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FRACTURE TOUGHNESS OF LASER STAKE WELDS IN SHIPBUILDING INDUSTRY

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A new technology of stake welding with the use of high power lasers was developed in the framework of EU research program "Advanced Welding for Closed Structures". This technology enable welding from outside of closed profiles due to high penetration of laser beam into the material. More than 650 static, fracture toughness and fatigue tests were performed during the research program to investigate strength of such welds. In this paper, investigations of static strength and fracture toughness are presented, results of fatigue testing will be reported elsewhere. As the result of the tensile and bend tests, very good strength and ductility of fusion zone (FZ) and heat-affected zone (HAZ) were found. Also the fracture toughness in lowered temperature was found to be satisfactory. Both traditional impact (Charpy) test and modern methods of measuring the crack tip opening displacement (CTOD) were utilised, and their results in the form of tearing energy per unit surface were compared. Also fatigue crack growth rate (FCGR) tests were performed at the constant ΔK value, the crack was propagating in the direction transversal to the weld midline. This technique allowed the observation of FCGR variations in different zones of the welded joint.

1. Introduction

Static tension test is still considered to be the most important testing technique of the shipbuilding materials. The basic strength properties like yield strength or ultimate tensile strength can be obtained as the result of such test, together with parameters regarding ductility of the material such as elongation at fracture or cross-sectional area reduction. For shipbuilding steels, information obtained as the result of such tests is insufficient to assess the safety of construction, because in low temperatures a very important phenomenon appears, regarding fracture behaviour of those alloys. Construction steels that nominally behave in ductile manner at room temperature (with significant plastic deformation preceding rupture) can behave in a brittle manner in lowered temperature. It can be very dangerous for the construction since in such conditions, very little energy is absorbed in the fracture process. There is a characteristic ductile-to-brittle transition temperature (nil-ductility transition temperature) below which shipbuilding steels behave in a brittle manner. That temperature can be found under various impact tests: Charpy test, dynamic tear or drop weight tear test. Modern fracture mechanics testing methods like K_{Ic}, CTOD or FCG tests can also be used to investigate the behaviour of the materials in lowered temperatures. From such tests we can obtain much more information about the fracture process than only the tearing energy and fracture appearance, as in the case of the Charpy test.

The fracture behaviour of construction material is very sensitive to chemical composition and thermomechanical treatment during the production process. Welding of such materials can also significantly change mechanical properties of the fusion zone (FZ) and heat-affected zone (HAZ). Many experimental investigations were performed to estimate mechanical properties of arc welds, and this problem seems to be well understood. Laser welding, due to high concentration of heat, can create different problems which must be intensively investigated before the technique can be widely accepted as the production method in industry. An extensive research program for butt welds has been already performed in the framework of European research program "Laser Welding in Ship Construction". As the result of that program, a set of approval guidelines [1] according to Classification Societies requirements have been published. Fracture toughness of parent material (PM), heat-affected zone and fusion zone were investigated with the use of standard impact (Charpy) test. In the case of laser butt welds there was a problem: for the fusion zone specimens, the crack had a tendency to migrate from the tip of the notch into base material. To guide the crack through the fusion zone, the standard Charpy specimen was modified by side notches in accordance with the annex "Standard instructions for the notch bending (Charpy impact) test with side-notched specimen geometry" [1]. Such tests were also performed in the framework of AWCS program in the temperature of $-20°$ C.

Although the test results gave a valuable information about the impact toughness of all the zones of weld, they were only of a comparative character. Another problem was the large scatter of data due to the weld defects, non-uniform distribution of material properties and presence of the residual stresses introduced to the material during welding. Modern fracture toughness testing methods seemed to be better suited for the investigations of the laser stake welds properties. The crack tip opening displacement (CTOD) and the fatigue crack growth (FCG) tests have been selected to be performed in the framework of the presented research program. Due to high accuracy and digital control of modern testing machines, such tests can give us more valuable results than the standard Charpy test. As result of CTOD test, one can obtain critical value of the crack tip opening displacement, which can be helpful to assess maximum size of the allowable weld defect. Besides, the tearing energy per unit of the fracture surface that can be also calculated for compact specimen and compared with the impact (Charpy) test results.

Also the fatigue crack growth test (FCG) gives a valuable information that can enable the estimation of fatigue life of the components. Usually this kind of test is performed with decreasing or increasing value of the stress intensity factor amplitude ΔK to find the relation between ΔK and the crack propagation rate da/dN, assuming, that the crack propagates in a homogeneous material. For the AWCS research program, the FCG test was modified in following way. Instead of finding the relation $da/dN = f(\Delta K)$ for PM, HAZ and FZ propagating crack in the direction parallel to the weld midline, the crack was propagated in the transversal direction passing through all the weld zones and the parent material. Since the value of stress intensity factor amplitude was kept constant during the entire test (that would result in constant da/dN value for homogeneous materials), the variations of the fatigue crack growth rate in different zones of weld could be observed. Those observations gave an answer to a simple question: does the crack accelerate or slow down passing through the weld and HAZ? Such test seems to be a very simple criterion of the weld quality.

Fracture mechanics tests were performed together with static tests such as the tension and bend test for different configurations of weld geometry, different materials and welding parameters. As a result, sufficient data to estimate the static strength, ductility and fracture toughness of stake welds were obtained. On the basis of such data conclusions were drawn by design engineers and Classification Societies specialists allowing the full-scale constructions to be designed.

2. Material and experimental procedure

The tests presented in this paper were performed on the specimens machined from weld samples in the form of T-joints. Power of a CO_2 laser necessary to weld through thick plates was 40 kW. Etched macrosection of the 20×15 mm joint made with two laser beam runs is shown in Fig. 1. Welding was performed from outside of the flange; penetration of the laser beam was sufficient to melt the material on the interface of the web and flange. Such kind of weld can be characterised by deep penetration, narrow heat-affected zone and incomplete fusion on the web and flange interface. Material for this kind of joint must be carefully selected due to high concentration of heat during welding and high cooling rate to avoid weld defects, residual stresses, formation of untempered martensite and brittle behaviour in lowered temperature. Shipbuilding steel denoted as "grade A" was selected for the web and flange. Three combinations of the web and the flange thicknesses were selected: 8×8, 15×12 and 20×15. For the 8×8 samples only the welds made with a single laser beam run were considered. For the 15×12 weld samples, three configurations of weld with 1, 2 and 3 laser beam runs were investigated, and for 20×15 weld, 2 and 3 laser beam runs configurations were taken into account. The chemical composition of the plates used for a 20×15 stake weld is given in the Table 1. In Fig. 2 the microstructure of weld metal is shown. Typical ferritic and perlitic microstructure can be observed, untempered martensite was not detected near the interface of the web and flange where the photograph was taken.

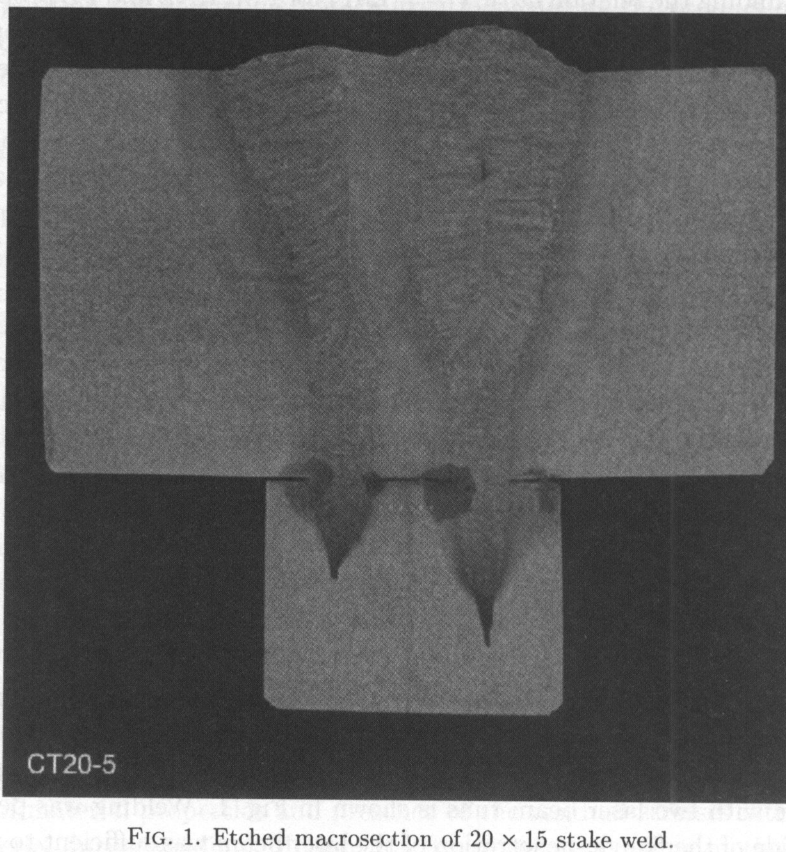

FIG. 1. Etched macrosection of 20×15 stake weld.

Table 1. Chemical composition of the *A* grade steel.

Thickness (mm)	Grade	Cast no.	Chemical composition of cast %							
			C	Mn	Si	P	S	Al	Nb	Cu
15	Gr *A*	9801142	**0.157**	0.63	0.239	**0.014**	**0.008**	0.048	0	–
20	Gr *A*	MB 20	**0.16**	1.12	0.21	**0.018**	0.005	0.047	0.001	0.010

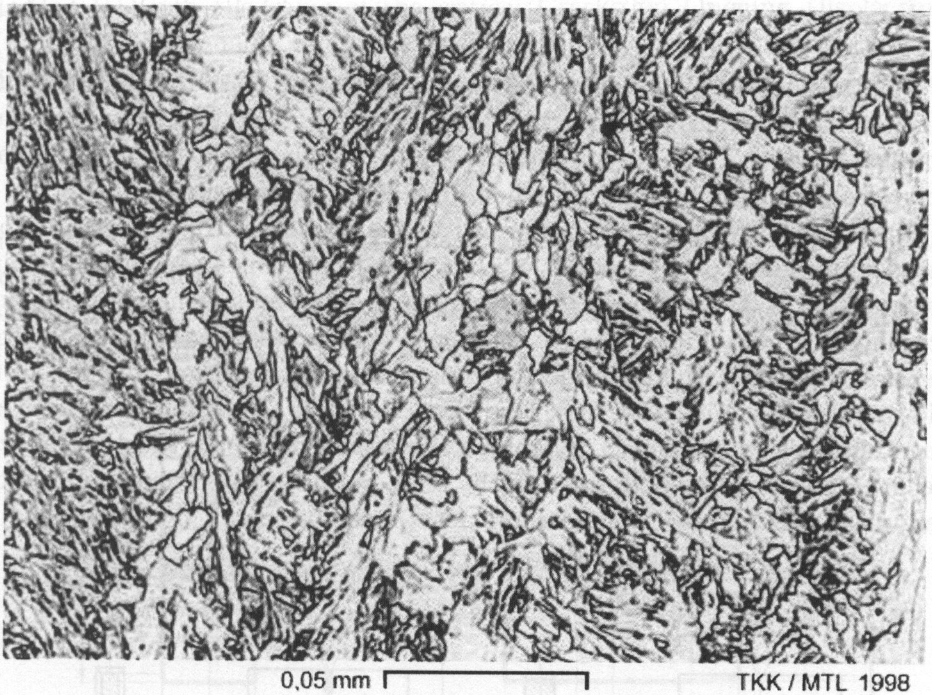

FIG. 2. Microstructure of fusion zone for grade *A* steel.

To obtain basic information on mechanical properties of the material, static tension tests were performed according to the ASTM 8 standard [8]. Three kinds of specimens were machined from the flange of the weld samples:

1. Specimen machined from parent material (PM specimen),
2. Specimen with transversal weld (TW specimen),
3. Longitudinal weld specimen with weld material occupying 80% of the measuring part cross-section (LW specimen).

TW and LW specimens were located as close as possible to the web and flange interface where mechanical properties of the material were expected to be the same (or at least not significantly different) as at the interface. Every test was performed on two identical specimens to check the test repeatability and the results were averaged after two measurements.

Ductility of the weld material was also investigated with the use of the bend test performed according to the IACS W2 specification [6]. Three kinds of specimens were machined from the flange of the weld sample:

1. Transversal face (TF) specimen – specimen with transversal weld, the face of weld was on the external side during bending,

2. Transversal root (TR) specimen – specimen with transversal weld, the root of weld (i.e. the interface side of flange) was on the external side during bending,

3. Longitudinal face (LF) specimen – specimen with longitudinal weld, the face of weld was on the external side during bending.

The thickness of all the specimens was equal to the plate thickness, mandrel diameter was 3.5 times plate thickness and the bend angle was 180°. Maximum allowable crack size was assumed to be 3 mm. Elongation of the specimen and transversal shrinkage on the external surface were also measured.

Impact (Charpy) test was performed in the framework of the research program for two kinds of specimens: for the standard specimen prepared according to the ASTM E 23 [9] and for the specimen modified by side notches machined according to [1] (see Fig. 3). Three specimens of each design were machined from the parent material, the heat-affected zone and from the fusion zone for all the weld samples. As previously, they were located as close as possible to the web and flange interface where impact toughness was assumed to be critical to the weld strength. The test was performed in the temperature −20° C and the absorbed energy was averaged for three measurements made on identical specimens.

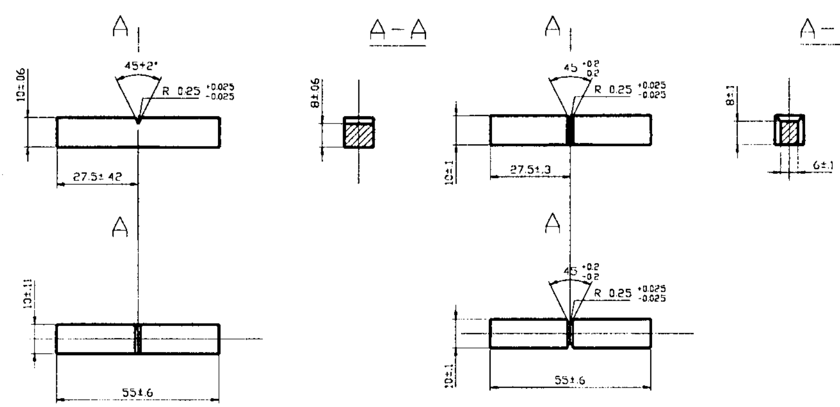

FIG. 3. Standard and modified (3-notch) Charpy specimen.

Since the results of static tension tests showed elastic-plastic behaviour and high ductility of the steel used, the Crack Tip Opening Displacement (CTOD) test was selected to investigate fracture toughness of the laser stake welds. The test was performed in the temperature -5° C, in agreement with the ASTM E 1290-93 standard [11]. Compact specimens shown in Fig. 4 were machined from three locations (5 for each location) in the flange of 20 × 15 mm stake weld: fusion zone, heat-affected zone and parent material. Two stages of the test: precrack and static tearing were performed at the same temperature, and during the second stage load, grip displacement and crack opening displacement (COD) were measured and recorded in digital form. On the basis of such data, characteristic values of load (P_m) and COD plastic component (V_p) were found. These two values were recalculated with the use of the formulas given in the standard [11] into the value of the critical Crack Tip Opening Displacement δ (CTOD). Additionally, on the basis of the load – grip displacement plot, the tearing energy per fracture surface unit was calculated according to the formula:

$$E_t = \frac{\int P dl}{B \cdot b_0}, \tag{2.1}$$

where P denotes load, l is the grip displacement, B denotes specimen thickness and b_0 – the uncracked ligament defined as the distance from the original crack front to the back surface of specimen after precracking. That energy was used to compare the results of the CTOD and Charpy tests.

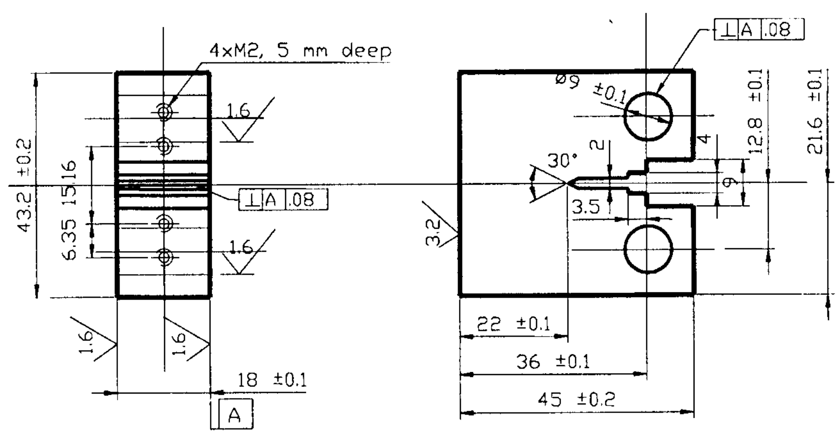

FIG. 4. Compact specimen used for CTOD and FCG tests.

The Fatigue Crack Growth test was performed in agreement with the standard ASTM E 647 – 95a [12]. Test temperature was $-5°$ C. Five compact specimens were machined from the flange with notch positioned transversally to the weld midline. The reason for such notch position was the attempt of investigating variations of the crack propagation rate da/dN passing through the different zones of material: parent material, heat-affected zone and weld material. The technique applied ($\Delta K = \text{const}, K_{\max} = \text{const}$) should allow the crack to propagate with constant rate in a homogeneous material. In the case of specimen shown in Fig. 5 this technique should allow to investigate the da/dN variations due to the change of material properties and the presence of the residual stresses. Two stages of the test: precrack and fatigue crack propagation were performed in the same temperature; during the second stage, the load and Crack Opening Displacement were measured, and the crack length was measured by means of the compliance technique. The digitally recorded data were post-acquisition analysed and the diagrams showing the number of cycles and crack propagation rate da/dN as the function of crack length were prepared.

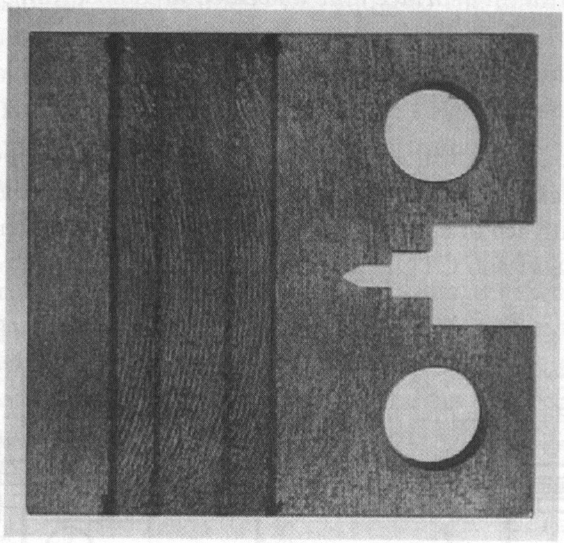

FIG. 5. Compact specimen with transversal weld (root side of the weld).

3. Results and discussion

Results of static tension tests are shown in Table 2. The following material parameters were calculated according to [8]: offset yield strength (OYS), lower yield limit (LYL), upper yield limit (UYL), ultimate tensile strength (UTS), elongation ($\Delta L/L$), cross-sectional area reduction ($\Delta A/A$). Every value is the average of two measurements. During each test, the load and axial strain were recorded in digital form. Example of such data in the form of stress – strain curve is shown in Fig. 6. It can be seen that the material in question is the construction steel with discontinuous yielding and the lower yield limit of approximately 350 Mpa, as supplied. Fusion zone and heat-affected zone have higher yield limits since fracture of TW specimens always occurs in parent material. Longitudinal weld (LW) specimens allow to estimate the material parameters of fusion zone that occupies approximately 80% of the specimen measuring part cross-section. Yield limit is elevated up to 420 MPa and the discontinuous yielding still can be observed. Ultimate tensile strength reaches almost 550 MPa. Ductility of the material decreases from 35% for the parent material down to 21% for the fusion zone, which is still acceptable for shipbuilding steels.

Table 2. Results of the static tension tests.

Flange thickness × web thickness		**8 × 8**	**15 × 12**			**20 × 15**
Number of laser runs		1 run	1 run	2 runs	3 runs	3 runs
OYS [MPa]	PM	–	–	–	–	–
	LW	–	–	–	–	–
	TW	–	–	–	–	354
UYL [MPa]	PM	417	346	337	363	358
	LW	448	423	437	452	477
	TW	375	355	353	351	–
LYL [MPa]	PM	341	294	291	282	304
	LW	411	402	411	419	459
	TW	346	320	303	315	–
UTS [MPa]	PM	473	440	437	444	480
	LW	535	526	535	545	586
	TW	477	460	461	461	494
$\Delta L/L$ [%]	PM	32	36	38	36	35
	LW	26	19	26	27	21
	TW	27	21	21	19	21
$\Delta A/A$ [%]	PM	56	58	62	62	66
	LW	61	40	62	57	43
	TW	61	57	54	52	63

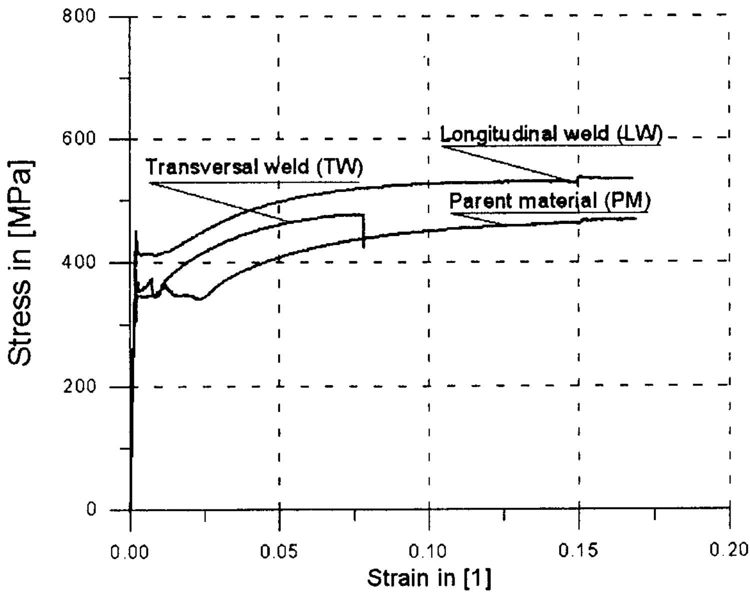

FIG. 6. Example of the stress-strain curves for three kinds of tensile specimens.

Table 3. Results of the bend tests.

Flange thickness × web thickness		8 × 8	12 × 12			20 × 15
Number of laser runs		1 run	1 run	2 runs	3 runs	3 runs
Passed [Yes/No]	TF	Yes	Yes	Yes	Yes	Yes
	TR	Yes	–	–	–	No
	LF	Yes	Yes	Yes	Yes	Yes
Maximum crack [mm]	TF	0	0	0	0	0
	TR	0	–	–	–	6
	LF	0	0	0	0	0
Longitudinal strain [1]	TF	0.23	0.26	0.26	0.27	0.25
	TR	0.23	–	–	–	0.25
	LF	0.24	0.26	0.25	0.26	0.26
Transversal strain [1]	TF	0.05	0.06	0.05	0.05	0.7
	TR	0.06	–	–	–	0.7
	LF	0.06	0.08	0.06	0.08	0.7

Ductility of the weld material was also investigated with the use of bending tests. Results of those tests are shown in Table 3. For the bend angle of 180°, the longitudinal strain on external surface of the specimen reached 0.26, transversal strain on external surface was close to 0.06. All the tests were performed successfully for transversal (TF) and longitudinal face (LF) specimens, for the transversal root (TR) specimens made of 20 × 15 joint, few cracks longer than 3 mm were observed. It seems that welding and cooling conditions were more severe on the root (interface) side of the flange resulting in lower ductility of the weld material. For this reason, all the specimens were machined from the flange as close as possible to the interface with the web.

Absorbed energy obtained as the result of impact (Charpy) test is shown in Table 4. These values are averaged after three measurements for the specimens machined of the fusion and heat-affected zone. Very large scatter of the data was observed due to the presence of weld defects, residual stresses and variation of the weld material properties. Results for 1 notch (standard) specimens are above the minimum criteria, which was assumed to be 27 J. Since there was no acceptance criteria for the specimens modified by side notches, results for this kind of specimens can only be compared for different zones of weld. It should be mentioned that no deviation of the crack from the notch tip into the base material was observed, so the results for standard (1 notch) specimens can be considered credible.

Table 4. Results of the impact (Charpy) tests.

Flange thickness × web thickness		**8 × 8**	**15 × 12**			**20 × 15**
Number of laser runs		1 run	1 run	2 runs	3 runs	3 runs
Absorbed energy [J] 1-notch specimen	Parent	33	–	–	–	–
	HAZ	27	56	91	40	73
	Weld	45	50	50	32	45
Absorbed energy [J] 3-notches specimen	Parent	8	–	–	–	21
	HAZ	5	16	12	19	22
	Weld	6	11	18	13	13

Results of the CTOD tests were recorded in digital form and on the basis of that data, plots showing the load as a function of COD were prepared. Typical plots for the parent material, heat-affected zone and fusion zone are presented in Fig. 7 together with fracture appearance for appropriate specimens. Characteristic values of the load P_m and plastic component of COD denoted by V_p that

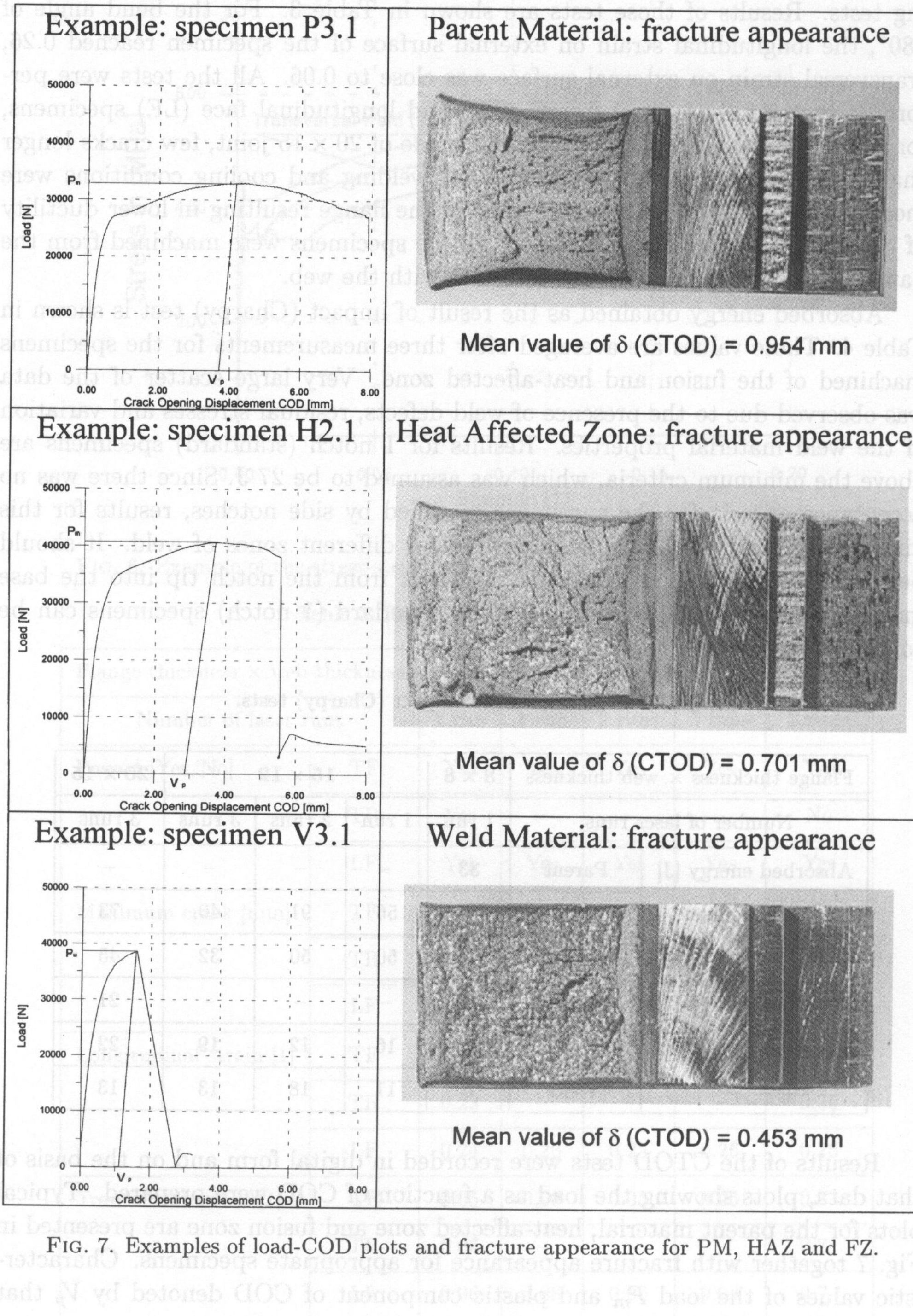

FIG. 7. Examples of load-COD plots and fracture appearance for PM, HAZ and FZ.

were used for CTOD calculations are also shown in this figure. It can be seen, that the maximum load necessary to break the specimen is higher for HAZ and FZ than for the parent material, but tear energy represented by area below the curve is smaller for FZ and HAZ than for parent material. Looking at the fracture appearance it is easy to observe that plastic deformation is also the smallest for the fusion zone. Tear energy per surface unit calculated according to the given formula is compared with results of the Charpy tests in Table 5. All the values of the energy absorbed during impact tests are averaged for 15 measurements for different configurations of the weld to avoid the data scatter. It can be seen that there is a clear relation between the unit tear energy and location of the specimens in the case of the CTOD test. That relation can be also hardly observed in the case of Charpy specimens with side notches, but the results for standard Charpy specimens seem to be randomly distributed in the weld zones. It is probably due to the fact that for elastic-plastic material (like the investigated steel), the result of impact test is strongly influenced by bending of the specimen. Also the notch tip radius variations play an important role (in the case of CTOD tests, sharp notch was produced by precracking) resulting in large scatter and random distribution of results.

Table 5. Comparison of tearing energy perunit of surface for CTOD and impact (Charpy) tests.

	Parent Material	Heat Affected Zone	Weld Material
Charpy (1 notch) Absorbed unit energy [J/mm^2]	0.550	0.738	0.591
Charpy (3 notches) Absorbed unit energy [J/mm^2]	0.358	0.285	0.270
CTOD test Absorbed unit energy [J/mm^2]	1.005	0.485	0.299

As a conclusion, it should be stressed that CTOD test is more appropriate to characterise fracture toughness of the material. Main results of the performed CTOD tests – the critical crack tip opening displacement (δ) for parent material, heat-affected zone and fusion zone are summarised in Table 6. Observing mean values for all the weld zones it is easy to notice the relation: δ (CTOD) value is the highest for parent material and decreases in the direction of the weld midline. This relation is similar to that in the case of unit tear energy and opposite to changes of the maximum load. It means that the more deformation the material can withstand without unstable crack growth, the more energy it can absorb during tearing, and from this point of view the fracture toughness of parent material is better. From the other point of view, the maximum load and maximum stress intensity factor K_I is higher for heat-affected and fusion zone. Designers should decide what is more important for the construction safety and appropriate material parameter must be used.

Table 6. CTOD test results.

Parent Material					
Specimen code	P3.1	P3.2	P3.3	P4.4	P4.5
P_m [kN]	32.87	32.84	32.26	33.08	35.62
V_p [mm]	3.84	3.24	3.36	3.68	4.22
δ [mm]	0.990	0.844	0.866	0.945	1.124
$\delta_{(mean)}$	Mean value of δ (CTOD) = 0.954 mm				
Heat-Affected Zone					
Specimen code	H2.1	H2.2	H2.3	H2.4	H4.5
P_m [kN]	40.56	37.75	38.32	37.73	37.28
V_p [mm]	2.87	2.23	2.74	2.19	3.04
δ [mm]	0.793	0.603	0.727	0.529	0.791
$\delta_{(mean)}$	Mean value of δ (CTOD) = 0.701 mm				
Weld Material					
Specimen code	V3.1	V3.2	V3.3	V4.4	V4.5
P_m [kN]	38.64	40.62	41.01	39.66	42.90
V_p [mm]	1.09	1.05	2.44	1.56	1.95
δ [mm]	0.315	0.317	0.650	0.433	0.551
$\delta_{(mean)}$	Mean value of δ (CTOD) = 0.453 mm				

Fatigue crack growth rate da/dN was investigated for a crack propagating transversally to the weld midline. For all the 5 specimens the data were recorded in digital form, and the plots showing da/dN and N as a functions of crack length were prepared. Example of such a plot is shown in Fig. 8. Thick line represents the number of load cycles necessary to obtain appropriate crack length, and thin line shows the fatigue crack growth rate da/dN. Vertical lines in this figure mark fusion zone on the root side of the flange, fracture appearance is shown above. Following parameters characterising the load level for all the test were applied: $K_{\max} = 36.4$ MPa·m$^{0.5}$, $R = 0.1$. It can be easily seen that crack slows down coming through the weld material. Averaged values of fatigue crack growth rates for all five tests are shown in Tab. 7. It should be stressed that the result of the test was the same for all cases: da/dN was lower for the weld than for the parent material. It seems to be very simple criterion of the weld fracture toughness – the weld material in question is of very good quality.

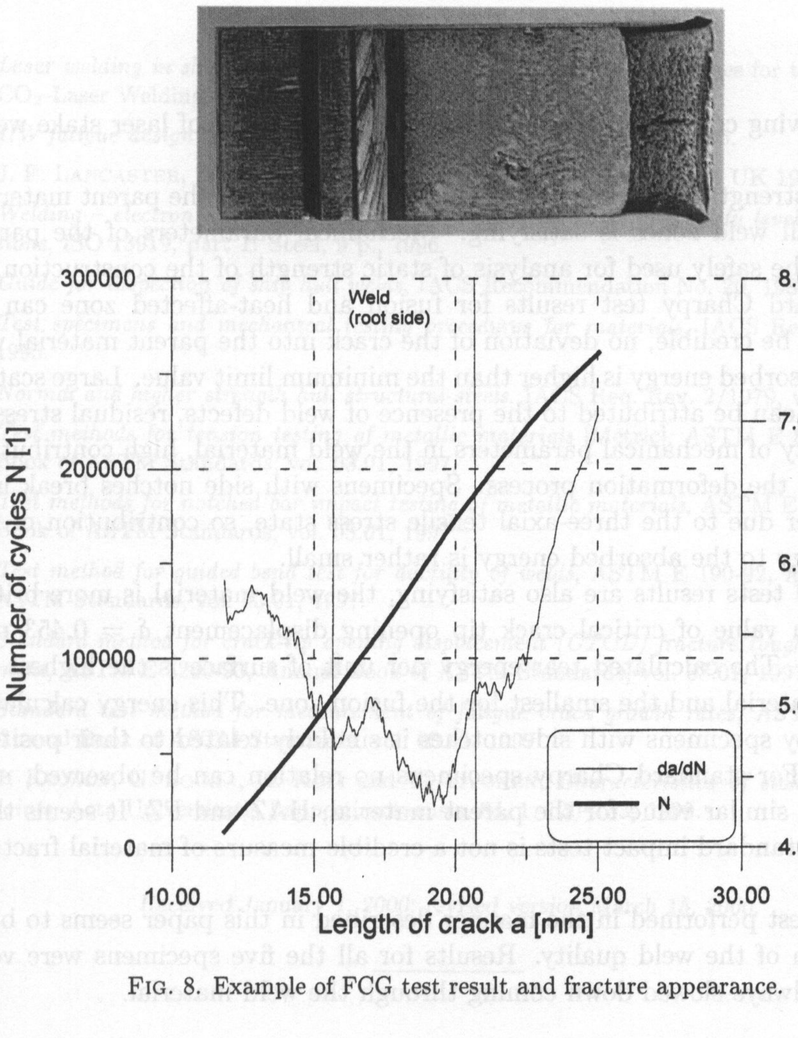

FIG. 8. Example of FCG test result and fracture appearance.

Table 7. FCG test results.

Specimen code	K_{max} [MPa· $m^{0.5}$]	$(da/dN)_{weld}$ [mm]	$(da/dN)_{HAZ}$ [mm]
G2.7	33.2	4.6E-5	5.6E-5
G2.8	36.4	8.0E-5	1.0E-4
G3.6	36.4	7.5E-5	9.0E-5
G3.7	36.4	7.5E-5	8.0E-5
G3.8	36.4	8.0E-5	8.5E-5

4. Conclusions

The following conclusions can be drawn from this study of laser stake welds strength:

1. Static strength of FZ and HAZ is better than that for the parent material, ductility of all weld zones is satisfying. Mechanical parameters of the parent material can be safely used for analysis of static strength of the construction.

2. Standard Charpy test results for fusion and heat-affected zone can be considered to be credible, no deviation of the crack into the parent material was observed. Absorbed energy is higher than the minimum limit value. Large scatter of the results can be attributed to the presence of weld defects, residual stresses, non-uniformity of mechanical parameters in the weld material, high contribution of bending in the deformation process. Specimens with side notches break in a brittle manner due to the three-axial tensile stress state, so contribution of the bending energy to the absorbed energy is rather small.

3. CTOD tests results are also satisfying, the weld material is more brittle but the mean value of critical crack tip opening displacement $\delta = 0.453$ mm is acceptable. The calculated tear energy per unit of surface is the highest for the parent material and the smallest for the fusion zone. This energy calculated for the Charpy specimens with side notches is similarly related to their position in the weld. For standard Charpy specimens no relation can be observed, unit energy is of a similar value for the parent material, HAZ and FZ. It seems that the result of standard impact tests is not a credible measure of material fracture toughness.

4. FCG test performed in the manner described in this paper seems to be a good criterion of the weld quality. Results for all the five specimens were very good; crack always slowed down coming through the weld material.

5. Mechanical parameters of the fusion zone and the heat-affected zone are very good. Only the stake weld geometry (stress concentration, weld defects etc.) can be the reason for construction failure. To check this possibility, extensive program of the fatigue tests was performed. Results of such tests will be reported elsewhere.

ACKNOWLEDGEMENTS

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