Relaxation of Welding Residual Stresses in Tubular Joints under Multiaxial Loading

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ABSTRACT. *In spite of an increased awareness of welding residual stress threat to structural integrity, the extent of its influence on fatigue strength especially under multiaxial cyclic loading is still unclear and matter of debate. This uncertainty which leads to conservative assumptions in fatigue design codes is based on the lack of insight into the initial welding residual stress field and its behavior during the three phases of fatigue damage namely; crack free, crack initiation and crack propagation periods. Since a significant amount of fatigue failures in welded joints are caused by torsion or combined tension-torsion in machinery components, estimating the potential threat of the inevitable residual stresses to structural integrity seems to be mandatory for the design of the future lightweight welded components and structures.*

In this paper the axial and hoop residual stresses in cylindrical specimens with bead on tube welds out of S355J2H were determined experimentally by means of x-ray and neutron diffraction. After discussing briefly the sources and origins of the residual stress field, its behavior under pure torsional and combined tension-torsion loading will be presented.

INTRODUCTION

The lack of clarities in estimating the residual stress threat to the structural integrity has led to conservative assumptions in the current fatigue design of welds. In fatigue design books [1, 2] and codes [3, 4] residual stresses in welded components are assumed to be of yield strength magnitude. It is also assumed that in general the influences of residual stress and mean stress on fatigue are equal and the distinct differences between these two concerning source, distribution and relaxation under load is not considered. Based on these assumptions a mean stress independency of the fatigue strength is postulated i.e. regardless of the stress ratio, it is recommended to use the S-N curves which are evaluated under pulsating tension loading. The complexities concerning the residual stress influence manifest themselves even more in the case of multiaxial fatigue in which the majority of welded components e.g. power generation and transmission, aircraft and marine engines suffer fatigue failure. In multiaxial fatigue investigations of welds by Siljander [5], Sonsino [6], Maddox [7], it has been almost always avoided to consider the effect of residual stresses by using stress relieved specimens and components in order not to be disturbed by their influence on fatigue. Thus the experimentally determined residual stresses in tubular welds are scarce and not as wide spread as those of the flat welds. A deeper insight into the source and nature of residual stresses in tubular welds based on experimental work is the first step towards better understanding their threat to the structural safety. In the second step the behavior of the residual stress field under multiaxial loading should be studied.

EXPERIMENTAL WORK

In order to study the residual stresses in tubular welds, S355J2H was chosen as the base material. The metallurgical analysis of this steel revealed a ferritic-pearlitic (figure 1) microstructure with an average hardness of 180 HV10.

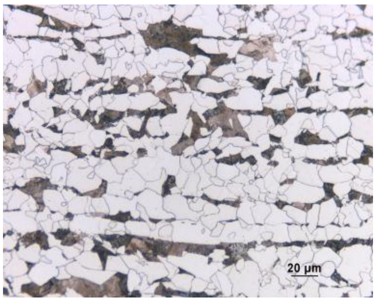

Figure 1. Microstructure in S355J2H

Welding the specimens

After machining the specimens to their final dimension and before welding, they were all stress relieved thermally at 600^{o}C for 30 minutes in order to have specimens in similar material condition before welding. In order to produce the specimens, the tubes were fixed horizontally at one end in a rotating fixture and the welding torch was held vertically above the tubes. By rotating the tubes 5mm-wide beads (dummy welds) in the middle of the specimens were produced with filler wire (figure 2). This type of specimens was chosen for this investigation because of some reasons. One reason is that in the previous investigations [8] the similarity of the surface residual stress fields in bead on plate and multiple pass welded specimens out of the same base materials were shown. Another fact is that by producing the sample in this way weld defects in the root side which could be the fatigue crack initiation sites are eliminated. It makes studying the surface residuals stresses under loading easier. The angular misalignment and its effect on fatigue would be also excluded and only the influence of the residual stress could be studied.

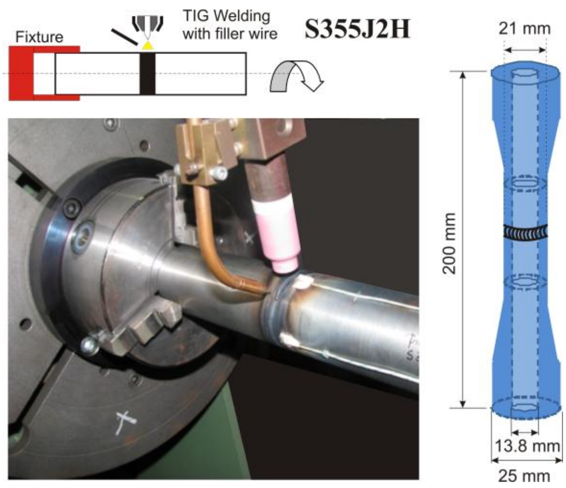

Figure 2 Representation of welding the specimensthe and dimension of the investigated samples in this study.

The geometry of the weld surface profile and the dimension of the welding zones and their characteristic microstructures are presented in figure 3. The hardness field measurement by means of ultrasonic contact impedance (UCI) shows an average hardness of 180 HV in the base metal and higher values up to 340 HV in the weld metal.

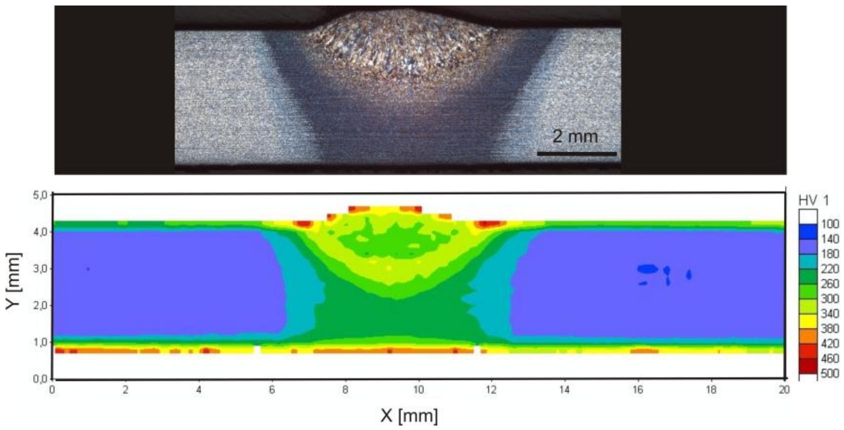

Figure 3 Cross section of the weld bead and the corresponding hardness field determined by means of UCI method.

Residual stress analysis

Based on the x-ray diffraction technique, the residual stress determination was accomplished by using Cr-K_{α} radiation (35kV, 30 mA) and studying the interference line from {211} ferrite, bainite and martensite lattice planes under seven tilt angles (ψ) 0^o, 13^o, 18^o, 30^o, 39^o, 42^o and 45^o for 2θ between 149^o and 163^o. The diameter of the collimator was 2 mm. For the stress determination the $\sin^2\psi$ method [9] was used. The scatter band at the base material was +/- 10 MPa and at the irregular places such as weld toe and bead amounts +/- 40 MPa.

Initial residual stresses in tubular specimens

The surface residual stresses in axial and hoop directions on 4 parallel lines which divide the tube to four quarters were determined by means of x-ray diffraction methods. The distribution profiles could partly describe the mechanisms of the development of welding residual stresses in tubular joints. The residual stress profiles in both directions show a good symmetry on all the Q1 to Q4 lines. The distribution profiles also have the same common characteristic features and the position and the order of appearance of the peaks and dips on Q1 to Q4 lines are the same. In the axial direction the residual stress distributions show W-type profile. The peaks in the weld seam however do not show the same maxima in different quarters. In the axial direction a maximum tensile residual stress of 400 MPa is observed in the weld bead center line. High compressive residual stresses are present in the heat affected zone. Some 10 mm from the weld centerline the residual stresses approach zero. In the hoop direction a maximum tensile residual stress of 300MPa could be found in the weld bead. From the fatigue point of view, it is interesting to observe that the regions of maximum stress concentration i.e. weld toes do not coincide with the regions with maximum tensile residual stresses. The residual stresses at the weld toes (marked with dash lines) which could be potentially the fatigue crack initiation sites are compressive.
The neutron strain scanner instrument E3 at the Helmholtz Zentrum Berlin was used for the in depth determination (Z= -0.336, -0.469, -0.716, -1.117, -1.688, -2.327, -2.828 mm from the surface) of residual stresses. The determined residual stress profiles on the surface by x-ray and the strain mapping in one cross section (Q3) are presented in figure 4. As expected in deeper layers in order to satisfy the equilibrium conditions, the residual stress distributions should be different with that of the surface profiles. The tensile residual stresses on the surface should be in balance with compressive residual stresses in deeper layers and vice versa. The in depth residual stress determination was done using neutron diffraction method. Because of technical limitations in the neutron diffraction technique the residual stresses up to a certain depth from the surface cannot be measured. So there is a gap of data between the surface residual stresses which can be measured by x-ray and deeper residual stresses which could be measured by neutron diffraction. In order to fill this gap the synchrotron measurement technique are planned to be applied as a complementary method to determine the whole residual stress field in the tubular samples.

Relaxation of residual stresses under multiaxial loading

For an accurate estimation of the fatigue performance of welded joints, not only the initial residual stress field but also its variation under load is decisive. The portion of residual stress which stays stable can shift the load stress range much the same way as the mean stresses do in fatigue loading. The relaxation of residual stresses during fatigue loading however reduces this hazard to the structural health. That is, before considering the influence of residual stresses in fatigue, the effect of fatigue on residual stresses should be understood.

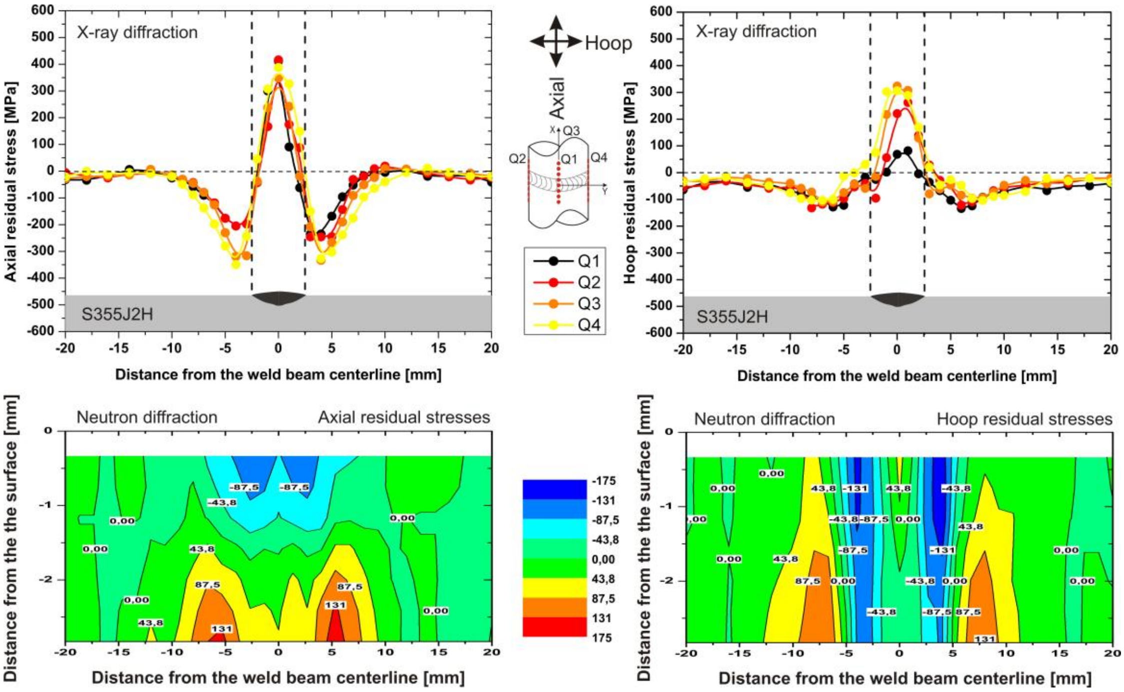

Figure 4. Residual stress field determination by means of x-ray and neutron diffraction.

The specimens which were used to determine the initial residual stress fields in different investigated steels were used for this part of the work. After initial residual stress determination one specimen was further studied under pure torsion and the other under tension torsion loading by a hydraulic material testing machine (Instron 8850, 100kN, 100Nm). The first specimen subjected to gradually increasing torsion load was unloaded at specific nominal shear stress levels where after the residual stresses were determined before re-loading the samples until the next stress level. In Figure 5 the variation of welding residual stresses in the axial and longitudinal detections are shown. By increasing the applied nominal shear stress the first considerable variation of the residual stress field is observed when a nominal shear stress of 261 MPa is applied. In this case the axial compressive residual stresses at the weld toe and in the heat affected zone are relaxed. In the weld bead centerline where high tensile residual stresses are present no changes could be observed. By increasing the moment and thus applied nominal shear stress, the relaxation continues at the weld toe and its vicinity in the heat affected zone, while the tensile residual stresses in the weld bead remain unchanged. The test was stopped reaching the nominal shear stress of 283 MPa since the specimens yielded and reached an angle of rotation of 4 degrees. In the hoop direction some variations in the residual stress profiles is observed but these changes are not as pronounced as the relaxation in the axial direction.

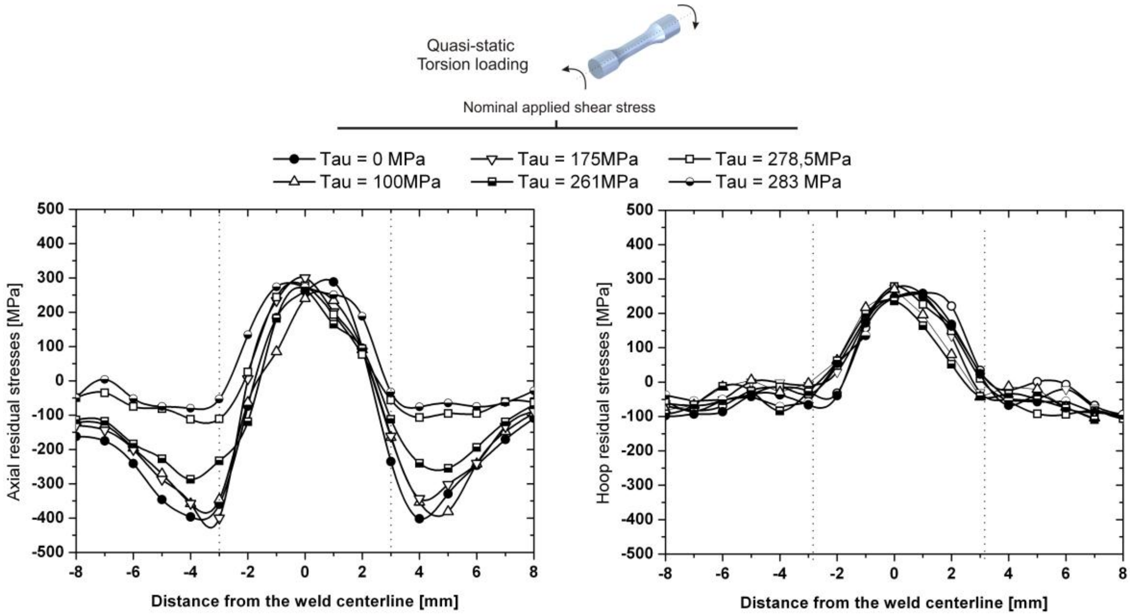

Figure 5. Welding residual stress relaxation under pure torsion.

For the next step the behavior of the welding residual stresses under multiaxial loading was studied. Since a pure nominal surface shear stress of up to 175 MPa did not lead to relaxation in the previous step, it was aimed here to investigate the influence of the combination of 100 MPa surface shear stress with tensile stresses on the residual stress field (figure 6).

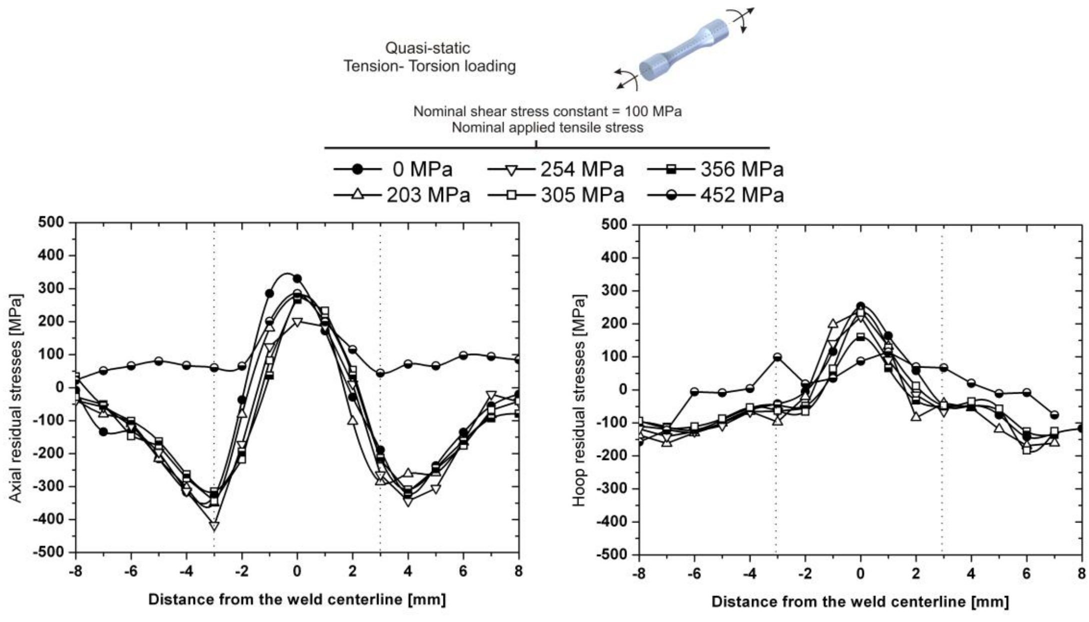

Figure 6. Welding residual stress relaxation under tension-torsion loading.

It is observed that increasing the applied tensile stress combined with the applied torsion stress does not induce a stress state in the weld and its vicinity so that plastic deformation is inevitable. So the residual stresses in both axial and hoop direction show a high level of stability until the applied tensile stress reaches the yield strength of the base material i.e. 450 MPa. At this level of applied tensile load stress the compressive residual stresses at the weld toe and heat affected zone are completely eliminated and transform to tensile stresses. In the weld bead again no changes in the axial direction occur although the reduction in the hoop direction is noticeable.

DISCUSSION AND CONCLUSION

In spite of high tensile residual stresses in the weld bead centerline a gradual increase in the applied shear or tensile load stresses did not lead to a continuous relaxation. In previous studies by the authors [10] on flat welded specimens it was shown that axial loading even at low levels lead to relaxation of residual stresses (figure 7). The relaxation is more pronounced in the transverse direction which is the loading direction.

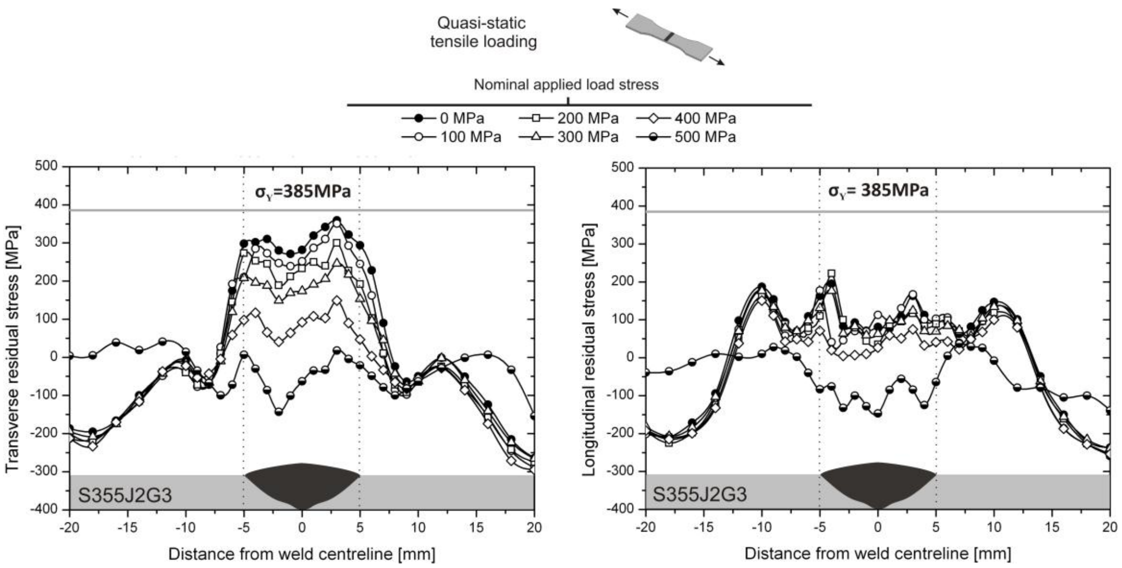

Figure 7. Welding residual stress relaxation under tension loading in flat steel specimens.

In tubular specimens the welding residual stresses are more stable even under high tensile loads combined with torsion loading. In the case of relaxation, the main changes of the residual stress profile occur at the weld toe and heat affected zone. This is because of the concentration of the plastic deformation in these regions under the applied load combinations and thus residual stress field variation. In the weld bead which has a larger cross section lower amount of shear or tensile stresses lead to lower plastic deformation and the residual stress field in these regions remain unchanged.
Compressive residual stresses at the weld toe were present in the investigated tubular joints. If the compressive residuals stresses which stay stable even under high tensile and torsion load are advantageous or detrimental for multiaxial fatigue properties of the specimens should be investigated further.

ACKNWOLEDGEMENT

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