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Effect of Ultrasonic Impact Treatment on the Fatigue Behaviour of the Fillet Welded Lap Joints between Steel Plates

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Abstract

This paper outlines the experimental research conducted by the authors to highlight the efficiency of post-welding application of the ultrasonic impact treatment (UIT) on fillet welded lap joints in case of metal constructions subject to variable operating stress. The series of experiments consisting in fatigue testing specimens extracted from test-plates presenting fillet welded lap joints, subject and respectively not subject to post-welding UIT, led to the conclusion that increased fatigue behavior performances under UIT is relatively low by reference to the increased construction costs generated by the application of such a treatment.

Key words: *filet welded lap joint, ultrasonic impact treatment, fatigue strength, cyclic endurance*

Introduction

Fillet welded lap joints of metal structures subject to variable operating stress are characterized by low fatigue strength and cyclic endurance.

The fatigue life of welded metallic structures can be considered in two stages: crack initiation (nucleation) and crack propagation to final fracture (crack growth), the initiation may be the most significant part of fatigue life.

A good method to improve fatigue strength of these welded joints is to increase the normally very short crack initiation period observed in weld.

Methods for increasing the initiation period of fatigue endurance can generally be divided in two categories: a) methods that modify the stress distribution near the weld to produce beneficial compressive residual stress; b) methods that modify the local geometry of the weld toe to eliminate the initial defects and decrease the local stress concentration [1,2].

Ultrasonic Impact Treatment – UIT is a post-weld improvement method, which removes weld toe effects, decreases tensile stresses and reduces the stress concentration in the fatigue critical region. When properly applied, the method is able to provide a more gradual weld metal to base metal transition reducing the local stress concentration. The area being treated is highly plastically deformed which has the effect of both work hardening the material and introducing favorable compressive residual stresses [3,4].

Experimental Data

This paper presents a series of experiments conducted by the authors to highlight the effects of Ultrasonic Impact Treatment – UIT on the fatigue strength and endurance of the fillet welded lap joints between steel plates.

The main steps and materials used during the experiments were as follows:

➢ The semi-finished fillet welded lap joints tested under variable operating stress consisted in laminated steel plates (S355 J2G3), 6 mm and 10 mm thick (s = 6 mm and s = 10 mm); the traction test of specimens extracted from the 6 mm thick steel plate revealed the following characteristics: yield strength $R_{p0,2}$ = 466 MPa; tensile strength R_m = 597 MPa; elongation A = 25 %; the features revealed by the traction test of specimens extracted from the 10 mm thick steel plate were: $R_{p0,2}$ = 381MPa; R_m = 530 MPa; A = 29 %.

➢ Experiments were conducted on fillet welded lap joints between steel plates used for manufacturing specimens presenting the configuration and dimensions in figure 1; two specimens (P1 and P2) were fabricated out of each standard dimension steel plate (s = 6 mm and s = 10 mm), the welding process was metal – arc active gas welding – MAG / 135 ISO 4063, and the welding consumablews used were: filler material: G3Si – EN 440 , d_f = 1,2 mm; shelding gas: Corgon 18 / M21 – EN 439 (82 % Ar + 18 % CO_2).

➢ Specimens P1 were maintained in the post-welding state, while specimens P2 were subject to ultrasonic impact treatment applied to the surface of both welded joints. UIT was performed at a company in Germany by using 27 kHz ultrasonic impact treatment equipment, with a 3 mm pin diameter handheld tool. Fillet welded lap joints on specimens can be observed in figure 2.

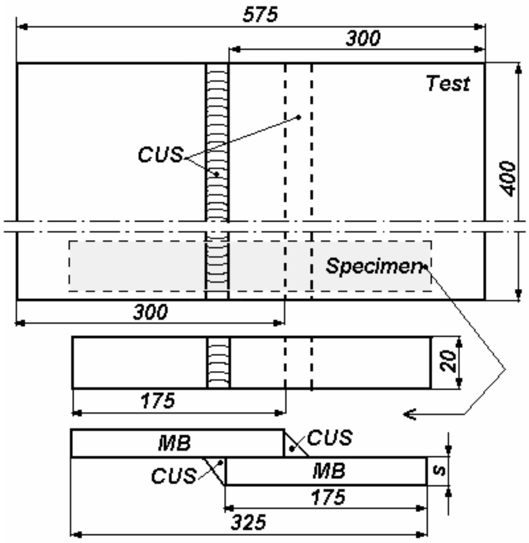

Fig. 1. Configuration and dimensions of the specimens and test-plates

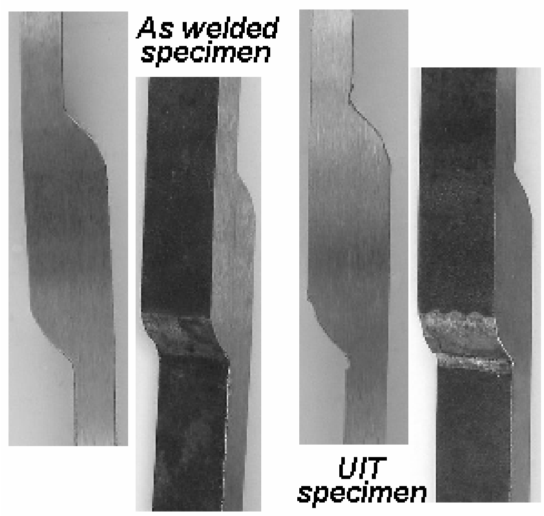

Fig. 2. Specimens ready for undergoing fatigue tests

➢ Tested specimens were the result of a splintering process (applied to test-plates following the above mentioned specifications) and had the dimensions shown in Fig. 1. Specimens were subject to variable operating stress (traction waves with an asymmetry coefficient $R = \sigma_{min}/\sigma_{max}$ = 0.1, and different values of maximum tension σ_{max} and tension amplitudes / cyclic tension variation $\Delta\sigma = \sigma_{max} - \sigma_{min} = \sigma_{max}(1 - R)$) on an INSTRON 8011 testing machine, as shown in figure 3.

➢ Seven specimens P1 with s = 6 mm were used in order to determine the slope of the Wőhler fatigue curve under variable operating stress (with traction cycles of the type described earlier), for welded lap joints not undergoing UIT; similary, 5 specimens P2 with s = 6 mm were used in order to determine the slope of the Wőhler-curve under stress (same traction cycles) for welded lap joints subject to UIT. For each tested specimen, the number N_r of stress cycles before fatigue failure was established, and by means of logarithmic representation of the experimental dependencies Δσ = f(N_r) for both specimen categories, Wőhler-curves were determined and analytically described as [5-7]:

$$N_r(\Delta\sigma)^m = C_o\,. \tag{1}$$

➢ Using the Locati method, three to five specimens extracted from each test-plate were tested in order to determine the fatigue strength limit of the fillet welded lap joints, According to this method, the Wőhler-curve for all test-plates made of the same type of steel has the same parameter value *m* (previously determined), but different fatigue strengths R_{ft}, depending on the construction particularities, the microstructure of the welded joints, the residual tensions generated at the moment of welding the test-plates, etc.

➢ Therefore, the following procedure was applied in order to determine fatigue strength R_{ft} for each specimen. [7]:

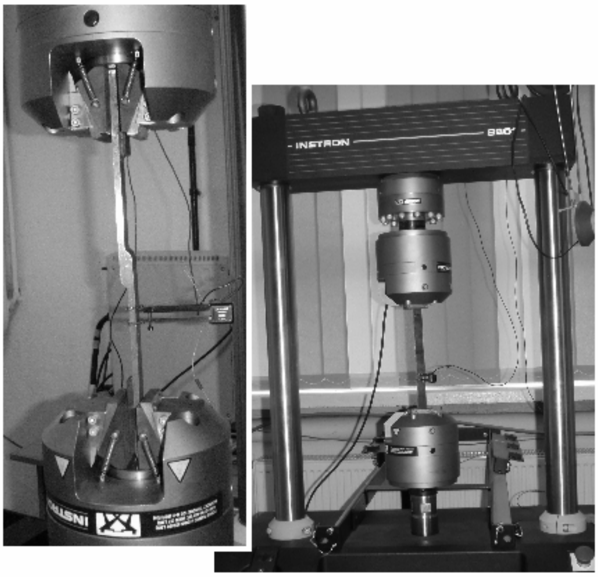

Fig. 3. Fatigue testing model

➢ The specimen was subject to different stress-levels i = 1...n; at each stress level i, a number N_i of stress cycles with $R = \sigma_{min}/\sigma_{max} = 0.1$ and different levels of maximum tension σmaxi and tension amplitudes $\Delta\sigma_i = \sigma_{maxi} - \sigma_{mini} = \sigma_{maxi}(1 - R)$ was performed; it is obvious that, due to $\Delta\sigma_i$ increasing accordingly to the stress level, the specimen failed when reaching the stress level n;

➢ Considering a random value of fatigue strength level R_x and assuming that the slope of the fatigue curve is *m* (previously determined), the number of stress cycles/stress level that could lead to specimen N_{ri} fatigue failure was calculated by means of the following formula:

$$N_{ri} = \left[\frac{R_x(1-R)}{\Delta\sigma_i}\right]^m N_{ref}\,,\ i = 1...n, \tag{2}$$

where N_{ref} stands for the reference strength used for defining fatigue strength R_x (R_x is the highest value of the maximum tension of the variable stress cycles for which fatigue failure does not occur after N_{ref} cycles); N_{ref} considered was $N_{ref} = 10^6$ cycles;

➢ Considering the known values of N_i and N_{ri}, i = 1...n, the fatigue damage/stress level D_{ti} was calculated using the formula:

$$D_{ti} = \frac{N_i}{N_{ri}} < 1,\ i = 1...n \qquad (3)$$

and the cumulative fatigue damage resulted from all stress-cycles was calculated using the formula:

$$DC = \sum_{i=1}^{n} D_{ti} = \sum_{i=1}^{n} \frac{N_i}{N_{ri}}. \qquad (4)$$

Repeating the same procedure mentioned above for different R_x values, fatigue strength of specimen R_{ft} was determined; R_{ft} is defined as the R_x value for which the cumulative fatigue damage reached $DC \cong 1$.

Results

The results of the test conducted for establishing the configuration of Wőhler-curves for the welded joints on specimens P1 and P2 (s = 6 mm) subject to variable stress are summarised in in table 1 and interpreted in figure 4.

Table 1. The results of the fatigue tests determining the slope of Wőhler-curves for specimen P1 and P2, s = 6 mm

Specimen mark	Maximum cyclic load F_{max}*, N	Maximum tension cyclic stress σ_{max}, MPa	Stress range $\Delta\sigma$, MPa	Cyclic endurance N_r
Specimens P1, s = 6 mm				
P1/1	36000	300.00	**270.0**	**1750**
P1/2	22000	183.33	**165.0**	**14502**
P1/3	19000	158.33	**142.5**	**51043**
P1/4	14000	116.67	**105.0**	**194092**
P1/5	12000	100.00	**90.0**	**326530**
P1/6	10000	83.33	**75.0**	**588516**
P1/7	9000	75.00	**67.5**	**928908**
Specimens P2, s = 6 mm				
P2/1	27260	227.17	**204.5**	**22760**
P2/2	19800	165.00	**148.5**	**82867**
P2/3	13000	108.33	**97.5**	**593011**
P2/4	12000	100.00	**90.0**	**1002550**
P2/5	11000	91.67	**82.5**	**1986532**

* cyclic traction stress , cycle asymmetry coefficient R = 0.1

The procedure for calculating specimens' fatigue strength by applying the Locati method can be easily understood when examining figure 5 and table 2 presenting R_{ft} calculation for a specimen P1 and P2 with s = 10 mm.

Table 3 summarises presents the results of all the experiments to identify the characteristics of fatigue behavior of the fillet welded lap joints between steel plates: fatigue strengths of the joints tested under traction waves (R = 0.1) and analytical expressions of the Wőhler-curves for these joints.

Table 4 shows the values of two efficiency indicators of UIT application on fillet welded lap joints between steel plates: $k_{ft,}$ is ratio between fatigue strength of joints subject to post-welding UIT and fatigue strength of joints not undergoing post-welding UIT, and k_{Nf} is ratio between fatigue life of post-welding treated joints subject to variable stress and fatigue life of joints not undergoing such a post-welding treatment under variable stress.

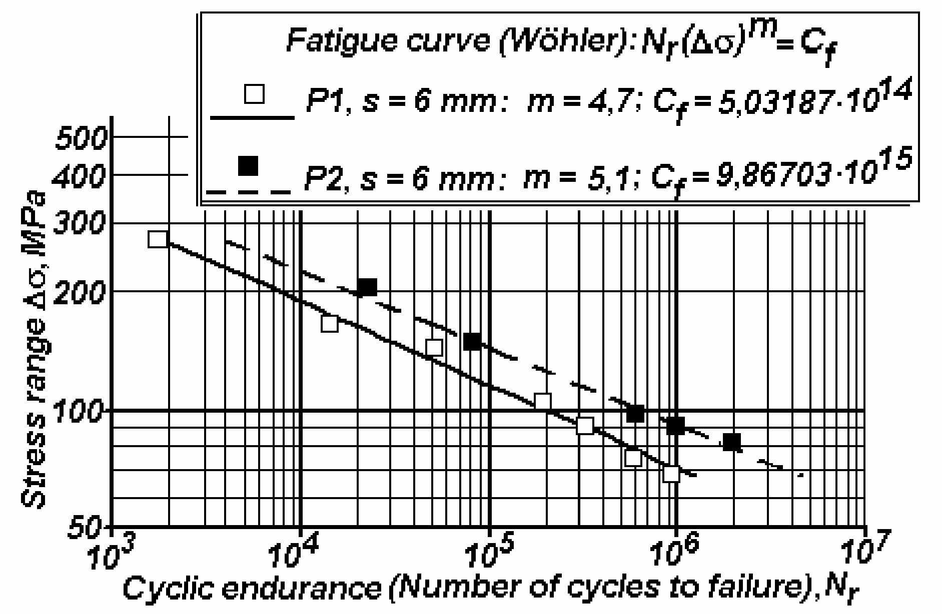

Fig. 4. Experimentally determined Fatigue curve (Wőhler)

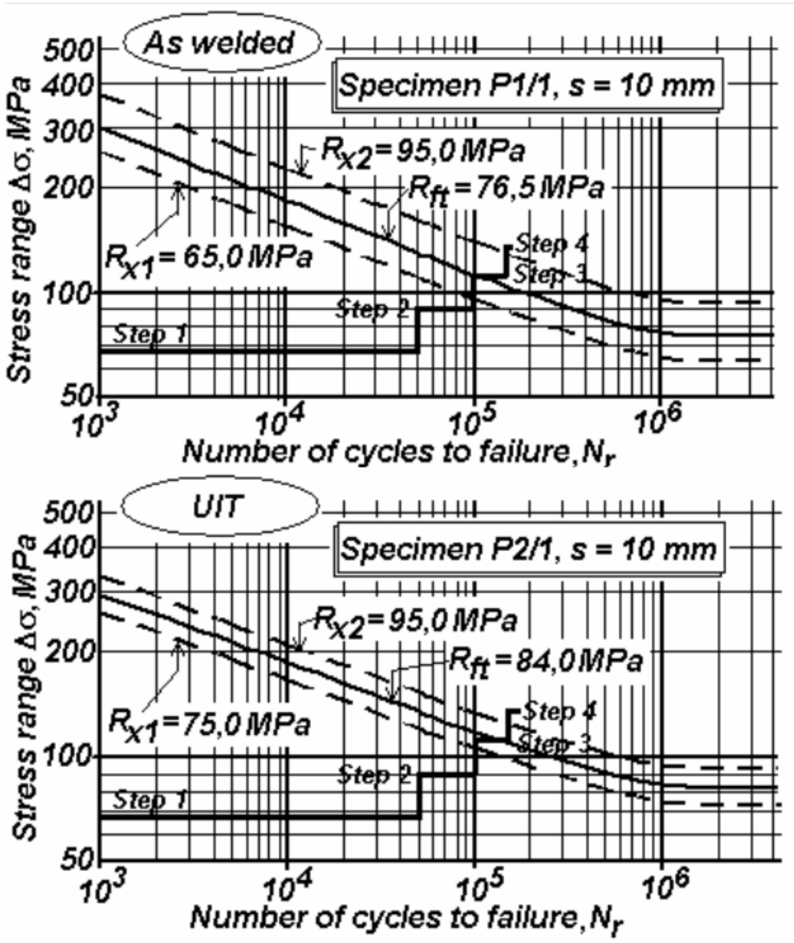

Fig. 5. Testing specimens P1 and P2, s = 10 mm using the Locati method

Figure 6 shows that in the case of fillet welded lap joints between steel plates, the critical area (where fatigue cracks appear) is the weld toe. UIT improves the cyclic endurance and fatigue strength, but it lacks the capacity of transferring in the position of this critical area to the parent metal MB. The way tested specimens fail under variable mechanical stress also suggests that applying UIT in the upper part of the fillet welded lap joints does not influence their fatigue life; as a result, when deciding whether UIT should be applied, such treatment must only strengthen (through deformation and then reconfiguration of the residual stress field [3,4]) the weld toe area, where fatigue cracks initiate.

Table 2. The results of applying the Locati method on specimens P1 and P2 with cu s = 10 mm

As welded Specimen P1/1; Plate thickness s = 10 mm				
Step of loading i =	F_{max}, N	σ_{max}, MPa	$\Delta\sigma$, MPa	Number of cycles N_i
1	15000	75	67.5	50000
2	20000	100	90.0	50000
3	25000	150	112.5	50000
4	30000	175	135.0	13100

Step of loading i =	R_{x1}, MPa	C_f =	R_{ft}, MPa	C_f =	R_{x2}, MPa	C_f =
	65.0	$2.0456\cdot10^{14}$	76.5	$4.4009\cdot10^{14}$	95.0	$1.2187\cdot10^{15}$
	N_{ri}	N_i/N_{ri}	N_{ri}	N_i/N_{ri}	N_{ri}	N_i/N_{ri}
1	510179	0.098005	∞	0.000005	∞	0.000000
2	131869	0.379163	283705	0.176239	785662	0.063641
3	46172	1.082899	99336	0.503343	275090	0.181759
4	19588	0.668765	42143	0.310849	116705	0.112249
	$DC=\sum N_i/N_{ri}$	2.228832	$DC=\sum N_i/N_{ri}$	0.990437	$DC=\sum N_i/N_{ri}$	0.357653

UIT Specimen P2/1; Plate thickness s = 10 mm				
Step of loading i =	F_{max}, N	σ_{max}, MPa	$\Delta\sigma$, MPa	Number of cycles N_i
1	15000	75	67.5	50000
2	20000	100	90.0	50000
3	25000	125	112.5	50000
4	30000	150	135.0	26000

Step of loading i =	R_{x1}, MPa	C_f =	R_{ft}, MPa	C_f =	R_{x2}, Mpa	C_f =
	75.0	$2.1352\cdot10^{15}$	84.0	$3.8059\cdot10^{15}$	95.0	$7.1290\cdot10^{14}$
	N_{ri}	N_i/N_{ri}	N_{ri}	N_i/N_{ri}	N_{ri}	N_i/N_{ri}
1	1000000	0.050000	∞	0.000005	∞	0.000000
2	230575	0.216849	410983	0.121659	769822	0.064950
3	73888	0.676704	131699	0.379653	246689	0.202685
4	29157	0.891716	51971	0.500281	97348	0.267084
	$DC=\sum N_i/N_{ri}$	1.835268	$DC=\sum N_i/N_{ri}$	1.001599	$DC=\sum N_i/N_{ri}$	0.534724

Conclusions

The experimental research conducted by the authors led to the following conclusions:

- ➢ The fatigue strength of fillet welded lap joints between steel plates is low; fatigue strength values R_{ft} for joints not subject to UIT reach 12....14% of the traction strength R_m of the parent metal (steel).
- ➢ When subject to UIT, fatigue strength of fillet welded lap joints between steel plates of metallic constructions increases by 16…20%, reaching a level of R_{ob} = (0,17...0,20)R_m .

Table 3. The results of experiments research using the Locati method – summary

Specimen mark	R_{ft}, MPa	Fatigue curve (Wőhler)	Specimen	R_{ft}, MPa	Fatigue curve (Wőhler)
Welded joints between 6 mm thick steel plates; traction cycles, R =0.1					
P1/7	75.0	$N_r(\Delta\sigma)^{4,7}=$ $5.180689{\cdot}10^{14}$	P2/6	93.3	$N_r(\Delta\sigma)^{5,1}=$ $6.154113{\cdot}10^{15}$
P1/8	81.9		P2/7	95.8	
P1/9	77.3		P2/8	90.4	
P1/10	82.5		P2/9	92.2	
			P2/10	89.6	
Average	79.2		Average	92.3	
Welded joints between 10 mm thick steel plates; traction cycles, R =0.1					
P1/1	75.0	$N_r(\Delta\sigma)^{4,7}=$ $4.188625{\cdot}10^{14}$	P2/1	85.5	$N_r(\Delta\sigma)^{5,1}=$ $5.724636{\cdot}10^{15}$
P1/2	77.3		P2/2	90.3	
P1/3	74.8		P2/3	97.5	
P1/4	76.5		P2/4	92.2	
P1/5	74.9		P2/5	89.6	
Average	75.7		Average	91.0	

Table 4. UIT efficiency indicators in fillet welded lap joints between steel plates

Plate thickness s, mm	Fatigue strength ratio $k_{ft} = R_{ft}(P2)/R_{ft}(P1)$	Cyclic endurance ratio $k_{N\,f} = N_r(P2)/N_r(P1)$
6	1.165	$11.879/(\Delta\sigma)^{0,4}$; $\Delta\sigma = 90...220$ MPa $\Rightarrow k_{Nf} = 1.96...1.28$
10	1.202	$13.667/(\Delta\sigma)^{0,4}$; $\Delta\sigma = 90...220$ MPa $\Rightarrow k_{Nf} = 2.26...1.48$

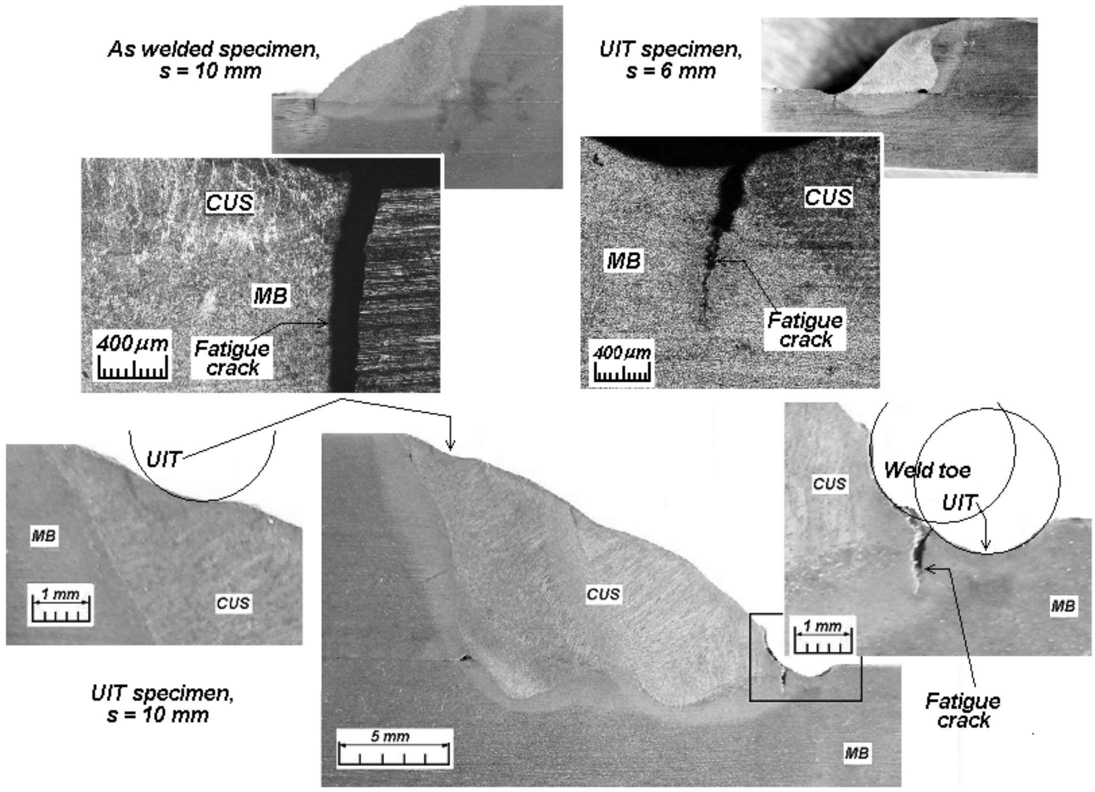

Fig. 6. Fatigue failure initiation areas on the fillet welded lap joints between steel plates

➢ The fatigue endurance of fillet welded lap joints between steel plates is also low (when subject to a mechanical stress generating tensions higher than R_{ob}) and post-welding UIT causes these limits to increase by 30-130%.

➢ When comparing the high costs of applying UIT with the quality improvement obtained by applying such treatment to fillet welded lap joints, we conclude that UIT is not always efficient; a thorough analysis of the technical features as well as avoiding the use of this type of joints are recommended as alternative solutions for welded metallic constructions subject to variable operating stress.

References

1. Maddox S.I. - *Fatigue strength of welded structures*, Woodhead Publishing Ltd in association with The Welding Institute, Cambridge, 1991.
2. * * * BS 7608:1993, *Code of practice for Fatigue design and assessment of steel structures*.
3. Statnikov, E.S. - Applications of Operational Ultrasonic Impact Treatment (UIT) Technologies in Production of Welded Joints", *IIW/IIS,* Doc. XII-1667-97.
4. Statnikov E.S. - Guide for application of ultrasonic impact treatment improving fatigue life of welded structures, *IIW/IIS* – Doc. XIII - 1757 – 995.
5. Udatov F.P., Moskaleva E.M., Gnezdilov V.M. - Effect of step duration on the evaluation of the fatigue limit of welded steel structures, *Strength of Materials*, Vol. 14, no. 9/1982, pp. 1183-1189.
6. Radaj D. - *Design and analysis of fatigue resistant welded structures*, Technology & Engineering Abington Publishing, 1990.
7. Rusu O.,Teodorescu M., Laşcu Simion N. - *Oboseala metalelor. Baze de calcul*, Vol. 1, Editura Tehnică, Bucuresti, 1992.

Efectul tratmentului prin impact cu ultrasunete asupra comportării la oboseală a îmbinărilor sudate în colț între table din oțel suprapuse

Rezumat

În lucrare se prezintă cercetarea experimentală efectuată de autori pentru a evidenția eficiența aplicării postsudare a tratamentului prin impact cu ultrasunete la îmbinările sudate în colț ale construcțiilor metalic cu solicitări variabile în exploatare. Programul experimental, constând din încercarea la oboseală a unor epruvete prelevate din probe conținând îmbinări sudate în colț între table din oțel suprapuse, fără şi cu UIT aplicat postsudare, a condus la concluzia că sporirea performanțelor de comportare la oboseală produsă de UIT este scăzută în comparație cu creşterea costului construcțiilor implicată de aplicarea acestui tratament.