FATIGUE COD - A METHOD OF QUALITY CONTROL OF WELDS

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A method of controlling specified minimum toughness values for welds and other inhomogeneous materials is presented.

By use of fatigue loading a crack is grown through the zones of interest in the specimen while maintaining constant crack tip loading conditions. For QA applications loads equal to specified minimum toughness are applied.

The advantage of the method as compared to conventional fracture mechanics testing is that a large volume of material is investigated in each specimen thereby increasing the possibility of hitting a local brittle zone.

The efficiency of the method is demonstrated.

INTRODUCTION

In large welded components and structures cracks or crack-like defects are inevitable and the consequences of the defects on the safety of the structure should be assessed. Even if non-destructive testing does not give any crack indications it will be safe to assume that cracks may be found the size of which equal the sensitivity limit of the NDT method used. Based on known stress levels and possible or measured crack sizes the methods of fracture mechanics may be used to specify necessary minimum toughness of the material. It is then the task of quality assurance to ensure that actual weld properties are above the lower-bound values specified.

Unfortunately, the material properties in a multi-pass weld vary very much over small distances especially near the fusion line and because crack tips could be positioned anywhere a test method is needed which quickly can be used to assess lower-bound toughness value in welds.

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Conventional COD testing is not a suitable method because only the properties of a small volume of material at the tip of the crack contribute to the test result. In order to find lower-bound COD-values a large number of test specimens is required with the fatigue crack fronts positioned in different regions of the weld. Use of conventional COD testing is therefor a costly way of establishing lower-bound values.

The fatigue COD test method proposed by Tanaka, Sato and Ishikawa (1), (2), is a relatively new test method which was proposed to measure minimum COD in welds by growing fatigue cracks across fusion lines.

Søvik (3), (4), investigated the usability of the method but with less promising results due to excessive plasticity of the test specimens and difficulties in controlling the path of the fatigue crack.

The approach taken here is to view the fatigue COD test method not as a mean of determining lower-bound COD values, but as a mean of controlling quality. By growing a fatigue crack through the weld zones of interest at specified and constant crack tip loads and not allowing pop-ins or failure to occur, then, after a successful test, it might be stated, that for the chosen crack path, the minimum COD-value is higher than the value used in the test.

PRINCIPLES OF THE FATIGUE COD TEST METHOD

The principle of the fatigue COD test method is to grow a fatigue crack through the zones of interest while maintaining constant stress intensity factor conditions at the crack front, i.e. constant K_{max} and ΔK.

If the crack front eventually enters a brittle region in the material, the crack may jump. Depending on load, geometry and size of the brittle zone the jump may be small, i.e. a pop-in, or it may lead to total failure of the specimen. A jump indicates, that the strength of the brittle zone is smaller than K_{max}.

Each load cycle is regarded as an individual COD test and a fatigue COD load is calculated as shown on fig. 1. In contrast to a conventional COD test, fracture is not intended and indeed for QA applications fracture is not wanted.

As the fatigue crack length increases during the test, the loads on the specimen must be adjusted in order to maintain constant crack tip loading conditions. Therefor the crack length must be monitored accurately and the loads corrected correspondingly.

TEST PLAN FOR FATIGUE COD TESTING

Fatigue COD tests were conducted for a variety of test parameters for which conventional COD data had already been generated (Poulsen and Rotvel (6)). Parameters investigated were steel type, weld heat input and notch position.

Steel type. Data for the steels are given in Table 1. Both steels were delivered as 50 mm plate.

Specimen. SENB type specimens with square cross section as shown on figure 2 were used. Side notches were machined before fatigue loading. Side notches are essential because they increase the constraint and they help to control the path of the fatigue crack.

Test temperature. Test temperatures were chosen in the lower end of the transition range of the base materials.

TABLE 1 - Chemical analysis and mechanical properties of materials.

Steel D: Normalized low-carbon steel.							
C %	Mn %	Si %	P %	S %	Cr %	N %	B %
.10	1.23	.44	.015	.008	.01	.0075	.0004
R_e (MPa)		R_m (MPa)		A_5 (%)		KV, 0°C (J)	
351		488		33		L:253; T:198	

Steel J: TMCP low-carbon steel.							
C %	Mn %	Si %	P %	S %	Cr %	N %	B %
.07	1.56	.30	.004	.001	.02	.003	.0012
R_e (MPa)		R_m (MPa)		A_5 (%)		KV,-30°C (J)	
410		498		34		413, 357, 339	

Weld. Weld geometry is shown on figure 3. Heat inputs of 3 and 10 MJ/m were used. The number of passes were 16 and 6 respectively.

Notch position. The starter notches were either through thickness or surface notches (figure 3). Both the starter notches and the side notches were positioned as much as possible in the coarse grained heat affected zone (HAZ) as indicated by an etching on the sides of the specimens. Due to the wavy nature of the HAZ in depth, especially for the high heat input welds, correct positioning was not always achieved as was later revealed in metallographic examinations.

Load. The loads were chosen on basis of previous conventional COD test results (6). The maximum K_I value in the load cycle was chosen to be smaller than the lowest K_I value reported for conventional COD tests in the same test group. ΔK in the load cycle was chosen to be relatively large (1100 to 1500 $MPa\sqrt{mm}$) in order to speed up the fatigue crack growth. Corresponding R-values ($R = K_{min}/K_{max}$) varied between 0.2 and 0.5. The frequency of the fatigue loading was 10 Hz.

Monitoring. The specimens were equipped with transducers for measuring notch opening, temperature and DC potential drop as shown on figure 2. For each of the transducer signals the maximum and the minimum value in each load cycle were stored. After a specified number of cycles (usually between 200 and 1000) average values were calculated. The DC potential drop signal was used to calculate an effective crack length using an experimental calibration curve (figure 4) measured on a specimen with the same geometry.

Test machine. A servohydraulic test machine equipped with a cooling chamber was used. The cooling medium was CO_2. During the test the control signal for the load of the test machine was automatically adjusted according to the measured length of the fatigue crack.

TEST RESULTS

A summary of the fatigue COD test results is given in Table 2. The results shown are crack tip loadings just before final fracture. On figure 5 the values of δ_{FCOD} and K_{Imax} at fracture are compared with corresponding values obtained in conventional COD tests. In all FCOD tests fracture occurred at crack tip loads in the low end of conventional COD test values, i.e. with the FCOD test it is possible to find the brittle zones in the HAZ.

TABLE 2 - Test Results.

Test grp. no.	Steel	Heat input MJ/m	Notch pos.	Test temp °C	Crack growth mm	δ_{FCOD} mm	K_I MPa√mm
2.1	D	3	Thr.	-60	27.7	-	970
2.2	D	3	Surf.	-60	13.6	.080	3450
3.1	D	10	Thr.	-60	0.0	.053	1800
3.1	D	10	Thr.	-60	1.5	.023	1530
3.2	D	10	Surf.	-60	2.5	.023	1470
3.2	D	10	Surf.	-60	0.0	-	2500
5.1	J	3	Thr.	-80	3.5	.053	2570
5.2	J	3	Surf.	-80	15.2	.045	2460
6.1	J	10	Thr.	-80	0.5	.044	2370
6.1	J	10	Thr.	-80	11.9	.032	1640
6.2	J	10	Surf.	-80	0.6	.041	2060

On the FCOD specimens, fatigue crack growth between 0 and 27.7 mm were registered before final fracture. Examples of crack tip loading versus crack length are shown on figure 6. It is clear that the crack tip loading has not been quite constant during the test.

The fracture surfaces were plane and followed the root of the side notches.

DISCUSSION

In conventional fracture mechanics testing it is a recommended practice to use small fatigue loads when producing the starter fatigue crack in order to minimize crack tip blunting. In Fatigue COD tests comparatively high fatigue loads must be used because each load cycle is regarded as an individual COD test. However, the results obtained in this report show that the Fatigue COD test consistently measures low toughness values, i.e. crack tip blunting is not a problem. The reason may be that crack tip blunting also occur in a conventional COD test in the final monotonic load application.

It is crucial for the application of the FCOD method that crack tip load conditions be maintained constant during the intended crack growth. For long crack growth this is difficult and the method of monitoring crack length needs further improvement.

The FCOD test method finds limitations when high toughness values are specified. If the loads are high the specimens may deform plastically and it may be difficult to control the path of the fatigue crack, (4). However in QA applications this is not a restriction because the values of interest normally will be in the low end.

The FCOD method may also be used to investigate fusion lines lying in an angle to the plate surface by cutting out samples in the appropriate directions. Large size specimens may then be manufactured using electron beam welding techniques (Klausnitzer (8)).

CONCLUSIONS

The tests demonstrate that the fatigue COD test method is well suited to scan a weld HAZ for local brittle zones. It has been possible to grow a fatigue crack along the coarse-grained HAZ in a controlled way and to obtain fracture toughness data that are consistently lower than conventional COD test results. The fatigue COD test method is therefor a better method to be used in quality control.

The results raise questions about the suitability of conventional COD testing for measuring the fracture toughness of welds. Even though every precaution was taken to manufacture and to pre-fatigue identically all specimens, conventional COD tests gave a very large scatter. Therefor a large number of conventional COD tests is needed to find minimum strength values.

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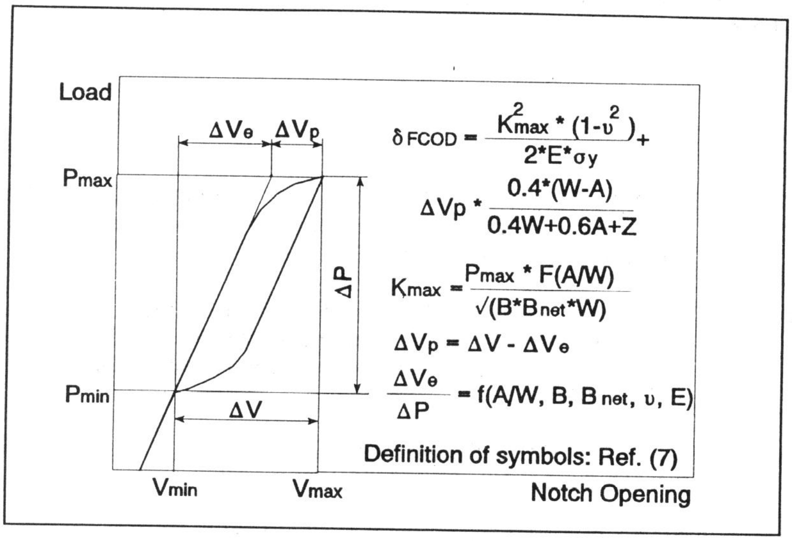

Figure 1. Definition of maximum fatigue COD load on the crack tip in a fatigue load cycle.

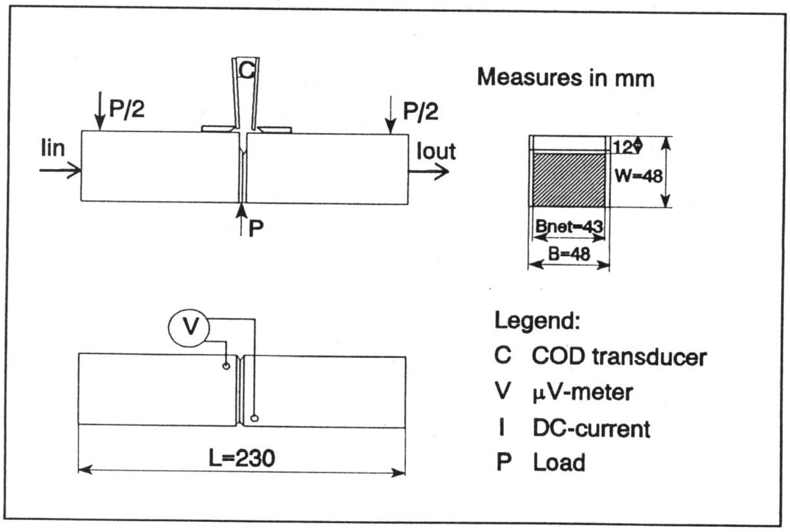

Figure 2. Specimen geometry and instrumentation.

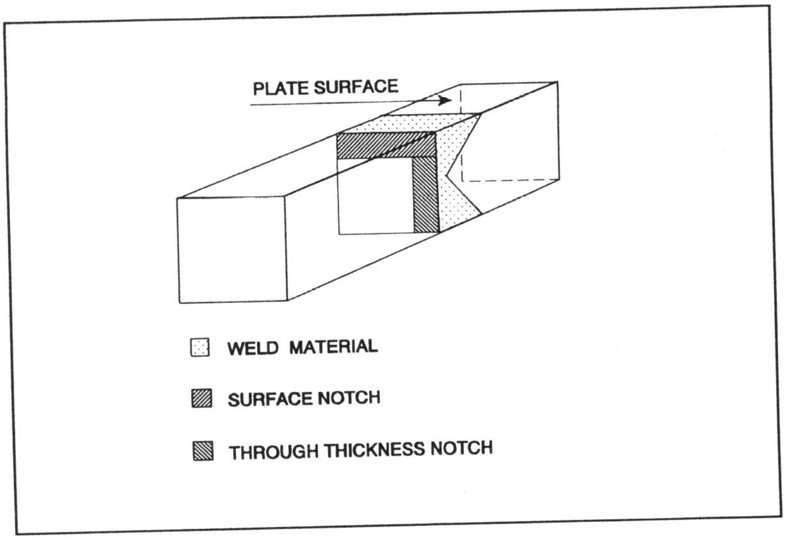

Figure 3. Weld cross section and starter notch positions.

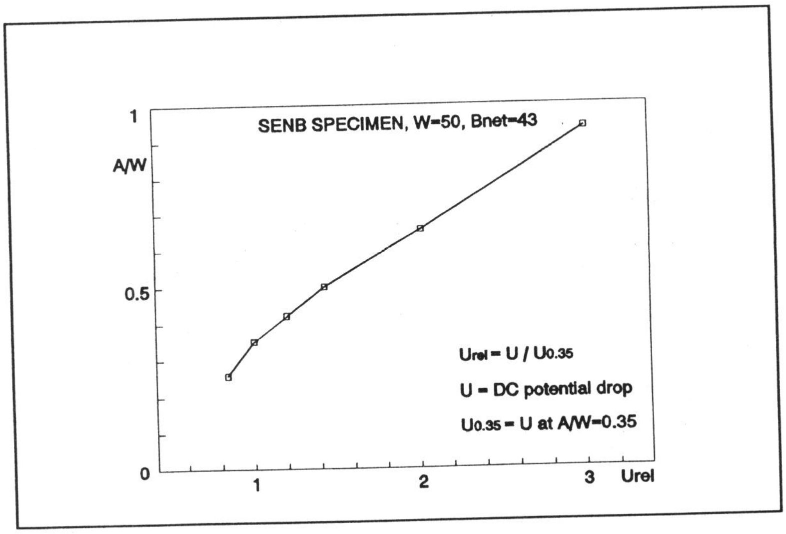

Figure 4. DCPD calibration curve measured on a specimen with the same geometry as the test specimens.

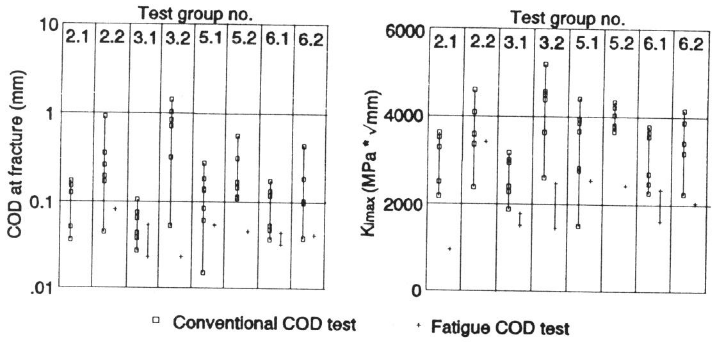

Figure 5. Comparison between conventional COD results and fatigue COD results.

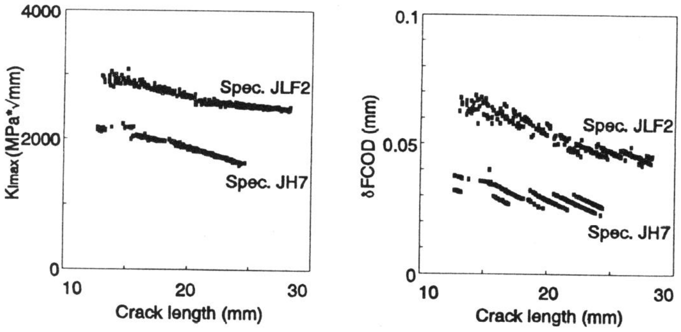

Figure 6. Examples of maximum crack tip loads in the fatigue cycle versus crack length.