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Fully Dynamic Numerical Simulation of the Hammer Peening Fatigue Life Improvement Technique

R. Baptista[a,b]*, V. Infante[b], C. Branco[b]

[1] Escola Superior de Tecnologia de Setúbal (Instituto Politécnico de Setúbal), Campus do IPS, Estefanilha, 2941-508 Setúbal, Portugal

[2] ICEMS - Instituto de Ciência e Engenharia de Materiais e Superfícies, Instituto Superior Técnico, TULisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

Abstract

This paper presents the results of the development process for a Finite Element Analysis of the Hammer Peening Fatigue Life Improvement Technique. The Fatigue Life of welded structures is still in need for improvement. The sheer number of Fatigue Live Improvement Techniques parameters leads to the need of simulating and predicting their results.
For this study, two different materials were used, an Austenitic Stainless Steel and a Duplex Stainless Steel. Non-load carrying cruciform weld joints were produced and fatigue tested, with and without the Hammer Peening treatment. Finally a FEA code (*ABAQUS*®) was used to simulate the Hammer Peening technique. A fully dynamic model was used, combined with the *Chaboche* Kinematic-hardening material model and different Hammering parameter experimentally determined. Alongside the residual stresses introduced by the Hammer Peening Technique, the predicted Fatigue Life using the FEA model were compared with the experimental results, showing a very good agreement between them. Also the effect of several parameters, like the hammering impact load, the hammer positioning or the number of hammering passages, were analysed as a way to validate the FEA model.
The most important result was of course the Fatigue Strength Gain factor, for the Hammer Peening Technique, that in both cases was found to be superior to 1.3.

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Keywords: Hammer Peening; Fatigue Life; Improvement; Finite Element Analysis; Fully Dynamic Model

1. Introduction: Background

In order to reduce the cost of developing a new fatigue life improvement technique, and therefore reduce the cost of operating a more secure welded structure, the correct modelling using a FEA program is essential. These programs can nowadays easily simulate almost every detail and effect present on the experimental test runs, and a fatigue life improvement technique [1], like the hammer peening can be modelled.

Several developments have already been made by *Baptista* and *Infante*, in order to produce accurate simulation of this technique, and its experimental application on [2] and [3]. Fatigue life improvement

* Corresponding author. Tel.: +351-265790000.
E-mail address: ricardo.baptista@estsetubal.ips.pt.

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techniques rely on extending the initiation phase, by reducing the severity of the weld toe details and introducing a compressive residual stress field. Improvement techniques also reduce the crack propagation speed; which increases the total fatigue life of the structure. In a review recently presented by *Maddox* [4], conclusions and recommendations were defined for hammer peening which is now part of an official IIW document of Commission XIII [5].

In the present work the full development process of a fully dynamic simulation analysis of the hammer peening technique is described, like in [6], taking into account the latest developments on the fatigue life prediction methods [7]. This technique will be model using a deformable hammering tool and several experimental results, in order to make it closer to the real process. Finally the numerical results are compared with the ones obtained experimentally, in order to validate the numerical model.

2. Experimental and Numerical Data

2.1. Numerical Material Models

The first step for an accurate fully dynamical model of the Hammer Peening Fatigue Life Improvement technique using FEA, is to obtain a numerical model for the material behavior. There were two materials in study within this work, a Duplex Stainless Steel, referred as Duplex Type S31803 and an Austenitic Stainless Steel, referred as Austenitic Type 304L. Table 1. give us the normal tensile properties of both materials.

Table 1. Tensile Properties of Duplex and Austenitic Stainless Steels

Steel	**$\sigma_{0.2\%}$ [MPa]**	**$\sigma_{1\%}$ [MPa]**	**σ_R [MPa]**	**ε_R [%]**
S31803	478	-	789	34
304L	256	280	698	52

These properties must be translated in to a numerical model using a FEA program, therefore a complete elasto-plastic material model is necessary. When a Nonlinear and Kinematic hardening model are combine, the *Lemaitre and Chaboche* [8] is obtained and therefore the most complete cyclic behavior can be simulated. Table 2 shows the parameters for a *Chaboche* model, were the parameters were calibrated from experimental results.

Finally in order to apply the local approach method, a Cyclic stress-strain curve is also necessary, equation (1) express the *Ramberg-Osgood*, model for the Duplex Steel, and a *Morrow*'s modified strain-life equation,(2), is also required for fatigue life prediction. All these equations are based on experimental data obtained in order to calibrate the material models by *Magnabosco*, [9]

Table 2. Duplex and Austenitic Steels *Chaboche* material models [10]

Material	*E* [MPa]	*Poisson coefficient*	*Yield Stress*[MPa]	*C*	Q_∞	*b*
S31803	179000	0.3	187.6	134771	16.5	0.0073
304L	200000	0.3	82	162400	60	8

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2\cdot 179000} + \left(\frac{\Delta\sigma}{2\cdot 733}\right)^{1/0.060} \quad (1)$$

$$\frac{\Delta\varepsilon}{2} = \frac{(912-\sigma_m)}{179000}(2N)^{-0.057} + 0.254(2N)^{-0.478} \quad (2)$$

2.2. Specimen Geometry and Boundary Conditions

The second step is to model the specimens geometry using the *ABAQUS®* design tools, using a 1/8 symmetry simplification in order to reduce the problem computational load, and the data on table Table 3.

The values for the weld toe radii (ρ1), the weld toe angle, and the secondary radii (ρ2) were obtained from an experimental geometry analysis, [11], using a digital coordinate table and where then statistically analysed.

Table 3 Specimen geometry, obtained for the Duplex Stainless Steel

Steel	Specimen	ρ1 [mm]	Angle [º]	ρ2 [mm]	Steel	Specimen	ρ1 [mm]	Angle [º]	ρ2 [mm]
	ProvAvg02Std	1.053				ProvAvg02Std	0.996		
	ProvAvg01Std	1.737				ProvAvg01Std	2.625		
S31803	ProvAvg	2.420	38.238	1.645	304L	ProvAvg	4.253	42.556	2.240
	ProvAvg1Std	3.104				ProvAvg1Std	5.881		
	ProvAvg2Std	3.787				ProvAvg2Std	7.510		

Taking into account the nonlinear nature of the hammer peening technique, which includes a nonlinear material model, a contact condition and finally a dynamically applied load, recommended by *L. Hacini* in [12], the specimen wide had to be reduced from 25 mm to 1.125 mm (Fig. 1b)), in order to get the best ratio between the quality of the results and the computational effort. Therefore both lateral surfaces were restrained in the ZZ (or transverse) direction (Fig. 1b)), to simulate the specimen plane strain state. Finally a 12 mm in diameter hammer peening tool was defined using a linear elastic material model, but the full body is deformable. A contact pair was also defined between the tool (master surface) and the specimen (slave surface), using a hard contact model, that allows separation after contact, for the normal to surface direction, and a penalty model, with a 0.5 friction coefficient, for the tangential direction. The model is still not complete, as the simulation is fully dynamic; using the *ABAQUS® EXPLICIT* solver, a linear spring (with 2500 N/m elastic constant) was added.

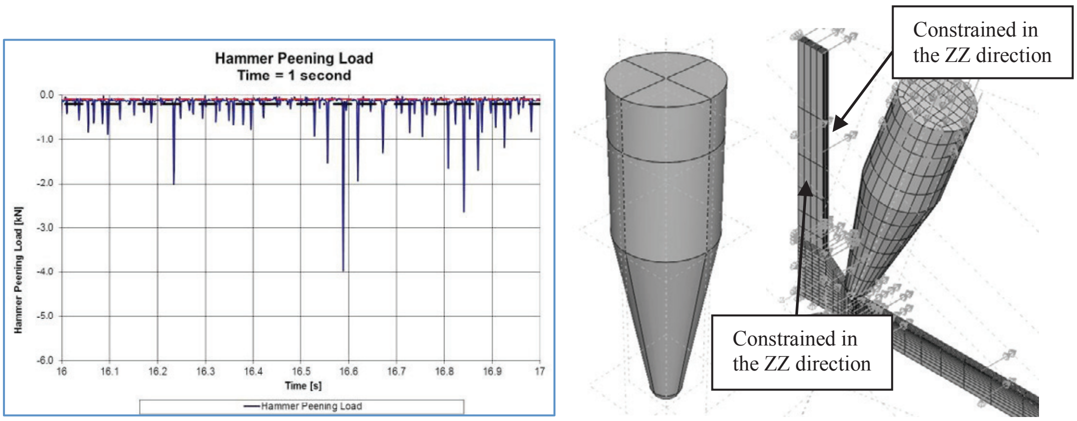

Fig. 1. a) Experimental Hammer Peening Load 1 second spectrum; b) Hammer peening tool; model only and full assembly

2.3. Hammer Peening Loads

The next required step was to determine the hammer peening load, needed to be applied to the numerical tool. This was done experimentally using a hammer peening tool instrumented with two strain gauges, these were calibrated using a servo-hydraulic test machine, in order to translate one hammer peening run, in a load spectrum, Fig. 1a). This spectrum was analyzed using the Rainflow method and several characteristic loading cycles were defined. Comparing the residual stress obtained numerically with the experimental measures taken using the X-Ray technique, a 7 MPa load was chosen as it allowed obtaining the best correlation. This load is applied to the top of the tool, and it was modelled as an instantaneous load by the *EXPLICIT* solver. This load is applied each 0.02 seconds, and has a decay time of 0.002 seconds.

3. Results and Discussion

3.1. Movement Dynamics

Using the above referred specimen wide, hammer peening tool tip radii, positioning and load, the 4 runs of 5 hammering strokes were applied to the five specimens with different weld toe radii from Table 3. The major advantage of simulating the hammer peening fatigue life improvement technique using a fully dynamical model is the fact that one can measure the velocity of the hammer peening tool. In previous papers, the authors have created a static model, using the *STANDARD* solver in *ABAQUS®*. Now using the *EXPLICIT* solver, applying an instantaneous load to the tool, it is possible to study the tool velocity over time. Unlike the static model, a fully dynamic model allows to simulate the major impact of each stroke, but also simulate the secondary impacts that occur between strokes. On Fig. 2, one can see the full duration of a 20 strokes simulation. The higher velocity attained by the tool is 50 mm/s, this velocity is a consequence of the applied load, and is responsible for the obtained residual stresses on the material. After the first impact the tool performs several secondary impacts, while it travels between the tool and the material, until the next load is applied.

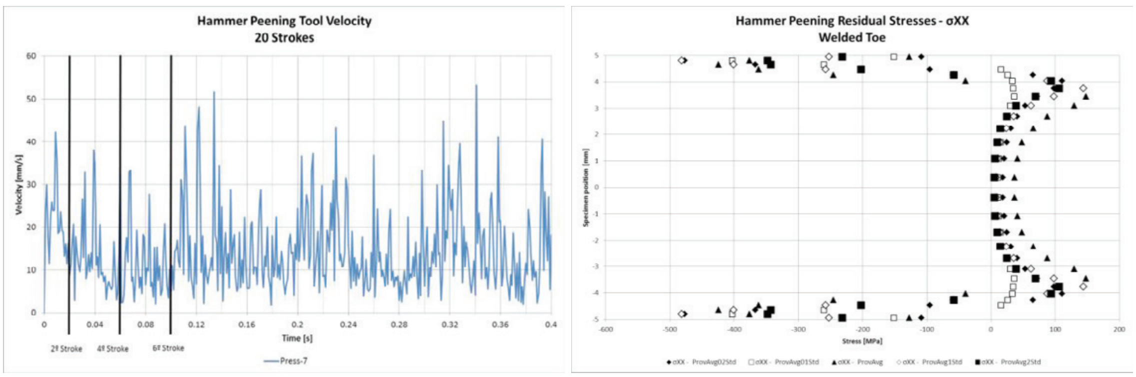

Fig. 2. a) Hammer Peening Tool velocity variation during operation; b) Residual Stress distribution, after the hammer peening

3.2. Residual Stress in the Welded Joints

Fig. 2 b) shows the influence of the weld toe radii on the residual stress distribution on the longitudinal direction, at the weld toe. As expected the residual stress distribution through the specimens thickness has two inflection points, the first one, near the material surface, where the higher residual stress value is obtained, and the second one, at a depth of 1 mm to 2 mm, where the residual stresses are now on the positive side.

When compared with the residual stresses obtained experimentally by the X-Ray diffraction technique, Table 4, one can see that the values show a good agreement. On the weld toe, the residual stresses obtained experimentally and the numerical value obtained with the specimen created using the average weld toe radii only differ 13% in the longitudinal direction and 7% on the transverse direction. Therefore it is possible to validate the numerical model.

Table 4. Experimental and numerical Residual Stresses on the welded toe and 1 mm after the welded toe

	Weld Toe Longitudinal	Weld Toe Transverse	1 mm Longitudinal	1 mm Transverse
Experimental	-485 ± 31	-524 ± 26	-269 ± 9	-162 ± 18
Numeric	-424 ± 55	-439 ± 71	-249 ± 58	-15 ± 67

3.3. Fatigue

Having analyzed the residual stresses after the hammer peening technique, one can apply several fatigue cycles to the specimen, in order to simulate the fatigue life tests applied to real specimens. These cycles have constant frequencies, and stress ranges, with a stress ratio of 0.1. Table 5 shows that the local stress ($\Delta\sigma$) and strain ($\Delta\varepsilon$) range are not significantly influenced by the weld to radii. The biggest difference is 15% between the strain range obtained with the average weld toe radii and the minimum one. When the mean stress (σ_m) is analyzed the differentials are higher. Unfortunately unlike in the static model, in the fully dynamic model there is no correlation between the mean stress and the weld toe radii, with the lowest value obtained for the average radii. The nominal loading also has the expected behavior, changing not only the stress and strain range values, but more significantly the mean stress value.

Using the above results and the local approach method it was then possible to calculate the fatigue life, using the methodology developed by *Pinho-da-Cruz et al* in [13], and therefore create the S-N curves from Fig. 3. Three numerical S-N curves were calculated, like in [14], using the minimum, average, and the maximum weld toe radii values. It is very interesting to see that the experimentally obtained S-N curve fits between the minimum and maximum radii S-N curves (Fig. 3), which mean that the numerical model is working well, and is able to correctly predict the fatigue life. The influence of the weld toe radii can also be quantified, like in [15] by *Chin-Hyung Lee et al*, using a 350 MPa stress range fatigue cycle, and several different radii. With the minimum weld toe radii the predicted fatigue life is 106'183 cycles, increasing to 371'603 cycles, when the radii changes from 1.053 mm to 2.420 mm. Increasing the radii to 3.104 mm, the fatigue life increases to 545'498 cycles, which represents highest value for the fatigue life.

Table 5. Fatigue Life Prediction for the Duplex Steel after weld toe hammer peening

Specimen	ΔS [MPa]	$\Delta\sigma$ [MPa]	σ_m [MPa]	$\Delta\varepsilon$	Ni [Cycles]	Specimen	K_t	ΔS [MPa]	$\Delta\sigma$ [MPa]	σ_m [MPa]	$\Delta\varepsilon$	Ni [Cycles]
	400	580.4	-23.3	3.02E-03	188419	ProvAvg02Std	1.95		550.331	105.262	3.07E-03	106183
	350	509.9	-30.1	2.66E-03	371603	ProvAvg01Std	1.77		560.4776	142.6767	2.91E-03	116699
ProvAvg	300	429.0	-34.6	2.25E-03	1000563	ProvAvg	1.68	350	509.927	-30.077	2.66E-03	371603
	250	353.5	-42.1	1.87E-03	3518322	ProvAvg1Std	1.56		485.71	45.0355	2.32E-03	545498
	200	270.3	-56.0	1.44E-03	10000000	ProvAvg2Std	1.50		481.688	54.466	2.77E-03	209432

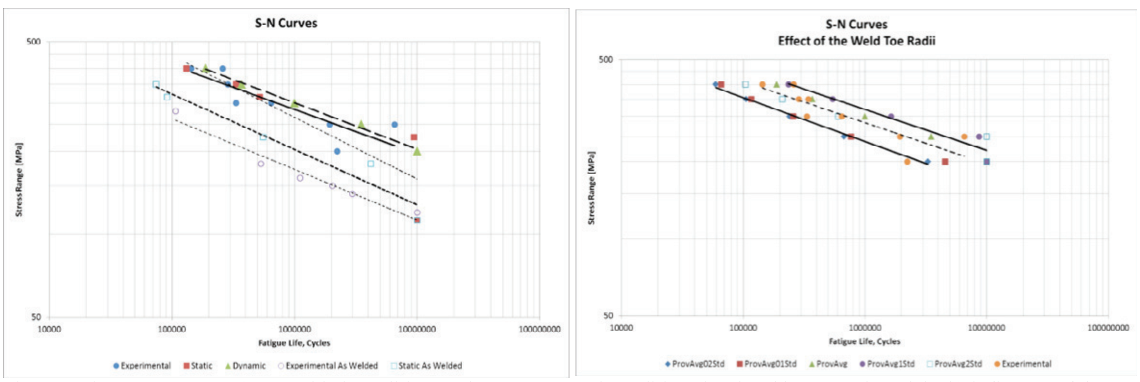

Fig. 3. Fatigue S-N curves a) As welded condition vs. hammer peened condition simulated by several models; b) influence of the weld toe radii

Therefore one can conclude that the fully dynamic model is not as regular as the static one. The results are dependable on more parameters, and as a consequence more unpredictable. Nevertheless the predicted fatigue life is very similar for both models, with the biggest advantage of the dynamic model being the inferior consumed computing time. A fully dynamic FEA can be up to 5 times faster.

4. Conclusions

- It is possible to obtain a fully dynamic model for the hammer peening fatigue life improvement technique, using a deformable linear elastic model for the tool over an elasto-plastic weld toe, with a minimum 1.125 mm wide specimen in order to obtain good results;
- The fully dynamic model is more computational efficient than the previously developed static one, allowing for more complex and closer to real component simulations;
- In order to model the hammer peening technique it was necessary to determine the hammering force, this value was then applied to the FEA model. An instrumented hammer peening tool was used and a 7 MPa hammering pressure was determined;
- As expected the residual stress distribution through the specimens thickness has two inflection points, the first one, near the material surface, where the higher residual stress value is obtained;
- By adding the residual stress distributions to the nominal load stress profiles, it is possible to conclude that the resulting stress range decreases, while the strain range is slightly increased, the mean stress value is also considerably decreased when compared with the as welded condition;
- Based on these values it is possible to predict the fatigue life, for the as welded and hammer peened conditions, attesting therefore the efficiency of the hammer peening it is possible technique as an fatigue life improvement technique;
- There is a very good agreement between the experimental and the numerically obtained S-N curves, while altering the hammer peening tool radii proves to be an effective way improve this agreement-

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