Residual stress determination in mechanically treated weldments with help of different measurement methods

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1. Introduction

The determination of residual stress depth profiles in welded joints with mechanical surface treatments which are applied in welded components with regard to a better fatigue performance is of great importance. The reason is that in principal considerations it could be shown, that the residual stress depth profile in the surrounding of the weld toe resulting from a mechanical post weld treatment can be correlated in combination with the local cold hardening directly with the local fatigue performance and therefore with a definite fatigue strength improvement of the welded joint.

This theory was originally developed in order to evaluate the fatigue behaviour of quenched and tempered steels with a higher ultimate strength after different mechanical surface treatments [Mac85]. However many investigations on welded steels have shown evidently, that this local fatigue strength concept (Fig.1) can be applied also for the evaluation of the fatigue strength of welded joints. From bending experiments it is well known, that the application of mechanical surface treatments is the more effective the lower the plate thickness is [Haa94, Haa98, Mad04, Son04]. This is due to the effect, that the penetration depth of such treatments is usually limited. Because the slope of the load stress gradient over the plate thickness under bending decreases with increasing thickness mechanical surface treatments are of less importance in thick plates because then the cracks may start in the non-affected zones below the surface [NiP06, Dil07]. This means that the benefit of such a treatment is the higher the more the depth profile of the resulting local fatigue strength matches with the profile of the load stresses [NiP06]. Consequently many efforts are made in order to maximize the penetration depth with help of a higher intensity of the treatment [Mad00]. Actually the application of very high intensive hammer peening techniques like the ultrasonic impact treatment (UIT), ultrasonic peening

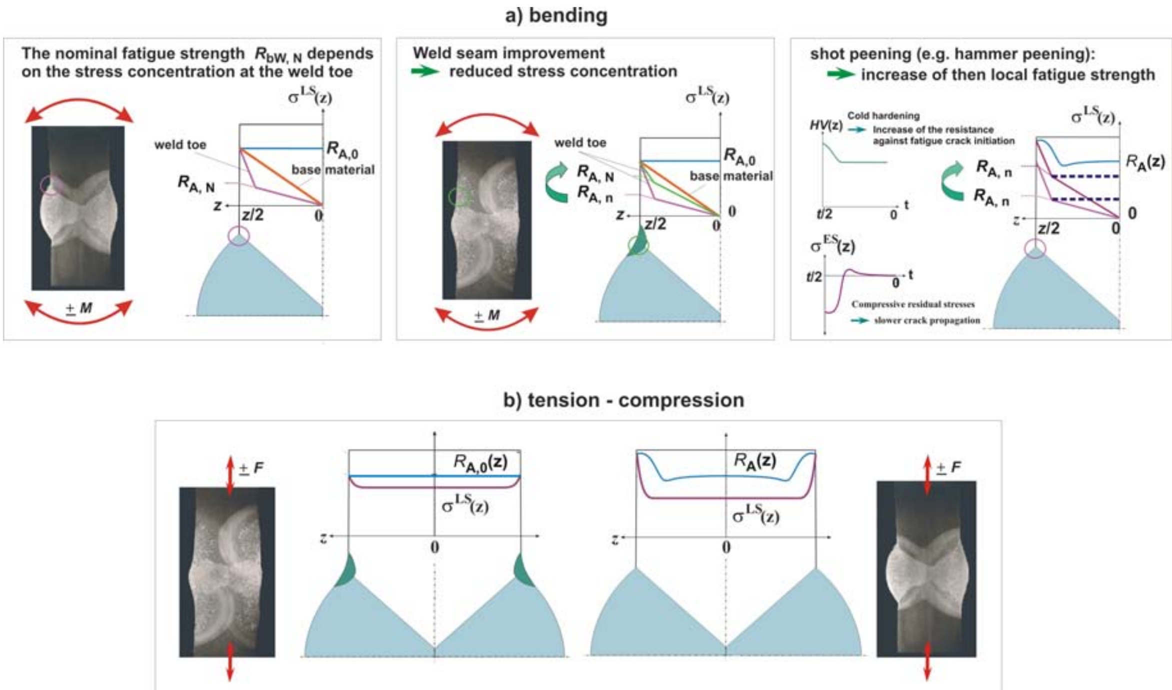


Figure 1: Schematical representation of the influence of compressive residual stresses and cold hardening due to mechanical surface treatments on the local fatigue strength of welded joints.

(UP) or the high frequency impact treatment (HiFit) are very popular in the field of civil engineering [NiP05]. The reasons for the high acceptance of these methods are a simple applicability of the tools and on the other side the so propagated high penetration depth of the generated compressive residual stresses at the weld toes. On the other side a big problem is to control such treatments and that means, that certain methods for the determination of the generated residual stress profiles in welded joints must be available [NiP07]. This requirement is of great importance independently from the question, if a very high penetration depth is required with regard to the best fatigue performance or if a method with lower intensity like shot peening guarantees the same benefit due to its better reproducibility.

The conclusion is, that reliable knowledge about the residual stress depth distributions in the surrounding of the treated weld toe must be recommitted by certain measurement techniques. In this investigation different measurement techniques were combined with the aim to provide comprehensive informations about the residual stress depth distributions at the weld toe of mechanically treated joints.

2. Measurement methods

A state of the art technique for the determination of residual stresses in welded joints which was used generally in this investigation is the X-ray diffraction method. Surface distributions of residual stresses can be determined with high accuracy and a relatively high spatial resolution. The most important advantage of the method is, that due to its non-destructive character measurements can be performed in different stages of manufacturing a welded construction. So the influence of different treatments, for instance mechanical treatments or stress relief annealing can be controlled directly by repeated measurements. Limitations of the method are given by the material condition. Perhaps the coarse grain structure in the heat affected zone of welded steels or in the weld seam of aluminium alloys complicates the measurements. Additionally unfortunately geometrical conditions at the most interesting weld toes, which are an important factor for the failure behaviour under different load conditions are complicating such measurements and are often responsible for results with a lower reliability.

A very important problem is that the depth information about the residual stress distributions cannot be obtained by the results of surface residual stress measurements. For this purpose usually the electrochemical removal of thin surface layers and the repeated measurement at the resulting surface is necessary. A problem is that a smooth surface layer removal is difficult at the sharp notched weld toe even after a local mechanical post weld treatment. On the other side it is not known which influence on the equilibrium stage of the residual stresses is connected exactly with the removal. Furthermore it must be accepted, that the information depth is limited because a removal of much more than approximately 0.5 mm cannot be controlled with a sufficient accuracy. Nevertheless in this investigation residual stress measurements with help of X-ray diffraction were carried out with help of a ψ-diffractometer (see Fig. 3). The {211}- diffraction patterns were measured with a szintillation-counter using CrK_{α}-radiation. The diffraction angles were calculated with a modified Lorenz-function and the residual stress calculation was performed with help of the sin²y-method using the X-ray elastic constant $1/2s_2$=6.08 10-6 mm^2/N.

An alternative method used in this investigation is the hole drilling method. The advantage of this technique is, that it allows the relatively easy determination of residual stress depth profiles by incremental drilling. The spatial resolution is given by the hole diameter and the range of the depth information is also depending on the diameter. For applications on welded joints usually strain gage rosettes with a hole diameter of approximately 1.5 mm are used. The depth information is limited up to a hole depth of just under 1 mm. The problem is, that measurements with the hole drilling method require a plane surface for the application of the strain gage rosette and the smooth generation of the hole. As (Fig.2) shows this condition is not fulfilled at the weld toe respectively at the weld toe after a local mechanical surface treatment. The local hammer peening process produces a very smooth surface but with a radius corresponding to the tip radius of the tool (depending on the tool usually between 2 and 4.8 mm). This leads to geometrical conditions as shown in (Fig.2). The surface below the drilling tool is not plane but an adhesive layer with a thickness which depends on the radius is below the strain gage and the tool. The consequence during applying the hole drilling procedure is that depending on the radius the signals which are produced from the strain gages are not uniformly related to a corresponding hole depth. This means that the general assumptions for the calculation of the residual stresses are not maintained. At least it must be conceded, that the hole drilling method cannot be used for a reliable measurement of the residual stresses at the weld toe. An overview about the entire test equipment used in this investigation is given in (Fig.3)

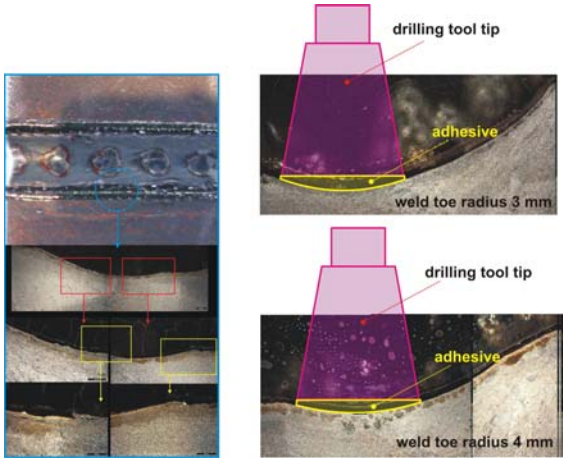


Figure 2: Geometrical shape of the weld toe after different local hammer peening procedures and resulting systematic barriers for hole drilling measurements.

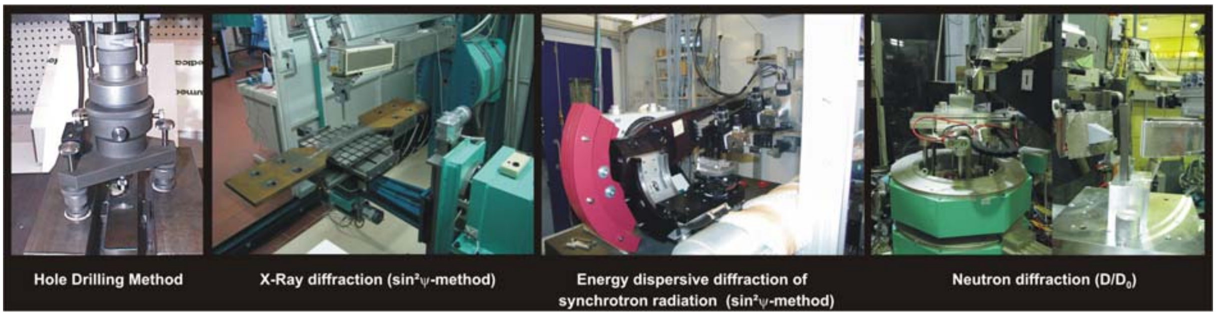


Figure 3: Overview of the used test equipment

However comparative measurements with the hole drilling method where performed on base metal specimens with hammer peened areas as presented in Fig.4. The aim of these measurements was to observe the principal effect of different intensities of the peening processes on the magnitude of the surface residual stresses, on the penetration depth, the cold hardening and the surface roughness. On the other side the measurements in these fields allowed an application and comparison of the results different measurement techniques. In addition to the described investigations high energy diffraction experiments were performed by means of energy dispersive diffraction of synchrotron radiation using the EDDI-Beamline at Berlin electron synchrotron (BESSY) [Gen06] and furthermore by means of neutron diffraction using the E3-diffractometer at the Berlin neutron scattering center (BENSC) of the Hahn-Meitner-Institute [Poe06]. These experiments were performed with the simulated base metal specimens as well as with mechanically treated welded joints of the structural high strength steels S355J2G3 and S690QL.

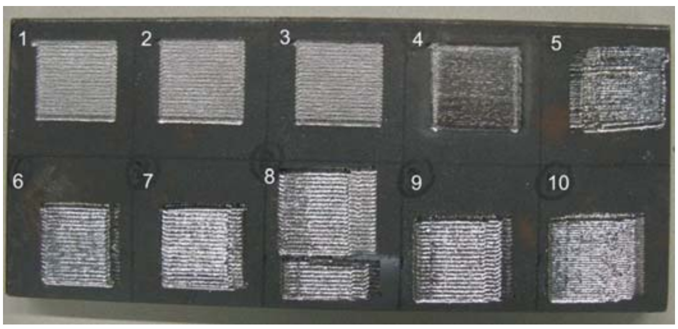


Fig 4: Base metal specimen with hammer peening track generated with different methods and intensities.

3. Experimental results

(Fig.5) shows the typical residual stress distributions which where measured in the fields presented in (Fig.4). Although the series of adjacent tracks where generated on the flat base metal their geometrical and that is to say the shape of the each single track was comparable to those presented in (Fig.2). This means that an application of the strain gage rosette on the treated surface would have resulted in a more or less strong smoothing effect of the adhesive layer between the strain gage and the surface. Consequently the treated surface was prepared by milling 0.1…0.2 mm from the surface tips. The so prepared surface was electrochemically polished to avoid an effect from residual stresses resulting from milling. The consequence is, that the residual stress informations obtained by the hole drilling method started at a depth of approximately 0.2 mm. In the case of a smoother surface after peening with a lower intensity and a larger tool tip diameter this starting depth was close to 0.1 mm. In the diagram additionally the residual stresses measured with X-rays at the treated surface before the layer removal are given. The imaginary connection of these values with the starting values measured with the hole drilling method is not as uniform as desirable but a great leap is not present. Anyway it has to be conceded, that this depth information is not complete. The information about the residual stresses in a thin surface layer of 0.1…0.2 mm cannot be measured with this combination of both methods.

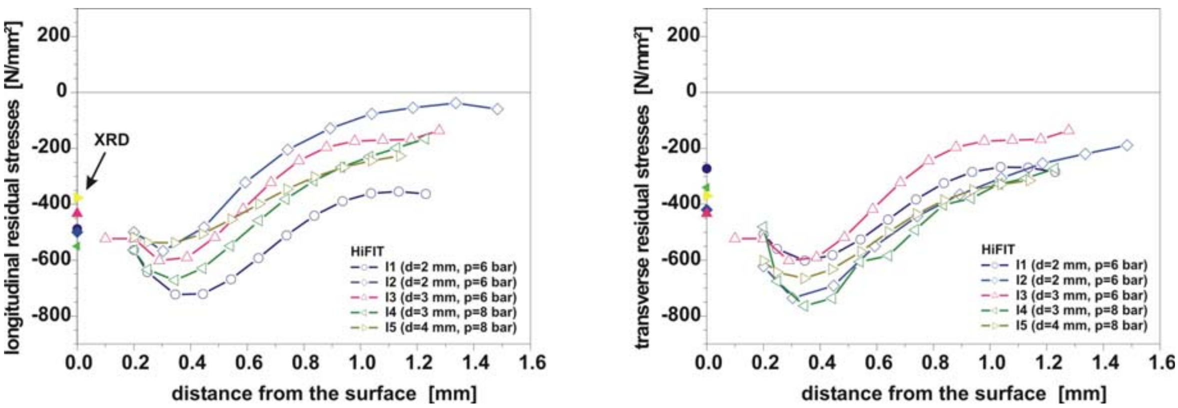


Fig 5: Residual stress depth profiles in HiFIT-treated fields in the base material S690. Treatment was performed with different intensities.(p [bar] is the excitation pressure of the air driven tool).

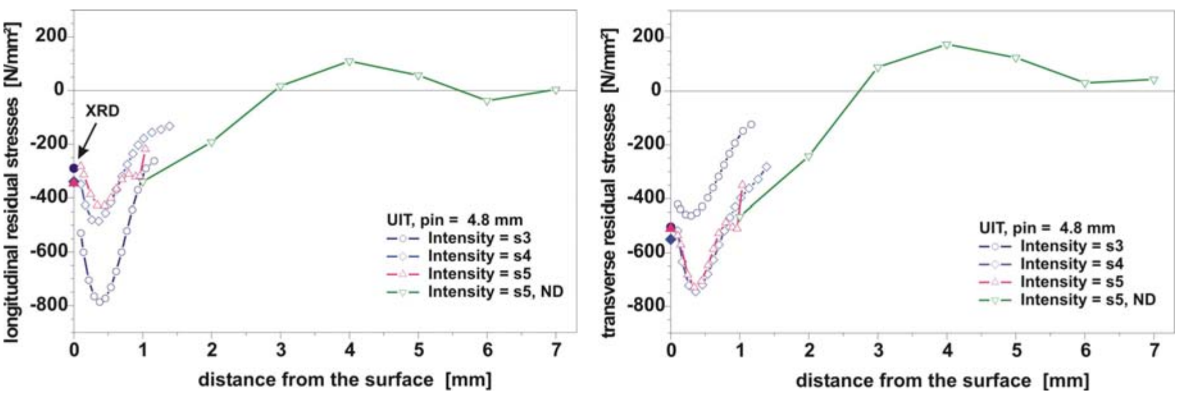


Fig 6: Residual stress depth profiles in UIT-treated fields in the base material S690. Treatment was performed with different intensities. XRD: X-ray diffraction, ND: Neutron diffraction, rest: Hole drilling method. (s3…s5 is a device specific intensity (e.g.tool amplitude) indicator which is not explained more detailed by the manufacturer of the device, s1 is the lowest, s5 the highest possible intensity).

As (Fig.6) reveals the neutron diffraction allows the determination of the missing residual stresses in deeper layers. Fig.6 shows, that the depth profiles determined with the hole drilling method and with neutron diffraction match together rather good. Minor variations of the residual stress values (and this is valid for the results obtained with XRD too) can be explained with an important effect. Due to the

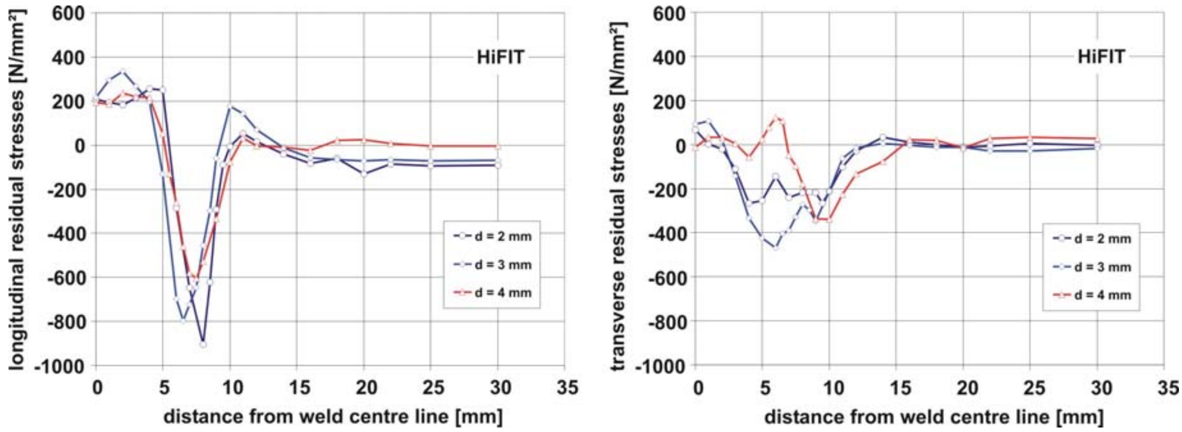
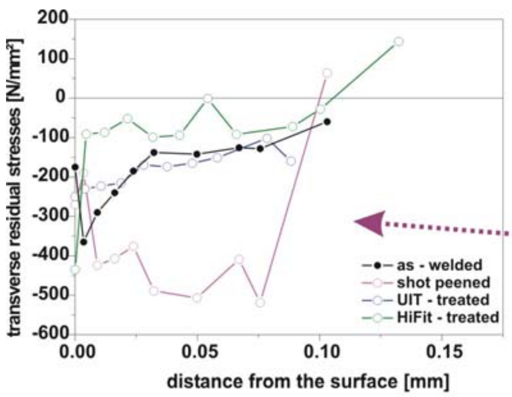


Fig 7: Residual stress profiles around the treated weld toe of double-V-welds after hammer peening with different pin diameters (HiFIT).

strong cold working of the surface layers by the hammer peening process obviously second order micro residual stresses are produced which are included in the residual stresses determined with the diffraction methods. The residual stresses determined with the hole drilling method are affected only by the macro-residual stresses due to the inhomogeneous plastic deformations. Under consideration of this aspect the agreement between the results of the different methods is rather good.

Even if (Fig.6) has shown that the combination of the different measurement methods generally enables to supply a full information about the through thickness distribution of the residual stresses, the results obtained on flat treatment fields cannot be assigned on the adverse geometrical conditions which can be found at the toe of a weld seam. An important aspect is that contrary to the well known



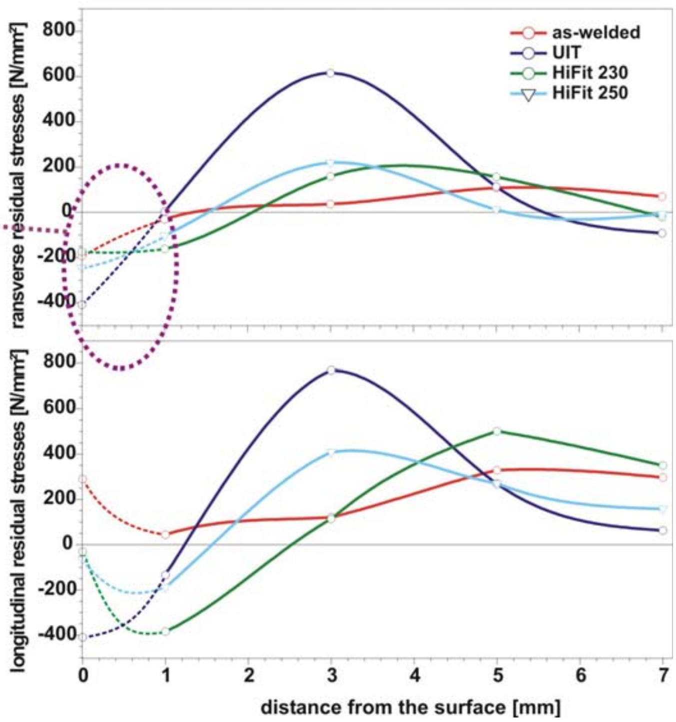


Figure 8: Residual stress distributions in the subsurface region of the weld toe of mechanically treated welds (left hand side: results from synchrotron experiments) and in deeper zones (Neutron diffraction).
HiFit:air driven tool excitation; UIT: ultrasonic excitation of the tool tip.HiFit230=230Hz, HiFit250= 250Hz (tool frequency).

shot peening process, which normally generates a hydrostatic residual stress stage with nearly uniformly distributed residual stresses in every direction the continuous generation of a hammer peening track along the weld toe leads to different magnitudes of the residual stresses in track direction and perpendicular to the track (Fig.7). As (Fig. 8 (right hand side) reveals, the residual stresses in deeper layers of the the weld toe region show significant differences to those measured in flat samples. In a depth of 1….2 mm the high intensity procedures are generating tensile residual stresses and the maximization of the peening intensity (UIT) leads to extremely high tensile residual stresses in deeper layers

(Fig.8, left hand side) shows that the gap of knowledge about the residual stresses in the near surface layers can be closed with energy dispersive synchrotron measurements [Gen06]. The used energy spectrum allowed the calculation of the residual stresses at 10 different lattice planes and that is to say with a depth resolution from 4µm {110} to 110 µm {431}. The residual stresses were determined with help of the $\sin^2\psi$-method using ψ-angles from 0 to 82°. It must be conceded, that the gap in the residual stress profile (resulting from the used resolution for the neutron diffraction experiments of 2x2x2 mm³) could not be closed completely by this procedure. However the residual stress distributions of the surface layers obtained by the synchrotron experiment as shown in Fig.8 (left hand side)

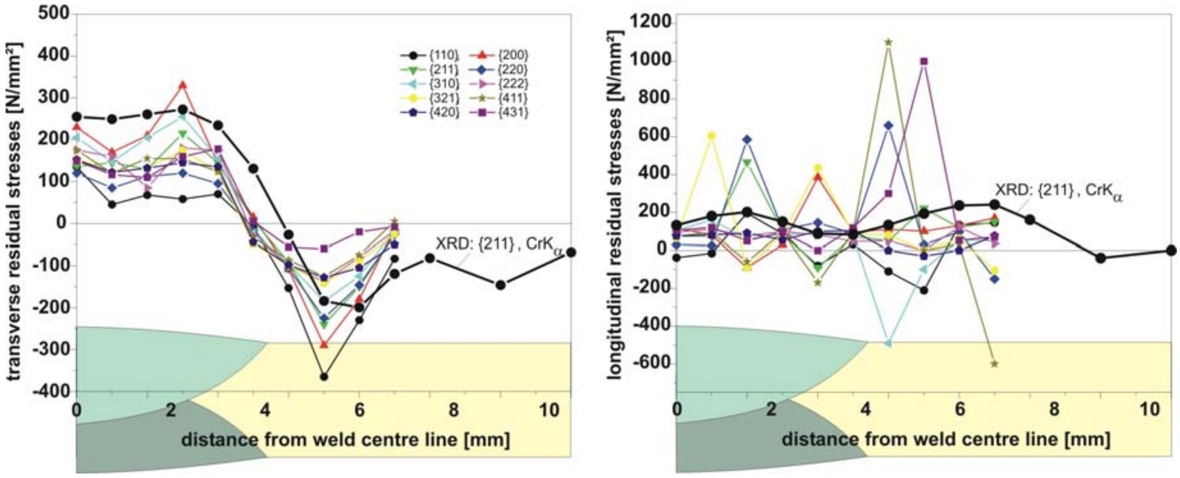


Figure 9: Residual stress distributions from energy dispersive measurements in a TIG-welded sample of the structural steel S355J2G3. Calculations from different lattice planes in comparison to measurements with help of X-ray diffraction. Left hand side: transverse residual stresses, right hand side: longitudinal residual stresses

reveal two very important results. First it can be seen that the results of the synchrotron measurements and the results of the XRD-measurements match together as well as it could be expected. Furthermore it can be seen that the typical residual stress profile of the shot peened specimen can be found, while the distributions in the hammer peened samples are scattering with relatively low compressive values.

A problem of the setup used for the synchrotron experiments is, that due to the configuration of the

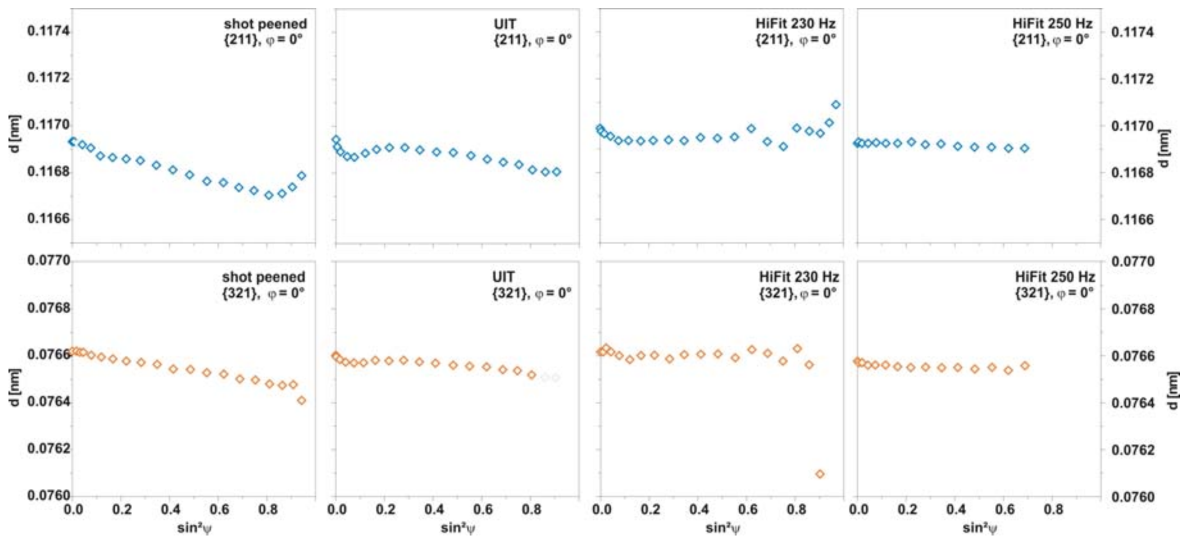


Figure 10: d-$\sin^2\psi$-distributions of mechanically treated samples measured with synchrotron radiation.

beam geometry both residual stress components (transverse and longitudinal) cannot be measured without limitations. As (Fig.9) shows the transverse component can be measured obviously with a high accuracy. The comparison with the residual stress profile measured at the surface with XRD shows a rather good agreement with those measured in different depth layers. On the other hand the distribution of the longitudinal residual stresses and that is to say the residual stress component in weld direction is characterized by a huge scatterband with unrealistic single values which are not matching with the given material properties. This can be attributed to the beam geometry with a 2Θ of 14°. This flat angle was chosen in order to maintain a higher number of diffraction lines. Unfortunately this results in the consequence that at certain positions at the weld toe and in the weld seam the weld builds a barrier for the reflecting beam at a large number of higher ψ-angles. This leads to a stronger scattering of the related D_ψ -$\sin^2\psi$-distributions with the consequence of a poor reliability of particular single values.

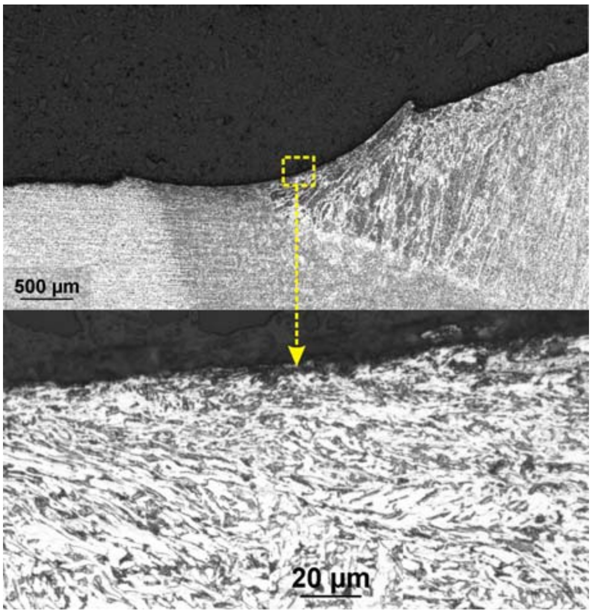


Figure 10: shape of a UIT-track and oriented grain structure in the centre of the track surface.

A further important result of the investigations can be demonstrated with Figure 10. Here the d- $\sin^2\psi$ -distributions of the {211}- and of the {321}-lattice planes measured at the weld toe are given. Due to the geometry of the treated zone the measurements could not be performed up to the highest ψ -angles in all specimens. On the other side the distribution show a tendency of a stronger scattering with increasing intensity. The UIT-specimen even shows a tendency of a lightly texture after the treatment. This effect which is obviously a result of the combination of a high deformation intensity and a continuous movement of the tool with a manually controlled velocity and a high angle between the tool and the surface can also be seen in the oriented grain structure at the surface of such a track (Fig.11).

4. Conclusions

The presented investigations have shown, that the combination of different measurement techniques enable a reliable description of the entire through thickness residual stress conditions of welded joints with and without mechanical post weld treatments. For further investigations it is of great importance that each method is connected with certain advantages and limitations. General problems are connnected with the local resolution and that means with the beam size or at least with the size of the irradiated area. Since every diffraction method includes the problem, that the quality of the obtained information decreases with the size of the irradiated area or at least the duration of the measurements increase in an unacceptable quantity a reasonable compromise of an improved resolution and acceptabele time effort must be found. As the investigations have shown reliable results with the chosen measurement conditions (2x2x2 mm³ for Neutron diffraction, 1x1 mm² for synchrotron radiation and collimator diameter Ø1.5 mm for XRD) are acceptable compromises, which lead to rather good matching results without unacceptable extended exposure times. However further investigations are necessary to improve the results for instance in order to measure longitudinal components in welds by means of synchrotron radiation or in order to gather layers closer to the surface by means of neutron diffraction. This is desirable because the very easy to handle hole drilling method contains serious limitations with regard to its application for untreated or treated welds. Indeed good agreements between hole drilling and diffraction experiments are generallly possible but the reliability of the hole drilling measurements especially in locally post weld treated zones is only guaranteed, if the local geometry is considered carefully and if a control with diffraction experiments is performed.

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