Hammer peening treatment: fatigue strength improvement and repair of welded structures

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Abstract
The main objective of this paper is to reveal and identify the parameters (residual stresses, geometry, strain hardening, etc.) which have an effect during the hammer peening operation and to understand the phenomena involved during fatigue stressing.
Fatigue resistance of high-frequency mechanical impact treatment is investigated. Cyclic four-point bending tests are performed on high-strength welded steel S690 welded samples and hammer peened samples with different conditions of treatment with or without stress-relieving heat treatment. Microstructural characterisations with EBSD (electron backscattering diffraction) observations and residual stress analyses are presented. The main conclusions of this paper showed that hammer peening treatment improves the fatigue performance of welded joints. The residual compressive stresses are prominent. The microstructure does not seem to have any effect, despite the nanostructured layer. The geometry is of secondary importance. This point is confirmed by comparing with shot peening.
Hammer peening treatment is also presented as repair technic.

Introduction
Hammer peening treatment is one of the most recent finishing techniques, and probably one of the most efficient [1].
Although all the results (mainly bibliographic) seem to demonstrate that hammer peening could be the optimum solution for improved fatigue strength, a few questions arise for which the bibliography has no answers:
- What are the influential parameters (residual stresses, geometry, strain hardening, etc.)?
- What are the mechanisms involved?

Therefore, the purpose of this study is to try to answer these questions. The obtained results are compared with shot peening which is a more classical treatment.
Another important point is the effectiveness of this technique as a method of repair with fatigue crack closure by hammering [2] and lifetime extension of aged structure [3]. Works performed on specimen and structures confirm this effect.

Methodology
Material and treatments
The material used in this study is the S690Q steel quenched and tempered at 650 °C; it has been supplied in the form of 500 × 200 × 10 mm plates. The mechanical characteristics of the base material S690Q, determined by monotonic tensile tests, are given in Table 1.
The plates are welded without restraint (clamping), in order to obtain a rounded weld bead and promote crack initiation at weld toe.

Table 1 : Mechanical characteristics of base metal S690

E (GPa)	Rm (MPa)	Rp0,2 (MPa)	A (%)
210	812	745	5.1

The hammer peening treatment is performed on the welded plates (on both sides of the weld bead, and on both faces, i.e. all the weld beads have been treated) either with a PITEC© system or a Sonats© system.
For the PITEC system, the hammer vibrates at a frequency of the order of 80 Hz [4].
Hammering Stressonic® Ultrasound is performed by the SONATS society. The frequency is in the ultrasonic range, typically 15, 20 or 40 kHz [5].
For both techniques, the radius of the hammer tool is fixed to 2,5 mm. Different conditions of treatment are considered:

- ✓ PITEC device "with single sweeping in the weld bead toe" (movement in one direction along the weld toe)
- ✓ PITEC device "with double sweeping" (hammering with movement in both directions (longitudinal and transversal).
- ✓ SONATS device "with single sweeping in the weld bead toe"

On some welded plates a groove is reproduced by machining (same radius, same depth). A thermal treatment (550 °C for 1 h) is applied to relieve residual stresses. This allows highlighting the geometrical effect. In the same way, the same thermal treatment has been applied on some as welded and hammered specimen in order to provide information about residual stress effect.

Characterizations

Topography

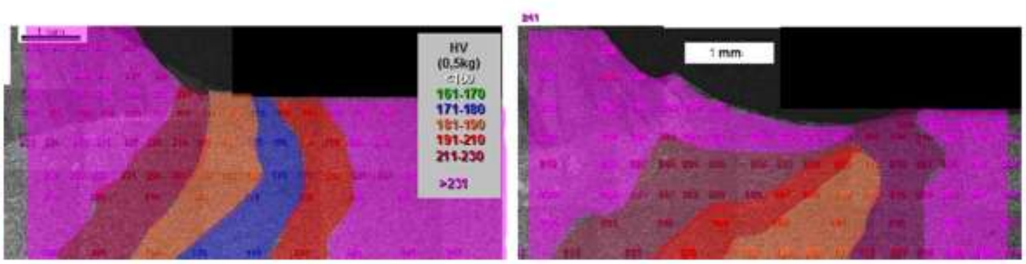
Surface topography is characterized using a three-dimensional noncontact optical profilometer. The radius and depth in the weld toe for as-welded samples, hammer peened samples and machined samples are given in Table 2.

Table 2 : Topographic characteristics

	As welded	Hammer peening	Machined
Radius	0,4mm	2,56mm	2,52mm
Depth	0µm	140µm	300µm

Microstructural analysis

Microhardness tests, with a load of 0.5 kg, are performed on cross sections perpendicular to the welding direction in order to obtain the hardness evolution in the weld toe region.
Figure 1 gives the hardness mapping at weld bead toe before and after hammer peening treatment. Before hammer peening, it can be noted a hardness gradient, due to the welding process. After hammer peening treatment, the hardness increases from 180 to 220 HV.



Before Hammer peening After Hammer peening

Figure 1: Hardness maps

Additionally, EBSD (electron backscattering diffraction) [6] analyses have been performed on welded samples before and after hammer peening in order to characterize the surface layer observed by SEM. These analyses show the presence of a nanostructured layer over 60µm (Figure 2).

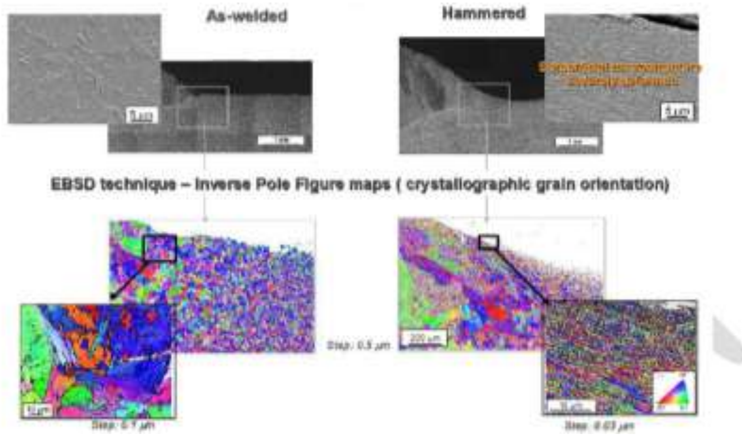


Figure 2 : Microstructure before and after hammering

Residual stresses

Residual stresses have been determined using XRay diffraction method, on fatigue samples, for each configuration: as welded, hammer peened and machined.

The analyses are performed at the weld toe or in the middle of hammered groove (Figure 3). Results are given in Figure 4.

Figure 4. All hammered specimen exhibit similar longitudinal compressive stress level around -400MPa.

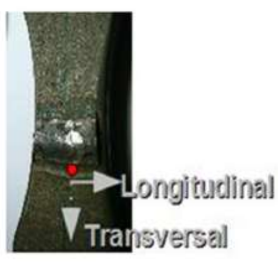


Figure 3 : Position of residual stress analyses on fatigue specimen

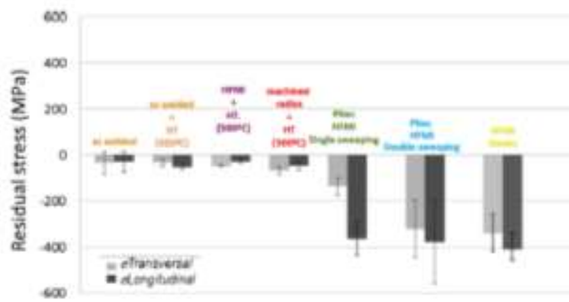


Figure 4 : Residual stress values on different configurations

Fatigue tests

Experimental procedure

The fatigue test specimen geometry is described in Figure 5. This geometry has been chosen in order to force crack initiation and propagation in the hammered region. Electron discharge machining was used to produce the samples.

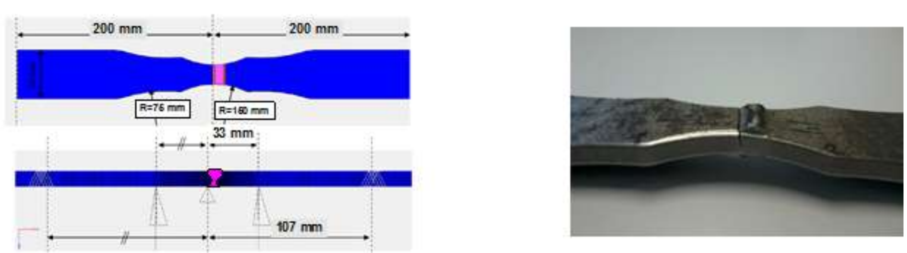


Figure 5 : Fatigue specimen geometry

Specimens are tested in four points bending fatigue with the device shown in Figure 6. Fatigue tests are carried out under the followed conditions: R=0.1, f=8Hz, failure criteria 2.10^6 cycles.

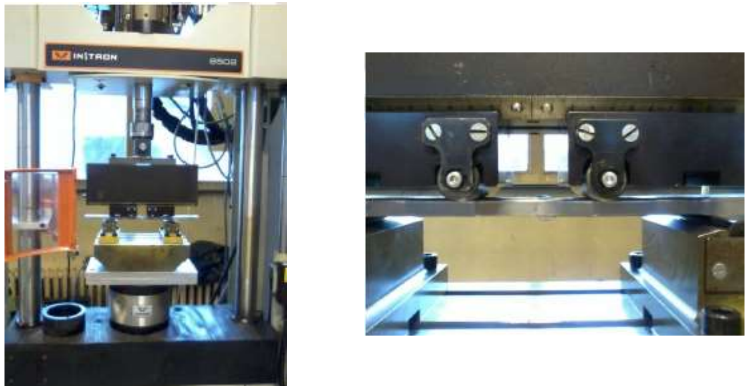


Figure 6 : Experimental setup for fatigue test

Results and analysis

Tests have been performed on 3 load levels. Results obtained for all configurations are shown in Figure 7. It has to be reminded that these configurations have been investigated in order to understand which parameter is the most important one in fatigue life improvement, due to hammer peening.

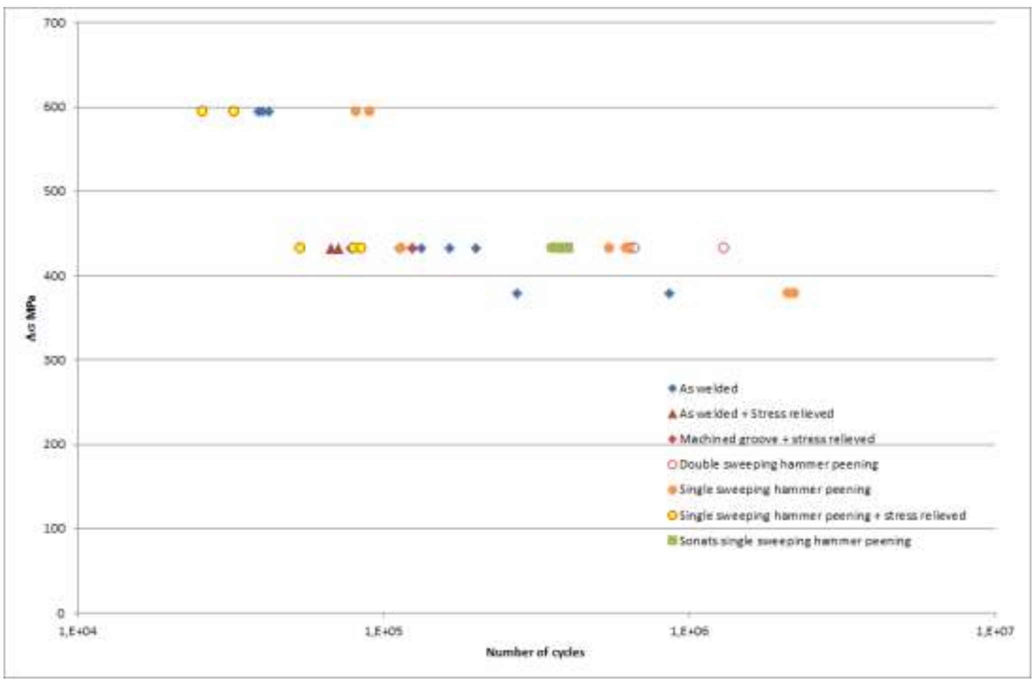


Figure 7 : Fatigue test results for the different configurations

As expected [1, 2], hammer peening improves fatigue life whatever the applied treatment.
It can be seen that fatigue resistance is increased by a factor of 2 to 3 in comparison to the as-welded state. The improvement factor is equal to 5 for the double sweeping hammer peening treatment. This leads to the first conclusions:

- ✓ Single sweeping motion with the HFMI system is necessary.
- ✓ Double sweeping motions in transversal and longitudinal directions in the weld toe are preferable.

Comparing results on hammer peening and hammer peening + stress relieved treatment, clearly shows that compressive residual stresses induced by hammering is of great importance.

On this configuration, as residual stress equals "0", the groove geometry should be the most influential parameter with may be the microstructure. It should leads to the same result than machined stress-relieved groove specimen and to an improved fatigue life compared with as-welded stress-relieved specimens. But, the results in Figure 7 show that the hammer peening stress-relieved specimens have a lower fatigue strength than the as-welded specimens. This unexpected result has been well explained by the presence of micro cracks created during hammer peening [7, 8]. However and as expected, the specimens with machined groove have a better fatigue strength than the as-welded stress-relieved specimens due to improved toe geometry. Nevertheless the fatigue life increasing is not very important. These results show that the global geometry of the groove left by the hammer peening treatment is not a first-order parameter with respect to the fatigue resistance.

Effect of shot peening

Shot peening is another finish treatment used to improve fatigue life component. It also introduces compressive residual stresses, but in case of welded structure, hammer peening is often preferred because shot peening does not improve toe geometry.

As it has been shown that geometry is not a first-order parameter with respect to the fatigue resistance, it could be interesting to compare these two finish treatments.

Welded specimens have been shot peened with conditions giving residual stress distribution similar to hammer peening.

Fatigue tests have been then performed on the same load level than the hammer peening ones. Results are shown in Figure 8. It can be seen that, as for hammer peening, shot peening increases fatigue life compared with as welded. The results are quite similar to those obtained with hammer peening. Scattering seems to be more important for shot peening, certainly due to the fact that it is easier to treat correctly the weld toe with hammer than with shot peening nozzle.

Nevertheless, these results confirm that global geometry is not of first order but the local geometry might be also important due to the presence of cold lap in the weld toe.

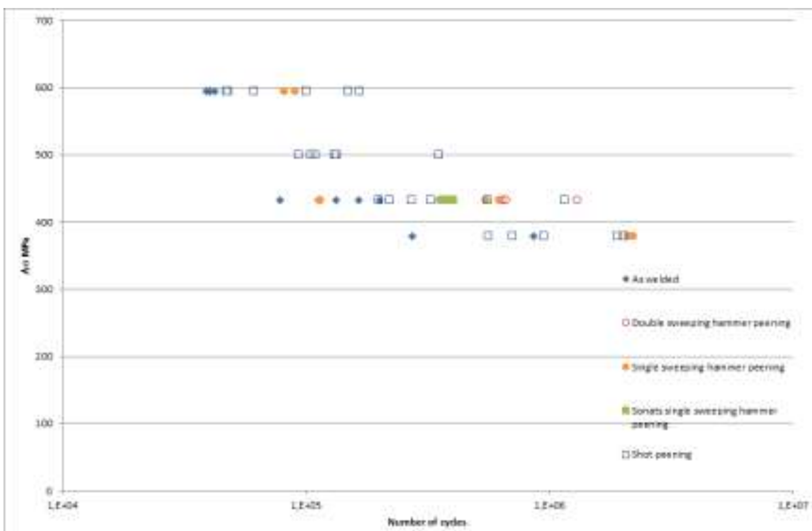


Figure 8 : Comparison between hammer peening and shot peening

Repair of welded structures

Tests on specimens

To evaluate the effectiveness of hammer peening as repair treatment, some specimens have been pre-cracked in fatigue ($\Delta\sigma$ = 433MPa, R=0.1). The crack length is monitored with gage control. Test is stopped after 5% deformation variation.

After pre-cracking, hammer peening is applied, and then, fatigue test is restarted up to failure. Results are summarized in Table 3 and in Figure **9**.

Table 3: Fatigue results after repairing

Number of cycle for pre-crack	number of cycles after hammer peening	Initial crack length mm(post mortem analysis)
134669	2000000	0,5
53996	245281	1
240718	112730	3
113113	1405808	1
40565	217672	1
50261	339040	1
64931	625406	1

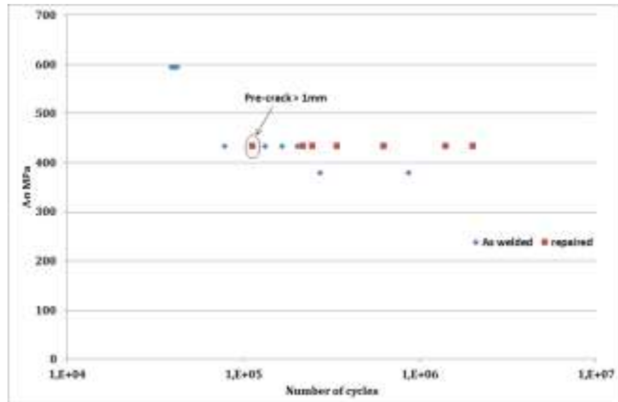


Figure 9: Comparison between as welded and as welded+ pre-cracked + repaired

Except the case for which the initial crack is >1mm, an improvement of the fatigue life after retrofitting by hammer peening treatment may be observed.

For a depth equal or inferior to the millimeter, hammer peening treatment operation can be considered as a retrofitting operation which puts compressive residual stress field in the cracked weld toe area that blocks or slows down the crack.

Beyond 1 mm, the residual compressive stress field created by the hammer peening operation is no longer large enough to block the propagation of the crack or greatly slow the crack growth.

Validation on components

Two components with single weld bead (Figure 10) are treated by SONATS hammer peening system after initial fatigue tests with an initial crack. The gain obtained on parts already cracked is between 8 and 23%, which is significant. The HFMI repair solution may be an alternative waiting for a part change.

Figure 10 : Welded component tested after hammer peening repairing

Conclusion

The purpose of this study was to identify the most important parameter in fatigue life improvement when using hammer peening process as finish treatment.
Three parameters have been investigated: microstructure, groove geometry and residual stresses.
From the obtained results, these conclusions may be proposed:

- ✓ Hammer peening treatment improves the fatigue life performance of welded joints
- ✓ The residual compressive stresses induced by Hammer peening play a major role.
- ✓ The microstructure does not seem to have any effect, despite the nanostructured layer.
- ✓ The geometry is of secondary importance. However, the presence micro-cracks generated by the hammer peening operation seems to encourage crack initiation.

Some tests performed with shot peened specimens lead to quite similar results, confirming the conclusion that residual stresses are of the first order.

Finally, it has been shown that hammer peening can be used as repair treatment on cracked welded structure if the initial crack is less than 1mm length.

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