FATIGUE IMPROVEMENT OF WELDED COMPONENTS BY SHOT PEENING

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Abstracts

Among the variables which affect the fatigue behaviour of welded components, the microgeometry and the residual stress conditions play a major role, in particular as regards the fatigue life spent in the crack initiation stage. The objective of post weld treatments applied for increasing the fatigue strength of such components is to create, as far as the two above-mentioned parameters are involved, situations more favourable than in as welded conditions.

Shot peening is considered among the most-efficient techniques.

The goal of this paper is, first to describe the mechanical characteristics due to shot peening, then to list the main parameters, in order to optimize the shot peening process, and to emphasize the effect of the initial weld quality, finally to summarize the effects of the loading parameters on the improvement level.

1 - INTRODUCTION

Even when properly controlled, welding operation introduces a number of defects which, even they do not reduce the static resistance of the joint, often have a decisive influence on its fatigue strength. Cold laps, undercuts (even when shallow), beads that are too convex and incomplete penetration all lead to the creation and subsequent propagation of fatigue cracks whose initiation phase can be very short and even non-existent.The aim is to find a solution that will increase, or even create the initiation phase, either by inhibiting defects through the introduction of compressive residual stress or by improving the local geometry of potential initiation sites. In this case, any acute defects that act like initial cracks must be eliminated and a more appropriate geometry achieved. [1)

Once the risk of fatigue crack initiation has been eliminated at the weld root, numerous solutions can be used to improve the fatigue strength of welded joints, whose critical point is located at the weld toe ; these solutions are all aimed at one of the following :

- to reduce, or even eliminate, welding defects, particularly open flaws,
- to improve the local geometry of the weld toe by reducing the stress concentration coefficient,
- to introduce fields of compressive residual stress.

This paper is devoted to the application of shot peening to the improvement of the fatigue strength of the welded joint.

2– MECHANICAL CHARACTERISTICS INDUCED BY SHOT PEENING

2-1– Residual stress field

A shot peening treatment of a welded joint induced two gradients [2].

- the transversal gradients shows that the greatest compressive residual stresses are observed in the weld seam after shot pening.
- the depth profiles of the residual stresses (figure 1a) displays a maximum compressive stress underneath the surface, in a depth between 0.05 and 0.15 mm for the aluminium alloys and between 0.10 and 0.30 for the steels.

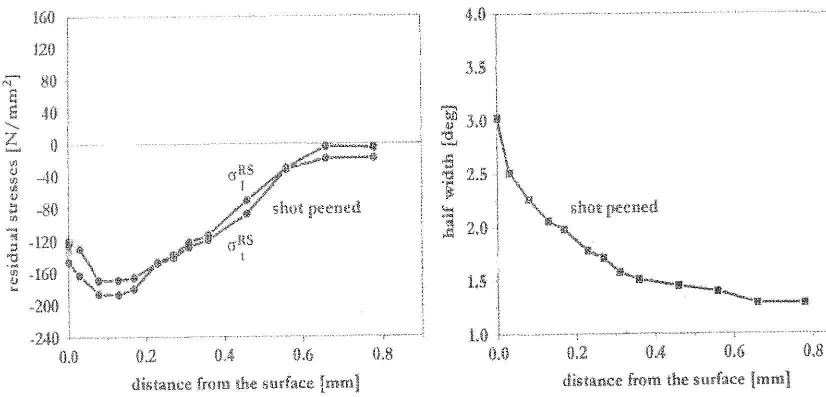

Figure 1 – In depth characteristics induced by shot peening in a aluminium alloy butt welded joint [2]
a) residual stress profile b) – Half with distribution

Due to the higher level of mechanical characteristics of the heat affected zone, the maximum absolute value of the compressive residual stress is the greatest and the depth of the compressive part of the stress gradient is the smallest [3] in the HAZ.

2.2– Hardness gradient

The changes of local strength properties can be characterized [2] by the half width (figure 2b) or the microhardness profile [4].

This depth distribution indicates a remarkable cold hardening fo the surface layers. The width of the cold hardened zone corresponds roughly to the part in compression of the residual stress profile.

2.3– Fatigue strength

2.3.1 – Fatigue strength improvement

The analysis of the fatigue test results of improved welded joints proposed by Huther *et al.* [5] involves more than 300 sets of results. The analysis concerns the four improvement techniques which have given rise to the greatest number of studies : burr grinding, TIG dressing, hammer peening ad shot peening.In this study, different parameters have been analysed such as the type and thickness of the welded joint, the yield strength ($230 < \sigma_y < 800$ MPa) and the stress ratio R ($-1 < R <$

0.5).In each case, the proposed " improved " *S-N* curves enabled to compare the behaviour of the welded joint, using the corresponding EUROCODE 3 curve as a reference.

Table 1 compares the design stress, S_{Rk} , stastistically determined at 2 x 10 ^{6} cycles for shot peened specimens where S_{Rk} (AW) corresponds to the EUROCODE 3 for the same as welded detail.Depending of the welded detail the ratio S_{Rk} / S_{Rk} (AW) varies between 1.5 and 2.5 (improvement range : 50 to 150 %).

Table 1 – Comparaison fo the design stress, S_{Rk} , for shot peened and as welded specimens (from [5]).

Joint type	σ_y (MPa)	m	$\Delta\sigma$ (MPa)	S_{Rk} (MPa)	$S_{Rk\,(AW)}$ (MPa)	S_{Rk} / S_{Rk} (AW)
butt	> 600	9	326	226	90	2.5
cruciform	< 400 > 600	9	278	220	90	2.4
T- joint	< 400 > 600	9 9	196 232	144 146	71 71	2.0 2.0
Longitudinal attachment	< 400 > 600	5 5	123 148	95 121	63 63	1.5 1.9

2.3.2 – Slope of the S-N curves

Compared to the unique slope used in the codes (for instance EUROCODE 3), m=3, table 1 shows a marked increase in the slope when improvement techniques are applied ; especially for shot peening m=9 means that a significant increase of the fatigue strength is obtained where a long life is concerned (figure 3) [6].

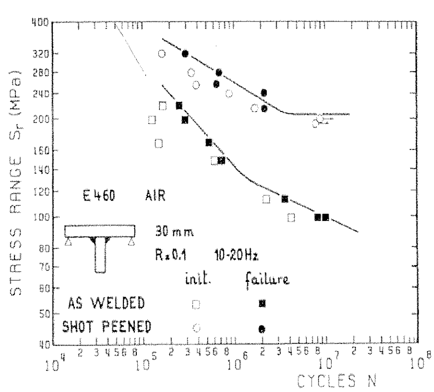

Figure 3 – Fatigue strength of weld joints in steel E460 in as welded ar the shot peened conditions

2.3.3 – Scatter of the fatigue test results

When properly applied, shot peening leads to a reduction in the test result scatter. For fatigue testing carried out on T-joint in aluminium alloys, HUTHER et al [7] found that the ratio : $s / \Delta\sigma_{2 \times 10^6 c}$ (s : standard deviation, $\Delta\sigma_{2 \times 10^6 c}$ stress range at 2 x 10 ^{6} cycles) decrease from 13 % (as welded conditions) to 7% (shot peened condition). The same tendency is found by MENIGAULT et al. [8] .The narrow scatterband can be related to the good reliability of the shot peening treatment. [9].

2.3.4 – Respective behaviour of steel on aluminium alloys welded joints

HUTHER et al. [7] compares the fatigue behaviour on shot peened T-joints respectively in S690 steel and aluminium alloys (5083 and 6061). By using the ratio $\Delta\sigma / E$ (E : Young modulus) plotted versus the number of cycles *N*, the test results are similar for both. In addition, $\Delta\sigma_{2 \times 10^6 c}$,in as-welded condition, is multiplied by two after shot peening

2.3.5 – Influence of the base material yield strength, σ_y

Figure 4 shows that the increase of the fatigue strength improvement due to shot peening, as a function of σ_y, follows the mean line obtained for TIG dressing [10].

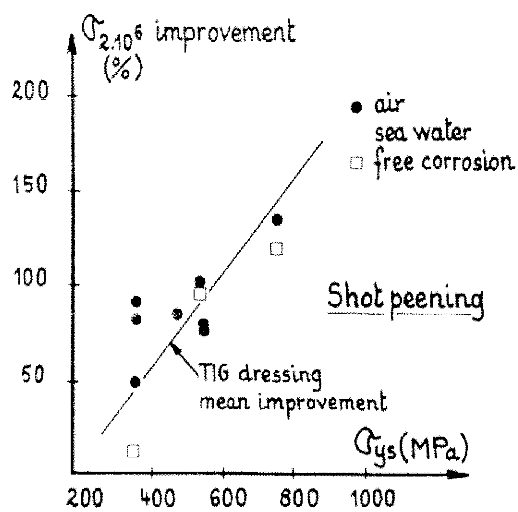

Figure 4 – Influence of base metal yield strength on the fatigue strength improvement by shot peening [10]

3.1 – Shot peening parameters

The choice of peening conditions is based on the residual stresses and affected depth induced by different peening parameters, and the compatibility of shot size with the dimension of the weld toe defects [6] [11].Usually, for welded joints, the maximum affected depth is desirable, unless other imperatives have to be taken into account such as roughness, shot size, ...

- **Influence of coverage rate**

Increasing coverage from 1 to 3 does not result in strong modification of the stress distribution, but a small increase in affected depth is noted for large intensity shot peening. Therefore a coverage of 200 % is desirable.

- **Roughness of the peened surfaces**

The importance of the surface roughness produced by shot peening has to be considered only in high strength steels [12].

- **ALMEN intensity**

Investigation from HOFFMANN et al [13] shows (figure 7) that the ultimate strength of the structural steel, the higher is the ALMEN intensity which is necessary to get optimum results.

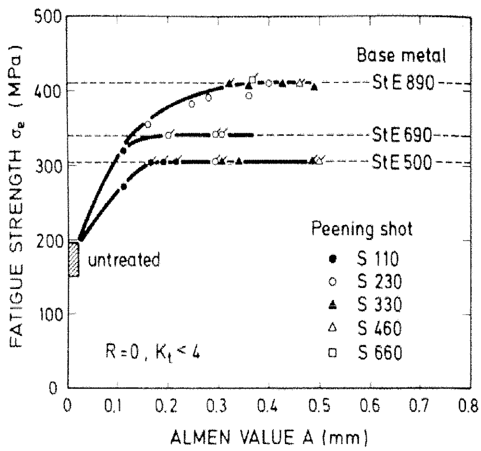

Figure 7 –Almen value vs. fatigue strength of butt weld [13]

3.2 – The choice of optimum shot peening parameter

Based on the work done by BIGNONNET et al. [5], two types of procedures are discussed.

3.2.1 – Single shot peening (only one shot size)

For this procedure the maximum depth by compressive residual stresses is to obtain.For the purpose, it is then necessary to choose a high ALMEN intensity. In other respects shot size must be compatible with the dimension of the defects to treat. For high quality welds (geometrically speaking) S330 shot can be chosen, which authorizes a rather high ALMEN intensity. Inversely for lower quality welds a smaller shot has to be used, S230, S170.. In that case only low intensities can be reached and the efficiency of the peening would be smaller.

3.2.2 – Double shot peening

Although single peening, gives good laboratory results in relation to fatigue life of welded joints, it could be improved. In fact it can happen that sharp weld defects which are present are not treated by the chosen shot. One can imagine that such defects keep their noxious influence on fatigue. In this line of thought a double peening can be envisaged. It consists of a first run with a small shot to assure the treatment and open even sharp defects. The second run would then be done with a large size shot to assure high ALMEN intensity i.e a large affected depth.

The aim of the double peening is not to get a larger improvement in fatigue life than with a single peening, but to reduce the scatter in fatigue and so to reach an increased reliability and confidence in shot peening on welded structures (see 2.3.3).

1 – EFFECT OF THE INITIAL WELD QUALITY [14]

The fatigue strength of welded joints in high strength steels or high strength aluminium alloys is strongly dependent upon the sharpness of the notch geometry of the weld toe and, consequently, the fatigue strength of the weldments in these materials may be very low in relation to the base material. The efficiency of the notches at the weld toe will be the higher, the higher the ultimate strength of the base material is. Therefore, techniques for improving the fatigue strength become more important, if high strength materials are used for welded joints.

4.1 – Improvement of the weld seam profile

The weld seam profile of conventional steel or Al-alloy weld joints can be improved through TIG-dressing or by using mechanized TIG-welding for the cover passes or for the last load carrying passes of cruciform welds.Nevertheless the fatigue strength of welded joints with an improved weld seam profile will be lower than the fatigue strength of the base material. The reason for this is that in steels the macroscopic notch of the weld toe is reduced, but the microscopic notches at the weld toe are more effective, especially in high strength steels with regard to the fatigue strength.

4.2 – Combination of both improving the weld seam profile and shot peening

A post weld shot peening treatment on a conventional as-welded joint improves also the fatigue strength (+ 50 to + 70 %), but the reached fatigue strength is always lower than the those corresponding to the unpeened base material.

This means that an optimization of the fatigue strength (when the fatigue strength of the welded joints reaches the base material one) requires, at first a minimization of the macroscopic notches. Then the secondary effects (structural inhomogeneities, microscopic notches and tensile residual stresses) can be completely compensated through cold work hardening and / or the compressive residual stresses induced by shot peening.The combined application of weld seam improvement methods and shot peening lead to an optimum fatigue strength .

4.3 – Welded joint type

A.BIGNONNET [5] indicates that for joints with longitudinal attachment the improvement induced by shot peening varies between 35 and 70 %.For cruciform joints the improvement is larger (90% and more). These tendencies are in line with those mentioned in [5] (table 1). Nevertheless, the improvement level due to shot peening depends on the initial weld bead quality.

2 –INFLUENCE OF THE LOADING PARAMETERS

2.1 – Stress ratio (mean stress)

Too few results corresponding to a large range of *R* are given in the litterature in order to derive any quantitative assessment of the *R* effect.
Nevertheless HUTHER et al. [8] compares fatigue testing results on Al-alloys T-welded joints loaded in bending, with *R*= 0.1 or 0.5 (tables 3) :

- the influence of the stress ratio is more significant for shot peening joints ($\Delta\sigma_{0.1} = 2\ \Delta\sigma_{0.5}$) than for base material specimens ($\Delta\sigma_{0.1} = 1.2\ \Delta\sigma_{0.5}$).
- at *R* = 0.1, for both studies Al-alloy (5053 and 6061), $\Delta\sigma_{2x10^6c}$ corresponding to the shot peened joints are roughly the same as those obtained on the base material specimens ; compared to the as welded specimens the shot peened joints exhibit a large improvement (respectively 176 and 170 %).
- on the other hand, at *R* = 0.5, the results on the shot peened joint are roughly 2/3 the base material ones ; as compared to the as welded joints the fatigue strength improvement is only 46 / 47%.
- a residual stress relaxation takes place at *R* = 0.5 for 5083 Al-alloy (before testing : 200 MPa, after testing : 150 MPa).

Table 3 - $\Delta\sigma_{2x10^6c}$ (mean – 2 standard deviation) as a function of *R* (from [7])

Al-alloy	condition	*R* = 0,1	Improvement (%)	*R* = 0.5	Improvement (%)
5083	AW SP	38 105	0 + 176	34 50	0 + 47
5083	BM	107		86	
6061	AW SP	44 119	0 +170	41 60	0 + 46
6061	BM	119		95	

T- joint loaded in four points bending (BM : base material)

2.2 – High stress ranges

LIEURADE and col. carried out residual stress measurement [7][15] in the vicinity of the weld toe on untested or fatigue-tested butt joints in S 490 steel :

- For R = 0.1, at the conventional fatigue strength ($\Delta\sigma_{2 x 10^6 c}$ = 340 MPa) no relaxation of the initial residual stresses appears.
- For high stress range level (respectively 420 and 460 MPa) an important relaxation occurs. The residual stress near the weld toe increases from – 300 to respectively –150 and + 200 MPa.

5.3 – Cyclic preloading

BIGNONNET et al. [6] have studied the influence of repeated stress peaks either in tension or in compression on shot peened T-joints in S 460 steel.
The results presented in figure 8 give the life of test specimens in E 460 steel (30 mm thick) subjected to an applied stress of 200 MPa, but which had previously been subjected to a preloading for 50 cycles at different levels ($\sigma_{preload}$ = 450, 350, 0, -100, - 250, - 300 and – 400 MPa).

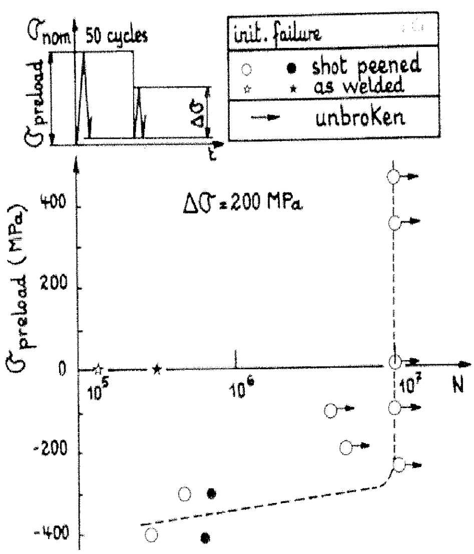

Figure 8 – Influence of high stress peaks (tensile or compressive preloading) on the fatigue life of a welded shot peened joint in E460.

These tests confirmed that peak tensile stresses do not have an adverse influence on the stress field introduced by shot-peening and hence on the life of the shot peened test specimens. On the other hand, the high stresses with negative values partially relieve the shot-peening stresses. Nevertheless, preloading up to –250 MPa have no influence on the life. Futhermore even the high amplitude compressive loadings (-300 and –400 MPa) do not completely relieve the shotpeening stresses. After 50 cycles of preloading at – 400 MPa, there still remains –190 MPa at the surface. In all cases, the life is superior to that obtained on test specimens in the as welded condition without preloading.

5.4– Variable amplitude loading

T-joint specimens have been tested using the load sequence COLOS simulating the succession of sea states, for offshore structures (*R* = -1) [16].

The fatigue test results are expressed as a function of the equivalent stress range.

$$\Delta S_{eq} = \left[\frac{1}{N} \sum_i n_i (\Delta S_i)^m \right]^{1/m}$$

Figure 9 compares on the same basis (with m=3) as **welded** and **shot peened** specimens subjected to the same load sequence. The results show the benefit provided by shot peening.

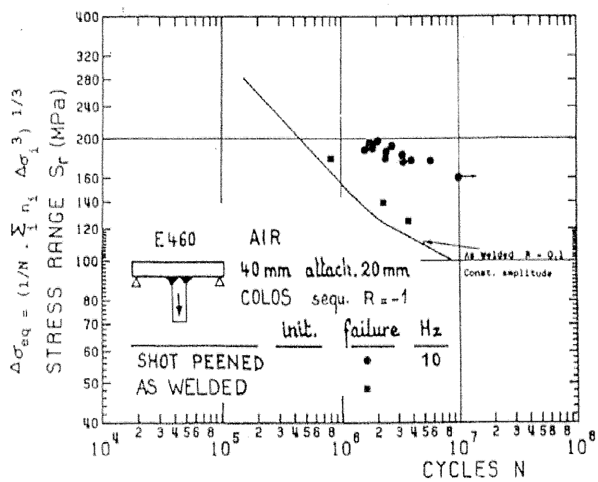

Figure 9 – Fatigue strength under variable amplitude loading (load sequence COLOS) for as welded and shot peened T-joints [16]

The same load sequence (R=-1) have been also applied to thick fillet welded V-shaped specimens [13].

The test results, on these specimens simulating the condition found in a welded pipe node, display also a considerable improvement of the fatigue strength due to shot peening, compared with the corresponding V-shaped specimens.

6 – FATIGUE LIFE ASSESSMENT

6.1– Taking the residual stresses into account

- Goodmann diagram

At the level of the fatigue limit for which the relaxation of residual stresses is not significant, the residual compressive stresses induced by shot peening may be regarded as static stresses which lower the level of the mean cyclic stress applied. [16].

Goodmann's chart in Figure 10 is a schematic representation of this effect. The Goodmann lines, plotted by the tensile strength R_m and by the maximum and minimum levels respectively of the fatigue limit of weld joints in E 490 steel without postwelding treatment, pass through the maximum and minimum levels of the fatigue limit for the same type of joint after shot peening, on condition that to the mean stress of the loading cycle be added algebraically the residual stress level (= 320 MPa) measured at the surface of the shot peened joint prior to fatigue testing.

This simple explanation no longer applies in the case of higher stress levels, where a measurable relaxation of residual stresses occurs. Other applications of this approach have been published concerning mild steels [17][18] and Al-alloys [7].

- Effective stress approach

In order to discuss fatigue testing results obtained on shot peened Al-alloy welded joints BERTINI et al. [5] uses a F.E model of the specimen in order to simulate a complete fatigue loading-unloading cycle, with a special attention to the residual stress distribution acting at the fillet root after load removal. An elastic shakedown was predicted after the first fatigue cycle and the effective stress cycles parameters ($\Delta\sigma_{eff}$, $\sigma_{m,eff}$). The global comparaison of experimental results, based on effective fatigue cycles is presented on a GERBER parabola.

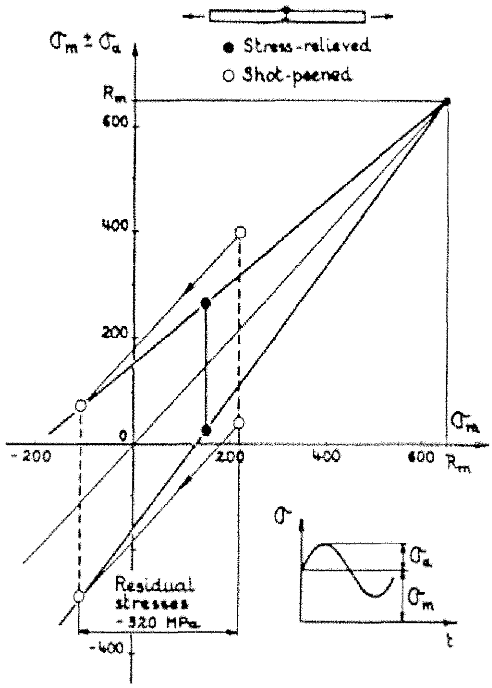

Figure 12 – Influence of a static stress on the fatigue limit of butt welds E 490 steel (MAG welding process) [15] .

7 – CONCLUSION

Shot peening is a convenient way to improve the fatigue strength of welded structures. By this treatment, surface compressive residual stresses are induced, especially in the stress concentration areas (for instance weld toe) and the defects which exist at the surface must be included in this residual stress field. For this purpose one should look for conditions which induce a maximum depth affected by the peening.

That is the case with high ALMEN intensities, which are obtained with large shot. Nevertheless other imperatives interfer : all the surface defects (i.e. undercuts...) must be treated by the peening conditions used. Weld. So far shot peening of welded joints must meet two requirements :

- maximum affected depth by doing a large ALMEN intensity.
- treatment of all the defects by using small shot.

Two possibilities are proposed to find a compromise : the single shot requires a careful choice of the shot so that it would be as large as possible while remaining compatible with the size of defects to be treated.

A double peening can also be carried out. A first run with a small shot (or appropriate sand blasting) to assure the treatment and to open even sharp and deep defects. A second run with a larger shot must then be performed to reach a high ALMEN intensity i.e. a large affected depth. In all cases coverage rate higher than 100 % must be realized, 200 % is recommanded.

The fatigue results show a significant improvement in the fatigue strength of shot-peened welded joints, particularly where a long life is concerned. An improvement from 50 to 150 % is found, with respect of the initial quality of the welded joint.

An undesirable residual stress relaxation can appear only for high stress ratio or high stress peaks in compression.The application of load sequences,even with R = -1 emphasizes the large improvement induced by shot peening.

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