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Study of the fatigue behavior in welded joints of stainless steels treated by weld toe grinding and subjected to salt water corrosion

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Abstract

This paper presents the fatigue results obtained in two types of stainless steels: Duplex S31803 and Austenitic 304L. The main objective was to compare the fatigue behavior in terms of environment (air and 3% NaCl) and weld toe treatment (as welded and toe grinding). The tests were carried out in tension on cruciform specimens with a constant amplitude fatigue cycle of $R = 0.1$. A few tests were also carried out for $R = 0.5$. These data values were also compared with results available in the literature.

The fatigue performances of austenitic and duplex stainless steel joints are similar.

It was found that the fatigue strength of the tested austenitic toe ground joints was greater than the fatigue strength of the as welded specimens. The fatigue performance improves in as welded specimens with the increase of stress range.

For a number of cycles near of $N = 10^7$ cycles it was obtained increase of 60% in terms of stress range.

Measurements of the radii of curvature and weld toe angle were obtained in the as welded and toe grinding specimens.

The variations in fatigue life are basically due to changes in residual stress and weld toe geometry at the weld toe zone. These results were also assessed by numerical results obtained by 2D FE.

Keywords: Stainless steels; Fatigue life improvement; Weld toe grinding; Water corrosion; Fatigue testing

1. Introduction: background

Today engineers have great a task when designing a new structural component. One of the objectives is to extend to the maximum its mechanical strength and fatigue life.

Designing, monitoring and repairing the new structure is fundamental to achieve this goal, and the sooner the engineer starts in this process, better results will be obtained.

Rehabilitation techniques are important, but improving techniques are also relevant. If one can extend the fatigue life of the structure before crack initiation begins, then a greater and safer life is obtained.

Current research deals with the fatigue behavior of welded joints in a structural Steel subjected to the so-called "*local post-welding improvement techniques*", and is a follow-up of early research work [1–5]. Improvement techniques began to be applied to other types of materials, like stainless steels [6] (in the case of the work), and aluminum alloys.

Most of the life improvement techniques, as applied to original or new welds, were established in the 1960s and early 1970s. 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 [7] and pressure vessels [8]. TIG and plasma dressing can be even more effective than grinding [5,9], but there is limited work to support this trend and, therefore, additional work is needed.

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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 [10]. Improvement techniques also reduce the crack propagation speed; which increases the total fatigue life of the structure.

In a review recently presented by Maddox [11], conclusions and recommendations were defined for hammer peening which is now part of an official IIW document of Commission XIII [12].

In the present work the main improving technique used is weld toe grinding. This technique 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. Another objective of this investigation is to compare weld toe grinding discussed in the present paper, with other improvement techniques, like TIG dressing and air-hammer peening. The obtained gain in fatigue strength and fatigue life will be assessed later in next projects.

The study of improvement techniques has been publisher by the authors only for as welded and defective welds [13–16]. This subject has also been considered by others investigators but essentially in application to standard structural.

The present paper reports the fatigue results obtained in two different types of stainless steels (Austenitic 304L and Duplex S31803 type, welded by TIG and MAG processes), in two different environments (air and aerated 3% NaCl solution) and for two different conditions (as welded and weld toe grinding).

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 Austenitic Type 304L (SAE 30304L, DIN 1.4306) and the second one is referred as Duplex Type S31803 (DIN 1.4462). In Tables 1 and 2 the chemical composition of the materials can be found. These compositions show good agreement with the original compositions presented in [6].

Table 3 gives the mechanical properties of both steels, taken from [6].

Table 1
Chemical composition of Austenitic 304L stainless steel (6)

C	Si	Mn	P	S	Cr
0.03	0.33	1.23	0.023	0.007	18.1
Mo	Ni	Al	Cb	Cu	W
0.56	8.2	–	0.11	0.31	–

Table 2
Chemical composition of Duplex S31803 stainless steel (6)

C	Si	Mn	P	S	Cr
0.03	0.25	1.55	0.031	0.009	22.3
Mo	Ni	Al	Cb	Cu	W
2.81	5.7	–	0.13	0.09	–

Table 3
Tensile properties (6)

Steel	Proof strength 0.2% (MPa)	Proof strength 1% (MPa)
304L	256	280
S31803	478	–
	UTS (MPa)	Elongation (%)
304L	698	52
S31803	789	34

Both steels were received in as welded condition, with a plate thickness of 10 mm and the specimen geometry can be found in Fig. 1.

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 (Fig. 2a 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.

The probability density functions of these data, with the Gauss normal distributions, are plotted in Figs. 3 and 4 for the radii of curvature of Austenitic 304L stainless steel series, concerning as welded condition and weld toe grinding in air, respectively. It is seen that, in the weld toe grinding joints, a increase of the radii was obtained as against the as welded joints (Table 4).

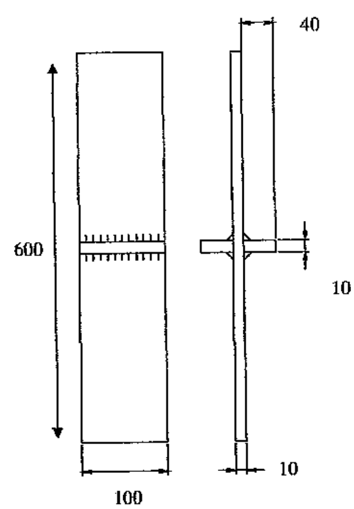


Fig. 1. Transverse fillet weld joint.

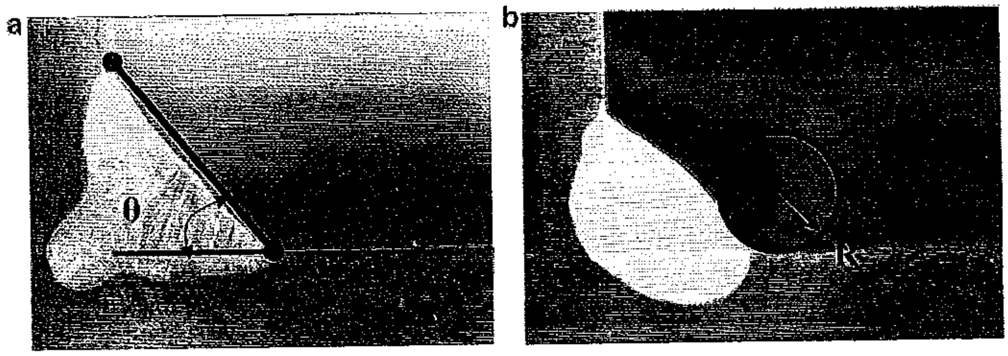


Fig. 2. (a) Weld toe tangent angle, θ, in as welded specimen and (b) weld toe radii after weld toe grinding.

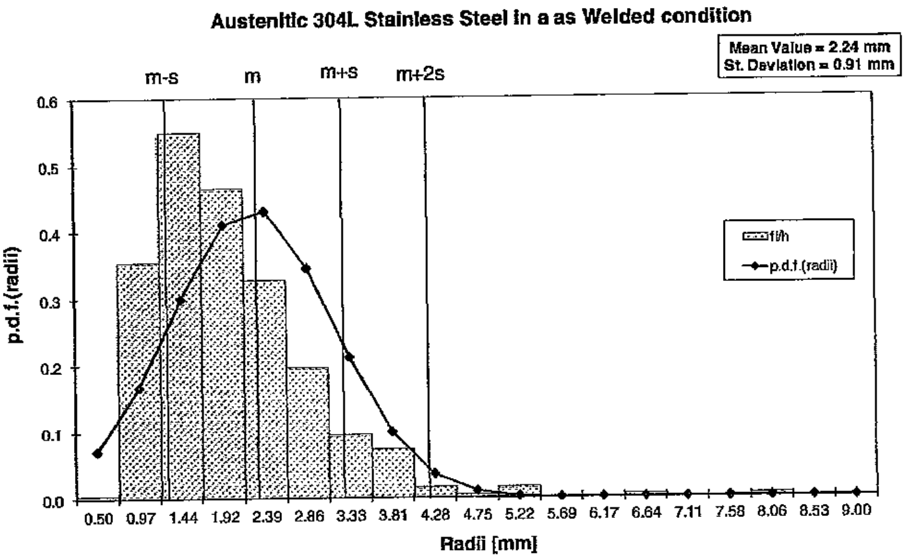


Fig. 3. Probability density function for the Austenitic 304L stainless steel series welded by the MAG process.

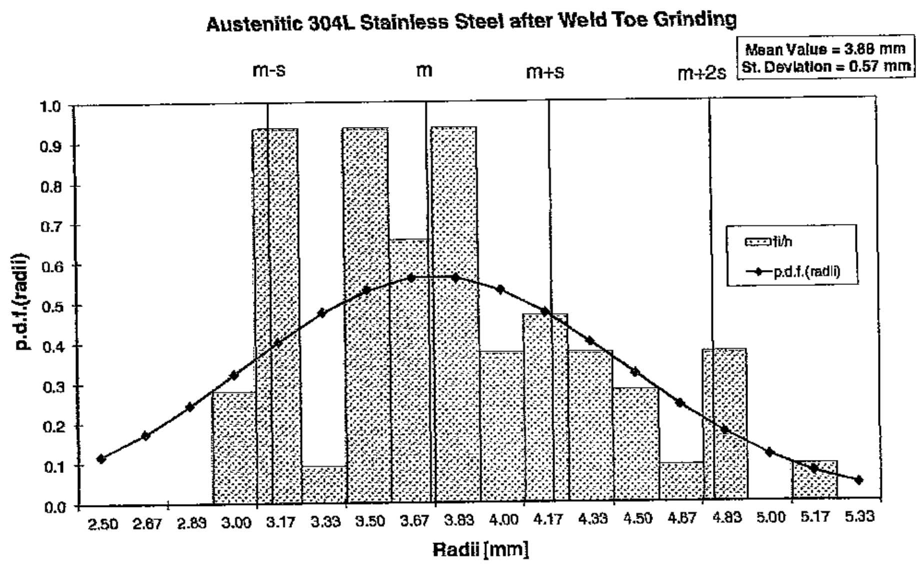


Fig. 4. Probability density function for Austenitic 304L stainless steel series welded by the MAG process, after weld toe grinding in air.

Table 4
Values of weld toe radii

		# Measurements	Mean value (mm)	Standard deviation (mm)
Duplex S31803 stainless steel	As welded	488	1.65	0.63
	Weld toe grinding	88	5.59	1.10
Austenitic 304L stainless steel	As welded	400	2.24	0.91
	Weld toe grinding	64	3.88	0.57

The results show a small variance suggesting that the welding process presents a very good quality (Table 4).

For weld toe grinding a pneumatic weld toe grinding tool with the following specifications was used: pressure: 7 Bar; rotation speed: 24,000 rpm; work angle, sideways: 45° and work angle, weld direction: 45°.

Fig. 2 presents a macro of both conditions showing the difference in the weld toe radii after the weld toe grinding technique is applied.

For the Duplex S31803 stainless steel series the weld toe radii was 0.53 mm for the specimens welded by the TIG process and 1.65 mm for the specimens welded by the MAG process (Fig. 5). The first one is a small value and means that the welding process creates a severe geometry detail.

On the whole, the grinding treatment applied to the Duplex stainless steel has increased the mean radii by about 240% as against the weld toe radii of the equivalent zone at the weld toe for the as weld joints (Table 4).

For both materials the weld toe tangent angle was found to be very close to 45° however the weld thickness is only marginally lower in the austenitic steel.

2.2. *Residual stress values*

The influence of the weld toe grinding technique 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 (Fig. 6). This is a beneficial effect leading to a higher fatigue life as the increase in the weld toe radii.

Fig. 6 shows a decrease in the residual stress level close to the weld toe. In the longitudinal direction the residual stress decreases from −71 MPa to −196 MPa, while in the transverse direction the residual stress decreases from 7 MPa to −163 MPa. To compensate this effect the residual stresses have to increase elsewhere, so 25 mm to the right of the weld toe, the residual stress increase from −37 MPa to 75 MPa in the longitudinal direction and from −43 MPa to −16 MPa in the transverse direction.

This increase will not affect the fatigue strength since it was located remote from the weld toe where the stress concentration factor has a diminutive effect.

2.3. *Finite element analysis*

The finite element analysis (FEA) technique was used to describe the influence of the weld toe radii in the experimental results and also the influence of the fatigue life improvement techniques. One of the most significant fatigue life improvements is the increase of the weld toe radii; methods which can reduce the weld toe stress concentra-

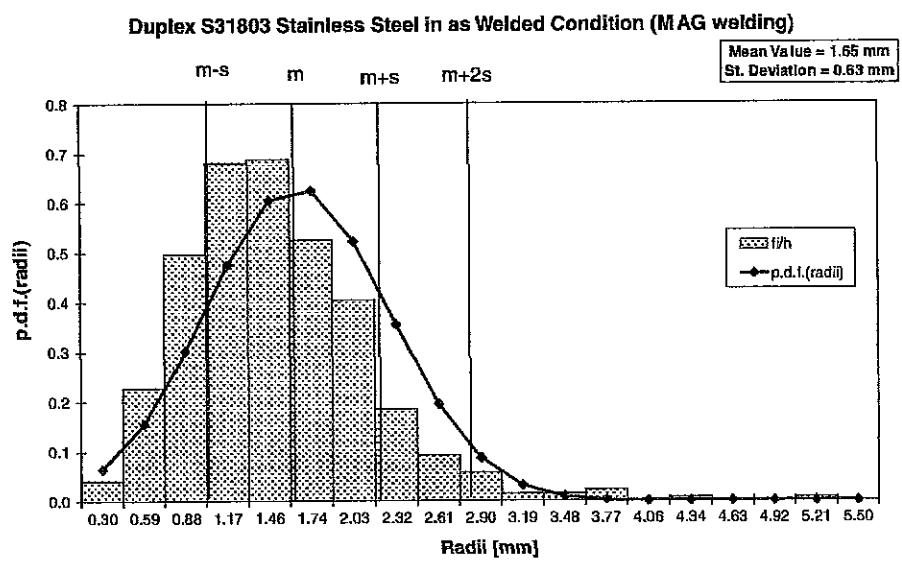


Fig. 5. Probability density function for Duplex S31803 stainless steel series welded by the MAG process, mean value for TIG: 0.53 mm.

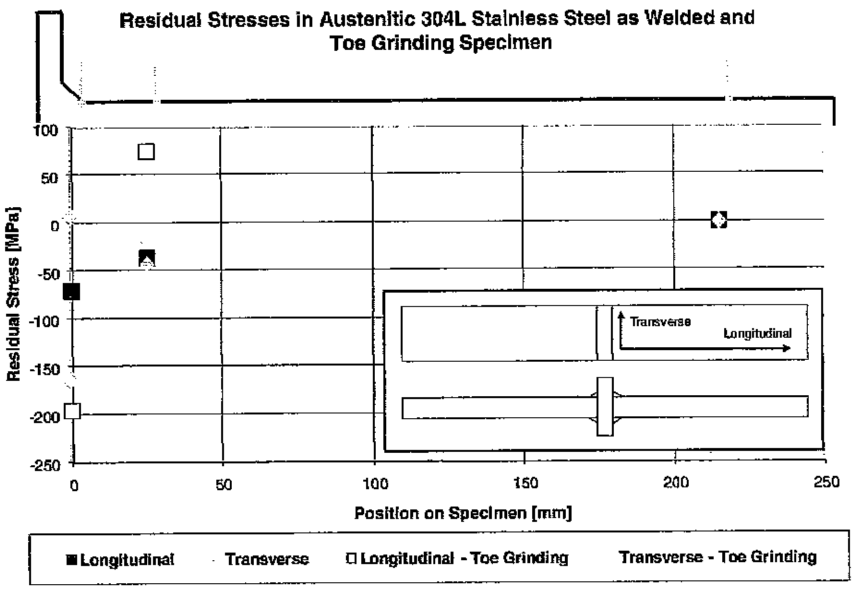


Fig. 6. Residual stress in the weld toe and base material of Austenitic 304L stainless steel.

tion factor and consequently increase the fatigue life by locally reducing the stress levels.

Using a commercial FE code (ABAQUS) the above geometry was modeled with six different weld toe radii and 6 different stress concentration factors. For this joint, the best results were obtained with 1983 quadratic plane elements; with a total number of 6478 nodes (Fig. 7).

The stress concentration factor results in the longitudinal direction, $K_t = \frac{\sigma_{\text{longitudinal}}}{\sigma_{\text{nominal}}}$, range from 1.50 to 2.00 when the weld toe radii increase (Fig. 8). It is then possible to conclude that fatigue life improvement techniques, like weld toe grinding who increase the weld toe radii, decrease the stress concentration factor and the local stress levels leading to an improved fatigue life.

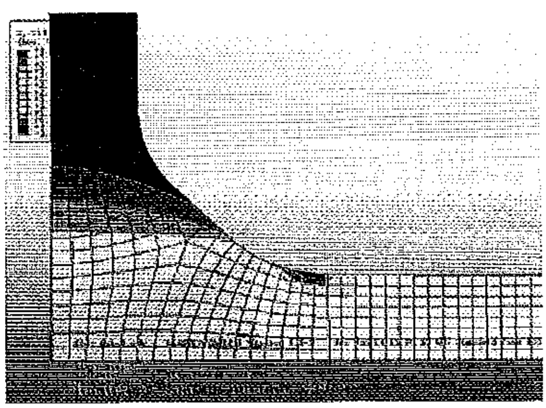


Fig. 7. Finite element mesh and normal stress distribution in the longitudinal direction.

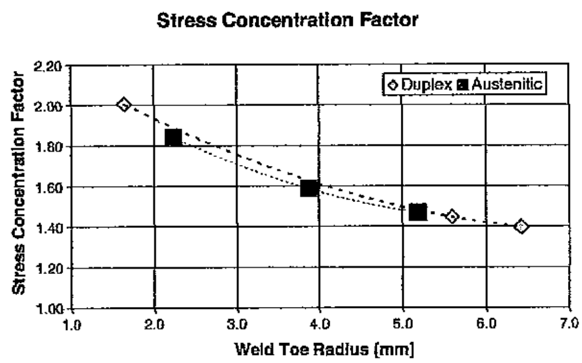


Fig. 8. Stress concentration factors for both stainless steel materials.

2.4. Fatigue and hardness tests

The fatigue tests were carried out under constant amplitude loading in a ±250 kN capacity servohydraulic 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 maybe 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 8.0×10^6, time when the fatigue test was stopped.

Vickers hardness data with 1 kg load was 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 weld toe ground specimens.

3. Results and discussion

3.1. Hardness data

Hardness data was collected for both steels and for two different conditions. For the Austenitic 304L stainless steel the conditions were: as welded and weld toe ground. In the first case the average value obtained in the longitudinal direction was 257 HV, a usual value for this type of Steel, while in the crack propagation direction the average value was 260 HV. One can then conclude that there is a negligible change in the hardness value with the direction.

The hardness value in the crack propagation direction changed after the weld toe grinding process and increased to 270 HV. This increment is close to the weld toe and therefore is higher mainly due to the weld toe grinding technique.

In an as welded condition the same analysis was applied to the Duplex S31803 stainless steel. The Vickers hardness average value was increase to 290 HV. It was found that the hardness in the heat affected zone is lower in comparison with the middle of the plate thickness.

Since the hardness average value was increased after the application of the weld toe grinding treatment it was expected an improvement in fatigue strength (Fig. 13) confirming itself by the *S–N* fatigue results.

3.2. Fatigue data in the welded joints

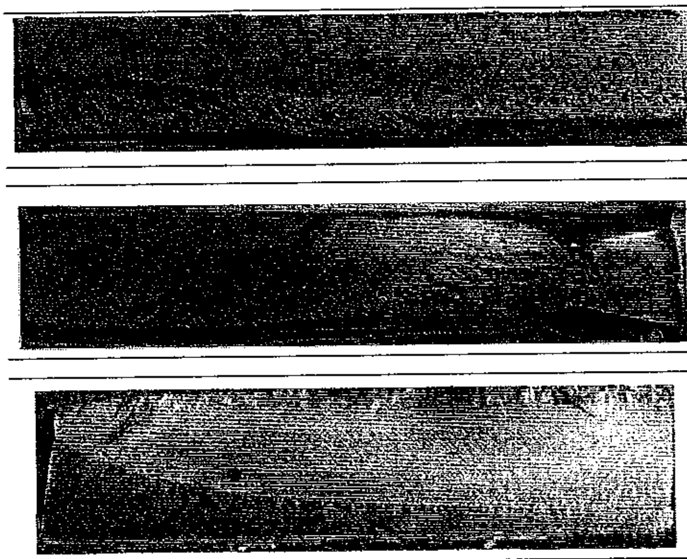
The details for the *S–N* fatigue tests are presented in Table 5.

Some of the most important fracture surfaces are shown in Fig. 9, with the goal of demonstrating the most common fatigue initiation locals, crack propagation and final fracture types. Most of the fatigue initiation takes place on the center of the specimens but some also occurred on the right or left sides (second picture of Fig. 9).

Table 5
Results for the *S–N* tests ($R = 0.1$)

Material/welding technique	Fatigue life improving technique	Environment	$N \cdot (\Delta\sigma)^m = C$
Duplex S31803/TIG[a]	–	Air	$C = 2.9580E+15$, $m = 4.4254$
Duplex S31803/MAG	Weld toe grinding	Air	$C = 4.9746E+24$, $m = 7.4234$
Austenitic 304L/MAG	Weld toe grinding	Air	$C = 7.4105E+33$, $m = 11.672$
Duplex S31803/MAG	–	3% NaCl solution	$C = 4.5042E+14$, $m = 3.9541$
Duplex S31803/MAG	Weld toe grinding	3% NaCl solution	$C = 4.6263E+18$, $m = 5.3908$
Duplex S31803/MAG[a]	–	Air	
Austenitic 304L/MAG[b]	–	Air	

[a] Tested with $R = 0.5$.
[b] Results in reference [6].



Duplex S31803 Stainless Steel (MAG)
As welded
$\Delta\sigma = 250 MPa$
$R = 0.1$
$N_r = 103708 cycles$
$r_{med} = 1.98 mm$

Duplex S31803 Stainless Steel (MAG)
Weld toe grinding
$\Delta\sigma = 175 MPa$
$R = 0.1$
$N_r = 8617147 cycles$
$r_{med} = 4.67 mm$

Austenitic 304L Stainless Steel (MAG)
Weld toe grinding
$\Delta\sigma = 270 MPa$
$R = 0.1$
$N_r = 4878619 cycles$
$r_{med} = 4.07 mm$

Fig. 9. Macros for three different test conditions, including the mean value for the weld toe radii, r_{med}.

In the present work seven test conditions were analyzed. Some were not tested by the authors, as referred in reference [6].

In all cases Fig. 9 the crack propagated uniformly trough the specimen thickness, while in the second macro the crack propagated from one side, leading to an unsymmetrical fracture surface, on a weld toe grinding Duplex S31803 stainless steel specimen.

The fatigue life of the weld toe grinding specimens gives a higher value in comparison with the as welded Duplex S31803 stainless steel specimens (Fig. 10).

The weld toe grinding technique is especially superior for lower loads and increases the high cycle fatigue strength.

A second comparison is between the as welded and the weld toe grinding condition for Duplex S31803 stainless

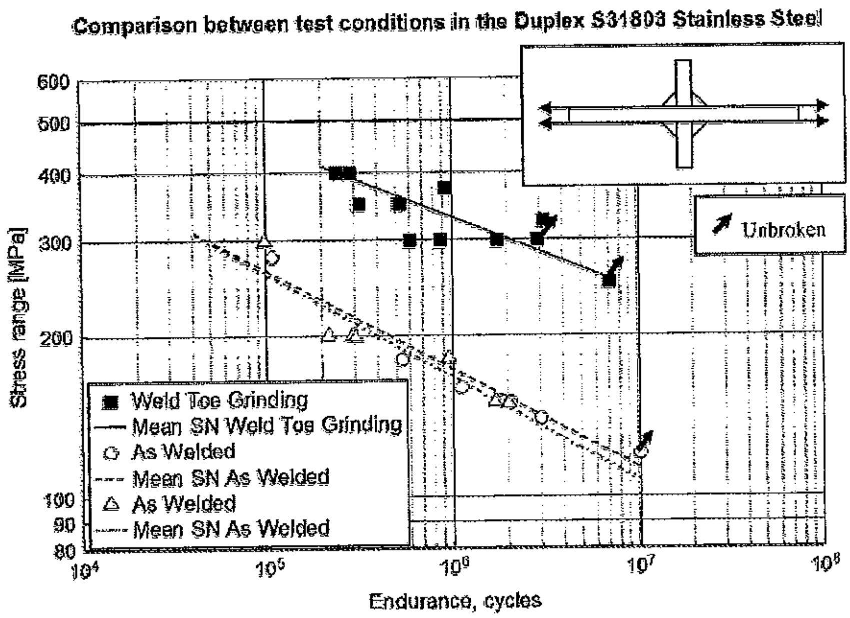


Fig. 10. Comparison between test conditions, to analyze the influence of the improving technique in Duplex S31803 stainless steel MAG welding, air.

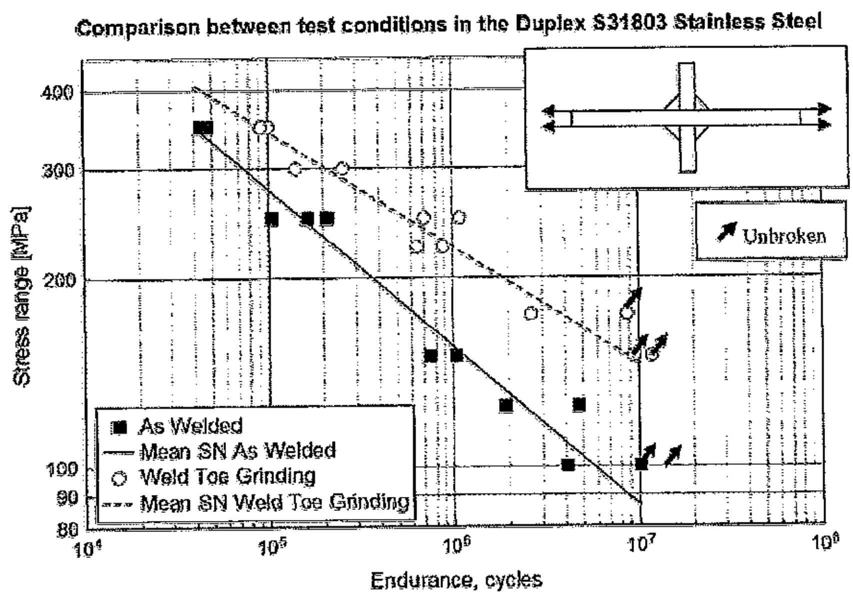


Fig. 11. Comparison between test conditions, to analyze the influence of weld toe grinding technique in Duplex S31803 stainless steel MAG welding in 3% NaCl environment aerated solution.

steel to analyze the influence of the fatigue life improving technique in 3% NaCl.

Weld toe grinding specimens for Duplex S31803 stainless steel tested in 3% NaCl show higher fatigue strength through the entire load spectrum in comparison with the as welded specimens for the same conditions (Fig. 11).

Weld toe grinding is an effective fatigue life improvement technique and the gains in life extension are quantified in Table 6. The gain value varies from 2 when a high load is applied up to 7.68 when a lower load is applied.

The values of the fatigue strength gain factors for the lives of 10^5 and 10^7 cycles are shown in Table 7. The results assured the recommended value of 1.3 for a acceptable improving technique like TIG dressing as referred in [17,18].

Table 6
Gain in life extension

$\Delta\sigma$ (MPa)	$\frac{N_{R\ \text{weld toe grinding}}}{N_{R\ \text{as welded}}}$
G_{150}	7.68
G_{200}	5.08
G_{250}	3.69
G_{300}	2.84
G_{350}	2.27

Weld toe grinding and as welded in the Duplex S31803 stainless steel MAG welding.

Table 7
Gain in fatigue strength

N_R (cycles)	$\frac{\Delta\sigma_{\text{weld toe grinding}}}{\Delta\sigma_{\text{as welded}}}$
G_{10^5}	1.24
G_{10^7}	1.69

Weld toe grinding and as welded in the Duplex S31803 stainless steel MAG welding.

The high cycle fatigue strength is also increased from approximately 100–150 MPa, for weld toe grinding specimens.

These results are backed up by previous tests and analysis, while on Table 4 it is showed that the weld toe grinding technique provides a 439 % increase in the weld toe radii, Fig. 8 shows a 28% decrease in the Stress Concentration Factor. Therefore weld toe grinding is an effective improvement technique.

The environment has a significant effect on the fatigue strength of the Duplex S31803 stainless steel specimens (Fig. 12). Additional experimentation did not allowed to confirm the existence of corrosion in the specimens but the *S–N* curves confirm that the fatigue strength is reduced when the Duplex S31803 stainless steel is subjected to a saline environment (Table 8).

For the Austenitic 304L stainless steel only a few valid results were obtained in Fig. 13 and it is very difficult to quantify the gain in life extension obtained from the application of the weld toe grinding technique. As said before Table 4 show a 73% increase in the weld toe radii after the weld toe grinding and Fig. 8 show a 14% decrease in the stress concentration factor, for the Austenitic 304L stainless steel. Neverthless the values of the fatigue strength gain factors for the lives of 10^6 and 10^7 cycles (Table 9) are still above 1.3, proving that the weld

Table 8
Gain in fatigue strength, air and 3% NaCl environment aerated solution in the Duplex S31803 stainless steel MAG welding

N_R (cycles)	$\frac{\Delta\sigma_{\text{air}}}{\Delta\sigma_{3\%\ \text{NaCl}}}$
G_{10^5}	1.46
G_{10^7}	1.20

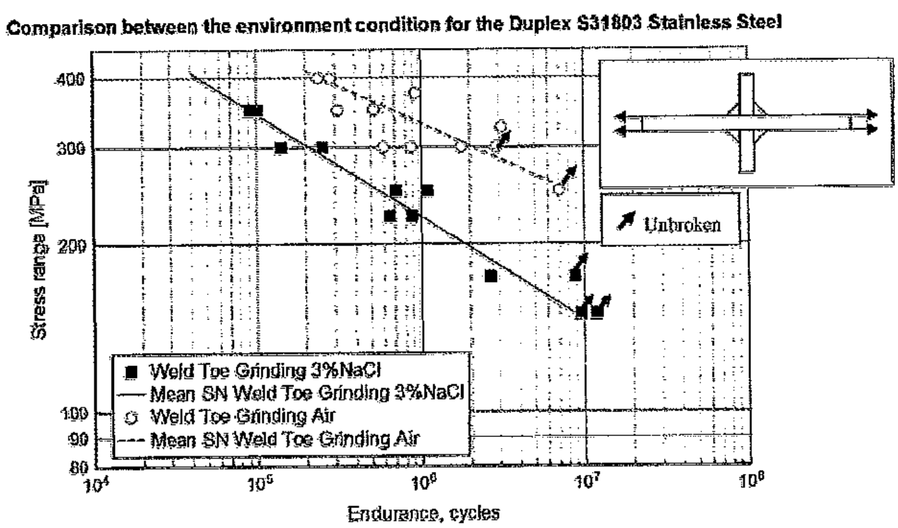


Fig. 12. Comparison between several test conditions, to analyze the influence of the environment in the Duplex S31803 stainless steel MAG welding.

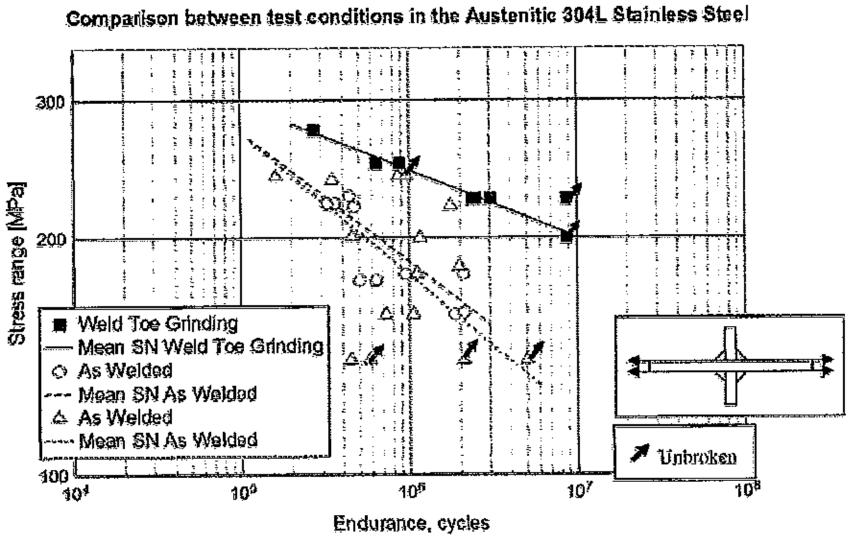


Fig. 13. Comparison between several test conditions, to analyze the influence of the weld toe grinding technique in the Austenitic 304L stainless steel MAG welding.

Table 9
Gain in fatigue strength, weld toe grinding and as welded in the Austenitic 304L stainless steel MAG welding

N_R (cycles)	$\Delta\sigma_{weld\ toe\ grinding} / \Delta\sigma_{as\ welded}$
G_{10^6}	1.34
G_{10^7}	1.64

toe grinding technique is also applicable to the Austenitic 304L stainless steel. The hardness values measured also confirm the last conclusion, as a 5% increase with the weld toe grinding technique supports the fatigue strength gain obtained.

On the other hand for the Duplex Steel the effect resulting from this technique is very clear (Figs. 10 and 11), a considerable life extension was obtained and the high cycle fatigue strength was increased.

4. Conclusions

- The MAG welding process applied to the Austenitic 304L stainless steel specimens produces larger weld toe radii than the TIG welding process used in the Duplex S31803 stainless steel.
- The weld toe grinding treatment increases the Vickers hardness mainly close to the treated zone.
- These tests also show a normal hardness profile for the as welded specimens with the hardness value decreasing in the vicinity of the heat affected zone.
- Comparing the first test condition with the as welded condition tested on 3% NaCl environment, does not allow concluding about the influence of the environment in the Duplex S31803 stainless steel. This is due of the differences between these two test conditions, the value of R is higher in the first one (0.5) and the welding process (TIG also in the first one), leads to a small difference between the results which was not expected.
- Comparing the weld toe grinding specimens with the as welded specimens it is clear that weld toe grinding treatment is very successful in case of 3% NaCl environmental. It leads to a very good gain in life extension and increases significantly the fatigue strength for these specimens, between 10^5 and 10^7 cycles.
- For Austenitic 304L stainless steel specimens the same conclusion can be taken from the comparison between the different test conditions [17,18].
- The present work shows that improving techniques can give a very good fatigue life gain and essentially the weld toe grinding technique is a simple way to improve the strength of a new structure [17].

Acknowledgements

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