THE INFLUENCE OF SHOT-PEENING ON THE FATIGUE STRENGTH OF WELDED JOINTS IN HIGH-STRENGTH STRUCTURAL STEELS

L. PICOUET*, A. BIGNONNET*, H.-P. LIEURADE*, L. CASTEX**, J.L. LEBRUN**

The fatigue behaviour of welded joints in high strength structural steels was studied in as welded and shot peened conditions.
Various parameters have been taken into account :
- the technological parameters of the shot peening,
- the possible evolution of the residual stresses under constant amplitude loading or after preloading
The fatigue results show significant improvement of the fatigue strength of shot-peened welded joints, particularly in the high life domain.

INTRODUCTION

Metal structures, the numbers of which increase as the years go by, are often subjected to fatigue loadings, and it is necessary to guard against the risk of failure due to this type of loading. On the other hand, in order to produce lighter structures, designers now opt for the use of high-strength steels (HSS).

The steel producers have learnt how to manufacture such steels. However, the advantages which are obtained by the use of "modern" steels, particularly the HSS steels, can be limited by the fatigue strenght of welded joints. We know, in fact, that, for basic welded joints (with no final treatment), the major part of the fatigue life is wiped out by the propagation of cracks initiated by defects at the weld toes. Since the propagation characteristics of low- and high-strength steels are not significantly different, the sole means of improving the fatigue life of HSS welded joints lies in extending the time necessary for crack initiation. For this, it is necessary to apply post-weld improvement treatments to the most highly-stressed areas, so as to eliminate defects introduced during the welding (undercuts, etc), or to nullify their harmful effects.

* IRSID Saint-Germain-en-Laye France
** ENSAM Paris France

The results hereby presented thus concern the use of these final treatment techniques on HSS welded joints, and in particular the influence on the fatigue strength of welded joints formed of such steels, of an improved welding procedure, and of the final treatment of the weld beads by shot-peening.

MATERIALS AND WELDING CONDITIONS

Materials

The materials used were two high-strength structural steels, USIRAC E 460 and USIRAC E 550, produced by the continuous casting process. They were rolled into sheet, 30 mm thick for the E 460 steel, and 20 mm for the E 550 steel.

Their high mechanical properties are obtained by quenching in the hotrolled condition, using the controlled accelerated cooling process, followed by tempering.

The chemical compositions of the two steels studied are given in table 1.

TABLE 1 - Chemical composition (in thou. % by wt.) of the grades studied.

Grade	C	Mn	Si	P	S	Al	Nb	Ti	N	Cr	Ni	Cu
E 460	171	1270	341	22	1	68	21		12	22	22	13
E 550	144	1411	353	20	1	61	16	34	11			

After quenching, the E 460 sheets were subjected to tempering at 690°C for 20 minutes, and the E 550 sheets were tempered at 625°C for 20 minutes.

The mechanical properties obtained are given in table 2.

TABLE 2 - Mean mechanical properties of the grades studied

Grade	σ_y (MPa)	UTS (MPa)	Elong (%)	R.A. (%)	KCV at -40°C (J/cm^2)
E 460					
transverse surface	570	670	18	-	70
core	460	585	25	75	-
short-transverse	460	590	23	68	-
E 550					
transverse surface	640	720	21	-	60
core	550	660	22	76	-
short-transverse	560	665	23	77	-

Welding conditions

The welding conditions are given in table 3.

TABLE 3 - Welding parameters for T joints.

Welding parameters	E 460 (30 mm)	E 550 (20 mm)
Position Electrode Pre-heating No. of passes Current Voltage Heat input	Vertical upward 3G E-90-18D1 Ø 3.2 mm 100°C (flame) 35 120 A 25 V 8.5 to 19 KJ/cm	Vertical upward 3 g E-110-18-M Ø 3.2 mm 100°C (flame) 19 105 A 22 V 8.4 to 22 KJ/cm

Figure 1 shows the geometry of the weld beads. The weld toe pass was made at the start of the welding so that the welder was able to deposit this pass, without having to cover the previous passes. By this technique, described in greater detail in reference(1), the local geometry at the weld toe can be significantly improved. Furthermore, since this pass is not the last one, it benefits from the stress relief effect induced by the subsequent temper bead and buttering passes.

The measurements of the geometrical parameters the weld toe - the radius and the blend angle θ - were taken for each test specimen, giving 170 measurements. The mean, minimum and maximum values for ρ and θ at the weld toe, measured with a magnification of 7, are given in table 4.

TABLE 4 - Local geometry at the weld toe.

	Mean	Standard error	Min/Max
ρ (mm) θ (°)	1.7 36	0.6 8	0,5/3,2 17/69

FATIGUE STRENGTH OF WELDED JOINTS

Experimental methods

Test speciments. The test specimens used were T-joints with a loading mode which simulated the load transfer from a distance-piece to a member, via the welded joint.

The test specimens were obtained as samples sawn from short welded lengths, then machined to their final dimensions. The test specimens were 90 mm wide and 500 mm long, the height of the stiffener being 150 mm. On each test specimen, one of the two weld toes was ground, so that only one side had to be monitored to detect crack initiation due to fatigue.

All tests were carried out in air, with a loading ratio R of 0.1.

Crack initiation detection. Crack initiation was detected by the alternating current potential drop technique at 50 Hz with 30 amperes. This is a relative method which measures the differences between the potential at the weld toe where crack initiation takes place and the opposite weld toe which has been neutralised by grinding. Five measurement points of the potential spaced along the weld toe were checked in succession every 10 seconds. With this technique, cracks of a few tenths of a millimetre in depth could be detected.

Influence of shot-peening on the fatigue strength of the welded joints

Choice of the shot-peening parameters. For the testing of the shot-peened joints, we carried out several preliminary tests, in order to determine which were the best shot-peening parameters.

Measurements. On T-joints in E 460 steel, 30 mm thick, three shot-peening operations were carried out, with different technological parameters, as shown in table 5.

TABLE 5 - Technological parameters for the various preliminary shot-peening operations

Shot-peening	Shot diameter		ALMEN intensity (10^{-3}) mm	Coverage
	MI Standard	mean dia. (mm)		
1	MI 170	0.43	14-16 A 0.35-0.40 mmA	200 %
2	MI 330	0.84	20-22 A 0.50-0.55 mmA	200 %
3	MI 550	1.4	8-10 C 0.20-0.25 mmC	200 %

In the region of the weld toe, we measured the distribution with respect to the depth of the residual stresses introduced by each type of shot-peening, before the tests and after the fatigue failure of the test specimen. These measurements were made by X-rays. By studying the displacement and the distortion of the diffraction peaks, we were able to determine the condition of the residual stresses and the microstrains which characterised the plastic deformation of the material (2).

Figure 2 shows the condition of the residual stresses after shot-peening. The shot-peening operation 1 introduced surface stresses of -300 MPa, to a depth of approximately 0.15 mm. By 0.2 mm, the residual stress had fallen to -200 MPa.

The shot-peening operations 2 and 3 resulted in surface stresses of the order of -400 MPa, to a depth of approximately 0.25 mm. It was 0.35 mm before the stress fell below -200 MPa. The results of the measurement of the width of the diffraction peaks shown in figure 3 confirm that the depth affected is of the order of 0.4 to 0.5 mm for shot-peening operations 2 and 3 , while for shot-peening operation 1, it is only 0.2 mm.

The measurement of the residual stresses after the fatigue tests ($\Delta\sigma$ = 400 MPa, R = 0.1) are shown in figure 4. These measurements were taken after failure of the test specimen in the region of the weld toe, as shown in figure 4. A redistribution of the initial stress field will be noted, with the stress relief less for shot-peening operations 2 and 3 than that for 1 .

The results of the fatigue tests on T-joints 30 mm thick for the three shot-peening conditions are given in table 6.

TABLE 6 - Life of welded T-joints after shot-peening ($\Delta\sigma$= 400 MPa, R = 0.1).

Shot-peening	N crack initiation	N failure
1	17×10^3	55×10^3
2	23×10^3	86×10^3
3	37×10^3	68×10^3

N failure : length of crack greater than ½ the thickness,
N crack initiation : detection by the alternating current potential drop technique, 50 Hz/30 A.

Choice of the optimum shot-peening parameters. As a result of these preliminary tests, we eliminated the shot-peening operation 1 because of the shallow depth affected by the shot-peening, and the fatigue of the test specimen with shot-peening operation 1 certainly confirms that the latter is less effective than the other two. The shot-peening operations (2) and (3) give practically the same residual stress field. The lives are fairly similar. The shot-peening operation (2) was selected since the shot, which is smaller than that for shot-peening operation (3), is capable of dealing with the smallest defects encountered in our welded joints (see table 4).

Results

For the fatigue tests, all the test specimens had been shot-peened using MIL 330 shot (average diameter = 0.84 mm), an ALMEN intensity of 20-22A (0.51 - 0.56 mm A) and a coverage of 200 %. The results obtained are shown in figure 5 for the steel E 460 and figure 6 for the steel E 550.

A significant increase in the fatigue strength will be noted, particularly where a long life is concerned.

For a nominal stress ΔS of 200 MPa, no crack initiation was found after 10^7 cycles, for any of the two series of test specimens (E 460 and E 550).

The detection of crack initiation indicates that the time required for crack initiation is generally greater than 50 % of the total life :
($\frac{Ni}{Nf}$ = 50 % to 80 %).

In both cases it would seem that there is an endurance limit (no crack initiation after 10^7 cycles).

$$\Delta S_{D10^7} = 200 \text{ MPa}$$

The improvement in the fatigue strength obtained by shot-peening is entirely comparable with that which is obtained by other final treatment techniques (3). Table 7 shows the increase in the allowable stress at 2 x 10^6 over that for the basic post-weld condition.

TABLE 7 - Improvement in the fatigue strength at 2 x 10^6c due to shot-peening.

Grade	σ_y (MPa)	Thickness (mm)	Condition of the bead	R	$\Delta\sigma_{2.10^6}$ (MPa)	Improvement (MPa)	Improvement (%)
E 460	570	30	basic post-weld shot-peened 20-22A	0.1 -	125 230	105	84 %
E 550	640	20	basic post-weld shot-peened 20-22A	0.1 -	140 250	110	78 %

While this improvement is comparable with that which is obtained by TIG refusion or grinding of the weld toe, shot-peening has the advantage of being an overall technique, in other words, the treatment does not affect only the weld toe, but the whole of the weld bead and the surrounding area. This is an important feature since, in a real structure, the initiation points in tubular nodes are not necessarily limited to the weld toe, but can be in the region of the hot point for the first or the second intermediate pass above the weld toe (1). This situation is also met in welded joints with improved profiles. In fact, several of our test specimens failed from cracks which were initiated in the first or second intermediate pass.

REDISTRIBUTION OF THE STRESSES DUE TO SHOT-PEENING

Variation of the shot-peening stresses with a fatigue loading of constant amplitude

The stresses introduced by shot-peening were measured by the X-ray diffraction method. The irradiated zone was a rectangle, 20 x 1 mm^2, on the weld toe. These measurements were taken on the 20 mm thick test specimens (E 550 steel), for different values of the applied stress : $\Delta\sigma$ = 200, 250, 300 and 320 MPa.

Figure 7 shows the variation in the residual stresses with respect to the number of cycles. In general, these results reveal no particular variation in the shot-peening stresses up to the point when a crack is initiated. However, for the highest value, $\Delta\sigma$ = 320 MPa, relief of the shot-peening stresses was noted during the initial cycles, levelling out at about - 200 MPa.

Influence of overloads on the fatigue strength of shot-peened welded joints

Tests were performed to evaluate the ability of the shot-peening to improve the fatigue strength when the loading was of varying amplitude, so as to simulate the influence of high peak stresses during the life of a structure.

The results presented in figure 8 give the life of test specimens in E 460 steel, 30 mm thick, subjected to an applied stress $\Delta\sigma$ of 200 MPa, but which had previously been subjected to a preloading for 50 cycles at different levels (σ preload = 450, 350, 0, -100, -250, -300 and -400 MPa).

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 (see table 8). Nevertheless, preloadings up to -250 MPa have no influence on the life. Furthermore even the high amplitude compressive loadings (-300 and - 400 MPa) do not completely relieve the shot-peening 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 basic post-weld condition without preloading (see figure 8).

TABLE 8 - Variation of the mean shot-peening stresses in the weld toe after 50 cycles of preloading.

$\sigma_{preload}$	$\sigma_{residual}$ after 50 cycles of preloading
- 100 MPa	- 328 $\pm$ 53 MPa (15 measurements)
- 400 MPa	- 192 $\pm$ 34 MPa (27 measurements)

initial condition $\sigma_{res} \simeq - 330 \pm 50$ MPa.

CONCLUSIONS

In this study we have attempted to obtain basic data concerning the fatigue behaviour of welded joints in quenched and tempered high-strength structural steels E 460 and E 550.

Shot-peening was studied, as an "overall" final treatment to improve the fatigue strength of welded joints. The choice of technological parameters (ALMEN intensity, size of shot, etc) was based on preliminary study of the stresses introduced by different shot-peening operations : the values of the stresses and the depth affected. In addition, it is necessary to use a shot size which is small enough to deal with all defects at the weld toe.

The fatigue results show a significant improvement in the fatigue strength of shot-peened welded joints, particularly where a long life is concerned.

The study of the reduction of the shot-peening stresses due to fatigue shows that, where R = 0.1 with a constant amplitude, even with high levels of applied stresses, there is little or no reduction up to the point where a crack is initiated.

In order to simulate the influence of high peak stresses during the life of a structure, fatigue tests with a preloading were carried out. It was shown that the tensile preloading did not exert an adverse effect on the shot-peening. Only negative stresses whose amplitude was greater than 250 MPa were able partially to relieve the shot-peening stesses and thus to minimise the beneficial effect of the shot-peening on the fatigue strength.

REFERENCES

(1) BIGNONNET, A., LIEURADE, H.P., PICOUET, L.
Improvement of the fatigue life for offshore welded connections conference IIS-IIW "Welding of tubular structures. Soudage des structures tubulaires" juillet 1984, Boston MA, Pergamon Press (1984) pp. 271-278.

(2) MAEDER, G., LEBRUN, J.L. SPRAUEL, J.M.
Caracterisation mécanique des surfaces par diffraction X. Matériaux et Techniques avril-mai 1981, pp. 135-149.

(3) BIGNONNET, A.
Influence des traitements d'amélioration du pied des cordons de soudure sur la tenue à la fatigue des joints soudés.
Rapport IRSID RE 1050, nomenclature IIS-IIW : XIII 1085-83
Bulletin du Bureau Véritas août-septembre 1984, pp. 467-497.

Acknowledgements

The report on which this article is based was compiled on behalf on the Association de Recherche de Structures Métalliques Marines (ARSEM), which has authorised its publication.

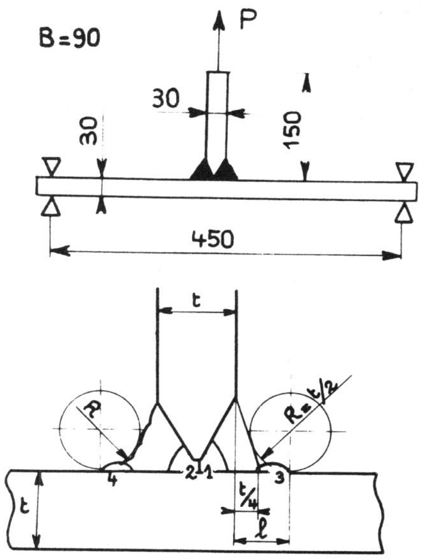

Figure 1 Geometry of the test specimens and the weld bead

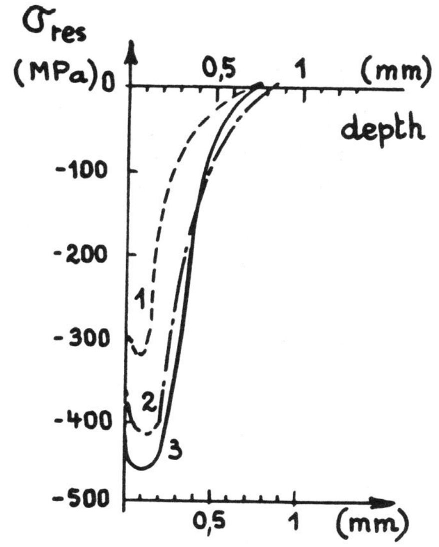

Figure 2 Distribution of shot-peening stresses with depth for different shot-peening operations

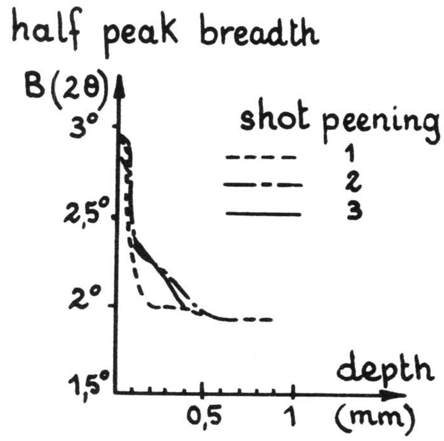

Figure 3 Distribution in the sublayers of the chord widths at midheight of the X diffraction peaks

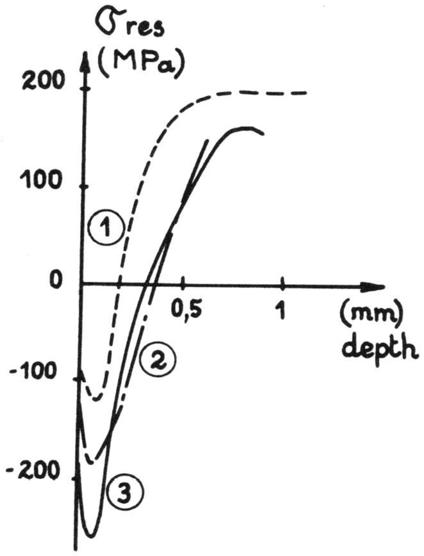

Figure 4 Distribution of the residual stresses in the region of the weld toe after failure in fatigue

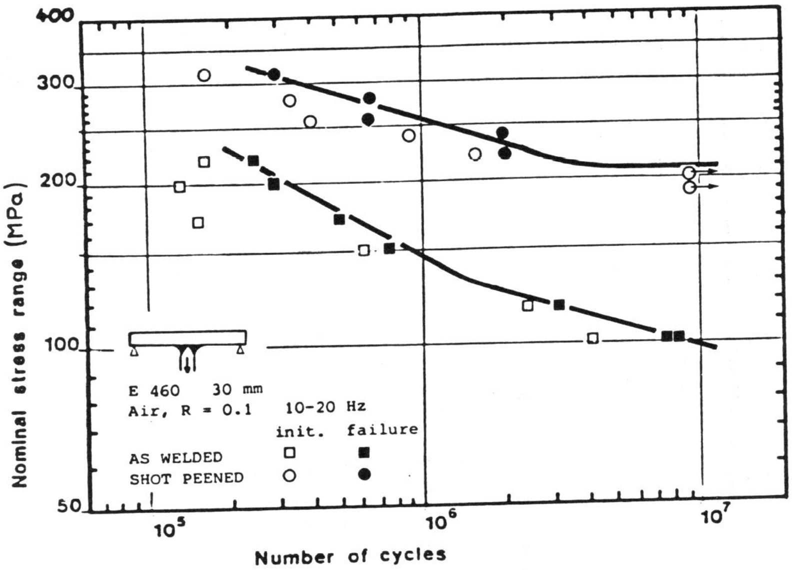

Figure 5 Fatigue strength of welded joints in steel E460, in the basic post-weld and shot-peened conditions

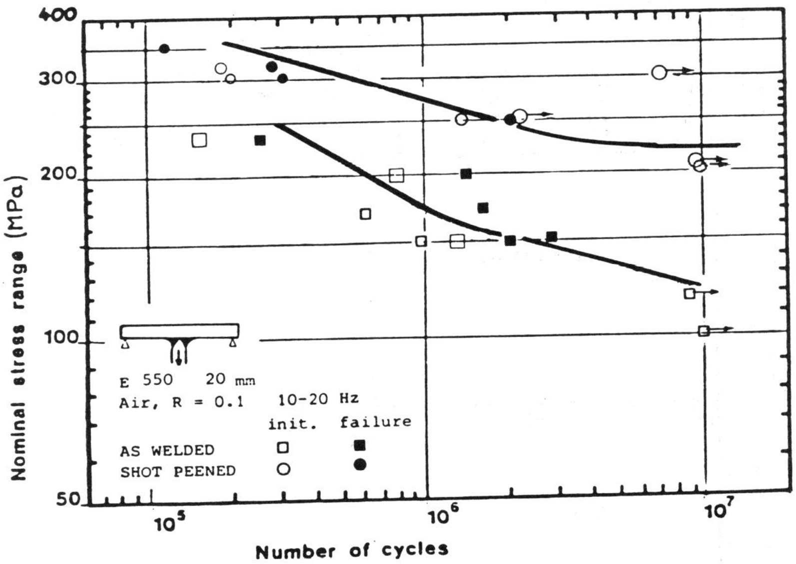

Figure 6 Fatigue strength of welded joints in steel E550, in the basic post-weld and shot-peened conditions

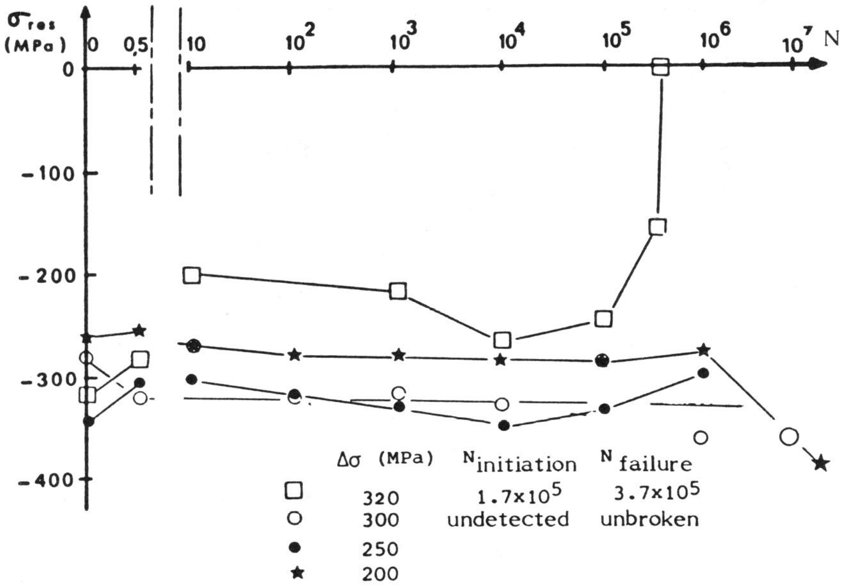

Figure 7 Variation of the shot-peening stresses in the weld toe during the fatigue tests (steel E550)

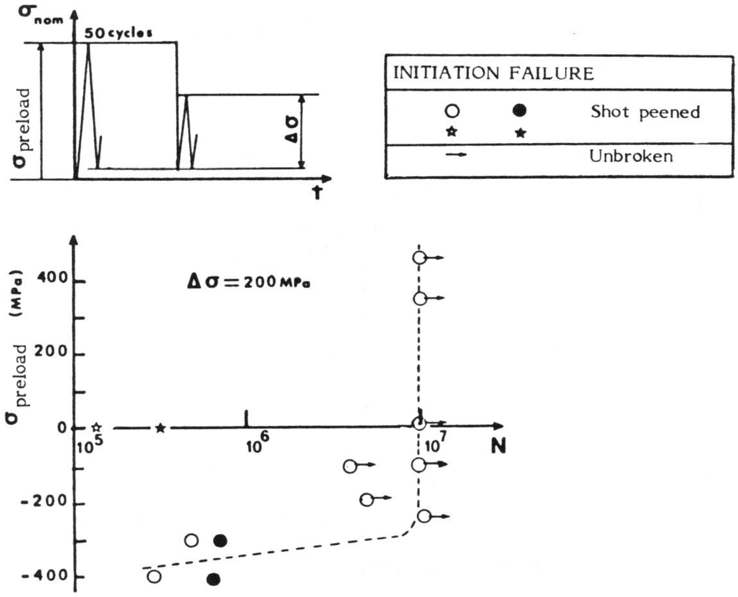

Figure 8 Influence of high stress peaks (tensile or compressive preloading) on the fatigue life of a welded shot-peened joint (steel E460)