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# IDENTIFICATION OF RESIDUAL STRESS DISTRIBUTION IN HIGH STRENGTH STEEL WELDS USING NEUTRON DIFFRACTION

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**Abstract:** *Residual stress distribution in the vicinity of single pass high strength steel test welds has been studied using neutron diffraction. Two butt welds were prepared using basic shielded metal arc electrodes – one using conventional electrode producing a bainitic weld metal and one using experimental low temperature transformation (LTT) electrode depositing a martensitic weld metal. Welding was done under restraint in a test frame. Residual stress components* $R_x$, $R_y$ *and* $R_z$ *were measured across the weld using neutron diffraction after removing the test weld from the frame. Stresses were generally on a lower level for the LTT weld. The largest difference was seen for the transverse residual stress some distance into the heat affected zone.*

**Keywords:** *welding, residual stress, neutron diffraction, phase transformations*

## 1. Introduction

Residual stresses are a consequence of the heterogeneous temperature distribution during welding of any structural material. Other effects are local structural changes leading to inhomogeneous properties across the weld. The combined effect of stresses and structural changes can cause distortions and local defects such as hot, cold or lamellar cracks in steel welds.

Many investigations have been performed in order to define the influence of residual stresses on weld joint properties. One important aspect is the influence on fatigue life. Steel fatigue properties increase when either yield or tensile strength increases. However, the strength of a welded joint has little or no effect on fatigue strength. Consequently there is little to gain by using a higher strength steel for welded structures subjected to fatigue loads [ 1 ]. The influence of local stress concentrations, microstructural changes in HAZ and residual stresses often on the order of yield strength are considered to be responsible for this effect.

The most common method of reducing residual stresses is to perform a post weld heat treatment. A more recent approach is to influence residual stresses metallurgically by using filler material producing a weld metal with low transformation temperature (LTT). The new filler metal concept (LTT) has been presented in the literature [1, 2, 3, 4] for welding of high strength steels. It is based on the influence of phase transformations on the final stress level**.** By undergoing displacive transformation at a comparatively low temperature, the weld metal counteracts the thermal contraction stresses, thereby reducing the levels of residual stress in the welded construction as it reaches ambient temperature**.** It has also been shown that

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modifying the residual stress distribution by using low transformation temperature filler materials can remarkably increase the fatigue life of welded joints.

There are a number of methods for estimation of residual stress levels. Several methods, including the hole drilling method using special strain gauges, ultrasonic measurements as well as X-ray and neutron diffraction can be used to measure the stress level after welding. Both diffraction methods (X-ray or neutron) can provide information about the stress distribution in the vicinity of welds. However, neutron diffraction is due to the high penetration of thermal neutrons very well suited to non-destructive 3D-mapping of residual stresses at welds [ 5, 6 ].

The results of residual stress measurements in the vicinity of single pass test welds are presented in this paper. The influence of the weld metal chemical composition on the residual stress distribution was investigated. All three stress components $R_x$, $R_y$ and $R_z$ were measured by neutron diffraction for two welds in a 800 MPa strength steel.

## 2. Experimental procedure

Parent material

A high strength steel WELDOX 700, with thickness of 10 mm, has been used for the preparation of the test specimens. The chemical composition of the parent material is presented in Table 1 and mechanical properties in Table 2.

| **Steel** | Content (weigth %) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cr | Ni | Mo | V |
| **Weldox 700** | 0.1440 | 0.3140 | 1.0040 | 0.0060 | 0.0013 | 0.3720 | 0.0570 | 0.0190 | 0.0470 |

| **Steel** | Content (weigth %) | | | | | | ( % ) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Ti | Cu | Al | Nb | B | N | Ce | PCM | Ca |
| **Weldox 700** | 0.0150 | 0.0160 | 0.0430 | 0.0200 | 0.0015 | 0.0050 | 0.4000 | 0.2385 | 0.0024 |

Tab. 1 Chemical composition of the WELDOX 700 parent material

| Type | Yield strength (MPa) | Tensile strength (MPa) | A5 (%) |
|---|---|---|---|
| Weldox 700 | 700 | 780-930 | 14 |

Tab. 2 Mechanical properties of parent material WELDOX 700

Test welds

Single pass butt welds were used for neutron diffraction measurements. Welding was done under restraint in a VUZ-ERC test frame. The VUZ-ERC (elastic rigid cracking) test is a technological test originally developed at the Welding Research Institute (VÚZ) in Bratislava to identify the critical restraint for cold cracking and also to identify the reactive force built up during and after welding. The test specimens consist of two pieces firmly fixed between the two frame halves, made of quenched and tempered steel with a rough surface, using eight high strength steel bolts Figure 1 [ 7 ]. The restraint level can be varied using different frame sizes.

Two test pieces with the dimensions of 115 mm in width, total length of 250 mm and thickness of 10 mm, were firmly fixed in the VUZ-ERC test frame with dimensions 490 x 10 x 260 mm. A specimen V–bevel preparation and a gap of 1.5 mm was used. This configuration produce a restraint length of 300 mm. The test specimens were removed from the frame approximately 1 hour after welding.

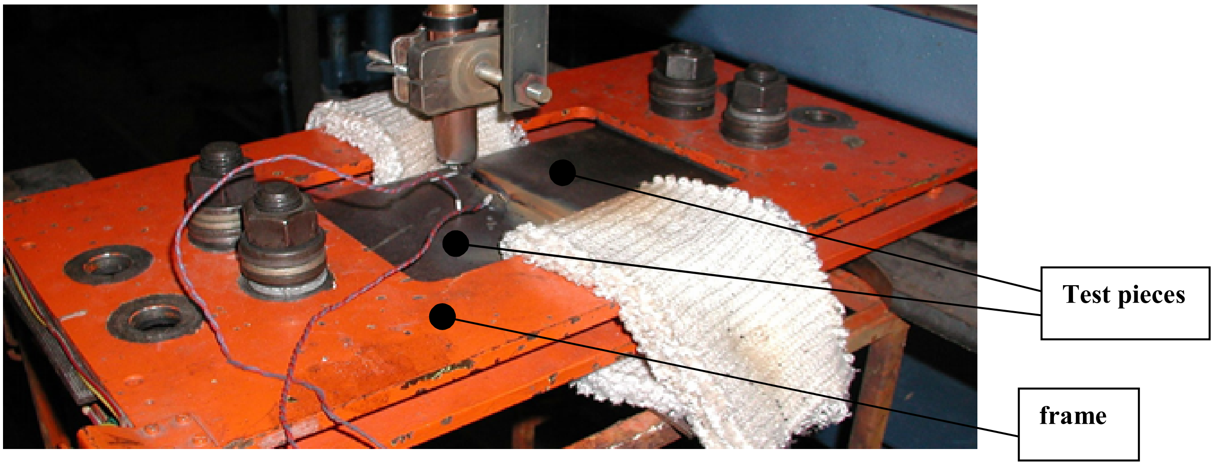

Fig. 1VÚZ – ERC test frame

Welding procedure

Two types of basic shielded metal arc electrodes with a diameter of 4 mm, one commercial type ESAB OK 75.78 and one experimental, labelled LTT, were used for the test welding. Electrode OK 75.78 (E 89 6 Z B 42 H5 according to EN 757) is a bainitic electrode suitable for welding of ultra high strength steels. The LTT electrode is an experimental martensitic electrode highly alloyed with Ni and Cr. The chemical composition and mechanical properties of the all-weld metal is summarised in Table 3 and 4 respectively. Chemical composition of experimental welds are given in Table 3.

| **Type** | **Specimen** | **Content (weight %)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **C** | **Si** | **Mn** | **P** | **S** | **Cr** | **Ni** | **Mo** |
| **OK 75.78** | all - WM | 0.045 | 0.33 | 2.20 | 0.009 | 0.005 | 0.45 | 3.10 | 0.63 |
| | real - WM | 0.100 | - | 1.85 | - | - | 0.42 | 1.94 | 0.39 |
| **LTT** | all - WM | 0.089 | 0.28 | 1.35 | 0.01 | 0.007 | 8.98 | 8.56 | 0.04 |
| | real - WM | 0.094 | - | 1.29 | - | - | 6.29 | 5.81 | 0.02 |

Tab. 3 Chemical composition of all-weld metal and experimental test weld metal

| Type | Yield strength (MPa) | Tensile strength (MPa) | A5 (%) |
|---|---|---|---|
| OK 75.78 | 951 | 957 | 19 |
| LTT | 1135 | 1287 | 6 |

Tab. 4 Mechanical properties of all-weld metal OK75.78 and LTT electrodes

The welding parameters used for welding are presented in **Table 5**.

| Electrode type | Diameter (mm) | I (A) | U (V) | t (s) | Weld length (cm) | v (cm/min) | Q (kJ/mm) |
|---|---|---|---|---|---|---|---|
| **OK 75.78** | 4.0 | 150 | 23 | 42 | 10 | 14.29 | 1.45 |
| **LTT** | 4.0 | 150 | 22 | 40 | 10 | 15.00 | 1.32 |

Tab. 5 Welding parameters for single pass test weld preparation

Neutron diffraction residual stress measurements

Residual stress measurements were carried out at the neutron strain scanner SPN-100 installed at the medium power research reactor LVR-15 in Řež, Czech republic [ 5, 6 ]. The instrument has a curved Si (111) monochromator and is equipped with linear high-resolution position-sensitive detectors for fast recording of diffraction profiles. The monochromator provides a neutron beam with a wavelength of 0.232 nm (Figure 2).

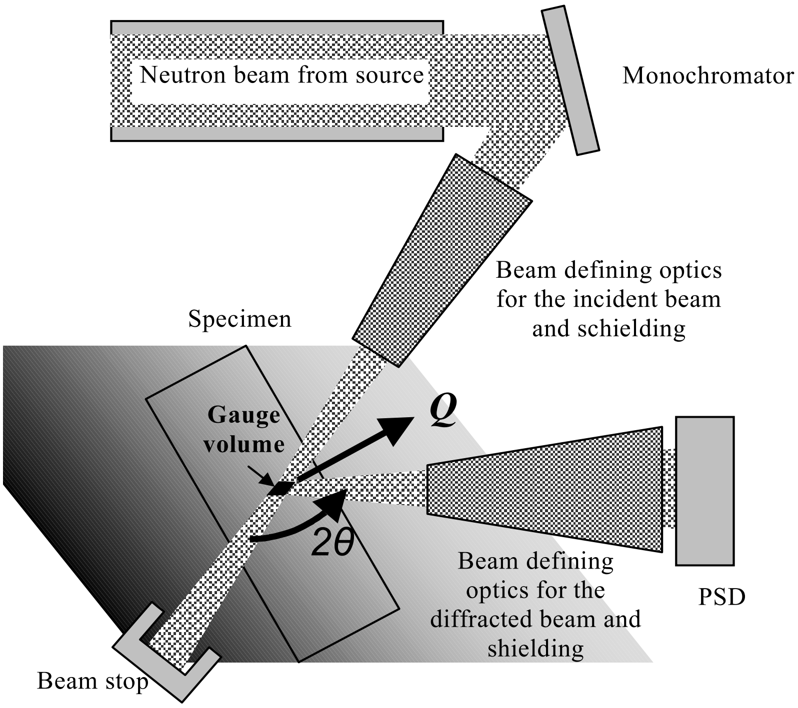

Fig. 2 Neutron diffraction techniques dedicated to strain measurements.

The shift in the Bragg angle (relative to that of the stress-free material) permits determination of the average lattice macrostrain over the irradiated gauge volume. The strain scanning was carried out by means of diffraction on α-Fe (110) lattice planes for $2\cdot\theta_{110}= 70^{\circ}$. For the evaluation of the strains it was necessary to determine the angular position $2\cdot\theta_{o,hkl}$ of the diffracted neutron beam for the strain free material. As the chemical composition of the weld is different from that of the steel it is necessary to have strain free steel and weld metal reference material for calibration. Therefore, after carrying out the strain scanning, small cubes with a volume of about 300 $mm^3$ were cut off from the steel plates and the welds in which the strains were relaxed and the material was considered as strain free.

The measurement points were located at a distance of 3 mm from the plate bottom surface (Figure 3). During the measurement a gauge volume of 2 x 2 x 2 $mm^3$ was used for scanning of the X and Y strain components (the samples were moved in the horizontal plane) and of the Z-component (the samples were moved in the vertical plane). The following orientation has been used for measurements: X – perpendicular to the weld, Y – through thickness, Z – parallel to the welding direction.

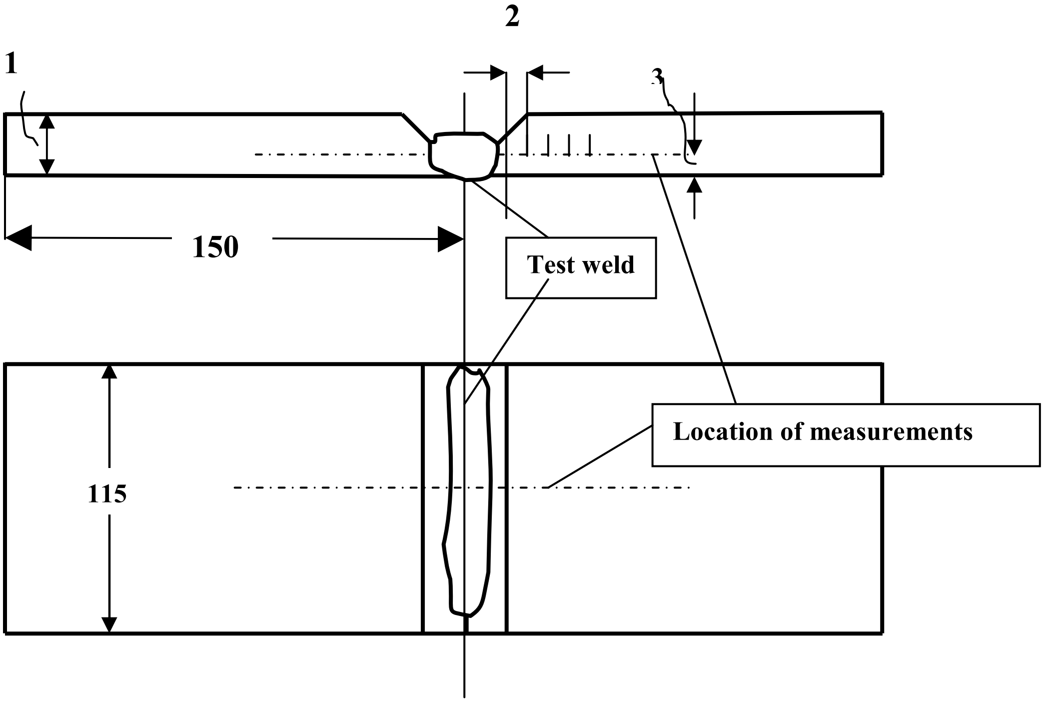

Fig. 3 Locations of residual stress measurement

The stress components $R_x$, $R_y$ and $R_z$ were finally calculated from the measured strains using standard equations and appropriate modules.

## 3. Results

The actual weld metal composition of the two single pass test welds, labelled real weld metal, is summarised in Table 3.

Residual stress distributions in X, Y and Z directions are shown in Figure 4 (OK 75.78) and Figure 5 (LTT). The distribution of the individual stress components $R_x$, $R_y$ and $R_z$ across the welds are presented in Figures 6 to 8.

The results show a minimum stress level almost at the same position for all three stress components. This minimum is located in the HAZ approximately 5 mm from the weld centre. According to metallographic examinations (Figures 4 and 5) this location coincides with the HAZ line heated up approximately to the $A_{c3}$ temperature.

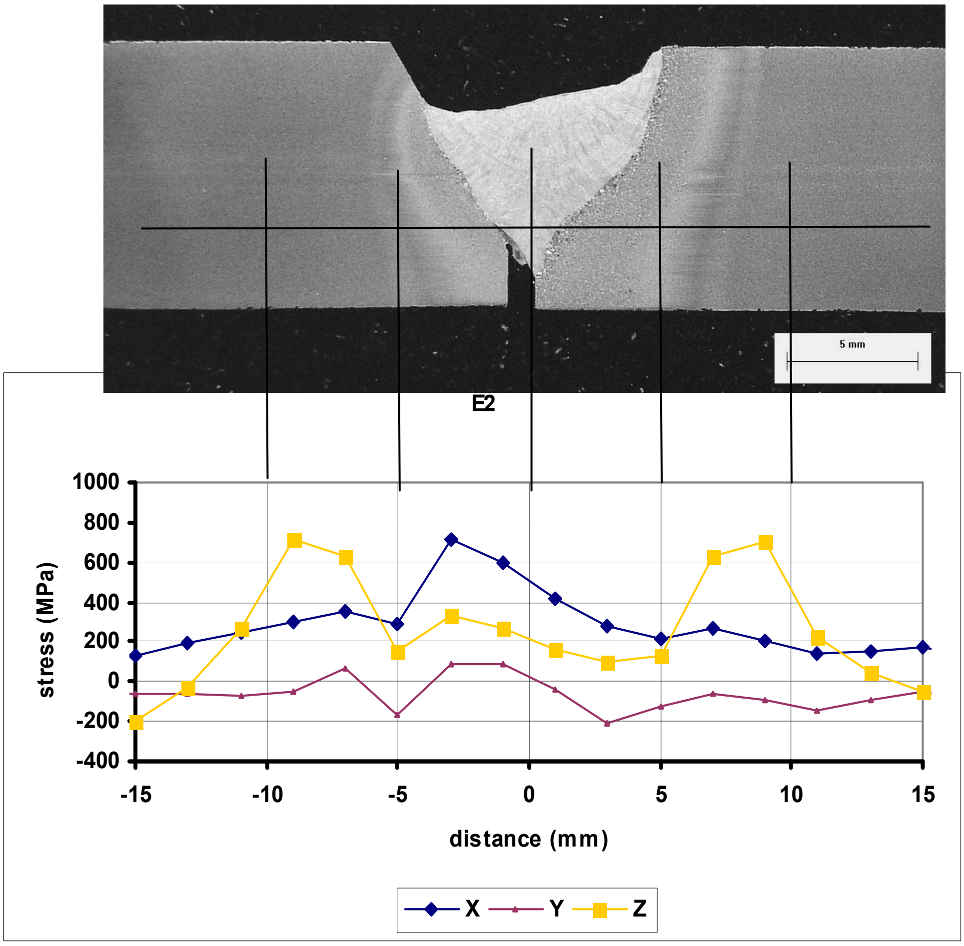

Fig. 4 The residual stress distribution in X - transverse, Y – through thickness and Z – longitudinal directions of the OK 75.78 test weld

The general appearance of the measured residual stress distribution curves is very similar for both test specimens. In both cases the curves are more or less symmetric around the weld centre. There are three maxima, one at the weld centre and one on each side approximately 7-8 mm from the weld centre, and two minima, one on each side, approximately 5 mm from the weld centre.

An effect of the weld metal chemical composition was recognised mainly for $R_x$ (transverse) and partially for $R_y$ (trough thickness) and $R_z$ (longitudinal) stress components. The main differences were found in the area of the local minimum approximately 5 mm from the weld centre. A compressive transverse stress ($R_x$) of approximately -100 MPa was measured in this location for the LTT weld and a tensile stress of 300 MPa for OK 75.78 (Figure 6). As can be seen in Figures 6 to 8 a lower residual stress along the weld ($R_z$) was also measured for the LTT weld metal in this location. There is also a difference in the through thickness residual stress $R_y$. This stress component is higher for the LTT weld at the local maxima (weld centre and 7 to 9 mm from the weld centre) and lower at the location of minimum stress 5 mm from the weld centre.

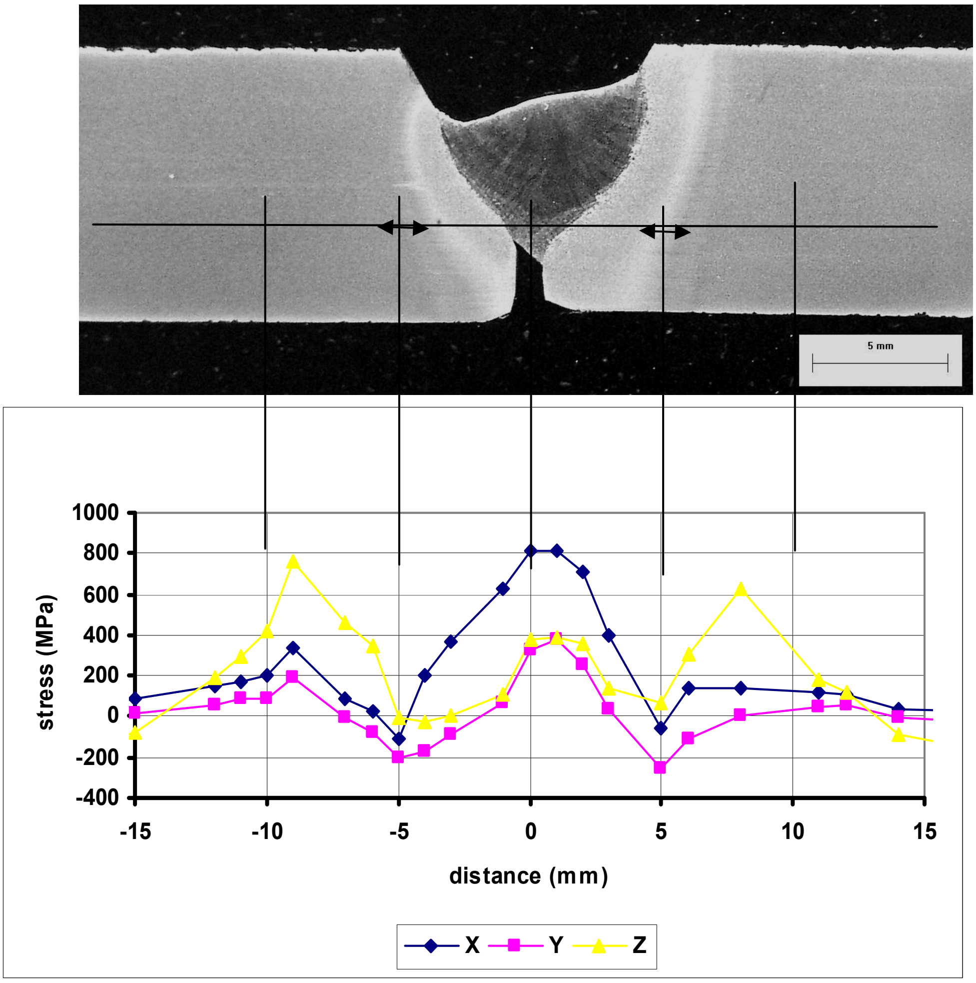

Fig. 5 The residual stress distribution in X, Y and Z directions of the LTT test weld

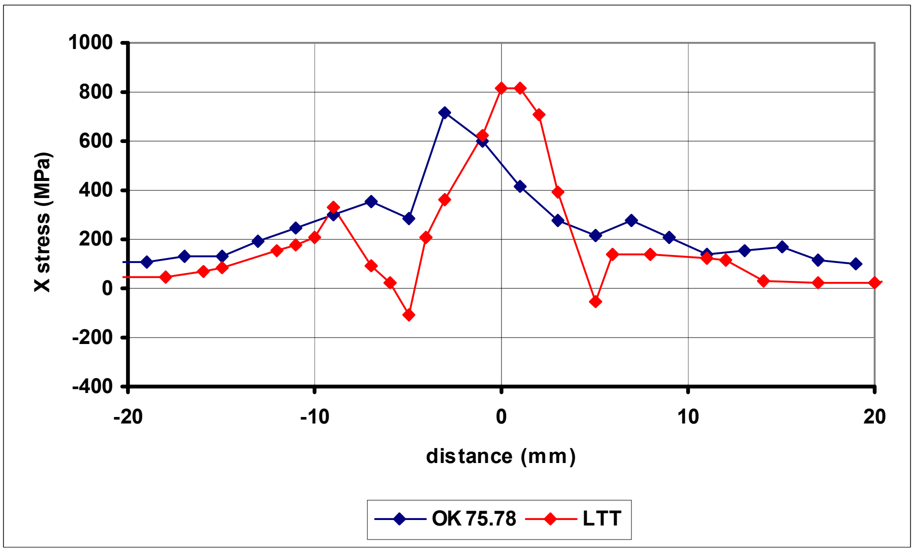

Fig. 6 Residual stress component Rx (transverse to the weld axis)
of both OK 75.78 and LTT test welds

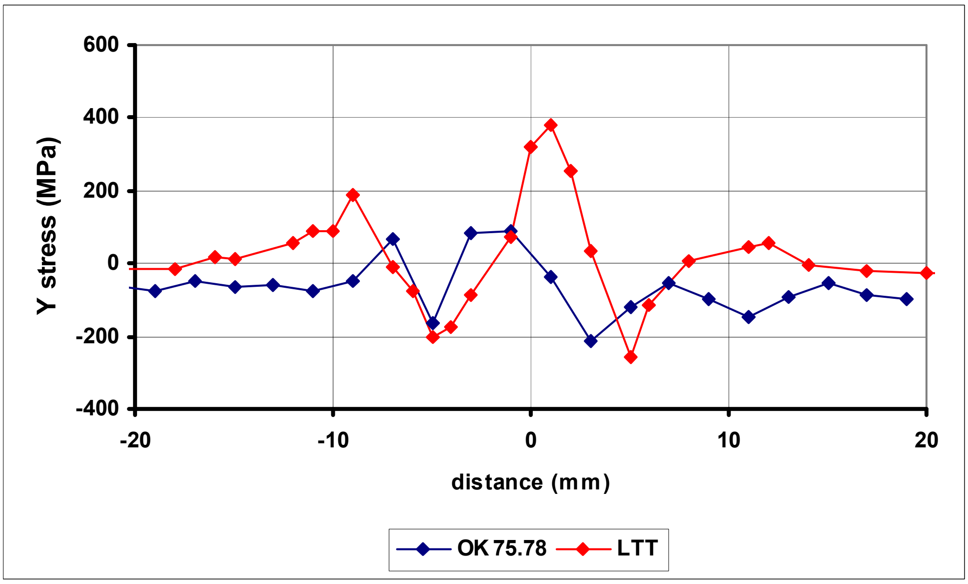

Fig. 7 Residual stress component Ry (through thickness direction) of both OK 75.78 and LTT test welds

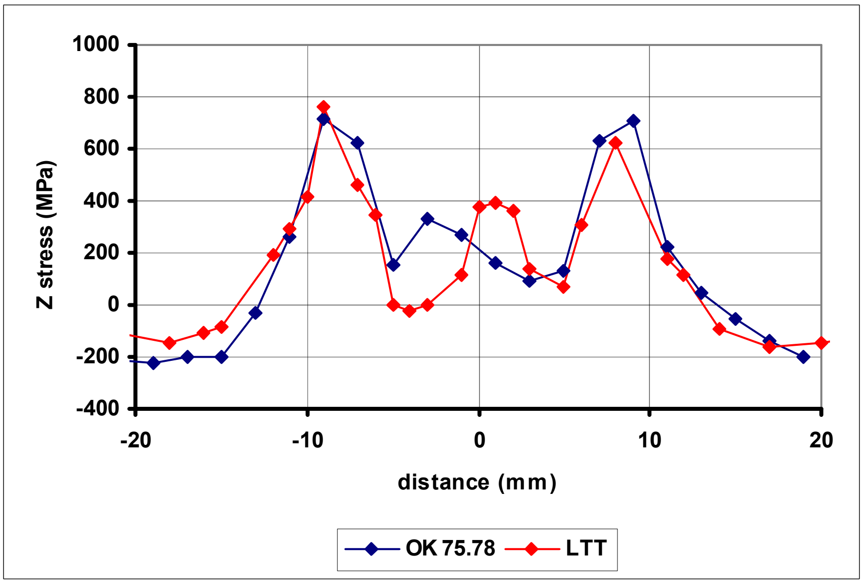

Fig. 8 Residual stress component Rz (longitudinal to the weld axis) of both OK 75.78 and LTT test welds

## 4. Discussion

Neutron diffraction was used to measure the residual stresses across two single pass welds and the influence of the weld metal chemical composition on stress distributions has been investigated. The distribution of all three stress components $R_x$, $R_y$ and $R_z$ were measured. One conventional OK 75.78 and an experimental electrode labelled LTT were used for the deposition of the test welds. The main alloying elements are Ni (≈ 3 %) for OK 75.78 and Cr (≈ 9 %) and Ni (≈ 8%) for the LTT electrode.

An effect of the weld metal chemical composition on residual stresses was recognised mainly for $R_x$ (transverse) and partially for $R_y$ (trough thickness) and $R_z$ (longitudinal) components. The results show the largest effect approximately 5 mm from the weld centre. All components $R_x$, $R_y$ and $R_z$ of residual stresses were lower in this location when applying the LTT weld metal concept.

The accuracy of the ND method for the residual stress measurements is an important factor when evaluating results. Variations of the residual stress across the welds were smooth. No unexpected extreme values (very high or low) that could indicate inconsistency of the measurements have been identified. Furthermore, maximum weld metal stress levels were on the order of the yield strength suggesting results are reasonable.

The maximum residual stress level in the weld, i. e. in the weld metal, is higher for the LTT weld for all stress components. This can be related to the higher strength coming from the more highly alloyed martensitic microstructure of the LTT weld metal.

Differences in residual stress distributions can be associated with the phase transformation temperature of the weld metal [ 1, 2 ]. The effect of Ms temperature on fatigue properties has been studied by Shiga et al. who showed a positive effect of a filler material with lower Ms on fatigue strength [ 2, 4 ]. In order to evaluate this parameter the Ms and Bs temperatures have been calculated from the all-weld metal and also the actual weld metal chemical compositions (Table 6) using standard empirical equations [ 8, 9 ]. Calculations predict Ms temperatures of 398°C and 276°C for OK 75.78 and LTT real weld metals, respectively. A bainitic transformation temperature of 503°C was calculated for OK 75.78 weld metal. The calculated bainitic transformation temperatures for the LTT weld metal should be ignored since they are lower than the Ms temperatures. The austenite is expected to transform only to martensite for this weld metal.

| **Type** | **specimen** | **Temperature ( °C )** | |
|---|---|---|---|
| | | **Bs*** | **Ms*** |
| **OK 75.78** | all - WM | 421 | 388 |
| | actual - WM | 503 | 398 |
| **LTT** | all - WM | -264 | 200 |
| | actual - WM | 28 | 276 |

*calculated according to the following equations

Bs = 830 - 270 C - 90.0 Mn - 37.0 Ni - 70.0 Cr - 83.0 Mo [ 8 ]

Ms = 539 - 423 C - 30.4 Mn - 17.7 Ni - 12.1 Cr - 7.5 Mo [ 9 ]

Tab. 6 Calculated Bs and Ms temperature of all-weld and actual weld metal

The measured differences in residual stress components are associated with a transformation temperature difference of 227°C (Bs $_{\text{(OK 75.78)}}$ = 503°C – Ms $_{\text{(LTT)}}$ 276°C = 227°C). Shiga [ 2 ] presented qualitatively similar results for fillet joints welded with filler materials with Ms temperatures of 100 and 440°C. A difference in the transverse residual stresses of about 200 MPa was in this case measured at the weld toe.

It is expected that further studies will concentrate on the effects on fatigue properties and also on the influence of the restraint on the residual stress distribution. The influence of local microstructural changes in the vicinity of the weld on ND diffraction results also needs to be studied in more detail.

## 5. Conclusions

The influence of the weld metal chemical composition on residual stress distribution has been studied by neutron diffraction. Single pass test welds were produced under restrained conditions in high strength steel. Two welds, different in Cr and Ni content, one conventional with 2%Ni and one experimental with 6%Cr and 6%Ni were tested. The first weld was deposited with the commercial electrode OK 75.78 and the second was produced with an experimental LTT electrode. All three stress components Rx, Ry and Rz were measured after releasing the test specimens from the test frame, thereby removing the external restraint.

Results can be summarised as follows:

- the application of the experimental LTT filler material produced compressive Rx stresses and lower Ry and Rz stresses in the location of minimum stress approximately 5 mm from weld centre,
- a tensile transverse Rx stress of 200 MPa for OK 75.78 test weld and compressive Rx stresses of approximately -100 MPa for LTT electrode were measured at this location,
- compressive through thickness Ry stresses were identified for both test filler material but were lower for the LTT test weld,
- the longitudinal Rz stress component was in the range up to 150 MPa for both filler material but generally on a lower level for the LTT weld.

The results clearly show that the residual stress distribution is influenced not only by welding conditions but also by metallurgical effects governed by the weld metal transformation behaviour.

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