Influence of Heat Control on Residual Stresses in Low Transformation Temperature (LTT) Large Scale Welds

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Abstract. The current paper presents residual stress analyses of large scale LTT (Low Transformation Temperature) welds. LTT filler materials are specially designed for residual stress engineering by means of an adjusted martensite phase transformation. Controlling the level of mostly detrimental residual stresses already during the welding process would be highly attractive as time and cost consuming post processing may be prevented. In large scale welds the residual stress state is influenced by the heat control (e.g. interpass temperature) during welding. Therefore, welding residual stresses are studied here putting the focus on the influence of welding process parameters while joining heavy steel sections with a thickness of 25 mm. The residual stress state was determined at the top surface using X-ray diffraction as well as in the bulk by neutron diffraction. The results show that control of the interpass temperature is vital for the residual stresses present in the joints. This accounts for the top surface but is most pronounced for the bulk of the welds. While high interpass temperatures are appropriate to induce compressive residual stresses in the weld metal, low interpass temperatures favor unwanted tensile residual stresses instead.

Introduction

Despite the well-known benefit of post-weld heat treatments on fatigue life due to altering welding residual stresses, such processes often lead to additional production costs. Novel Low Transformation Temperature (LTT-) filler materials are specially designed for controlling weld residual stresses by means of an adjusted martensite formation already during welding and thus its application may minimize costs. The volume expansion due to phase transformation counteracts the contraction due to shrinkage of the joint. Tensile residual stresses are reduced or even beneficial compressive residual stresses are formed. The strength of these filler materials makes them potentially applicable to high-strength steels as well as to repair works in existing steel structures. The influence of varying phase transformation temperatures on the residual stresses for different weld geometries was the aim of most investigations up to now. Shiga et al. [1] and Francis et al. [2] confirmed that compressive residual stresses can be achieved, when welding LTT-alloys with varying martensit start (M_S-) temperatures. The focus was also on the influence of the welding parameters. High interpass temperatures can delay the martensite formation during multi-pass welding. It follows that the whole weld metal undergoes the phase transformation not before cooling to ambient temperature after deposition of the last bead. On the other hand, low interpass temperatures allow repeated martensite formation in the already deposited layers. Both alters the residual stresses found in a welded joint [3]. But the final residual stresses are also influenced by the restraint conditions of the structure. That means the weld is restrained by the adjacent base material (BM) as well as by the stiffness of the whole weld construction. Zenitani et al. [4] already confirmed the influence of varying restraint intensities regarding residual stresses in LTT-joints. Therefore, the present study was focused on the evaluation of the residual stresses in thick walled LTT-joints showing a high restraint concerning the impact of the interpass temperature.

Experimental

Materials and Welding. Based on already published chemical compositions two LTT alloys were prepared. Some characteristics are presented in Table 2 and Table 1. Both fillers show the main alloying elements chromium and nickel or manganese respectively. Two different interpass temperatures were applied. Butt welding was carried out in eleven runs by Pulsed Gas Metals Arc Welding (P-GMAW) using LTT flux cored wires. The weld samples (250 mm × 200 mm) exhibit a thickness of 25 mm each and were prepared with an opening angle of 45°. The high strength steel S960QL was used as a base material. The specimens were heated to preheat temperature using a furnace. Preheat and interpass temperatures were controlled by thermocouples on various positions in the heat affected zone (HAZ). The welding parameters are shown in Table 3.

Table 1: chemical composition of the base and filler material (fcw)

Chemical composition (wt.-%), *measured on pure (weld-) samples using dilatometry tests									M_S^* (°C)
	C	Si	Mn	Cr	Ni	Mo	B	Fe	
base material	0.17	0.29	0.82	0.51	0.91	0.51	0.0002	Bal.	419
LTT CrNi	0.04	0.38	0.62	12.2	4.80	0.005	-	Bal.	232
LTT CrMn	0.08	0.25	6.40	11	0.02	0.041	-	Bal.	123

Table 2: mechanical properties of base and filler materials

	$R_{p0,2}$ in MPa	R_m in MPa	reference
base material	985	1018	-
LTT CrNi	900	1123	[5]
LTT CrMn	-	1074	

Table 3: welding parameters

wire diameter	1.6 mm
arc voltage (RMS value)	29 V
welding current (RMS value)	377 A
welding speed	520 mm/min
preheat- and interpass temperature	50 °C and 200 °C
$t_{8/5}$-time (averaged),	7 s and 11 s
shielding gas	M13, 1 % O_2

X-ray diffraction. The residual stress measurement was carried out midways on the top surface of the samples using the $\sin^2\psi$ technique [6]. Residual stresses were determined in longitudinal as well as in tranverse direction of the weld line using the parameters shown in Table 4.

Table 4: measuring and evaluation parameter for X-ray diffraction

Measuring position	weld, HAZ, BM (top surface, midway)
radiation	CrK_α
X-ray spot size	2 mm
Exposure time	5 s

Ψ-range	0...±45° in 7 steps
Diffraction line	ferrite/martensite: 211
E {211}	220.000 MPa
ν {211}	0.28

Neutron diffraction. Stress measurements were performed at the instrument E3 at the BERII facility of the HZB Berlin, Germany [7]. The setup is shown in Fig. 1 (left). As a multi-axial stress state was expected in the welded joints, strain measurements were necessary in the three principle directions covering the longitudinal, transversal and weld depth direction (normal). Using a neutron wavelength of approximately 0.147 nm the α/α′ -Fe {211} diffraction peak located at approximately $2\Theta = 78°$ was utilized for strain measurement. The exposure time varied between 10 min to 30 min. From lattice strains in principle directions the stresses were calculated. A gauge volume of 2x2x2 mm³ was chosen for the transversal as well as weld depth direction while in longitudinal direction the gauge volume was adapted to 2x2x10 mm³ to achieve a sufficient spatial resolution and acceptable exposure time. The measuring positions were realized midway along the specimens. Three measuring lines in distances of 4, 12.5 and 21 mm to the plate surface were chosen as indicated in Fig. 1 (right). The measuring range included in total 15 measuring points located in the weld and on both sides of the HAZ, while the BM was covered single sided only. Weld distortion was not balanced for the measuring lines. As the LTT weld metals are higher alloyed compared to the base material the unstrained lattice parameter a_0 was determined from appropriate reference specimens. For this purpose a thin comb was cut from each sample representing the weld cross section including the HAZ and BM. The prongs of the comb were prepared by Electrical Discharge Machining to reduce thermal effects to the material.

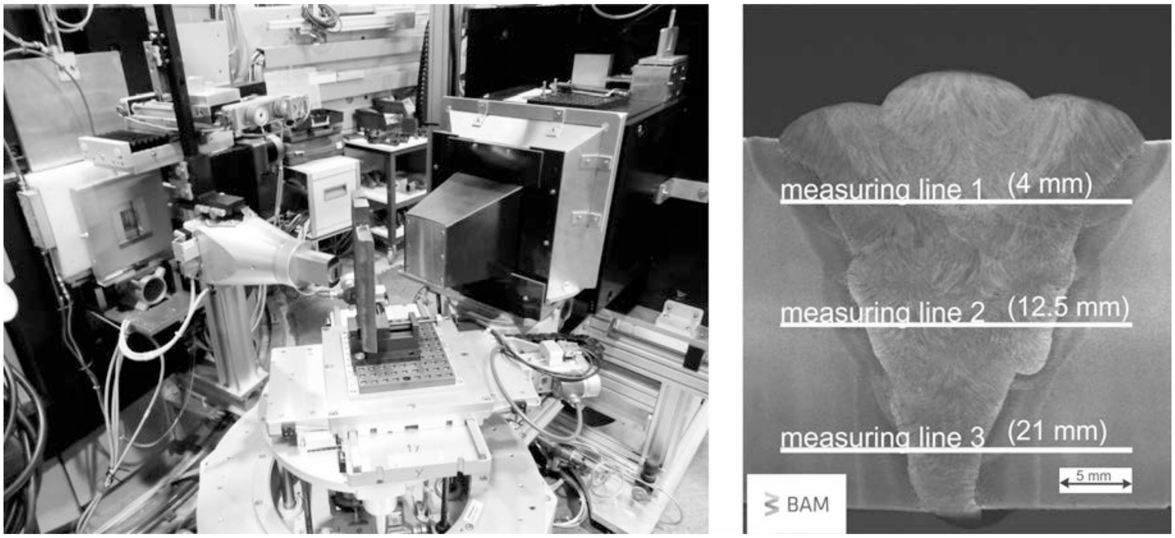

Fig. 1: setup of the neutron diffraction experiment at the instrument E3@BER II (left) and assignment of the measuring lines to the joints cross section (right)

Results and Discussion

Residual Stresses – Surface. Residual Stresses found in the surface of the welds are presented in Fig. 2 and Fig. 3. The longitudinal stress distribution of all joints is quite similar in quality. Moreover, the residual stress level in the LTT CrMn welds is almost identical except for a single tensile peak value in the left hand side weld metal at the lower interpass temperature. In case of the CrNi filler the residual stress level is slightly decreased when applying the higher interpass temperature. In this case the weld is characterized mainly by comparatively low tensile residual stresses up to about 300 MPa, while the lower interpass temperature shows peak values around

500 MPa. These stress levels are also to be found in the HAZ. In any case the transition to the BM shows a steep residual stress gradient. In this area the stresses change from tension into compression. Adjacent to the HAZ the residual stresses are decreased to compressive values between -200 MPa and -300 MPa given by the BM condition before welding (sand blasted). Some high measurement errors are due to microstructural reasons.

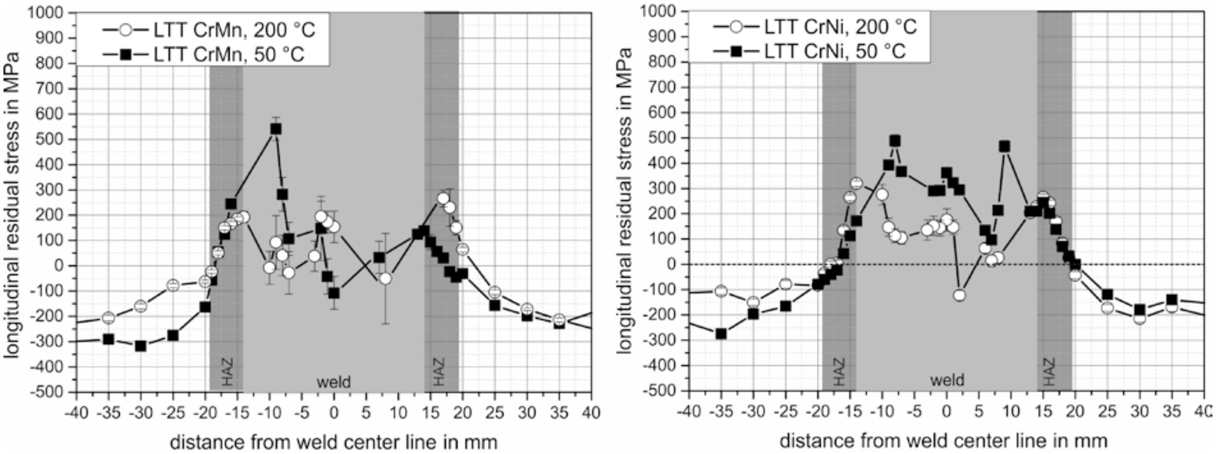

Fig. 2: surface longitudinal welding residual stresses for the CrMn-filler (left) and the CrNi-filler (right) induced during welding using different interpass temperatures

In contrast there are some differences to be observed in transversal direction. The weld metals are in tension up to about 800 MPa and the region showing tensile residual stresses is wider when using the high interpass temperature. Additionally, the residual stresses exhibit several maxima in the weld center. On the other hand, with lower interpass temperature single stress peaks appear in the center without dips. The HAZ shows low compressive residual stresses on the level of the BM up to about -300 MPa. Independent from the interpass temperature applied the longitudinal residual stresses are lower than the transverse ones. This is consistent to results found in other LTT joints [8]. Higher interpass temperatures lead to slightly decreased stress levels in longitudinal direction. But in transversal direction the high tensile residual stresses are limited to a smaller zone in the weld metal center in case of lower interpass temperatures.

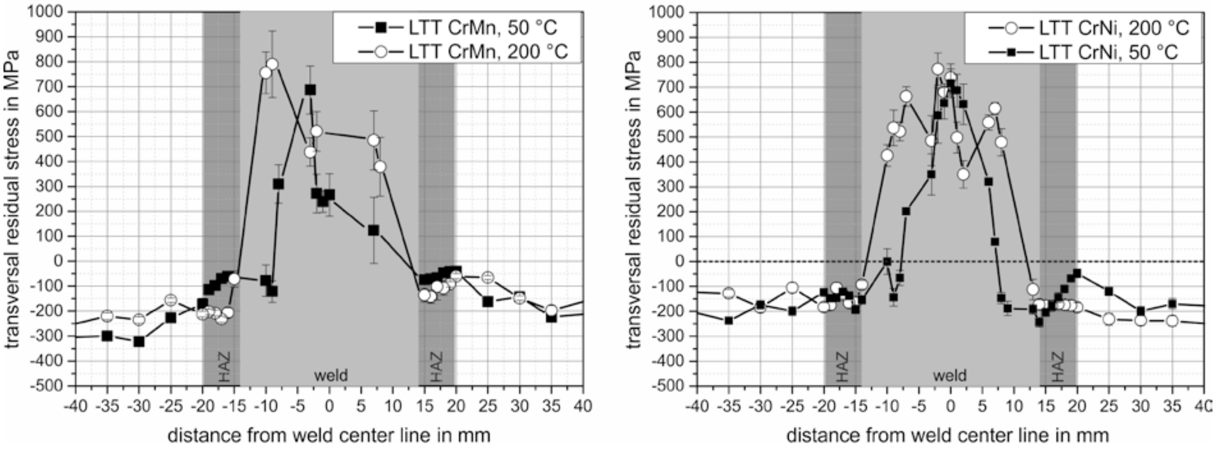

Fig. 3: surface transversal welding residual stresses for the CrMn-filler (left) and the CrNi-filler (right) induced during welding using different interpass temperatures

Residual Stresses – Bulk. Longitudinal as well as transversal residual stresses are shown for the LTT CrNi in Fig. 4. The LTT CrMn exhibits the similar residual stress distributions in quality and is therefore not shown. In case of an interpass temperature of 200 °C there are compressive longitudinal stresses detectable through the bulk. They are lost in case of the root (Fig. 1 line 3), where tensile stresses balance up to about 380 MPa in the weld metal. Similar to the top surface high tensile stresses are present in the HAZ independent from the depth. The stress magnitudes are higher than on the surface (max. 700 MPa). Also contrary to the surface in transversal direction there are quite low tensile residual stresses of up to about 350 MPa detectable in the weld metal only. The HAZ varies between tension and compression from 4000 MPa to -300 MPa. In case of an interpass temperature of 50 °C the longitudinal stress level is shifted completely into tension reaching the level of the surface stresses. Longitudinal stress peaks are also detectable through the material bulk in the HAZ up to 900 MPa. In transversal direction the welding residual stress distribution is less affected by lower interpass temperatures. The stress level shows low tensile stress up to 400 MPa in the weld and 430 MPa in the HAZ. High tensile stress levels as found at the surface are not detectable. In the normal direction the stress distribution of the LTT alloys is comparable to the transversal welding residual stresses and therefore not shown.

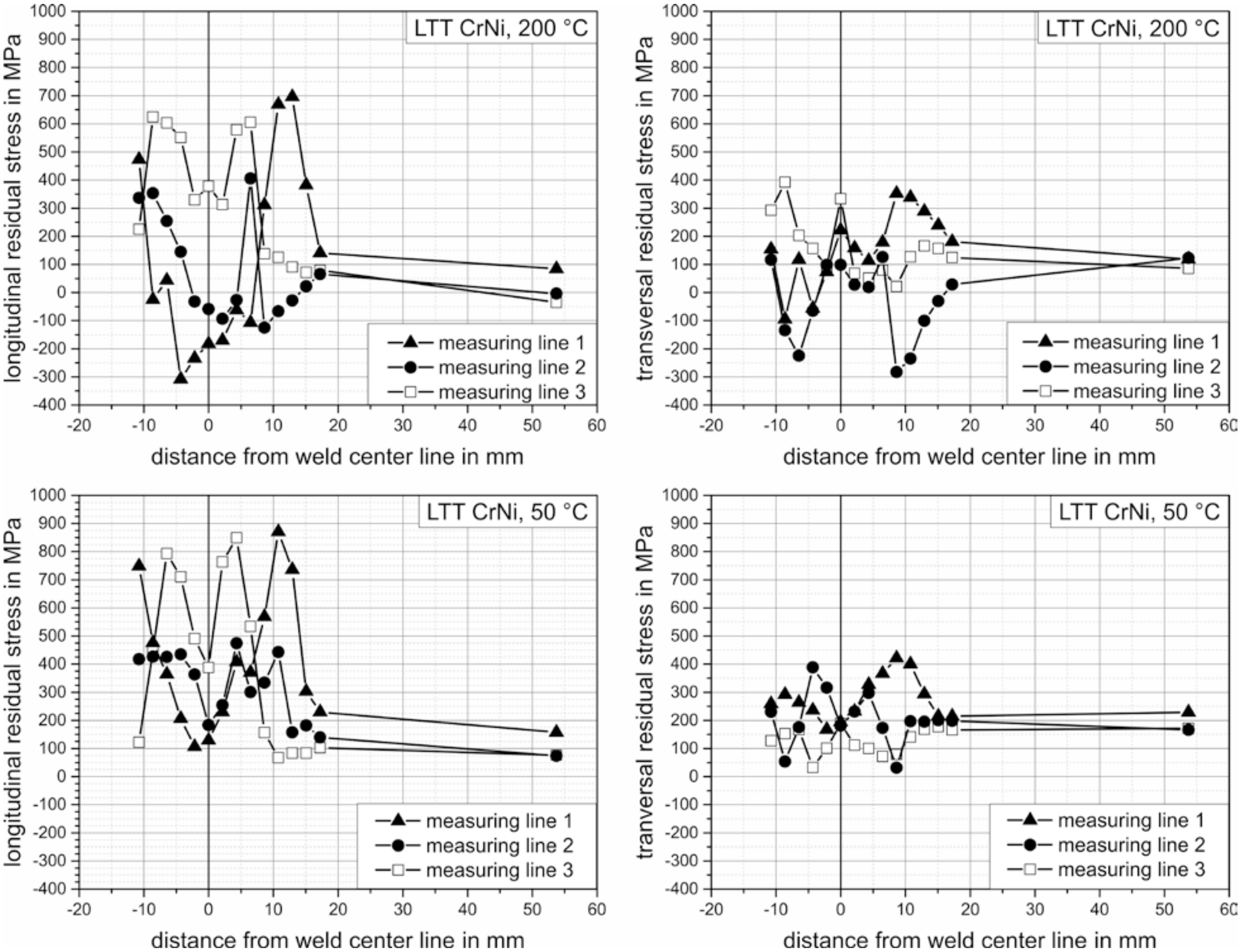

Fig. 4: residual stress in bulk for the LTT CrNi, interpass temperature 200 °C (above) and 50 °C (below)

Summary and Conclusions

The present work dealt with the residual stresses in high strength heavy plate joints welded with LTT fillers applying different interpass temperatures. The residual stresses were determined using X-ray (surface residual stresses) and neutron diffraction (bulk residual stresses). The following conclusions can be drawn:

- Independent from the interpass temperature residual stresses in longitudinal direction are lower than in transverse direction. This applies for the surface as well as for the bulk of the welds.
- Welding residual stresses in the bulk are lower compared to stresses found on the surface.
- Compressive residual stresses as a result of the martensite formation are determined in the bulk weld metal, only.
- Independent from the LTT filler used high interpass temperatures are beneficial to reduce the stresses mainly in longitudinal direction.
- Lower interpass temperatures tend to narrow the tensile zone in the weld metal but they also prevent the formation of compressive residual stresses.

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