Accepted Manuscript

Fatigue Behaviour of T Welded Joints Rehabilitated by Tungsten Inert Gas and Plasma Dressing

A. Ramalho, J.A.M. Ferreira, C.M. Branco

PII: S0261-3069(11)00459-6
DOI: 10.1016/j.matdes.2011.06.051
Reference: JMAD 3897

To appear in: *Materials and Design*

Received Date: 8 November 2010
Accepted Date: 22 June 2011

Please cite this article as: Ramalho, A., Ferreira, J.A.M., Branco, C.M., Fatigue Behaviour of T Welded Joints Rehabilitated by Tungsten Inert Gas and Plasma Dressing, *Materials and Design* (2011), doi: 10.1016/j.matdes.2011.06.051

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

TITLE

Fatigue Behaviour of T Welded Joints Rehabilitated by Tungsten Inert Gas and Plasma Dressing

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Fatigue Behaviour of T Welded Joints Rehabilitated by Tungsten Inert Gas and Plasma Dressing

Armando L. Ramalho
Escola Superior de Tecnologia
Instituto Politécnico de Castelo Branco
6000-767 Castelo Branco
Portugal

José A. M. Ferreira
CEMUC, Universidade de Coimbra
Rua Luís Reis Santos
3030-788, Coimbra
Portugal

Carlos A. G. M. Branco
ICEMS, DEM
Instituto Superior Técnico da UTL
Avenida Rovisco Pais
1096 Lisboa Codex
Portugal

Corresponding author :
Armando L. Ramalho
Escola Superior de Tecnologia
Instituto Politécnico de Castelo Branco
6000-767 Castelo Branco
Portugal
E-mail: ramalhoarmando6@gmail.com; aramalho@ipcb.pt
Telephone: 00351272339300 Fax: 00351272339399

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Fatigue Behaviour of T Welded Joints Rehabilitated by Tungsten Inert Gas and Plasma Dressing

A. Ramalho [a,*], J. A. M. Ferreira [b], C. M. Branco [c]

[a] ESTCB, Polytechnic Institute of Castelo Branco, 6000-767 Castelo Branco, Portugal

[b] CEMUC, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal

[c] ICEMS, DEM, IST, Avenida Rovisco Pais, 1096 Lisboa Codex, Portugal

[*] Corresponding author : aramalho@ipcb.pt; Telephone: 00351272339300;
Fax:00351272339399

Abstract

This paper concerns a fatigue study on the effect of **tungsten inert gas** (TIG) and plasma dressing in non-load-carrying fillet welds of structural steel with medium strength. The fatigue tests were performed in three point bending at the main plate under constant amplitude loading, with a stress ratio of R=0.05 and a frequency of 7 Hz. Fatigue results are presented in the form of **nominal stress range versus fatigue life** (S-N) curves obtained from the as welded joints and the TIG dressing joints at the welded toe. These results were compared with the ones obtained in repaired joints, where TIG and plasma dressing were applied at the welded toes, containing fatigue cracks with a depth of 3-5 mm in the main plate and through the plate thickness. A deficient repair was obtained by TIG dressing, caused by the excessive depth of the crack. A reasonable fatigue life benefits were obtained with plasma dressing. Good results were obtained with the TIG dressing technique for specimens with shallower initial defects (depth lesser than 2.5 mm).

The fatigue life benefits were presented in terms of a gain parameter assessed using both experimental data and life predictions based on the fatigue crack propagation law.

Keywords

C. Repair of welded joints

D. Welding

E. Fatigue

ACCEPTED MANUSCRIPT

1. Introduction

Fatigue life of welded joints is mainly influenced by pre-existing cracks in the weld toe [1] inherent with welding techniques used in steel structures. The presence of such defects, together with the stress concentration induced in the weld toe section, explains the relatively poor fatigue strengths of fillet welds. The fatigue crack initiation from the weld toe is despicable, and therefore the fatigue life is largely spent in crack propagation.

In this case, for welded joints, fatigue life predictions can be done by using mechanical fracture parameters [2]. For this purpose, solutions **for stress intensity factors (K)** can be found in literature. Bowness and Lee [3, 4] have developed a very extensive research to obtain database-estimated equations for **the weld toe magnification factor (Mk)** to T-butt joints. The proposed Mk factors equations have been included in the British Standard BS 7910 [5], the replacement for PD6493 [6].

Post-weld improvement techniques remove the weld defects and/or reduce the stress concentration at the weld toe, increase the fatigue crack initiation period and afterwards improve fatigue strength. Techniques such as: TIG and plasma dressing, burr grinding, needle, shot and hammer peening have been studied in last decades and reported in numerous papers [7-11]. More recently, some attention has been placed on the investigation of high frequency peening treatment, referred to as ultrasonic impact treatment or as ultrasonic peening, that has proved to be an efficient way for fatigue life improvement [12, 13]. The published results indicate, in general, large increases of fatigue strength by using these techniques [1, 7, 11]. TIG and plasma dressing are important industrial techniques, which produce more effective benefits than grinding [11]. However, the efficiency of these processes seems to be lower than hammer and ultrasonic penning [7, 11]. The fatigue strength improvement achieved through these techniques, increases with nominal yield stress and therefore the greatest benefits are obtained for high strength steels [7, 9, 12, 14, 15]. Recently, some work has been focused on the application of these steels and post-weld treatments in the medium cycle regime, i.e. 10000 to 500000 cycles [15]. Since the best benefits obtained in the high strength steels appear to be related to the introduction of residual stresses, some studies have been conducted in order to analyze the effect of relaxation of these stresses under

ACCEPTED MANUSCRIPT

constant and variable amplitude loading and the effect of variable amplitude loading on the benefits of the improved joints [16-18].

Despite the large number of studies in this area, the use of these techniques in the design codes is still very limited. One reason for this reluctance is the wide spread of results reported by these studies [19]. The new approach of fatigue by hot spot stress, instead of nominal stress, appears to contribute to a smaller scatter of results obtained in as-welded specimens as well as in the improved ones [20]. There has been a standardization effort in order to define the conditions for implementing the various improvement techniques [21, 22]. A procedure specification was created, in order to assure that the treatment in industrial field is applied in the same way as those specimens tested in the laboratory [21]. Some studies have been conducted with the purpose of optimizing the application of the improvement technique of TIG dressing [1, 15].

Recently, the recommendations of the International Institute of Welding on fatigue of welded joints have been updated [23]. In this new code, the improvement techniques are considered by the use of an improvement factor. This minimum factor of the improvement effect is established for each of the considered techniques and can be used without any complementary experiments. For the TIG dressing, the improvement is given by a factor in terms of stress [23-25]. The update of the Recommended Practice for Fatigue Design of Offshore Steel Structures also considers the improvement techniques of grinding, TIG dressing and hammer peening [26]. For these techniques, in this code, the improvement is given by a factor on life. However, for reasons connected with the quality assurance of the post-welding process in offshore structures, the TIG dressing has a very limited application at the design stage.

Improvement treatments of the welded joints allow significant gains in fatigue strength, enabling lighter structures, economic gains and better performances in the structure or equipment. However, to obtain the desired improvements with the post-weld techniques, it is necessary that the as welded joints and the improved welded joints, in case of rewelding treatments, have certain quality requirements, to ensure the absence of welding defects, or its limitation, as well as the fulfillment of certain requirements on bead geometry [14, 27, 28]. Although the existing weld class system [29, 30] will guarantee the requirements of industrial quality control, it doesn't allow relating the quality of the weld joint with its fatigue strength in an efficient way [31]. Recently was developed by a manufacturer a new weld class system [32, 33], in which performed

ACCEPTED MANUSCRIPT

studies shows promising results regarding the correlation between the quality of welded joints and their fatigue strength.

The main objective of the present study is to evaluate the benefits of fatigue improvement techniques, particularly the TIG and plasma dressing, to repair cracked joints. Fatigue, corrosion or other service conditions can damage the weld joint. The damaged toe can be removed or refused and this way the fatigue life will be restored or even improved [34].The methods to repair weld cracks are reviewed [35], and the emphasis to obtain good benefits is put in the compressive residual stresses. In peening treatments, the compressive residual stresses are generated at the surface, close to the weld toe, so a good efficiency will be obtained only for shallow cracks. However, it is reported in literature the use of rewelding techniques to repair cracks with a depth greater than 3 mm [36]. The ultrasonic peening is also reported as an enhancement technique to repair damaged steel bridges [37].

The use of improvement techniques to repair welded joints is referred to in guidelines and recommendations for maintenance of structures [38-40]. Important fatigue life extensions were also obtained [41] in the same joints of the present study with cracks lesser than 2 mm and repaired by hammer peening.

2. Materials and experimental procedure

2.1. Materials and rehabilitation techniques

The base material used in this study was medium strength steel, St 52-3 DIN 17100 [42], in the form of plates with 12.5 mm of thickness, and the chemical composition presented in table 1. The welds were made by covered electrode process. Chemical composition of the weld metal is presented in table 2.

The mechanical properties of the based material were obtained using a tension specimen with 8 mm diameter, according with the European standard EN 10 002-1 [43]. The tests were carried out in a servo-hydraulic machine (Instron model 1341). The load rate was constant and the strain was measured using a strain gauge with 50 mm length mounted directly on the specimen. The machine software calculated the strain and stress.

The mechanical properties obtained in the base material were (average value of 5 tests):

0.2 % yield stress, σ_{ys}=384 MPa

Ultimate tensile stress, σ_{uts}=555 MPa

ACCEPTED MANUSCRIPT

Rupture strain, ε_R=22.5 %

For weld material it was obtained:

0.2 % yield stress, σ_{ys}=690 MPa

Ultimate tensile stress, σ_{uts}=770 MPa

Rupture strain, ε_R=15 %

The welding T specimens were produced from main plates with 12.5 mm thickness and low penetration fillet welded with an attachment of equal thickness. From this plate, specimens with 70 mm width and 270 mm length were cut. The weld leg length presented a medium value of 9 mm. The specimens were made with the geometry shown in Fig. 1.

The welded joints with fatigue cracks at the weld toe were re-habilitated by TIG and plasma dressing techniques, using the parameters indicated in table 3. The pre-cracks were previously induced by fatigue loading. Fig. 2a) and b) show the profile of the two dressed joints, where the transition of the weld toe can be observed, and distinguish the re-melted, thermal affected and base material zones.

2.2. Fatigue and complementary tests

The fatigue tests were carried out in the servo-hydraulic Instron machine with a load control (R=0), frequency of 7 Hz with a sinusoidal wave loading. The tests were carried out in three points bending as schematically shown in Fig. 1.

Forty four specimens were tested, distributed in the followings four series:

AW – set formed by as weld specimens, without any improvement treatment, tested until rupture, with a constant fatigue load.

TAS – set formed by specimens in which the weld is followed by TIG re-fusion in the weld toe; The used TIG welding parameters are presented in table 3.

TDR – set formed by specimens that are obtained by the following procedure:

As welded specimens are submitted to a fatigue loading until the generation of big deep cracks; this loading is performed in load or in displacement control; The process of detecting cracks was not rigorous, and the loading was conducted without accurate record of the number of cycles until registering an increase of 10% of the initial

ACCEPTED MANUSCRIPT

deformation; After this initial fatigue loading, the specimens are repaired by TIG re-melting using the welding parameters presented in table 3.

PDR– set formed by specimens that are obtained by the following procedure:

The same as the TDR specimens, but the re-melting repair was done by plasma; For the plasma re-melting, in order to improve the depth of fusion, was adopted the key-hole technique and the welding parameters are presented in table 3.

The curvature radius at the weld toe of the welded joints was measured using a Maxtascan model micrometry table XY, with an accuracy of 0.01 mm.

Using an optical Zeiss Axiotech microscopy the microstructures of the base metal (BM), weld metal (WM) and thermal affected zone (TAZ) were identified.

The Vickers hardness were obtained in the base, in weld metal and thermal affected zone, particularly for longitudinal and transverse directions from the weld toe for the four series of specimens: it was used a load of 0.3 kgf applied during 15 s. It was used a Struers micro hardness tester model Duramin.

Residual stresses in the proximity of the weld toe were evaluated using two different techniques: the X ray and the strain gauge. For the X ray technique were used the Elphyse diffractometer Set X model. For the strain gauge technique, a strain gauge rosette, TML type FRS-2-11, was attached on the polished surface and a hole of 0.4 mm diameter was drilled using the drilling equipment Vishay RS-200.

The fracture mechanisms and fatigue initiation zones were observed using a Philips XL 30 scanning microscope.

3. Results and discussion

Fig. 3 a), b), c) and d) show the experimental points and confidence limits (95 %) of the S-N curves for the series of tests in AW, TAS, TDR and PDR specimens. Fatigue results were fitted by using the equation $\Delta\sigma = K_0 N_r^m$ as approach, where $\Delta\sigma$ is the nominal stress range at the weld toe, N_r the number of cycles to failure, K_0 and m are constant parameters. The best fit parameters obtained by linear regression are indicated in table 4.

In a preliminary analysis of the obtained S-N curves it can point out some relevant aspects: did not occur the expected improvement of fatigue life for the specimens of the TAS series; after reparation by plasma dressing (PDR series) the specimens

ACCEPTED MANUSCRIPT

achieve fatigue lives close to the ones of the AW series; the fatigue life results obtained for the specimens repaired by TIG dressing were clearly lower than those of repaired by plasma; however, the S-N curves obtained for all series are above the design curves stipulated by the codes [23, 26] for this welded joint (detail without improvement); The slopes of S-N curves obtained for the series treated by TIG re-melting are close to those obtained in [14] for similar welded joints, but lower than those referred in [27, 37].

All the specimens got broken in the weld toe, which implies that the fatigue lives are strongly influenced by the profile of the weld toe [1]. Table 5 shows the statistical analysis of the curvature radius at the weld toe for AW, TIG dressed and PDR series, respectively. An average weld toe radius of 6.25 mm, with a standard deviation of 1.99, was obtained for TIG series. AW shows an average weld toe radius 30 % lower. PDR series show a big scatter of the weld toe radius caused by big changes in bead shape induced by the key-hole technique used in plasma dressing manufacture. In order to obtain a fusion weld depth of about 40 % of the thickness plate, it was used unusual plasma dressing parameters. **Consequently, the expected improvement in fatigue life caused by the toe radius increase characteristic of re-melting methods did not occur in this case [11].**

In Fig. 4 a), b) and c) are shown the microstructures of base metal, TAZ in TIG and TAZ in plasma dressed specimens, respectively. The microstructure of base metal is formed by ferrite grains and perlite eutectic. A preferential alignment of the perlite grains was induced in the plate manufacture process. In TIG dressing, the thermal affected zone is formed by upper and lower bainite showing some primary ferrite in grain boundaries. This ferrite will cause a lower hardness when compared to the weld zone. In Plasma dressing, the thermal affected zone is also formed by upper and lower bainite, showing some martensite.

Another important aspect related to the fatigue is the hardness of the material [15]. Fig. 5 a) and b) present the longitudinal and transversal hardness profile for TIG dressed and PDR series, respectively. In Fig. 5 a) are presented the results of the hardness distribution along the longitudinal and transverse directions in the specimen TDR 10. The longitudinal distribution covers the weld and thermal affected zones for TIG dressing. It was measured in a parallel line at the distance of 0.1 mm from the upper surface of the main plate. Transverse distribution was obtained from the weld toe.

ACCEPTED MANUSCRIPT

The higher values of hardness, in the thermal affected zone, are about 270 HV0.3 and in the weld zone about 300 HV0.3. In parent metal, the values are about 180 - 200 HV1. **This level of hardness after TIG dressing is representative of the results obtained by others authors in steels similar to the one used in this study. In [10] for a steel less sensitive to microstructure changes, after TIG dressing, were attained 300 HV in the TAZ. In [14] for a similar steel were attained 280 HV, but in this case the base material have initially a bainitic microstructure. In some structural applications hardness levels higher than 300 HV are not acceptable. In [11, 21], for the TIG dressing in the C-Mn steels with a relatively high carbon content (greater than 0.12 weight %), was referred the possibility of attain levels of hardness higher than 300 HV. To overcome this problem it was suggested a second TIG run procedure. In the present study this second TIG re-melting was not applied.**

In Fig. 5 b) are presented the results of the hardness distribution along the longitudinal and transverse directions in the specimen PDR 2. The longitudinal distribution covers the weld and thermal affected zones for plasma dressing. It was measured in a parallel line at the distance of 0.3 mm from the upper surface of the parent plate. Transverse distribution was measured at the thickness direction along a line passing through the weld toe. The higher values in thermal affected zone are about 340 HV0.3 and in the weld zone about 400 HV0.3. In parent metal, the values are about 180 - 200 HV1. For the AW specimens the higher values of hardness, in thermal affected zone, were about 235 HV0.3 and in the weld zone about 275 HV0.3.

The fatigue strength of the welded joints is strongly affected by the residual stress field in the weld toe region [11, 16]. Fig. 6 a), b) and c) show the longitudinal residual stresses at the surface versus dimensionless distance from the weld toe for AW series, TIG dressed and PDR series, respectively. In order to group the results obtained from different techniques and from different specimens, also facilitating the comparison of results obtained in different series, a dimensionless distance is used, in which x is the distance to the symmetry plane of the specimen and x_{toe} is this distance for the toe of each specimen.

The characteristic fracture surfaces obtained for the TDR and PDR series are shown in Fig. 7 and Fig. 8. In the TDR series, for all the specimens, it was found that the TIG penetration was insufficient to remove the initial deep cracks (Fig. 7 a). For the PDR series there were some specimens in which all initial cracks were re-melted (Fig. 7 c), but in others, part of the initial crack remain inside the parent plate (Fig. 7 b). The

ACCEPTED MANUSCRIPT

fatigue failure surfaces were observed in scanning microscopy. The most important aspects can be observed in Fig. 8. Fig. 8 a) presents the fracture surface of the parent metal in the specimen TDR 10 obtained in the position indicated in Fig. 7 a). A transgranular propagation mode is observed. Fig. 8 b) and c) present the fracture surface of the specimen PDR 3 in the positions indicated in Fig. 7 b). A transgranular propagation mode was observed in the bottom region of re-welded zone (Fig. 8 c), but in the upper zone of the weld (Fig. 8 b) a mist failure mode with boundary fracture was observed.

From the analysis of these results, it was possible to conclude:

- Although the weld toe radius of TAS series was about 30 % greater than the AW series fatigue life did not increased significantly; Also, the hardness at TAZ did not produce significant effects on the fatigue life; **The existence of undercuts in the TIG dressed welds could explain this behaviour [15];**
- TDR series present a much lower fatigue strength than AW series; **The main cause for this is related with an insufficient TIG dressing penetration to remove the deep initial cracks [36]**; This means that TIG dressing is not adequate to the rehabilitation of welded joints with deep cracks (3-5 mm) at the weld toe;
- Although the weld toe radius of PDR series was lesser than the AW series, the fatigue lives of these two series are very close; Benefit effects on fatigue life of PDR series are induced by higher hardness values and high compressive residual stresses induced by re-fusion at the weld toe region; **The decrease of residual stresses on the surface has already been reported for re-melting methods [17];**
- Plasma dressing is adequate to the rehabilitation of welded joints with deep cracks (3-5 mm) at the weld toe; However, there were some scatter in the results caused by insufficient re-melting of the initial cracks and by poor quality of the re-melted bead (related to the key-hole technique). **The influence of poor quality of the re-melted bead in the decrease of fatigue life has already been reported [1, 15].**

A gain parameter was defined to quantify the benefit effect of rehabilitated joints, given by the equations:

$$G = N_{reab}/N_{exp} \quad (1)$$

and

$$N_{reab} = N_{ab}+N'_{reab} \quad (2)$$

ACCEPTED MANUSCRIPT

Where:

N_{exp} - Total life, expressed in number of cycles, of welded specimens (AW) for an equal stress amplitude to the one applied to the repaired specimen ($\Delta\sigma=4848.6N_{exp}^{-0.21044}$);

N_{ab} - The number of cycles of the crack initiation and propagation up to the crack depth of repair ($N_{ab}=N_{exp}-N_p$);

N'_{reab} - Total life, expressed in number of cycles, for the repaired specimens, obtained experimentally;

N_p - The number of cycles of the crack propagation from a_{reab} (depth of repair) up to a_f (0.6 of the plate thickness), predicted by the program.

Experimental data was available to define crack initiation and propagation up to the repair of crack and also to define the propagation period, after reparation, of residual cracks up until the rupture.

A fracture mechanical prediction, using Paris law relations obtained in similar steels [44], was carried out to obtain a simulation of crack propagation period. The predicted results, as well as the experimental ones obtained in the fatigue tests, are represented in table 6. The predictions were carried out using the crack propagation program presented and tested in reference [45]. The PD 6493 [6] formulation was used for the factor equations of stress intensity.

Crack growth was analysed in two stages: from an initial defect with a depth of 0.15 mm up to a visible crack stage of reparation by re-fusion process; and from this crack up to the final crack depth of 60% of plate thickness (~7.5 mm). The formulation for crack propagating shape explained in reference [46] was assumed.

For the plasma repaired specimens, the gains in fatigue against the depth of the repaired cracks are represented in Fig. 9.The results show that the gains due repair by plasma range from a factor of 1.14 to about 2.12 of the expected life for the as welded joint. The obtained gain is lesser than expected, mainly in the TDR specimens. In fact, these specimens have greater radius in the weld toe but the obtained gain is insignificant and inadequate, caused by the insufficient performance of this method to re-melt the deep initial cracks. For plasma dressing and in the specimens in which the total re-melt of the initial cracks was achieved, it was obtained a good performance of the rehabilitated joints.

ACCEPTED MANUSCRIPT

To test the performance of TIG re-melting in better initial conditions, were performed new fatigue tests for different TDR specimens with shallower initial cracks (with depth lesser than 2.5 mm). In these new TDR specimens the process of generation of initial cracks has been replaced by a more rigorous one.

To detect the initiation and propagation of fatigue cracks from the weld toe it was used a strain gauge method technique [41]. Three small strain gauges were bonded very close to the weld toe, at each side of the specimen. These strain gauges measure the variation of the local strain at the weld toe caused by the initiation and propagation of fatigue cracks in this place and through the thickness direction of the longitudinal plate. Fig. 10 presents photography of a tested specimen.

As documented by Infante V. and Branco C. M. [41], for identical specimens and tests, a 25 % variation in local strain measured in the strain gauges at the weld toe is related to cracks with depth lesser than 2.5 mm.

Fig. 11 presents the variation of strain along a test of fatigue, in which cracks are initiated and propagated. These tests are carried out in the same conditions as described in section 2.2. The tests were ended when it was attained a variation of 20 % in strain in any one of the strain gauges.

After this process of creating the initial cracks, these specimens were repaired by TIG dressing in the weld toe. **To increase the depth of penetration were used the parameters indicated in table 7 [1].**

The mean weld toe radius obtained in these specimens after TIG dressing is 12.33 mm. This value is much higher than the one previously obtained.

In the fatigue tests that were carried out after this rehabilitation were obtained fatigue lives much higher than the ones obtained previously. These tests are carried out in the same conditions as described in section 2.2**. In this case it was obtained a mean gain of 2.45, which correspond to a gain on fatigue life similar to that expected for TIG improvement [1, 14, 23, 27].**

In Fig. 3 a) and Fig. 3 c) are superimposed an example of the results obtained in these new tests carried out with TDR specimens that have got previously cracks with depth lesser then 2.5 mm. **The obtained results were clearly above the design curve (for this detail improved by TIG) stipulated in the Code For Fatigue Design Of Offshore Steel Structures [26].**

4. Conclusions

ACCEPTED MANUSCRIPT

For the as welded joint with deep fatigue cracks at the weld toe (a_{reab} greater than 4 mm) repaired by TIG dressing (TDR series) the fatigue lives were found to be insignificant. TIG dressing does not proved to be adequate for the rehabilitation of welded joints with deep cracks at the weld toe.

For the as welded joint with deep fatigue cracks at the weld toe (a_{reab} greater than 4 mm) repaired by plasma dressing (PDR series) the fatigue lives were found to be similar to the lives of the as welded joints (AW series). However some scatter in these results was observed. Plasma dressing promotes the repair of welded joints with deep cracks at the weld toe, however the quality of the re-melting bead and the total re-melt of the initial cracks should be guaranteed.

For the as welded joint with fatigue cracks at the weld toe with depth below 2.5 mm, repaired by TIG dressing, the fatigue lives were found to be significantly higher, compared to the fatigue lives of the as welded joints (AW series). TIG dressing is a good rehabilitation technique for welded joints with shallower cracks at the weld toe, including promoting its improvement compared to the as welded ones.

Acknowledgements

The authors acknowledge the Portuguese Science and Technology Foundation by the financial support given to this work within the PRAXIS XXI 3/3.1/CEG/2705/95 project.

References

[1] Manteghi S, Maddox SJ. Methods for Fatigue Life Improvement of Welded Joints in Medium and High Strength Steels. IIW Doc. XIII-2006-04; 2004.
[2] Darcis P, Santarosa D, Recho N, Lassen T. A Fracture Mechanics Approach for the Crack Growth in Welded Joints with Reference to BS 7910. Proceedings of the 15th European Conference of Fracture. Stockholm, Sweden; 2004.
[3] Bowness D, Lee MMK. Prediction of weld toe magnification factors for semi-elliptical cracks in T-butt joints. International Journal of Fatigue 2000; 22(5): 369-387.

ACCEPTED MANUSCRIPT

[4] Bowness D, Lee MMK. Weld toe magnification factors for semi-elliptical cracks in T-butt joints – comparison with existing solutions. International Journal of Fatigue 2000; 22(5): 389-396.

[5] BS 7910. Guide to methods for assessing the acceptability of flaws in metallic structures. British Standards Institution; 2005.

[6] PD 6493. Guidance on methods for assessing the acceptability of flaws in fusion welded structures. British Standards Institution; 1991.

[7] Huther I, Lieurade HP, Souissi R, Nussbaumer A, Chabrolin B, Janosch JJ. Analysis of results on improved welded joints. Welding in the World 1996; 37(5): 242-266.

[8] Branco CM, Maddox SJ, Infante V, Gomes EC. Fatigue performance of TIG and plasma welds in thin sections. International Journal of Fatigue 1999; 22(6): 602-589.

[9] Dahle T. Design fatigue strength of TIG dressed welded joints in high strength steels subjected to spectrum loading. International Journal of Fatigue 1998; 20(9): 681-667.

[10] Kirkhope KJ, Bell R, Caron L, Basu RI, Ma K-T. Weld detail fatigue life improvement techniques. Part 2: application to ship structures. Marine Structures 1999; 12: 477-496.

[11] Kirkhope KJ, Bell R, Caron L, Basu RI, Ma K-T. Weld detail fatigue life improvement techniques. Part 1: review. Marine Structures 1999; 12: 447-474.

[12] Marquis G. Failure modes and fatigue strength of improved HSS welds. Engineering Fracture Mechanics 2010; 77 (11): 2051-2062.

[13] Roy S, Fisher JW, Yen BT. Fatigue resistance of welded details enhanced by ultrasonic impact treatment (UIT). International Journal of Fatigue 2003; 25: 1239-1247.

[14] Lieurade HP, Huther I, Lefebvre H. Effect of Weld Quality and Post Weld Improvement Techniques on the Fatigue Resistance of Extra High Strength Steel. IIW Doc. XIII-2184-07; 2007.

[15] Pedersen MM, Mouritsen OØ, Hansen MR, Andersen JG, Wenderby J. Comparison of Post Weld Treatment of High Strength Steel Welded Joints in Medium Cycle Fatigue. IIW Doc. XIII-2272-09; 2009.

[16] Sonsino CM. Effect of residual stresses on the fatigue behaviour of welded joints depending on loading conditions and weld geometry. International Journal of Fatigue 2009; 31: 88-101.

[17] Martinez LL, Lin R, Wang D, Blom AF. Investigation of Residual Stresses in As-Welded and TIG-Dressed Specimens Subjected to Static/Spectrum Loading.

ACCEPTED MANUSCRIPT

Proceedings of the North European Engineering and Science Conference, (NESCO) : "Welded High-Strength Steel Structures". Stockholm, Sweden; 1997.

[18] Huo L, Wang D, Zhang Y. Investigation of the fatigue behaviour of the welded joints treated by TIG dressing and ultrasonic peening under variable-amplitude load. International Journal of Fatigue 2005; 27: 95-101.

[19] Haagensen PJ. IIW's Round Robin and Design Recommendations for Improvement Methods. Proceedings of the IIW 50th Annual Conference. San Francisco, USA; 1997, p. 74-97.

[20] Zhao X, Wang D, Huo L. Analysis of the S–N curves of welded joints enhanced by ultrasonic peening treatment. Materials and Design 2011; 32: 88–96.

[21] Haagensen PJ, Maddox SJ. IIW Recommendations on Post Weld Improvement of Steel and Aluminium Structures. IIW Doc. XIII-1815-00; 2004.

[22] Statnikov ES. Guide for Application of Ultrasonic Impact Treatment Improving Fatigue Life of Welded Structures. Proceedings of the 52nd Annual Assembly of the International Institute of Welding. IIW Doc. XIII-1757-99. Lisbon, Portugal; 1999.

[23] Hobbacher AF (editor). Recommendations for Fatigue Design of Welded Joints and Components. IIW Doc. IIW-1823-07; 2008.

[24] Hobbacher AF. The new IIW recommendations for fatigue assessment of welded joints and components – A comprehensive code recently updated. International Journal of Fatigue 2009; 31(1): 50-58.

[25] Hobbacher AF. New developments at the recent update of the IIW recommendations for fatigue of welded joints and components. Steel Construction 2010; 3(4): 231-242.

[26] DNV-RP-C203 (2010) Recommended Practice For Fatigue Design Of Offshore Steel Structures. DET NORSKE VERITAS; April 2010.

[27] Barsoum Z, Jonsson B. Influence of weld quality on the fatigue strength in seam welds. Engineering Failure Analysis 2011; 18(3): 971-979.

[28] Marquis G. Advances in fatigue assessment methods for welded structures. Proceedings of the Swedish Conference on Light Weight Optimized Welded Structures. Borlänge, Sweden; March 24-25, 2010, p. 108-121.

[29] EN-25817. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) - Quality levels for imperfections. European Committee for Standardization; 1993.

ACCEPTED MANUSCRIPT

[30] SS-EN ISO 5817. Welding-fusion-welded joints in steel, quality levels for imperfections, ISO 5817. Swedish standard; 2004.

[31] Hobbacher A. Problems of Effect of Weld Imperfections on Fatigue and their Consideration on Design Codes. Steel Structures 2006; 6: 289-298.

[32] Volvo Group weld quality standard, STD 181-0004; 2008.

[33] Jonsson B, Samuelsson J. A new weld class system. IIW Doc. IIW-XIII-2235-08; 2008.

[34] Fisher JW, Dexter RJ. Weld Improvement for Fatigue Life Extension. Proceedings of the International Conference of Fatigue. Toronto, Canada; 9-10 May, 1994, p. 82-87.

[35] Miki C. Repairing and reinforcing of fatigue damaged steel bridges. Proceedings of the International Conference on Performance of Dynamically Loaded Welded Structures, IIW 50st Annual Assembly Conference. San Francisco, USA: publ. Welding Research Council; July 1997, p. 286-298.

[36] Fisher JW, Dexter RJ. Field experience with repair of fatigue cracks. Proceedings of the International Conference on Fatigue. Toronto, Canada: publ. AWS; 9-10 May, 1994, p. 45-52.

[37] Fisher JW, Statnikov ES, Tehini L. Fatigue Strength Enhancement by Means of Weld Design Change and the Application of Ultrasonic Impact treatment. Proceedings of the International Symposium on Steel Bridges. Chicago, USA; 2001.

[38] Zhao X-L, Herion S, Packer JA, Puhtli RS, Sedlacek G, Wardenier J, Weynand K, van Wingerde AM, Yeomans NF. Design Guide For Circular And Rectangular Hollow Section Welded Joints Under Fatigue Loading. CIDECT Editions. Germany: TÜV-Verlag; 2001.

[39] Connor RJ, Dexter R, Mahmoud H. Inspection and Management of Bridges with Fracture - Critical Details. NCHRP Synthesis 354. Washington DC, USA: NCHRP; 2005.

[40] Dexter RJ, FitzPatrick RJ, St. Peter. DL.SSC-425 (2003) Fatigue Strength And Adequacy Of Weld Repairs. Washington DC, USA: SHIP STRUCTURE COMMITTEE; 2003.

[41] Branco CM, Infante V, Baptista R. Fatigue behaviour of welded joints with cracks, repaired by hammer peening. Fatigue Fract Engng Mater Struct 2004; 27(9): 785-798.

[42] DIN 17100. Steels for General Structural Purposes. Deutsches Institut fur Normung E. V.; 1980.

ACCEPTED MANUSCRIPT

[43] EN 10002-1. Metallic materials – Tensile testing – Part 1: Method of testing (at ambient temperature). European Committee for Standardization; 2001.
[44] Ferreira JM, Pereira AH, Branco CM. A fracture mechanics based fatigue life prediction for welded joints of square tubes. Thin Welded Structures 1995; 21: 107-120.
[45] Martins RF. Application of probabilistic fracture mechanics of fatigue of welded structures. MSc thesis, Technical University of Lisbon, IST; April 1999.
[46] Berge S. On the effect of plate thickness in fatigue of welds. Engineering Fracture Mechanics 1985; 21(2): 423-435.

Figure captions

Fig. 1 – Geometry of the specimens; Three point bending fatigue tests.
Fig. 2 – Profile of welded joints. a) TIG dressed b) plasma dressed.
Fig. 3 – S-N curves and confidence limits. a) AW series. b) TAS series. c) TDR series. d) PDR series.
Fig. 4 – Microstructures. a) Base metal. (Magn. 620x.) b) TAZ in TIG dressed specimens. (Magn. 620x.). c) TAZ in plasma dressed specimens (Magn. 620x.).
Fig. 5 – Longitudinal and transversal hardness profile a) TIG dressed. b) PDR series.
Fig. 6 – Longitudinal residual stresses versus distance from the weld toe. a) AW series. b) TIG dressed. c) PDR series.
Fig. 7 – Surface fracture aspect of rehabilitated joints. a) TIG dressed. b) and c) PDR series.
Fig. 8 – Scanning microscopy observations of surface fracture. a) Base metal. b) Near surface of plasma dressed zone. c) Inner of plasma dressed zone.
Fig. 9 – Gain parameter versus the repaired crack depth (PDR series).
Fig. 10 – Instrumented specimen for detect initiation of fatigue cracks from the weld toe.
Fig. 11 – Detection of shallow fatigue cracks in weld toe, associated to the increment of strain.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 1

Chemical composition of the steel St52-3 (percentage in weight).

C	Si	Mn	Cr	Mo	Ni	Ti	Al	V	Cu	Co	Nb	P	S
0.131	0.413	1.44	0.063	0.024	0.034	0.009	0.029	0.043	0.018	0.013	0.005	0.011	0.005

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 2

Chemical composition of the weld material (percentage in weight).

C	Si	Mn	Cr	Ni	Mo	P	S
0.08	0.45	1.28	0.5	1.87	0.37	0.017	0.01

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 3

TIG and plasma dressing parameters.

TIG dressing	Plasma dressing
Argon flux;	Argon flux;
Current intensity – 110 A;	Current intensity – 200 A;
Tension DC – 19 V;	Tension DC – 30 V;
Linear rate -1.08 mm/s.	Linear rate –2.47 mm/s.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 4

Parameters of S-N median curves equations $\Delta\sigma = K_0 N_r^m$ (R is the correlation coefficient).

Série	K_0	m	R
AW	4848.6	- 0.210	0.943
TAS	5817.1	- 0.224	0.967
TDR	3744.5	- 0.236	0.963
PDR	5566.2	- 0.233	0.835

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 5

Statistical parameters of weld toe radius [mm].

Series	Mean value	Standard deviation
AW	4.11	1.23
TIG dressed	6.25	1.99
PDR	2.25	1.73

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 6

Experimental and predicted values used to the definition of gain parameter.

Specimen	a_{reab}	$\Delta\sigma$	N_p	N_{exp}	N'_{reab}	G
PDR2	2.20	203.4	16843	3504512	1185720	1.33
PDR3	5.18	176.6	1487	6858123	988050	1.14
PDR4	4.83	226.7	1007	2093198	615786	1.29
PDR5	5.43	294.4	310	604693	127110	1.21
PDR6	4.74	289.1	617	659213	550079	1.83
PDR7	5.90	346.5	134	278782	311338	2.12
PDR8	5.06	349.8	279	266504	178495	1.67
PDR9	3.63	237.1	2583	1691387	1482055	1.87
PDR10	5.80	393.0	116	153245	116388	1.76
TDR1	6.50	354.2	60	251134	22680	1.09
TDR2	5.10	151.2	2209	14343932	329711	1.02
TDR3	4.80	204.7	1402	3400004	361890	1.11
TDR4	5.40	122.0	2948	39765559	1998624	1.05
TDR5	5.90	143.9	1269	18146433	691645	1.04
TDR6	4.70	235.5	1043	1746694	159236	1.09
TDR7	4.83	293.3	532	615546	61808	1.10
TDR8	4.35	182.8	2535	5820975	521075	1.09
TDR9	4.72	177.1	2097	6766601	582198	1.09
TDR10	6.90	228.1	118	2032848	92327	1.05

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

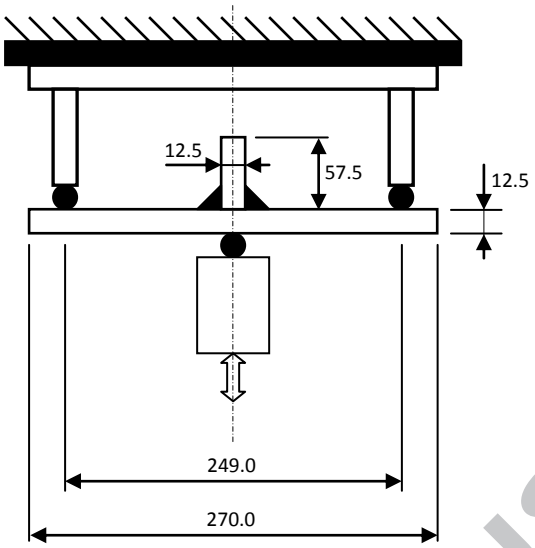
Table 7
New TIG dressing parameters.

New TIG dressing
Argon flux
Current intensity – 135 A;
Tension DC – 15 V;
Linear rate -0.66 mm/s.

ACCEPTED MANUSCRIPT

Figure 1

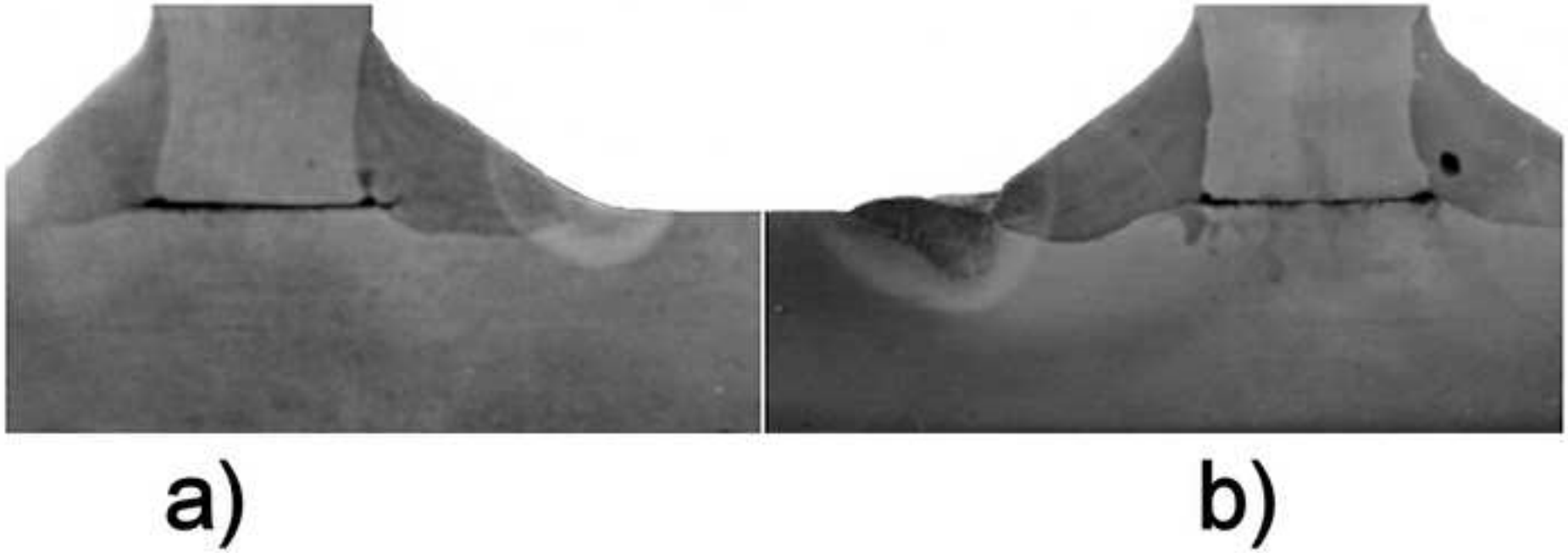
ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT

Figure 2

ACCEPTED MANUSCRIPT



ACCEPTED

Figure 3

ACCEPTED MANUSCRIPT

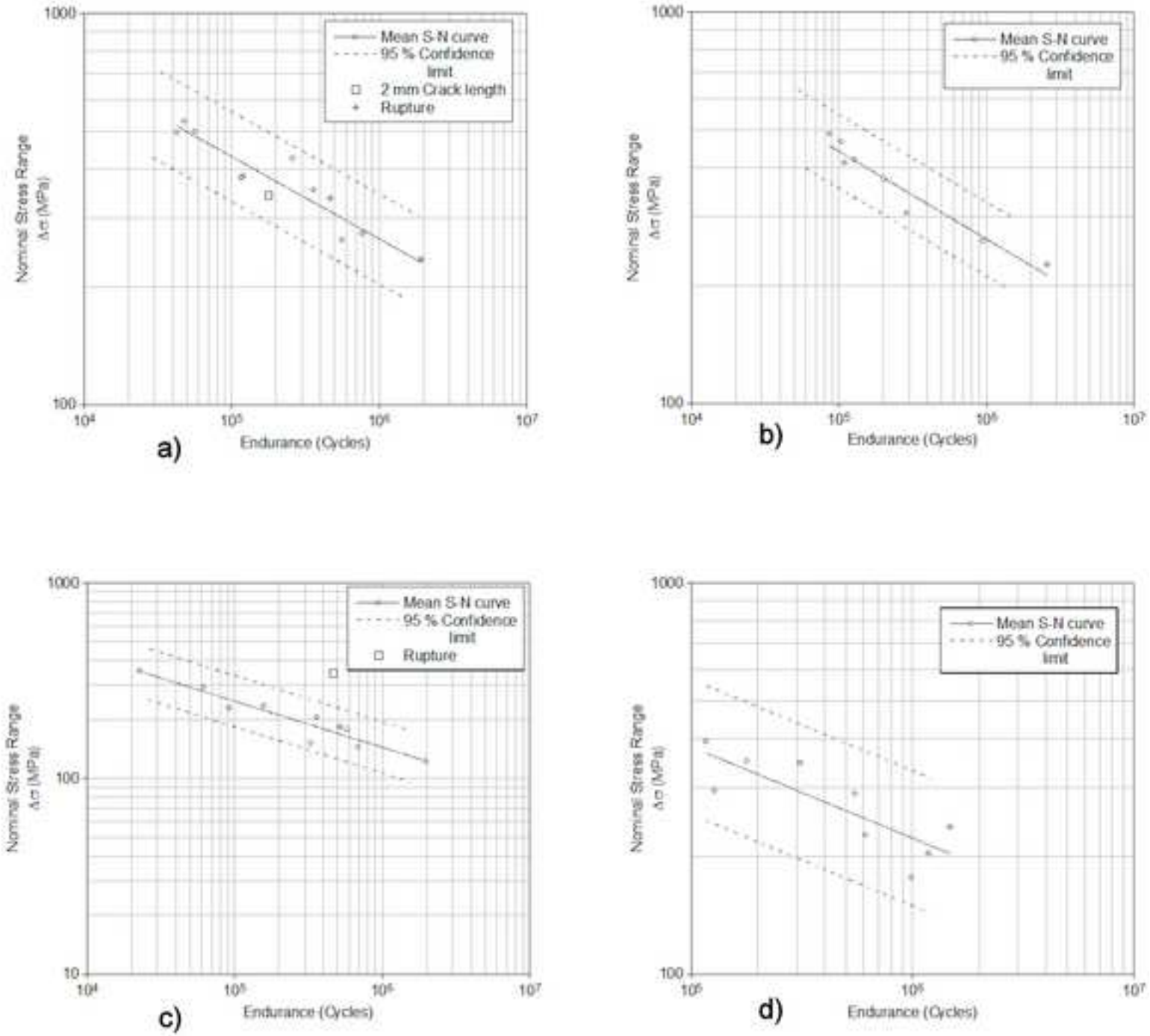
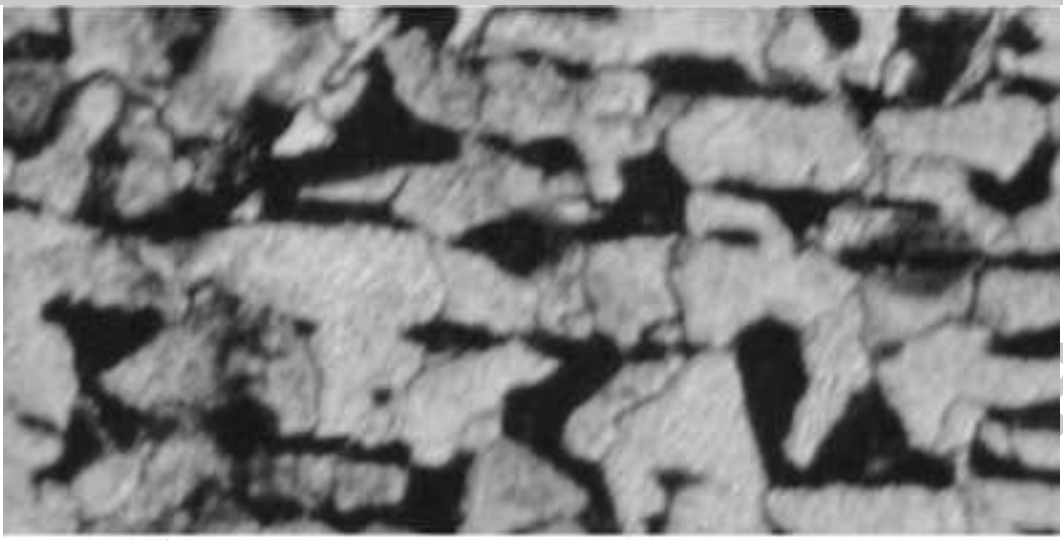
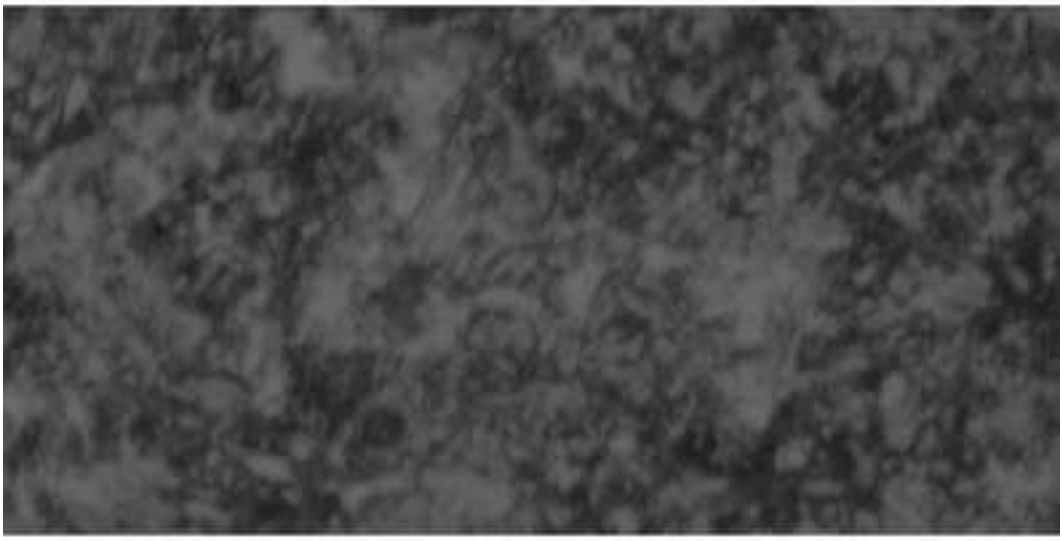


Figure 4

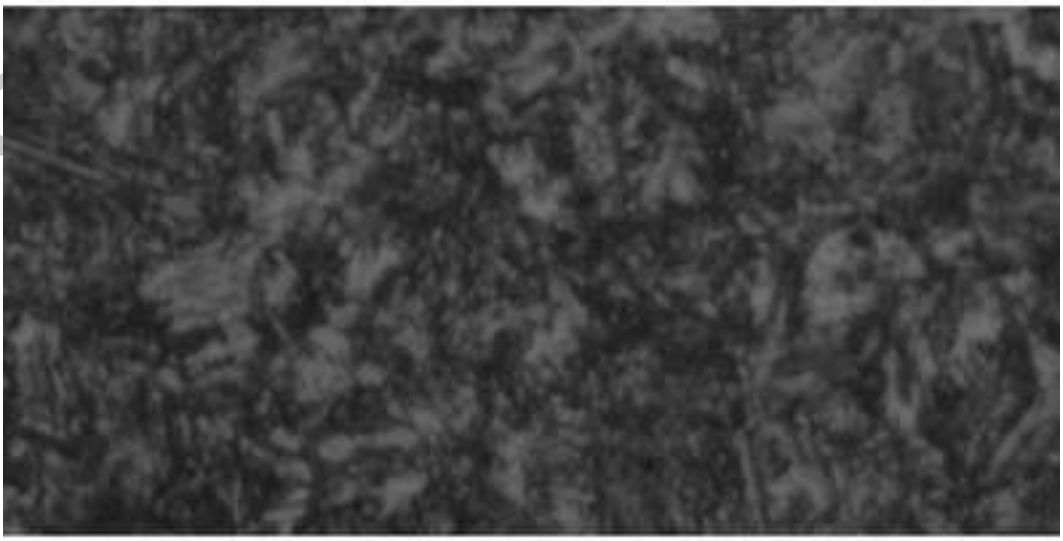
ACCEPTED MANUSCRIPT



a)



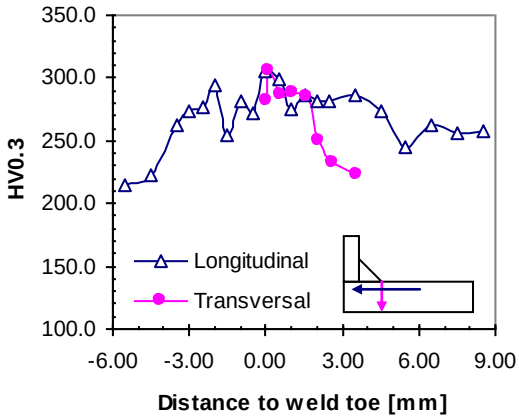
b)



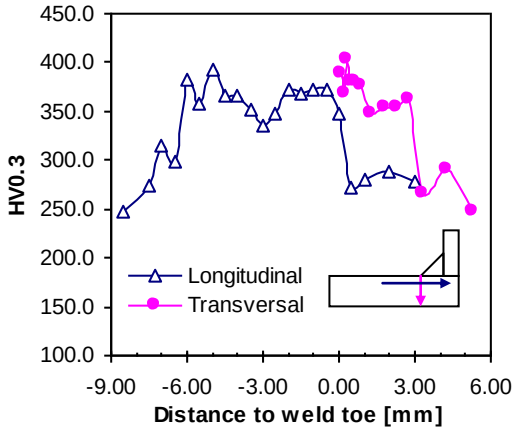
c)

Figure 5

ACCEPTED MANUSCRIPT



a)

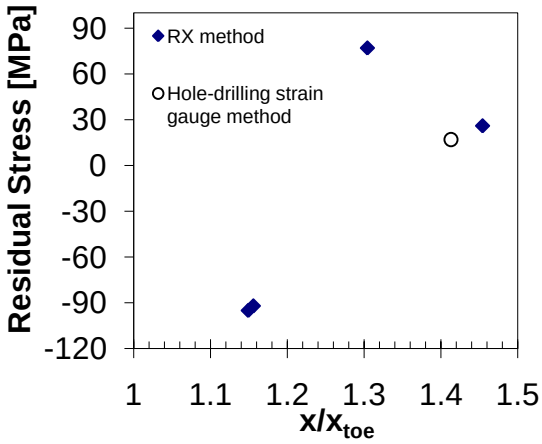


b)

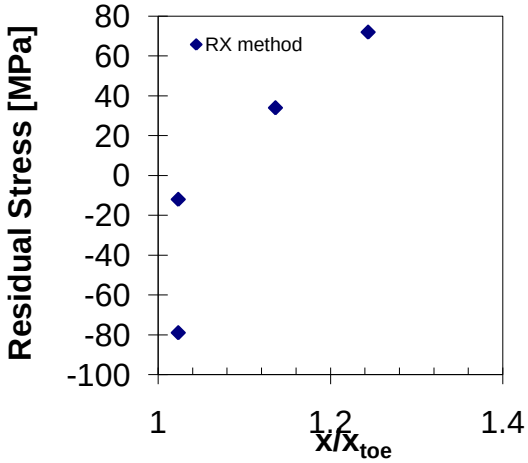
ACCEPTED MANUSCRIPT

Figure 6

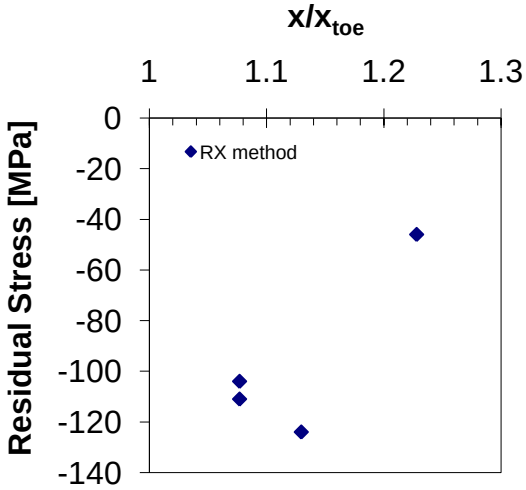
ACCEPTED MANUSCRIPT



a)



b)



c)

Figure 7

ACCEPTED MANUSCRIPT

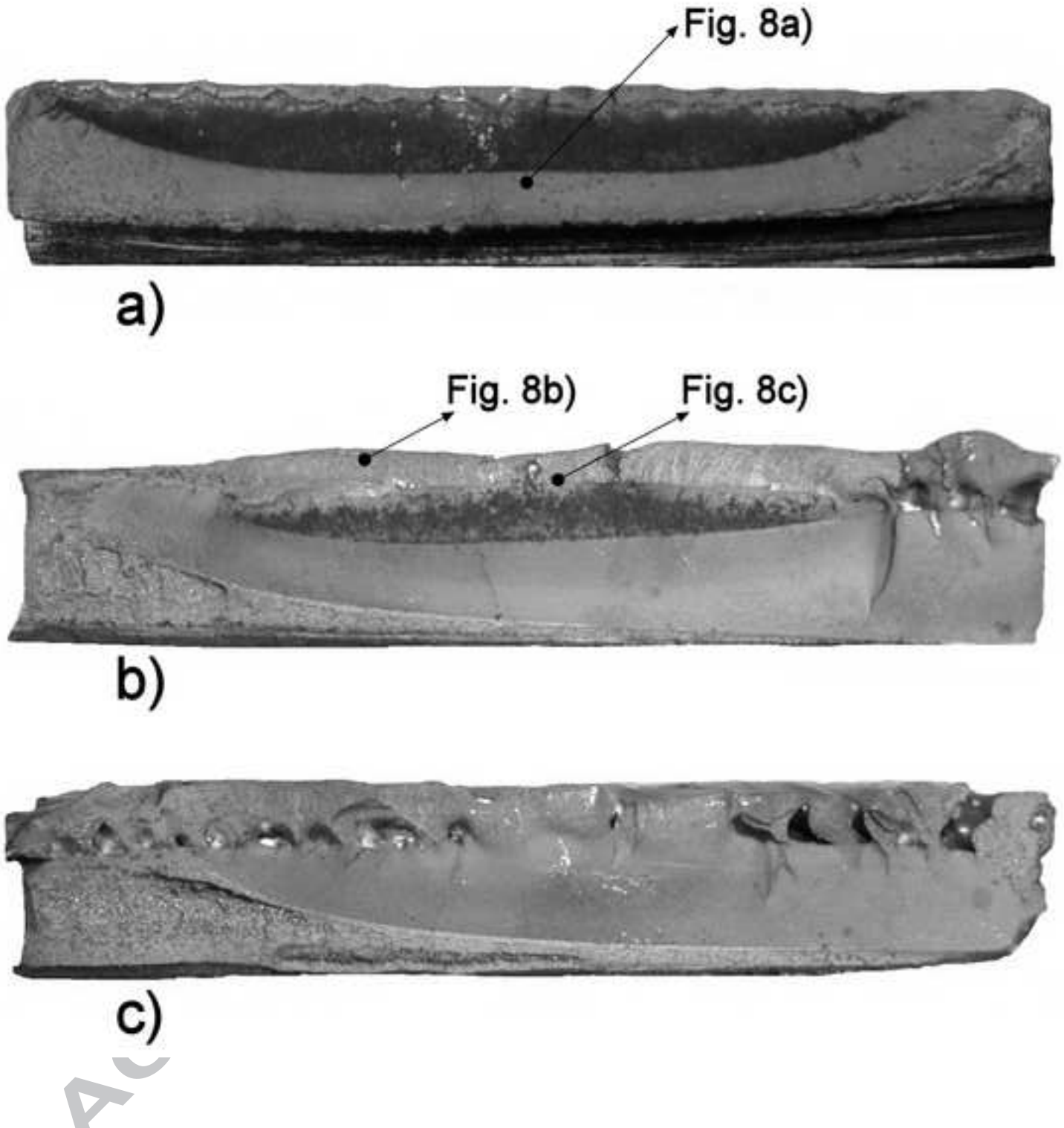
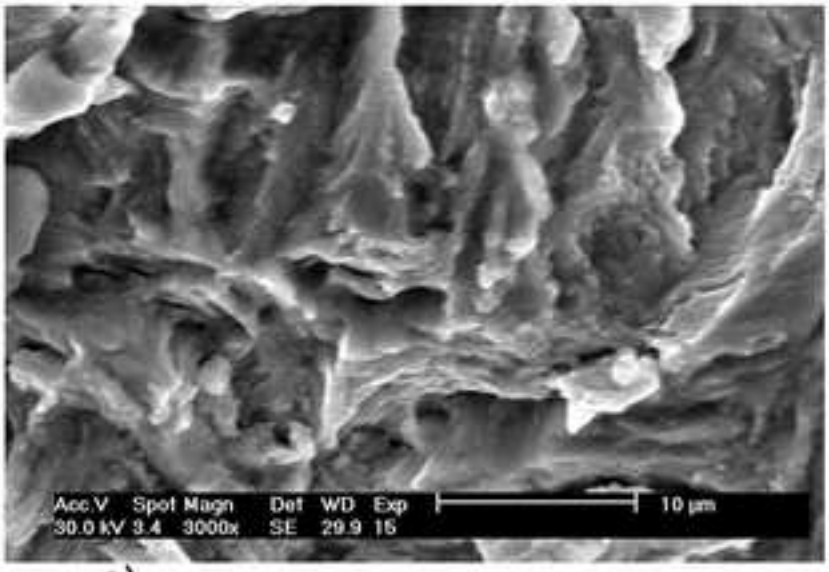
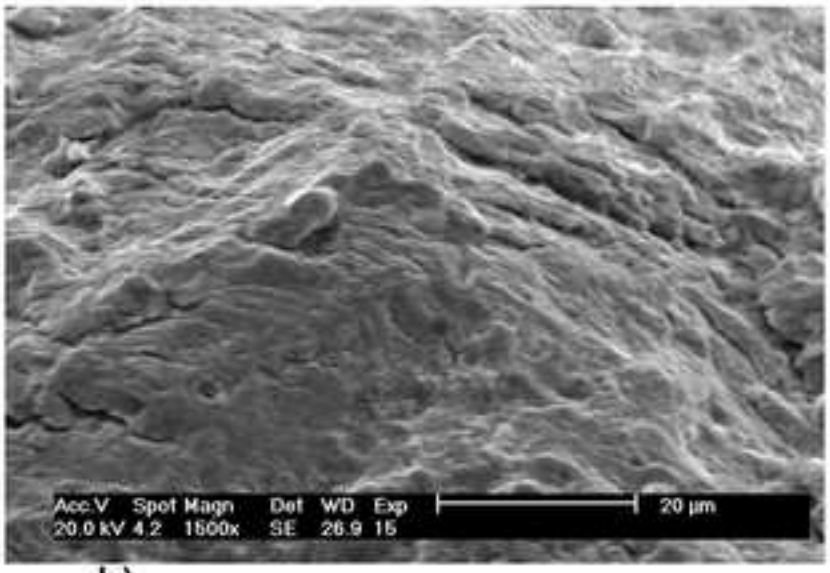


Figure 8

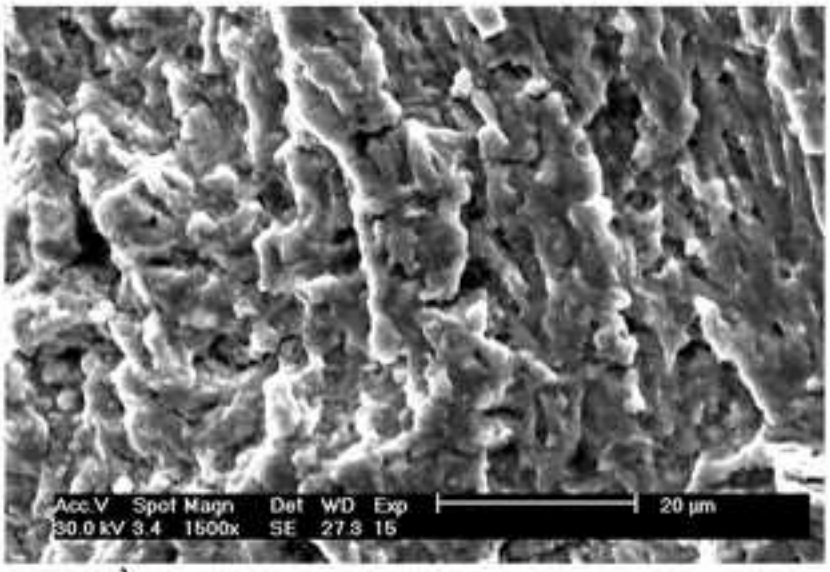
ACCEPTED MANUSCRIPT



a)



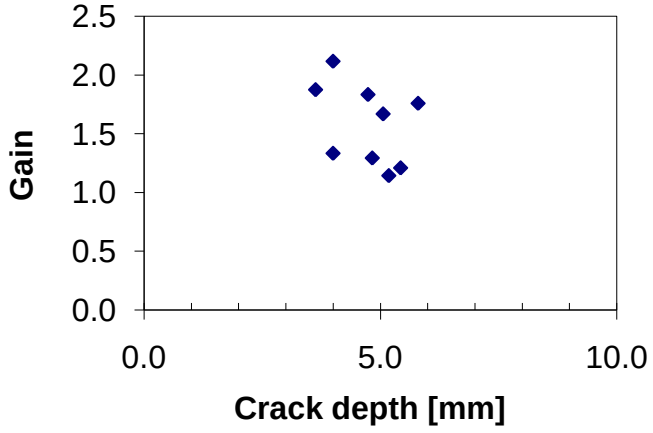
b)



c)

Figure 9

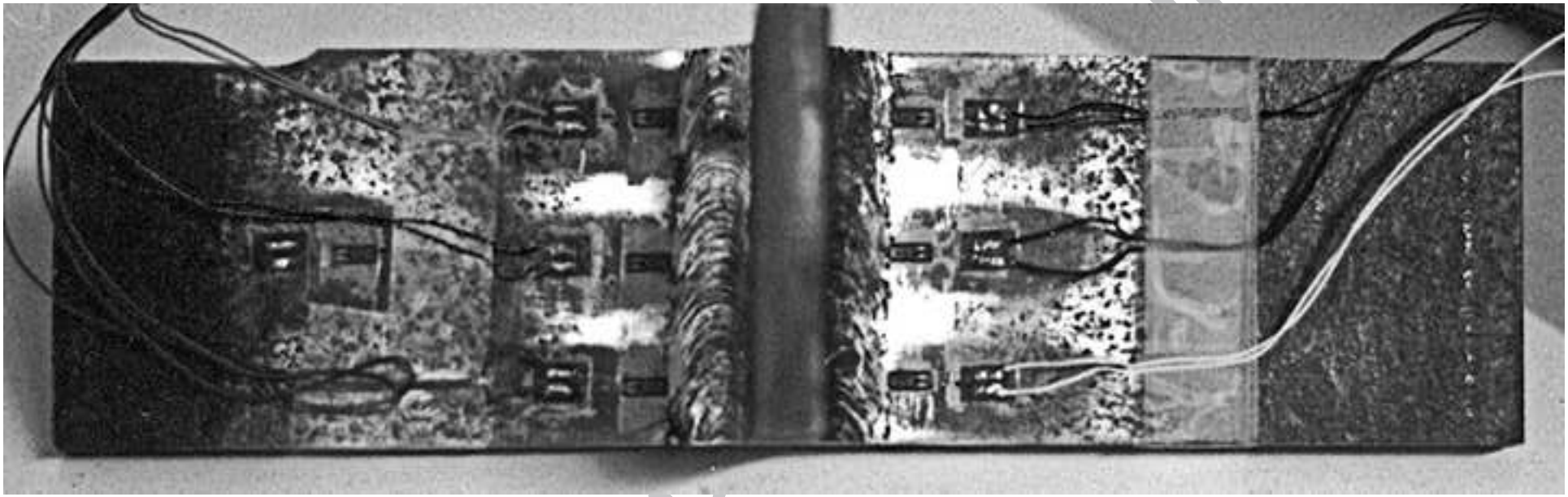
ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT

Figure 10

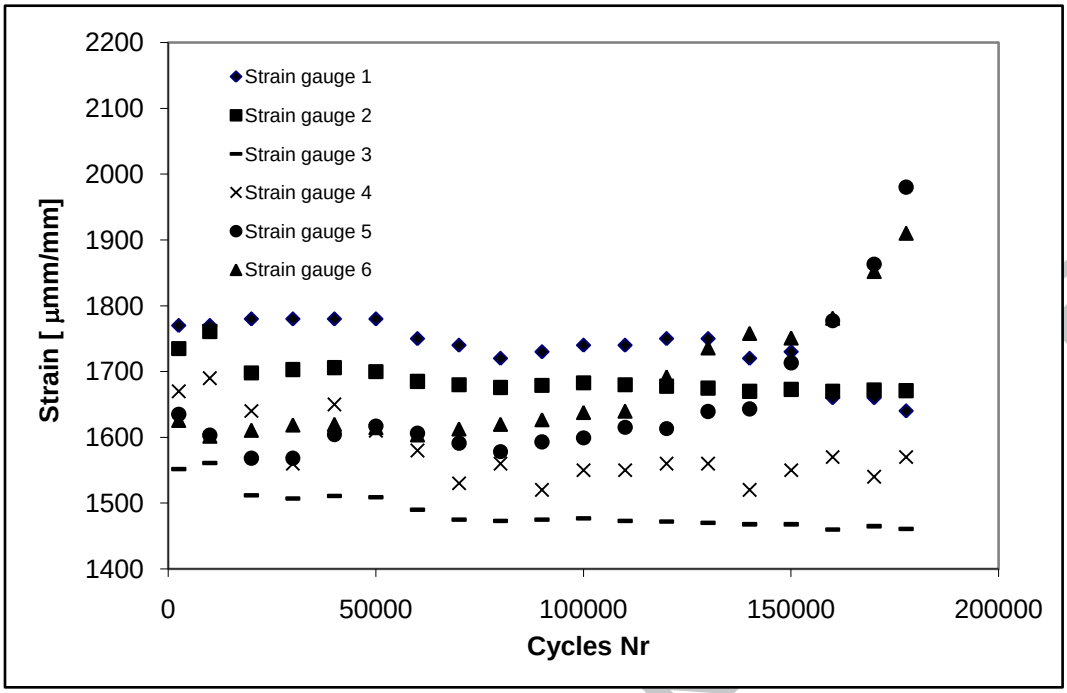
ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT

Figure 11

ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

- This study addresses the use of improvement techniques for repair T welded joints.
- TIG and plasma arc re-melting are applied in joints with fatigue cracks at weld toes.
- Plasma dressing provides reasonable repair in joints with cracks greater than 4 mm.
- TIG dressing produces a deficient repair in joints with cracks greater than 4 mm.
- TIG dressing provides good repair in joints with fatigue cracks lesser than 2.5 mm.

ACCEPTED MANUSCRIPT