A STUDY ON THE FATIGUE BEHAVIOUR OF DAMAGED WELDED JOINTS REPAIRED BY HAMMER PEENING

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ABSTRACT

The paper presents results obtained on a fatigue study on the effect of hammer peening in non load carrying fillet welded joints of a medium strength structural carbon steel loaded in bending at the main plate and with fatigue cracking at the weld toes of the attachment in the main plate and through the plate thickness.
The fatigue tests were carried out under constant amplitude loading, with a stress ratio, R≅0.1, and the frequency was between 10 and 15Hz. Hardness distributions in the hammer peened joints are also presented.
Fatigue data is presented in the form of S-N curves obtained in as welded joints and, for ground and hammer peened joints at the weld toes. The first set of treatments was applied in the as welded joints without fatigue cracks. These results were compared with those obtained in tests on repaired welds, where hammer peening was applied at weld toes containing previously obtained fatigue cracks with 1 to 4mm depth. The event of crack initiation was obtained with strain gauge readings at the weld toe, and control of the depth of the propagating cracks and also of the pre-cracks before repair was achieved by appropriate fatigue crack tip marking. Significant improvements in fatigue life were obtained in the damaged cracked joints due to the application of hammer peening. Also, the improvement ratios were obtained and predicted using a fracture mechanics model, developed by the authors.

1. INTRODUCTION

Life extension of ageing structures is possible to achieve without putting in danger the integrity of the structures, if rehabilitation methods are introduced. This paper will deal 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 previous work carried out by the authors in this field (1, 2).

In this context, rehabilitation of the structure is achieved when the local treatment for repair gives a fatigue strength in the joint equal to the fatigue strength of the original detail before it was damaged. If the treatment is properly applied, the rehabilitation of the detail is assured, and the nature of the weld toe improvement methods can even produce a joint, after repair, with a fatigue strength and residual life higher than the initial detail.
An analysis of an extensive amount of data available in the literature was made by Lieurade and co-workers (3). Four improvement techniques (*grinding, TIG dressing, hammer peening, shot peening*) for four joints (*butt, T joints, cruciform and longitudinal joints*) were taken into account in this study (3). 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 the occurrence of a co-called initiation phase, in addition to the crack propagation phase.

A report of significant fatigue life extensions in repaired welds by air-hammer peening is presented in (4). In another work by the same authors (5) it is shown that air-hammer peening of the local weld toe region is a practical and reliable technique for repairing welds with shallow surface cracks up to 3mm long. A review of the methods of repair is presented in (6), where emphasis is put on the fact that good results can only be obtained with local treatments by introduction of compressive residual stresses, if the depths of the existing crack are within the residual stress field created by the treatment.

The present paper reports the results obtained on a study on the effect of the hammer peening process, both as a fatigue life improvement method in sound welds and as a repair technique to rehabilitate fatigue cracked joints at the weld toe. Results are shown of the fracture mechanics predictions, compared with fatigue crack growth data. Crack initiation data was obtained and analysed.

2. EXPERIMENTAL DETAILS

Table I gives the composition and 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, and more details can be found in (7). The mechanical properties were obtained at room temperature in tensile, and LCF tests carried out in cylindrical specimens of 8mm diameter and 25mm gauge length machined from 12.5mm thick steel plates.

Table 1 - Chemical Composition and Mechanical Properties of the Base Metal of the Steel Tested

A- Chemical Composition

<u>Base Metal</u>

Element and Content													
C	Si	Mn	Cr	Mo	Ni	Ti	Al	V	Cu	Co	Nb	P	S
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

<u>Weld Metal</u>

Element and Content							
C	Si	Mn	Cr	Ni	Mo	P	S
0.08	0.45	1.28	0.50	1.87	0.37	0.017	0.01

B- Mechanical Properties
(Average values of five tests)

<u>Base Metal</u>
0.2% yield stress, σ_{ys}=410 MPa
Ultimate tensile stress, σ_{uts}=555 MPa
Rupture strain, ε_R=28%

<u>Weld metal</u>
σ_{UTS} = 770 MPa
0.2 yield stress = 690 MPa
Rupture strain, ε_R = 15%

The cyclic stress-strain curve of the material was obtained with one step level tests in twelve cylindrical specimens and under reversed cycling (R=-1).

The fatigue tests were carried out under constant amplitude loading in a ± 250 kN capacity servohydraulic 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 $6.0x10^6$, time when the fatigue test was stopped. The fracture surfaces of selected specimens were analysed at macro level and with the SEM.

In the majority of the specimens, strain gauges were bonded very close to the weld toes of the attachment, as shown in Fig. 1. 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 was used to establish the onset of fatigue crack tip marking, to define the crack geometry to be repaired by hammer peening.

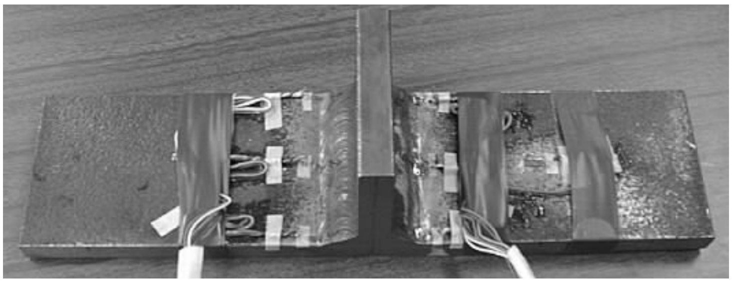

Fig. 1 - Set-up of the strain gauges used to monitor the onset of crack initiation and detect marking.

Vickers micro hardness data with 1Kg and 25gf loads were obtained. The variation of hardness along the thickness of the specimen at the weld toe and in the crack propagation direction is plotted in Fig. 2 for the hammer peened joints. It shows the decrease in hardness along the thickness. A peak value close to 320HV was obtained (Fig. 2). The main objective of these tests was to compare the hardness distributions for the as welded and hammer peened specimens.

3. RESULTS AND DISCUSSION

A typical macro of the fracture surface of one repaired fatigue specimen is shown in Fig. 3. Multi-crack initiation is visible at different locations.
The appearance of the fracture surface is modified when the crack depth seems to exceed the depth of the region affected by the hammer peening process (Fig. 3).

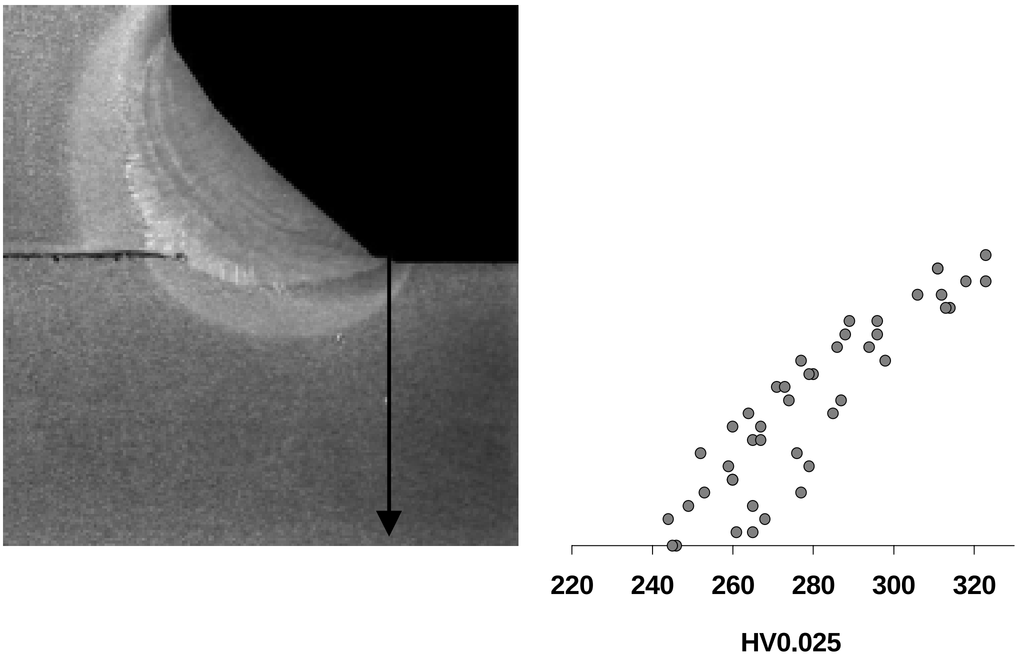

Fig. 2 - Hardness profiles in the welded joints. **c)** Hammer peened, microhardness, 25gf.

In the specimen of Fig. 3 with marking initiating at 25% strain reduction, a crack of 2.23mm depth in the central region of the specimen was identified and, after the 15000 cycles of marking, as defined above, the depth of the crack has increased to 2.413 mm. At this stage, hammer peening was applied to this crack, and the test proceeded until final failure of the specimen. The number of elapsed cycles before repair was N=252406+15000 (marking), and final failure of the specimen after repair occurred with 1398259 cycles. Note a large ductile crack in Fig. 3, initiating at the tip of the semi-eliptical central fatigue crack repaired by hammer peening.

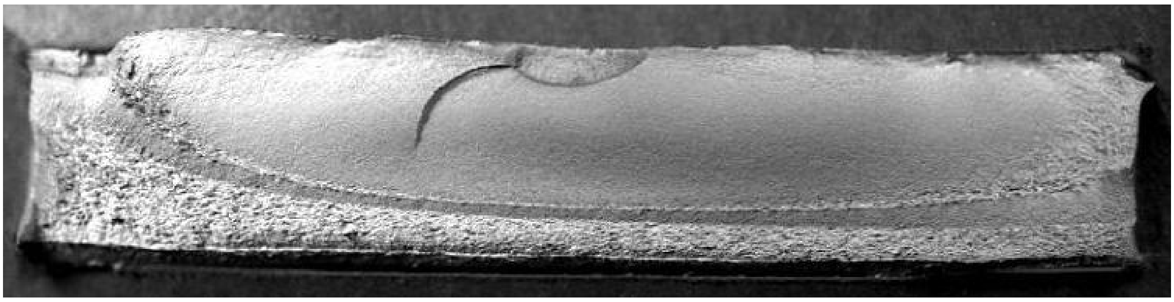

Fig. 3 - Fatigue fracture surfaces of the 3PB specimens. As welded, followed by hammer peening of a crack of 2.23mm. Fatigue marking at 25% strain reduction. $\Delta\sigma$=325MPa. N_i=252406. N_T=1398259 cycles.

The S-N curves of the T joints are plotted in Fig. 4. The equations obtained for the mean regression lines for 50% probability of failure, assuming N_r as the dependent variable, are given in Table 2, next. The gains in fatigue strength for $2x10^6$ cycles were also calculated.

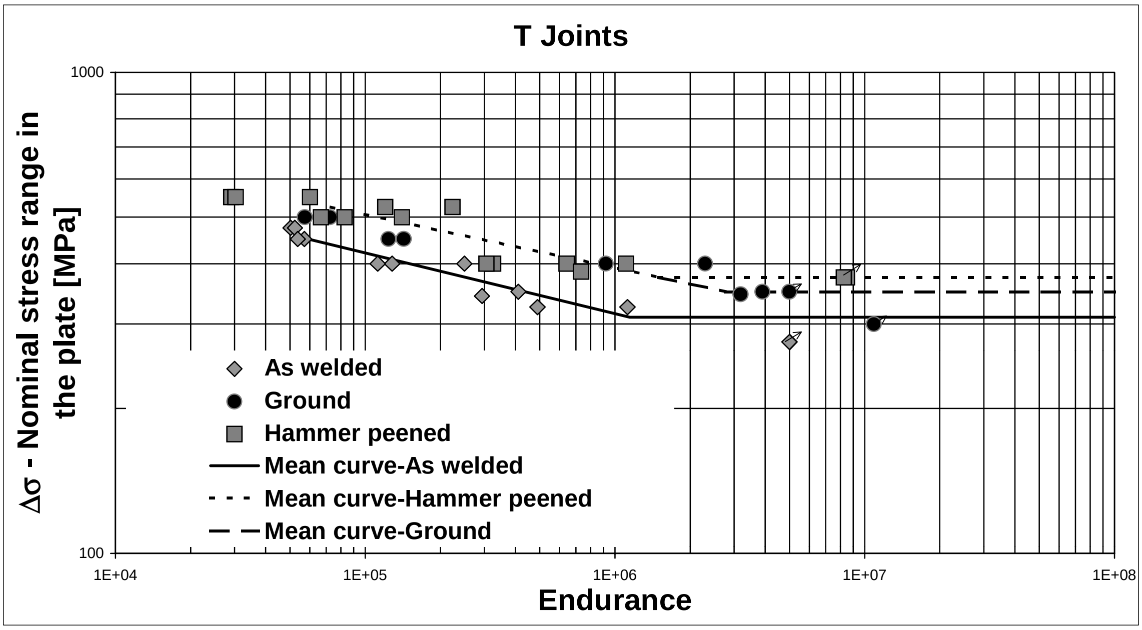

Fig.4 - S-N curves of the as welded, hammer peened and ground joints. 3PB T non-load carrying joints. St S2-3 steel.

Table 2 - Equations of the mean fatigue S-N curves of Fig. 4. T joints. Bending. St 52-3 steel.

$N_r Äó^{m} = K_o$ r^2 – correlation coefficient

Ref^a (R=0.1)	m	K_0	R^2	Gain in fatigue strength at $2x10^6$ cycles
As welded	8.263	4.99E+26	0.9469	1
Ground	11.068	1.68E+34	0.9380	(333.4/294.0)=1.13
Hammer peened	7.245	7.68E+24	0.7866	(367.4/294.0)=1.25

An improvement in fatigue behaviour was obtained in the treated joints. The results (Table 2) show that the toe ground joints gave the same fatigue strengths as the hammer peened joints. However, for fatigue lives above 10^6 cycles (Fig. 3), 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.

A study was made on predictive techniques to quantify these periods. Thus, a fracture mechanics prediction was carried out using Paris law relationships obtained previously in this and other steels, similar in what concerns the composition and the mechanical properties (8,9). The selected values for the constant C and exponent, m, were

Weld metal: $C=4.02\times10^{-9}$ mm/cycle; m=2.48   Base metal: $C=1.36\times10^{-11}$ mm/cycle; m=3.34

Table 3 a), b) gives the results of the predictions, as well as the experimental results obtained in the tests in the instrumented as welded specimens. The predictions were carried out using a crack propagation program, already tested successfully in welded geometries (10,11). The formulations of the PD6493 document (12) were used for the stress intensity factor equations.

Crack growth was analysed in two stages, from an initial defect up to the crack marking, and from crack marking up to the final crack depth of B/2. It was assumed that the shape of the propagating crack was such that a/2c=constant from a_o up to a_f. In these tables,

- Ni– cycles for the first measurable crack initiation, as detected by the first loss in strain detected by the strain gauges placed at the weld toe;
- a_o, c_o – average depth and semi-surface length of the initial measured crack;
- a_m, c_m –average depth and semi-surface length of the crack at the marking;
- N'_{bm} – experimental number of crack propagation cycles before marking;
- N'_{am} –experimental number of crack propagation cycles after marking, up to a_f=B/2≅6.25mm.
- N'_{amp}, N'_{bmp} –Similar as N'_{am} and N'_{bm}, but predicted by the program (10,12).
- N_{Te}, N_{Tp} – total experimental and predicted number of cycles of crack propagation) for the as welded specimen;

Table 3 – Experimental and predicted values of fatigue life for the 3PB instrumented as welded specimens. R=0.1. St 52-3 steel.

a) crack propagation data.

Spec.	a_o (mm)	c_o (mm)	a_m (mm)	c_m (mm)	N'_{bm}(1)	N'_{bmp}(2)	Ratio (1)/(2)	N'_{am}(3)	N'_{amp}(4)	Ratio (3)/(4)
22	0.1	0.912	1.67	15.224	310000	356992	0.87	356992	59230	6.03
23	0.1	0.698	3.862	26.947	123600	105601	1.17	105601	18665	5.66

b) crack initiation data. Final crack size, a_f=B/2.

Spec.	N_i (1)	N_{Te} (2)	N_{TP}	Ratio (1)/(2)
22	1357537	2024529	416222	0.67
23	260000	489201	124266	0.53

The results show good agreement between the experimental and the predicted number of cycles of crack propagation up to marking, i.e., when the crack is basically growing in the weld metal affected area. For crack lengths greater than the marking crack (a_m, c_m) the experimental values N'_{am} are higher than the predicted N'_{amp}, which could be attributed to variations in microstructure and also inaccuracies in the measurement of the marking crack. In these as welded specimens, nearly 50% of the total fatigue life is spent in crack initiation up to a measurable size or event.

Similar results as in Table 3, but for the specimens repaired by hammer peening at a detected crack of geometry corresponding to a loss of 25 to 40% in the local strain at the weld toe, are given in Table 4.

Table 4a) gives an assessment of the effect of hammer peening, and Table 4b) gives the experimental results obtained on the cracked specimens repaired by hammer peening, together with the predicted values given by the program. In these tables,

a_H, c_H – average depth and semi-surface length of the crack repaired by hammer peening;
N_i – cycles for crack initiation of the first crack (before repair);
N'_{bH} – experimental number of cycles of crack propagation before hammer peening (a_H, c_H);
N'_{bHp}, N'_{aHp} – similar as N'_{bH} and N_{aH}, but the number of cycles of crack propagation predicted by the program;
N_{aH} – experimental number of cycles after hammer peening (initiation, N_{iH}, + propagation, N'_{aHp});
N_{Te} – total experimental number of cycles; N_{Tp} – total predicted number of cycles.

The number of cycles for crack initiation after hammer peening of the repaired crack, N_{iH}, was not yet obtained, since strain gauge data was not collected after the repaired weld toes.
For these results, in Table 4 a), b), , the following equations apply:

$$N_{Tp} = N'_{bHp} + N'_{aHp} + N_i \quad (1)$$

$$N_{Te} = N_i + N'_{bH} + N_{aH} \quad (2)$$

$$N_{aH} = N_{iH} + N'_{aHp} \quad (3)$$

Table 4 – a) Experimental and predicted values of the fatigue lives of the repaired joints. 3PB welded joints. St S2-3 steel. R≅0.1.

Spec.	a_o (mm)	c_o (mm)	a_H (mm)	c_H (mm)	N'_{bH}(1)	N'_{bHp}(2)	Ratio (1)/(2)	N_{aH}(3)	N'_{aHp}(4)	Ratio (3)/(4)
24	0.1	0.222	2.413	5.357	202306	217984	0.93	1130853	76992	14.69
26	0.1	0.575	3.18	18.292	42321	42485	1.00	38934	7202	5.41
27	0.1	0.271	2.85	7.717	88458	105845	0.84	132155	28283	4.67
28	0.1	0.230	4	9.2095	109237	146011	0.75	170344	21558	7.90
29	0.1	0.176	3.3	5.8065	427107	414061	1.03	894786	96768	9.25
53	0.1	0.829	1.441	11.959	38746	24692	1.57	405064	8407	48.18

b) Comparison of fatigue lives of the specimens in Table 4a)

Spec.	N_i (1)	N_{aH} (2)	N_{Te} (3)	N_{Tp} (4)	Ratio (1)/(3)	Ratio (2)/(3)	Ratio (3)/(4)	Ratio g
24	65100	1130853	1398259	360076	0.05	0.81	3.88	4.06
26	75100	38934	156255	124687	0.48	0.25	1.25	1.25
27	10000	132155	230613	144128	0.04	0.57	1.60	1.82
28	100000	170344	379581	267569	0.26	0.45	1.42	1.64
29	2080000	894786	3401893	2590829	0.61	0.26	1.31	1.31
53	100000	405064	543810	33066	0.18	0.74	0.89	3.69

In these specimens, the geometry of the repaired crack was clearly defined and very good agreement was found between N'_{bH} and N'_{bHp}. After hammer peening, N'_{bHp} is much lower than N_{aH}, since hammer peening introduces a long crack initiation period in the repaired crack.

The predicted results in Table 3 were obtained using the values of C and m for the weld metal. For the analysis of crack propagation after marking, the values of C and m assumed were those for the base metal, since for the size of these repaired cracks, crack tip is essentially in the base metal. Work is in progress to simulat also the HAZ's properties and also to take into account the residual stress field induced by the hammer peening treatment.

The S-N data for the repaired joints (Table 4) is plotted in Fig. 5 and show that there is an increase of fatigue life with repair.

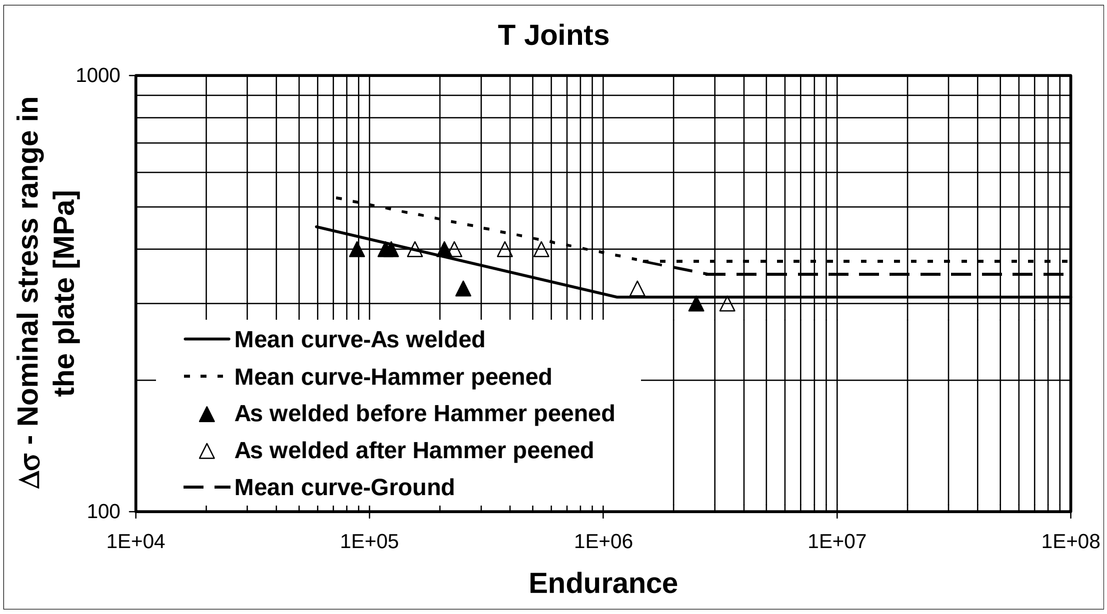

Fig. 5 - S-N curves of the repaired joints by hammer peening. 3PB T non-load carrying joints. Medium strength St S2-3 steel.

The gains in fatigue life due to treatment, g, can be given by the relation:

$$g = \frac{N_{Te}}{N_{ebh}} \quad (4)$$

where N_{ebh} is the expected life of the joint, without the repair, given by the relation

$$N_{ebh} = N_i + N'_{bH} + N'_{aHp} = N_{bH} + N'_{aHp} \quad (5)$$

The results (Fig. 6) show that the gains due to repair by hammer peening of a cracked joint range from a factor of 1.3 to about 4 times the expected life of the joint, in case it was not repaired at all. There is a trend to indicate that the higher benefits can be obtained with small repaired cracks (Fig. 6), but additional work is needed to analyse this trend in a more detailed manner.

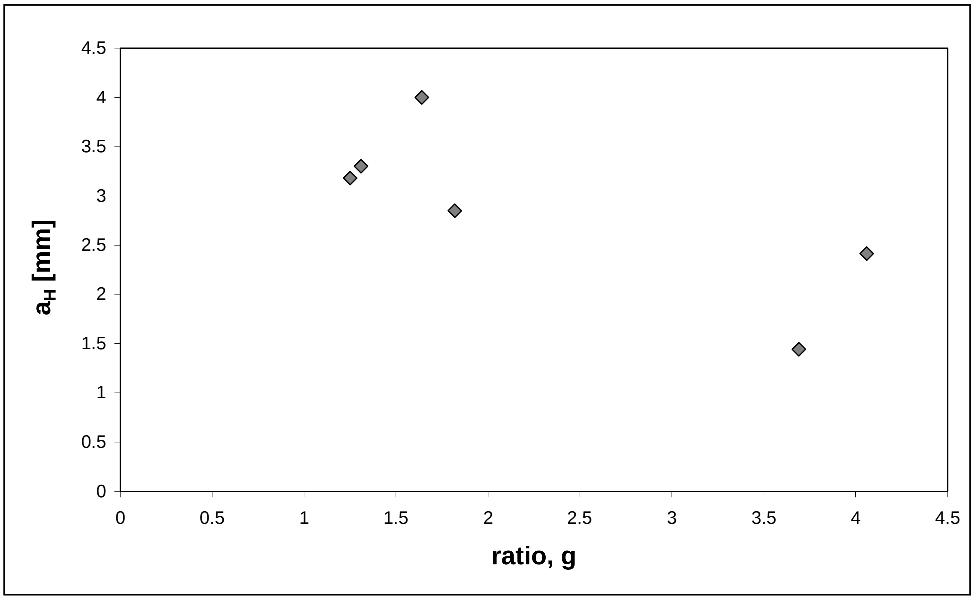

Fig.6 – Gains in fatigue life due to treatment against depth of the crack repaired by hammer peening. 3PBT non load carrying joint.

CONCLUSIONS

- The results have shown that the depth of the zone affected by the hammer peening is about 3.5mm, i.e., the material has hardened up to this depth. This should be the limit of the residual stress field created by the hammer peening.
- An improvement in fatigue behaviour was obtained in the treated joints. The results show the toe ground joints gave similar fatigue strengths in comparison with the hammer peened joints. 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.
- The effect of hammer peening to repair an as welded joint with fatigue crack of known depth is detailed, and equations based on fracture mechanics are given to quantify this effect, that is very benefitial.

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