Residual stresses and near surface material condition of welded high strength steels after different mechanical post-weld treatments"

Th Nitschke-Pagel*, Klaus Dilger*, H.Eslami*, I.Weich**, T.Ummenhofer**,
*)Institute of Joining and Welding, University of Braunschweig
Langer Kamp 8, D-38106 Braunschweig, Germany
**) Institute of Rehabilitation of Buildings and Structures
Pockelsstraße 3, D-38106 Braunschweig, Germany

1. Introduction

Many efforts have been realized in the last three decades to develop methods for a fatigue strength improvement of welded constructions [Haa00, Tak00, Fis02, Nit03]. This is due to the well known effect that the fatigue strength of welded steel and aluminium joints usually is very low after welding in comparison to the base material. Thus the usage of modern materials like fine grained high strength steels does not lead to remarkable improvement of the fatigue strength under alternating or partially tensional loading conditions if the same welding procedures are used. As many investigations have shown a post weld treatment with help of thermal or mechanical treatment methods can be very helpful regarding to the final fatigue strength.

Target of the REFRESH-project, which is supported by the German Federal Ministry for Education and Research (BMBF), where the presented investigations are related to, is to develop strategies which allow a significant extension of the fatigue endurance of welded steel constructions like bridges or the supporting structures of wind energy plants. The beneficial effects of easy to handle post weld treatment techniques shall be used to generate surface hardening and compressive residual stresses in order to extend the life time of such constructions. It is well known, that the benefit of mechanical improvement techniques depends on the combined effect of an increasing hardness due to cold working of the surface, on the magnitude and the distribution of near surface compressive residual stress and on the reduction of local load stress concentrations due to a cold forming of the weld toe. Each of the available treatment techniques has certain advantages, and the results which are summarized in literature do not reveal, that a certain method will lead to the best results under any condition.

Many investigations have shown that post weld treatments which are generating compressive residual stresses are more effective in welds which are loaded under reversed bending. In this case the treatment is the more effective, the lower the plate thickness is or the higher the depth of penetration is. Therefore many efforts are made to increase the intensity of mechanical surface treatments in order to maximize the amount of the compressive residual stresses as well as the penetration depth.

2. Investigated mechanical surface treatment procedures.

In this Investigation three processes are observed. These are the classical shot peening process which is a state of the art method for many industrial applications and two relatively new hammer peening procedures. These are an air pressure driven hammer peening process (HiFIT) and a process where the excitation of the tools is realized by means of ultrasonic waves (UIT). The characteristic feature of both processes is, that the working frequency of the tool which is cold forming the surface, is very high in comparison to older hammer peening techniques. Both methods use a frequency of approximately 200 Hz. This surface treatment with a high intensity leads to strong plastic deformations concentrated at the weld toe. Beside the generation of residual stresses and the cold hardening of the surface the treatment is connected with a deformation of the treated zone, e.g. the weld toe. This results in a shape of the weld toe after the treatment which is related strongly to the shape of the tool, and that is to say the weld toe radius after the treatment is very similar to the radius of the tool tip. Because this radius usually will be much higher than the weld toe notch radius after welding the stress concentrations at the weld toe may be lowered with a beneficial effect with regard to the fatigue strength. Preliminaray Investigations (IIW-Doc XIII-2099-06) have shown, that the geometry of the weld toe after the treatment is very important with regard to the crack initation as well as to the fatigue strength. In relatively soft materials like aluminium alloys a too high intensity of the treatment can produce overlaps or material undercuts with the consequence, that the beneficial effect of the residual stresses and the increased hardness is compensated partially by these new geometrical defects. However in steels the intensity of the treatment is more important. Nevertheless a fine adjusted intensity which combines a beneficial residual stress and hardness profile with an improved geometry is required.

3. Equipment and parameters of the treatment

The shot peening process was performed by a company using state of the art parameters and that is to say no special optimization of the parameters are required. On the other hand the parameters of the hammer peening procedures require an opimization because of less experiences with such methods. Therefore treatments where applied uniformly on MAG-welded specimen of the high strength steel S690Q with transverse butt welds and on specimens with longitudinal stiffeners.

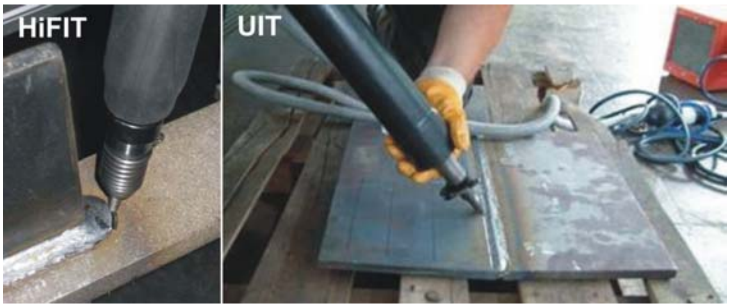

Figure 1: Application of air driven (HiFIT, left hand side) and ultrasonic excited (UIT) hammer peening processes (right hand side).

Both hammer peening procedures use small metal pins which are working with frequencies of less more than 200 Hz at the weld toe. The HiFIT-treatment operates with only one single pin which is accelerated by air pressure. Unlike the UIT-device consists of 2 to 4 pins which are excited by an ultrasonic converter so that also ultrasonic waves are introduced into the treated material. The size and necessary equipment of the devices is also slightly different: The HiFIT device is approximately 20 cm long and needs only air pressure. In order to run the 34 cm long UIT-device a generator and water cooling is necessary. Figure 1 shows the two devices, Figure 2 gives an impression about the shape of the treated zone after the application of both methods.

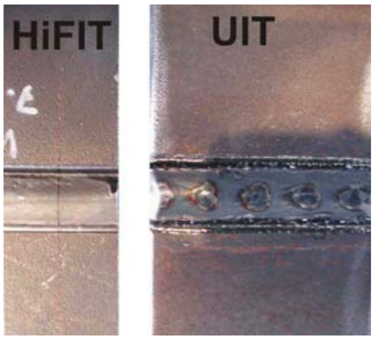

Figure 2: Shape of the weld toe after a HiFIT-treatment (left) and after a UIT-treatment (right).

For both methods the influence of the pin diameter, the angle and intensity of application has been analyzed. Further the influence of the treatment velocity and the number of hammer passes was examined for the HiFIT method. Regarding the UIT instructions the methods has to be applied by moving several times over the same area. Above that two to four pins are used so that in any case a multiple treatment is applied. The residual stresses were determined with help of X-ray diffraction using a ψ-diffractometer. 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 $\sin^2 y$-method using the X-ray elastic constant $1/2s_2$=6.08 10-6 mm^2/N. Depth profiles of the residual stresses were determined after stepwise electrochemical surface removal.

4. Experimental results

Figure 3 shows the micrographs of the weld toe profile of hammer peened double-V-weld specimens of the steel S690Q. The figures show, that the the shape of the weld toe is smoothened corresponding with the hammer pin shape and diameter but at the boarders of the treated zones an overlap is produced which can be understood as a small notch. The modification of the weld toe profile is also demonstrated by the height profiles at the weld toe given in Figure 4, which have been measured with help of a laser triangulation sensor. The comparison of the profiles shows, that the hammer peening

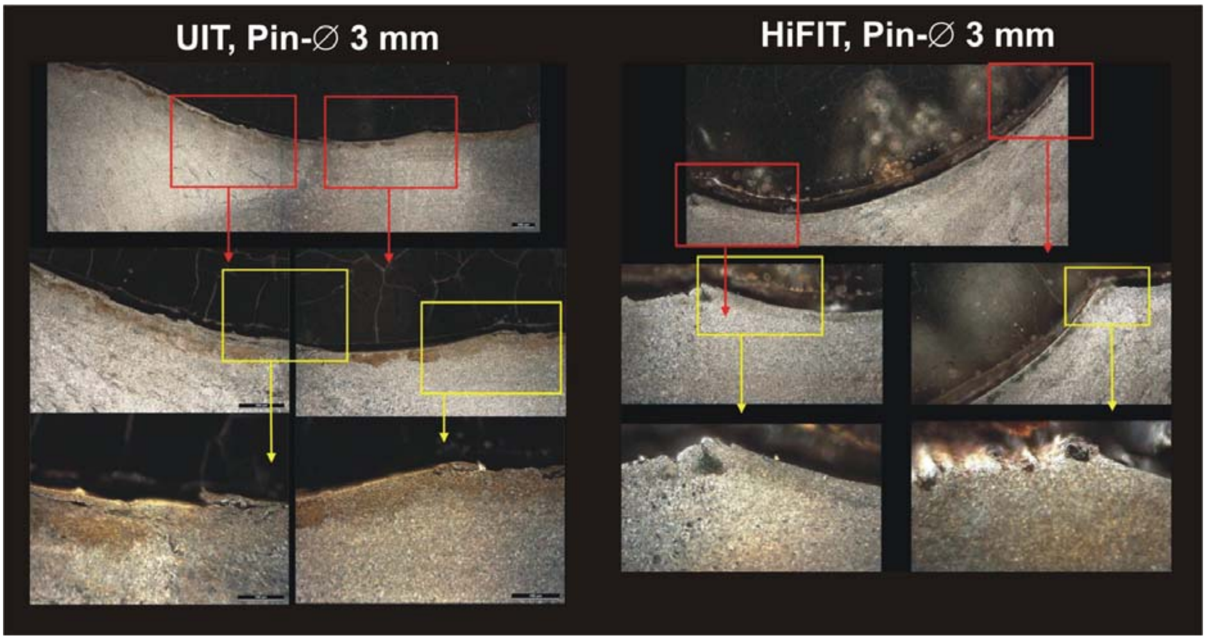

Figure 3: Micrographs of the weld toe region of hammer peened samples, left hand side: UIT, right hand side: HiFIT.

process not necessarily produces an improved profile. The details of the geometry depend on the pin diameter and as well on the intensity of the treatment. Higher intensity e.g. lower diameter leads to an overlap which can be interpreted in the same manor as a sharp notch connected with the weld seam or a welding induced reinforcement.

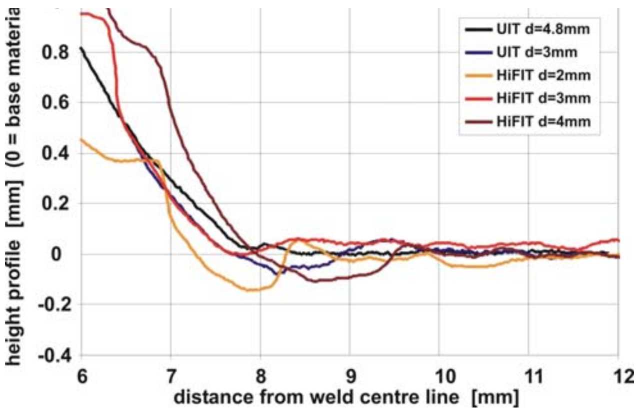

Figure 4: Height profiles of the surface close to weld toe of hammer peened specimens.

Figure 5 shows the transverse and the longitudinal residual stress distributions around DV-welds of the hih strength steel S690 in the as-weled state and after a HiFIT and after a UIT-Treatment. The treatments were applied only at one weld toe in order to show, if the treatment could also lower the welding induced residual stresses as frequently propagated in connection with UIT. The distributions clearly show, that the change of the surface near residual stress state is limited on the treated zone. The plastic deformation of the surface at the weld toe produces a sharp peak of compressive residual stresses. In the adjacent base material and in the weld seam the welding residual stresses are not influenced by the treatment as expected. This is also demonstrated by the distribution of the full width half maximum values (FWHM) of the diffraction lines in Figure 6 which show a strong increase at the weld toe after the different treatments. This is an indicator for the

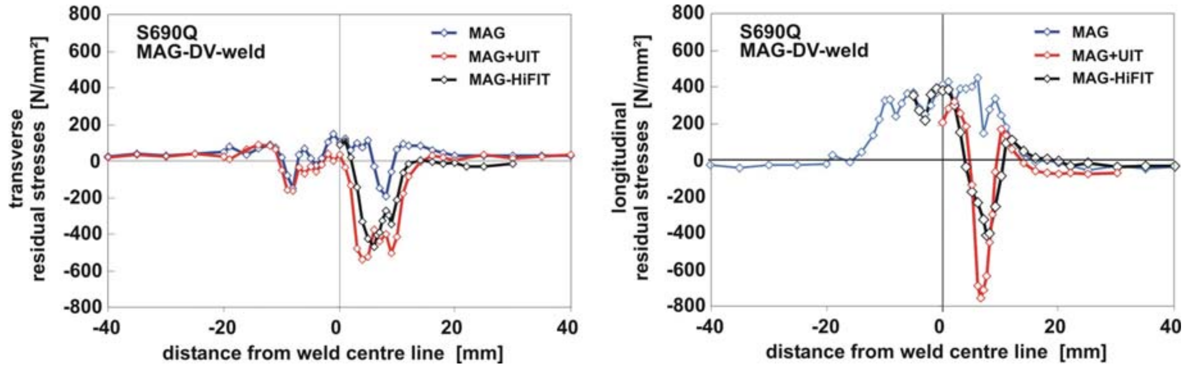

Fig 5: Residual stress distributions in DV-welds after welding and after different hammer peening treatments.

cold hardening effect connected with the strong plastic deformations due to the peening process which is also pointed out by the hardness distributions summarised in Figure 7.

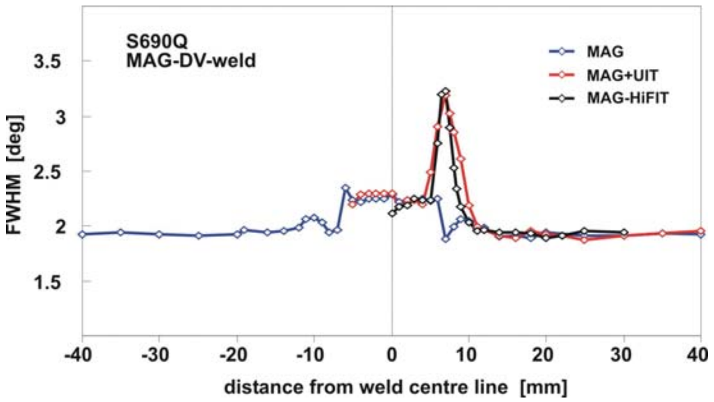

Fig 6: Full width half maximum values of the diffraction lines measured in DV-welds after welding and after different hammer peening treatments.

Figure 8 gives a detailed view about the transverse and longitudinal residual stress distributions generated in the weld toe region with the different hammer peening processes. In this example the air driven HiFIT process leads to the higher compressive residual stresses at the surface in longitudinal direction. The total amount of the transverse residual stresses is equivalent for both methods. It can be asserted, that

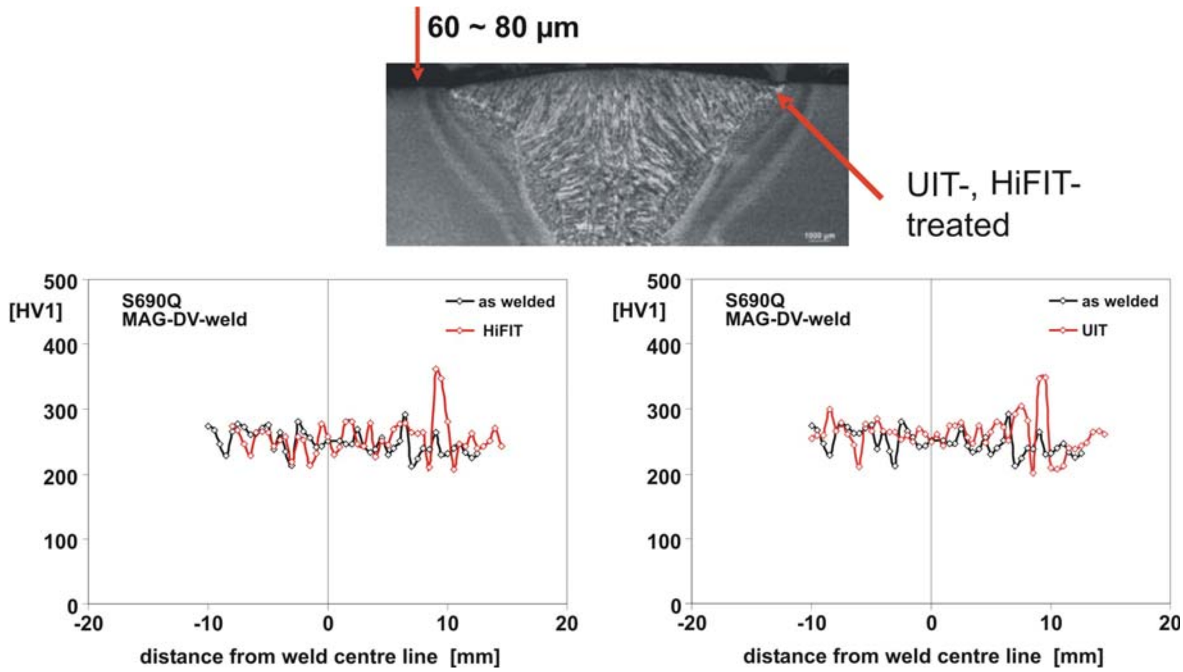

Fig 7: Hardness distributions in DV-welds after welding and after different hammer peening treatments.

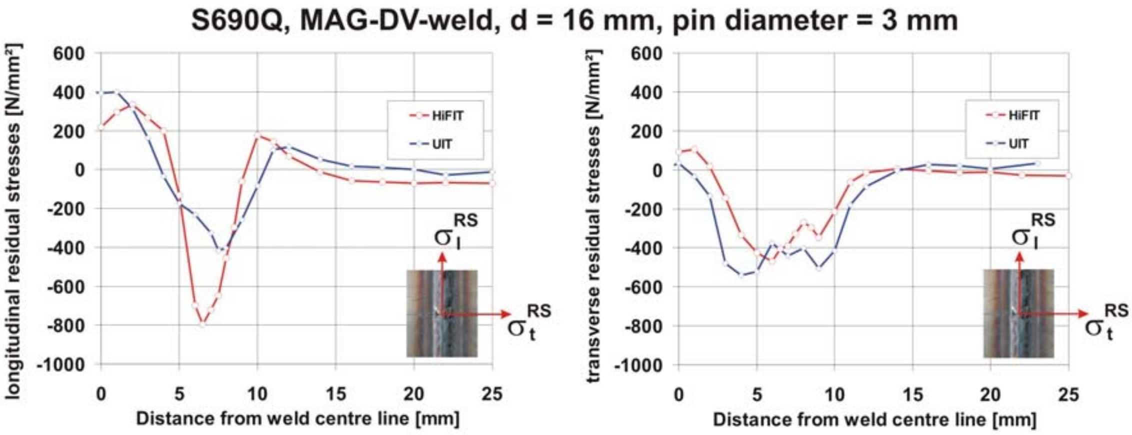

Fig 8: Transverse residual stress profiles at the surface of double-V-welds after a HiFIT and after a UIT treatment.

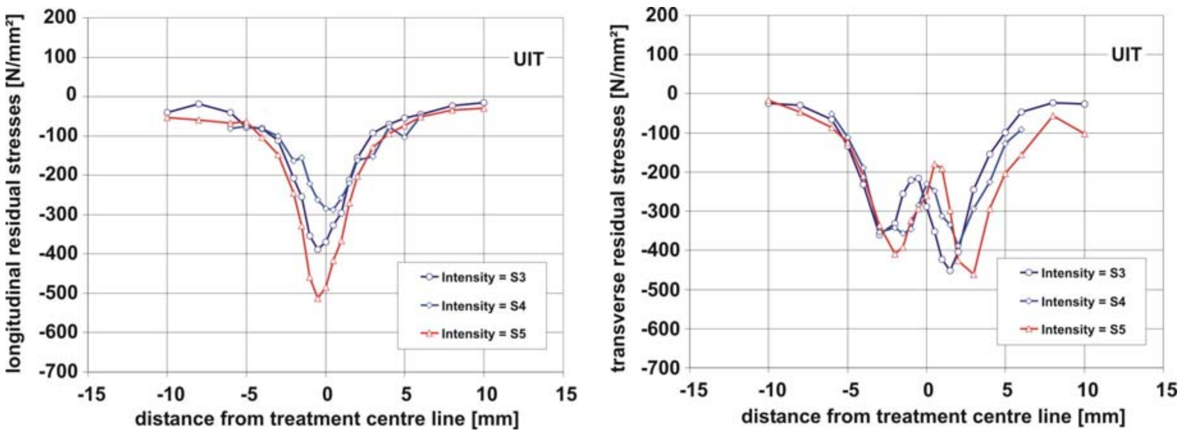

Fig 9: Residual stress profiles around single hamer peening tracks (UIT).

generally the magnitudes of the residual stresses are not uniformly in longitudinal and in transverse direction independent of the type of the treatment process.

The characteristic properties of the induced residual stress conditions depend on the intensity and the details of the treatment parameters. In Figure 9 the residual stresses around single UIT treatment tracks, which were produced in base material samples are given. It can be seen clearly that a higher intensity not generally will generate an improved residual stress condition. The longitudinal residual stresses (e.g. in track direction) increase with higher intensity of the UIT treatment but the magnitude of the transverse residual stresses is not influenced. However in the centre of the treatment zone a relative peak is generated with increasing intensity where the compressive residual stresses are much lower than at the boarders of the track.

As Figure 10 and 11 reveal the pin diameter obviously has no remarkable influence with regard to the magnitude and the characteristic distribution of the induced compressive residual stresses. A larger pin diameter leads to a broadened treatment zone with an improved weld toe profile (see Figure 4) but the magnitude of the compressive residual stresses does not depend on the diameter if the intensity of the treatment is the same.

Another parameter which may influence the treatment results is the tool position in relation to the surface. For instance this position can vary during the treatment if it is performed manually by different operators. Therefore Figure 12 shows the residual stresses at the surface after treatments with different angles of the UIT tools. Obviously a variation of the tool angle between 45° and 90 °has no remarkable influence on the magnitude of the compressive residual stresses. However the broadening

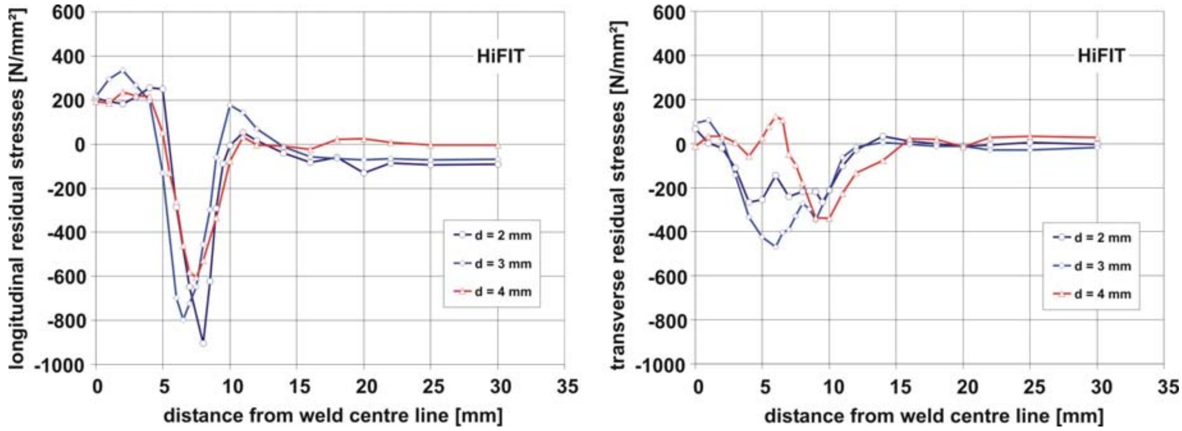

Fig 10: Residual stress profiles around the treated weld toe of double-V-welds after hammer peening with different pin diameters (HiFIT).

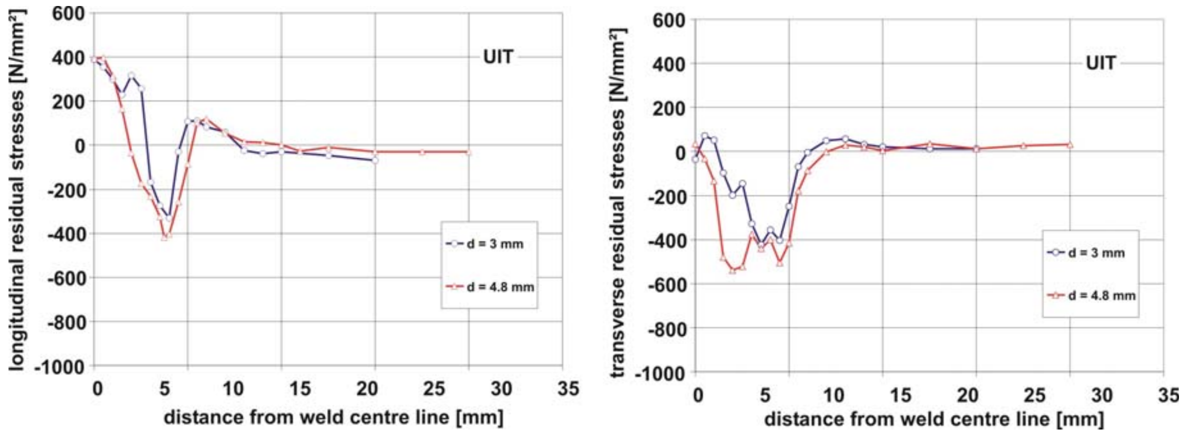

Fig 11: Residual stress profiles around the treated weld toe of double-V-welds after hammer peening with different pin diameters (UIT).

of the transverse compressive residual stress profile indicates, that the flatter application angle broadens the treated zone. This is due to the effect, that a flatter angle complicates the handling of the process with regard to a concentration of the application directly on the weld toe notch. This has to be considered also when welds with very flat weld toe angles shall be treated.

Additional investigations have been performed in order to examine the general depth distributions after different hammer peening treatments. The Figures 13 and 14 show residual stress distributions which have been measured after stepwise electrochemical removal of surface layers. The figures show, that the measurements have been realized up to a depth of approximately 1 mm, which is the limit of the examinable depth. This is due to the effect, that the electrochemical removal o a larger field, which is

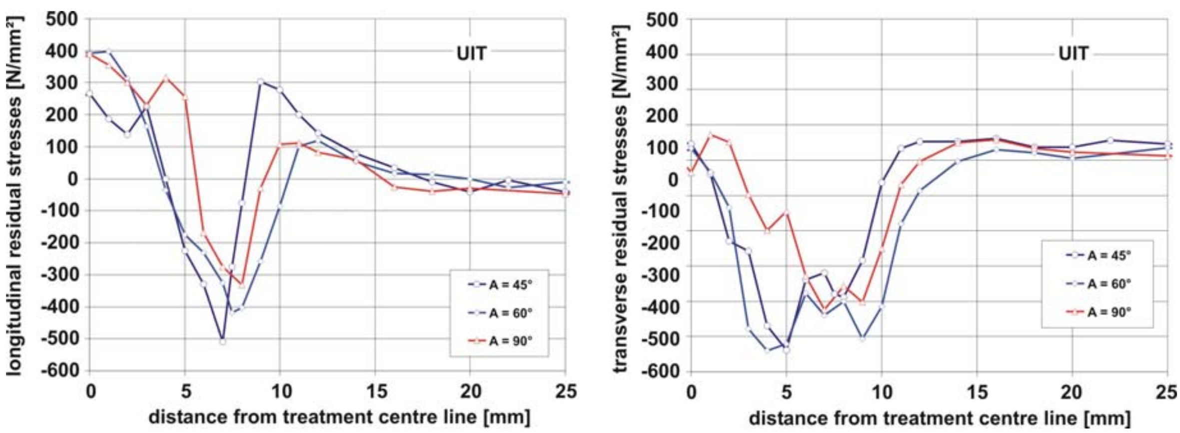

Fig 12: Residual stress profiles around the treated weld toe of double-V-welds after hammer peening with different tool position angles in relation to the surface (UIT).

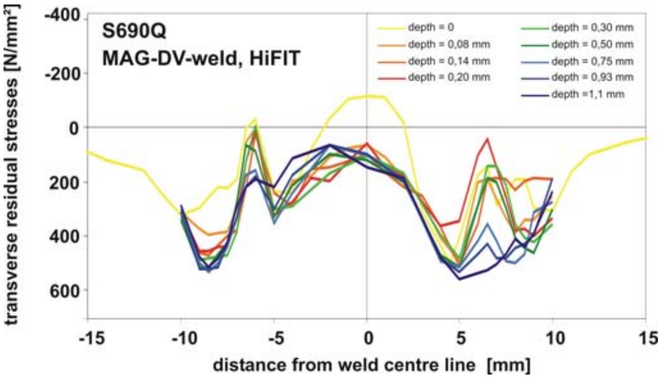

Fig 13: Transverse residual stress profiles in a HiFIT treated specimen measured with X-rays successively after electrochemical surface removal.

required across the weld seam, can be realized uniformly only in a small depth and that is to say up to 1 mm. On the other side the time effort for these measurements is very high. The application of the hole drilling method theoretically would allow a strong reduction of this effort but on the other hand it must be considered, that this method does not work precisely without an adjustment with XRD-measurements in cases where the residual stresses are higher than 50% of the yield strength. Furthermore the hole drilling method

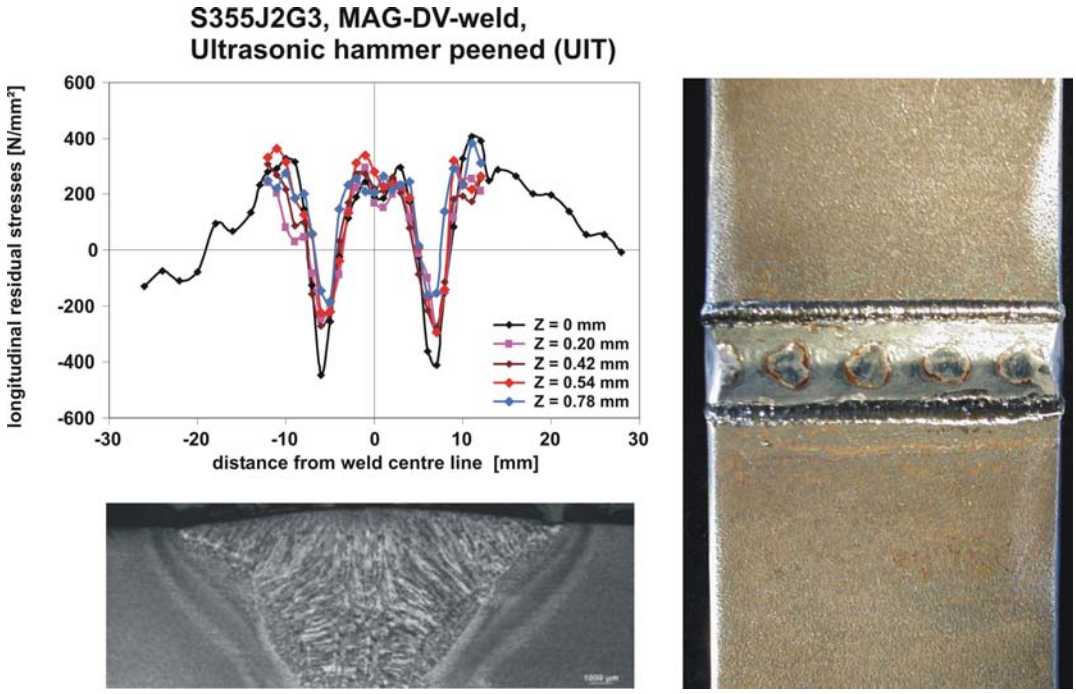

Fig 14: Transverse residual stress profiles in a UIT treated specimen measured with X-rays successively after electrochemical surface removal.

cannot be applied at the weld toe or in a locally hammer peened zones due to the geometrical properties because the requirement of a plane surface where the strain gauges of the hole drilling rosette could be applied is not given . Therefore additional experiments were performed on specimens with larger fields of adjacing hammer peening tracks produced by UIT and HiFIT. An Example for such a UIT-Field is given in Figure 15. The adjacent tracks were produced with help of a robot. However it was necessary to remove 0.1..0.2 mm of the surface by milling, because the strong roughness of the UIT-surface (e.g. the HiFIT-surface) did not allow the application of the requested strain gauges. The milling process was realized very smooth and with strong cooling to avoid the generation of new residual stresses.

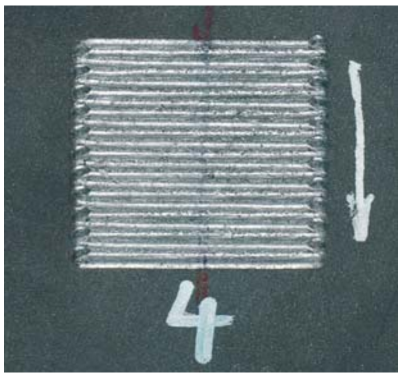

Fig 15: Specimen of the base material S690Q with a Field of adjacing UIT tracks.

The results of measurements in differently treated fields are given in Figures 16 and 17. Figure16 shows results of measurements in HiFIT treated plates, where the intensity of the process was varied with help of a combination of different pin diameters, air pressure and the force which was applied by the robot. The Intensity of the UIT-process was varied by the intensity switch positions which are offered by the equipment. As Figure 16 reveals the highest intensity of the HiFIT process not necessarily produces the highest compressive residual stresses as well as the penetration depth is not influenced significantly by the intensity. The maximum of the compressive residual stresses can be found in a depth between 03. and 0.4 mm and this is a result which could be found after the UIT treatment too. The slope of the decreasing compressive residual stresses with increasing depth is a

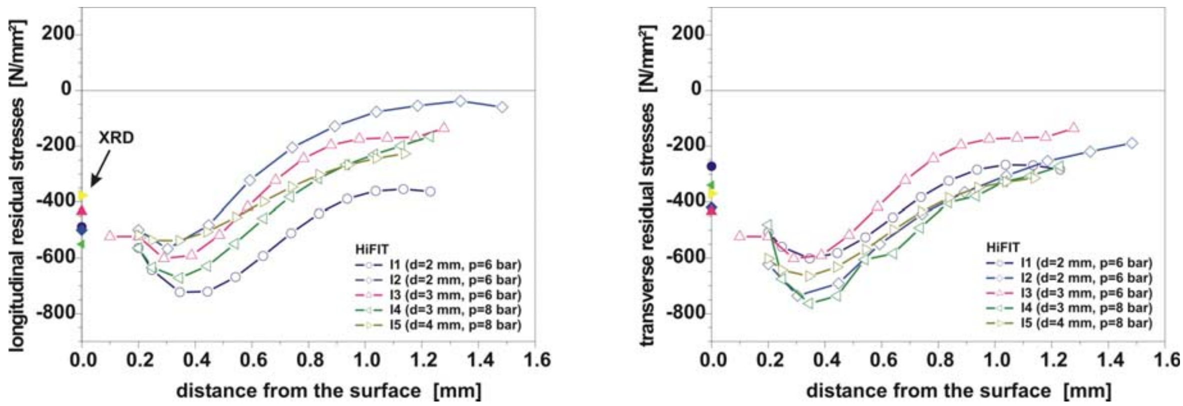

Fig 16: Residual stress depth profiles in HiFIT-treated fields in the base material S690. Treatment was performed with different intensities. (p [bar] is the excitation pressure of the air driven tool).

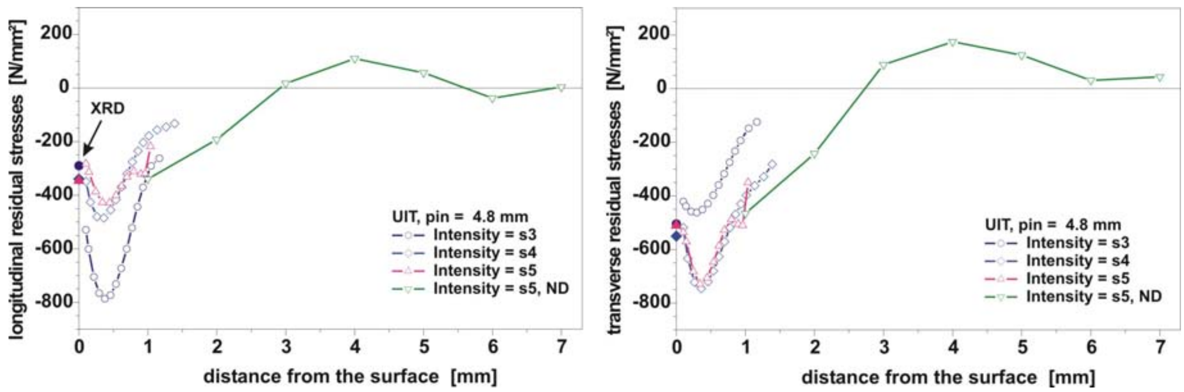

Fig 17: Residual stress depth profiles in UIT-treated fields in the base material S690. Treatment was performed with different intensities. XRD: X-ray diffraction, ND: Neutron diffraction, rest: Hole drilling method. (s3…s5 is a device specific intensity (e.g.tool amplitude) indicator which is not explained more detailed by the manufacturer of the device, s1 is the lowest, s5 the highest possible intensity).

little bit smaller after the UIT treatment. At the surface the compressive residual stresses are lower for all conditions. The surface values which were measured with X-rays match very well with the tendency of the residual stress distributions measured with the hole drilling method. In fact all these measurements are in good agreement with additional measurements which have been performed with help of neutron diffraction measurements up to a depth of 7 mm (Figure 17). These investigations have shown, that the residual stresses also may change into tensile values in a depth of mm. The details of these very new results will be presented later. Anyway the combination of all these measurements results reveal, that the investigated hammer peening processes HiFIT and UIT are able to generate compressive residual stress conditions with a penetration depth, which is significantly higher as it can be realized with shot peening techniques. However the penetration depth is far away from promises, which can be read in some publications where penetration depths of 4 mm and more are mentioned.

However Figure 18 shows, that at the weld toe the residual stress conditions are not necessarily trhe same as in a simulated plane treated zone on a flat specimen. The residual stress depth profiles in this zone indivcate, that a high intensity of the local hammer peening procedure produces extremely high tensile residual stresses in deeper layers. This is an effect which is supported by the weld toe geometry and therefore it can be found only on joints with a real weld geometry. A simulation on flat samples with single peening tracks which allow measurements with alternative methods is not representative. Further investigations are necessary.

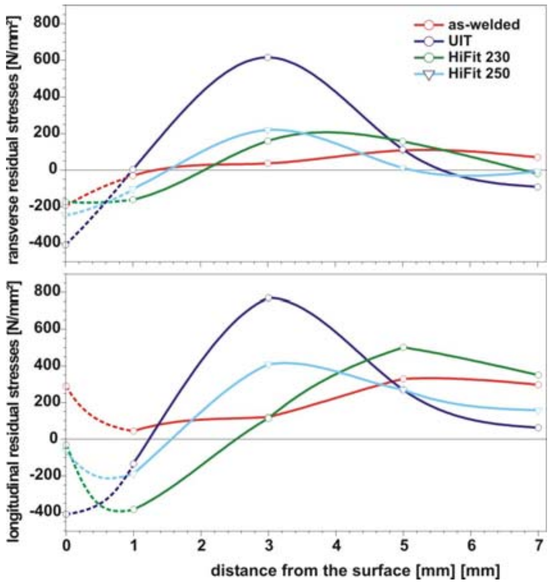

Figure 18: Residual stress depth profiles at the weld toe. UIT = hammer peened with ultrasonic excitation. HiFit = air driven excitation with 230 and 250 Hz.

5. Summary

Residual stress measurements with different methods, e.g. X-ray diffraction, Neutron diffraction and hole drilling method have been performed on welded joints of a high strength steel S690Q in the as-welded state and after different mechanical surface treatments of the weld toes. New high frequency hammer peening methods like the air driven HiFIT-process and the ultrasonic-excited UIT-process have been examined in order to demonstrate the interaction between peening parameters and the resulting residual stress conditions. The results of the investigations have shown, that compressive residual stresses with higher penetration depth than known from other processes like shot peening are generated. The total amount of these compressive residual stresses and their uniformity in different directions depends on the intensity o the treatment, the number of repetitions and the angle of the tools relative to the surface during the treatment. However the highest applicable intensity of the process not necessarily produces the residual stress depth distribution with the best performance. Further investigations will show the stability of the residual stresses due to mechanical surface treatments and their effect on the fatigue properties of the welds.

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