Experimental and Numerical Analysis of Fatigue Life Improvement Techniques in Welded Joints of Stainless Steels

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Abstract

This paper presents fatigue life improvements results obtained in two types of stainless steels: Duplex S31803 and Austenitic 304L. The objectives were to compare the fatigue behavior in terms of environment (air and 3% NaCl) and weld toe treatment (as welded, toe grinding, PPAW Dressing and Hammer Peening).
The tests were carried out in tension on cruciform specimens with a constant amplitude fatigue cycle of R=0.1. When available these results were also compared with results obtained in the literature. Using an elasto-plastic material model and the finite element analysis, all the experimental tests were simulated, including all the weld toe treatment conditions, and the fatigue life of these specimens was predicted.
Measurements of the radius of curvature (weld toe radii) and weld toe angle were obtained in the as welded, toe grinding, PPAW dressed and hammer peened specimens, in order to more accurately predict their fatigue life. The variations in fatigue life are basically due to changes in residual stress and weld toe geometry at the weld toe zone.
Experimental and numerical results were compared, in terms of the S-N curve parameters, fatigue strength gain for a 10^5 and 10^7 cycles life and fatigue life improvement for several nominal load setups.

Key-words: Fatigue Life; Improvement; Experimental tests; Finite Element Analysis; Weld Toe Grinding; PPAW Dressing; Hammer Peening

1 Introduction: Background

Fatigue life improvement techniques are very important today, because it is imperative to increase the fatigue life of welded structures, while decreasing the global cost of producing maintaining them.
Most of the fatigue life improvement techniques were established in the 1960's and early 1970's. 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, weld toe grinding, has been allowed for in the design of offshore structures [1] and pressure vessels [2]. TIG and plasma dressing can be even more effective than grinding [3] and [4], but there is limited work to support this trend and, therefore, additional work is needed.
Fatigue life improvement techniques rely on extending the initiation phase, by reducing the severity of the weld toe details or introducing a compressive residual stress field [5]. Improvement techniques also reduce the crack propagation speed; which increases the total fatigue life of the structure. In a review recently presented by *Maddox* [6], conclusions and recommendations were defined for hammer peening which is now part of an official IIW document of Commission XIII [7]. The authors also have actively worked on techniques like hammer peening and burr grinding, presenting their results on [8], [9] and [10].
The present paper reports the fatigue results obtained in [11], where the influence of fatigue life improvement techniques like the weld toe burr grinding, PPAW dressing or hammer peening, is covered over two different types of stainless Steels (Austenitic 304L and Duplex S31803 type, welded by TIG and MAG processes), and two different environments (air and aerated 3% NaCl solution).
The weld toe burr grinding, [12], is based on removing surface material from the weld toe, increasing the weld toe radii and consequently reducing the severity of this detail. The technique also reduces the residual stress field resulting from the welding process. While the PPAW dressing, [13], is based on refusing the weld toe, using the Powder Plasma Arc Welding technique to remove possible defects and increasing the weld toe radii. Finally the hammer peening technique, [14], [15] and [16] not only increases the weld toe radii as it is also based on the introduction of a compressive residual stress field, on the weld toe.

2 Experimental Details

2.1 Material and Specimens

There are two materials in study within this work, both Stainless Steels, the first one is referred as Duplex Type S31803 (DIN 1.4462) and the second one is referred as

Austenitic Type 304L (SAE 30304L, DIN 1.4306). In Table 1 and Table 2 the chemical composition of the materials can be found. Table 3 give us the normal tensile properties of both steels, becoming clear that while the duplex is more stress resistant, with 789 MPa of ultimate normal stress, the 304L steel has a much higher strain limit, showing a 52% elongation at break point.
Both Steels were received in as welded condition, with a plate thickness of 10 mm and the specimen geometry can be found in Figure 1.

Table 1 Chemical Composition of Duplex S31803 Stainless Steel

C	Si	Mn	P	S	Cr
0.024	0.220	1.550	0.023	0.002	22.400
Mo	**Ni**	**N**	**Al**	**Cb**	**Cu**
2.980	5.700	0.157	-	0.130	0.090

Table 2 Chemical Composition of Austenitic 304L Stainless Steel

C	Si	Mn	P	S	Cr
0.027	0.320	1.230	0.024	0.003	18.100
Mo	**Ni**	**N**	**Al**	**Cb**	**Cu**
0.480	8.200	-	-	0.11	0.31

Table 3 Tensile Properties

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

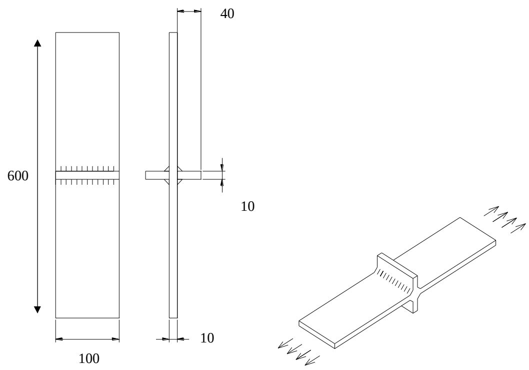

Figure 1 Transverse fillet weld joint

Measurements of the radii of curvature and weld toe angle were obtained for both Steels, in an as welded condition and after weld toe grinding, PPAW dressing and hammer peening (Figure 2 a) and b)). These measurements were made using an X-Y coordinate table, fitted with a video camera and monitor. The system has an accuracy of one micron, and is fitted with a special built-in facility to measure radii and angles.

On Table 4 it is possible to see the mean value obtained for the radii and the weld toe angle for the duplex Stainless Steel, welded by MAG, where the radii mean value measured starts from 1.645 mm in a as welded condition, increases to 5.605 mm after weld toe burr grinding, 6.412 mm after PPAW dressing and only to 2.420 mm after the weld toe is hammer peened. It is also possible to check that the PPAW dressing produces a smaller weld toe angle on this material. Finally on Table 5 the analysis to the 304L Steel shows a more relevant increase in the weld toe radii after the hammer peening process, while the angle it is not affected by any fatigue life improvement technique.

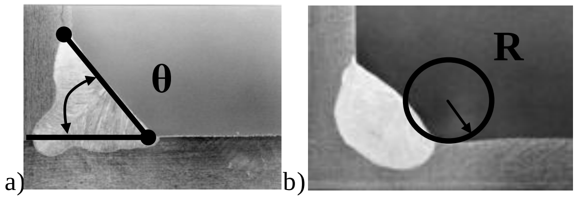

Figure 2 a) Weld toe tangent angl; b) Weld toe radii

Table 4 Weld Toe Radii and Angle values for the Duplex Steel (MAG)

	As Welded		**Burr Grinded**	
	Radii [mm]	Angle [º]	Radii [mm]	Angle [º]
Mean	1.645	38.238	5.605	
St. Dev.	0.630	5.310	0.869	
#	488	280	88	
	PPAW Dressed		**Hammer Peened**	
	Radii [mm]	Angle [º]	Radii [mm]	Angle [º]
Mean	6.412	33.395	2.420	
St. Dev.	1.612	3.333	0.683	
#	48	44	64	

Table 5 Weld Toe Radii and Angle values for the 304L Steel (MAG)

	As Welded		**Burr Grinded**	
	Radii [mm]	Angle [º]	Radii [mm]	Angle [º]
Mean	2.240	42.556	3.876	
St. Dev.	0.906	3.470	0.568	
#	400	256	64	
	PPAW Dressed		**Hammer Peened**	
	Radii [mm]	Angle [º]	Radii [mm]	Angle [º]
Mean	5.192	42.494	4.253	
St. Dev.	2.146	3.593	1.628	
#	112	112	40	

A total of 2448 measures show that the previous study can correctly characterise the weld toe geometry of the fatigue tested specimens and will be used not only to analyse those results, as recommended by Branco on [17] and [18], but most importantly to correctly model a finite element analysis of every fatigue life improvement technique.

2.2 Residual Stress Values

The influence of the weld toe grinding, PPAW Dressing and the Hammer Peening techniques was also characterized measuring the residual stresses at the weld toe. This was done using the X-Ray diffraction technique. The weld toe grinding technique decrease the residual stress level in the weld toe, introducing compressive residual stresses (Table 6). This is a beneficial effect leading to a higher fatigue life as the increase in the weld toe radii. Residual Stresses move from 76 MPa in the longitudinal direction on the Duplex Steel to – 200 MPa, and from – 71 MPa to – 196 MPa on the 304L Steel, on the weld toe. When the same results are analyzed for the weld toe PPAW Dressing technique, on can see that the residual stresses are not always decreased, in fact the increase from – 71 MPa to 10 MPa on the weld toe of the 304L Steel in the longitudinal direction and from 7 MPa to 05 MPa on the transverse direction. This is a result of a new thermal cycle that is applied to the material when the weld toe is dressed and the corresponding procedure should be revised. As expected the hammer peening technique is the one that allows obtaining the highest compression residual stresses. On the weld toe of the Duplex steel, on the longitudinal direction, the residual stress moves from 76 MPa to – 485 MPa, and from – 78 MPa to -524 MPa in the transverse direction. As a less resistance steel, the residual stresses on the 304L only manage to decrease to – 276 MPa and – 98 MPa, in the longitudinal and the transverse directions of the weld toe respectively.

Table 6 Residual Stresses obtained by X-Ray Diffraction (cont.)

	1.0 mm Longitudinal	1.0 mm Transverse	0.0 mm Longitudinal	0.0 mm Transverse
Specimen	Value [MPa]			
Duplex (MAG) As Welded			76 ± 13	-78 ± 21
Duplex (MAG) Burr Grinded	42 ± 6	-203 ± 17	-200 ± 30	-118 ± 31
Duplex (MAG) PPAW Dressed			-16 ± 29	-88 ± 52
Duplex (MAG) Hammer Peened	-269 ± 9	-162 ± 18	-485 ± 31	-524 ± 26
304L (MAG) As Welded			-71 ± 9	7 ± 5
304L (MAG) Burr Grinded			-196 ± 55	-163 ± 20
304L (MAG) PPAW Dressed			10 ± 10	95 ± 20
304L (MAG) Hammer Peened	-216 ± 21	-89 ± 16	-276 ± 22	-98 ± 5

2.3 Fatigue tests

The fatigue tests were carried out under constant amplitude loading in a ± 250 kN capacity servo hydraulic fatigue test machine. The frequency was 6-12 Hz and the stress ratio R=0.1, for every fatigue test (including the corrosion fatigue tests) in order to assess the influence of the test environment. Therefore the frequency used in the corrosion fatigue tests may be considered high, but it was maintained between 6-12 Hz in order to equal to the frequency used in the normal fatigue tests. The bulk of the tests were carried out until complete failure of the specimen or up to a number of cycles close to 10^7, time when the fatigue test was stopped.

3 Results and Discussion

3.1 Fatigue Data in the Welded Joints

Figure 3 show the obtained S-N curves for every fatigue test condition on the MAG welded duplex steel, in a non corrosive environment. Therefore it is possible to compare the effect of the three fatigue life improvement techniques used vs. the as welded test condition. An analysis to the mean S-N curves shows that the best technique is the weld to burr grinding, including at higher nominal test loads, the S-N curve for this technique stays above the other ones. The hammer peening technique is the second best one, especially for lower loads, while the PPAW dressing can provide better results at higher stress fatigue life tests. Table 7 quantifies the gain (1) in fatigue life obtained for the several fatigue life improvement techniques used for both a 175 MPa and 300 MPa stress test, where one can see that the burr grinding technique makes the fatigue life increase 13 time, while the hammer peening makes it only 4.19 time better for the lower stress level. When a higher stress level is applied, the gain factor of the burr grinding technique decreases to 6.8.

$$Gain = \frac{N_{r_{Treated}}}{N_{r_{As\ Welded}}} \qquad (1)$$

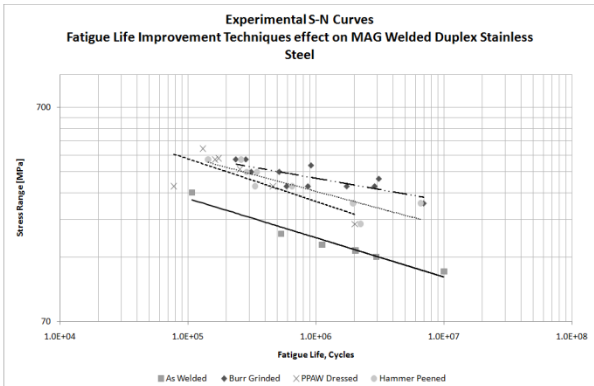

Figure 3 S-N curves experimentally obtained, for comparing the effect of several fatigue life improvement techniques on the duplex Steel

In fact one could expect to obtain better results with the hammer peening technique, especially because of the higher compression residual stresses introduced, but that fact is that the higher weld toe radii obtained with the burr grinding technique is more effective for a fatigue life increase.

Table 7 Gain factors for the fatigue life, obtained in the duplex steel

Specimen	ΔS [MPa]	Nr [Cycles]	Gain
As Welded	175	533843	
Burr Grinded	175	6954875	13.03
Hammer Peened	175	2237619	4.19
PPAW Dressed	175	2015486	3.78
As Welded	300	107287	
Burr Grinded	300	729374	6.8
Hammer Peened	300	491307	4.58
PPAW Dressed	300	461246	4.3

Table 8 compare the same results obtain with a corrosive environment, and as one would aspect the gain factor decrease considerably, to 5.54 when a 175 MPa stress level is applied to a burr grinded duplex steel specimen, and to 2.32 when the same test condition was subject of a 350 MPa stress level.
On Table 9 one can see the same analysis now applied to the 304L Steel when tested on a non corrosive environment, with a 225 MPa stress level. Again the burr grinding technique is more effective than the other two fatigue life improvement techniques, with a gain factor of 9.43, while the second best technique is now the PPAW dressing, with a 2.18 factor vs. a 1.17 factor for the hammer peening technique.

Table 8 Gain factors for the fatigue life, obtained in the duplex steel under a corrosive environment

Specimen	ΔS [MPa]	Nr [Cycles]	Gain
As Welded	175	1013402	
Burr Grinded	175	5616334	5.54
PPAW Dressed	175	2781915	2.75
As Welded	350	42929	
Burr Grinded	350	99546	2.32
PPAW Dressed	350	86715	2.02

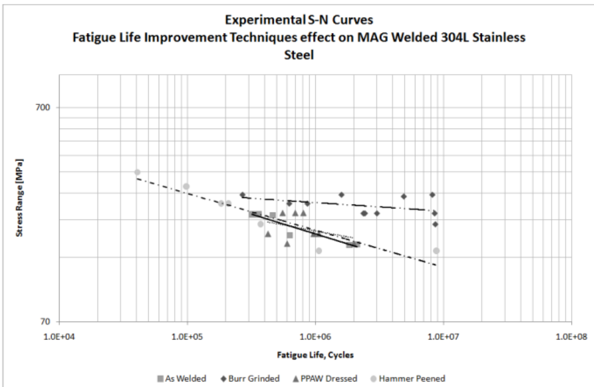

Figure 4 S-N curves experimentally obtained, for comparing the effect of several fatigue life improvement techniques on the 304L Steel

The previous results are seen on Figure 4 where the S-N curves for the four fatigue test conditions are plotted. Again the weld toe burr grinding is a clear winner vs. the as welded condition, while the other two techniques results are not so clear to check.
As a less resistant material, this stainless steel fatigue life improvement results are more limited on techniques that require plastic deformation, like the hammer peening, or thermal resistance like the PPAW dressing. Therefore the burr grinding technique that acts by removing a superficial layer of probably defective material, without deformation, is more effective on this steel.

Table 9 Gain factors for the fatigue life, obtained in the 304L steel

Specimen	ΔS [MPa]	Nr [Cycles]	Gain
As Welded	225	319382	
Burr Grinded	225	3012115	9.43
Hammer Peened	225	373408	1.17
PPAW Dressed	225	696217	2.18

3.2 Numerical Results

In order to numerically simulate the fatigue life test runs on every welded condition on study in this paper, a 1.125 mm wide slice specimen was model on the FEA program ABAQUS. The full specimen thickness was not model because the resources for numerically model the hammer peening technique are still too much to handle on a normal computer. Therefore in order to reduce the number of degree of freedom the specimen wide is reduced, fixing its lateral movement in order to simulate a plane strain state. Using the natural symmetry of the specimen only 1/8 was simulated, using model with 15’855 DOF, composed with C3D8R linear elements.
Every condition were simulated, the as welded, burr grinding and PPAW dressing techniques were modeled only by weld toe radii and angle changing, using the previously obtained values. No other effect was simulated, and therefore the stress range, medium stress and strain range, needed for the local approach method are easily obtain from the FEA simulations.
Finally the hammer peening technique was simulated using an elastic and deformable tool, also model with C3D8R linear elements that added 3’798 DOF to the original simulation. This 12 mm in diameter tool was simplified to represent only the extreme end of the full tool and the influence of its contact radius and position were also analyzed. A 800 N impact force was applied dynamically to the tool, after a experimental analysis of the hammer peening process. In this case 4 hammer peening runs, each one with 5 strokes per millimeter, where applied to the specimen.
As stated the fatigue life prediction was made using the Local Approach Method, [19], using the results obtain under the weld toe. Table 10 and Table 11 show the final results for fatigue life prediction on the MAG

welded duplex steel, using a 225 MPa and a 350 MPa Stress level. The calculated fatigue life's ranges from 434594 cycles, in a as welded condition, to 6193594 cycles when the weld toe is hammer peened, and a 225 MPa stress is applied to the specimen. This can be translated in to a 14.25 gain factor, which decreases to 3.61 when the stress level is increased to 350 MPa. But numerically the hammer peening technique is the one that gives us the best fatigue life improvement, unlike the experimental results. The second best technique is the PPAW dressing because the weld toe radii mean values experimentally obtained where larger.

Figure 5 shows the complete S-N curves for all the test conditions, and once again clearly the hammer peening technique is the one with the best results. Finally the influence of the weld toe radii is also visible on Figure 5, spanning the fatigue life from 100'000 cycles to 3'000'000 cycles, has the radii is increased using the data collected experimentally.

Table 10 Gain factors for the fatigue life (ΔS = 225 MPa Stress range), obtained in the duplex steel by FEA and the Local Approach Method

Specimen	σ_m [MPa]	$\Delta\varepsilon$ [μ]	Ni [Cycles]	Gain
As Welded	220.1	2020	434584	
Burr Grinded	175.9	1609	2047467	4.71
Hammer Peened	-185.7	1969	6193594	14.25
PPAW Dressed	171.7	15700	2450755	5.64

Table 11 Gain factors for the fatigue life (ΔS = 350 MPa Stress range), obtained in the duplex steel by FEA and the Local Approach Method

Specimen	σ_m [MPa]	$\Delta\varepsilon$ [μ]	Ni [Cycles]	Gain
As Welded	200.7	3573	52442	
Burr Grinded	197.8	3188	135804	2.59
Hammer Peened	223.6	3327	189304	3.61
PPAW Dressed	196.2	3010	152273	2.90

Table 12 Gain factors for the fatigue life (ΔS = 225 MPa Stress range), obtained in the 304L steel by FEA and the Local Approach Method

Specimen	σ_m [MPa]	$\Delta\varepsilon$ [μ]	Ni [Cycles]	Gain
As Welded	138.9	1959	338933	
Burr Grinded	136.5	1745	494292	1.46
Hammer Peened	80.8	1745	517438	1.53
PPAW Dressed	135.1	1646	599171	1.77

For the 304L steel results are again shifted, on Figure 6, one can see that the hammer peening technique is no longer the best one. Numerically the best predicted technique is the weld toe PPAW dressing, while the hammer peening and the burr grinding lay not very far away. Table 12 and Table 13 show that the less resistant steel does not allow to obtain decreased medium stresses, and therefore the fatigue life predicted by the local approach method are smaller than one could expect. On the 304L steel is the weld toe radii the most important factor for predicting the fatigue life, and therefore the value that should be higher.

Table 13 Gain factors for the fatigue life (ΔS = 350 MPa Stress range), obtained in the 304L steel by FEA and the Local Approach Method

Specimen	σm [MPa]	$\Delta\varepsilon$ [μ]	Ni [Cycles]	Gain
As Welded	200.7	3573	52576	
Burr Grinded	197.8	3188	73208	1.39
Hammer Peened	223.6	3327	63666	1.21
PPAW Dressed	196.2	3010	86857	1.65

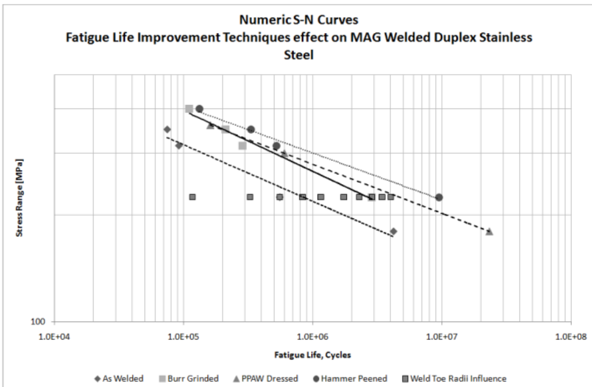

Figure 5 S-N curves numerically obtained, for comparing the effect of several fatigue life improvement techniques on the duplex Steel

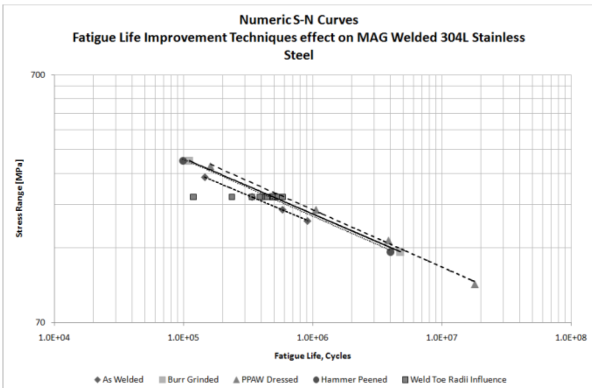

Figure 6 S-N curves numerically obtained, for comparing the effect of several fatigue life improvement techniques on the 304L Steel

4 Conclusions

- Fatigue life tests allow obtaining S-N curves for several combinations of specimen materials, welding process, and post welding fatigue life improvement techniques. Some of these combinations lead to problems, like fractures in the base material or near the grips;
- The hammer peening technique is more effective for higher loads testing conditions, while the weld toe burr grinding is more effective for lower loading conditions;

- For the 304L steel the same analysis can be made between the burr grinding and the PPAW dressing, which leads to the same conclusion;
- Under a corrosive environment, the duplex steel subjected to weld toe burr grinding has a gain factor that ranges from 1.00 to 5.54, which proves the highly efficiency of this technique;
- Under the same conditions the PPAW dressing technique is less efficient, with a 2.75 maximum gain factor;
- The most effective fatigue life improvement technique is the weld toe burr grinding, on both materials, and testing environments;
- Considering the higher resistance of the duplex steel, the fatigue life improvement results are better on this material, but all the obtained results reveal satisfactory gain factors;
- It is possible to model the fatigue life improvement techniques using a FEA program and the local approach method, especial the hammer peening technique.

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REFERENCES

[1] Offshore Installations; Guidance on Design, Construction and Certification, UK Department of Energy, HMSO, Fourth Edition, 1990.

[2] "British Standard Specifications for Unfired Fusion Welded Pressure Vessels", BS5500, 1990, British Standards Institution, London, UK.

[3] Booth, G.S. (ed.), "Improving the Fatigue Performance of Welded Joints", The Welding Institute, Cambridge, UK, 1999.

[4] Haagensen, P.J., Slind, T., "Weld Improvement Methods and Fatigue Design Rules", Proc. Int. Conf. Fatigue and Welded Constructions, The Welding Institute, UK, 1987.

[5] Huther, I, Lieurade, H.P., Sonissi, R., Nussbaumer, A., Chabrolin, B., Janosh, J.J., "Analysis of Results on Improved Welded Joints", Welding in the World, 37, 5, pp. 242-266, 1996.

[6] Maddox, S.J., "The Application of Fatigue Life Improvement Techniques to Steel Welds", IIW Commission XIII Workshop on Improvement Methods, International Institute of Welding, Proc. 51st Annual Assembly, Hamburg, Germany, September 1998.

[7] Haagensen, P.J., Maddox, S.J., "Specifications for Weld Toe Improvement by Burr Grinding, TIG Dressing and Hammer Peening for Transverse Welds", IIW Document, Commission XIII, Working Group 2, WG2, International Institute of Welding, 2001.

[8] Infante, V., Branco, C.M., Baptista, R., Gomes, E.C., "Residual stresses and fracture mechanics analysis of welded joints repaired by hammer peening", Proc. 8th Portuguese Conference on Fracture, Vila Real, UTAD, Ed. SPM, Lisboa, pp. 339-354, Março 2002

[9] Infante, V., Branco, C.M., Baptista, R. "Failure analysis of welded joints rehabilitated by hammer peening", Paper XIII 1892/01, IIW Meeting, July 2001, Llubljana, Slovenia, Ed. International Institute of Welding

[10] Infante, V., Branco, C.M. "A study on the fatigue behaviour of damaged welded joints repaired by hammer peening", Proc. ECF13, 13th European Conference on Fracture, San Sebastian, Spain, Ed. ESIS, 2001

[11] TWI, " Improving the Fatigue Performance of Welded Stainless Steels", Final Report for contract No. 7210-PR-303, 2005

[12] Haagensen, P., Maddox, S.J., "IIW recommendations for weld toe improvement techniques", Commission XIII, International Institute of Welding, July 2001

[13] Marksmann, J. et al, "Powder plasma arc welding: a process with special applications", DVS-Berichte 194, 09/98, pp. 21.26

[14] Infante, V., Branco, C.M., Baptista, R., "Fatigue Analysis of Welded Joints Rehabilitated by Hammer Peening", ICEMS/IST, Paper for IIW Meeting Ljubljana, Slovenia, 2001

[15] Infante, V., Branco, C.M., "A comparative Study of the Fatigue Behaviour of Repaired Joints by Hammer Peening", Paper XIII-1836-2000

[16] Dexter, R.J., Kelly, B.A., "Research on Repair and Improvement Methods", Proc. 50th Annual Assembly, San Francisco, EUA, WRC, 1997, pp. 74-97

[17] Branco, C.M., Gomes, E., Infante, I., "Influência da Geometria do Pé do Cordão no Comportamento à Fadiga de Juntas Soldadas Melhoradas", Proc. 3as Jornadas Ibéricas de Fractura, Luso, Portugal, 27 a 29/03/96, Publ. Grupo Espanhol de Fractura, pp. 368-373, Madrid, 1996.

[18] Branco, C.M., Gomes, E.C., "Fatigue Behaviour of Plasma and Pulsed TIG Joints", International Conference on Fatigue of Welded Components and Strutures, SF2M, Senis, France, 12-14 June, pags. 131-138, 1996.

[19] Dowling, N.E., "Fatigue at Notches and Local Strain and Fracture Mechanics Approaches", ASTM, STP 677, pp. 247-273, 1979