INTERNATIONAL INSTITUTE OF WELDING
A world of joining experience

Delegation of Germany/Austria

IIW Document XIII-WG2-138-13

Pneumatic Impact Treatment (PIT) – Application and Quality Assurance

P. Gerster[1], F. Schäfers[1] and M. Leitner[2]

[1]PITEC GmbH, Germany
[2]Montanuniversität Leoben, Chair of Mechanical Engineering, Austria

Abstract

Post-treatment techniques like the high frequency mechanical impact treatment (HFMI) exhibit a significant fatigue life enhancement of welded joints. In general this effectiveness is primary based on three effects, where as the notch stress concentration at the weld toe is reduced, the local hardness increased and compressive residual stresses are induced. This paper deals with one specific HFMI-method, the Pneumatic Impact Treatment (PIT). First, an overview of the local properties in the post-treated area by weld toe topography and residual stress measurements is given. Further on fatigue test results show a major benefit especially in case of highly notched high-strength steel weld geometries. Second, referring to the recent proposed procedures and quality assurance guidelines for HFMI-treated joints, a main topic of the work is to represent experiences in application and descriptions of reasonable methods in regard to quality monitoring. Topics involve suggestions for staff training, preparation of treatment instructions, verification of post-treatment intensity and visual inspection. A final presentation of the operative range in industrial sector shows the widespread applicability of the presented HFMI-method.

Keywords
High frequency mechanical impact (HFMI), Pneumatic Impact Treatment (PIT), Quality assurance

1. Introduction

One of the most common techniques for joining complex structures in industrial applications is welding. To meet these requirements, an additional improvement in fatigue of welded high-strength steel joints at this stage is essential. Basically, the lifetime of welded structures is dominated by the local fatigue strength at the weld toe or the root wherein crack initiation appears. In the finite lifetime area, the fatigue behaviour of welded high-strength steel joints is beneficial due to the increase in yield limit. In regard to the high-cycle fatigue region, the notch topography, microstructure in the heat-affected-zone (HAZ), and the residual stress state have a significant influence on the fatigue lifetime. According to the IIW-recommendation [1] the fatigue life is independent of the yield strength of welded steel components. Preliminary studies [2, 3] showed that an optimization of welding process parameters, as filler metal and shielding gas, influence fatigue behaviour and may lead to an enhancement of the lifetime of high-strength steel joints in the as-welded condition.

Post-treatment methods upgrade the fatigue resistance significantly by reducing the stress concentration at the weld toe and introducing local compressive stresses at the vicinity of the weld. Several post-treatment methods for welded joints have been investigated and recommendations about the application, fatigue assessment and quality assurance are summarized in [4]. Almost all techniques are only applicable in case of weld toe cracks due to the limited accessibility. The most common are burr grinding [5] and TIG-dressing [6] which only influence the weld toe topography. Processes like stress relief annealing [7] and shot peening [8] are predominant to reduce global distortion and tensile residual stresses of welded structures. Finally, the HFMI-treatment [9, 10, 11, 12] considers both a change of the local notch geometry and a modification of the residual stresses.
In the last few years special attention was given to the HFMI-treatment, industrial driven by the easy to handle application and the significant increase in fatigue. Based on comprehensive fatigue test results [13, 14, 15], proposals for the fatigue assessment of HFMI-improved joints by local approaches are given in [16, 17]. A general and recently updated overview of the numerous different HFMI devices, proposed procedures and quality assurance guidelines is provided in [18].

In this work special attention is laid on the Pneumatic Impact Treatment (PIT). Thereby the operation of the HFMI-treatment device is more user-friendly due to the high frequency of the intenders compared to conventional hammer peening processes. Further on, a finer surface caused by a small spacing between the impacts is achieved (Fig. 1). The intenders are made of high-strength steel with different tip geometries and diameters depending on the weld seam geometry and application.

Fig. 1: PIT-device (hand-held and control unit) and depiction of HFMI post-treatment (by PIT) at longitudinal attachment [19]

In principle influences like the yield strength of the base and filler material, type of weld seam and intender and also the application conditions influence the result of the post-treatment. General values for the HFMI-treated notch topography are recommended in [20] and imply a width of *2-7 mm* and a depth of *0.2-0.5 mm* depending on the radius of the notch. Suggestions for pin design in dependence of the weld seam geometry and a proper application to avoid cracks and failures in the course of the HFMI-treatment are given in [21]. In case of a poor welding quality, intenders exhibiting a great tip radius may cause cracks in the curvature of the weld toe. Therefore, an adjustment of the pin geometry to the type of application is necessary to guarantee a high quality including no initial cracks within the post-treated area.
A limitation of the increase in fatigue strength by HFMI-treatment may be caused by the appearance of alternative failure modes which are documented in [22]. It is shown that the crack behaviour is influenced by the material strength, the type of loading and the post-treatment conditions. One further key influence factor represents the local microstructure. In [23] experimental investigations show an ultra-fine grain microstructure in the HFMI-treated area in case of a high-strength steel, which is significant for the increase of the local hardness and furthermore for the improvement in lifetime.

2. Local properties

A comparison of the weld toe topography by non-destructively inspection with the aid of laser-scanning-confocal (LSCM) and light-optical-microscopy (LOM) is shown in Fig. 2. Basically, the cross section of the welded specimens can be subdivided into three zones; filler metal (FM), coarse and fine-grained microstructures within the heat-affected-zone (HAZ) and the untreated base material (BM).

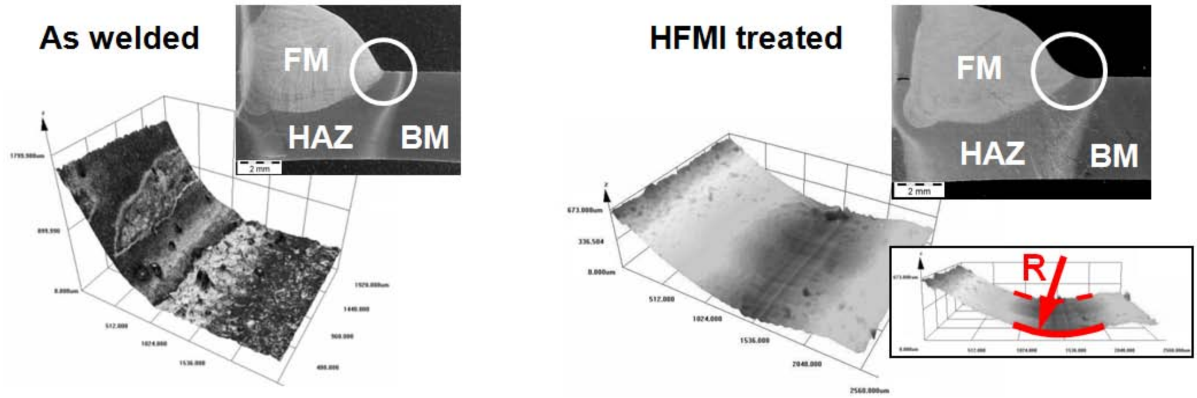

Fig. 2: Local notch topography [24]

The as welded condition shows a sharp geometric transition from the base to the filler metal. In contrary the HFMI-treated specimens exhibit a reduced notch effect by an increase of the weld toe radius (*R=2 mm*) depending on the size of the used pin at the post-treatment process.
Residual stress measurements based on X-ray diffraction technique in case of a high-strength *S960* T-joint are depicted in Fig. 3. Thereby a significant reduction of the residual stresses in transversal (loading) direction at the surface layer due to the superposition of the inherent compressive stresses is recognizable. Measurements in depth show a penetration up to *z=1.3 mm* in x- and *z=2 mm* in y-stress direction.

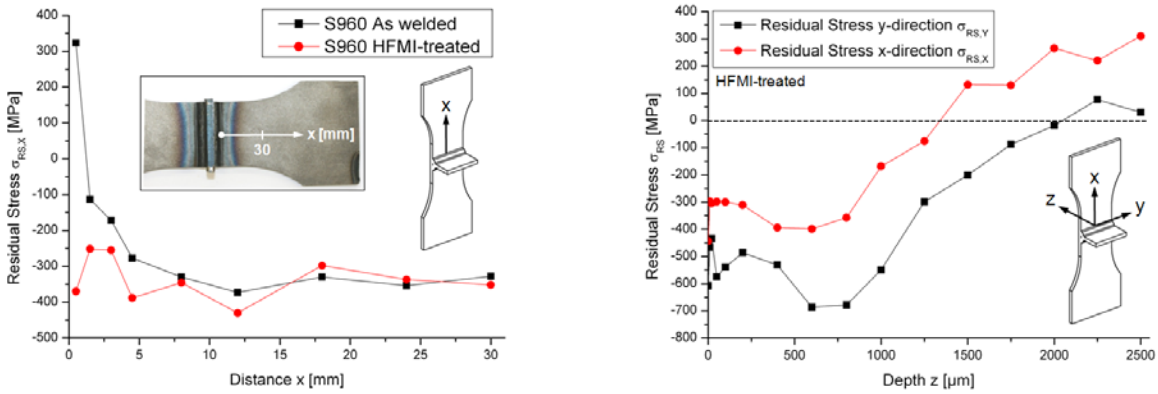

Fig. 3: Residual stress distributions on surface layer (left) and in depth at the weld toe (right) for high-strength *S960* T-joint [24]

In general it can be stated that the beneficial decrease of surface residual stresses by the HFMI-treatment at the weld toe rises by the application of a higher base material yield strength. Precedent measurements of the residual stress conditions in the base material showed maximum values of *-630 MPa* at a depth of *50 µm* for the *S960* steel plate. An explanation for this high compressive residual stresses can be the rolling process where at high plastic strains due to the forming appear.

3. Fatigue test results

In [25] fatigue test results based on butt welds, T-joints and longitudinal attachments on five millimetres, thin-walled specimens are summarized. An excerpt of the results for a high-strength *S960* butt joint and longitudinal attachment is shown in Fig. 4. Herein the HFMI-treated condition offers a high fatigue level, close to the base material fatigue behaviour. In case of the butt joint only a minor increase in the fatigue behaviour is evaluated. A significant benefit is obtained for the longitudinal attachment, caused by a small, highly stressed volume at the weld toe at which the local HFMI-treatment is very effective.

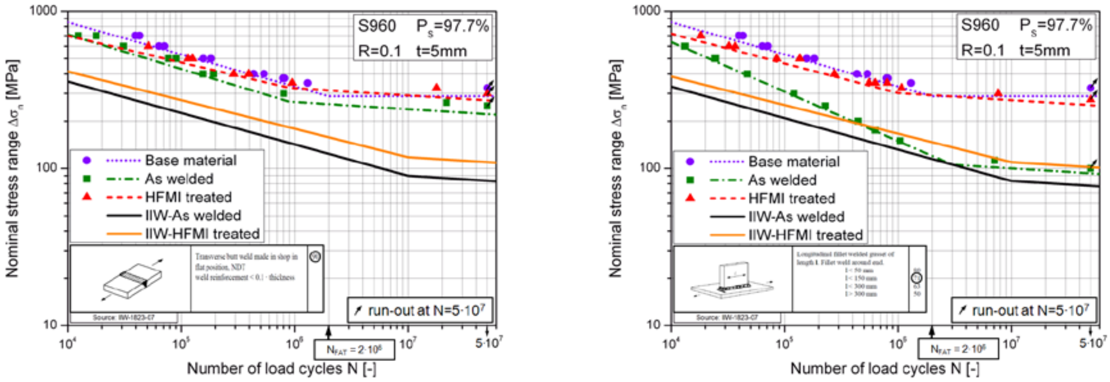

Fig. 4: Fatigue test results for high-strength *S960* butt joint (left) and longitudinal attachment (right) [25]

Summarized, the fatigue test results show that the increase of the fatigue behaviour is mostly dependent on the applied base material strength and the stress concentration at the weld toe. Especially in the high-cycle fatigue region a significant enhancement is achieved caused by a shift of the transition knee point to a lower number of load cycles. Furthermore in case of high-strength steels the fatigue strength of the base material can be reached by the HFMI-treatment.

4. Description of reasonable methods for quality assurance

4.1 Training of staff

In general the post-treatment should only be applied by sufficiently trained users which are aware with the handling of the machine and the purpose of the HFMI-treatment. Only by this way it can be assured that the work is carried out professionally and the post-treated area shows a high quality and possible discontinuities at the welding seam are detected before treatment.

4.2 Preparation of treatment instructions

In order to achieve a desired result, the user should have been provided with sufficiently comprehensive treatment instructions whereat type and scope of the treatment as well as the required parameters are summarized in an understandable way.

4.3 Ensuring intensity of the machine

As a non-destructive measurement of residual stresses is not yet possible without relatively much time and cost effort it is indispensable to ensure the sufficient intensity of the post-treatment device. According to the globally acknowledged “Almen test“, which is common for shot peening, PITEC GmbH developed a feasible test procedure to check the intensity of the device (Fig. 5, left). When setting the machine to “Test“, a test strip is treated two times for *45 sec* in a defined way and afterwards the deflection of the strip is measured as a result of the induced residual compressive stress (Fig. 5, right).

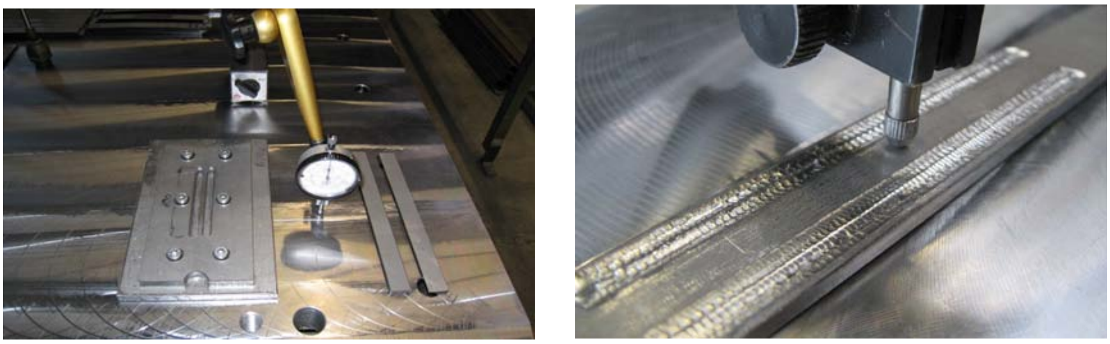

Fig. 5: Testing equipment (left) and measurement of test strip (right)

4.4 Visual inspection

If the user is well trained and the intensity has been checked, it finally has to be ensured that the defined area is completely treated and the notch at the weld toe is completely removed. After treatment the groove needs to be checked for remaining notches, e.g. by a magnifier (Fig. 6).

Fig. 6: Remaining notch of treated groove and magnifier for better recognisability

From time to time the selected radius of the bolt should be controlled by a radius gauge. In the event of high wear the bolt should be exchanged or re-grinded.

4.5 Testing of treated areas

In practice the appearance of seams which ends run out so flat that the actual notch transition is hard to detect at all is quite common. To avoid a non-completely treatment of the actual notch, such areas should also be treated in the vicinity of the weld toe.

4.6 Edges at highly stressed regions

By the aid of a concave bolt, it is possible to post-treat also edges at endangered positions or bore edges, see Fig. 7.

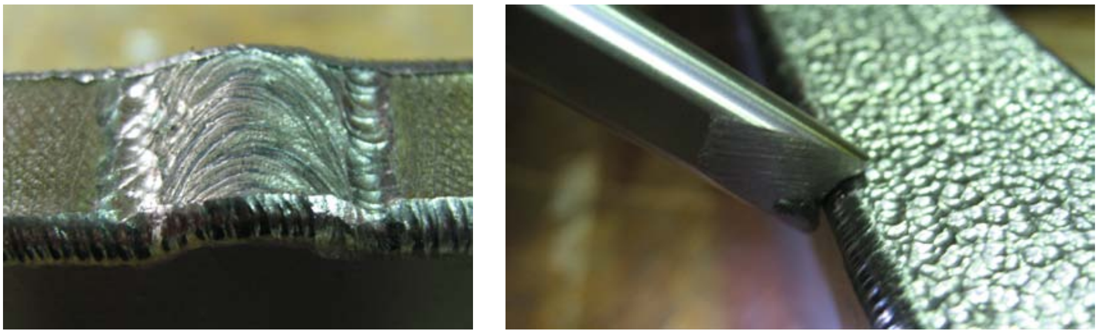

Fig. 7: Edge treatment by concave bolt

5. Unsafe method for quality monitoring

In practice there is a wide variety of different parameters, which may have significant influences on the depth of the treatment groove despite reaching the necessary hardness and desired residual compressive stresses. Such influence parameters are:

- Different hardness profiles along the weld seam
- Undercuts which actually would still be permissible according to the quality standard
- High weld reinforcements with deep transition grooves

Even in the strictest evaluation group B according to DIN EN ISO 5817, undercuts in sheet metals higher than *3 mm* are permitted up to a maximum depth of *0.5 mm*. In this case, a deeper treatment would be necessary. A quality monitoring by only checking the depth of the groove, e.g. by a depth gauge, seems to be an unsafe method, because in practice seam transitions are quite often irregular. A measurement by depth gauge might lead to an improper quality check, due to the reason that unfavourable influencing parameters could lead to a situation at which the depth defined on the gauge is actually achieved, but still a sharp notch might be a remaining. Instead of this method a visual inspection of the remaining notch is preferable safer and therefore recommended.

6. Practical application

6.1 Use of technology in tubular structures

Once this technology has already been successfully used in structures of road bridges, the company DCC Doppelmayr Cable Car GmbH & Co KG has decided to use the PIT technology to increase the lifetime of their steel constructions including tubular joints (Fig. 8).

Fig. 8: DCC cable liner in Las Vegas and guide way with tubular joints

The guide ways for Cable Cars are sometimes routed over roads and motorways, in this case the United States of America have stronger requirements for fatigue strength. These requirements could be fulfilled by the PIT post-treatment without changing the design.
The accompanying fatigue strength tests of the original pipe node of the guide way design were carried out at the University of Stuttgart, Institute for design and development. Since the first guide way was built and post-treated by PIT in Oakland (California) Airport, also parallel, various tests were carried out at the University of Seattle (WA), to obtain the approval of the PIT technology.
The results of several fatigue tests at the University of Stuttgart and also at the University of Seattle (WA) showed an increase of the lifetime by a factor of *4.5* compared to the as-welded condition.

6.2 Application of PIT in the construction of a nuclear fusion reactor

To ensure enough energy resources in future, research focusing on nuclear fusion is being conducted in several countries. Controlled nuclear fusion is a great hope of mankind - all energy problems may be solved. In the reactor "Wendelstein 7-X" in Greifswald this method seems to succeed. By a refined magnetic field, the researchers want to tame temperatures up to unbelievable *100 Mio.°C.* Germany is also working on this technology, e.g. the Max Planck Institute for Plasma Physics (IPP). During the process hydrogen atoms fuse to form helium and set free large amounts of energy. The required cage for the plasma can only be built by a strong magnetic field.

Fig. 9: Plasma vessel under construction and PIT treatment of each weld layer

The reactor weighs *700 t* and the plasma vessel consists of an inner and outer shell. For the base material an austenitic steel *1.4429* and a *1.4455* as filler metal is used. The individual components were manufactured and installed for a trial of MAN DWE GmbH, Deggendorf. Construction started in 2009 and the plant is scheduled to be completed in 2014. Fears that the higher frequency mechanical impact treatment could damage the electronics components were eliminated by an endurance test over several days accompanied by frequency measurements. Fig. 9 shows the plasma vessel under construction and the PIT treatment of each bead to keep the tensile stresses generated during welding to a minimum. The PIT treatment is mainly used during the welding of many supports from the inner to the outer vessel wall. The nozzles should be used preferably without air gap, but this is not possible in practice. For this reason a buffer layer is first welded, and then pushed through the pipe. The buffer layer is deformed by PIT (Fig. 10) and therefore the remaining air gap is closed. Thus, such conditions are ensured that allow a proper use of the shielding gas on the opposite side. Furthermore the heat input is kept as low as possible and in addition the seam is cooled down after welding by dry ice. Then each bead is immediately PIT-treated to keep the residual tensile stresses as low as possible.

Fig. 10: Plasma inner shell and deformation of buffer layer

6.3 Use of PIT at a ladle turret in a steel plant

The ladle turret for continuous casting is a cyclical heavy-duty welded construction (Fig. 11). The manufacturer SMS Siemag is now building the first ladle turret for a German steel plant in Salzgitter where the most highly stressed welds (hot spots) are PIT-treated to enhance the lifetime.

Fig. 11: Ladle turret for a continuous casting machine

SMS SIEMAG decided to create the system more sustainable. Due to numerical calculations the "hot spots" of the system are well known for the post-treatment. In this case the SMS Group would also like to focus the PIT technology for repair purposes.

6.4 Use of PIT in rail vehicles

A rail vehicle manufacturer has already conducted relatively early on a cross joint (with fillet welds) cyclically oscillating bending loads. This welded joint is classified according to the Eurocode 3 to a FAT class of *80 MPa*. The results of the post-treated samples were significantly higher than *160 MPa*, which actually corresponds to the base material. Based on the experiments it can be expected an increase factor of *1.8* in regard to fatigue strength.

In highly loaded wagons to transport complete trucks ("Rola") fatigue cracks at the multiple chassis frame appeared during the driving operation. In considering whether and how this framework can be rehabilitated, the PIT technology was recommended for repair.

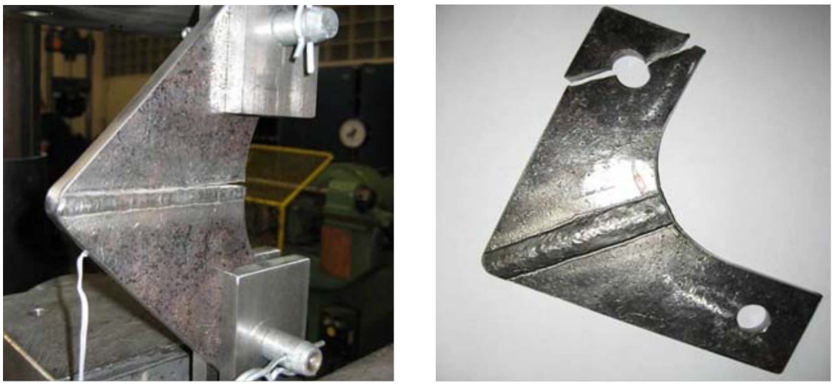

Fig. 12: Crack at *153,000* and failure at clamping after *417,000* load cycles

Fig. 12 shows a sample plate with a weld repair without PIT-treatment and a crack appearance at 153,000 load-cycles. The PIT treated fracture after *417,000* load-cycles appeared at the clamping. Based on this results it was decided to use the PIT technology for repair. Therefore the cracks were properly grouted and sealed by a welding procedure. To keep the tensile residual stresses low, each layer was PIT-treated.

Fig. 13 shows the individual situation of the PIT-treatment. After the repair process the repaired chassis frame was assembled again and fatigue tested under practical load.

Fig. 13: PIT treatment of a steel frame and treatment after each weld layer

At *3.2 Mio.* load-cycles a crack occurred at a non-repaired weld at a reinforcing rib on a tear, which was then repaired in a common way, without PIT-treatment. After further *100,000* load-cycles this region is torn again. At this time each layer was repaired by PIT. Afterwards no further crack initiated at this point. After *8.4 Mio.* load-cycles, a crack occurred on the opposite side at a stiffening rib. After *12 Mio.* load-cycles the experiment was terminated (Fig. 14).

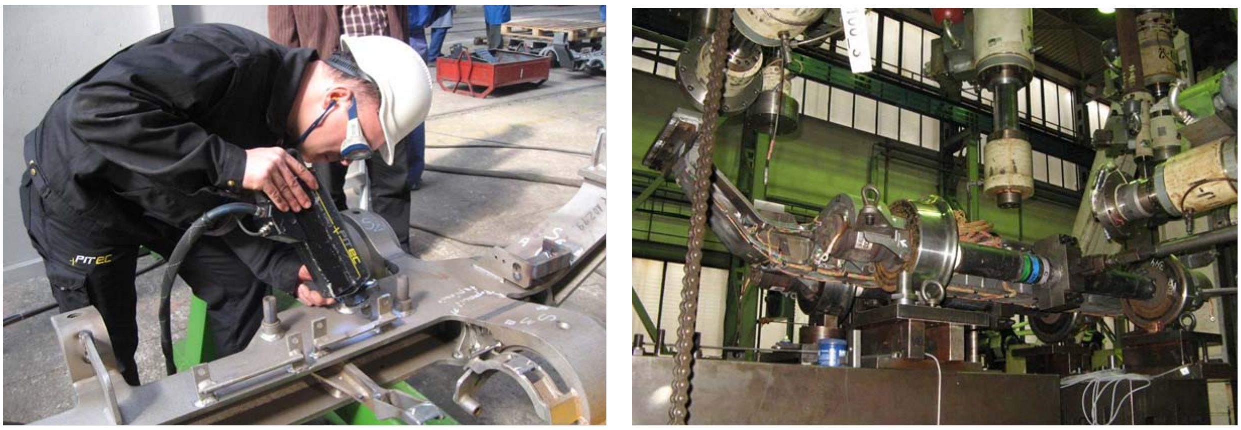

Fig. 14: Preventive treatment of attachments and boogie on the testing machine

It is shown that none of the PIT-treated and repaired welds are torn during the entire term. Furthermore, other vulnerabilities have been identified in reinforcing ribs that have not yet occurred when driving.

6.5 Rehabilitation of large systems (presses, turbines, etc.)

PITEC GmbH specializes aforementioned reasons for the rehabilitation of large-scale systems. Thus the upper part of a forging press with *200 MN* press force, and various turbine housing and other hydraulic presses were successfully repaired in which each individual layer and finally the surface was PIT-treated.

7. Conclusion

Pneumatic Impact Treatment (PIT) is a specific HFMI-treatment method to increase the fatigue life of welded joints, especially beneficial for high-strength steels. The local properties in the treated region, e.g. at the weld toe, are improved leading to a smooth notch transition, a local hardening of the material and the introduction of compressive residual stresses. The effectiveness of the PIT-process using a tool with two millimetre radius was shown by residual stress measurements into a plate depth of up to one and a half millimetres. The benefit in fatigue is extremely high; it is even possible to achieve almost base material strength HFMI-treated high-strength steel joints.

In regard to quality control, an optical inspection is recommended since in technical good workmanship joints undercuts with some tenth of millimetres are quite common. An absolute measurement of the penetration depth in the HFMI-treated weld toe might be insufficient in some manufacturing cases. The presented method contributes to the recent proposed procedures and quality assurance guidelines for HFMI-treated joints.

Finally, an overview of the PIT application in industry is shown by several examples including fatigue improvement in repair welded and HFMI-treated structures. In general a full-penetrated weld is necessary to obtain the fatigue benefits due to HFMI-treatment.

References

[1] Hobbacher A.: IIW Recommendations for Fatigue Design of Welded Joints and Components, WRC Bulletin 520, The Welding Research Council, New York, 2009.

[2] Stoschka M., Leitner M., Fössl T., Posch G.: Effect of high-strength filler metals on fatigue, Welding in the World, Vol. 56, No. 3/4, pp. 20-29, 2012.

[3] Stoschka M., Leitner M., Posch G., Eichlseder W.: Effect of high-strength filler metals on the fatigue behaviour of butt joints, Welding in the World, Vol. 57, No.1, pp. 85-96, 2013.

[4] Haagensen P., Maddox S.: IIW Recommendations on Post Weld Fatigue Life Improvement of Steel and Aluminium Structures, IIW-Document XIII-2200r7-07, 2007.

[5] Zhang Y., Maddox S.: Fatigue life prediction for toe ground welded joints, International Journal of Fatigue, Vol. 31, pp. 1124-1136, 2009.

[6] Huo L., Wang D., Zhang Y.: Investigation of the fatigue behaviour of the welded joints treated by TIG dressing and ultrasonic peening under variable-amplitude load, International Journal of Fatigue, Vol. 27, pp. 95-101, 2005.

[7] Kanga H., Leeb Y., Sunb X.: Effects of residual stress and heat treatment on fatigue strength of weldments, Materials Science and Engineering A, Vol. 497, pp. 37-43, 2008.

[8] Lieurade H.: Fatigue improvement of welded components by shot peening, Proceedings of the International Conferences on Shot Peening, Paris/France, pp. 16-27, 2005.

[9] Gerster P.: Erhöhung der Lebensdauer bzw. der Ermüdungsfestigkeit durch Schweißnahtnachbehandlung, der praktiker, Vol. 9, pp. 302-310, 2009.

[10] Zhao X., Wang D., Huo L.: Analysis of the S-N curves of welded joints enhanced by ultrasonic peening treatment, Materials and Design, Vol. 32, pp. 88-96, 2011.

[11] Maddox S., Doré M., Smith S.: A case study of the use of ultrasonic peening for upgrading a welded steel structure, Welding in the World, Vol. 55, No. 9/10, pp. 56-67, 2011.

[12] Weich I., Ummenhofer T., Nitschke-Pagel T., Dilger K., Eslami H.: Influence of treatment and loading conditions on the fatigue strength of welds improved by high frequency peening, IIW-Document XIII-2218-08, 2008.

[13] Yildirim H., Marquis G.: Overview of fatigue data for high frequency treated welded joints, IIW-Document XIII-2362r1-11, 2011.

[14] Yildirim H., Marquis G.: A round robin study of high frequency mechanical impact treated welded joints subjected to variable amplitude loading, IIW-Document XIII-2411-12, 2012.

[15] Leitner M., Stoschka M., Eichlseder W.: Fatigue enhancement of thin-walled high-strength steel joints by high frequency mechanical impact treatment, Welding in the World, in review.

[16] Yildirim H., Marquis G, Barsoum Z.: Fatigue assessment of high frequency mechanical impact (HFMI)-improved filletwelds by local approaches, International Journal of Fatigue, Vol. 52, pp. 57-67, 2013.

[17] Leitner M., Stoschka M., Eichlseder W.: Assessment of HFMI post-treated joints by the notch stress approach, Proceedings of the 13th International SF2M Spring Meeting, Paris/France, pp. 90-102, 2013.

[18] Marquis G., Barsoum Z.: Fatigue Strength Improvement of Steel Structures by High Frequency Mechanical Impact: Proposed Procedures and Quality Assurance Guidelines, IIW-Document XIII-2453r1-13, 2013.

[19] Leitner M., Stoschka M.: Influence of steel grade on the fatigue strength enhancement by high frequency peening technology on longitudinal fillet weld gusset, Journal of Engineering and Technology, Vol. 1, Issue 3, pp. 80-90, 2012.

[20] Kudryavtsev Y., Kleiman J., Lobanov L., Knysh V., Prokopenko G.: Fatigue Life Improvement of Welded Elements by Ultrasonic Peening, IIW-Document XIII-2010-04, 2004.

[21] Statnikov E., Korostel V., Vekshin N., Marquis G.: Development of Esonix ultrasonic impact treatment techniques, IIW-Document XIII-2098-06, 2006.

[22] Marquis G.: Failure modes and fatigue strength of improved HSS welds, Engineering Fracture Mechanics, Vol. 77, pp. 2051-2062, 2010.

[23] Revilla-Gomez C., Buffiere J-Y., Verdu C., Daflon L., Peyrac C., Lefebvre F.: A study of the effect of microstructure on the fatigue behavior of high strength welded steel treated by hammer peening, Proceedings of the 13th International SF2M Spring Meeting, Paris/France, pp. 72-80, 2013

[24] Leitner M., Stoschka M., Schörghuber M., Eichlseder W.: Fatigue Behaviour of High-Strength Steels using an Optimized Welding Process and High Frequency Peening Technology, Proceedings of the International Conference of the International Institute of Welding, Chennai/India, pp. 729-736, 2011.

[25] Leitner M., Stoschka M., Eichlseder W.: Contribution to the fatigue enhancement of thin-walled high-strength steel joints by high frequency mechanical impact treatment, IIW-Document XIII-2416-12, Denver/USA, 2012.