doi: 10.1111/j.1460-2695.2004.00777.x

Fatigue behaviour of welded joints with cracks, repaired by hammer peening

C. M. BRANCO[1], V. INFANTE[1] and R. BAPTISTA[2]

[1] ICEMS/IST, Lisbon University of Technology, Lisbon, Portugal, [2] ESTG/IPT, Polytechnical Institute of Setúbal, Setúbal, Portugal

Received in final form 18 February 2004

ABSTRACT Rehabilitation of a welded structure, which involves repair of cracked joints, is achieved when the local treatment for repair gives a fatigue strength in the joint equal or above the fatigue strength of the uncracked original detail. If the treatment is properly applied the rehabilitation of the detail is assured, and the nature of the weld toe improvement methods can produce a joint, after repair, with a fatigue strength and residual life greater than the initial detail. The paper presents the results obtained on a fatigue study on the rehabilitation of non-load carrying fillet welded joints loaded in bending at the main plate and with fatigue cracking at the weld toes of the attachment in the main plate and though the plate thickness. Residual stresses were measured at the surface, with X-ray diffraction. The residual stresses induced by hammer peening at the weld toe were found to be greater along the longitudinal direction of the plate than in the transverse direction. The peak residual stresses near the weld toe were found to be close to yield in compression, justifying the great benefit of hammer peening. Results of a derived gain factor, g, in fatigue life were obtained as a function of the crack depth repaired by hammer peening.

Keywords fatigue, hammer peened; improvement techniques; life prediction; weld specimens.

INTRODUCTION

The present trend is to use welded structures to the maximum of their life potential. To achieve this aim, considerable effort should be made to inspection, monitoring and repair of the damaged zones. Life extension of ageing structures is possible to achieve without putting in danger the integrity of the structures, if repair methods are introduced. Current research deals with the fatigue behaviour of welded joints in a structural steel subjected to the so-called 'local post-welding improvement techniques', and is a follow-up of research work carried out by the authors in this field.[1,2]

The local treatment for repair should give a fatigue strength not below the fatigue strength of the original detail before it was damaged. If the treatment is properly applied, the nature of the weld toe improvement methods can produce a joint, after repair, with a fatigue strength and residual life higher than the initial detail, if this was not subjected to an improvement treatment. The repair treatment may arrest the original fatigue cracks.

Correspondence: C. M. Branco. E-mail: cmbranco@dem.ist.utl.pt

Most of the life improvement techniques, as applied to original or new welds, were established in the 1960s and early 1970s.[3–5] A number of investigations have confirmed the benefit to be gained from improvement techniques, and large increases in the fatigue strength are usually obtained. In spite of this, some reluctance has been observed towards the introduction of improvement techniques into design recommendations, and only recently one method, toe grinding, has been allowed for in the design of offshore structures[6] and pressure vessels.[7]

An analysis of an extensive amount of data available in the literature was made by Lieurade and co-workers.[8] Four improvement techniques (*grinding*, *TIG dressing*, *hammer peening and shot peening*) for four types of joints (*butt*, *T-joints*, *cruciform and longitudinal joints*) were taken into account in this study.[8] All the S–N curves were above those of as-welded assemblies. The best results were obtained with hammer peening.

The rather large increase in the fatigue strength, due to the use of improvement techniques, can be explained by

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the significant increase of a so-called initiation phase. During the initiation phase, the extension of existing 'crack-like' defects is slowed down or even stopped. The duration of this phase increases with the local fatigue life (or the decrease in the stress range).

In a review recently presented by Maddox,[9] conclusions and recommendations were defined for hammer peening which is now part of an official IIW document of the Commission XIII.[10]

Damaged weld toes can be treated locally, and most frequently while the structure is in service. If the repair is successfully applied, after the treatment, a significant life extension period can be obtained. This will avoid the need for repair welding that would be the case if the detail had to be rewelded and set back into service again.

A report of significant fatigue life extensions in repaired welds by air-hammer peening is presented in Ref. [11]. In another work by the same authors[12] it is shown that air-hammer peening of the local weld toe region is a reliable technique for repairing welds with shallow surface cracks up to 3 mm long.

The more traditional fusion rewelding repair procedures are susceptible to induced metallurgical problems associated with the formation of brittle phases or another embrittling phenomenon.

There is evidence, from tests on welded steel beams, that improvement techniques, notably those relying on the introduction of compressive residual stresses, are less effective in large welded structures containing high tensile residual stresses, due to welding, than when they are used to treat small-scale specimens. That is undoubtedly linked to the fact that the increase in fatigue life, resulting for an improvement technique—particularly one relying on compressive residual stresses—tends to decrease with increase in applied tensile mean stresses.

However, recent results obtained on real structures were very good as far as the benefit of hammer peening is concerned.[13]

Recently the authors have published data in this area, both for as-welded and defective welds.[14–16]

The results presented in this paper cover the effect of hammer peening, mainly as a repair technique for fatigue cracks at the weld toe. Results are presented also on the impact forces, distribution of residual stresses induced by the process and S–N data for the repaired cracks.

EXPERIMENTAL DETAILS

Material, specimens and improvements processes

Table 1 gives the composition and the nominal mechanical properties of the base and weld metal used in this study—a medium strength structural steel of the 400 MPa yield class (St 52-3, DIN 17100 specification) with a weld metal in a overmatching condition. The welds were made by the covered electrode process more details of which can be found in Ref. [13]. The mechanical properties were also obtained at room temperature in tensile, compressive and LCF tests carried out in cylindrical specimens of 8-9 mm diameter and 25 mm gauge length machined from 12.5 mm thick steel plates. The results are presented in Table 2.

Table 1 Chemical compositions of base metal and weld metal

C	Si	Mn	Cr	Mo	Ni	Ti	Al	V	Cu	Co	Nb	P	S
Base metal (St 52-3 steel)													
0.131	0.413	1.44	0.063	0.024	0.034	0.009	0.029	0.043	0.018	0.013	0.005	0.011	0.005
Weld metal (E 11018-G; over matched)													
0.08	0.45	1.28	0.50	0.37	1.87							0.017	0.01

Table 2 Parameters of the monotonic and cyclic stress–strain curves [13]. St 52-3 steel

	$\sigma_{0.2}$ (Mpa)	$\varepsilon_{0.2}$ (%)	E (MPa)	σ_R (MPa)	σ_f (MPa)	ε_R (%)	K'	n'	r^2
	(A) Tension (monotonic) and reversed cycling ($R = -1$)								
	415.3	0.56	200302	571.2	356.5	14.27	–	–	–
	406.9	0.50	218254	569.4	358.3	15.04	–	–	–
Average	411.1	0.53	214273	567.3	357.4	14.65	1015.31	0.1535	0.966
	(B) Compression (monotonic) and reversed cycling ($R = -1$)								
		0.27	205949	696.5	696.5	12.77	–	–	–
		0.31	203625	638.0	638.0	7.92	–	–	–
Average		0.29	204787	667.3	667.3	10.35	1015.31	0.1535	0.966

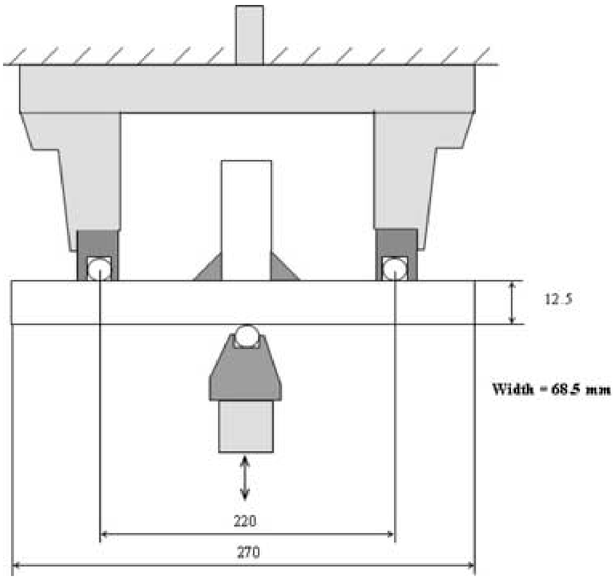

Fig. 1 Geometry of the specimens and loading arrangement. 3PB. $R = 0.1$. T-joint. St 52-3 steel.

The cyclic stress–strain curve of the material was obtained with one step level tests in cylindrical specimens and under reversed cycling ($R = -1$ and, also, $R = 0$ in tension and compression). The material exhibited mainly cyclic strain hardening behaviour. Values of the strain hardening coefficient and exponent were obtained in tension and compression.[13] In Table 2: $\sigma_{0.2}$ and $\varepsilon_{0.2}$ are the yield stress and strain, respectively, for 0.2% offset parallel line to the elastic line, with Young's modulus, E, σ_R is σ_{UTS}, σ_f is the failure stress ($\sigma_f > \sigma_R$)ε_R is the rupture strain for σ_f. K' and n' are the cyclic strain hardening coefficient and exponent, respectively, of the Ramberg–Osgood-type curve. This was obtained with a correlation coefficient of r^2 (Table 2).

Macros of the cruciform joints of the fatigue specimens are shown in Fig. 2 as indicated. The specimen is a non-load carrying T-joint failing from the weld toe in the thickness direction. The dimensions of the specimens and details of the loading arrangement are given in Fig. 1. In the macros of Fig. 2 the boundaries of the base metal, weld metal and HAZ are clearly visible. The material has a pearlitic–ferritic-type microstructure with an average grain size of 20 μm. In the macros of Fig. 2 it is possible to detect the differences in geometry of the local geometric parameters at the weld toe, the radii, ρ and the tangent angle, θ. The toe grounding technique changes the values of ρ and θ at the weld toe as can be seen in Fig. 2.

Toe grinding was carried out with a small portable grinding fitted with a rotary barrel type tool rotating at high speed along the width of the specimen. The operation procedures were those recommended in Ref. [10].

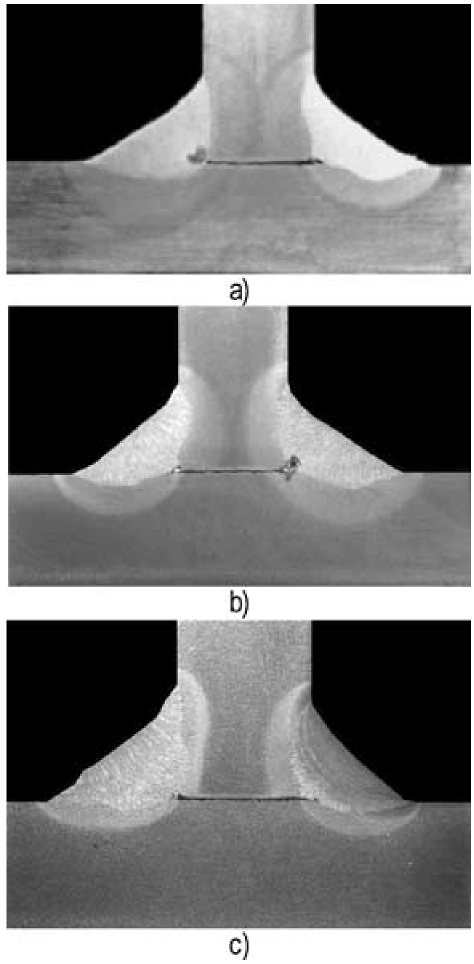

Fig. 2 Macros of the welded joints. T-joint. St 52-3 steel (a) as-welded; (b) toe ground; (c) hammer peening at weld toe.

For hammer peening, a small portable pneumatic hammer was used (Fig. 3), fitted with a special hard a metal tool, instrumented with four strain gauges bonded in full bridge (Fig. 3) to measure the impact forces and stresses during the hammer peening working cycles. The tool diameter was approximately 8.5 mm, the air pressure was 3.5 bar and four passes, along the transverse direction of the specimen, were applied.[10] The frequency was 3000 blows/min.

Local geometry at weld toe

Values of ρ and θ at the weld toe were obtained by optical measurement using an x–y co-ordinate table with an accuracy of 0.01 mm and 0.1 degrees, respectively. More than 100 measurements were obtained and the statistical data is given in Table 3 for the as-welded and hammer-peened specimens. A Gaussian-type correlation was obtained and the main parameters are given in Table 3 and Fig. 4a the

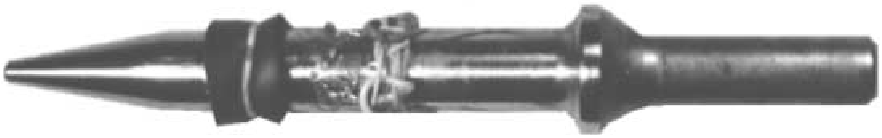

Fig. 3 Hammer-peening tool (high strength steel) to measure the impact forces. T-joint (Fig. 1).

Table 3 Statistical data of the measurements of radius and tangent angle at weld toe. T-joint (Fig. 1)

	Mean value	Standard deviation	Quadratic error
As-welded			
Radius	3.56 mm	2.1 mm	4.38 mm
Angle	27.33°	10.6°	112.64°
Hammer-peened			
Radius	3.05 mm	1.2 mm	1.44 mm

latter being the probability density function. The empirical fit of the probability of occurrence of the value above, is shown in Fig. 4b for the radius and for the as-welded specimens only. Analysis of the results indicates that there is a very small difference in the values of ρ between the as-welded and hammer-peened specimens. However for toe grinding ρ is greater than for as-welded and hammer peening (Fig. 2b & c). Hence the benefit of hammer peening for an increased fatigue life is due mainly to the introduction of compressive residual stresses.

Due to the morphology of the surface, in the weld toe region, after hammer peening, it was not possible to measure accurately the angle at the weld toe in the hammer-peened specimens.

Fatigue and hardness tests

The fatigue tests were carried out under constant amplitude loading in a ±250 kN capacity servo-hydraulic fatigue test machine. The frequency was 10–15 Hz, and the stress ratio, $R = 0.1$. The bulk of the tests was carried out until complete failure of the specimen or up to a number of cycles close to 6.0×10^6, time when the fatigue test was stopped.

In the majority of the specimens, including all the cracked ones subjected to repair, six strain gauges were bonded very close to the weld toes of the attachment. These strain gauges measured the variation of the local strain at the weld toe and along the width of the specimen, caused by the initiation and propagation of the fatigue cracks at the weld toe through the thickness direction of the longitudinal plate. The strain data were used to establish the onset of fatigue crack tip marking and to define the crack geometry to be repaired, afterwards, by hammer peening. The strain gauge data are presented in. Ref. [13].

Misalignment was checked in some specimens, using strain gauges, and it was found to be negligible.

Vickers data with 1 kg was obtained along the longitudinal directions of the plate, close to the upper and lower surfaces. The variation of hardness along the thickness of the specimen at the weld toe and in the crack propagation direction was also obtained. The main objective of these tests was to compare the hardness distributions for the as-welded and hammer-peened specimens.

RESULTS AND DISCUSSION

Analysis of the hammer-peening process

The variation of the hammer peening impact forces and stresses in the tool, as measured by the strain gauges, is depicted in Fig. 5. The duration of the treatment (working cycles) is indicated in Fig. 5. The mean values quoted in Fig. 5 are the static values that produce the same area under the dynamic stress or load cycle imposed by the tool in the material.

In the fast cycle (approximately 3 s duration) the mean force is significantly larger than in the slow cycle (approximately 35 s duration). The latter cycle follows the procedures recommended in Ref. [10] giving an impact speed between 50 and 100 mm/min in the direction of the length of the weldment (width of the specimen). With these results (Fig. 5) it is expected that the residual stresses in fast cycles will be higher than in the recommended slower impact cycles. Work is in progress to assess this behaviour.

The fatigue tests were only carried out with specimens treated with 'fast' cycle (Fig. 5a).

Hardness data

In the hammer-peened joints, an increase in hardness was obtained, and the hardness profile, through the plate thickness, shows peak values close to 260 HV near the surface at the weld toe zone (Fig. 6). Figure 6 also shows that the depth of the zone affected by the hammer peening is about 2.5 mm, i.e. the material has hardened up to this depth, and this could be the limit of the residual stress field created by hammer peening. This result also indicates that the treatment could be effective if the crack is inside this hardened zone, where the hardness increases

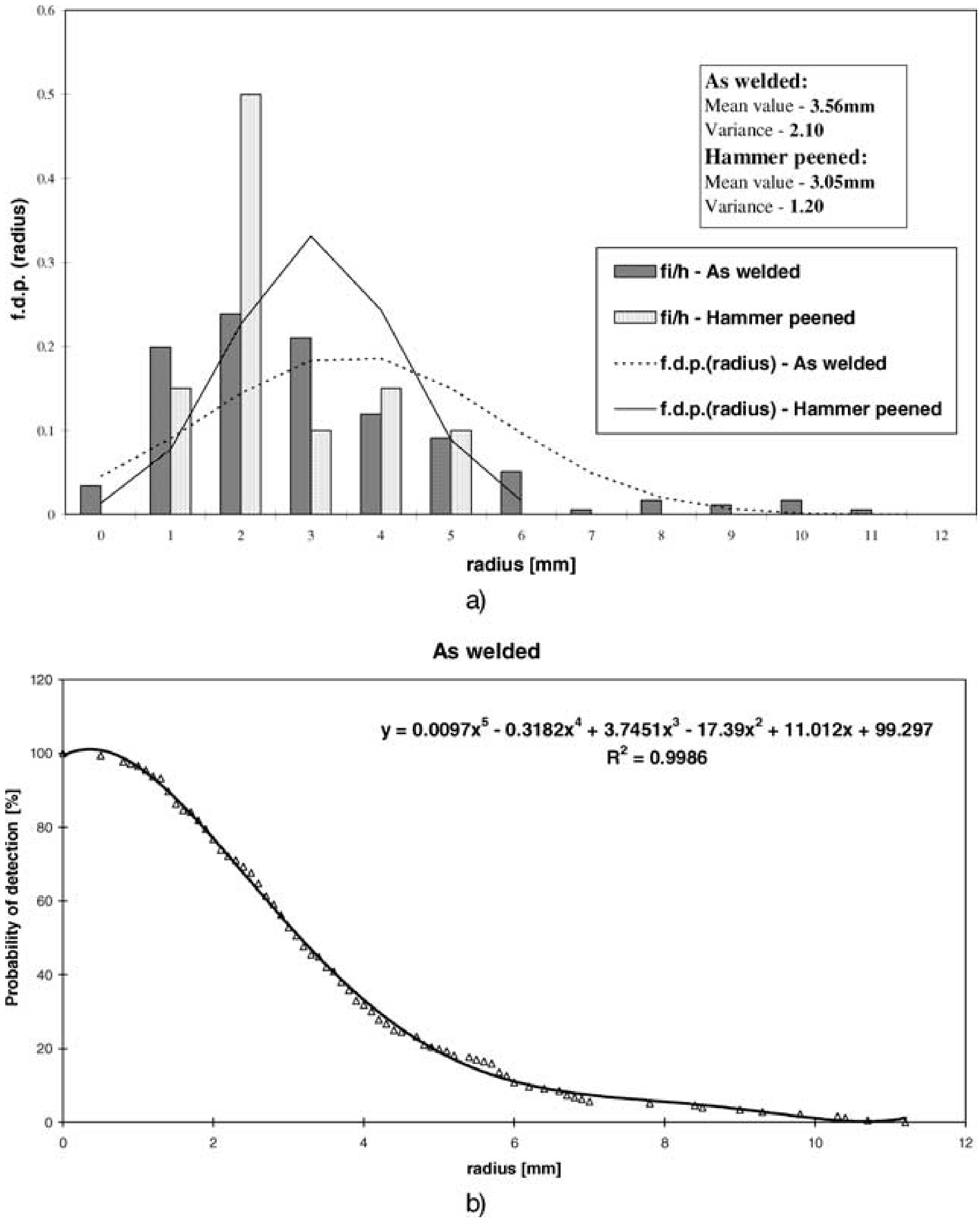

Fig. 4 Statistical data of the local geometry at the weld toe. T-joint (Fig. 1). St 52-3 steel (a) P.D.F. for the radius ρ (as-welded and hammer-peened joints); (b) probability of occurrence of the value above for the radius ρ. As-welded joints.

from near the value 190 HV of the base metal up to near 260 HV at the surface at the weld toe in the WM/HAZ hammer-peened zone.

Fatigue data in the welded joints

Two typical plots of the variation of strain in the weld toe region are shown in Figs 7a and b. These can be used to detect crack initiation life, N_i, and also to define a crack marking death, at the associated number of cycles, N_{bm}, or the number of cycles of crack propagation, N_{bH}, before hammer peening was carried out N_{bH}.

The crack initiation life, N_i was defined for the first variation in strain in the strain gauge(s) due to the nucleation of the crack near the strain gauge closest to the crack. (strain gauge 5 in Fig. 7a and strain gauge 2 in Fig. 7b). The depth of the repaired cracks was defined as indicated in Fig. 7.

Specimens failed by crack propagation from the weld toe and through the plate thickness.

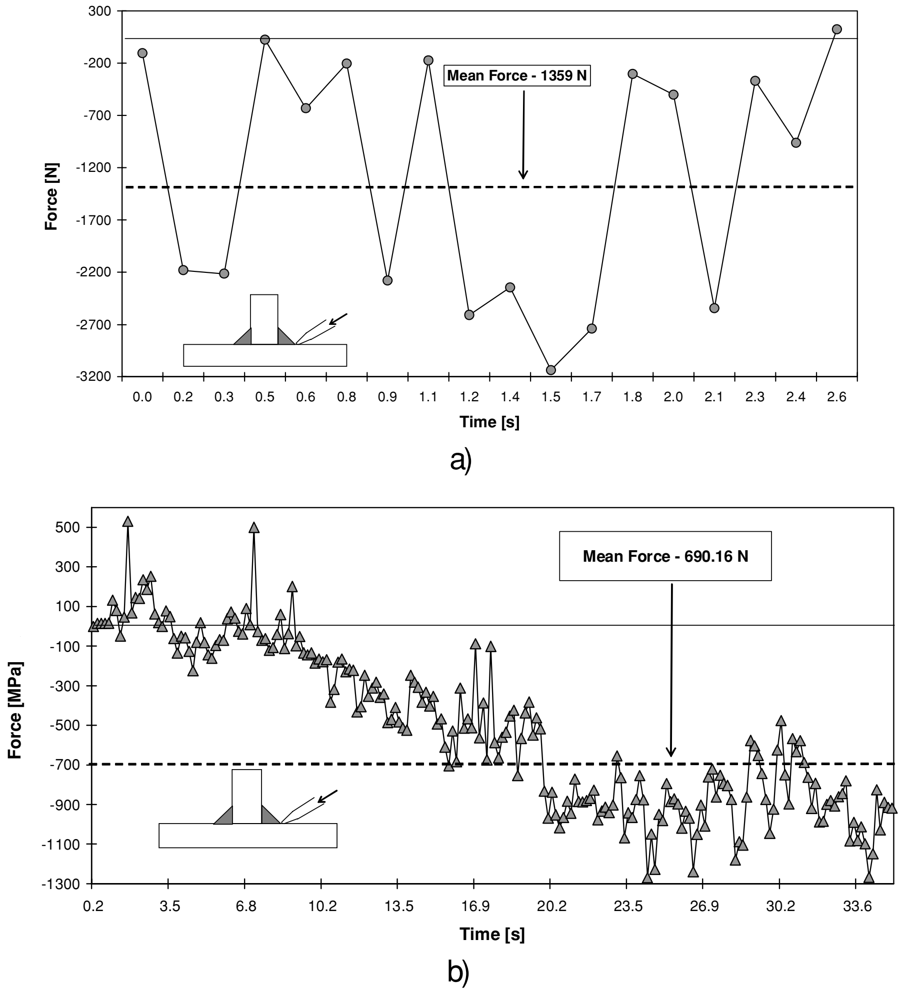

Fig. 5 Variation of impact forces and stresses measured in the hammer-Ipeening tool (Fig. 3) during the treatment at weld toe (one pass). (a) Fast hammer-peening cycle; (b) slow hammer-peening cycles (recommended in Ref. [10]).

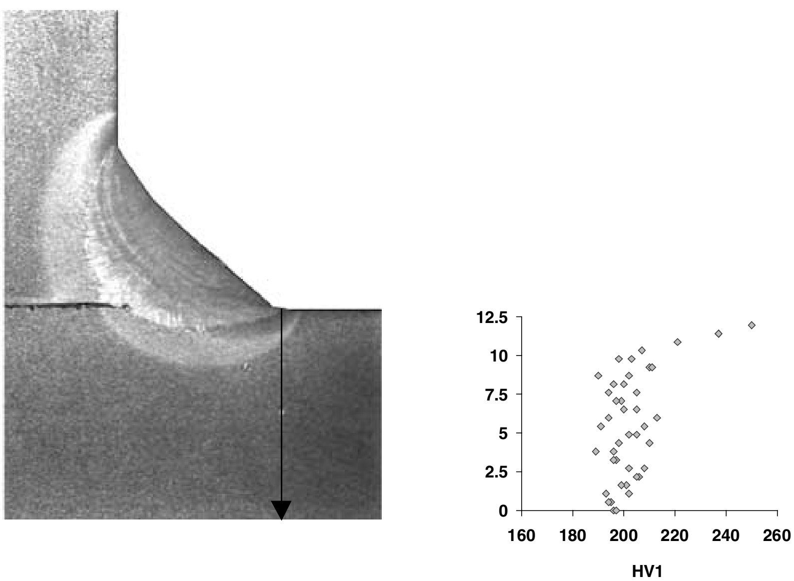

Fig. 6 Hardness plot along the plate thickness y_i in the weld toe line for the hammer-peened joints. HV1. T-joints. St 52-3 steel.

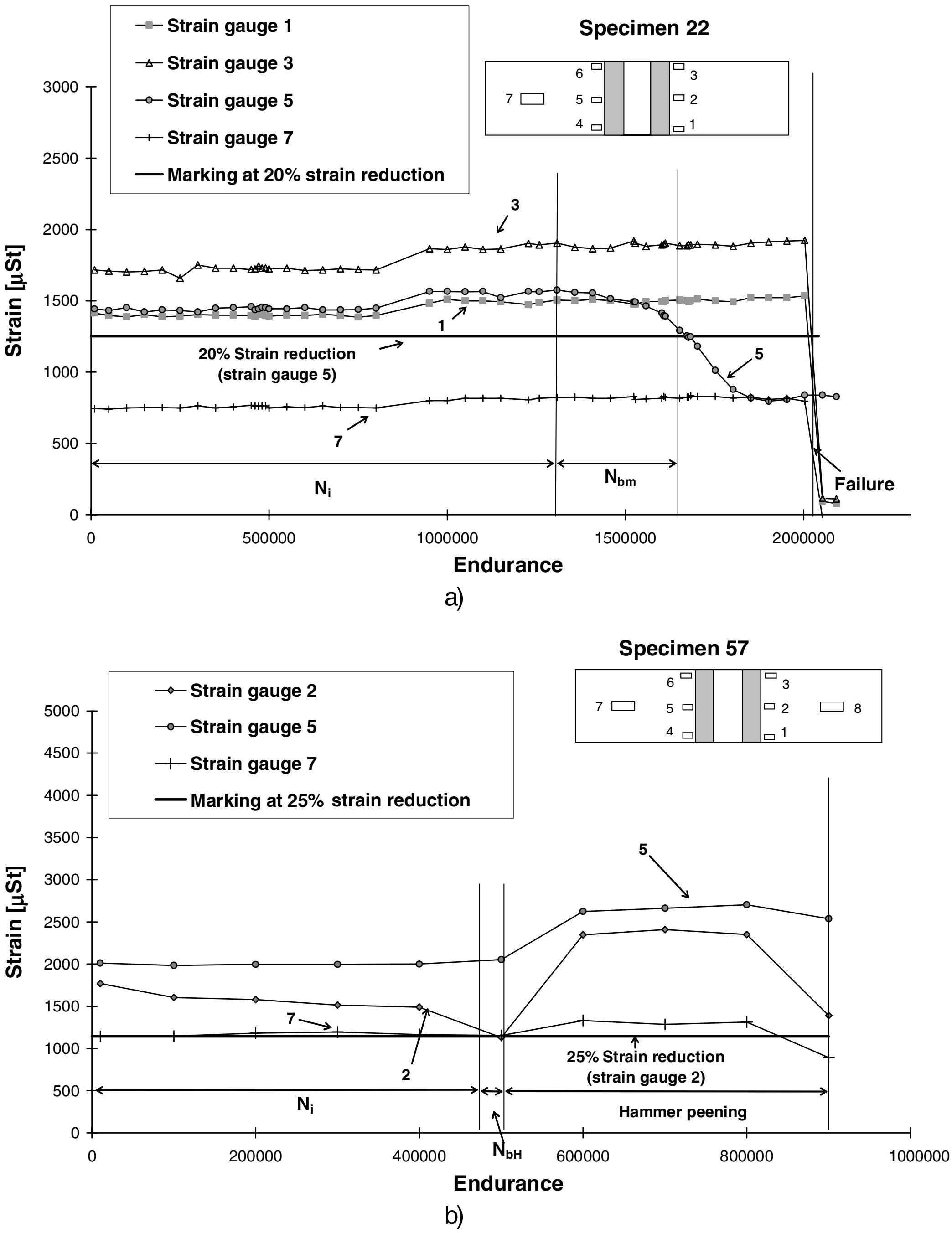

Fig. 7 Variation of strain, at weld toe region, with the number of cycles to detect crack initiation and define number of cycles to detect crack initiation and define number of cycles of marking. N_{bm}. T-joints (Fig. 1). $R = 0.1$. St 52-3 steel (a) as-welded with marking of a crack depth $a_H = 1.67$ mm. $\Delta\sigma = 325$ MPa (20% of strain reduction); (b) specimen repaired by hammer peening of a crack of $a_H = 1.27$ mm (25% reduction of strain) $\Delta\sigma = 325$ Mpa.

An improvement in fatigue behaviour was obtained in the treated joints. Thus, for fatigue lives above 10^6 cycles, hammer peening provides higher fatigue strength since higher fatigue limit stresses were obtained (≈350 MPa). Progressively higher fatigue crack initiation periods were obtained in the toe ground and hammer-peened joints, as reflected by the higher values of m in the equation of the S–N curve (Table 4 and Fig. 8).

The results (Fig. 8) show that the fatigue strength of this detail is very high. Comparisons can be made with available fatigue design S–N codes.[17,18]

Table 4 Values of K_o and m for the non-repaired specimens. S–N curves. $N_r = \frac{K_0}{(\Delta\sigma)^m}$ T-joint. 3 PB. $R = 0.1$ (Fig. 1)

Ref. ($R = 0.1$)	M	K_o	r^2	Gain in fatigue strength (2×10^6 cycles)	Gain in fatigue strength (3×10^6 cycles)	Gain in fatigue life ($\Delta\sigma = 350$ MPa)
As-welded	8.263	4.99×10^{26}	0.9469	1	1	1
Toe grinding	11.068	4.93×10^{34}	0.9380	(367.4/294.0) = 1.25	(350.0/294.0) = 1.19	($3.4 \times 10^6/4.7 \times 10^5$) = 7.22
Hammer peening	6.751	1.85×10^{23}	0.7866	(325.6/294.0) = 1.11	(375.0/294.0) = 1.27	($1.2 \times 10^6/4.7 \times 10^5$) = 2.60

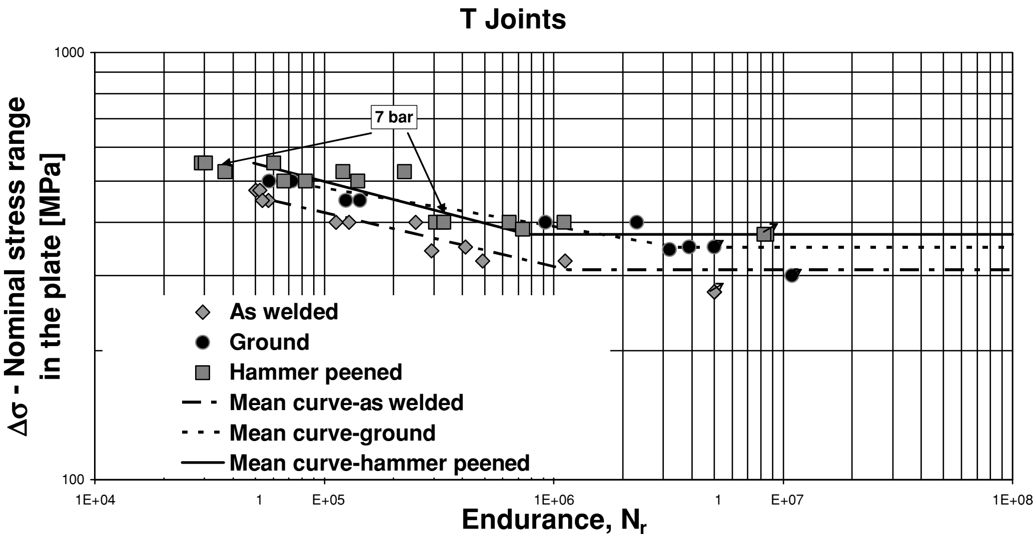

Fig. 8 S–N data and best fit of data for the as-welded, toe ground and hammer-peening joints. T-joint (Fig. 1). Unrepaired specimens. $R =$ 0.1. 3PB. St 52-3 steel.

Table 5 S–N data for the repaired joints by hammer-peening T-joint (Fig. 1)

Ref.	$\Delta\sigma$ (MPa)	N_i (cycles)	$\mathbf{N_r}$ (cycles)	Condition
22	325	1 357 537	2 024 529	As-welded only with fatigue marking
23	325	260 000	489 201	As-welded only with fatigue marking
24	325	65 100	1 398 259	As-welded initially and repaired by hammer peening
26	400	75 000	156 255	As-welded initially and repaired by hammer peening
27	400	10 000	230 613	As-welded initially and repaired by hammer peening
28	400	100 000	379 581	As-welded initially and repaired by hammer peening
29	300	2 080 000	3 401 893	As-welded initially and repaired by hammer peening
53	400	100 000	543 810	As-welded initially and repaired by hammer peening
		261254*	–	
54	325	360 000	514 619	As-welded initially and repaired by hammer peening
57	325	470 000	3 506 191	As-welded initially and repaired by hammer peening
		263809*	–	
57	400	–	900 266	As-welded initially and repaired by hammer peening
38	500	10 000	111 939	Hammer-peened initially and repaired by hammer peening
46	500	85 000	144 252	Hammer-peened initially and repaired by hammer peening
47	500	30 000	93 809	Hammer-peened initially and repaired by hammer peening

Note: $\Delta\sigma$ is the nominal stress range in bending in the weld toe area. It was only possible to obtain N_{iaH} values after hammer peening in a few specimens (Table 5).
*N_{iaH}—Number of cycles of crack initiation after hammer peening.

Fatigue endurance was defined as the number of cycles, N_r, to initiate and propagate fatigue cracks up to final failure.

Results of fatigue life in the repaired joints

The S–N data is given in Table 5 and these results are plotted in Figs 9 and 10 for comparison with the appropriate S–N curves for the unrepaired joints shown in Fig. 8. It is seen that, for the initial untreated welded joints (Fig. 8), an increase in fatigue life was obtained after repair by hammer peening (Fig. 9) because all the data points (Table 5) of the repaired joints are above the S–N curve of the unrepaired as-welded joints. Also, the results of the repaired joints are very close to the S–N curve of the specimens which were subjected initially to the hammer-peening treatment (Fig. 10). Therefore repair of fatigue cracks by hammer peening gives an improved life in comparison with the unrepaired joints and only a negligible variation of fatigue life was obtained as against the fatigue life results obtained in the joints subjected to hammer peening initially (with no fatigue cracks). Then repair by hammer peening of existing fatigue cracks gives a very similar improvement in fatigue life as if the treatment was applied initially.

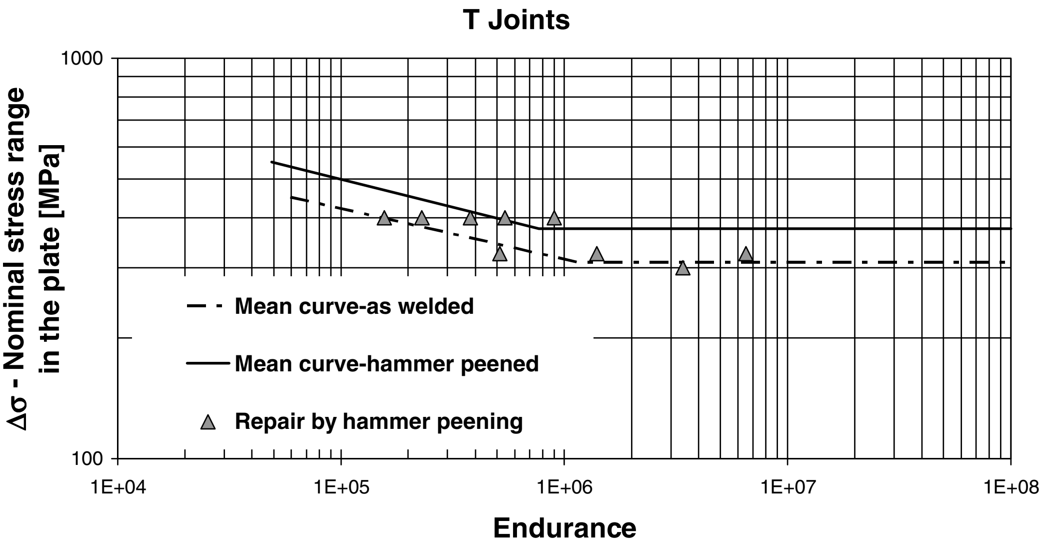

Fig. 9 S–N results for the as-welded specimens with fatigue cracks repaired with hammer peening. T-joints (Fig. 1). $R = 0.1$. 3PB. St. 52-3 steel.

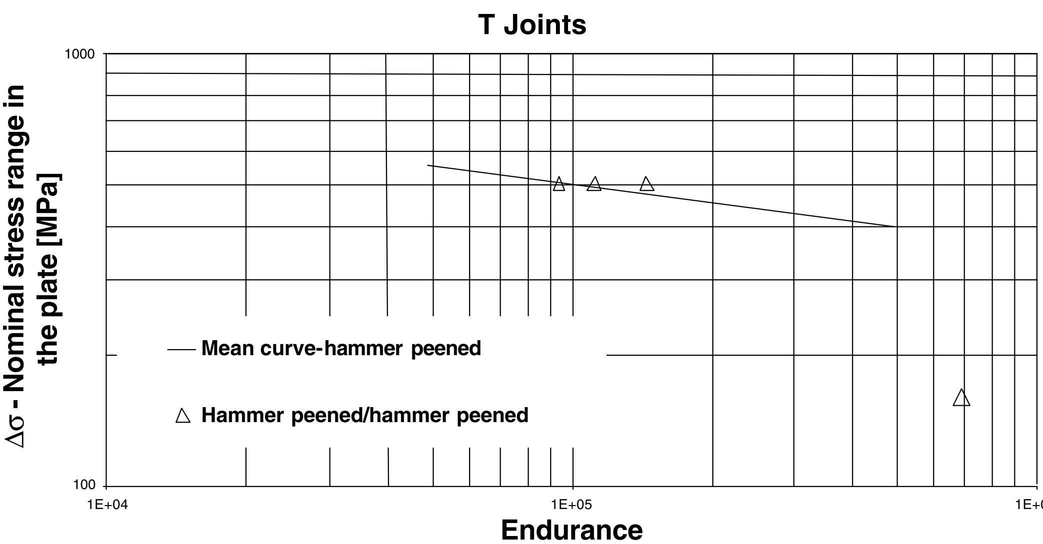

Fig. 10 S–N results for hammer-peened specimens with fatigue cracks repaired by hammer peening. T-joints (Fig. 1). $R = 0.1$. 3PB. St 52-3 steel.

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Table 6 Fatigue life data for as-welded specimens with cracks treated (repaired) by hammer peening. $R = 0.1$. T-joint (Fig. 1)

Specimen	$\Delta\sigma$ (MPa)	$\Delta\sigma$ (as-welded) (MPa)	a_H (mm)	c_H (mm)	N_{bH} (cycles)	N_i (cycles)	N^{**}_{paH}, N^{*}_{aH}
24	325	307	2.41	5.36	202306	65100	1130853*
26	400	400	3.18	18.29	42321	75000	38934**
27	400	382	2.50	7.72	88458	10000	132155*
28	400	360	4.0	9.21	109237	100000	170344**
29	300	276	3.3	5.81	427107	2080000	1194786**
53	400	344	1.44	11.96	38746	100000	405064*
54	325	347	6.1	26.84	132775	360000	21914**
57	325	275	1.27	3.69	–	470000	–
57	400	324	1.27	3.69	–	–	394075*

N^{**}_{paH}, Calculated values of N_{paH}; $N_{iaH} = 261254$ cycles.

For the repaired joints (Fig. 9) a correlation was not fitted to the results since crack depth is another variable, but comparisons can be made on a basis of constant stress or for a range of fatigue lives.

From data in Fig. 9 It is apparent that a crack may not change significantly the compressive residual stress field of hammer peening. For initial hammer-peened joints (Table 5) a second hammer-peening treatment applied for repair of an existing crack does not provide any significant improvement in fatigue life as shown in Fig. 10. This is due to the fact that the beneficial effect of hammer peening is mainly a consequence of the initial residual stress field left in compression, due to hammer peening, as will be analysed later.

For the conditions in Fig. 10 the material attains a shake down state in the initial treatment by hammer peening, and any additional impact stresses induced by a second set of hammer peening will not change significantly the residual stress field.

Detailed work is in progress in this area using an elastic–plastic 3D FE model to compute the residual stresses caused by hammer-peening operations.[19]

Gain factors g_N and g_s to quantify the beneficial effects of hammer peening in repair could be defined as:

$$g = \frac{N_r}{N_e}. \tag{1}$$

For g_N, N_r is the fatigue life of the repaired joint and N_e is the expected fatigue life of the joint if it was not repaired. The g factor depends on the crack depth, a_H of the repaired crack and also on the applied stress range. No correlation was obtained with the stress range but a correlation was obtained with the crack depth. This is valid since for these specimens stress range variation in the fatigue specimens was small (Table 5)

In Eq. (1a) N_r and N_e are given by the equations

$$N_r = N_i + N_{bH} + N_{aH}, \tag{2}$$

where N_i is the crack initiation life before the first crack for repair starts (Figs 7a & b) N_{bH} is the fatigue life in crack propagation (Figs 7a & b) and Table 6 before repair by hammer peening was carried out in a crack with dimensions a_H; and c_H and N_{aH} is the fatigue life after repair which will include crack initiation and crack propagation periods (Fig. 7a & b). Both N_{bH} and N_{aH} were obtained experimentally:

$$N_{aH} = N_{iaH} + N_{paH}. \tag{3}$$

N_{iaH} was obtained experimentally and N_{paH} can also be calculated.[13]

Finally, N_e will given by the equation:

$$N_e = N_i + N_{bH} + N'_{aH}, \tag{4}$$

where N'_{aH} is the fatigue life (in crack propagation) that would be obtained in the specimen if repair by hammer peening was not introduced.

N'_{aH} is therefore the number of cycles to propagate an initial crack from the size (a_H; c_H) to the size for the failure criterion (a_H = B/2) where B is the specimen plate thickness. This failure criterion is acceptable as seen in the macros of fracture surfaces in Fig. 11a and b, since the applied nominal stress range has not varied very significantly in the specimens (Table 5).

Calculated values of N_{paH} were obtained from integration of the Paris law of the material with values of constant C and exponent m obtained in crack propagation tests carried out on the same material[20] $C = 1.36\,x\,10^{-11}$ [mm/cycle]; $m = 3.34$. The appropriate LEFM K solution was taken from B57910.[21]

For the specimens in Table 5 the results obtained for the terms in Eqs (2)–(4) are presented in Tables 6 and 7 and the values of the gain factor g_N (Table 7) are plotted in Fig. 12 against crack depth of the repaired crack.

More appropriate values of C and m should have been used to predict the N_{paH} values in the hammer-peened material (Fig. 11b). However, it is known in the literature[8,9] that the values of C and m do not vary significantly with the hardness and strength in carbon steels. Therefore crack propagation behaviour in the hammer-peened zone is expected to have values very similar to the metal leading also to similar values of N_{paH} for both regions. Thus, the increase in fatigue life in hammer-peened joints is due to increased crack initiation life induced by the compressive residual stresses in the critical areas. A discussion on residual stress values is presented in in the section 'Residual stress management'.

For the initial as-welded joints the gain factor g_N increases for small repaired crack depths and one order of magnitude in fatigue life $g \approx 10$ could be obtained for crack depths in the region 1–1.5 mm. For crack depths above 3 mm, the increase in fatigue life is very small (Fig. 12) (g_N between 1 and 2.5) and for crack depths above 5 mm, the value of g_N is very close to 1 (no benefit). Therefore, repair by hammer peening is effective if the crack tip region is still within the depth of the region where hardness has increased due to the hammer-peening treatment (Fig. 6). The scatter obtained in the results of Fig. 12 should be mainly attributed to the values of stress range, $\Delta\sigma$, in the specimens which were not constant (Tables 6 & 7) although with a small variation.

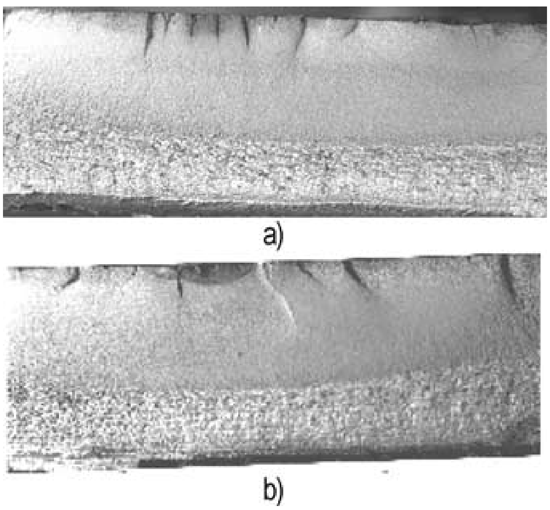

Fig. 11 Macros of fracture surfaces of fatigue specimens. T-joints (Fig. 1). 3PB. $R = 0.1$ St 52-3 steel. (a) As-welded only with fatigue marking at 40% strain reduction. $a_H = 3.86$ mm. $\Delta\sigma = 325$ MPa. $N_T = 489201$ cycles. (b) Repaired by hammer peening of a crack depth of 1.27 mm. Fatigue marking of 25% strain reduction. $\Delta\sigma = 325$ MPa. $N_T = 900266$ cycles.

For the initial hammer-peened specimens, and as expected from above and from the S–N curves in Fig. 10, the gain factor is very small (Fig. 12 & Table 7). In the majority of specimens the number of cycles after repair by hammer peening, N_{aH}, was greater than N_{bH}. This is due to the greater crack initiation phase after hammer peening ($N_{iaH} > N_{paH}$ in Eq. (3)). Work is in progress to predict the crack initiation phases using LCF data obtained in the base metal (Table 2) applied to local stress–strain models.[22] Also for the specimens subjected to the second hammer peening for repair (Fig. 10) prediction of N'_{aH} should be made taking into account the strain hardening and increase in hardness induced by the initial hammer peening applied after welding.

The gain factor for strength, g_S was calculated for the fatigue endurance, N_r of the repaired specimens. The values of g_S are in Table 7 and the plot g_S against crack depth a_H, as in Fig. 12, is in Fig. 13. In Eq. (1b) for g_S, $\Delta\sigma$ is the applied stress range in the fatigue tests of the repaired specimens and $\Delta\sigma_{aw}$ is the fatigue strength for the as-welded specimen and for the same value of N_r, whose values are in Table 7. The results for g_S show some scatter due to the difference in N_r values from specimen to specimen. However g_S is always greater than 1, and increases

Table 7 Continuation of Table 6 and also Hammer-peening specimens repaired by hammer peening. $R = 0.1$. T-joint (Fig. 1)

Specimen	$\Delta\sigma$ (as-welded) [Mpa]	a_H (mm)	N^{**}_{paH}, N^{*}_{aH}	N_e	N_r	g_N	g_S
24	307	–	344398**	344399	1398259	4.06	1.06
26	400	–	124523*	125004	156255	1.25	1.00
27	382	–	126741**	126710	230613	1.82	1.05
28	360	–	230795*	208561	379581	1.82	1.11
29	276	–	2603875*	2074325	3401893	1.64	1.09
53	344	–	147153**	415122	543810	1.31	1.16
54	347	–	493360*	139086	514619	3.70	0.94
57	275	–	594434**	6255953	3506181	1.04	1.18
57	324	–	–	82211	900206	10.95	1.23
38	417	2.37	36107	86107	111939	1.30	1.20
46	404	3.98	19330	137383	144252	1.05	1.24
47	426	2.87	33507	80870	93809	1.16	1.17

$N_{iaH} = 263809$ cycles.

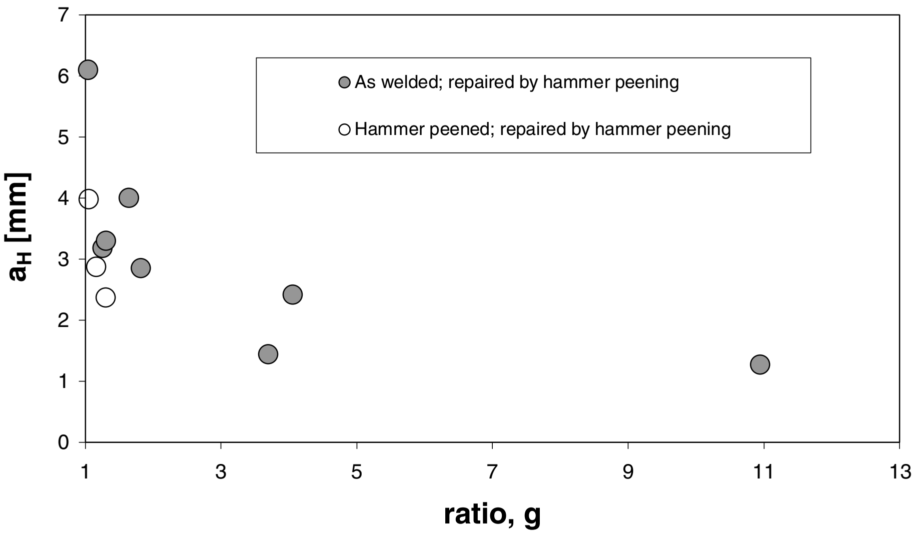

Fig. 12 Gain factor, g_N, in fatigue life, against depth of fatigue crack repaired by hammer peening. T-joints (Fig. 1). $R = 0.1$. 3PB. St 52-3 steel.

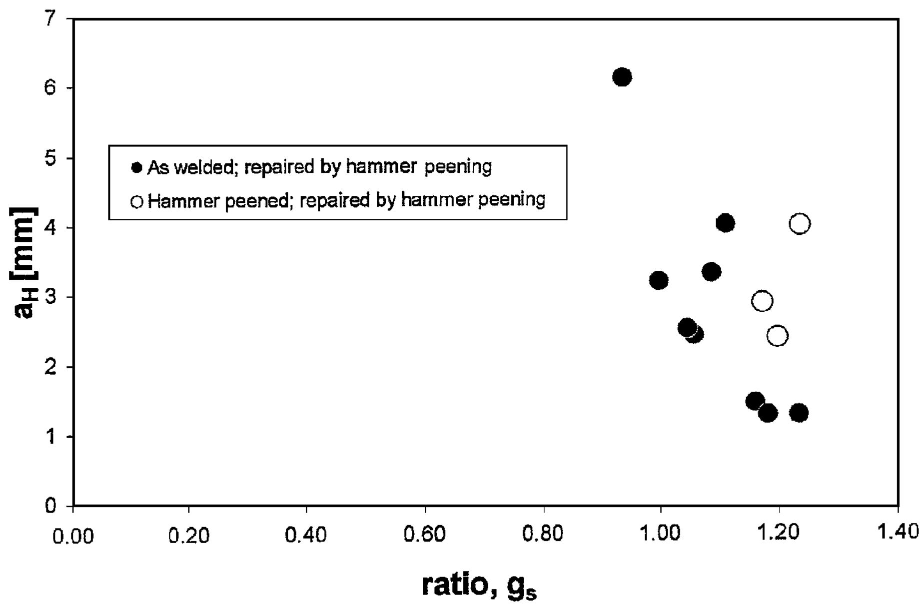

Fig. 13 Gain factor, g_S is strength against depth of fatigue crack repaired by hammer peening and for the N_r values. T-joints (Fig. 1). $R = 0.1$.3PB. St 52-3 steel.

when the depth of the repaired crack decreases (Fig. 13). This result indicates that the fatigue strength of the repaired joints is above the as-welded joint (Figs 13 & 9). Hence, with repair by hammer peening there is gain in fatigue life and fatigue strength from very tiny cracks up to cracks with a depth close to half of the thickness of the specimens.

Scatter in the results of gain factors can be reduced by testing treated specimens with variable crack depths, and fixed (few) stress ranges, to obtain g_N, or with fixed (few) crack depths and variable stress ranges, to obtain g_S data.

Residual stress measurements

Values of the residual stresses were obtained in some selected specimens by X-ray diffraction at the weld toe and at 1–3 and 5 mm from the weld toe in the longitudinal x-direction. The residual stresses were obtained for different types of specimens, as-welded and hammer-peened after a fatigue test. The objectives of these tests were to quantify the residual stresses introduced by the hammer-peening process. The residual stresses decrease as the x-distance increases (Table 8(a) & 8(b)).

Table 8a Values of the longitudinal residual stress, σ_x (MPa) at the surface along the longitudinal direction, x from the weld toe. X-ray diffraction (for orientation see axes in Fig. 1)

	Weld toe $x = 0$	$x = 1$ mm	$x = 2$ mm	$x = 3$ mm	$x = 5$ mm
As-welded not tested	–	–	−18	–	14
Hammer-peened	−334	−298	−258	−185	−7

Table 8b Values of the transverse residual stress, σ_z(MPa) at the surface along the longitudinal direction, x from the weld toe. X-ray diffraction. (for orientation see axes in Fig. 1)

	Weld toe $x = 0$	$x = 1$ mm	$x = 2$ mm	$x = 3$ mm	$x = 5$ mm
As-welded before fatigue testing	22	–	–	–	11
Hammer-peened	−439	−288	−213	−172	−22

The results (Table 8(a) & 8(b)) have shown that the residual stresses in the x-direction are usually significantly higher than in the transverse z-direction. This effect is predicted in the theory of welding. Both in the x- and z-directions, the residual stresses in the hammer-peening condition are above those of the as-welded condition. The maximum value of residual stresses is compressive, and occur in the location at the weld toe and in the transverse z-direction.

Because the residual stress is of yield magnitude in compression its effect is beneficial for the fatigue behaviour of the joint, thus explaining the large increase in fatigue strength obtained for the hammer-peened joints. The results also show that the effect of hammer peening, in terms of residual stresses, is localized near the weld toe where the treatment is applied since, at the zone 5 mm away for the weld toe $x = 5$ mm, the residual stresses are negligible (Table 8a). The residual stresses decrease as the longitudinal distance from the weld toe increases (Table 8(a) & 8(b))

The residual stresses in the as-welded tested specimens are low, at least 5 mm away from the weld toe. Some relaxation effect of stresses may occur after the fatigue tests.

CONCLUSIONS

For non-load carrying T-joints loaded in 3PB in the main plate, gain factors, g, were obtained to assess the fatigue lives of repaired fatigue cracks at the weld toe, using the hammer-peening process. A correlation was found between g and the crack depth, a_H, of the repaired crack.

The results of hardness distributions at the weld toe have shown that the depth in the thickness direction of the zone affected by hammer peening is about 2.5 mm, the limit of the compressive residual stress fields induced by hammer peening.

For the as-welded joints with fatigue cracks of known size obtained by marking, and repaired by hammer peening, the fatigue lives were found to be significantly above the fatigue lives of the initial as-welded specimens only.

Beneficial effects of repair were found to be greater (high values of gain factors, g) in small repaired fatigue cracks with depths below 2.5 mm.

For specimens initially subjected to hammer peening, treatment repair of the fatigue cracks by hammer peening did not produce any significant increase in fatigue life. However the fatigue data obtained in the repaired specimens fitted rather well with the S–N curve for the as-welded hammer-peened specimens without fatigue cracks. Hence the benefits of hammer peening, in terms of increase in fatigue life, are identical whether there is or is not a fatigue crack at the weld toe.

In the hammer-peened specimens, values close to the yield stress in compression were obtained at the weld toe region using the X-ray diffraction technique, which is the main reason for the great increase in fatigue life when hammer peening is applied.

Acknowledgements

This project was financed by FCT, in Portugal, under the PRAXIS XXI program (Contract 3.1/CEG, 2705/95). The specimens were kindly supplied by The Welding Institute (TWI), Cambridge, U.K. The authors express their gratitude for the support and useful discussions with Dr S.J. Maddox, of TWI.

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