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Some considerations about fatigue failure in milled butt-welded joints affected by residual stress[†]

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Abstract

Many factors are involved in determining the fatigue strength of welded joints. It is, however, very difficult to consider their relative importance. The aim of this paper is to isolate the effect of residual stress from other factors, establishing a relation between the amount of residual stress and fatigue life. A geometrical notch due to the weld bead is removed by milling the upper surface of the welded plates. Moreover, specimens are subjected to four-point bend loading. Before conducting the fatigue test, the magnitude of residual stress for each specimen is experimentally evaluated, and then linked to the number of cycles to failure. This relation is analyzed for three different plate thicknesses and for different stress amplitude levels in the high cycle regime. The results clearly show the significant influence of residual stress on fatigue behaviours when the load level is near the fatigue limit.

Keywords: Fatigue; Milling; Residual stress; Welded joints

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1. Introduction

Fatigue failure originates from a local phenomenon on the more stressed zones of a component. The presence of geometrical and material heterogeneities increases the probability of crack initiation and produces lower fatigue strength in components. The fatigue phenomenon is well-known and has been studied extensively [1, 2], but experimental results are often inconsistent. In practice, there is no consensus about a methodology to forecast with a sufficient reliability the number of cycles leading to the failure of a component. It is more convenient to evaluate a probabilistic fatigue life and consider an appropriate safety factor for the component design. In this manner, designers neglect to consider all the local phenomena, which will determine the real fatigue life of materials, and the vague factors are interpreted as the source of the statistical variability of fatigue tests.

A deeper understanding of the fatigue phenomenon requires the identification of all the local factors affecting fatigue behaviour. An important factor to be considered is the presence of residual stress. From a qualitative point of view, the effect of residual stress has been acknowledged and analyzed theoretically [3-8]. Tensile residual stress encourages local plasticization and subsequent crack initiation and propagation, while compressive residual stresses are often beneficial. In fact, mechanical superficial treatments (e.g., shoot-peening and other cold working processes), which introduce compressive residual stresses to the superficial layers of components, are used to improve fatigue strength.

The qualitative effects of residual stress are well documented, although it is very difficult to derive a quantitative relationship between the amount of residual stress and the number of cycles to failure. This negative outcome is due to the presence of confounding factors. In the case of welded joints, the factors influencing the fatigue life have been clearly identified and are qualitatively understood [9-12]. The definition of global and local joint geometries of welded material behaviour, however, is often arbitrary. In fact, the shape of the weld seam is very far from being a regular and geometrical one, resulting in a difficult definition and evaluation of the associated stress concentration factor.

Moreover, heating, fusion, and the subsequent cooling of welded material strongly change its mechanical and metallurgical properties and structure, aside from introducing a residual stress field and distortions. Pores, inclusions, undercut, and cracks also often affect welded joints. Nevertheless, it is very difficult to consider the relative importance of each factor in determining the fatigue life of a weld. These factors are present all at the same time and it is often impossible to tell them apart. In particular, the effects of a residual stress induced by welding are accumulated and mixed with all other aspects.

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This paper analyzes the effects of residual stress on the fatigue life of welded joints. In particular, butt-welded joints subjected to bending load in the direction orthogonal to the weld line are considered. The aim is to give an interpretation of the fatigue behaviour of particular welded specimens, trying to isolate the effect of the residual stress from the others. The leading objective is to interpret, at least partially, the large variation in the data on welded joint fatigue by considering the presence of different levels of residual stress fields. As explicitly reported in the literature [13], the influence of residual stress on the fatigue life of welded joints is inconsistent; specifically, some studies show the existence of an alteration of the fatigue behaviour of welded parts, while other studies show no effect [14-16]. Furthermore, other works by the authors [17-21] do not allow a reliable clarification of the problem. It is, in general, true that, qualitatively, the effects depend on the relationship between residual and applied stress. If the applied stress is relatively high, the residual stresses are expected to be quickly relaxed and relatively unimportant, while an applied stress near the fatigue limit will exacerbate the effects of the residual stress.

A detailed account of the choice of specimens and testing method considered in this research is provided below. The effect of residual stress on the fatigue strength of a welded joint is simply evaluated by comparing the Wöhler curves of as-welded and thermally relaxed joints. This methodology, however, is problematic in that it changes the metallurgical properties of the stress-relieved welded joints. Hence, fatigue tests remain influenced by weld bead geometry, distortion, and changes in metallurgical structure. In particular, the effects of weld bead geometry and distortions are not eliminated. This is a serious problem because it does not permit a correct comparison of fatigue curves in order to identify the effect of residual stress on fatigue.

In order to overcome these limitations, we implement the fatigue tests on specific specimens with the following characteristics:

- Absence of geometrical discontinuities in the weld seam

These discontinuities are eliminated by means of milling that removes a 2-mm thick layer on the weld plate. Hence, fatigue tests will not be influenced by the notch on the weld seam. It is also important to note that the resulting residual stress field is altered after machining with respect to as-welded joints [22-29]. This is numerically shown in the literature [20]. This fact does not influence the aim of the experimental work, which is completely devoted to the evaluation of residual stress effects on fatigue. In other words, welding is utilised as a means of introducing a residual stress field in a plate.

- Implementation of the tests with four-point bending

Distortions and misalignments are always present in welded joints, and the application of a uniform tensile stress is often associated with spurious bending stress. Four-point bending changes the specimen curvature independently of the initial specimen configuration, thus assuring the correct application of the desired nominal stress amplitude.

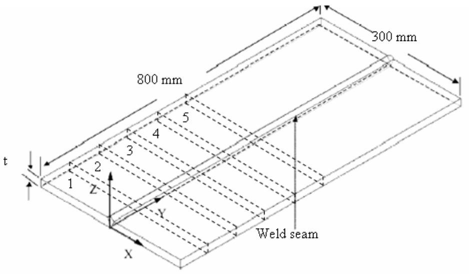


Fig. 1. Geometry of welded plates and transversal joints.

Another problem is identified by the evaluation of the residual stress field. In general, measurement methodologies allow only discrete and limited knowledge (in few points) of residual stress. This problem is empirically approached in two ways, namely, the hole drilling method and X-ray diffraction. In this paper, the hole-drilling method is preferred because it supplies a macro-stress at different depths. A single measurement point is used and is considered representative of the amount of residual stress in the critical region. As far as the choice of this region is concerned, the correct zone from a theoretical point of view would be one that corresponds to the weld toe, where experimental fatigue cracks nucleate. Unfortunately, this choice is very difficult to apply on a milled surface, where it is not so easy to localize the weld toe exactly. Moreover, the introduction of the notch constituted by a blind hole in the weld toe zone could provoke a remarkable alteration in fatigue behaviour. For these reasons, the measurement point is chosen in the geometrical centre of the weld line. This assumption would seem arbitrary, but it allows the comparison of quantitatively and effectively different welded joints and establishes the residual stress severity affecting each joint.

From a practical point of view, we carry out analysis for three different plate thicknesses (i.e., 8, 12, and 20 mm) and for different stress amplitude levels in a high cycle regime.

The experimental plan described above is, in our opinion, best suited to isolate the residual stress from other effects. However, a certain number of factors, which are intrinsic to the welded joints, cannot be eliminated, such as the presence of defects and heterogeneities in the weld material, changes in the metallurgical structure, and, in general, all the transformations induced by thermal cycle of a weld process. This means that the results can be imputed to the residual stress field only as long as these other factors can be considered negligible.

2. Geometry and methods

The study is performed on low-carbon steel Fe430 transversal welded joints obtained from plates of three different thicknesses (i.e., 8, 12, and 20 mm) as represented in Fig. 1. Mechanical properties of the Fe430 are reported in Table 1. The Fe430 is a hot-rolled structural steel of the Italian Standard CNR-UNI 10011 simply identified by its Ultimate Tensile Strength and widely used in mechanical structures. The orientation of the welding cord with respect to the rolling direction

Table 1. Mechanical properties of Fe430.

Yield Stress [N/mm^2]	Ultimate Tensile Strength [N/mm^2]	Elongation at break [%]
275	430	≥ 21

was not specified. A gas tungsten-arc welding having a maximum power of 15 kVA and a welding speed of v = 0.01275 m/s is used. For the 8 and 12 mm thick plates, single-pass welding is used, whereas for the 20 mm thick plate, two-pass welding is applied without a cooling interval.

After welding, each plate goes through a milling process to remove a 2-mm thick layer in order to eliminate discontinuity and stress concentration effects caused by the weld seam.

Mechanical tooling alters the previous stress distribution. A numerical model for the prediction of the modifications produced in the residual stress field is discussed extensively in literature [20]. In this paper, the authors show that peak values of longitudinal residual stress are reduced by about 50%, and that they are localized in the Heat Affected Zone. Stress redistribution due to milling has a relevant effect on the weld cord, which is now subjected to compressive stress. Finally, each plate is cut to obtain ten transversal welded joints that are 80 mm wide. This width is sufficiently high to neglect significant changes in transversal residual stress distribution. It was numerically shown in literature [20] that cutting the transversal joints, starting from the whole plate, does not alter stress distribution, but further reduces peak values.

In order to evaluate the influence of a residual stress field on fatigue resistance, it is necessary to determine the magnitude of the residual stresses. For this purpose, the residual stress field was experimentally determined by means of the hole-drilling method. This methodology is implemented according to ASTM E 837-01 standards. The diameter and depth of the hole are 1.6 mm and 2 mm, respectively, and subdivided in 40 steps. A vertical motion of 0.05 mm/min and a HBM strain gauge rosette named 1.5/120RY61S are used. Such incremental hole drilling allows the measurement of non-uniform residual stresses in the respective thickness, that is, the residual stress dependence against depth is calculated using the power series method [30-31]. The correction of the residual stresses that exceed one half of the yield stress was carried out based on literature [32].

The measurement point is localized in the centre of the weld and coincides with the geometrical centre of each joint obtained by cutting the milled plate.

The experimental work can be summarized as follows:

Step 1. Measurement of the residual stress field in the geometrical centre of each specimen;

Step 2. Selection of the fatigue load to be applied to each specimen (two or three different stress amplitudes) repeated at least for 3 times; and

Step 3. Fatigue test from four-point bending up to rupture (about 10^7 cycles for run-out specimens).

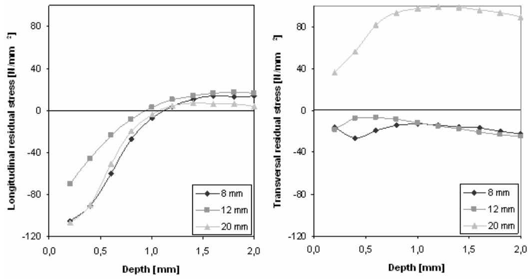


Fig. 2. Residual stress distribution on the weld axis for milled plates.

3. Results and discussions

Before cutting the specimens, we implemented a series of preliminary residual stress measurements over all milled plates in the geometrical centre of Specimen 5. The longitudinal stress is referred to as a direction parallel to the weld axis, while transversal stress indicates a stress in the direction normal to the welding axis. Fig. 2 reports the residual stress distribution versus depth in milled plates. It can be observed that the longitudinal residual stress on the specimen surface is compressive for all the three plates. This behaviour is very different from that originating from the welding process, where a high tensile residual stress is always present near the weld seam, as well-known in literature [9-11]. Fig. 2 shows an evident alteration due to the milling process; the longitudinal residual stress near the weld bead was highly compressive on the surface and decreased up to 1 mm in depth when it reached a constant positive value. This behaviour was common to the three thicknesses. The transversal residual stress field was quite low for the 8 and 12 mm thick plates, while it was tensile and relevant for the 20 mm thick plate.

In Figs. 3-5, for each thickness, the comparison between the longitudinal and transversal residual stress distribution for the milled plates and for transversally cut joints is shown. The longitudinal residual stress field was qualitatively similar for all cases, specifically, it was fully compressive in the thickness, but it was different for each case from a quantitative point of view. In particular, the longitudinal stress field varied in the range between -20 and -260 N/mm^2, depending on the thickness. Only Specimen 9, having a 12 mm thickness, showed an irregular and different behaviour. The transversal residual stress field was quite consistent in all cases and was characterized by a relatively low magnitude, both in traction and in compression. This field reached absolute values of about 50 N/mm^2. Plate thickness influenced the mean value of transversal residual stress, that is, curves representing transversal stress distribution against depth were close to zero stress for the 8 mm and 12 mm joints and were in the tensile zone for the 20 mm thick joints. This is compatible with the well-known observation that thin welded joints are preferably affected by distortions and misalignments, while thicker joints are affected by higher residual stress field [9]. The transversal residual stress also changed considerably between adjacent specimens, suggesting that differences observed were due to

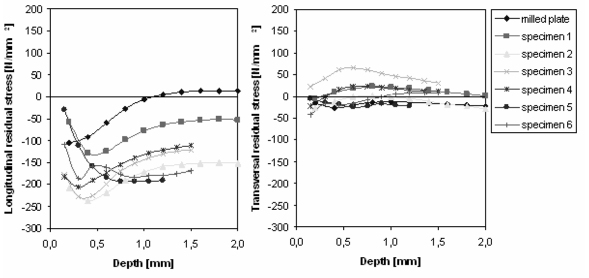


Fig. 3. Residual stress distribution on the weld axis for milled plates and transversal joints 8 mm thick.

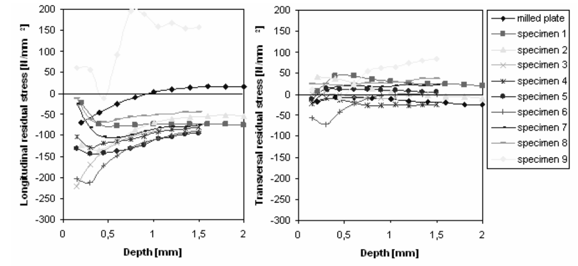


Fig. 4. Residual stress distribution on the weld axis for milled plates and transversal joints 12 mm thick.

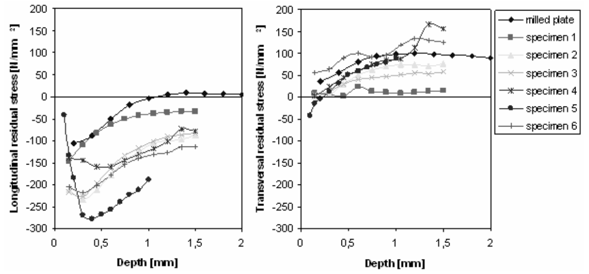


Fig. 5. Residual stress distribution on the weld axis for milled plates and transversal joints 20 mm thick.

high variability inherent to the residual stress phenomenon. In the case of the 20 mm thick plate, the transversal residual stress field was always tensile, and in some cases, it showed a higher magnitude with respect to the lower thickness.

In order to relate fatigue life with residual stress acting on a specific specimen, we needed to summarize the detailed residual stress distribution presented before into a simple and reliable indicator of the residual stress severity. Since the applied stress due to bending is distributed linearly in the thickness, the maximum stress is localized in the tensile surface of the specimen, and fatigue crack nucleation interests this surface, the residual stress field that must be considered is on the specimen surface. More exactly, considered layer is referred to 0.2 mm depth that is the minimum depth compatible with reliable residual stress evaluation.

A four-point bend loading mode was used to carry out the fatigue tests (Fig. 6). About 15-20 specimens per thickness were available. Some specimens were used exclusively to determine fatigue curves in order to select the correct load amplitude for the subsequent test.

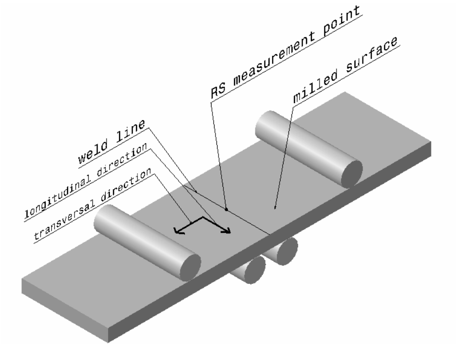


Fig. 6. Fatigue test set-up.

Residual stress measurements were carried out on the remaining specimens before the fatigue tests, which continued until failure occurred. The fatigue curves reported in Figs. 7-9 for each main plate thickness reflect all the fatigue data. The presence of the drilled holes and their associated notches did not alter the specimen failure, since all the fatigue data were consistent. In effect, only three specimens showed a fatigue failure starting from the hole, but this did not produce loss of test significance. In the other cases, failure started in a section generally close to and between internal bearings. Since fatigue cracks generally nucleate in the Heat Affected Zone rather than in correspondence with the blind hole, it is reasonable to consider that the fatigue behaviour is not influenced by stress concentrations due to the hole used for residual stress measurements. Only the fatigue behaviour of plates 20 mm thick seemed to be slightly different from the others, showing a slight reduction of fatigue limit. Two load levels were selected for the plates of 8 mm thickness. The first one corresponded to a fatigue life of about 0.5 x 10^6 cycles and the second one corresponded approximately to the reference value of 2 x 10^6 cycles, close to the fatigue limit. Because of the fatigue limit reduction when plate thickness increases, an additional load level was considered for the plate of 12 mm thickness. In the case of the plates of 20 mm thickness, only the two lower load levels were considered. The tests were carried out on a resonant testing machine RUMUL Testronic 50 kN ± 20 kN, and the load ratio was $R = \sigma_{min}/\sigma_{max} = 0.1$. For each load level, three specimens were tested. The transversal loading mode was chosen because it represented the typical and more critical working conditions of butt-welded joints. The specimens were chosen in such a manner that they were affected by different transversal residual stress levels. This was necessary in order to evaluate their effects on fatigue life. The transversal residual stress was considered as the most relevant because it was in the same direction as the applied load. Unfortunately, the magnitude of the transversal residual stress was quite low, while measurement errors in residual stress were generally large (about ± 20 N/mm^2 for residual stress equal to 100 N/mm^2 according to the standard experimental practice [33-34]). Consequently, in the interpretation of the experimental data, one needs to be cautious given the data roughness, as it often happens in residual stress measurements.

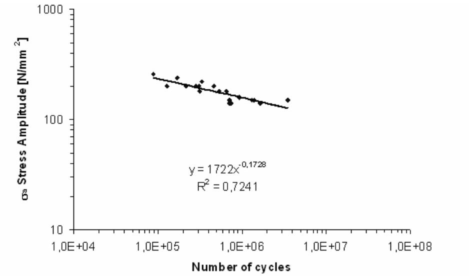


Fig. 7. Fatigue curve for 8 mm thick transversal joints.

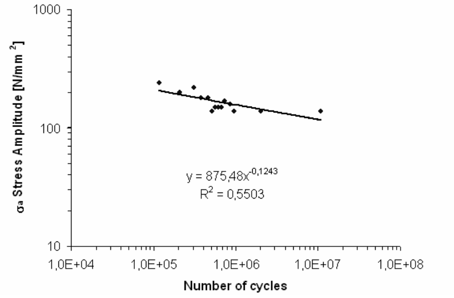


Fig. 8. Fatigue curve for 12 mm thick transversal joints.

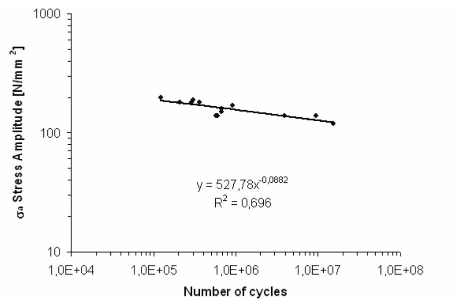


Fig. 9. Fatigue curve for 20 mm thick transversal joints.

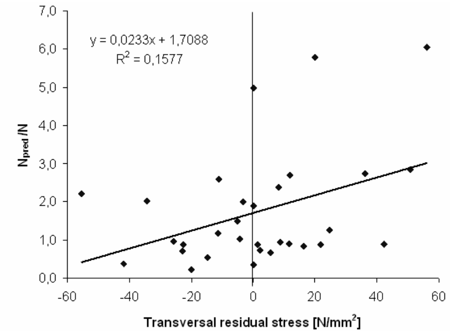


Fig. 10. Ratio of predicted and actual number of cycles to failure versus transversal residual stress.

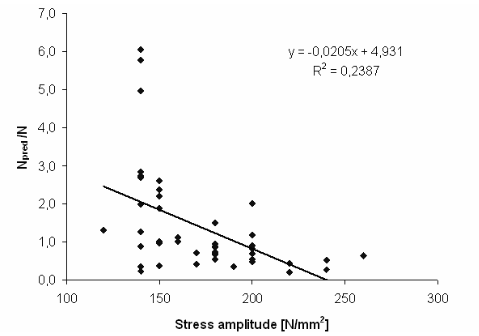


Fig. 11. Ratio of predicted and actual number of cycles to failure versus stress amplitude.

Moreover, a stress-relieved specimen was tested at the lowest load level for each thickness.

Stress-relieved specimens were obtained by thermal treatment, which consisted of slow heating to 650° C, maintenance of heat for 5 h, and then air-cooling. Since residual stress annealing is a well-established practice which has been experimentally verified in previous works, it was considered unnecessary to carry out further residual stress measurements.

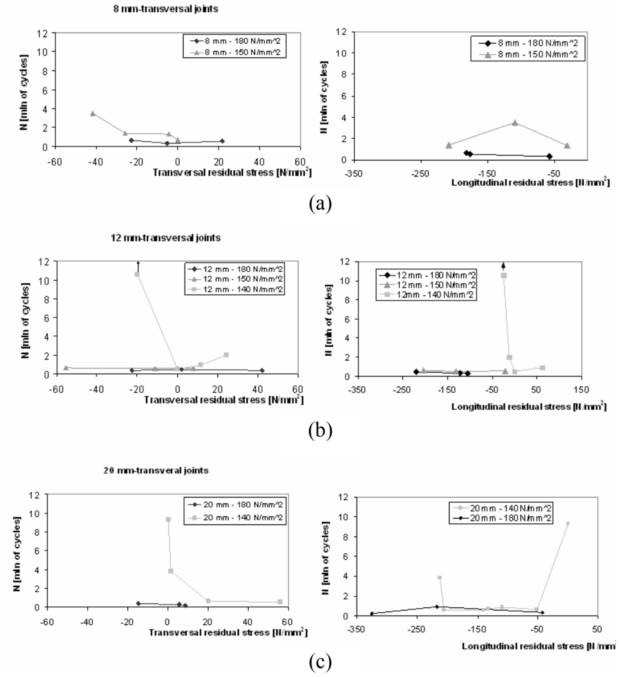
The number of cycles to failure and the measured residual stresses, expressed as longitudinal and transversal, Von Mises, and principal stresses, for each specimen are reported in Table 2. It was assumed that a zero residual stress field characterized stress-relieved specimens. Among all these indicators of residual stress severity, it was reasonable to consider transversal residual stress as the most relevant. Applied stress due to bending produces stress that acts in the same direction as the transversal residual stress. Therefore, as a first approximation, the actual uniaxial stress acting on the specimen was obtained by the superposition of external bending stress distribution and transversal residual stress. The relevance of transversal residual stress in determining fatigue behaviour could be derived by other indirect considerations. By calculating the number of cycles corresponding to the applied stress amplitude on the basis of the Wöhler line reported in Figs. 7-9, it is possible to determine the ratio of the predicted and actual number of cycles to failure, which is also reported in Table 2. This parameter was plotted versus transversal residual stress (Fig. 10) and stress amplitude (Fig. 11). Although the data scatter was quite sparse, a general qualitative tendency could be recognised, as represented by the interpolation lines shown in the graphs. The first diagram (Fig. 10) shows that the prediction error is higher when transversal residual stress increases. Moreover, the cases for which the prediction of fatigue life were very far from the experimental data occurred when a non-negative transversal residual stress was present. The second diagram (Fig. 11) shows that not only is the prediction error magnified, but the fatigue life scatter is also higher when the amplitude load is close to the fatigue limit. In other words, the prediction of fatigue life on the basis of an experimental Wöhler curve becomes less precise at stress amplitudes close to fatigue limit. This scatter increase can be explained by supposing that residual stress plays a fundamental role in determining fatigue life at low stress amplitudes.

The number of cycles to failure is plotted against the longitudinal and transversal residual stress in Fig. 12. Each diagram refers to a plate thickness and the data are grouped with respect to the applied stress amplitude. The first clear-cut result is that at higher loads, the fatigue life is not influenced by the longitudinal and transversal residual stresses,

Table 2. Residual stress and fatigue data.

Thickness [mm]	Stress amplitude [N/mm^2]	Specimen	Longitudinal residual stress [N/mm^2]	Transversal residual stress [N/mm^2]	Von Mises residual stress [N/mm^2]	Principal residual stress [N/mm^2]	Number of cycles to failure [mln]	N_{pred}/N
8	180	4	-182.1	-22.7	176.1	-19.7	0.6605	0.718
		1	-58.0	-5.1	59.6	-2.4	0.3151	1.504
		3	-176.9	21.8	199.3	28.5	0.5387	0.880
	150	6	-109.8	-41.7	98.2	-39.7	3.5190	0.387
		2	-208.5	-25.6	200.4	-23.1	1.3978	0.974
		5	-30.6	-4.3	33.4	-0.98	1.3300	1.023
		10	Stress-relieved				0.7212	1.887
12	180	4	-104.4	-22.4	111.9	-10.2	0.3779	0.890
		3	-220.1	2.1	222.9	3.3	0.4547	0.740
		2	-122.1	42.2	164.0	51.9	0.3766	0.893
	150	6	-203.8	-55.4	193.1	-46.9	0.6606	2.207
		5	-130.9	-11.0	126.3	-10.6	0.5609	2.599
		1	-21.8	8.1	31.3	10.8	0.6126	2.380
	140	7	-24.7	-19.9	23.1	-18.9	**10.5668***	**0.240***
		9	61.8	11.8	104.5	93.3	0.9411	2.699
		8	-12.3	24.5	33.6	25.2	2.0107	1.263
		10	Stress-relieved				0.5112	4.968
20	180	5	-134.8	-14.8	129.9	-14.16	0.3630	0.546
		3	-217.3	5.5	223.6	7.8	0.2910	0.681
		1	-146.0	8.7	158.3	11.2	0.2077	0.954
	140	2	-212.3	1.4	213.3	1.6	3.8606	0.886
		4	-140.1	20.0	176.9	28.4	0.5934	5.767
		6	-205.8	56.1	240.7	57.3	0.5661	6.045
		10	Stress-relieved				9.3071	0.368

* The specimen in bold is a run out specimen.



(a)

(b)

(c)

Fig. 12. Fatigue resistance in million of cycles versus the transversal and longitudinal residual stress level for (a) 8 mm, (b) 12 mm, and (c) 20 mm thick transversal joints.

both compressive and tensile. This is because the cyclic external load, overimposed to the pre-existing stress, is sufficiently high to yield the material and to partially relax the residual stress, as confirmed by several authors [35-40].

The behaviour is more interesting when the load level is near the fatigue limit; specifically, in this case and for all three considered thicknesses, the number of cycles to failure was highly variable between specimens and depended on the reciprocal value of transversal residual stress. The results from the stress-relieved specimens are consistent with the assumption that the residual stress field is completely relaxed by heat treatment.

The amplitude stress level was reduced to 140 N/mm^2 for the plate of 12 mm thickness, since the stress amplitude of 150 N/mm^2 was too far from the fatigue limit. The consequence was that the residual stress field, which does not influence the fatigue limit at higher stress amplitudes, now had a remarkable effect, that is, a small reduction of 10 N/mm^2 in the external stress amplitude was discriminating in producing the appearance of the residual stress effect on fatigue.

Correlations between longitudinal residual stress and fatigue life can be found, confirming the importance of transversal residual stress with respect to other residual stress indicators.

4. Conclusions

The aim of this paper was to clarify how the residual stress field influences the fatigue strength of welded joints by presenting the results of an extended experimental plan. A particular geometry and loading mode were chosen for specimens to isolate the effect of the residual stress from the remaining factors affecting the fatigue life of welded joints. By milling the plate surface, we removed the stress concentration at the weld toe, while the use of a four-point bend loading mode allowed us to overcome the problems due to distortions in welded joints. The relative low number of tests and the low level of measured transversal residual stress suggest that the following considerations are not exhaustive of the phenomenon. Our results can be regarded as useful quantitative indications of the residual stress-fatigue interaction.

Our experimental results suggest that fatigue life scatter, expressed as the ratio of predicted and actual number of cycles to failure, increases when the fatigue load is close to the limit. Starting from this observation, an interesting dependence between the number of cycles to failure and the transversal residual stress level, in the same direction of the applied load, was found for all thicknesses, but only when the external load amplitude was close to the fatigue limit. In all remaining cases, the residual stress does not seem to affect fatigue life.

References

[1] R. I. Stephens, A. Fatemi, R. R. Stephens and H. O. Fuches, *Metal fatigue in engineering*, John Wiley & Sons 2001.

[2] E. Zahavi and V. Torbilo, *Fatigue design and life expectancy of machine parts*, CRC Press 1996.

[3] H. P. Lieraude, Rôle des contraintes résiduelles dans le comportement en fatigue des composants soudés, *Journées Scientifiques et Techniques '97 "Durabilité des Matériaux de Structures"*, 3-4 Novembre 1997, Nabeul (Tunisie).

[4] D. G. Bellow, M. A. Wahab and M. G. Faulkner, Residual stresses and fatigue of surface treated welded specimens, *Advance in surface treatments*; 2 (1986) 85-94.

[5] N. T. Nguyen and M. A. Wahab, The effect of undercut and residual stresses on fatigue behaviour of misaligned butt joints, *Engineering fracture mechanics*; 55 (3) (1996) 453-469.

[6] Sarkani, Shahram, Michaelov, George, Kihl and P. David, Stochastic fatigue damage accumulation in a T-welded joint accounting for the residualstress fields, *International Journal of Fatigue*; 23 (1) (2001) 71-78.

[7] M. Chiarelli, A. Lanciotti and M. Sacchi, Fatigue resistance of MAG welded steel elements, *International Journal of Fatigue*; 21 (10) (1999) 1099-1110.

[8] G. A. Webster and A. N. Ezeilo, Residual stress distributions and their influence on fatigue lifetimes, *International Journal of Fatigue*; 23 (1) (2001) 375-383.

[9] K. Masubuchi, *Analysis of welded structures*, Pergamon Press, USA, 1980.

[10] T. R. Gurney, *Fatigue of welded structures*, Cambridge University Press, Cambridge, 1979.

[11] S. Maddox, *Fatigue strength of welded structures*, Abington Publishers, Cambridge, 1991.

[12] D. Radaj and C. M. Sonsino, *Fatigue assessment of welded joints by local approach*, Abington Publishing, 1998.

[13] W. H. Munse, Fatigue of weldments - tests, design and service, *Fatigue Testing of Weldments* - ASTM STP 648 (Hoeppner D.W. editor), ASTM, 1978; 89-112.

[14] M. Ros, La fatigue des soudures, *Rev. Métallurgie*, n.11 (1948).

[15] F. Hebrant, H. Louis, W. Soete and A. Vinckier, The relaxation of residual welding stress by static and fatigue loading, *Welding Research Abroad*, (1957) 58-63.

[16] D. S. Dugdale, Effect of residual stress on fatigue strength, *Welding Jnl.; Research Suppl.*, 38 (1) (1959) 45-48.

[17] G. Casalino, M. De Giorgi, R. Nobile and F. W. Panella, Valutazione delle tensioni residue e della resistenza a fatica di lamiere piegate termicamente al laser, *Proc. of the XXXI Nat. Conf. AIAS*, Parma, 18-21 September 2002.

[18] V. Dattoma, M. De Giorgi and F. W. Panella, Experimental and numerical evaluation of residual stresses and effect on fatigue life for longitudinal joints, *Proc. Of the New trends in fatigue and fracture*, Metz (Francia) 8-9 April 2002.

[19] M. De Giorgi, Valutazione numerica e sperimentale delle tensioni residue in giunzioni saldate ed effetto sulla resistenza a fatica, *Ph.D Thesis*, 2002.

[20] V. Dattoma, M. De Giorgi and R. Nobile, On the evolution of the welding residual stress after milling and cut machining, *Computers and Structures*, 84 (2006) 1965-1976.

[21] V. Dattoma, M. De Giorgi and R. Nobile, On the residual stress and the fatigue resistance of butt-welded joints, International *Conference on Experimental Mechanics 12*, Bari, Italy. 2004.

[22] E. K. Henriksen, Residual stresses in machined surfaces, *Trans. ASME*, 73 (1951) 69-76.

[23] M. M. El-Khabeery and M. Fattouh, Residual stress distribution caused by milling, *Int. J. Mach. Tools Manuf.*, 29 (3) (1989) 391-401.

[24] K. Jacobus, S. G. Kapoor and R. E. DeVor, Experimentation on the Residual Stresses Generated by Endmilling, *J. Manuf. Sci. Eng.*, 123 (2001) 748-753.

[25] K. Jacobus, R. E. DeVor and S. G. Kapoor, Machining-Induced Residual Stress: Experimentation and Modeling, *J. Manuf. Sci. Eng.*, 122 (2000) 20-31.

[26] T. Berruti and G. Ubertalli, Influence of cutting parameters on residual stresses induced by milling in pressure die-cast aluminium alloy components, *J. Manu. Sc. Eng.*, 123 (4) (2001) 547-551.

[27] F. Ghanem, C. Braham, M. Fitzpatrick and H. Sidhom, Effect of near-surface residual stress and microstructure modification from machining on the fatigue endurance of a tool steel, *Journal of Materials Engineering and Performance*; 11 (6) (2002) 631-639.

[28] Kuang-Hua Fuh and Chih-Fu Wu, A residual-stress model

for the milling of aluminium alloy (2014-T6) *Journal of Materials Processing Technology*, 51 (1-4) (1995) 87-105.

[29] P. Chevrier, A. Tidu, B. Bolle, P. Cezard and J. P. Tinnes, Investigation of surface integrity in high speed end milling of a low alloyed steel, *International Journal of Machine Tools & Manufacture*; 43 (11) (2003) 1135-1142.

[30] G. S. Schajer, Application of Finite Element Calculation to Residual Stress Measurement, Journal of Engineering Materials and Technology, 103 (1981) 157-163.

[31] G. S. Schajer, Strain Data Averaging for the Hole-Drilling Method, *Experimental Techniques*, (1991) 25-28.

[32] M. Beghini, L. Bertini and P. Raffaelli, Numerical analysis of plasticity effects in the hole-drilling residual stress measurement, *Journal of Testing and Evaluation*, 22 (6) (1994) 522-529.

[33] K. Sasaki, M. Kishida and T. Itoh, The Accuracy of Residual Stress Measurement by the Hole-drilling Method, *Experimental Mechanics*, 37 (3) (1997) 250-257.

[34] R. Ottel, The Determination of Uncertainties in Residual Stress Measurement (Using the hole drilling technique), *Standard Measurement & Testing Project* No. SMT4-CT97-2165, Issue 1, (2000).

[35] K. Iida, S. Yamamoto and M. Takanashi, Residual stress relaxation by reversed loading, *Welding in the World / Le Soudage dans le Monde*; 39 (3) (1997) 138-144.

[36] S. J. Maddox, Influence of tensile residual stresses on the fatigue behaviour of welded joints in steel, *ASTM STP 776*, (1982) 63-96.

[37] S. Berge and O. I. Eide, Residual stress and stress interaction in fatigue testing of welded joints, *ASTM STP 776*, (1982) 115-131.

[38] D. V. Nelson, Effect of residual stress on fatigue crack propagation, residual stress effects in fatigue, *ASTM STP 776*, (1982) 172-194.

[39] V. Dattoma, M. De Giorgi and R. Nobile, Influenza delle tensioni residue sul comportamento a fatica di giunti saldati di testa, *Proc. of the XXXII Nat. Conf. AIAS*, Salerno, 3-6 September 2003.

[40] V. Dattoma, M. De Giorgi and R. Nobile, Numerical evaluation of residual stress relaxation by cyclic load, *Journal of Strain Analysis*, 39 (6) (2004) 663-672.

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