An Analysis of the Effect of Hammer Peening on the Repair of Fatigue Cracked Welded Joints

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ABSTRAT. *The paper presents the results obtained on a fatigue study on the life extension 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 through the plate thickness. Results of the stress distributions at the crack propagation line at the weld toe obtained by a 2D FE analysis were obtained. These results were obtained using a elastic-plastic model, with the elastic-plastic cyclic stress-strain curve derived from LCF tests carried out in the base material. The residual stresses were measured at the surface, using X-ray diffraction and hole drilling techniques. Very good agreement was obtained between the experimental residual stress and the computed values, using a 2D and 3D elastic-plastic finite element model of the hammer peened process. 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.*

INTRODUCTION

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. TIG and plasma dressing can be even more effective than grinding [1,2], but there is limited work to support this trend and, therefore, additional work is needed.

The rather large increase in the fatigue strength, due to the use of improvement techniques, can be explained by the significant increase of a so-called initiation phase, in addition to the crack propagation phase.

In a review recently presented by Maddox [3], conclusions and recommendations were defined for hammer peening which are now part of an official IIW document of the Commission XIII [4].

Recently the authors have published data in this area, both for as welded and defective welds [5-8]. However in these papers no results are presented of residual stress distributions and the crack propagation phase was not analysed in detail.

The results presented in this paper cover the effect of hammer peening, on the fatigue performance of non-loaded carrying cruciform joints loaded in bending in the main plate and made from a medium strength (class 400MPa yield) carbon steel. The hammer peening process is studied in some detail, and results are presented on the impact forces, distribution of residual stresses induced by the process.

EXPERIMENTAL DETAILS

Material and Specimens

The material used in this study is a medium strength structural steel of the 400 MPa yield class (St 52-3, DIN 17100 specification), with a weld metal in an overmatching condition. The welds were made by the covered electrode process.

For hammer peening, a small portable pneumatic hammer was used (Fig. 1), fitted with a special hard metal tool, instrumented with four strain gauges bonded in full bridge (Fig. 1) to measure the impact forces and stresses during the hammer peening working cycles. The tool diameter was approximately 8.5mm, the air pressure was 3.5 bar and four passes, along the transverse direction of the specimen, were applied [4]. The frequency was 3000 blows/minute (bumps/minute).

Fatigue and Hardness Tests

The fatigue tests were carried out under constant amplitude loading in a $\pm$ 250 kN capacity servohydraulic fatigue test machine. The frequency was 10-15 Hz, and the stress ratio, R=0.1.

Vickers micro hardness data with 25gf loads were 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.

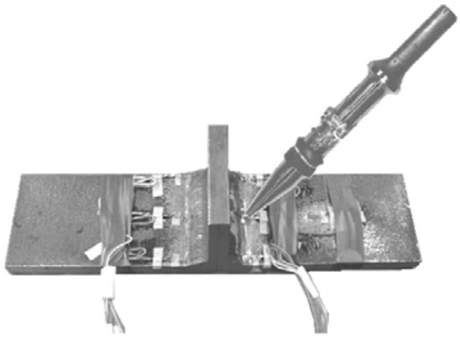


Figure 1: Specimen with strain gauges at weld toe and instrumented hammer peening tool.

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. 2. The duration of the treatment (working cycles) are indicated in Fig. 2. The mean values quoted in Fig. 2 are the static values who produce the same area under the dynamic stress or load cycle imposed by the tool in the material. These values of the force measured in the hammer peening working cycle (Fig. 2) were used later in the work in the numerical simulation of the process. The fatigue tests were only carried out with specimens treated with the "fast" cycle (Fig. 2 a)).

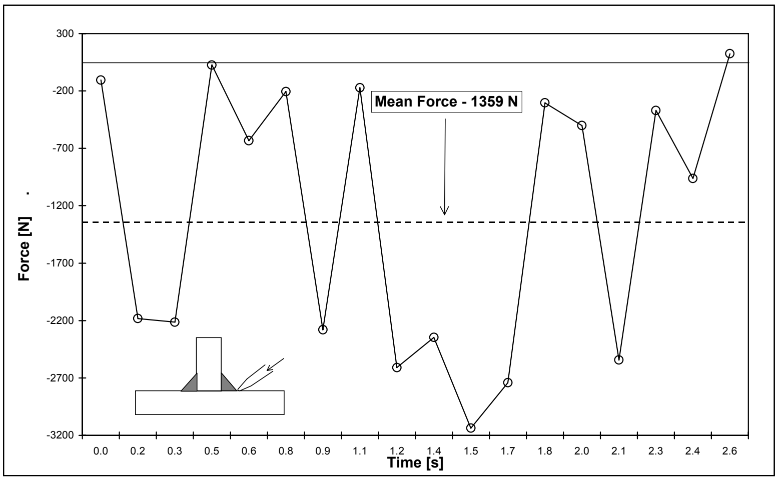
Hardness Data

In the hammer peened joints, an increase in hardness was obtained, and the hardness profile, through the plate thickness, shows peak hardness values close to 320HV near the surface at the weld toe zone (Fig. 3). Fig. 3 also shows that the depth of the zone affected by the hammer peening is about 2.5mm.

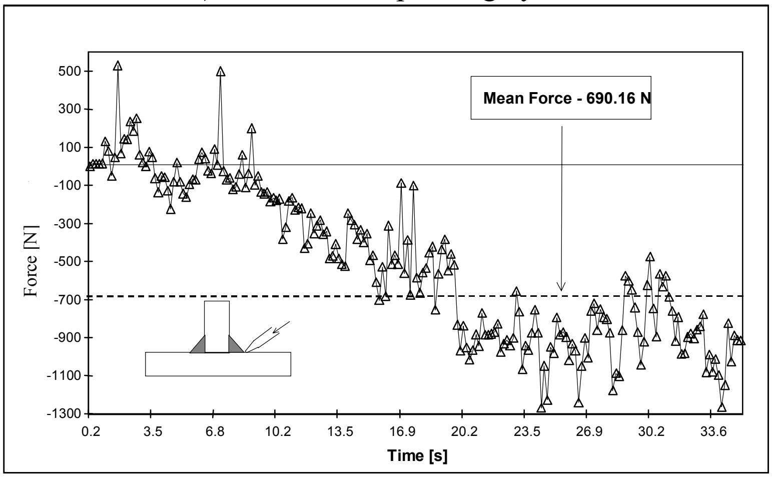
Fatigue Data in the Welded Joints

For the non-repaired joints the equations obtained for the mean regression lines for 50% probability of failure, are given in Table 1. The gains in fatigue strength for $2x10^6$ and 10^7 cycles were also calculated (Table 1).

Results for the repaired joints may be found in [8] and values of a gain factor, g, for the fatigue life increase, varied between 1.2 and 11 for repaired cracks by hammer peening. This factor, g, is the ratio between the fatigue life of the repaired joint and the predicted fatigue life of the original cracked joint, should hammer peening not be applied [8].



a) Fast hammer peening cycle.



b) Slow hammer peening cycle (recommended in [4]).

Figure 2: Variation of impact force measured in the hammer peening tool during the treatment at the weld toe (one pass).

TABLE 1: Parameters of the S-N curves for the non-repaired joints. 3PB. T joints. Non-load carrying. St 52-3 steel.
$N=K_0/(\Delta\sigma)^m$; $\Delta\sigma$ - nominal applied stress range.

Ref. (R=0.1)	m	K_0	r^2 correlation coefficient	Gain in fatigue strength at $2x10^6$ cycles	Gain in fatigue strength at 10^7 cycles
As welded	8.263	4.99E+26	0.9469	1	1
Ground	11.068	4.93E+34	0.9380	1.25	1.20
Hammer peened	6.751	1.85E+23	0.7866	1.11	1.29

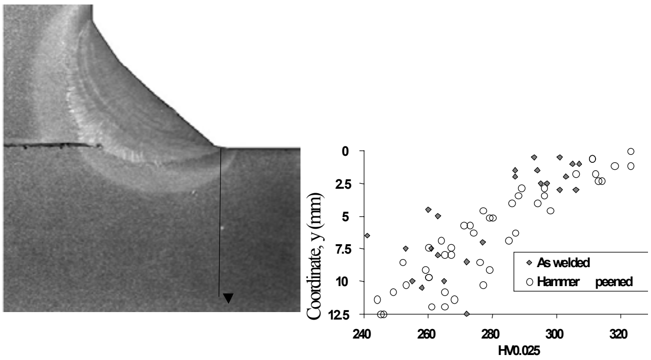


Figure 3: Hardness profiles in the welded joints. As welded and hammer peened, microhardness, 25 gf.

Residual Stress Measurements

Values of the residual stresses were obtained in some selected specimens by X-ray diffraction and the strain gauge hole drilling technique at the weld toe and in zones located at distances 1, 2, 3 and 5mm from the weld toe in the longitudinal x direction. The residual stresses were obtained for different types of specimens. The objectives of these tests were to quantify the residual stresses introduced by the hammer peening process, and to verify whether the fatigue loading changes the residual stress pattern in the as welded joints. The residual stresses decrease as the x distance increases (Table 2).

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 occurs in the location at the weld toe and in the longitudinal x direction.

Since the residual stress is of yield magnitude, when 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 localised near the weld toe where the treatment is applied since, at the zone 5mm away for the weld toe x=5mm, the residual stresses are negligible (Table 2).

The residual stresses in the as welded and after fatigue tested specimens are also low, at least 5mm away from the weld toe. Some relaxation effect of stresses may occur in the fatigue tested specimens, since both residual stresses in the x and z directions were found to be only slightly compressive, while the residual stresses in the as welded not fatigue tested specimens gave tensile values of low magnitude.

TABLE 2: Values of experimental residual stresses, at surface (y≅0). 3PB specimens. Non-load carrying joints. St 52-3 grade steel.

Condition and technique	**x = 0 mm**		**x =1 mm**		**x =2 mm**		**x =3 mm**		**x =5 mm**	
	σ_x	σ_z	σ_x	σ_z	σ_x	σ_x	σ_z	σ_x	σ_z	σ_x
As welded – Hole drilling	-90.7*	-25.7*	-	-	-18	11	-	-	91	66
Hammer peened – Hole drilling	-486*	-203.3	-	-	-286	-142	-	-	14	-50
Fatigue tested – Hole drilling	-	-70	-	-	-	-	-	-	-7	-33
As welded – X-ray diffraction	-189	-78	-	-	-138	-22	-	-	-86	22
Hammer peened – X-ray diffraction	-302 -334	-385 -439	-298	-288	-258 -206	-171 -213	-185	-172	-192*	150*

* Obtained by linear extrapolation.

FE Computations for the Residual Stresses

The stress distributions, σ_x, σ_y, σ_z and σ_{eq} were obtained by FE computation using the ABAQUS code for extra-refined meshes with eight node isoparametric elements and assuming an elastic deformed tool. The residual stresses induced by hammer peening were obtained basically at the weld toe line and for both the slow and fast working cycles (Fig. 2).

The stress plots of σ_{zz} and σ_{xx} along the plate thickness at the weld toe line are depicted in Figs. 4a), b), and these show the results obtained for both types of hammer peening cycles. Near the surface (y<0.5mm) very close results were obtained for both types of loading but, as the depth, y, increases, higher compressive stresses are obtained with the fast peening cycle, where the load is higher (Fig. 2a)). For depths above 2.5mm, there is practically no effect of the hammer peening, since the stresses are positive or close to zero and, as expected, will not be affected by the duration of the treatment (Figs. 4a), b)).

Note that the region of the higher compressive stresses (y<2.5mm approximately) corresponds to the surface region of the hardness plot, where hardness is higher than in the base metal (Fig. 3).

Near the weld toe (position, y≅0), the numerical values of the compressive residual stresses (σ_z and σ_x) are significantly above the experimental data (Table 2) and exceed the ultimate tensile strength of the steel, which is not possible. This behaviour is due to the numerical limitations of the method, and can be adjusted with a combination of more refined types of meshes and (or) elements, or a better definition of the local plastic deformation and formulations for stress calculations. Additional work is in progress in this problem.

With these very high compressive stresses repaired cracks with depths below 3.0 mm will significantly retard its growth and gain factors will decrease as the repair crack depth increases as reported [8,9].

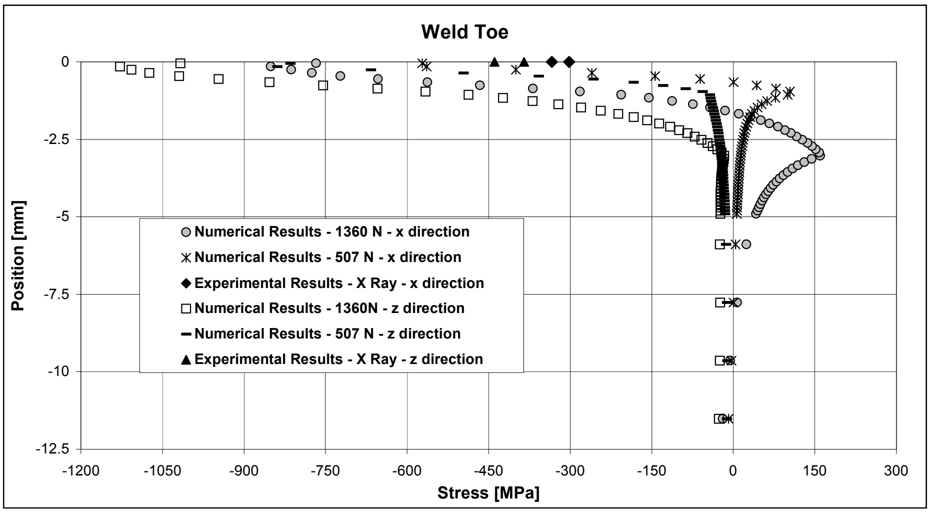


Figure 4: Comparison between the experimental and numerical residual stresses induced by hammer peening along the plate thickness. 3PB. Non load carrying joints. St 52-3 steel.

CONCLUSIONS

- The hardness distribution results have shown that the depth of the zone affected by hammer peening is about 2.5mm. This was found to be the limit of the residual stress field created by the hammer peening.
- The peak residual stresses near the weld toe were found to be of yield magnitude in compression, justifying the great benefit of hammer peening.
- For depths from the surface above 1 mm good agreement was found between the computed residual stress values resulting from hammer peening and obtained by an elastic-plastic 2DFE program, and the experimental values.
- At the surface however, the residual stresses were very high which requires additional refinement of the FE model.

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