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USE OF DIFFERENT METHODS OF FATIGUE CRACK CLOSURE MEASUREMENT AND THEIR COMPARISON

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Abstract: The paper contains results of a set of experimental works performed on two types of steels with different mechanical properties, particularly strength and yield stress, with the aim to contribute to the explanation of doubts about possibilities of measurement of fatigue crack closure conditions. Measurement on CT specimens was performed using: (i) videoextensometer on edges of crack mouth – initiation notch, (ii) mechanical semiconductor extensometer near the crack mouth, (iii) mechanical extensometer on opposite side to crack mouth, i.e. in the compression area, (iv) strain gauges at the immediate vicinity of crack tip and (v) strain gauges placed on the side area near opposite edge. Some differences of measurement results are compared and discussed from the viewpoint of pin hole clearance and other aspects like near crack tip plastic zone. It was shown that insufficient clearance fit strongly affects results particularly in the case of higher strength steel.

1. Introduction

Crack closure phenomenon has become a matter of numerous discussions since its publishing by Elber [1], indicating that its complete theoretical explanation and interpretation has been and still is a rather complicated task, much more complicated that it looked to be in the beginning, when the closure theory was quite successfully used to explain numerous differences in fatigue crack growth (FCG) behavior. Particularly in recent years, several papers has been published, which either infirm an existence of some types of closure effects on FCG in general, eg. plastic closure at plain strain conditions [2], experimentally measured crack closure values or methods of the measurement [3] or discuss problems with an interpretation of so called partial closure [4,5]. Some of the works are aimed at proposing modifications of FCG and closure theoretical models and their parameters, whereas an optimum consolidation of FCG data da/dN versus stress intensity factor range ΔK in the stable Paris or threshold regions are considered as an evidence to support such models [3]. On the other hand, such approaches working mainly on mathematical basis, though they lead to a promising universal expression of crack growth, may be unfortunately rather detached from physical meaning and technical reality.

It is clear that the recent discussions in the field have improved the general knowledge and have referred to the complexity of this phenomenon, which is not easy to be described using a uniform approach for different closure types. On the other hand, the problematic issues should not result in a general meaning that crack closure phenomenon is something which has nothing to do with physical – technical reality or cannot be applied in practice at all.

The aim of this work was to contribute to the explanation and solutions particularly of problems and uncertainties connected with consistency of results of experimental crack closure measurement obtained using different selected experimental methods, namely near

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crack mouth, on the opposite edge to crack mouth, i.e. in the compression area and eventually near crack tip.

2. Experiments

The crack closure measurement was performed on two CT-specimens of width 75 mm. Two types of high-pressure gas pipeline steel were used, namely X60 and X70 according to the API 5L standard nomenclature, with the aim to verify, weather and how different mechanical properties like yield stress and strength affect the results. Corresponding marking of the steels according to the EN 10208-2 standard is L 415 MB and L 485 MB, respectively. Concerning the X60 steel with lower strength and yield stress, the specimen thickness was 6 mm unlike the X70 steel with the specimen thickness 7 mm. The actually evaluated chemical composition and mechanical properties [6] are in the following Tables 1 and 2.

Table 1: *Chemical composition of experimental material in weight percentage*

Steel	C	Si	Mn	S	P	Mo	Al	V	Nb	Ti
X60	0,086	0,24	1,36	0,02	0,005	0,005	0,044	0,014	0,034	0,017
X70	0,097	0,43	1,64	0,008	0,002	0,079	0,05	0,057	0,055	0,049

Table 2: *Mechanical properties of experimental material*

Steel	Yield Stress (MPa)	Strength (MPa)	Ductility (%)	Area Reduction (%)
X60	434	538	29.2	74.5
X70	491	605	25.1	72.7

Fatigue cracks were prepared in both the specimens by the identical method. Load asymmetry was R = 0.5, load frequency was between 25 and 30 Hz. Crack growth was monitored using direct current potential drop (DCPD) method and computer controlled device developed in the laboratory in the past [7,8]. Both the specimens were loaded with the same nominal stress range in two stages. Details of the pre-cracking are in Table 3, *a* being crack length, $\sigma_{nom,max}$ maximum value of nominal stress, stress intensity factor K is expressed in MPa $m^{1/2}$.

Table 3: *Details of the procedure of preparation of fatigue cracks*

	Stage I, $\sigma_{nom, max}$ = 34.3 MPa				**Stage II, $\sigma_{nom, max}$ = 28.6 MPa**	
Specimen	**a_{ini} (mm)**	**a_{end} (mm)**	**$K_{max\ ini}$**	**$K_{max\ end}$**	**a_{end} (mm)**	**$K_{max\ end}$ (MPa $m^{1/2}$)**
X60	11.35	21.3	34.4	50.6	24.9	47.8
X70	11.35	23.4	34.4	54.4	24.7	47.5

It can be seen from Table 3 that there were similar conditions during fatigue pre-cracking. Particularly important are identical conditions after finishing the pre-cracking, namely maximum value of stress intensity factor Kmax = 47.8 MPa $m^{1/2}$ and 47.5 MPa $m^{1/2}$, respectively.

As regards the plastic zone size radius for the plain stress conditions, it was calculated according to the formula $r_p = (1 / 2\pi) (K_{max} / R_p0.2)^2$, where K_{max} is expressed in MPa $mm^{1/2}$. Total plastic zone size was assumed to be 2-times r_p. Plastic zone size for the plain strain conditions corresponding more to the specimen center is 3-times smaller than that for the plain stress conditions corresponding more to the specimen surface. Calculating actual values of the plastic zone size at the end of pre-cracking for the plane stress state, they corresponded to 3.9 mm and 3.0 mm, respectively, for the specimens X60 and X70, respectively.

Crack closure was measured at conditions of quasi-static loading, the total time of one loading / unloading cycle of triangular character being approximately between 20 – 30 s. Concerning the first method, fully computer controlled Videoextensometer NG of Messphysik Materials Testing GmbH was used for the recording of mutual displacement of crack mouth (more exactly notch mouth) edges – crack mouth opening displacement (CMOD). Within the second and third methods, respectively, displacement was measured by a high precision semiconductor extensometer INOVA PXA with the gauge length 20 mm. The extensometer was connected to the analogue-digital converter and computer to ensure automatic digital data recording. CMOD was measured near the notch mouth and alternatively, displacement was measured on the edge opposite to notch mouth. As regards the last method, measurement was performed using strain gauges bonded on sides of the specimens. One strain gauges was glued in the vicinity of crack tip, i.e. crack tip opening displacement (CTOD) was recorded. The position of the second gauge was 15 mm from the edge opposite to crack mouth. Specimen with the strain gauges and the extensometer INOVA attached on the loading machine is in Figure 1.

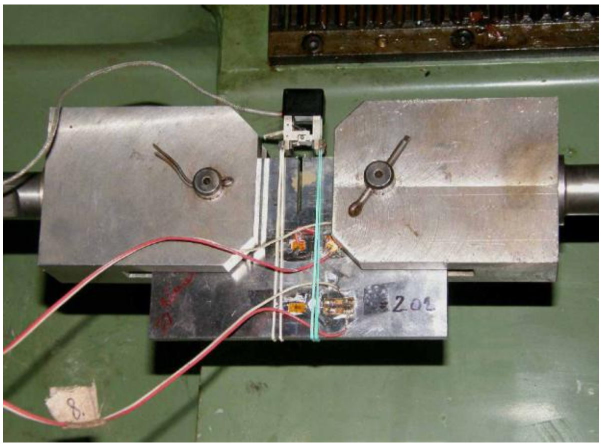

Figure 1: *Specimen during CMOD measurement using extensometer and CTOD measurement using strain gauges.*

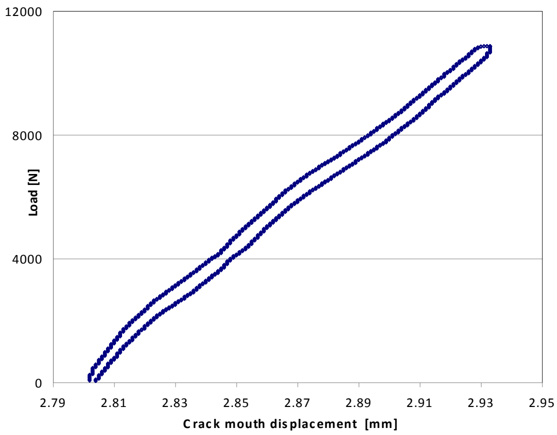

Figure 2: *Corrugated curve with considerable hysteresis during CMOD measurement with videoextensometer*

Crack closure measurement was carried out at two different conditions of attachment of the specimens. In the first case, there was quite a small clearance between the pins of the diameter 15.00 mm and the holes of the diameter 15.12 mm, i.e. there was total clearance of about 0.12 mm. Since during the first set of measurement, evaluated results did not look to be adequately self-consistent, the pins were machined by slight turning to the diameter of 14.00 mm resulting in considerably larger clearance fit of approximately 1.1 mm.

3. Results and Discussion

Examples of load – displacement curves, or load – strain curves, respectively, for the different measurement methods are shown in the following Figures 2-6. Crack closure always was evaluated from the point exactly corresponding to the first diversion of the specific measured curve from the linear part of the curve, which corresponded to the fully open crack at high load. As regards the method using the videoextensometer, it was ascertained that the load – CMOD curve was of a poor quality, considerably corrugated and so this method, though promising at first sight, unfortunately could not be more used. The corrugated character of the curve with the considerable hysteresis was likely caused by the technical parameters of the videoextensometer, namely the automatic computer correction of the position of measured moving points.

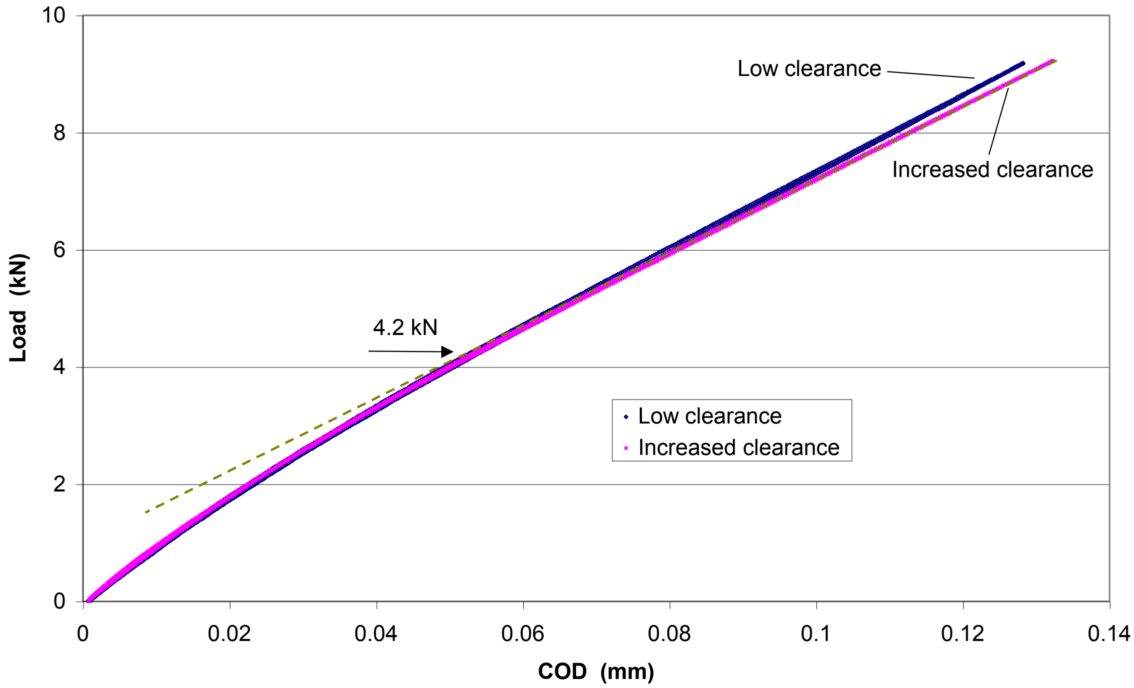

Figure 3: *Comparison of load – CMOD curves recorded at the conditions of small and enlarged clearance between pins and holes in case of X60 specimen, the differences being negligible*

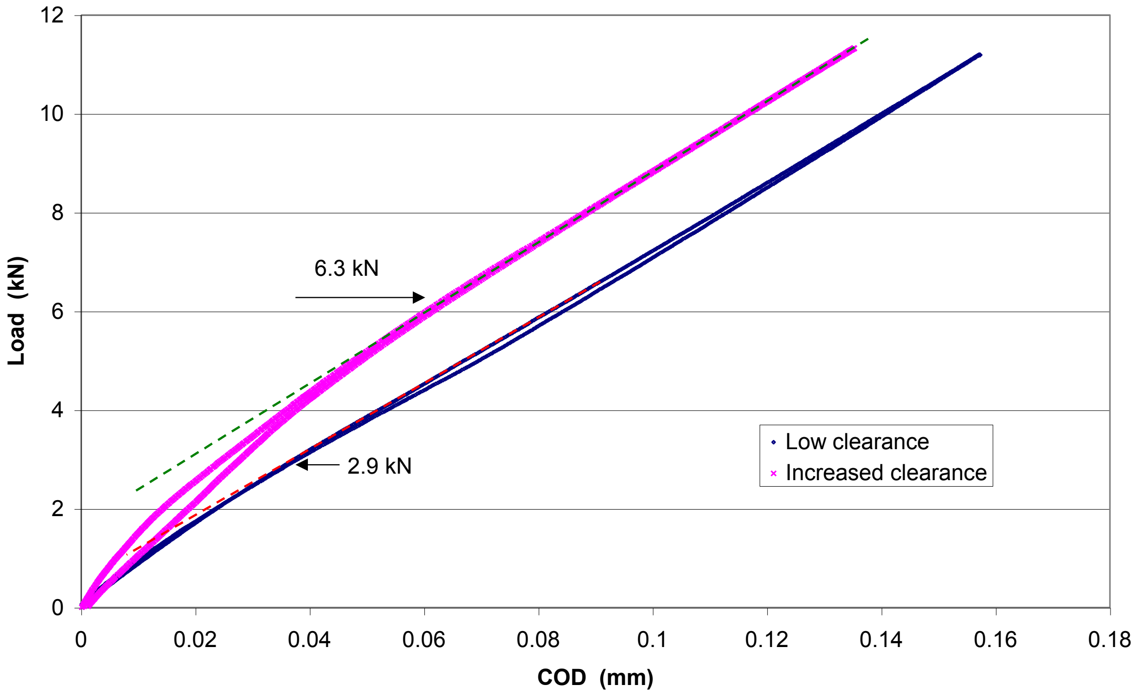

Figure 4: *Comparison of load – CMOD curves recorded at the conditions of small and enlarged clearance between pins and holes in case of X70 specimen with significant differences*

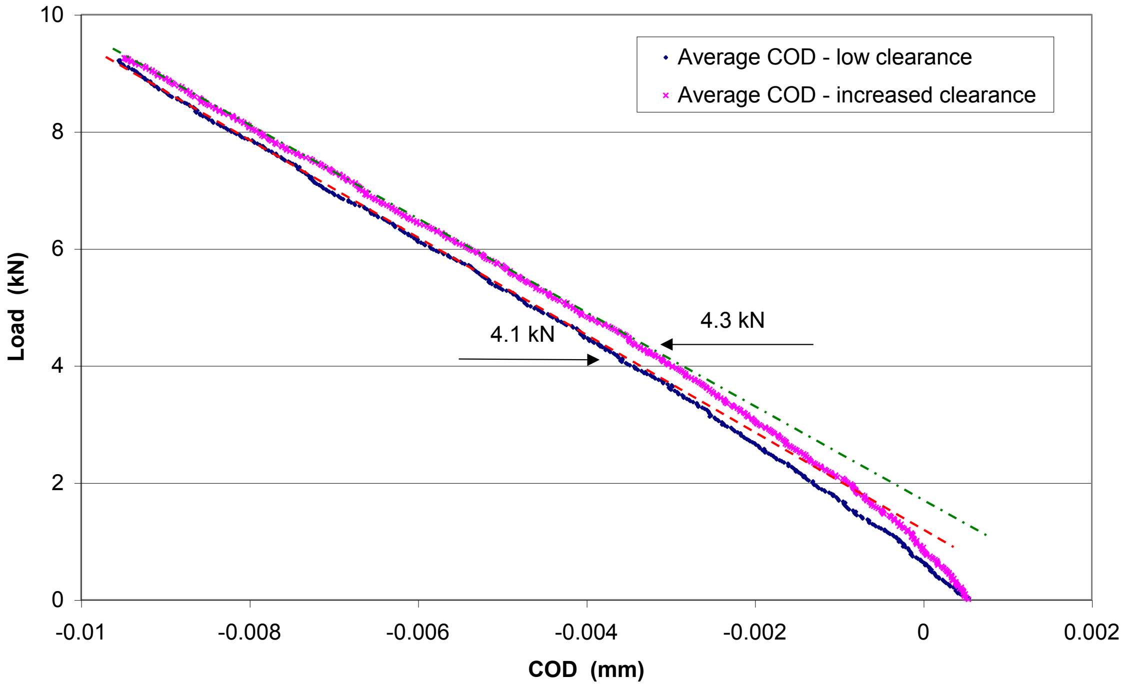

Figure 5: *Example of curves measured at opposite edge to notch at the conditions of small and enlarged clearance between pins and holes in case of X60 specimen*

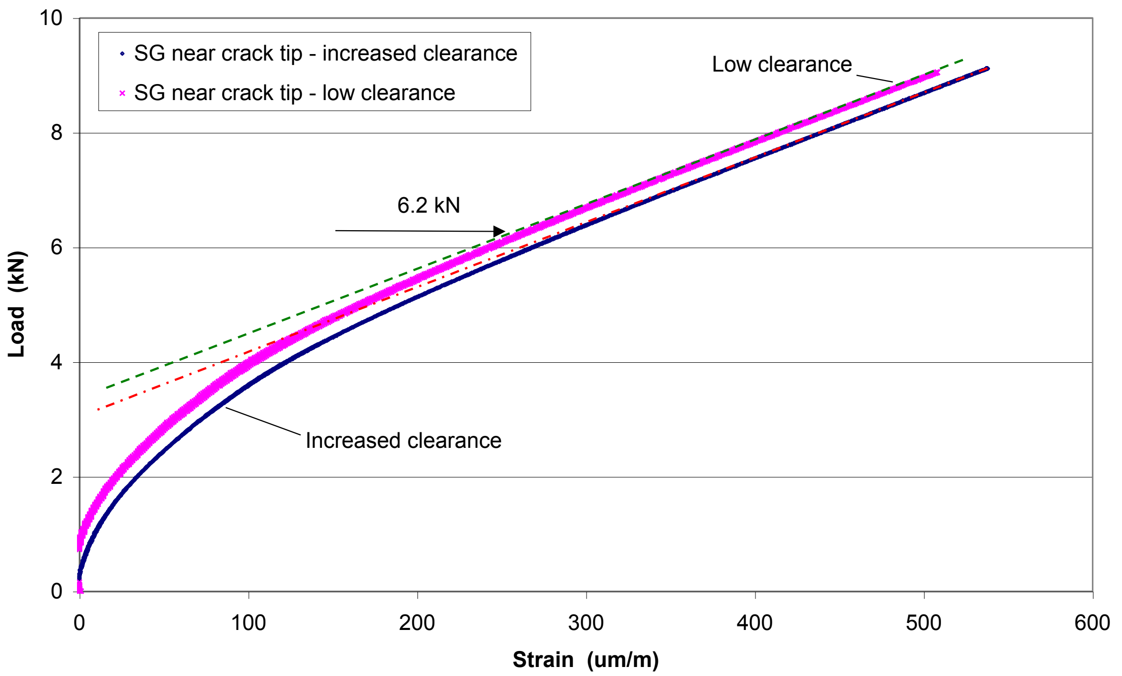

Figure 6: *Example of load – CTOD curve measured by strain gauge near crack tip at the conditions of small and enlarged clearance between pins and holes in case of X60 specimen*

The COD measurement performed using either the INOVA PXA extensometer or strain gauges provided curves of much higher quality. Therefore, crack closure points could be quite exactly determined. The only exception was strain gauge measurement at the point 15 mm from the edge opposite to notch mouth (not shown in this printed copy of the paper), where the load – strain curve was almost linear because this point was located already in the area of compression stresses, but quite close to the neutral axis.

Looking at Figures 3-6, it is evident that the character of load – displacement or strain curves is different. In particular, the effect of different clearance fit is not too significant in case of the X60 steel, unlike the X70 steel, where the effect of increasing clearance is considerable. It can be concluded in general that the CTOD measurement by strain gauges placed very close to the crack tip is, as expected, mostly sensitive. On the contrary, the measurement on the edge opposite to notch mouth is the less sensitive. However, even in this case, closure points could be quite distinctly identified.

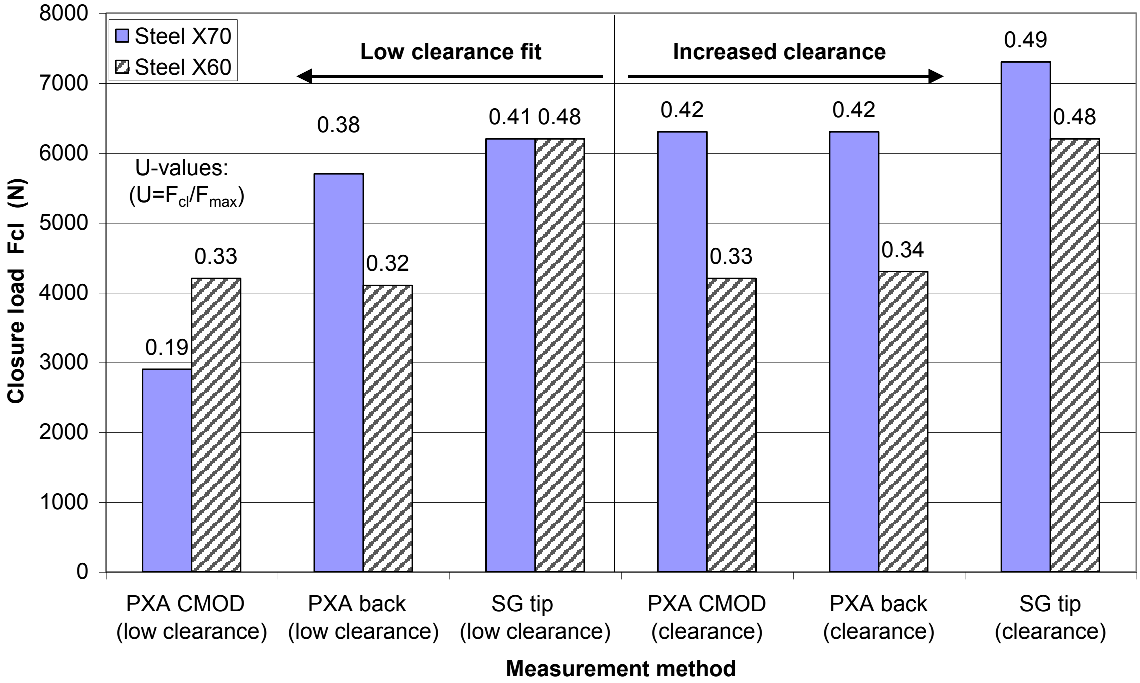

Figure 7: *Crack closure values for different clearance fit and methods of evaluation*

The evaluated crack closure values for different cases and methods are in Figure 7. Besides actual values of closure load F_{cl}, relative values of closure ratio U, $U = F_{cl} / F_{max}$ are shown in the diagram, too.

Some results in Figure 7 can be considered very important and interesting. Firstly, there are considerable differences between the X60 steel of lower strength and yield stress and the X70 steel of higher strength. Unlike the X70 steel, all the results concerning the X60 steel are very self-consistent and now effect of lower clearance fit took effect. On the other hand, CMOD values of the X70 steel measured in case of lower clearance are much lower in comparison with the increased clearance fit. This indicates an occurrence of additional stresses caused probably by an insufficient freedom of specimen rotation in the pins. A likely explanation, why this effect occurred only with the higher strength steel, can consist in the fact that holes of the specimen of lower strength steel were more able to accommodate their shape and did not cause a gripping effect between them and pins. Nevertheless, the obtained results confirm that for any case, clearance between holes and pins should be carefully complied with standard recommendations [9,10] for any material tested. It follows from Figure 7 that if clearance fit is free enough, there are no problems with self-consistency of results even with the higher strength steel X70. This is a very important result, because it has been recently published in the literature that results of crack closure measurement depend on the experimental method used [4,5].

The last point to be discussed are the higher crack closure values evaluated in case of CTOD measurement with strain gauges. Considering the positions of the gauges, there were placed in front of the crack tip at the distances 2.82 mm and 1.84 mm from the crack tip on the sides of X60 and X70 specimens, respectively. Since on the surface, stress conditions near crack tip correspond approximately to plain stress, both the strain gauges were in the plastic zones, whose dimensions were 3.9 mm and 3.0 mm, respectively. Crack closure in the surface area of plastic zone occurred at higher loads than inside the specimen. It looks that in this case, partial crack closure was sensitively measured unlike the other methods, which are able to measure global closure.

4. Conclusions

The most important results of crack closure measurement performed on CT-specimens of two types of high pressure pipeline steels of different strength and yield stress, X60 and X70 steels using different experimental methods, namely using (i) videoextensometer on edges of crack mouth – initiation notch, (ii) mechanical semiconductor extensometer near the crack mouth, (iii) mechanical extensometer on opposite side to crack mouth, i.e. in the compression area, (iv) strain gauges at the immediate vicinity of crack tip and (v) strain gauges placed on the side area near opposite edge can be summarised as follows:

- The method using videoextensometer, though attractive due to the high degree of computerisation, turned out to be inappropriate due to problems connected with the technical principle of the device, resulting in corrugated load – displacement curves. In a similar way, the method using strain gauging between crack tip and opposite specimen edge could not be used due to its low sensitivity to low stress changes in the area of compression near the neutral axis.
- An insufficient clearance between specimen holes and pins considerably affected closure values in case of the higher strength X70 steel. No such effect occurred with X60 steel.
- Closure values measured using extensometer on the edge opposite to crack mouth were very self-consistent with CMOD measurement.
- CTOD measurement using strain gauges placed very close to the crack tip, in the area of plastic zone, was very sensitive and higher closure loads were ascertained. It was likely due to the ability of this method to measure local surface partial crack closure, which occurs at higher loads than global closure.

Acknowledgement

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