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Residual Stress Distribution Measurement by Neutron Diffraction of the Single Pass Fillet Steel Welds

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Abstract. In this contribution the results of residual strain/stress measurements performed on several single pass fillet steel welds which were carried out at different welding conditions, namely, with different filler materials are presented.

Introduction

It is well known that fatigue strength of welded joints does not depend on steel strength. Better fatigue strength of welded joints, e.g. longer life time of fatigue loaded weld structures, can be achieved with a smooth transition between the weld and the base material to minimize stress concentration. It has also been recognized that residual stresses play a critical role in the fatigue behaviour of welds. The aim of the performed residual stress studies was to find optimum composition of the additive material in order to decrease residual stresses in the vicinity of the foot of the welding joint and consequently to increase the fatigue strength. It is based on the conception of so called LTT (low transformation temperature) metal used for electrodes which (according to the related theory) decreases the level of residual stresses and increases the fatigue strength. The following base materials were used:

- WELDOX 700 , DOMEX 650 – refined high strength steels having the yield strength 700 MPa (in reality up to 817 MPa resp. 650 MPa) and X2CrNi12 in combination with 7 different filler materials
- WELDOX 900 in combination with four different filler materials.

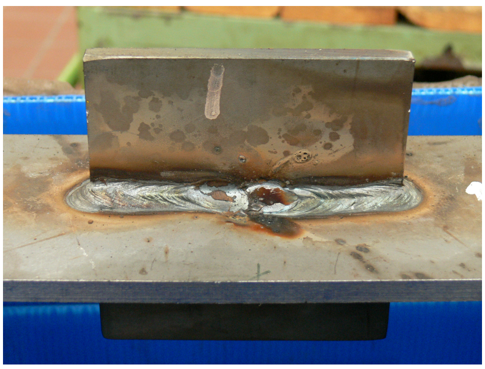


Fig. 1. Photo of the fatigue test specimen.

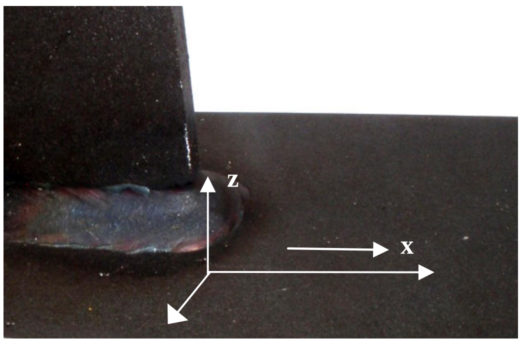


Fig. 2. Location of neutron stress measurements and related coordinates.

The photo of the test specimen and location of neutron stress measurements are shown in Figs. 1 and 2 and the related dimensions in Fig. 3.

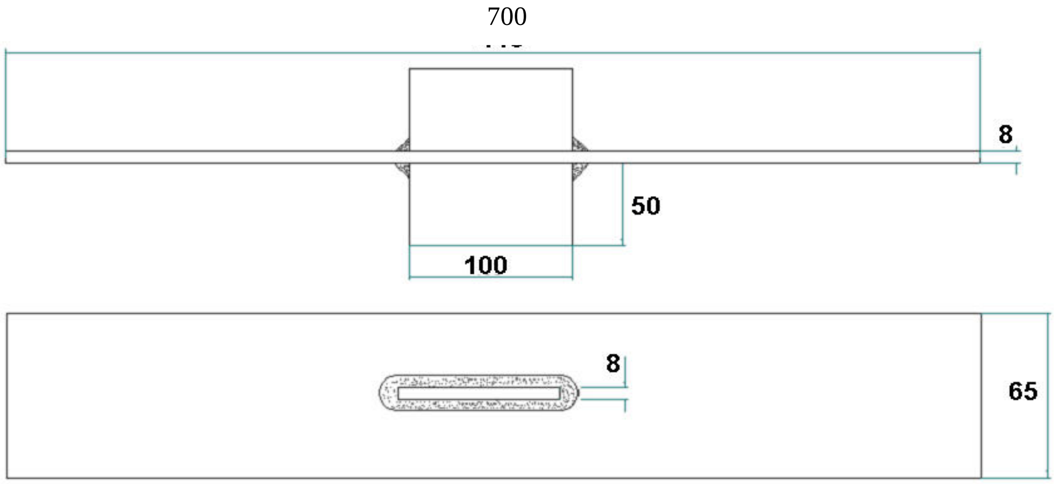


Fig. 3. Dimensions of the test specimen.

Principle of the Neutron Diffraction Method

The principle of the neutron diffraction method is quite simple. It consists in the precise determination of the d_{hkl}-spacing of particularly oriented crystal planes [1,2]. In neutron and X-ray diffraction the angular positions of the diffraction maxima are directly related to the values of the lattice spacing through the Bragg equation $2d_{hkl} \cdot \sin\,\theta_{hkl} = \lambda$ (d_{hkl} -lattice spacing, θ_{hkl} - Bragg angle, λ - the neutron wavelength) and thus offer a unique non-destructive technique for investigation of stress fields. When a specimen is strained elastically, the lattice spacing changes. Then, when defining the strain ε as $\varepsilon = \Delta d/d_{0,hkl}$, it is related to a change in the lattice spacing, i.e. to a component parallel to the scattering vector $\boldsymbol{Q}$

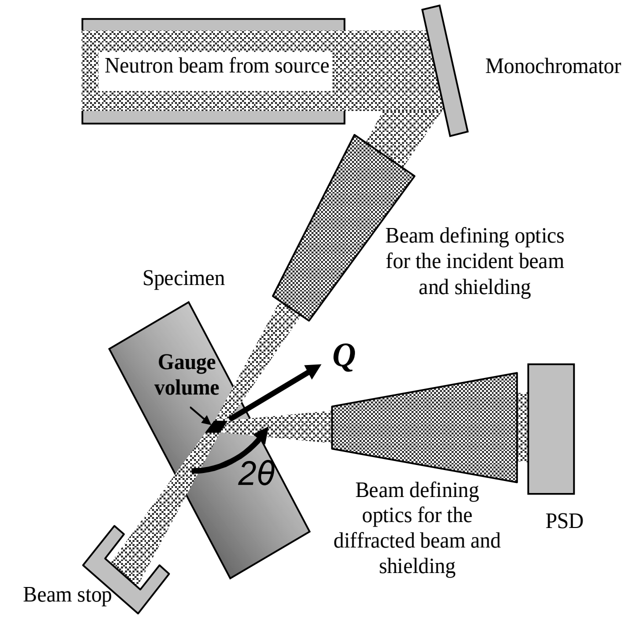


Fig. 4. Schematic illustration of a reactor source based diffractometer for strain measurement in parallel diffraction geometry.

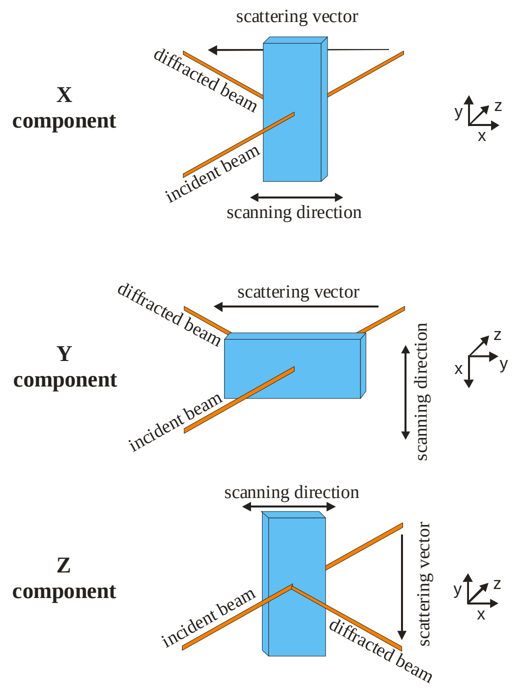


Fig. 5. Sketch of the sample setting for determination of three strain/stress components.

perpendicular to the reflecting set of planes. Therefore, the knowledge of the $d_{0,hkl}$ value ($d_{0,hkl}$ is the lattice spacing of the strain-free material) is a crucial task [3]. Then by differentiation of the Bragg condition we arrive at $\varepsilon = -\cot \theta_{\mathrm{hkl}} \cdot \Delta\theta_{\mathrm{hkl}}$. The relation for the strain ε indicates that it gives rise to a change in the scattering angle $2\theta_{hkl}$ resulting in an angular shift $\Delta(2\theta_{hkl})$ of the peak position for a particular reflecting plane illuminated by a fixed wavelength. In such a way, the shift in the Bragg angle (relative to that of the stress-free material) permits the determination of the average lattice macrostrain over the irradiated gauge volume (see Fig. 4). The conversion of strains to stresses is carried out by means of the relation

$$\sigma_x = \frac{E_{hkl}}{(1-2\nu_{hkl})(1+\nu_{hkl})}\left[(1-\nu_{hkl})\varepsilon_x^{hkl} + \nu_{hkl}(\varepsilon_y^{hkl} + \varepsilon_z^{hkl})\right] , \qquad (1)$$

where $\varepsilon_{x,y,z}^{hkl}$ is the *x,y,z*-component of the lattice strain measured at the *hkl* crystal lattice planes, E_{hkl} and ν_{hkl} are the diffraction elastic Young modulus and diffraction Poisson ratio, respectively. For the determination of the stress tensor in this case of steel samples, three strain components should be determined as schematically shown in Fig. 5. Experimental measurements were carried out on the dedicated neutron strain scanner installed at the medium-power (10 MW) research reactor LWR-15 in Řež, Czech Republic [4,5].

Experimental Results

Weldox 700, Domex 650 and X2CrNi12

Three parent materials and seven different filler materials were used for the test specimen preparation. Altogether seven test specimens were used for the residual stress distribution measured by neutron diffraction. Chemical composition of the parent materials and tested combintations of parent and filler materials are shown in the Table 1 and Table 2. Namely, main attention was focused on the influence of Cr+Ni concentration in the filler material.

Table 1. Chemical compositions of the parent materials.

Steel	**Content (weight %)**														
	C	**Si**	**Mn**	**B**	**P**	**S**	**Cr**	**Mo**	**V**	**Ti**	**Cu**	**Al**	**Ca**	**Nb**	**N**
Weldox 700	0.13	0.3	1.18	0.001	0.011	0.003	0.27	0.13	0.007	0.013	0.01	0.041	-	0.022	
Domex 650MCD	0.06	0.06	1.63		0.013	0.002	0.02	-						0.63	
X2CrNi12 1.4003	max. 0.03	max 1	max 1.5		max. 0.04	max. 0.015	10.5 12.5	max. 0.016			max. 0.09				0.03 0.14

Table 2. Combinations of the parent and filler materials.

	Parent material	**Filler material**	**Content (weight %)**		
			Cr	**Ni**	**Cr+Ni**
A	WELDOX 700	LTT-M6	5.68	5.33	**11.01**
B	WELDOX 700	B-M3	0.69	8.24	**8.93**
C	WELDOX 700	D4-6547	9.96	4.96	**14.92**
E	WELDOX 700	OK Tubrod 14.03	0.04	2.13	**2.17**
J	DOMEX 650MCD	D3-5724	9.55	4.49	**14.04**
K	X2CrNi12	D3-6547	12.69	4.23	**16.92**
L	X2CrNi12	OK Tubrod 15.30	16.30	5.61	**21.91**

The aim of the measurements was to study:

- The effect of filler material LTT-M6(A), B-M3(B), D4-6547(C), Tubrod 14.03(E) welded on high strength steel WELDOX 700 on residual stress distribution.
- The effect of filler materials D4-6547 and Tubrod 15.30 welded on high alloyed steel X2CrNi12 (1.4003) parent material on x, y and z residual stress components distribution.
- The effect of parent material high strength WELDOX 700/690QL and Domex 650MCD steels welded by D4-6547 and D3-5724, respectively, on x, y and z stress components.
- The effect on x, y and z stress components when parent materials WELDOX 700/S690QL and high alloyed X2CrNi12 (1.4003) steels are welded by D4-6547 filler material.
- The effect of parent materials high strength Weldox 700/S690QL and high alloyed X2CrNi12 (1.4003) steels welded by Tubrod 14.03 and Tubrod 15.30, respectively, on x, y and z stress components.
- The effect of weld location of test fillet welds prepared on high strength steel WELDOX 700/S690QL welded by D4-6547 filler material on x, y and z stress components.

The following figures show examples of the obtained experimental results:

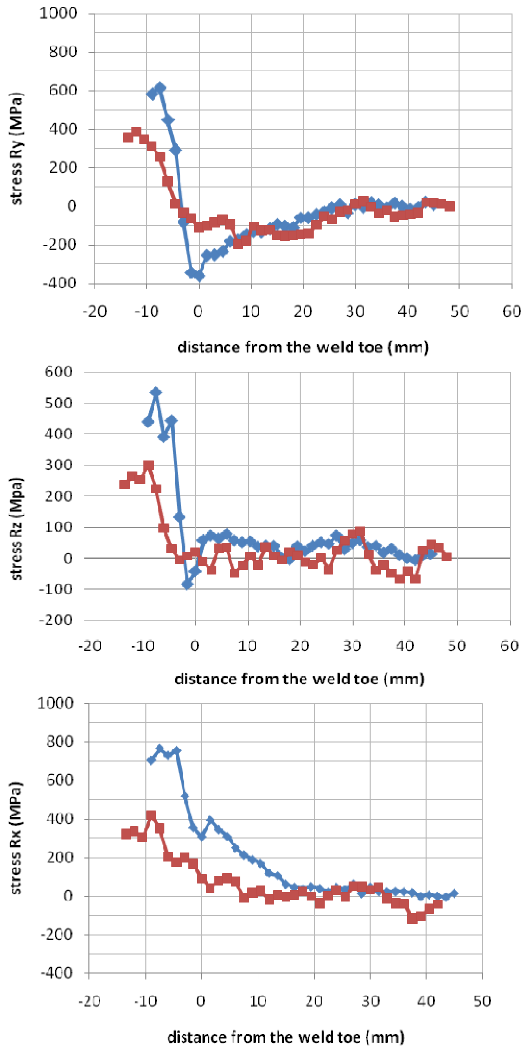


Fig. 6. Residual stress distribution in the vicinity of the welds welded by D4-6547 filler material. Parent materials: Weldox 700/S690QL (in blue) and X2CrNi12 (1.4003) (in red).

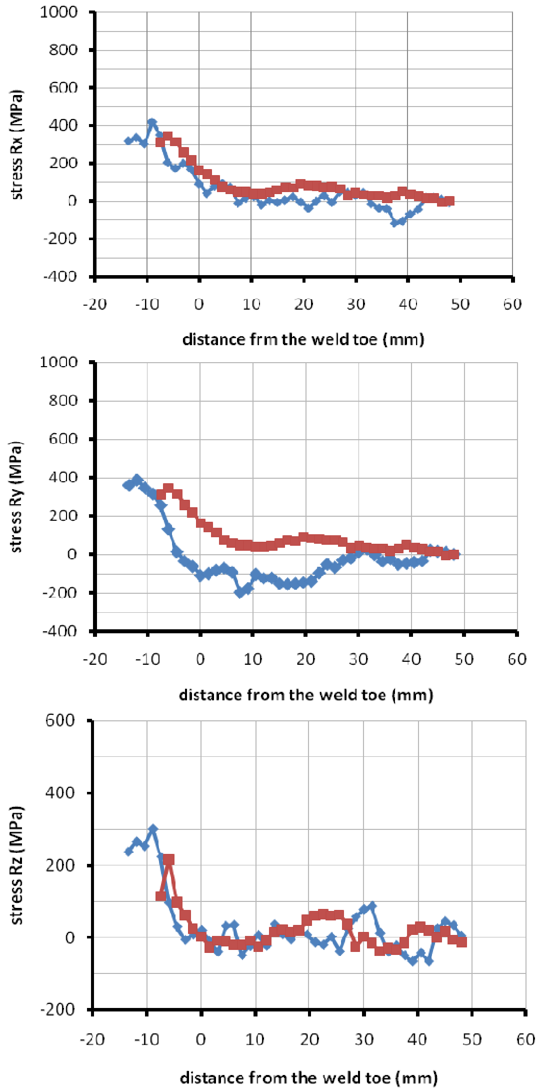


Fig. 7. Residual stress distribution in the vicinity of the welds made of X2CrNi12 (1.4003) steel welded by filler materials - D4-6547 (in blue) and Tubrod 15.30 (in red).

The strain scanning was carried out 3 mm below the surface when using diffraction on α-Fe(110) lattice planes at $2x\theta_{110} = 70^{o}$ for the neutron wavelength of 0.232 nm.

Weldox 900

Similarly, Weldox 900 in combination with four different filler materials was tested. Table 3 shows the chemical composition of the parent material and Table 2 shows the concentra-tion of the individual diluted weld metals. The experimental stress results are shown in Fig. 8. In

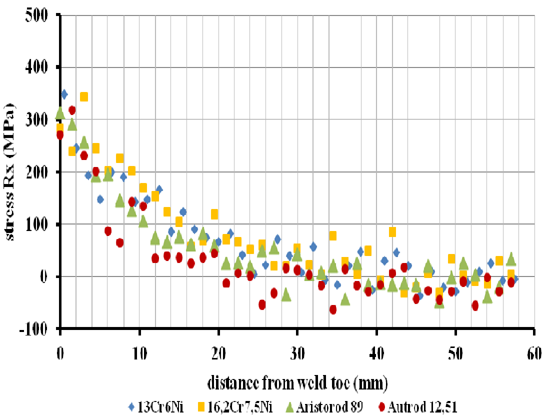
Table 3. Chemical composition of the parent material Weldox 900.

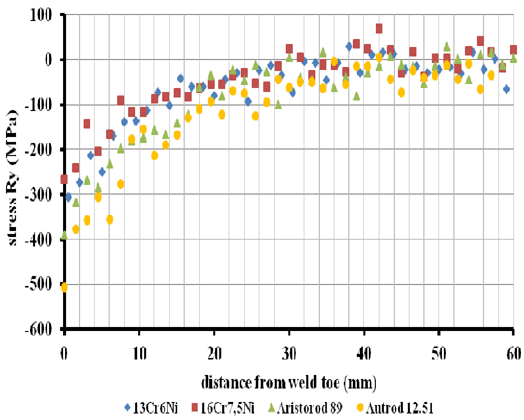
Steel	Content (weight %)							
	C	Si	Mn	P	S	Cr	Ni	Mo
Weldox 900	0.16	0.22	1.40	0.012	0.001	0.25	0.05	0.458

Content (weight %)						CEW (%)
V	Ti	Cu	Al	Nb	N	
0.040	0.004	0.01	0.053	0.017	0.003	0.54

Table 4. Chemical concentration of the diluted weld metals.

Filler material	Content (weight %)							
	C	Si	Mn	P	S	Cr	Ni	Mo
Cambridge-M (13Cr6Ni)	0.059	0.58	1.43	0.012	0.004	9.50	4.20	0.15
Cambridge-S (16Cr7.5Ni)	0.071	0.73	1.66	0.012	0.004	12.50	5.80	0.10
OK Aristorod 89	0.10	0.54	1.52	0.007	0.002	0.34	1.47	0.53
OK Autrod 12.51	0.11	0.49	1.28	0.011	0.003	0.11	0.03	0.21





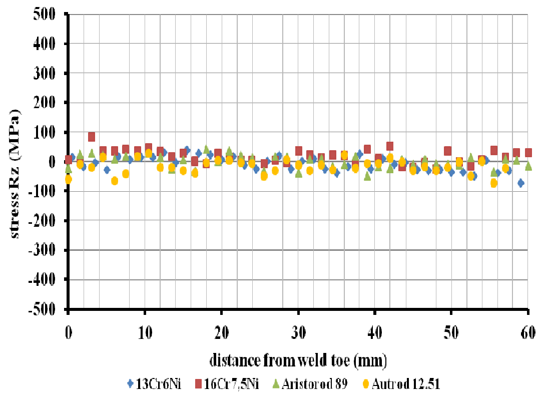


Fig. 8. Components of the residual stress for different filler materials.

this case the strain scanning was carried out 2 mm below the surface when using the same diffraction on α-Fe (110) lattice planes at $2x\theta_{110} = 70^{o}$. For the evaluation of the strains it was necessary to determine the angular position $2\theta_{0,110}$ of the diffracted neutron beam for the strain free material. As the chemical composition of the weld is different from that of the steel, for calibration it was necessary to have the strain free steel as well as the weld metal reference material. Therefore, after carrying out the strain scanning, small cubes with a volume of about 27 mm^3 were cut off from the steel plates and the welds in which the strains were relaxed and the material was considered as a strain free.

Summary

The purpose of the measurements was to demonstrate the effect of weld metal chemical composition having a direct relation of phase transformation temperature on the residual stress distribution in the vicinity of the high strength steel test weld. Then the results served as a basis for further designs of material with better properties of fatigue strength [6 - 8]. Several filler materials were chosen for the preparation of the test welds having remarkably different chemical composition, namely, different Cr and Ni content. As can be seen from the experimental results, maximum stress effect has been found, as expected, in the vicinity of the weld toe. Nevertheless, it can be stated that The weld metal chemical composition (phase transformation temperature) has strong effect on residual stress distribution of high strength steel welds.

Acknowledgement

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