Fatigue strength improvement of welded joints by means of shot peening and clean blasting

Thomas Nitschke-Pagel, Klaus Dilger, Hamdollah Eslami

Institut für Füge- und Schweißtechnik, Technische Universität Braunschweig,Germany

ABSTRACT

Shot peening is a well established state of the art mechanical surface treatment to improve the fatigue strength of metallic components, clean blasting a familiar process and used frequently in welding practice. The main difference is the peening media used and the minor or missing parameters of clean blasting. The clean blasting process is not yet qualified to optimize fatigue enhancement although it holds similar potential as regular shot peening. Clean blasting is usually applied with the purpose of surface preparation for application of corrosion protection. This article presents results of regular shot peened DV-butt welds made from construction steels S355N and S960QL, The peening parameters are varied widely. The effect of coverage and intensity is investigated to test the robustness of the peening processes. The data is completed with industrially clean blasted welds representing typical workshop conditions. The overall objective of this work is to demonstrate the fatigue strength potential of several variations of peening processes. The results indicate a high robustness of the applied process variations. This indicates high potential of shot peening and clean blasting for fatigue strength enhancement. If clean blasting is accompanied by a simple process control in terms of coverage and intensity the fatigue strength benefit is obvious-

Keywords: Welded joints, fatigue strength, shot peening, clean blasting, residual stresses

1. Introduction

The fatigue strength of welded joints is usually low related to the base material. Since the fatigue strength loss increases with increasing tensile strength due to the stronger notch sensitivity applicable stress amplitudes cannot be improved by changing to a higher-strength base material. Therefore the potential of modern high-strength steels can only be exploited in a meaningful way when high mean stresses are present, since the stress limit is then determined by the level of the upper stress. Extensive investigations over the last 50 years [1,2,6,8,10] have shown that several post weld treatment methods are capable of significantly increasing the fatigue by reducing the notch effect of the critical weld toe fracture. This includes methods such as grinding the seam transitions flat on the sheet or local, or remelting with additional wire-free welding processes like TIG or plasma processes.

Alternatively, mechanical surface treatment methods like hammer-, needle-peening or shot peening are established [4], in which the fatigue strength-increasing effect is achieved through strain hardening of the surface and the generation of favorable residual compressive stresses. While high-frequency hammer-peening processes, which work with high local intensity have recently become very popular and found their way into existing guidelines [5,13], shot peening is still not very common for welded joints, although there is sufficient evidence that it is at least as effective the mentioned methods. Nevertheless a high general scepticism is present about post-weld treatments because their use always involves additional work and costs that one would like to avoid if possible. Another obstacle is the rigid limitation of the usable fatigue strength by the existing set of rules, which is based on the fatigue design rules [3,4], which include a strong limitation of the fatigue strength on the basis of low-strength structural steel. The potential of post-treated welded joints, especially with high-strength materials, cannot currently be exploited in accordance with the regulations, although extensive studies have shown that considerable reserves are available [2,11]. This is particularly important in the current situation in view of the sharp rise in raw material prices and the need for economical and climate-friendly design principles. Better utilization of the strength reserves of construction materials seems urgently required.

In welding practice, clean blasting is a widespread standard procedure integrated into existing production chains. It is used to remove impurities and surface layers from welded or thermally cut components, which would prove to be a quality-reducing factor, e.g. The method is similar to shot peening except a less detailed control of the peening parameters. Since the cleaning effect is the main focus mostly simple shot as quartz sand, gravel or steel shot is used. Anyways clean blasting may also produce improving beneficial changes in surface layers. The aim of the presented work is to demonstrate the potential of different peening treatments and thus to create the prerequisite for an implementation in existing regulations for the fatigue design of welded components.

2. Shot peening and clean blasting of welded joints

Shot peening is a flexible method to modify surfaces of various metallic and non-metallic components. Typical applications are enhancement of surface roughness, cleanliness or enhancement of mechanical parameters and corrosion resistance [9]. The most important peening parameters affecting the fatigue performance are the shot type and size, shot geometry, peening intensity and coverage [10]. The user can influence the kinematic energy of the peening impacts by the choice of the shot type, its size and the impact velocity and additionally the coverage. Steel components are commonly shot peened using steel balls while glass beads are used in case of demands for low peening intensity or with regard to surface finishing. The shot peening process and its intensity is usually adjusted by peening parameters like impact velocity and coverage and the result is controlled by the Almen strip test [11]. Coverage of the surface is defined as the percentage of the peened surface related to the un-peened surface. A coverage of 98 % is the highest coverage value that can be experimentally determined as the indentation spots of the shots are here still distinguishable. A coverage of 98 % is normally denoted as “full” coverage. Higher or lower values of coverage are normally adjusted by a control of the peening time per surface area.

As mentioned the fatigue strength improvement due to shot peening relies on the generation of near surface compressive residual stresses and cold work hardening. According to [5,12] the significance of the generated residual stresses increases with the yield strength of the peened material while in low strength materials the effect of the cold hardening of surface layers is more important due to the higher stability of the residual stress under the particular load conditions which may reduce the residual stresses significantly in weak materials during the first load cycles. Reduction of surface roughness by plastic deformation also becomes more important with increasing ulitimate strength and that is to say in notch sensitive materials like high strength steels and Al-alloys [9]. While the induced compressive residual stress field may retard fatigue cracks or slow down crack growth considerably cold hardening increases the resistance against crack initiation. The residual stress field can be described by the magnitude of the induced compressive residual stress and their depth

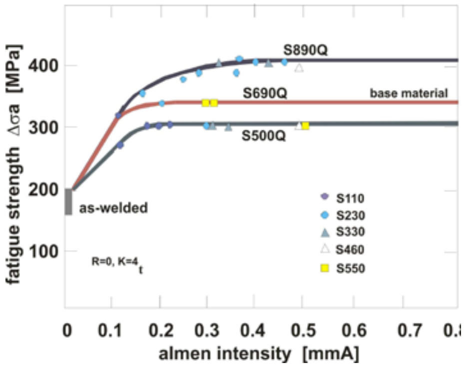

Figure 1: Relationship of peening intensity and expected fatigue strength for welds of different steel grades [1].

profile. Investigations on fatigue strength improvements by shot peening can be found in the literature [2,8,10], where the general benefit is proven clearly. Early investigations [1] have demonstrated clearly the possible benefit of the shot peening procedure, if the intensity is well adjusted to the ultimate strength of the used steel grade (Fig.1).

3. Experimental programme

The experiments where carried out using structural steels S355N (normalized) and S960QL (quenched and tempered), see Tab. 1. The peening media were varied reflecting regular shot blasting (steel shots S280) as well as clean blasting (glass beads and corundum). Further, the coverage (meaning peening time) was varied between 0.25…98% (under coverage) and 2 x 98% (double coverage). Coverage of 25 % reflects the useful lower boundary of clean blasting while 2 x 98% coverage is used in conventional shot peening processes. Another parameter investigated was the influence of the peening intensity which is in pratice described by means of the Almen intensity. The peening intensities used here were 0.3…0.4 mmA, mmN and mmC. Specimens prepared by means of combinations of the aforementioned parameters were used for fatigue testing. The metallographic condition, surface roughness, hardness and the near surface residual stresses were documented.

	R_e [MPa]	R_m [MPa]	A_5 [%]	CEV [%]	T [mm]
S355N	376	518	27	0.41	10
S960QL	995	1033	16	0.56	10

Table 1: Properties o the used steels

The samples were prepared as MAG (metal active gas welding) -welded DV-butt welds. Macrographs and the hardness distributions (HV1) are shown in Fig.2. Typically, steels show heat affected zones with fine and coarse grained zones. Welded steels both show an increase in hardness to approximately 300 HV1 (S355N) and 400 HV1 (S960QL) respectively. In S960Q an area of slight softening from 320 HV1 (base metal) to 280 HV1 is present in the zone, where the temperature was between A_{c1} and the annealing temperature of the base material (Fig.2). All samples were shot peened or clean blasted before testing according to industrial standards at the facilities of an industrial company. Further specimens made from S355N were clean blasted at workshops of different steelwork companies (Details see [14]).

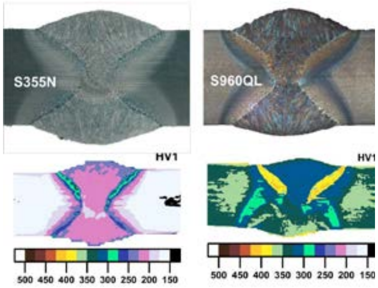

Figure 2: Macrographs of the investigated DV-butt welds.

Residual stress measurements were carried out mainly by means of XRD). The {211}-diffraction lines were measured using CrK_α-radiation at 11 ψ -tilts from 0…45°, the collimator size was ø2 mm. Residual stresses where calculated with the $\sin^2\psi$-method using the x-ray elastic constant $1/2 s_2 = 6.08$ mm²/N. The presented results are focused on the component in load direction (transverse residual stresses). Incremental hole drilling method was applied using an air driven milling turbine and 0°/45°90°-strain gage rosettes (HD). Near surface residual stress depth profiles were determined through incremental surface removal by means of electrolytic polishing and additionally applying the hole drilling method.

Fatigue testing was performed under axial loading with a uniform stress ratio of R=0.1. The fatigue strength of the related base material and of the untreated welds was used as reference. Within the test series the peening media, the intensity and the coverage were varied. Further specimens made from S355N were clean blasted at workshops of different companies from the structural steelwork industry The peening conditions of all test series can be found in detail in [14]. The fatigue data were evaluated by linear regression without consideration of run-outs. Stresses are described in the IIW-nomenclature $\Delta\sigma_a = 2\sigma_a$ [2].

4. Results

4.1 *Initial residual stress condition of the test samples*

Fig.3 represents the initial transverse residual stresses in the as-welded condition and after shot peening. Rather low residual stresses could be found in the as-welded condition, typical for relatively small sized samples. After shot peening compressive almost uniform residual stresses were generated at the surface while no significant differences of the amount was found here due to fifferent peening conditions. The profile of the measured integral width values represent qualitatively the effect of cold hardening of the near surface layer. More detailed information is given by the local residual stress depth profiles at the weld toe (Fig.4). As expected peening with steel shot generates the highest cmpressive residual stresses below the surface in the low strength steel S355N. The total amount of the maximum in the steel S960Ql is more uniform. The higher intensity furthers that the maximum is shifted to a deeper layer in both steels. Similar results were observed after variation of the coverage.

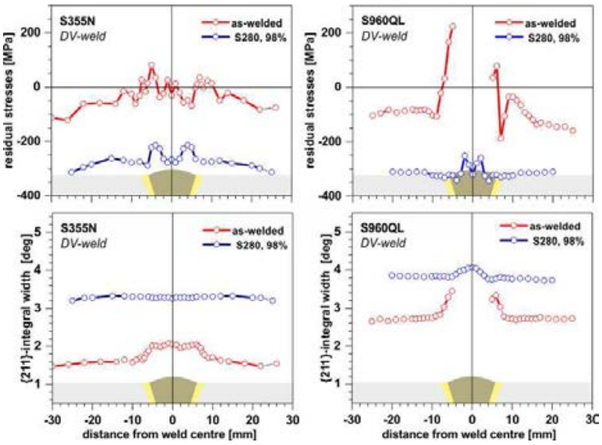

Figure 3: Initial residual stresses (XRD) and {211}-integral widths.

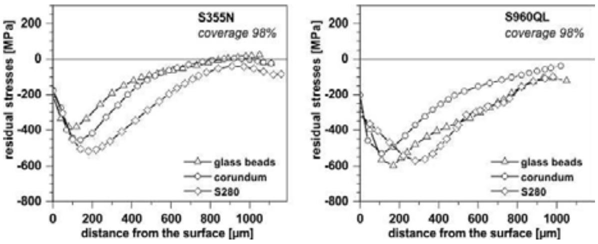

Figure 4: Residual stress depth profiles (Hole Drilling) at the crack sensitive weld toe.

4.2 *Stability of the residual stresses during cyclic loading*

The most popular argument against the practical use of shot peening for the fatigue strength improvement is the mistrusted stability of the generated beneficial residual stresses under different load conditions. It is assumed that they may be relaxed quickly during the first load cycles (constant amplitude loading) or in practice under service conditions (e.g. variable amplitude loading) due to unexpected single overloads. This narrow perspective is focused on the general major influence of the generated residual stresses. It disregards that their stability depends strongly on the material properties. As described in [5,12] the residual stress stability increases with increasing yield strength. Thus the effect of the residual stresses increases also with the yield strength while in weak materials the positive effect of near surface cold hardening becomes more important. As Fig.5 shows exemplarily for the low strength S355N-steel a static load leads

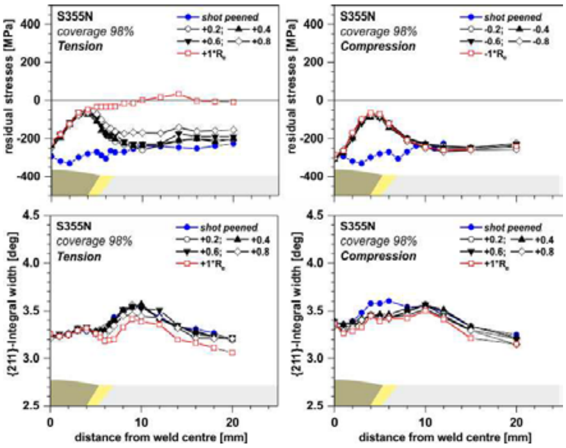

Figure 5: Residual stress surface profiles after different tensional and compressive loads.

to a residual stress relaxation in the weld toe surrounding. The base material is affected only after a nominal tensile at an amount of the yield strength. Similar results were found after different numbers of load cycles while the main relaxation ocurred after the first cycle. On the other hand the integral width distributions of the diffraction lines indicate a stable near surface hardening condition.

4.3 Fatigue test results

The results of the fatigue tests are summarized in Fig.6, (S355N). The SN-curves are always representing a lower confidence limit of 97.5% survival probability which is the reference for the design curves in the design rules (i.e. FAT.classes). The results reveal that the fatigue strength of the low strength S355N-steel is shifted almost to the level of the base material. The benefit is almost independent from the individual peening conditions (clean blasting). Controlled shot peening finally furthers the best performance. The highest improvement is given at high numbers of load cycles. The high strength S960QL shows the expected higher dependency of the fatigue strength improvement from the applied intensity, see Fig.7. The uncontrolled clean blasting treatment also furthers significant shift of the applicable stress amplitudes but the best performance is achieved after shot peening with a sufficient intensity reaching almost the level of the base material at stress levels in the high cycle regime.

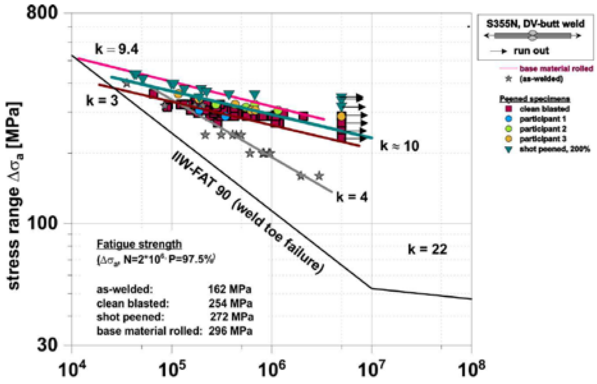

Figure 6: Fatigue test results of the different test series (low strength steel S355N).

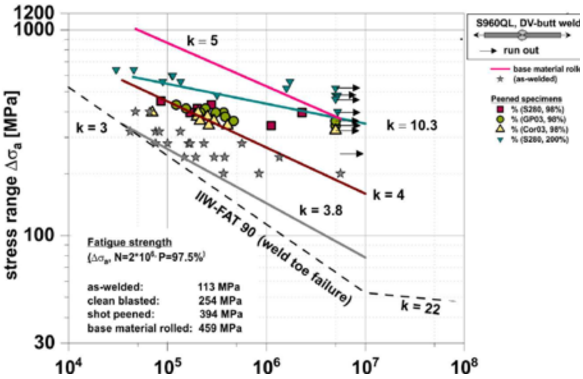

Figure 7: Fatigue test results of the different test series (high strength steel S960QL).

5. Conclusions

In accordance to elder research results the presented investigations show the high potential of the application of shot peening as ar recommended post weld treatment procedure for the fatigue strength improvement of welded joints. A comparison with the current design curves evidently shows demonstrates the potential of shot peening procedures. The presented results indicate SN-curves reepresenting a fatigue strength potential significantly above the existing design limits (Fig.7)

1. The shot peening process furthers a strong shift of the applicable stress amplitdes, even if the conditions are not precisely controlled and the procedure is primarily focused on the cleaning effect of he surface.
2. In low strength steels it can be expected that cold working induced surface hardening improves the fatigue crack resistance while the beneficial effect of the generated compressive residual stresses is mainly present at higher lifetime with lower load stress

levels. Clean blasting under common industrial conditions can be almost effective as a precisely controlled shot peening process.

3. In high strength steels clean blasting furthers a higher fatigue strength but the highest performance requires a well adjusted peening intensity. Here the effect of the generated compressive residual stresses is the main improvement factor. Shifting the fatigue strength on the level of the base materiali is generally possible.
4. Shot peening enables the sophisticated consideration of the mechanical properties of the used steel grades which is not yet accepted in a satisfying manor in the design codes.
5. It must be taken into account that the procedures can only be effective in welds without inner defects, i.e. in welds where the crack initiation is located at the weld toe.

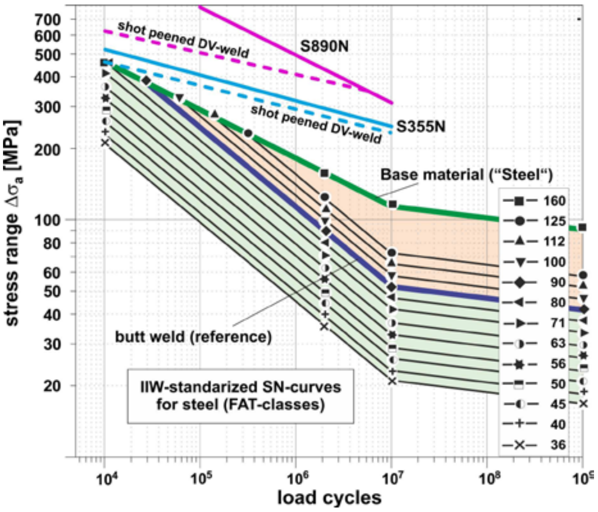

Figure 7: Comparison of the test results on shot peened DV-welds and the design curves fixed in the current design concepts according to [2].

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