Capability of martensitic low transformation temperature welding consumables for increasing the fatigue strength of high strength steel joints

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The use of low transformation temperature (LTT) filler materials represents a smart approach for increasing the fatigue strength of welded high strength steel structures apart from the usual procedures of post weld treatment. The main mechanism is based on the effect of the low start temperature of martensite formation on the stress already present during welding. Thus, compressive residual stress formed due to constrained volume expansion in connection with phase transformation become highly effective. Furthermore, the weld metal has a high hardness that can delay the formation of fatigue cracks but also leads to low toughness. Fundamental investigations on the weldability of an LTT filler material are presented in this work, including the characterization of the weld microstructure, its hardness, phase transformation temperature and mechanical properties. Special attention was applied to avoid imperfections in order to ensure a high weld quality for subsequent fatigue testing. Fatigue tests were conducted on the welded joints of the base materials S355J2 and S960QL using conventional filler materials as a comparison to the LTT filler. Butt joints were used with a variation in the weld type (DY-weld and V-weld). In addition, a component-like specimen (longitudinal stiffener) was investigated where the LTT filler material was applied as an additional layer. The joints were characterized with respect to residual stress, its stability during cyclic loading and microstructure. The results show that the application of LTT consumables leads to a significant increase in fatigue strength when basic design guidelines are followed. This enables a benefit from the lightweight design potential of high-strength steel grades.

Article Information

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High strength fine-grained structural steel aisre increasingly being used in industrial applications such as plants, buildings and cranes, primarily for reasons of lightweight design. By applying steel with yield strength ≥ 690 MPa in modern constructions, considerable weight reductions can be achieved due to reduced wall thickness. However, the application of high strength fine grained structural steel is limited by the service life of the welded joints under cyclic loading. Thus, for untreated GMAW butt welds of the base materials S 355 J2G3, S 690 Q and S 890 Q, comparable fatigue strength only occurs below the fatigue strength of the base material S 355 J2G3 [1-2], depending on the loading type. This means that the strength advantage does not apply or causes the welds to be transferred into less stressed areas of the component design [3]. Improvements in fatigue strength are possible by means of thermal and mechanical post-treatment [4]. In addition to the established surface treatment methods, a significant improvement in fatigue strength can be achieved by taking advantage of compressive residual stress that is already generated during welding.

Novel LTT (low transformation temperature) welding filler materials offer the promising possibility of achieving significant improvements in fatigue strength without additional post weld treatment [5-6]. The effect of these special consumables is based on the formation of compressive (residual) stress in the weld and or adjacent areas already during welding due to martensitic phase transformation. Particularly, compressive residual stress can be generated in the entire weld metal. This means that the weld root (unwelded gap), which is often critical, especially in fillet welds, is also covered. Classical post-treatment methods such as hammering or remelting the weld interface does not reach this area, making these methods often ineffective as the initial crack formation is then shifted into the root with hardly any change in the load-bearing capacity.

LTT welding consumables are still the subject of research. There are numerous studies on different aspects from several research groups, e. g. [7-24]. While the first investigations on LTT were mainly focused on fatigue strength, the authors of more recent studies tend to investigate the microstructure and mechanical properties of LTT welded joints. Even though previous results show that the LTT concept is in principle effective when based on proven compressive residual stress, this still remains to be confirmed by practical examples in order to provide appropriate welding recommendations. Furthermore, the behavior of beneficial compressive residual stress under service conditions must be understood in order to utilize this effect in fatigue design. In addition to residual stress stability and relaxation during loading, the entire residual stress field in LTT welds must be investigated since compressive residual stress due to phase transformation always cause equilibrating tensile residual stress in a joint. These tensile residual stress fields may appear in deeper layers or at very different locations on a welded structure, depending on the level of restraint, the welding procedures and the type of joint.

The aim of the investigations presented here was to clarify the suitability of LTT filler materials to influence the fatigue strength of both conventional steel joints (overhaul and repair) and high strength steel joints (weight, emission and cost savings in new constructions). The question had to be answered to what extent compressive residual stress with respect to the martensite formation of LTT filler materials can be used to replace cost-intensive and time-consuming post-treatments or to improve the fatigue strength of critical types of welded joints.

The original approach of using a filler metal specifically to generate compressive residual stress was introduced by Ohta et al. [25]. This Japanese research group presented the first experimental findings on the use of alloys with specially lowered M_s temperatures for residual stress control, primarily with the intention of increasing fatigue strength. A welding filler material based on an iron-chromium-nickel alloy as a solid wire was developed. Due to its chemical composition, this material shows a martensitic phase transformation at M_s = 180 °C. In addition to other authors adopting this approach, there are also publications with alternative chemical compositions. In [26] the element nickel was substituted by manganese. An attempt using nickel alone was also pursued [27].

Despite a large number of publications and results, LTT filler materials have not been commercially available yet. This is mainly due to the still lacking knowledge about residual stress distribution in practical applications. The state of the art does not permit any prediction on the level and distribution of residual stress when using LTT consumables under varying boundary conditions. As a result, it has not yet been possible to draw any conclusions about the influence on the fatigue strength.

High alloyed LTT fillers generally bear the risk of cracking due to their chemical composition and hard microstructure. Especially austenite-stabilizing elements (e. g. nickel), which are necessary to lower the M_s temperature, cause an austenitic solidification combined with a characteristic micro-segregation behavior. Unfortunately, this also promotes the formation of solidification cracks. In addition, pure martensitic microstructures have comparatively low ductility and poor impact toughness. The alloying approaches presented so far focused primarily on adjusting the transformation temperature and initially neglected the accompanying properties.

In most cases, LTT consumables were manufactured as coated stick electrodes or metal cored wires. These forms of the filler materials allow a comparatively simple adjustment of the chemical composition of the weld metal or allow specific improvements through selective alloying.

Experimental findings on increasing fatigue strength through the use of LTT filler metals can be found,for example, in [25], [28-31]. E. g.: Ohta et al. [28]. They achieved fatigue strength improvements (R = 0) of between 40 % and 60 % in overlap steel joints with a yield strength of 540 MPa and 780 MPa. Using the sectioning method, compressive residual stress could be detected in the weld metal and the HAZ.

That the increased fatigue strength is a consequence of compressive residual stress generated can be reasoned from the fact that the improvements were particularly evident in the range of high cycle fatigue and were smaller or non-existent at lower cycle fatigue. This behavior is known for low-strength steel even after mechanical surface treatment. The reason for this is that at high load amplitudes compressive stress can be reduced by plastification after only a few load cycles, while at lower fatigue loads stable residual stress is present. For this reason, residual stress has a greater effect on higher strength steel than the hardening associated with plastification.

Investigations dedicated to the repair welding of high strength steel structures using LTT welding consumables also indicate their effectiveness. For example, Ohta et al. [32] demonstrated on longitudinally welded plates of the base material SM570Q that repair welding with LTT filler materials is possible and can lead to an improvement on the fatigue strength of up to 40 %-50 %.

The fatigue strength improvement observed in laboratory tests can only be transferred to actual welded structures to a limited extent. The transferability is only given if a high degree of similarity between the samples is achieved, combined with realistic heat conduction and restraint conditions as well as multi-layer welding. Already in [33] it could be shown during multi-layer welding of a butt joint using LTT consumables that the restraint had a significant influence on the resulting residual stress in the weld as well as in the HAZ. The formation of martensite in each weld bead is associated with stress reduction, which depends on the amount of volume being transformed. While in longitudinal direction (welding direction) of the weld it shows only low tensile residual stress, high tensile transverse residual stress at the surface is essentially determined by the amount of restraint. On the other hand, pronounced compressive residual stress is to be expected in the bulk of the LTT weld metal [27], [34-38]. The results show that the design and process-specific boundary conditions (heat conduction) must be considered in the evaluation and that generally “high” compressive stress in the weld and in the HAZ must not be assumed.

The first studies on LTT fillers were primarily concerned with attempts to increase the fatigue strength of specific welded specimens due to compressive residual stress. This was successfully achieved using high alloyed iron-chromium-nickel fillers. Nonetheless, whether the compressive stress of a certain level produced due to transformation behavior is responsible for fatigue improvements remains open. Although the publications offer comprehensible explanations, evidence in the form of spatially resolved residual stress measurements, especially in the weld metal, are still required.

The fatigue strength of a welded joint essentially depends on the resistance to the formation and propagation of fatigue cracks at areas with high stress concentrations. The level and distribution of the locally stable residual stress is of particular importance here, since only these can have an effect relevant to strength. Our own investigations have shown that the residual stress generated during welding is in principle stable under quasi-static loading. Investigations were carried out on transverse tensile specimens of two-layer welded joints on high strength fine-grained structural steel S690Q using various LTT filler materials [37]. The results are consistent with investigations on residual stress relaxation on welded longitudinal stiffeners [39]. In contrast to conventional surface treatments, the zone affected by compressive residual stress can extend over large areas of the weld metal when metallurgically induced. However, detailed investigations on the distribution of the resulting residual stress, their relationship to the temperature-dependent microstructure and the resulting stress stability under cyclic loading are still to be carried out.

Therefore, no reliable predictions about expected service life enhancements of different welded joints using LTT filler materials are available so far. In addition, there is no knowledge about a combination of LTT welding consumables with conventional high-strength welding consumables, which is promising from an economic point of view. This applies above all to the local application of such filler metals in areas critical to cracking, such as the weld root, or as an additionally applied layer adjacent to fatigue crack-relevant areas between the top layer and the HAZ.

Experimental approach

The tests described below were carried out on welded joints of structural steel S355J2 (1.0577) and high-strength fine-grained structural steel S960QL (1.8933), each with a plate thickness of 8 mm. The Fe-Cr-Ni-based LTT filler material was selected based on experience gained in previous investigations [5], [16]. It was available as metal cored filler wire with a diameter of ∅ 1.2 mm. The filler material G Mn4Ni2 CrMo (ISO 16834 [40], ∅ 1.2 mm) served as a reference. This commercially available solid wire is used as standard for joining the base material S960QL. Commercial filler material G 4Si1 (ISO 14341 [41] ∅ 1.2 mm) was used with the base material S355J2. Metal active gas (MAG) welding was applied in all cases. Table 1 and Table 2 show the chemical compositions and the most important mechanical properties of the filler and base materials. The transformation temperatures of the LTT filler were determined by applying a quenching dilatometer on the pure weld metal. The austenization is situated between 730 °C and 830 °C (± 5 °C). The M_s temperature is 239 °C (± 7 °C). The LTT weld metal was classified as “hot crack resistant” by means of the standardized MVT hot crack test according to ISO 17641-3 [42].

The following joint types were selected for the fatigue strength tests: a single-V butt joint as well as a DY butt joint (with root gap) due to the fatigue critical weld root, which cannot be treated by means of mechanical and thermal post-weld treatment methods such as grinding, high frequency mechanical impact treatment (HFMI), shot peening or tungsten inert gas (TIG)-dressing. Hence, a possible increase in weld root fatigue strength by use of the LTT filler material could be investigated.

In a T-joint (longitudinal stiffener) with circumferential fillet weld, LTT filler material was deposited on both sides in the area of the end face of the web plate as an additional layer. The longitudinal stiffener was chosen because this specimen type shows behavior similar to that of larger welded components in terms of welding residual stress. The longitudinal fillet welds cause shrinkage at the center of the plate which is self-restrained by the outer plate areas resulting in high tensile residual stress in the fillet welds. The fusion weld made from conventional filler metals fulfils toughness requirements at low temperatures while the LTT filler metal is used at fatigue critical lo-

	C	Mn	Cr	Ni	Mo	Si
S355J2	0.17	1.42	0.11	0.03	0.006	0.38
S960QL	0.17	0.87	0.49	0.94	0.52	0.3
G 4Si1	0.07	1.33	0.03	0.02	0.01	0.82
G Mn4Ni2 CrMo	0.07	9.45	10.34	0.04	0.05	0.38
LTT	0.04	0.75	12	4.7	0.03	0.41
	Al	**Cu**	**V**	**Nb**	**Ti**	**Fe**
S355J2	0.029	0.03	0.006	0.001	0.002	balance
S960QL	0.07	0.02	0.05	0.01	< 0.01	balance
G 4Si1	–	–	–	–	–	balance
G Mn4Ni2 CrMo	–	–	–	–	–	balance
LTT	–	–	–	–	–	balance

Table 1: Chemical composition of base and filler materials in wt %

	$R_{eH}/R_{p0.2}$ in MPa	R_m in MPa	A_{gt} in %	A in %
S355J2	422	562	n/a	29.6
S960QL	1017	1046	6.5	17.7
G 4Si1	530	612	n/a	26
G Mn4Ni2 CrMo	900	1253	4.9	14.2
LTT	944	1121	3.4	11.3

Table 2: Mechanical properties of base and filler materials (ambient temperature)

cations, e. g. the weld toe at the end of the stiffener. The specimen geometry and dimensions chosen for the fatigue tests are shown in Figure 1. The most important welding process parameters are listed in Table 3. The picture of the longitudinal stiffener demonstrates the possible use of LTT-filler metals in combination with conventional filler metals in larger constructions.

The welded specimens were analysed with respect to near surface residual stress by means of X-ray diffraction. The residual stress was calculated from X-ray diffraction patterns applying the $\sin^2\Psi$-method [43]. Therefore, {211}-diffraction lines of martensite and ferrite were obtained by Cr-Kα-radiation. The diffraction patterns were determined at 11 Ψ-angles (0°,13°, 18°, 24°, 27°,30° 33°, 36°, 39°, 42° und 45°) in a 2Θ range of 150°-162°. The elastic parameters were chosen to ½ S_2 = 6.08 × 10^{-6} mm²/N (E = 206,000 N/mm², ν = 0.28).

Residual stress was determined initially in as-welded condition as well as after quasi-static and fatigue loading. All specimen surfaces were prepared before welding by means of sandblasting to remove mill scale and oxides. In consequence, compressive residual stress was induced in the surface layer of the non-welded samples. The welding itself caused recrystallization near the weld (at the locations of fatigue cracks) and released the compressive residual stress accordingly. Hence, the cleaning process did not affect the fatigue performance of the welded specimens.

Fatigue testing was conducted in a servo-hydraulic test rig (Walter & Bai 250 kN) via axial sinusoidal loading. The stress ratio applied was R = $\sigma_{min}/\sigma_{max}$ = 0.1. All tests were either stopped at specimen rupture or when reaching 5 million load cycles without failure (run-outs). All specimens tested were then analyzed regarding the location of fatigue crack initiation. S-N curves were calculated by regression analysis without consideration of run-outs.

	V-butt joint	DY-butt joint	Additional layer T-joint
Voltage in V	28	28	28
Current in A	270	262	330
Welding speed in mm × min^{-1}	421	803	370-600
Number of runs	2	2	2
Position	PA	PA	PB (70°)
Torch angle	15°	15°	0°
Root face in mm	0	3	–
Groove angle	50°	45°	–
t8/5-time in s	12	5	8
Preheating/interpass temperature in °C	30		

Table 3: Welding parameters used for LTT filler material

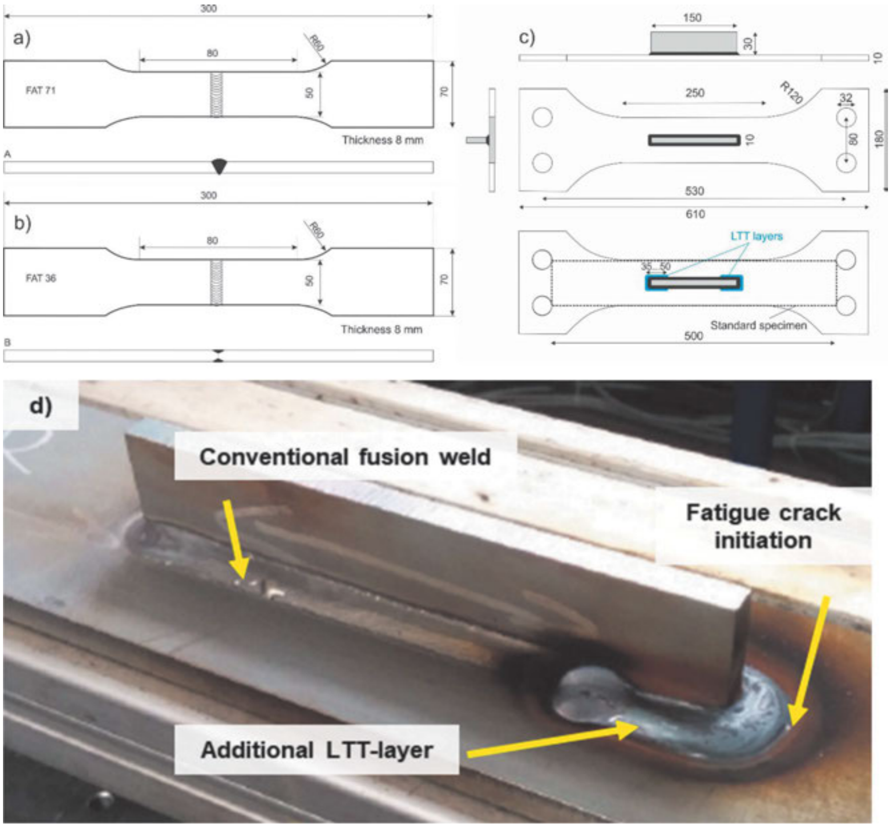

Figure 1: Specimens for fatigue tests: a) single-V butt joint, b) DY butt joint, c) T-joint (longitudinal stiffener), d) specimen overview, all dimensions in mm

Results and discussion

Weldability and characteristics of the LTT filler material. As the LTT filler was a non-commercial batch of material, a voltage current characteristic had to be established first. This was achieved based on manual fillet welds depending on the shielding gas and the operating point of the characteristic curve. From a wire feed speed of 8 m × min^{-1}, a spray arc was achieved. Process stability, weld bead shape as well as weld penetration were examined based on semi-automated bead-on-plate welds. Applying oxidizing shielding gases M20 and M21 [44], stable process control could be guaranteed in both GMAW and GMAW-pulse processes. By adjusting the pulse parameters and setting the current pulse in steps, droplet separation and process stability were optimized for the investigated shielding gases. The GMAW-pulse process was associated with reduced weld spatter. The chemical composition of the weld metal determined by spark emission spectroscopy showed no significant dependencies on the selected shielding gas (see Figure 2). The X-ray radiographic examination proved that no cracks or pores were found in the LTT welds (evaluation group B – ISO 5817) even with increasing wire feed speed.

The impact absorbed energy of the LTT weld metal is also only slightly dependent on the shielding gas used (see Figure 3). The values are just over 20 J, almost independent of the test temperature. One exception is the use of the shielding gas M12 [44]. Significantly higher toughness of up to 35 J can be found here, which, in this case, is attributable to the lower oxygen content in the weld metal. Nevertheless, the values of the weld metal of up to 40 J at -40 °C produced using the conventional filler material G Mn4Ni2 CrMo cannot be achieved by using this LTT filler material.

The LTT weld metal is martensitic without a detectable content of retained austenite. The microstructure is homogeneous within the two-layer V- and DY-joints. Figure 4 shows that the hardness in the weld metal varies just slightly. Due to the high strength, the average hardness is about 440 HV 0.1 (see Table 2). In the case of the double-sided DY joint, a slight annealing effect can be observed in the root area of the first layer.

Wavelength dispersive X-ray spectroscopy (WDX) was used to determine the distribution of the main alloying elements Cr, Ni, Mn, Mo and C along the paths shown in the microsection in Figure 5. According to Steven and Haynes [45], these values can be used to estimate the expected M_s temperature. This calculation rule has proved especially suited for LTT fillers based on Fe-Cr-Ni [45]. Figure 5 shows the M_s temperature for the weld metal calculated based on local element distribution. From this, considering deviation due to local segregation, nearly constant transformation temperatures are to be expected on average in both joints.

Accordingly, in the root areas, M_s temperatures of around 250 °C are also to be expected. Nevertheless, higher M_s temperatures than the nominal value of 239 °C are present. This is due to a loss of elements by burn-off and/or segregation. The transition into the adjacent heat affected zone (HAZ) is characterized by a sudden change of the M_s due to the element distribution. This means that in the entire weld metal, suitably low M_s temperatures are to be expected. Thus, the desired effect of the phase transformation on the residual stress can be achieved. In the HAZ, the calculation according to Steven and Haynes [45] at approx. 420 °C also reflects well the M_s temperature to be anticipated in the base metal.

Residual stress and residual stress relaxation. The near surface residual stress in the welded specimens was characterized by X-ray diffraction using the $\sin^2\psi$ method [43]. Examples of residual stress profiles perpendicular to the welding direction (transverse residual stress) along a line at the center of the fatigue test specimens made from S960QL are given in Figure 6. In particular, the diagrams show results from the weld root notch of a V-groove butt weld with LTT-filler metal (a). Furthermore, results from DY-groove butt welds with conventional (b) and LTT-filler metal (c) are presented.

At the locations of fatigue cracking (weld toe), residual stress values between -50 MPa and -150 MPa are present. The butt welds showed relatively low surface residual stresses in case of conventional as well as LTT-filler independent of the base material. The reason is the low shrinkage restraint of these joints. Note, that the compressive residual stresses of up to 300 MPa in the base metal resulted from the sandblasting process before welding.

By contrast, the residual stress in the longitudinal stiffeners varies between specimens with conventional and LTT-filler metals. Figure 7 shows residual stress in the loading direction of these samples along a line from the fatigue critical weld toe into

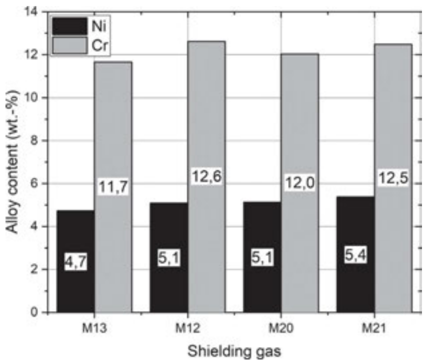

Figure 2: Content of main alloying elements Ni and Cr in pure LTT weld metal as a function of the shielding gas, designations after [44]

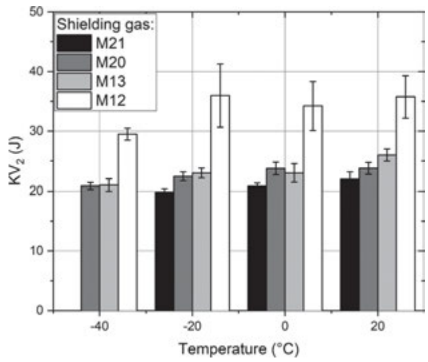

Figure 3: Impact absorbed energy as a function of the shielding gas [44] for pure LTT weld metal

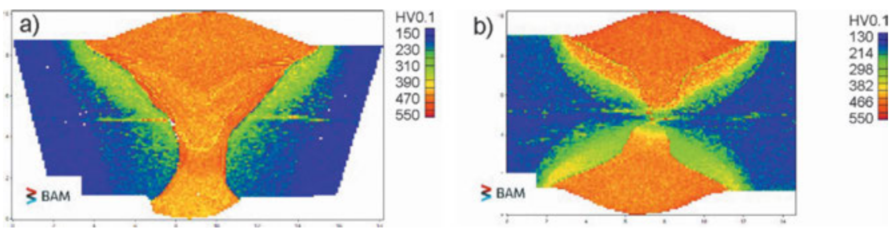

Figure 4: Hardness mappings of LTT welds, base material S355J2, V-joint a) and DY-joint b)

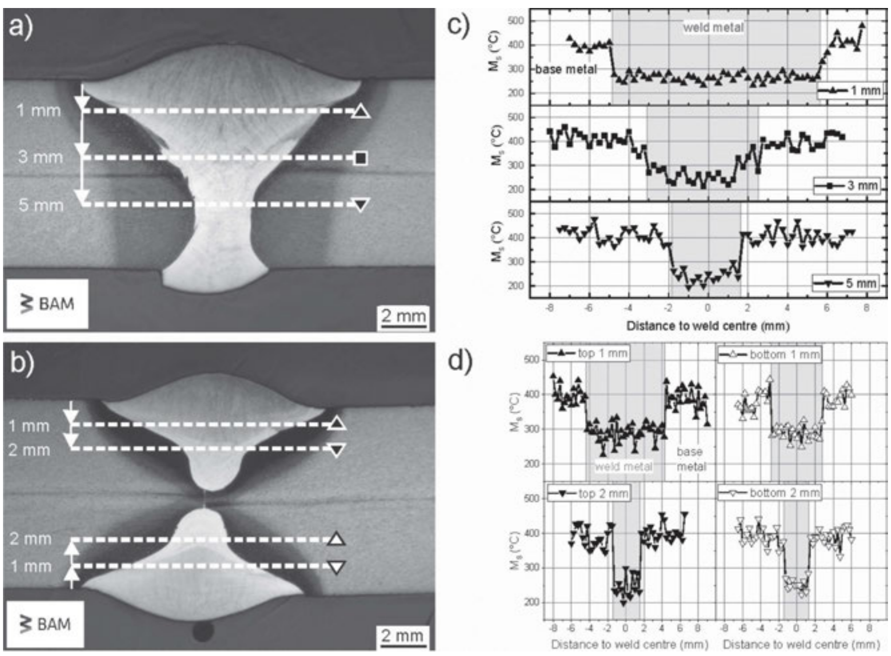

Figure 5: Macro-sections and measuring paths of WDX-element analysis, V-joint a) and DY-joint b) and M_s calculated by element distribution along measuring paths following [45], V-joint c) and DY-joint c)

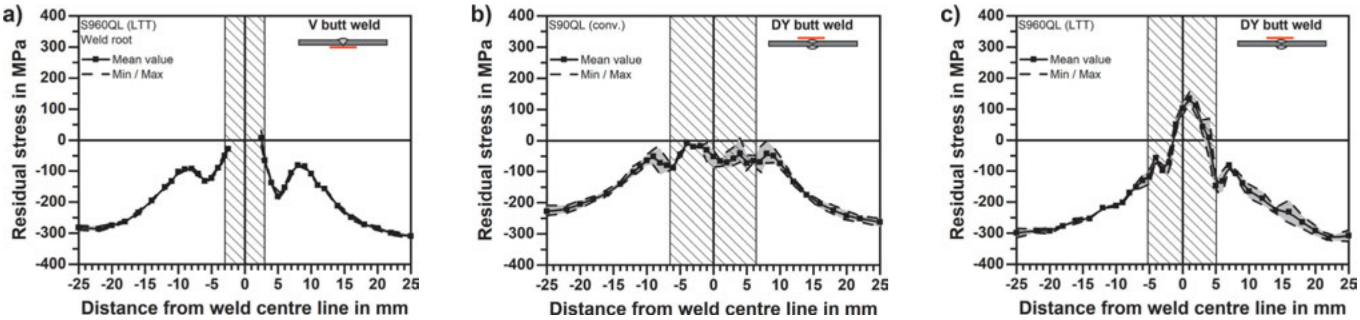

Figure 6: Transverse residual stress (in fatigue loading direction) at the surface of butt-welded S960QL, a) S960QL butt weld with V-groove and LTT-filler metal, b) S960QL butt weld with DY-groove and conventional filler metal, c) S960QL butt weld with DY-groove and LTT-filler metal

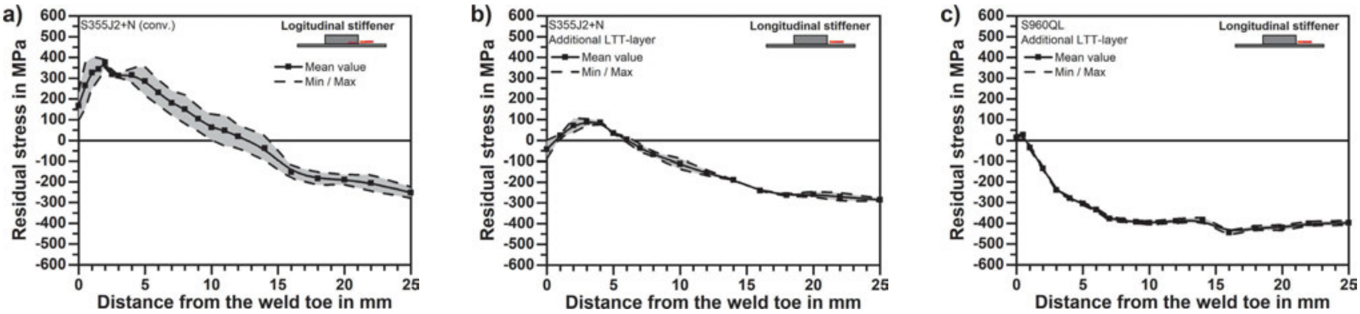

Figure 7: Residual stress in fatigue loading direction at the surface of longitudinal stiffeners, a) S355J2 longitudinal stiffener with conventional filler metal, b) S355J2 longitudinal stiffener with additional LTT- filler metal, c) S960QL longitudinal stiffener with additional LTT- filler metal

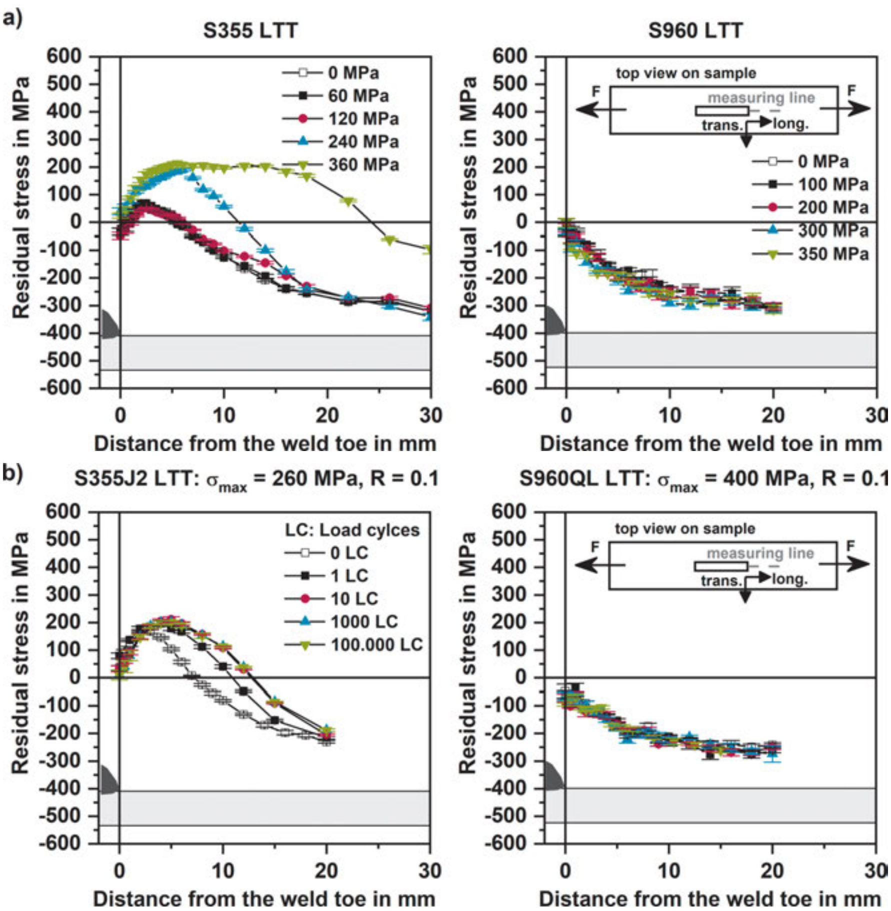

Figure 8: Residual stress relaxation of LTT-welded longitudinal stiffeners made from S355J2 and S960QL, residual stress measured in fatigue loading direction (longitudinal) at the surface, a) quasi-static loading, b) cyclic loading

the base metal. The self-restraining effect of the base plate yields comparably high tensile residual stress near the fillet welds. Although not shown here, it is known that this tensile residual stress is even higher below the welds in the base plate [46]. While the conventionally welded sample contains residual stress in the magnitude of approximately 150 MPa at the weld toe, the LTT-welded samples show significantly lowered residual stress close to zero.

The stability of the welding residual stress was investigated for quasi-static and cyclic loading (see Figure 8). Longitudinal stiffeners made from S355J2 and S960QL, both with additional LTT-weld beads, were tested. The residual stress field in the high strength steel S960QL is stable until 350 MPa tension load, while residual stress relaxation and re-distribution occurred in S355J2 already at 240 MPa.

Furthermore, cyclic tests were conducted in analogy to fatigue testing at a stress ratio of R = 0.1. The maximum stress applied in this test was 260 MPa in the case of S355J2 and 400 MPa in the case of S960QL. The residual stress field in S960QL remained stable until 100,000 load cycles. The sample made from steel S355J2 showed residual stress relaxation already at the first load cycle. The magnitude of residual stress relaxation as well as the resulting residual stress profile were comparable to the results of the quasi-static tests. However, additional residual stress relaxation was observed at increasing numbers of load cycles although a further change in the residual stress profile was of a lower order.

Fatigue strength. Figure 9 shows the fatigue test results of butt welds made from S960QL, in particular V-groove butt welds with LTT-filler metal and DY-groove butt welds with both conventional and LTT-filler metal. Fatigue design curves (FAT) from IIW are shown in addition for general reference. However, the probability of the survival of the experimental data is 50 %, and the results are not directly comparable to the design of the S-N curves, which are valid for varying R-ratios and the probability of survival. The design FAT-classes of butt welds with V-groove and of DY-butt welds are FAT 71 and FAT 36 respectively. These design S-N curves are valid for fatigue cracking at the weld root. For double sided butt welds without a root gap (DV-groove) and failure from the weld toe, FAT 90 can be applied. Moreover, a direct comparison of the experimental data is recommended.

The experimental fatigue data varies in terms of the achievable allowable stress and the inclination exponent k. LTT-welded specimens with V-groove showed the highest allowable stress, followed by the conventionally welded DY-groove and the LTT-welded DY-groove series. The DY-groove series failed at various locations. While LTT-welded specimens failed at the weld root gap as expected, the conventional samples failed at the weld toe. Accordingly, the fatigue strength of the conventional specimens is higher, compared to that of the LTT-specimens. As an explanation for this, the authors assume that the weld penetration of the conventional samples led to smaller root gaps shifting the fatigue crack initiation to the weld toe. Furthermore, the weld toe angle of LTT-specimens is slightly smoother resulting in lower stress concentration at the weld toe and thus promoting weld root failure. Interestingly, the fatigue strength of V-groove specimens with LTT-filler metal well overcomes the fatigue strength of the whole DY-groove series. This is particularly of interest since the V-groove samples all failed at the weld root which is normally interpreted as having relatively low fatigue strength. For direct comparison, the diagram provides fatigue strength values at 1 million load cycles. Furthermore, the test series with higher fatigue strength showed shallower S-N curves.

Fatigue test results of the component-like longitudinal stiffeners with additional LTT-weld are shown in Figure 10. All test samples failed at the weld toe, the interface of the additional LTT-layer and the base metal. The fatigue crack grew subsequently through the base plate until failure occurred. The diagram also contains the design S-N curve FAT 63 for general reference. The fatigue strength of the longitudinal stiffeners with an additional weld layer made from conventional weld metal is well describable by FAT 63. The use of the LTT-filler resulted in an increase in fatigue strength and shallower S-N curves. A fatigue strength at 1 million load cycles was determined as $\Delta\sigma$ = 160 MPa (S355J2) and $\Delta\sigma$ = 219 MPa (S960QL), respectively.

Conclusions

The use of LTT-filler metals led to an increase in fatigue strength in some of the tested weld details. A general mechanism of fatigue strength enhancement was not observed. However, the component-like specimens clearly indicated the possible benefit of a modification in the residual stress field by LTT-filler metals. The residual stress field is influenced positively by martensite formation at the lower temperature used in this research study and in the case of the self-restraining specimen geometry. Furthermore, these specimens demonstrate a possibility for a smart use of LTT-filler metals with less concern about their lower impact absorbed energy. This can be explained by the fact that the actual joint was made using a con-

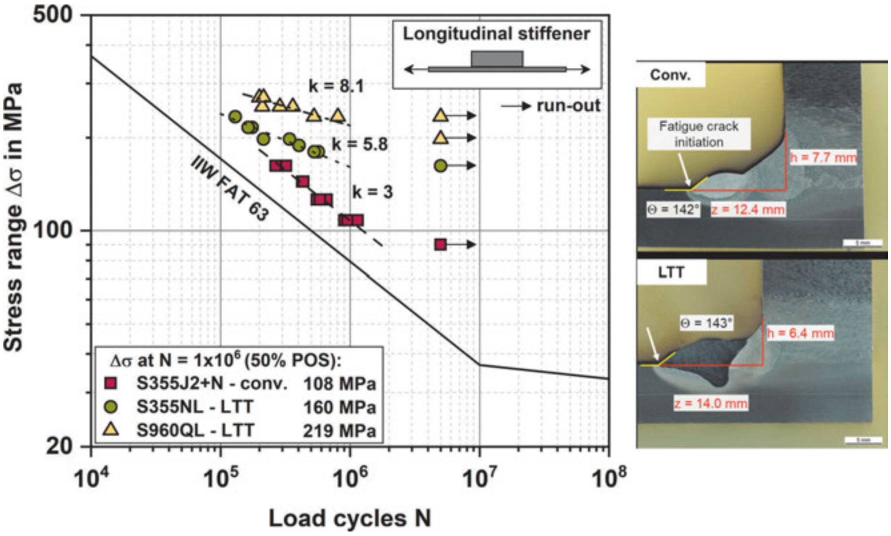

Figure 9: S-N data of butt welds with typical weld profiles and macroscopic metallographic cross sections of the fatigue crack initiation sites

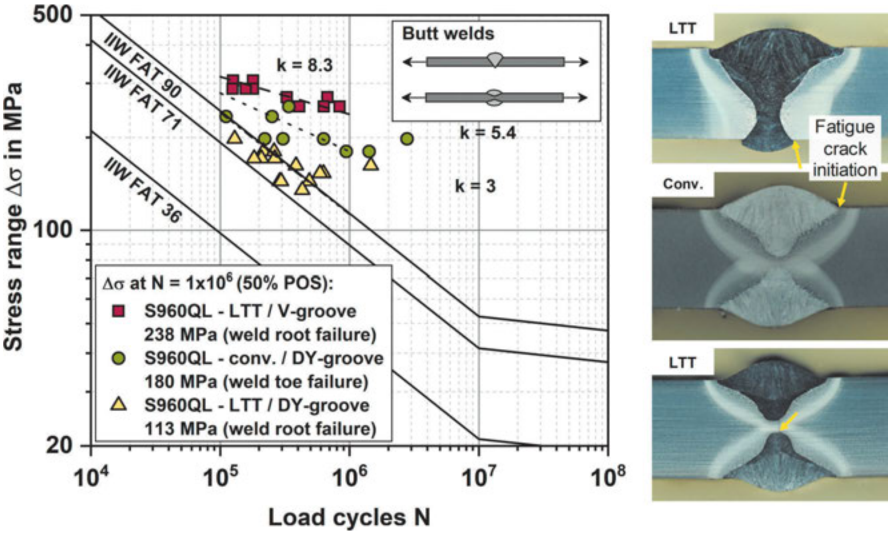

Figure 10: S-N data of longitudinal stiffeners with typical weld profiles and macroscopic metallographic cross sections of the fatigue crack initiation sites

ventional filler metal. The additional LTT-layer is less significant for toughness but highly effective for fatigue strength. A stable residual stress field and low tensile residual stress in LTT-welded longitudinal stiffeners most likely explain the fatigue strength enhancement due to the use of LTT-filler metals. Residual stress effects could not explain the high fatigue strength of the V-butt welds. The high hardness of the weld may be an explanation for delayed fatigue crack initiation, but this is still an open question.

In summary, the key findings of this work are:

- Fe-Cr-Ni-based LTT-metal cored filler material can be welded reliably without cracking or pore formation.
- The surface residual stress field in small scale butt welds was not affected significantly by the LTT-filler material using these welding parameters due to the low shrinkage restraint perpendicular to the weld.
- LTT-filler material can affect the residual stress field in a self-restrained component-like specimen (longitudinal stiffener). Tensile residual stress is reduced, and fatigue strength is increased.
- The use of LTT filler can also be effective for fatigue strength when applied as an additional layer.

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References

1 J. Heeschen: Untersuchungen zum Dauerschwingverhalten von Schweißverbindungen aus hochfesten Baustählen unter besonderer Berücksichtigung der Eigenspannungszustandes und der Nahtgeometrie. Dissertation. Universität – Gesamthochschule Kassel, Inst. für Werkstofftechnik, Kassel (1986)

2 Th. Nitschke-Pagel, H. Wohlfahrt: Einfluss von Eigenspannungen auf die Schwingfestigkeit geschweißter Feinkornbaustähle, D. Aurich, K.-H. Kloos, G. Lange, E. Macherauch (Eds.): DFG-Forschungsbericht „Eigenspannungen und Verzug durch Wärmewirkung“, WILEY-VCH, Weinheim (1999), pp. 291-308

3 W. Gundel, U. Hamme, S. Herion: Ermüdungsfestigkeit geschweißter Konstruktionen aus hoch- und höchstfesten Feinkornbaustählen in der Praxis. DVS Congress 2010 Nürnberg, DVS Media GmbH, Düsseldorf (2010), pp. 220-224

4 Th. Nitschke-Pagel, H. Wohlfahrt, K. Dilger: Application of the local fatigue strength concept for the evaluation of post weld treatments, Welding in the World 51 (2007), No. 11-12, pp. 65-75 DOI:10.1007/BF03266610

5 A. Kromm, J. Dixneit, T. Kannengiesser: Residual stress engineering by low transformation temperature alloys – state of the art and recent developments. Welding in the World, 58 (2014), No. 5. pp. 729-741 DOI:10.1007/s40194-014-0155-6

6 S. W. Ooi, J. E. Garnham, T. I. Ramjaun: Review: Low transformation temperature weld filler for tensile residual stress reduction, Materials & Design 56 (2014), No. 4, p. 773-781 DOI:10.1016/j.matdes.2013.11.050

7 H. Wang, W. Woo, D, Kim, V. Em, S. Y. Lee: Effect of chemical dilution and the number of weld layers on residual stresses in a multi-pass low-transformation-temperature weld, Materials & Design 160 (2018), No. 12, pp. 384-394 DOI:10.1016/j.matdes.2018.09.016

8 S. Wu, D. Wang, X. Di, Z. Zhang, Z. Feng, X. Liu, Y. Li, X. Meng: Toughening mechanisms of low transformation temperature deposited metals with martensite-austenite dual phases, Journal of Materials Science 53 (2018), No. 5, pp. 3720-3734 DOI:10.1007/s10853-017-1766-2

9 F. Vollert, J. Dixneit, J. Gibmeier: Effect of residual stress relaxation due to sample extraction on the detectability of hot crack networks in LTT welds by means of µCT. Materials Research Proceedings 4 (2018), pp. 85-90 DOI:10.21741/9781945291678-13

10 R. J. Moat, S. Ooi, A. A. Shirzadi, H. Dai, A. F. Mark, H. K. D. H. Bhadeshia, P. J. Withers: Residual stress control of multipass welds using low transformation temperature fillers, Materials Science and Technology 34 (2018), No. 5, pp. 519-528 DOI:10.1080/02670836.2017.1410954

11 W. Jiang, W. Chen, W. Woo, S. Tu, X. Zhang, V. Em: Effects of low-temperature transformation and transformation-induced plasticity on weld residual stresses: Numerical study and neutron diffraction measurement, Materials & Design 147 (2018), No. 6, p. 65-79 DOI:10.1016/j.matdes.2018.03.032

12 Z. Feng, X. Di, S. Wu, D. Wang, X. Liu: Comparison of microstructure and residual stress between TIG and MAG welding using low transformation temperature welding filler. Acta Metallurgica Sinica (English Letters), 31 (2018), No. 3, pp. 263-272 DOI:10.1007/s40195-017-0642-z

13 Th. Kannengiesser, A. Kromm, J. Gibmeier, M. Rethmeier: In-situ analysis of phase transformation kinetics during welding, Materials Testing 52 (2010), No. 10, pp. 204-210 DOI:10.3139/120.110122

14 X. Chen, P. Wang, Q. Pan, S. Lin: The effect of martensitic phase transformation dilation on microstructure, strain-stress and mechanical properties for welding of high strength steel, Crystals 8 (2018), No. 7, pp. 1-15 DOI:10.3390/cryst8070293

15 U. Reisgen, S. Olschok, R. Sharma, S. Gach: Influence on martensite-start-temperature and volume expansion of low-transformation-temperature materials used for residual stress relief in beam welding, Materialwissenschaft Und Werkstofftechnik 48 (2017), No. 12, pp. 1276-1282 DOI:10.1002/mawe.201700159

16 A. Kromm; V. van der Mee; T. Kannengiesser; B. Kalfsbeek: Properties and weldability of modified low transformation temperature filler wires. Welding in the World 59 (2015), No. 3, pp. 413-425 DOI:10.1007/s40194-014-0215-y

17 L. Novotny, H. F. G. de Abreu, C. de Miranda: Simulations in multipass welds using low transformation temperature filler material, Science and Technology of Welding and Joining 21 (2016), No. 8, pp. 680-687 DOI:10.1080/13621718.2016.1177989

18 M. Paquin, D. Thibault, P. Bocher, J. Lévesque, Y. Verreman, K. Shinozaki: Assessment of cold cracking tests for low transformation temperature martensitic stainless steel multipass welds, Welding in the World 59 (2015), No. 7, pp. 521-532 DOI:10.1007/s40194-015-0227-2

19 R. Gadallah, S. Tsutsumi, K. Hiraoka, H. Murakawa: Prediction of residual stresses induced by low transformation temperature weld wires and its validation using the contour method, Marine Structures 44 (2015), No. 12, pp. 232-253 DOI:j.marstruc.2015.10.002

20 S. H. Thomas, S. Liu: Analysis of low transformation temperature welding (LTTW) consumables – distortion control and evolution of stresses, Science and Technology of Welding and Joining 19 (2014), No. 5, pp. 392-401 DOI:10.1179/1362171814Y.0000000199

21 T. Ramjaun, H. J. Stone, L. Karlsson, J. Kelleher, R. J. Moat, J. R. Kornmeier, K. Dalaei, H. K. D. H. Bhadeshia: Effect of interpass temperature on residual stresses in multipass welds produced using low transformation temperature filler alloy, Science and Technology of Welding and Joining 19 (2014) No. 1, pp. 44-51 DOI:10.1179/1362171813Y.0000000162

22 T. Kasuya, R. Hamamura, H. Murakawa, H. Inoue, T. Kakeshita: Martensite transformation of a Cr-Ni type weld metal and its application to analysis of welded joints, Welding in the World 58 (2014), No. 7, pp. 477-489 DOI:10.1007/s40194-014-0131-1

23 M. Takahashi, H. Y. Yasuda: Variant selection of martensites in steel welded joints with low transformation temperature weld metals, Journal of Alloys and Compounds 577 (2013), No. 1: pp. S601 – S604 DOI:j.jallcom.2012.02.022

24 J. Dixneit, F. Vollert, A. Kromm, J. Gibmeier, A. Hannemann, T. Fischer, Th. Kannengiesser: In situ analysis of the strain evolution during welding using low transformation temperature filler materials, Science and Technology of Welding and Joining 24 (2019), No. 3, pp. 243-255 DOI:10.1080/13621718.2018.1525150
25 A. Ohta; O. Watanabe; K. Matsuoka; C. Siga; S. Nishijima: Fatigue strength improvement by using newly developed low transformation temperature welding material. Welding in the World 43 (1999), No. 6, pp. 38-42
26 F. Martinez Diez: Development of a compressive residual stress in structural steel weld toes by means of weld metal phase transformations, Welding in the World 52 (2008), No. 7/8, pp. 63-78 DOI:10.1007/BF03266655
27 J. A. Francis, H. J. Stone, S. Kundu, R. B. Rogge, H. K. D. H. Bhadeshia, P. J. Withers, L. Karlsson, Transformation temperatures and welding residual stresses in ferritic steels, PVP2007-26544, Proceedings of PVP2007, ASME Pressure Vessels and Piping Division Conference July 22-26 2007, ASME, San Antonio USA (2007), pp. 1-8
28 A. Ohta, N. Suzuki, Y. Maeda, S. J. Maddox: Fatigue strength improvement of lap welded joints by low transformation temperature welding wire – superior improvement with strength of steel, Welding in the World 47 (2003), No. 3/4, pp. 38-43 DOI:10.1007/BF03266382
29 E. Harati, L. Karlsson, L. Svensson, K. Dalaei: Applicability of low transformation temperature welding consumables to increase fatigue strength of welded high strength steels, International Journal of Fatigue 97 (2017), No. 4. pp. 39-47 DOI:j.ijfatigue.2016.12.007
30 W. Wang; L. Huo; Y. Zhang; D. Wang; H. Jing: New developed welding electrode for improving the fatigue strength of welded joints, Journal Materials Science and Technology 18 (2002), No. 6, pp. 527-531
31 C. Shiga, H. Murakawa, K. Hiraoka, N. Osawa, H. Yajima, T. Tanino, S. Tsutsumi, T. Fukui, H. Sawato, K. Kamita, T. Masuzaki, T. Sugimura, T. Asoda, K. Hirota: Elongated bead weld method for improvement of fatigue properties in welded joints of ship hull structures using low transformation temperature welding materials, Welding in the World 61 (2017), No. 6, pp. 769-788 DOI:10.1007/s40194-017-0439-8
32 A. Ohta; Y. Maeda; N. Suzuki: Fatigue life extension by repairing fatigue cracks initiated around box welds with low transforamtion temperature welding wire, Welding in the World 45 (2001) No. 5/6, pp. 3-8
33 A. Kromm, T. Kannengiesser: Effect of martensitic phase transformation on stress build-up during multilayer welding, Materials Science Forum 768-769 (2013), pp. 660-667 DOI:10.4028/www.scientific.net/msf.768-769.660
34 C. Shiga, H. Y. Yasuda, K. Hiraoka, H. Suzuki: Effect of Ms temperature on residual stress in welded joints of high- strength steels, Welding in the World 54 (2010) No. 3/4, pp. 71-79 DOI:10.1007/BF03263490
35 J. Gibmeier, E. Obelode, J. Altenkirch, A. Kromm, T. Kannengiesser: Residual stress in steel fusion welds joined using low transformation temperature (LTT) filler material. Materials Science Forum 768-769 (2013), pp. 620-627 DOI:10.4028/www.scientific.net/MSF.768-769.620
36 A. Kromm: Evaluation of weld filler alloying concepts for residual stress engineering by means of Neutron and X-ray diffraction, Advanced Materials Research 996 (2014), pp. 469-474 DOI:10.4028/www.scientific.net/amr.996.469
37 J. Altenkirch, J. Gibmeier, A. Kromm, Th. Kannengiesser, Th. Nitschke-Pagel, M. Hofmann: In situ study of structural integrity of low transformation temperature (LTT)-welds. Materials Science and Engineering: A 528 (2011), No. 16-17, pp. 5566-5575 DOI:j.msea.2011.03.091
38 J. Dixneit, A. Kromm, M. Boin, T. Kannengisser, J. Gibmeier: Influence of Heat Control on Residual Stresses in Low Transformation Temperature (LTT) Large Scale Welds. Residual Stresses 2016: Icrs-10 (2017), No. 2, pp. 223-228
39 J. Hensel, Th. Nitschke-Pagel, K. Dilger: Eigenspannungen im Schweißzustand und quasi-statische Eigenspannungsrelaxation an geschweißten Längssteifen aus Baustählen, DVS-Berichte 295 : 33. Assistentenseminar Füge- und Schweißtechnik, DVS Media GmbH, Düsseldorf (2013), pp. 102-110
40 DIN EN ISO 16834 : 2012 Welding consumables – Wire electrodes, wires, rods and deposits for gas shielded arc welding of high strength steels -Classification, German version (2012)
41 DIN EN ISO 14341 : 2011 Welding consumables – Wire electrodes and weld deposits for gas shielded metal arc welding of non alloy and fine grain steels – classification, German version (2011)
42 CEN ISO/TR 17641-3 : 2004 Destructive tests on welds in metallic materials – Hot cracking tests for weldments – Arc welding processes – Part 3: Externally loaded test, German translation (2004)
43 E. Macherauch, P. Müller: Das $\sin^2\psi$-Verfahren der röntgenographischen Spannungsmessung, Zeitschrift für angewandte Physik 13 (1961), No. 7. pp. 305-312
44 DIN EN ISO 14175 : 2008 Welding consumables – Gases and gas mixtures for fusion welding and allied processes, German version (2008)
45 W. Steven, A. G. Haynes: The temperature of formation of martensite and bainite in low-alloy steels. Journal of the Iron and Steel Institute 183 (1956), No. 8, pp. 349-359
46 J. Hensel, T. Nitschke-Pagel, K. Dilger: On the effects of austenite phase transformation on welding residual stresses in non-load carrying longitudinal welds, Welding in the World 59 (2015), No. 8, pp. 179-190 DOI:10.1007/s40194-014-0190-3

Bibliography

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