Spectrum fatigue of high strength steel joints welded with low temperature transformation consumables

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Abstract

In the present paper constant (CA) and variable amplitude (VA) fatigue testing have been carried out on out-of plane gusset fillet welded high strength steel joints. The joints were welded with conventional weld filler material and martensitic low transformation temperature weld filler, LTT, in order to study the influence of the residual stress on the fatigue strength. Residual stress measurements were carried out close to the weld toe using X-ray diffraction technique in order to study the relaxation due to VA fatigue. The residual stress showed different level of relaxation depending on the VA spectrum loading used. The LTT joints shows ~40% increase in mean fatigue strength compared to the conventional joints in CA. The LTT joints shows ~12% increase in mean fatigue strength compared to the conventional joints. The LTT joints shows 33% increase in mean fatigue strength in CA compared to VA testing. However, the improvement of the fatigue strength is less significant in variable amplitude testing mainly due to the relaxation of the compressive residual stresses.

Introduction

Welded structures contain residual stresses due to thermal shrinkage of the weld metal and HAZ in the welding cooling process. The residual stresses are static imposed on the cyclic stresses during fatigue loading. The fatigue resistance of the welded structure is affected by this stress ratio effect [1]. Residual stresses are often tensile at the weld toe region, in the magnitude of the base materials yield strength and reduce the fatigue strength of the welded structure. However, compressive residual stresses have beneficial effects on the fatigue strength since they keep the crack closed during the fatigue loading. An available technique for inducing compressive residual stresses in welds is by utilizing Low Transformation Temperature (LTT) weld filler material. The LTT weld filler exploit the transformation expansion due to austenite to martensite transformation at low temperature (approximately 200˚C down to ambient temperature) [2]. This is achieved by alloying elements e.g. high Cr and Ni content [3]. Figure 1 illustrates the difference between conventional and LTT weld filler material in residual stress and strain during cooling. For the conventional weld filler shrinkage is dominating and a small expansion occurs at 500˚C due to transformation from austenite to martensite, and tensile residual stresses are formed at ambient temperature. For the LTT weld filler expansion is dominated due to transformation at low temperature, 200˚C which continues down to ambient temperature. This low temperature expansion will introduce compressive residual stresses in the weld material and in the vicinity of the weld, i.e. at the weld toe were fatigue crack is likely to start. Many researchers [1-8] have reported the beneficial effects of using LTT weld filler particularly on the fatigue strength improvement.

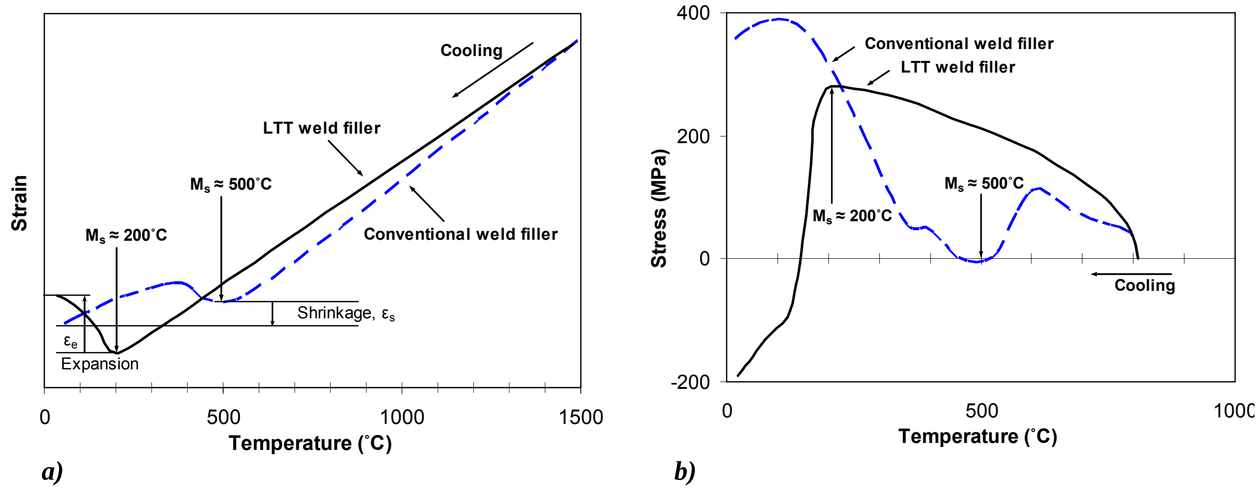


Figure 1. *Variation of strain and stress of weld metal during cooling process: a) strain, b) stress. After [8].*

However, the mainly fatigue strength improvement have been concerned with constant amplitude fatigue loading. Since the residual stress relaxation is smaller in constant amplitude (CA) loading, especially at higher cycles, the fatigue strength improvement is significant for joints welded with LTT consumables. In Eckerlid et al [3] CA fatigue testing was carried out on out-of plane gusset fillet welded joints. The achieved improvement of the mean fatigue strength was 25-90% at 2 million cycles for the LTT joints compared with joints welded with conventional weld filler. In Machida et al [6] CA fatigue testing was carried out on box welds failing from the weld toe. They compared joints welded with LTT versus conventional weld filler. The achieved improvement in fatigue strength was 12% at two million cycles.
In the present study, variable amplitude as well as constant amplitude loading is applied on out-of-plane gusset welded joints welded with LTT filler material. Joints with the same geometry welded with a conventional under-matching filler material are used as reference test series. Residual stresses at the weld toe are measured prior and after fatigue testing at different cycles in order to study the residual stress relaxation.

Weld filler materials

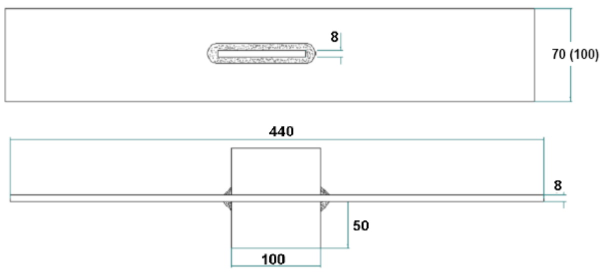
Two different weld filler materials were used in order to study the influence of the weld filler material properties on the fatigue strength. The weld filler OK Autrod 12.51 is a conventional (ferritic) weld filler material used in MAG/MIG welding for carbon steels. Weld filler OK Tubrod 15.55 is martensitic stainless Low Transformation Temperature (LTT) weld filler that is commonly used to weld stainless martensitic pipes. Table 1 shows the material composition of the two different weld filler materials used in this study [9-10].

Table 1. *Typical composition of the weld filler used in the welded specimens, (weight %).*

Weld filler	***C***	***Si***	***Mn***	***Cr***	***Ni***	***Mo***	***Cu***
OK Autrod 12.51 (Conventional)	0.1	0.7	1.1	-	-	-	-
OK Tubrod 15.55 (LTT)	0.01	0.4	1.8	12.5	6.7	2.5	0.5

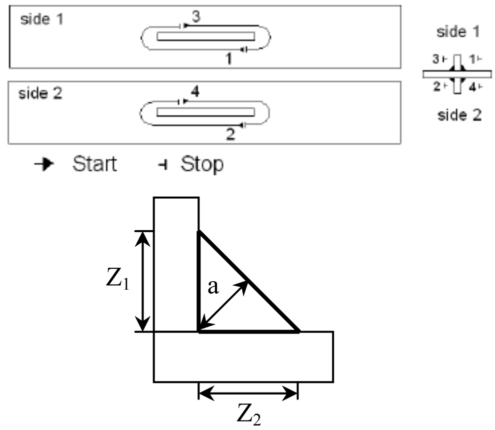
Welded specimens

The base material used to fabricate the welded joints was a cold forming high strength steel, Domex 700 MC, with minimum yield strength of 700 MPa and a tensile strength of minimum 750 MPa. The test specimens were out-of plane gusset fillet welded joints with longitudinal attachment welded to the main plate. Figure 2 illustrates the welded specimens, local weld geometry dimensions and the welding sequence. The specimens were manually MAG welded in position PB. In order to avoid influence of start and stop of weld sequences, these were located on each side of the attachment [9-10].



avarage/st. dev.	***a* (mm)**	***Z_1* (mm)**	***Z_2* (mm)**
OK Autrod 12.51 (Conventional)	4.5/0.9	6.4/1.2	11/1.2
OK Tubrod 15.55 (LTT)	4.7/0.8	6.7/1	12/1.3

a)



b)

Figure 2. *Welded specimens: a) Global and local weld geometry dimensions; b) welding sequences.*

Fatigue testing

Fatigue testing was carried out in both constant amplitude and variable amplitude on joints welded with LTT and conventional filler material, respectively. For the variable amplitude loading, a linear spectrum with high mean stress, $\sigma_{mean}=\sigma_{max}/2$, SP2 was mainly used. This spectrum has a positive and variable R-ratio and irregularity factor, I=1. Details about the fatigue testing and local weld geometry measurements are reported elsewhere Gustafsson et al [9-10]. The description of the variable amplitude linear spectrum *SP2* is outlined in Spennare et al [11] and Samuelsson [12]. Based on the results that are discussed in detail below, it was decided to perform additional fatigue testing on a limited number of specimens with a modified version of SP2. The modified version had an R-value equal to zero. This spectrum is here named SP2R0. The mean stress level was considerable lower for SP2R0 than for SP2. However, the maximum stress level and the distribution of stress ranges and number of cycles was the same for SP2 and SP2 R0. In addition, a third spectrum with rather low maximum stress level was used on a limited number of specimens. This spectrum is here denoted SP2PL (Peak limited).
Figure 3 shows the IIW [13] fatigue strength recommendation at 2 million cycles at 5% failure probability for gusset welded joints. The fatigue strength increases with decreasing fillet attachment length. For the out-of-plane gusset welded joints the IIW recommendation is FAT 71 MPa.

All the test specimens were failed due to fatigue cracking at the weld toe at the end of the stiffener plate. The fatigue test results for the constant amplitude testing with R=0 are presented in figure 4 in form of log (stress range) and log (cycles to failure). The LTT joints show a considerable higher fatigue resistance compared to the conventional joints. The fatigue test results for the constant and variable amplitude loading (SP2, variable R-ratio) are presented in figure 4-5. The σ_{eq} (equivalent) is calculated based on Palmgren-Miner damage rule summation and the load intensity capacity C ($C = N(\Delta\sigma_{eq})^m$); see Gustafsson [9] and Samuelsson [12] for detailed derivation of σ_{eq} and C.
The variable amplitude fatigue testing shows different trend compared with the constant amplitude loading, see figure 5. The gain in fatigue life using the LTT weld filler is discerned at higher cycles. Table 2 shows the mean fatigue strength at 2 million cycles for the CA and VA fatigue testing on LTT and conventional joints, respectively.

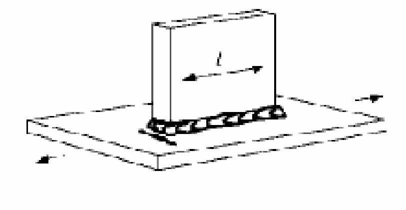
	Longitudinal fillet welded gusset at length **l**:	Fatigue Strength acc. to IIW [12]. FAT [MPa]
	l < 50 mm	80
	l < 150 mm	**71**
	l < 300 mm	63
	l > 300 mm	50

Figure 3. *Recommendation by IIW [12] on the fatigue strength for gusset welded joints, nominal stress.*

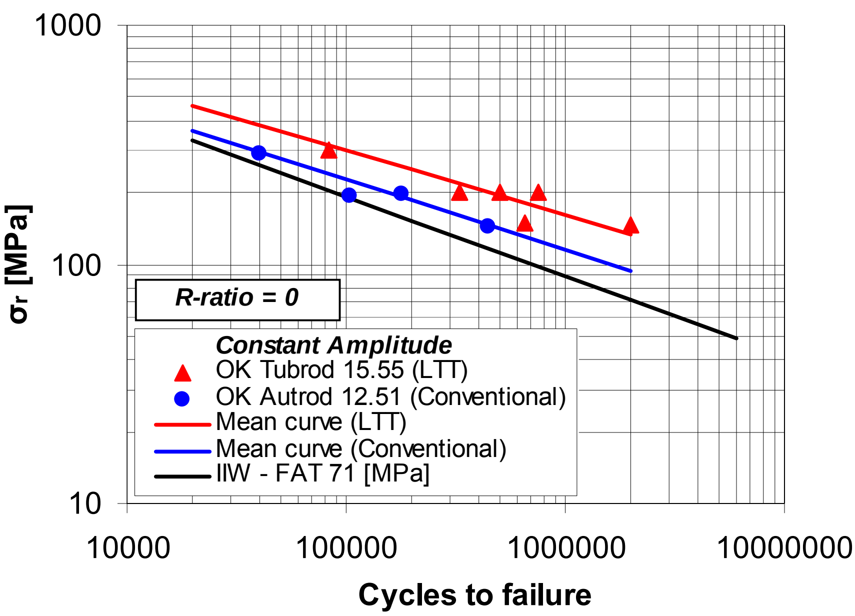


Figure 4. *Result from constant amplitude fatigue testing.*

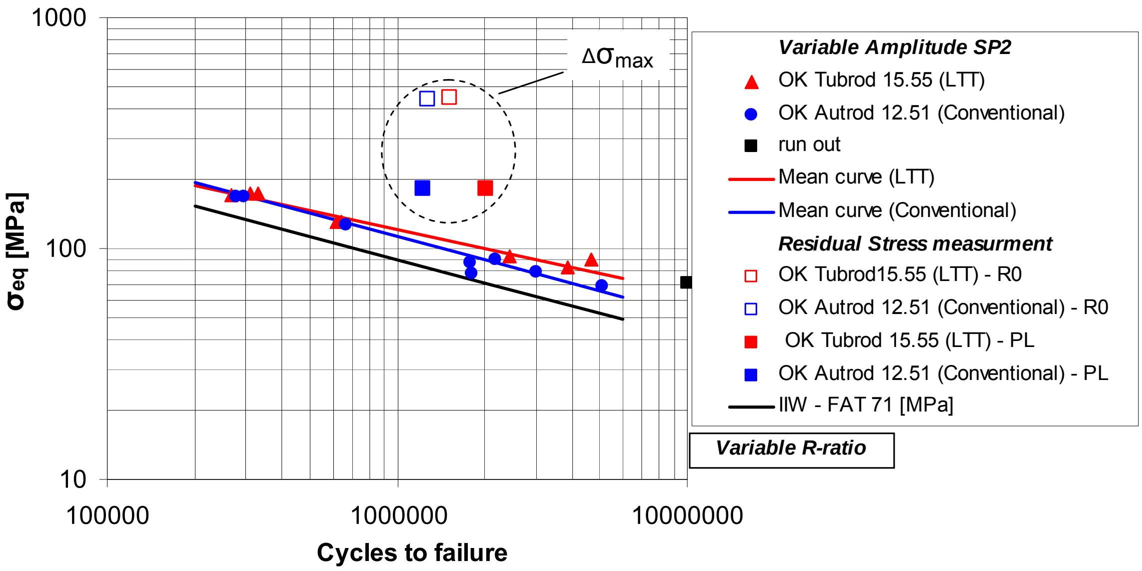


Figure 5. *Result from variable amplitude fatigue testing.*

Table 2. *Results from fatigue testing.*

	LTT joint		*Conventional joint*	
	[1]σ_{mean}[MPa]	m - slope	[1]σ_{mean} [MPa]	m - slope
Variable Amplitude SP2	100	3.7	89	3
Constant Amplitude R=0	133	3.7	94	3.4

[1]Mean fatigue strength at 2 million cycles with the natural slope.

Residual stresses

Residual stress measurements were carried out using X-ray diffraction technique. The objective of the residual stress measurements was to measure the residual stress in the longitudinal direction of the main plate in as-welded condition, after 50 0000 and after 600 000 numbers of cycles in order to study the residual stress relaxation due to variable amplitude loading. The measurements were carried out 1-2 mm out from the weld toe at all four weld toe locations on the specimen. Figure 6 illustrates the residual stress measurement positions for the different variable amplitude spectra. The residual stress measurements were carried out on two specimens from each weld filler material; two specimens welded with LTT OK Tubrod 15.55 and two specimens welded with conventional OK Autrod 12.51 weld filler, respectively. The specimens were fatigue tested with two different spectra for variable amplitude; SP2-PL (peak limited) and SP2-R0 (stress ratio, R=0), respectively. Table 3 shows the mean and max stress for the tested specimens, respectively.
Figure 7 shows the result from the residual stress measurements in the as-welded condition. The specimens welded with the conventional weld filler shows tensile residual stresses, approximately 100 to 350 MPa at vicinity of the weld toe (1-2 mm). The residual stress trends are in good agreement with residual stress measurements on similar test specimens welded with LTT weld filler materials found in the literature [3, 5, 6 and 14]. Table 4 summarizes

residual stress results found in the literature. Figure 8-9 shows the result from the measurements of the residual stresses after 50 000 and 600 000 cycles at the vicinity of the weld toe, respectively.

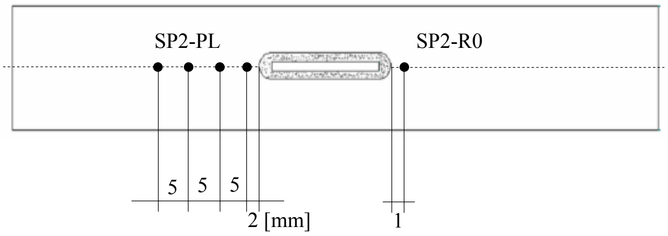


Figure 6. *Residual stress measurement positions for the two different spectrums studied; SP2-PL and SP2-R0, respectively.*

Table 3. *Variable amplitude fatigue testing of residual stress measured specimens.*

Specimen	Spectrum	σ_{max} (MPa)	σ_{mean} (MPa)	$\Delta\sigma_{eqv}$	N	N_{LTT}/N_{conv}
OK Tubrod 15.55 (LTT)	SP2-PL	181	$0.5*\sigma_{max}$	$0.49*\sigma_{max}$	2036000	1.6
OK Autrod 12.51 (Conv.)	SP2-PL	181	$0.5*\sigma_{max}$	$0.49*\sigma_{max}$	1236000	
OK Tubrod 15.55 (LTT)	SP2-R0	446	-	$0.24*\sigma_{max}$	1515000	1.2
OK Autrod 12.51 (Conv.)	SP2-R0	448	-	$0.24*\sigma_{max}$	1278000	

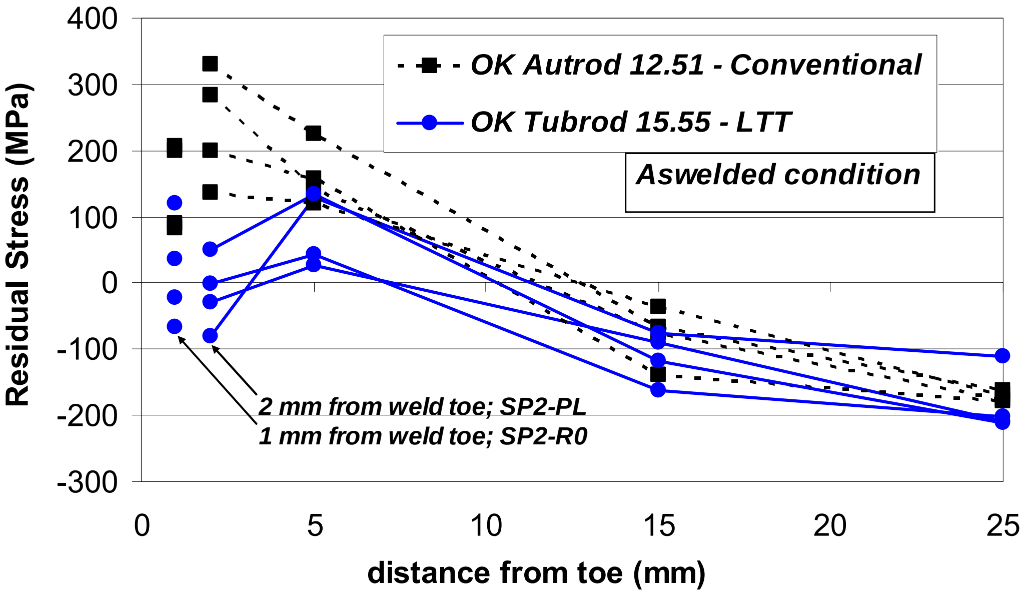


Figure 7. *Measured as welded residual stresses along the main plate for the four specimens fatigue tested in variable amplitude.*

Table 4. Comparison of longitudinal residual stress at the vicinity of the weld toe with results found in the literature.

Reference	Base material	Yield Strength [MPa]	Tensile Strength [MPa]	Weld fillers		Residual Stress [MPa]	
				Conventional	***LTT***	***Conventional***	***LTT***
3	Domex 700	709	778	OK 12.51	13Cr/LC35 B206	520 **	210** 300**
14	Domex 350 XP	370	470	PZ 6130	--	300**	--
6	SM490A	366	527	Type-S	Type-T Type-M	420*	80* 75*
5	HT780	821	859	KM80	10Cr/10Ni	400***	-100***

*) Measured longitudinal residual stress approximately **1 mm** from weld toe.
* *) Measured longitudinal residual stress approximately **2 mm** from weld toe.
** *) Measured longitudinal residual stress approximately **3 mm** from weld toe.

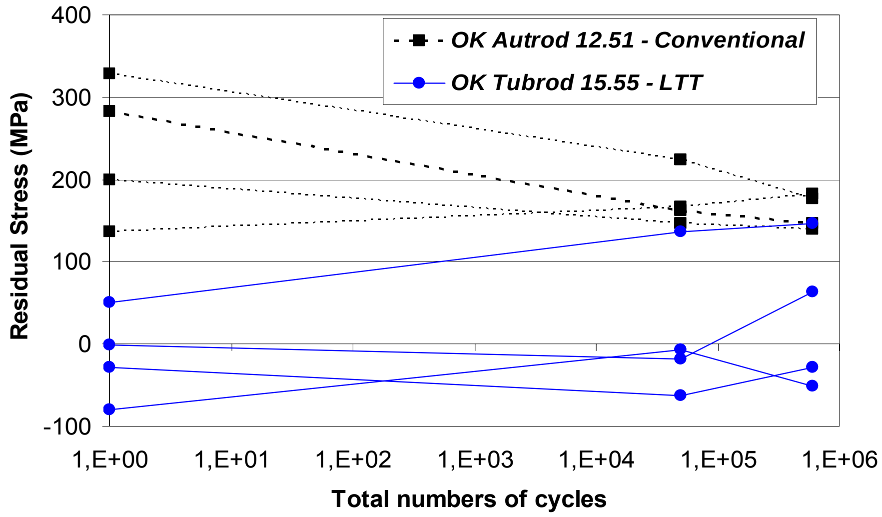


Figure 8. *Residual stress relaxation due to variable amplitude fatigue loading using SP2-PL spectrum. The measurements are 2 mm from the weld toe.*

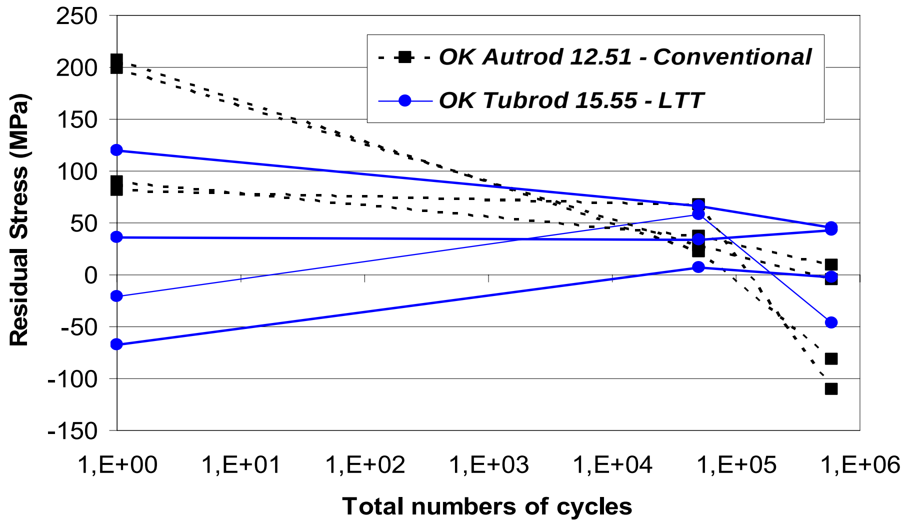


Figure 9. *Residual stress relaxation due to variable amplitude fatigue loading using SP2-R0 spectrum. The measurements are 1 mm from the weld toe.*

Discussion

The LTT joints show a considerable higher fatigue resistance compared to the conventional joints in constant amplitude fatigue testing. The LTT joints shows ~40% mean fatigue strength compared to the conventional joints. This is in close agreement with earlier results by Eckerlid et al [3] where 25-90% increase in mean fatigue strength was achieved.
The variable amplitude fatigue testing shows different trend compared with the constant amplitude loading. At higher stress ranges (σ_{eq}=130-170 MPa, σ_{max}=550-685 MPa) the LTT and conventional joints coincide. This is due to the relaxation of the compressive residual stresses in the LTT joints. At lower stress ranges (σ_{eq}=70-90 MPa, σ_{max}=300-365 MPa) the LTT joints shows a higher fatigue resistance compared to the conventional joints. This is due a smaller relaxation of the compressive residual stresses. The LTT joints shows ~12% increase in mean fatigue strength at $2 \cdot 10^6$ cycles compared to the conventional joints. The LTT joints show 33% higher fatigue strength at $2 \cdot 10^6$ cycles in constant amplitude compared to variable amplitude testing. However, the improvement of the fatigue strength is less significant in variable amplitude testing mainly due to the relaxation of the compressive residual stresses.
The specimens welded with LTT weld filler shows systematically lower residual stresses, approximately -100 to 100 MPa in magnitude for the as welded condition.
The residual stress relaxation for joints tested with SP2-Peak Limited is moderate. The measured residual stresses are more or less constant at the distinct number of cycles, especially for the LTT-joint where the stresses are mainly compressive. The conventional joint shows similar trends although the residual stresses are tensile. In the SP2-Peak Limited spectra, the peak amplitudes are cut off and the spectra resemble a constant amplitude loading. The welded joints tested with SP2-R0 shows a faster relaxation of the residual stresses just after 50 000 cycles. This illustrates the effect of the spectrum loading on the relaxation of the residual stresses. Peak loads may reduce the residual stresses, compressive and tensile, hence reducing the beneficial effect of using LTT weld filler material in welded structures that are exposed to spectrum loading.

Conclusions

1. Considerable less improvement in fatigue strength for the LTT joints tested with spectrum SP2 compared to improvement achieved in CA fatigue testing. Any improvement can be observed for SP2 only at low equivalent stress levels i.e. $\Delta\sigma_{eqv}$ <100 MPa.

2. The small increase in fatigue strength for the LTT joints in VA fatigue loading is mainly due to the relaxation of the compressive residual stresses.

3. Only small residual stress relaxation is observed when VA loading with SP2-PL spectrum is used. The relaxation is more severe when SP2-R0 is applied. This due to lower maximum stress levels in the case of SP2PL. This is also indicated in the fatigue life as the LTT specimen had considerable longer life than the conventional joint in the case of SP2PL. In the case of SP2R0 the fatigue life ratio between the LTT joint and conventional joint was 1.2 and in the case of SP2PL the life ratio was 1.6. However, it has to be emphasized that this is only an indication due to the limited number of specimen.

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References

1. Ohta A., Shiga C., Maeda Y., Suzuki N., Watanabe O., Kubo T., Matsuoka K., Nishijima S., *Fatigue strength improvement of box-welded joints using low transformation temperature welding material*, Welding International, 14 (10), pp. 801-85, 2000.

2. Ohta A., Matsuoka K., Nguyen N.T., Maeda Y. and Suzuki N., *Fatigue strength improvement of lap joints of thin steel plate using low-transformation-temperature welding wire*, Welding Journal, Vol. 82, No.4, pp. 78S-83S, 2003.

3. Eckerlid J., Nilsson T., Kalsson L., *Fatigue properties of longitudinal attachments welded by low transformation temperature welding filler*, Proc. Design and Analysis of Welded High Strength Steel Structures, EMAS, 2002.

4. Ohta A., Suzuki N., Maeda Y. and Maddox S.J., *Fatigue strength improvement of lap welded joints by low transformation temperature welding wire – superior improvement with strength of steel*, Welding in the World, Vol. 47, No.3/4, 2003.

5. Ohta A., Shiga C., Maeda Y., Suzuki N., Watanabe O., Kubo T., Katsuoka K., *Fatigue strength improvement of box-welded joints using low transformation temperature welding material. Triple fatigue strength by pos weld heat treatment*, Welding International, 16 (1), pp. 44-47, 2002.

6. Machida F., Fujita T., Yoshiie K., Kubo T., Morikage Y., *Improvement of fatigue strength of box weld on non-quenched steel by using low transformation temperature welding material*, International Institute of Welding, IIW-Document XIII-1771-99, 1999.

7. Karlsson L., Bruins W., Gillenius C., Rigdal S., Goldschmitz M., *Matching composition supermartensitic stainless steel welding consumables*, Belgian Welding Institute, Supermartensitic Stainless Steels 99, Conference proceeding, pp. 172-179, Belgium, May 27-28, 1999.

8. Bhadeshia H.K.D.H, *Development in martensitic and bainitic steels: role of the shape deformation*, Material Science and Engineering A 378, pp. 34-39, 2004.

9. Gustafsson M., *Fatigue strength of HSS joints welded with martensitic filler material*, Integrated Design and Manufacturing of Welded Structures, Proceedings International Symposium, pp. 373-379, March 13-14 Eskilstuna Report 18, Lappeenranta University of Technology, 2007.

10. Gustafsson M., Barsoum Z., S*pectrum fatigue testing and stress relaxation of high strength steel joints welded with low transformation temperature weld filler*, to be published.

11. Spennare H. and Samuelsson J., *Spectrum fatigue testing of a longitudinal non-load carrying fillet weld – a round robin exercise*, Jernkontoret, Stockholm, report 7317/89, 1990.

12. Samulesson J., *Fatigue design of vehicle components: methodology and application*, Department of Aeronautical Structures and Materials, Doctoral Thesis, Royal Institute of Technology, Sweden, Report No. 88-23, 1988.

13. Hobbacher A., *Recommendation for fatigue design of welded joints and components*, International Institute of Welding, Document XIII-1965-03/XV-1127-03, 2003.

14. Bogren J. and Lopes Martinez L., *Spectrum fatigue testing and residual stress measurements on non-load carrying fillet welded test specimens*, Fatigue under Spectrum Loading and Corrosive Environments, Warley, UK, EMAS, 1993.