Fatigue Crack Growth Rate Measurement in Welded Joints

P. Žlábek[1] and V. Mentl[2]

[1] West-Bohemian University Pilsen, Czech republic, zlabek@kme.zcu.cz
[2] SKODA Research Ltd., Pilsen, Czech Republic, vaclav.mentl@skoda.cz

ABSTRACT. *The paper gives a survey of experimental results of fatigue crack growth rate measurement in a CrMoV pressure vessel steel weldments. Within the repair welding technology project, the fatigue through-thickness, semi-elliptical surface crack growth rates measurement in weldments was carried out. Centre-Crack-Tension (CCT) test specimens of two different rectangular cross-sections were machined from a Cr-MoV steel. Two welding technologies, manual metal arc and tungsten inert gas welding, were applied and specimens in as welded state and after heat treatment were tested at room temperature. The crack growth rates were measured for both the base and weld metals and also in the case of crack subsequent transition through all the weld zones. The crack growth rate of semi-elliptical surface cracks was evaluated and compared with the CCT 2D results.*

INTRODUCTION

Majority of nowadays structures is produced as weldments of various geometry and technology and heterogenous and anisotropic structure of specific welds and heat affected zones and technology of welding affect the crack growth rate and the resistance to brittle fracture, what is the basic question when the structure safe life and service safety and reliability is concerned.

The phenomenon of fatigue is responsible for up to 95% of failures of structural components and structures. Fatigue is the result of cyclic loading of components by forces smaller than those required to cause immediate failures. Nevertheless there is certain time between crack initiation and final fracture, the amount of which depends upon the crack growth rate in the material and respective service conditions, and which is often described by means of fracture mechanics. The crack growth rate measurement of long cracks that are in the validity range of LEFM are most frequently used as a measure of fatigue crack growth rate in various materials and material structures.

The aims of this study were:

- to compare crack growth rates of surface cracks with those measured in CCT specimens
- to compare the results of as welded weldment and the properties of welds after heat treatment, and
- to provide designers and users simple experimental data for important subsequent safety and reliability assessment

Within the scope of an engineering practise, the phenomenon of the fatigue crack growth is generally solved as the problem of a crack growth in the elastic-plastic continuum and the Paris-Erdogan equation has been recognized as the basic solution of this problem. Thus we describe the growth of a crack in a continuum as the explicit relationship of crack growth rate and the stress intensity factor amplitude in the form:

$$da/dN = A\ (\Delta K)^{m} \qquad (1)$$

where the constants ***A*** and ***m*** characterize the properties of the material.

The basic Paris-Erdogan equation does not make it possible to describe the crack growth rate in other than phenomenologic manner. No other material parameters are included and assessed, nevertheless this equation is compatible with the basic engineering and mathematical approach that generally recognizes the structural component as a homogenous material.

MATERIAL AND TEST SPECIMENS

The fatigue crack growth rate measurement was performed on CrMoV pressure vessel steel and weldments at room temperature. The chemical composition and mechanical properties of the CrMoV steel are given in Tables 1 and 2.

Table 1. Chemical composition of the base metal [%]

C	Mn	Si	P	S	Cr	Ni	Mo	V	As	Co	Cu
0,15	0,37	0,34	0,011	0,012	2,68	0,16	0,60	0,26	0,008	0,010	0,10

Table 2. Room temperature mechanical properties of the base material

Ultimate strength	Yield point	Elongation	Contraction	Notch toughness
R_m	$R_p0,2$	A_5	Z	KCV
MPa	MPa	%	%	Jcm^{-2}
655	430	15	50	78

Test specimens were prepared by two welding technologies:
No.111, manual metal arc welding (MAW), and
No.141, tungsten inert gas (TIG) welding according to EN ISO 4063 .

Fatigue crack growth rate measurement was performed at room temperature both for test specimens in as welded condition and after heat treatment (HT). Three types of CCT test specimens, see Fig.1, were used for the fatigue crack growth rate measurement to simulate the repair welding procedure:
Type 1 - CCT test specimen of base material, dimensions 12 x 50 x 250 mm,

Type 2 - CCT test specimens, dimensions 12 x 50 x 250 mm, welded transversally so that the crack grew longitudinally in the weld metal only,

Type 3 - CCT specimens, dimensions 12 x 100 x 250 mm, containing weld metal areas, where the crack started to propagate from the base metal transversally across the heat affected zone (HAZ), weld metal, HAZ and again returned to the base metal symmetrically to the specimen axis.

EXPERIMENTAL PROCEDURE

The method of automatic fatigue crack growth rate measurement and registration in CCT test specimens based on the load control according to the compliance changes during the crack growth and the experimental data correction are in more detail described in [1].

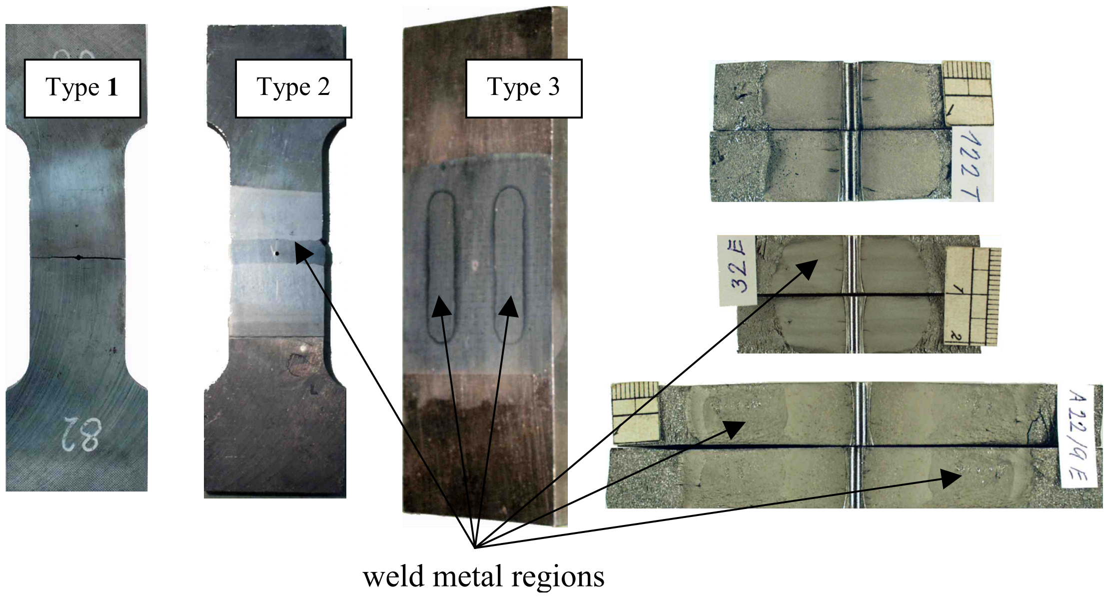

Figure 1. TYPE 1, TYPE 2 and TYPE 3 CCT test specimens.

The surface semi-elliptical cracks growth at cyclic loading was used to visualize the surface crack progress when cracks were growing through heterogenous structures of the weld. The crack starters were machined at the specimen surface and specimens then loaded in cyclic tension $F_{min}/F_{max} = 0,1$ at the frequency 8 – 10 Hz at room temperature. The crack progress was in detail measured after the test on fracture surfaces, where the crack dimensions in relation to number of cycles were determined by heat-tinting method. The ΔK levels were calculated by use of the simplest formula derived already by Irwin [2], and an average value of stress intensity factor was taken into account between two adjacent crack trajectories. The crack growth rate values of semi-elliptical surface cracks were calculated for the deepest point of the crack tip.

EXPERIMENTAL RESULTS OF CRACK GROWTH RATE MEASUREMENT

Figures 2 to 7 show examples of the experimental corrected crack growth rate data obtained for the TYPE 2 and TYPE 3 test specimens without and after heat treatment. A comparison was also made of weldments and basic material and the crack growth rates measured for surface semi-elliptical cracks. The „right-hand“ side of test specimens is shown in these figures only, in case of TYPE 3 test specimens two symmetrical cracks were initiated and grew in order that the symmerical loading could be assumed.

It is evident that the application of Paris – Erdogan crack growth rate equation in its simplest form can distinguish both the various welding technologies and also the effect of stress relieving heat treatment after welding. Also, the crack growth rate measured in discrete points of surface crack growth are in good agreement with the 2D CCT specimen results.

The surface crack progress curves can reflect the different mechanical properties of base and weld metals so that the crack changed its shape pronouncedly when it grew into the weld metal, see Figs 10 and 11 (The mechanical properties evaluation revealed the localized decrease of Charpy impact absorbed energy values along the bond boundary in as welded weldment, which was partially removed by the subsequent heat

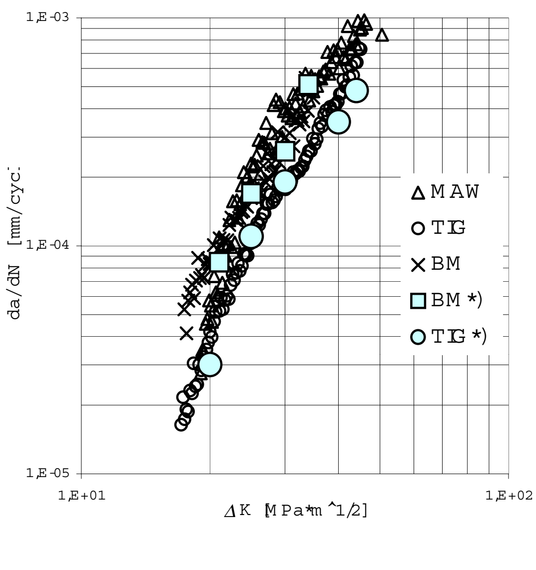

Figure 2. Type 2 specimen crack growth rate results in as welded condition (designation *) stands for surface cracks).

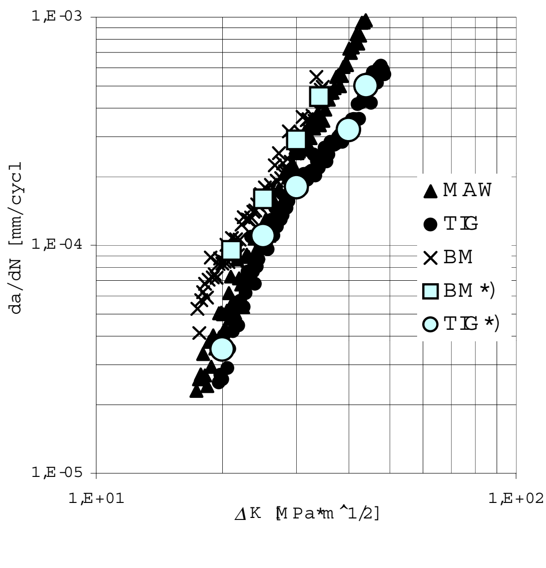

Figure 3. Type 2 specimen crack growth rate results after heat treatment (designation *) stands for surface cracks).

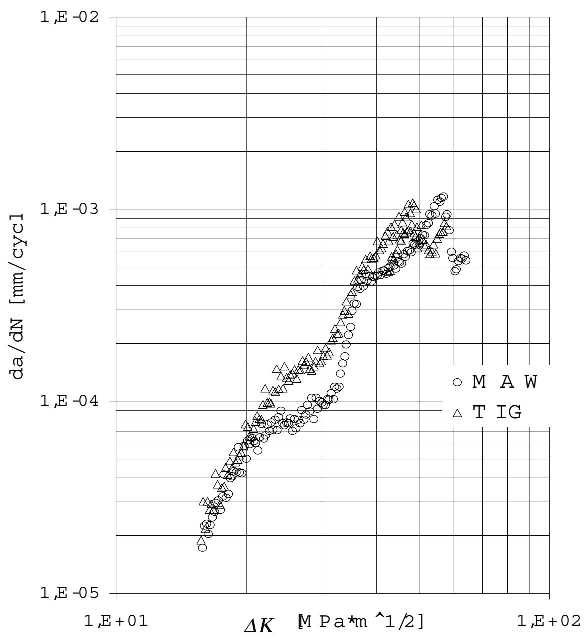

Figure 4. Type 3 specimen crack growth rate results in as-deposited condition.

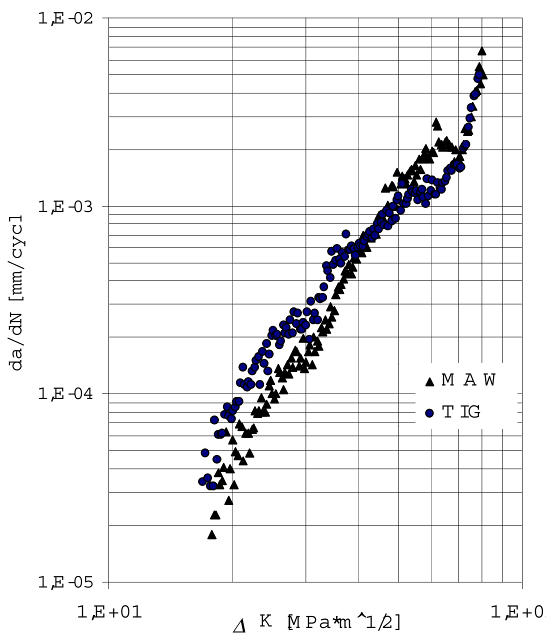

Figure 5. Type 3 specimen crack growth rate results after heat treatment.

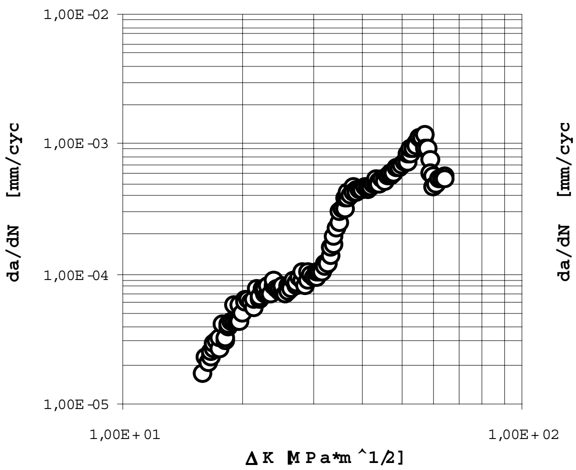

Figure 6. Fatigue crack growth rate data for TYPE 3 test specimen in as-deposited condition.

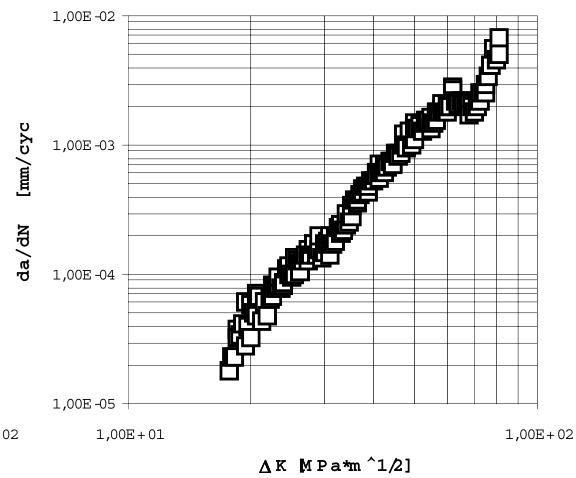

Figure 7. Fatigue crack growth rate data for TYPE 3 test specimen after heat treatment.

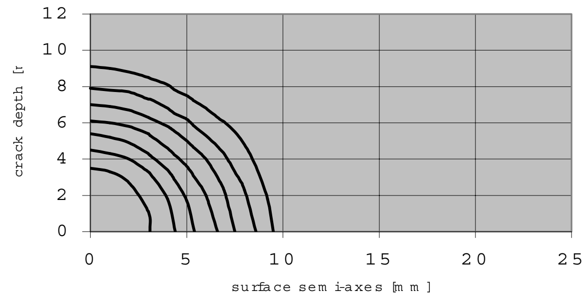

Figure 8. Cyclic Tension Surface Crack Shapes (Base Metal).

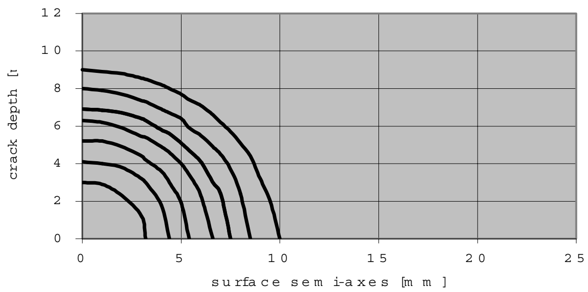

Figure 9. Cyclic Tension Surface Crack Shapes (Weld Metal).

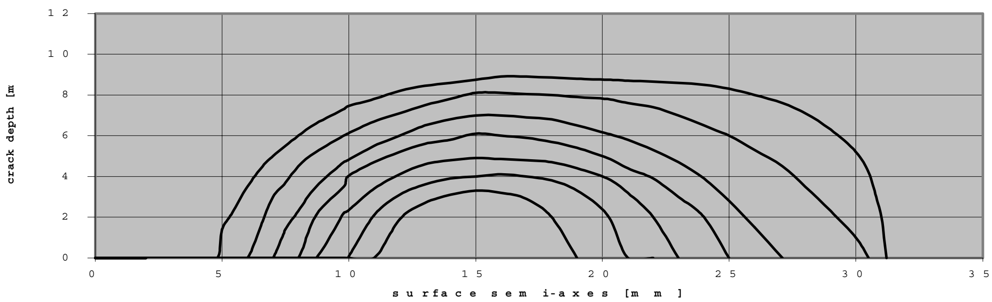

Figure 10. Cyclic Tension Surface Crack Shapes
(Crack Growth from Bond Line into Base and Weld Metals, As Welded).

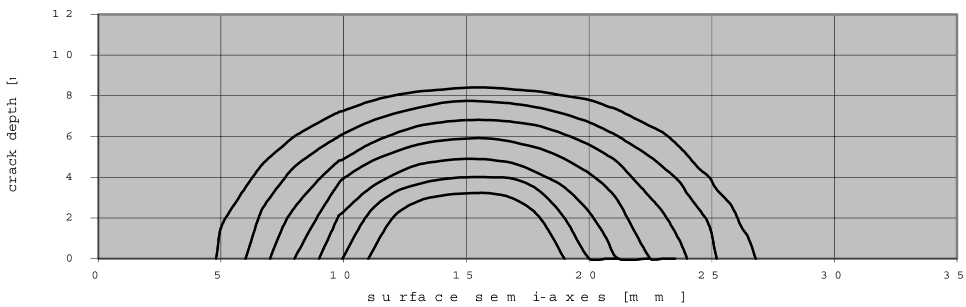

Figure 11. Cyclic Tension Surface Crack Growth Shapes
(Crack Growth from Bond Line into Base and Weld Metals, after HT).

treatment. The fact that the crack front did not reflect this decrease in a change of the shape from nearly semi-elliptic may be explained by a localized extent of this zone where the crack front along the bond line was fixed by less slowly growing cracks in base and weld metals.) In the case of TYPE 3 test specimens, the weld metal region inside the base metal can be seen between 15 and 30 mm along the X-axis in Figs 8 to 11.

DISCUSSION

The presented fatigue crack growth rate results of TYPE 2 test specimens, see Figs 2 and 3, revealed better quality of the TIG welding technology (from the crack growth rate point of view) in comparison both with manual arc welding and also the base material in as welded condition. Applied heat treatment caused pronounced retardation in the manual arc weld crack growth rate up to the level of TIG technology, so that the properties of by both the technologies produced welds are better than those of the base metal after heat treatment.

The presented fatigue crack growth rate results of TYPE 3 test specimens, see Figs 4 and 5 revealed a steep increase of crack growth rate within the heat affected zone in the as welded condition which was followed by an increased rate within the weld metal. At the end of the weld metal region, the crack growth rate decreased again monotonically to the values expected in the base metal. This steep changes in crack growth rates were not observed in the case of surface cracks, where the surrounding „better quality“ base and weld metals caused retardation of the crack growth rate along the bond lines.

The transition of the crack through the weldment thus resulted in the change of both ***A*** and ***m*** constants of the Paris-Erdogan Law within the heat-affected zone, whereas during the subsequent propagation through the weld metal was the ***m*** constant approximately of the same value as it was within the base metal and ***A*** change was observed only, what resulted in about half an order higher crack growth rate in the weld metal and approximately parallel lines of crack growth rates in base and weld metals expressed in double-log coordinates.

The stress-relieving heat resulted in removing steep changes of the crack growth rate and approximately one monotonic curve was obtained. It is also well visible at the semi-elliptical and corner crack propagation on the fracture surfaces.

CONCLUSION

- Basic Paris-Erdogan Law and the simplest Irwin´s equation describing the fatigue crack growth rate and stress intensity factor for surface crack respectively where used to describe the crack growth rates of surface cracks
- A distinct acceleration of crack growth rate ocurred in the TYPE 3 test specimen in as welded state without heat treatment.
- The crack growth rate revealed no pronounced changes among base metal, HAZ and weld metal after the heat treatment was applied. Applied heat treatment caused

retardation of the manual arc welding to the base metal level in case of manual arc welding.

REFERENCES

1. Žlábek, P. and Mentl, V. (2003) *Proc. ICM9*, Geneva , Switzerland.
2. Irwin, G. R. (1962) *J. Appl. Mech.* **29**, 651-654.

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