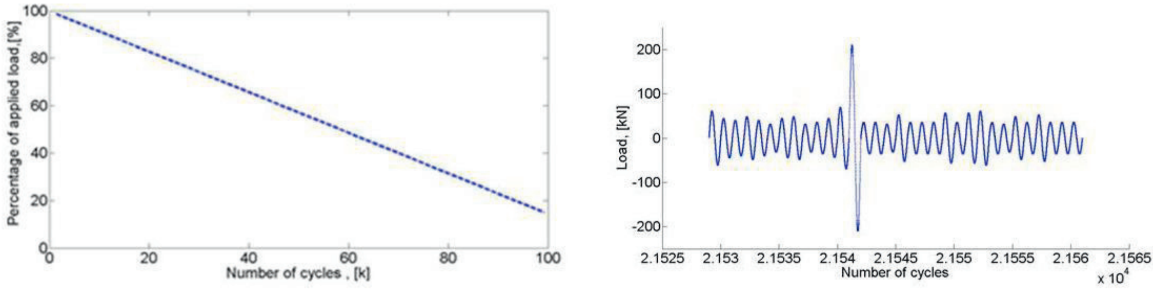

Fig. 6. Variable amplitude load spectrum

The IIW (International Institute of Welding) recommends fatigue strength of 71*MPa* for longitudinal stiffener joint at 2 million cycles with 95% probability of survival in as welded conditions. This value is called characteristic fatigue strength or FAT class. The fatigue testing results at CAL is shown in figures 7-9 and at VAL in figure 10-11. The achieved fatigue strength at 2 million cycles and slope of the curves are tabulated in table 2.

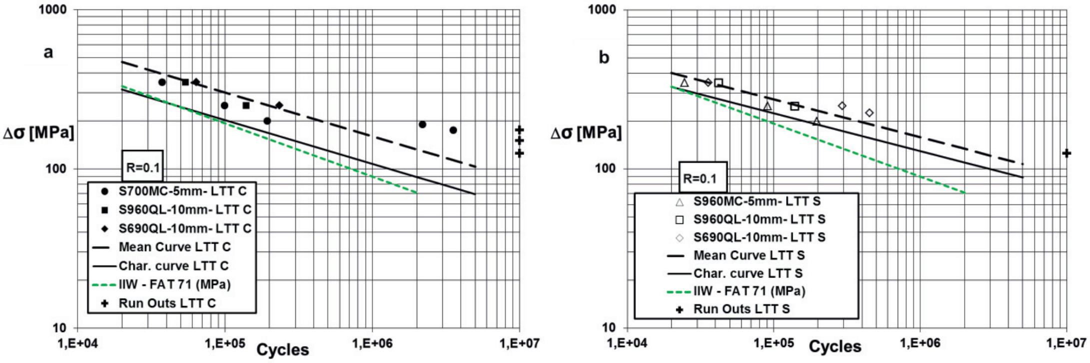

Fig. 7. Fatigue testing of specimen tested under CAL at *R*=0.1 (a) welded with LTT C filler wire; (b) welded with LTT S filler wire.

Table 2.Fatigue strength at 2 million cycles and slope of the curve

Weld filler	R	Mean fatigue strength*(MPa)*	Characteristic fatigue strength*(MPa)*	m
LTT C	0.1	133	89	3.6
LTT S	0.1	134	110	4.2
LTT C and S	0.1	155	124	4.9
LTT C	0.5	86	70	3
LTT S	0.5	85	67	3.2
LTT C and S	0.5	86	69	3.1

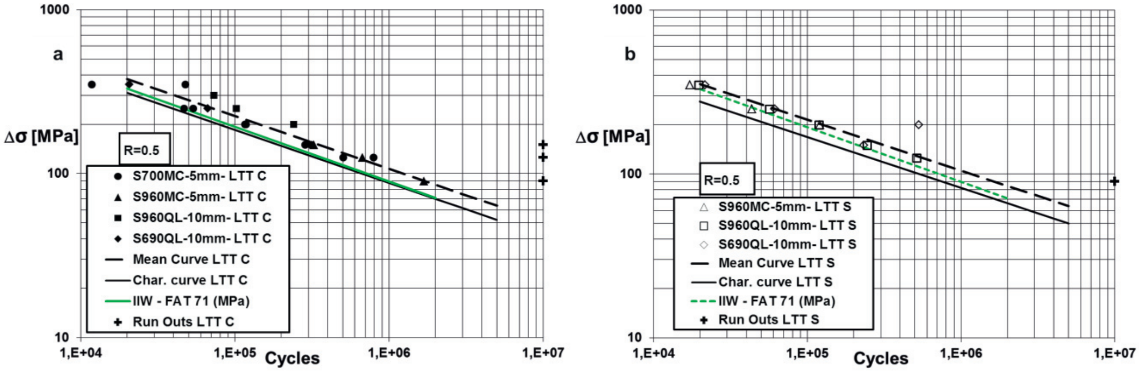

Fig. 8. Fatigue testing of specimen tested under CAL at *R*=0.5 (a) welded with LTT C filler wire; (b) welded with LTT S filler wire.

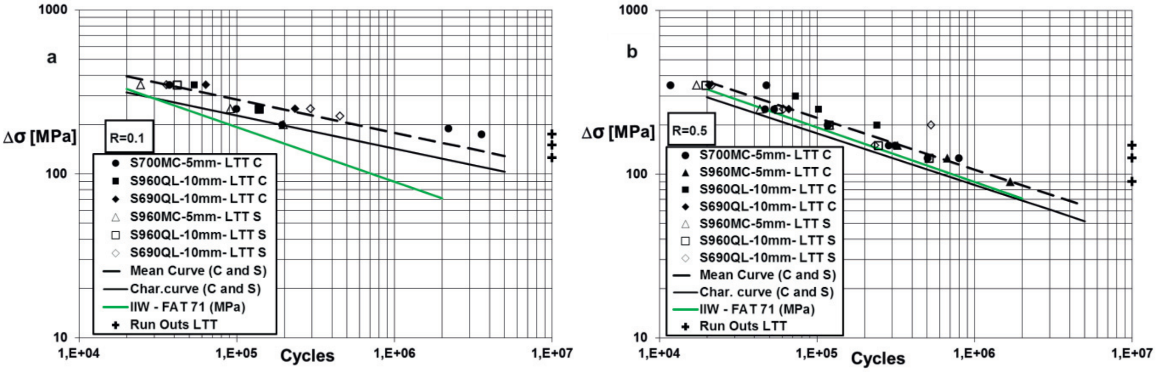

Fig. 9. Fatigue testing of specimen welded with LTT C and LTT S wires (a) tested under CAL at *R*=0.1; (b) tested under CAL at *R*=0.5.

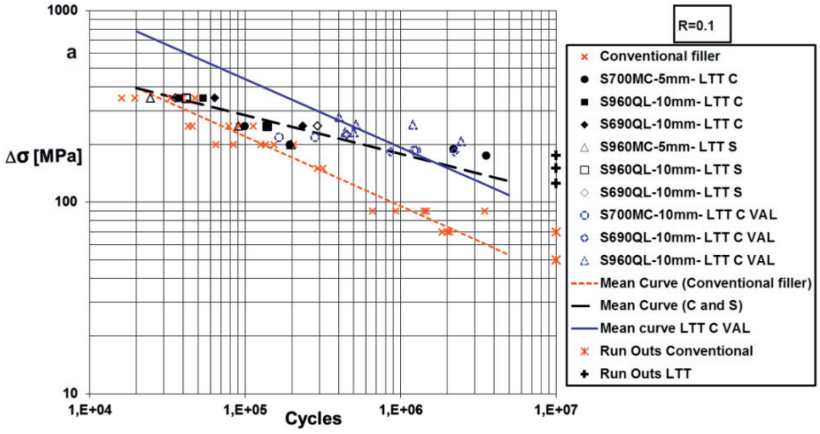

Fig. 10. Comparison of specimen tested under CAL at *R*=0.1 and VAL

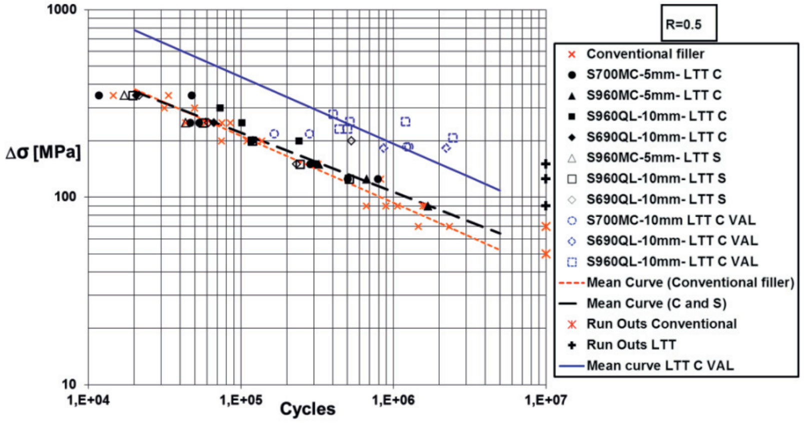

Fig. 11. Comparison of specimen tested under CAL at *R*=0.5 and VAL

Table 3.Estimation of equivalent stress range, testing specifications and results

Weld filler	Steel grade	Thickness (*mm*)	Max σ_R in spectrum (*MPa*)	Equivalent stress range σ_{eqv}(*MPa)*	Cycles at failure
LTT C	S700MC	10	910	219	165 214
			770	186	1 214 582
					1 256 536
			910	219	2 799 97
LTT C	S690QL	10	759	183	2 210 776
					861 972
LTT C	S960QL	10	1152	278	402 140
			1056	254	1 196 259
					514 582
			960	231	440 769
					497 769
			864	208	2 448 729

4. Discussion

The reduction in the final state of tensile welding residual stresses is observed for S700MC 5mm longitudinal stiffener joint welded with LTT C filler wire as shown in figure 4. The reduction is not significant when compared with other results [7-10] where compressive residual stresses are observed. Moreover, almost identical welding residual stress distribution is observed for S960MC 5mm specimen welded with LTT C and LTT S filler wires as shown in figure 5.The residual stress measurements are carried out on only two specimens therefore it is difficult to conclude that the both wires have the similar effects on the reduction and distribution of welding residual stress.

The main aim in this work is to study the influence of newly developed LTT filler wires on the fatigue strength of the longitudinal stiffener joint when tested under CAL (at different *R*-ratios) and VAL. The fatigue testing results are presented in the form of *logΔσ-logN* curves in figures 7-11. During the testing few specimen failed in the base plate near the clamping location, hence those results are not included here. All tested specimen were failed from the weld toe (at the end of stiffener).

In figures 7-8, the fatigue testing results under CAL (at R=0.1 and 0.5) for specimens welded with LTT C and LTT S wires are shown separately. And, the results are compared with the IIW recommended fatigue strength of such type of joint at 2 million cycles in as welded conditions.

At R=0.1 it can be seen that a fatigue strength improvement of 20% and 36% is achieved with LTT C and S joints respectively when compared with IIW recommend fatigue strength of 71MPa. However, no improvement in fatigue strength at 2 million cycles is observed for LTT welded joints tested at R=0.5. The most probable reason for this behavior could be the stress rearrangements at high mean stress levels. Also, the main purpose of welding with LTT material is to reduce the tensile welding residual stress, which it has done as seen in figure 4, but it has no contribution in improvement of the local weld toe geometry which can give very high stress concentrations due to smaller notch radii. Barsoum et al [10] has reported smaller weld toe notch radii and angle for the specimen welded with LTT filler wire when compared with the conventional one.

Since, not very significant difference in fatigue strengths of LTT C and LTT S welded joints is observed therefore in order to increase the sample size, the fatigue testing results under CAL (at R=0.1 and 0.5) are put together as shown in figure 9. An overall improvement of 42% in fatigue strength is achieved with LTT welded joints when tested at R=0.1. The slope of the curve obtained is 4.9, which is steeper than the IIW recommended slope of 3. The steep slope of 4.9 also shows that the improvement in the fatigue strength of LTT welded joints will be more significant at lower level of nominal stresses. At higher stress levels no improvement in the fatigue strength is observed. Similar results are also reported by [11]. No improvement in fatigue strength is observed for the LTT joints tested at R=0.5.

The fatigue testing is also carried out at variable amplitude loadings. Figure 10 shows the fatigue testing results under CAL (at R=0.1) for the specimens welded with LTT (filled marks) and conventional filler wires (cross marks) and the fatigue testing results under VAL for some LTT welded joints (broken unfilled marks).An improvement in the fatigue strength can be seen for joints welded with LTT filler wires when compared to the joints welded with conventional wire. This improvement can be accredited to the reduction of residual stresses due to LTT filler wires. Also, in figure 10 it can be seen that almost identical mean fatigue strength at 2 million cycles is observed for LTT joints when tested under VAL and CAL. If the mean stress effects are to be taken into account only then, the VAL testing must have higher mean fatigue strength because of zero mean stress but as reported by [10] the residual stresses can get relaxed in variable amplitude loadings. The figure 11 shows the fatigue testing results under CAL (at R=0.5) for the specimens welded with LTT and conventional filler wires and the variable amplitude fatigue testing results for LTT welded joints. Much higher mean fatigue strength at 2 million cycles is observed for LTT welded specimen tested at VAL as compared to LTT specimen tested at CAL. This difference in the mean fatigue strength can be attributed to mean stress effects. And also, due to high stress concentrations at weld toe notch radii at very higher stress levels.

5. Conclusions

In the present study two different LTT alloy compositions have been developed, with different Martensite Start (Ms) temperature. The main aim is to study the amount of tensile/compressive residual stresses produced by these wires and also their effect on the fatigue strength of the joint under constant amplitude loadings at R-ratio 0.1 and 0.5 and variable amplitude loadings. From the study following conclusions can be made

Reduction in the tensile residual stress near the weld toe area of the longitudinal stiffener joint is achieved when welded with LTT filler wire. Both of the newly developed LTT wires have shown same distribution of the residual stresses on S960MC 5mm thick longitudinal stiffener joint.

An increase in the fatigue strength is observed for LTT welded specimens when compared with the specimen welded with conventional filler wire. The increase in the fatigue strength is noticeable when specimens are tested at R=0.1. Also the improvement is more significant for low nominal stress levels. However, no improvement is observed when LTT welded specimen are tested at R=0.5.

The difference in the mean fatigue strength of LTT specimen tested under CAL at R=0.5 and VAL can be attributed to mean stress effects. And also, due to high stress concentrations at weld toe notch radii at very higher stress levels.

Further investigations are required regarding measurement of weld toe radii and residual stress relaxation and also more fatigue testing is required since these presented results are just an indication of the behavior of the joint under different loading conditions.

Acknowledgements

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