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THE DIGITAL IMAGE CORRELATION TECHNIQUE APPLIED TO SINGLE SPECIMEN FRACTURE TOUGHNESS METHODOLOGY

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ABSTRACT

The ASTM E 1820 standard provides procedures and guidelines for the determination of fracture toughness of metallic materials, characterized by the J-integral. The recommended specimens are single-edge bend, SEN(B), compact, C(T), or disk-shaped, DC(T). Two alternative procedures for measuring crack extension are provided in the standard, the basic procedure and the resistance curve procedure. The basic procedure involves physical marking of the crack advance and multiple specimens are used to develop an R-curve (or J-Da curve). The resistance curve procedure is an elastic-compliance method where multiple points are determined from a single specimen.

To use the elastic-compliance method, the displacement transducer (clip-gage) must have a very high resolution and stability, and a very low noise. For temperature ranging from -200°C to 100°C, a clip-gage with conventional strain gages (i.e. plastic resistance strain gages) gives generally good results. However, at higher temperatures, one must use either high temperature inductive or capacitive clip-gages, or conventional clip-gages placed outside of the oven and connected to the specimen by ceramic or quartz rods. In both cases, the results are not very satisfactory.

For the measurement of the load-line displacement, a new method using the digital image correlation (DIC) technique is under development at EDF R&D. The CT specimens have integral-machined knife edges and a thermally resistant paint is sputtered on these edges, in order to get irregular patterns. During the test, a high resolution camera placed outside of the oven takes pictures of the knife edges at regular time intervals. These pictures are real time processed to calculate the displacement of the dots, and deduce the load-line displacement. The paper presents the technique and the results obtained on various materials.

NOMENCLATURE

a	Crack depth
B	Specimen thickness
B_N	Net thickness of a side-grooved specimen
b	Remaining ligament
CT	Compact tension specimen
E	Young's Modulus
J	J-integral
J_{el}	Elastic component of J-integral
J_{pl}	Plastic component of J-integral
P	Applied load
W	Specimen width
Δa	Crack extension
γ	Non-dimensional factor to account for crack growth effects on J-integral
η	Non-dimensional factor, relating the plastic work with the J-integral
μ	Non-dimensional compliance
ν	Poisson's ratio

1 INTRODUCTION

The ASTM E 1820 (ASTM, 2011) standard provides procedures and guidelines for the determination of fracture toughness of metallic materials, characterized by the J-integral. The recommended specimens are single-edge bend, SEN(B), compact, C(T), or disk-shaped, DC(T). Two alternative procedures for measuring crack extension are provided in the standard, the basic procedure and the resistance curve procedure. The basic procedure involves physical marking of the crack advance and multiple specimens are used to develop an R-curve (or J-Δa curve). The resistance curve procedure is an elastic-compliance method where multiple points are determined from a single specimen. Other procedures for measuring crack extension are allowed, typically the electric potential drop method.

To use the elastic-compliance method, the displacement transducer (clip-gage) must have a very high resolution and stability, and a very low noise. For temperature ranging from -200°C to 100°C, a clip-gage with conventional strain gages (i.e. plastic resistance strain gages) gives generally good results. However, at higher temperatures, one must use either high temperature inductive or capacitive clip-gages, or conventional clip-gages placed outside of the oven and connected to the specimen by ceramic or quartz rods. In both cases, the results are not very satisfactory.

So, for the measurement of the load-line displacement, a new method using the digital image correlation technique (DIC) was developed at EDF R&D. The CT specimens have integral-machined knife edges and a thermally resistant paint is sputtered on these edges, in order to get irregular black dot patterns. During the test, a high resolution camera placed outside of the oven takes pictures of the knife edges at regular time intervals. These pictures are real time processed to calculate the relative displacements of the dots, and deduce the load-line displacement. The paper presents the technique and the results obtained on various materials.

2 THE SINGLE SPECIMEN TECHNIQUE

2.1 Estimation procedure for the J-integral and crack length

The experimental determination of J from the applied load and the crack-opening displacement uses a J estimation scheme, whose main features are recalled herafter.

J is split into an elastic component J_{el} and a plastic component J_{pl}:

$$J = J_{el} + J_{pl}$$

The elastic component J_{el} is computed from the mode I elastic stress intensity factor K_I and the equivalent Young's modulus E':

$$J_{el} = \frac{K_I^2}{E'}$$

where $E' = E/\left(1-\nu^2\right)$ in plane strain and E' = E in plane stress.

The stress intensity factor K_I is defined as follow:

$$K_I = \frac{P}{B\sqrt{W}} F\left(a/W\right)$$

where F is a shape factor depending on the relative crack depth a/W.

The plastic component J_{pl} is computed by:

$$J_{pl} = \eta \frac{A_{pl}}{B_N b}$$

where A_{pl} is the plastic area under the load vs. displacement curve, b is the uncracked ligament, B_N is the net thickness. Factor η is a non-dimensional parameter with relates the plastic contribution to the strain energy for the cracked body A_{pl} with J; it is assumed to be a function of the flawed configuration and independent of the loading level.

With the partial unloading method, the computation of J becomes iterative, so for the unloading step k:

$$J_k = J_{el}^k + J_{pl}^k = \frac{K_{I(k)}^2 \left(1-\nu^2\right)}{E} + J_{pl}^k$$

$$J_{pl}^k = \left[J_{pl}^{k-1} + \frac{\eta_k}{b_k B_N}\left(A_{pl}^k - A_{pl}^{k-1}\right)\right]\left[1 - \frac{\gamma_k}{b_k}\left(a_k - a_{k-1}\right)\right]$$

where a_k is the crack length at step k, $b_k = W - a_k$ is the uncracked ligament at step k, A_{pl}^k is the plastic area under the load vs. displacement curve at step k.

The γ factor is deduced from the η factor:

$$\gamma_k = \left[-1 + \eta_k - \left(\frac{b_k}{\eta_k} \left. \frac{d\eta}{da} \right|_k \right) \right]$$

As shown on Fig. 1, during the partial unloading, the compliance C – inverse of the elastic stiffness of the specimen – is computed: C = ΔV/ΔP, where ΔV is the COD range corresponding to the load range ΔP.

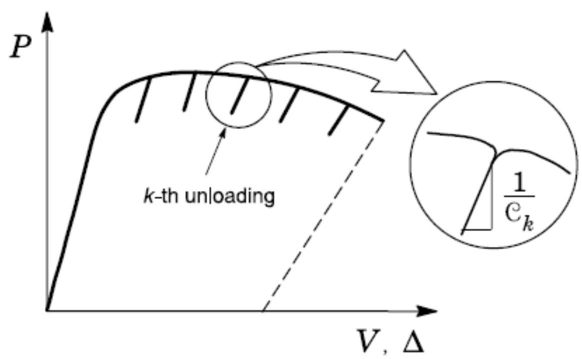

Figure 1: Measurement of the compliance C during a partial unloading

The normalized compliance μ is obtained by:

$$\mu = \frac{1}{1 + \sqrt{E\, B_{ef}\, C}}$$

where B_{ef} is the effective thickness, equal to B when there are no side grooves. Finally, the relative crack depth is computed from the normalized compliance.

2.2 Case of the CT specimen

The equations of the factors F and η, as well as the relation between the normalized compliance μ and the relative crack depth a/W are specific to each specimen geometry. For the case of the CT specimens, these equations are provided in Appendix A2 of the ASTM E 1820 standard. Moreover, to take into account the rotation of the specimen during the test, a rotation corrected compliance $C_{c(i)}$ is computed from the measured compliance C_i during the unloading i, the load-line displacement, the crack length and some dimensions of the specimen.

3 DESCRIPTION OF THE DIC TECHNIQUE

3.1 Overall modelling strategy

Digital image correlation is widely used in different fields of experimental mechanics as a non-contact optical method. The basic procedure in the DIC method is to correlate two digital images taken from a specimen before and after loading (Fig. 2). The first image is named the reference image and the second one is named the deformed image. In order to improve the accuracy of the correlating procedure, a random speckle pattern is created on the surface of the specimens. So, the light intensity of each pixel can be identified and the intensity of the target region can be discretized into a range of numbers called gray scale. Then, by using a computer program, a small region of the specimen in the reference image is traced to the same region at the deformed image. This small region which consists of different pixels with different gray scales is called the subset. In the image correlation, each subset of the reference image is compared with each of the deformed images and the correlation coefficient is computed. The correlation coefficient can be written as:

$$C(x,y,u,v)=\frac{\sum_{i=-n}^{n}\sum_{j=-n}^{n}\left(I_R\left(x_p+i,y_p+j\right)-I_D\left(x_p+i+u_p,y_p+j+v_p\right)\right)^2}{\sum_{i=-n}^{n}\sum_{j=-n}^{n}\left(I_R\left(x_p+i,y_p+j\right)\right)^2}$$

where x_p and y_p are the pixel coordinates of each point in the reference image and I_R and I_D are the light intensity of reference and deformed images, respectively. The displacement fields in the target region can be obtained by minimizing the correlation coefficient.

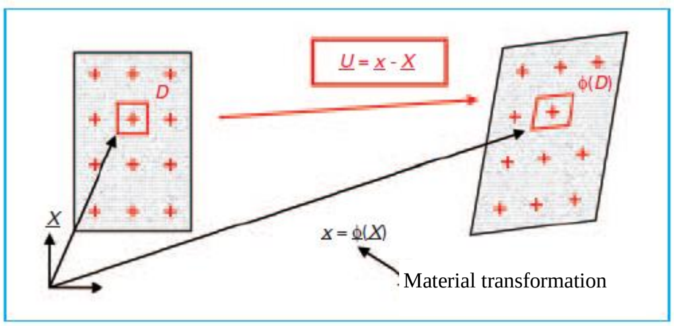

Figure 2: Principle of the image correlation

A digital image is composed of a set of discrete values, the gray level at each integer value of the pixel. To get displacements at a sub-pixel scale with the correlation procedure, an interpolation is used to obtain the gray level between two pixels.

3.2 Main results obtained with that first set of modelling

The DIC technique is used for several applications in fracture mechanics: strain measurements at the surface of specimens (Abbassi, 2011; Fagerholt, 2012), direct evaluation of J integral (Vavrik, 2014), elongation measurements, 3D surface deformation using stereo-correlation, necking measurements during tensile tests, measurement of thermal expansion coefficient, etc.

4 APPLICATION TO SINGLE SPECIMEN TECHNIQUE IN FRACTURE TOUGHNESS TESTING

4.1 Principle of the method

The method is developed for CT specimens with integral knife edges, machined by electric-discharge machining. The principle of the method is to obtain the load-line displacement during the fracture toughness test, by measuring the relative displacement between the knife edges by DIC. A layer of white paint is applied first on the knife edges, then a pattern of black spots is applied by spray painting. The images are processed at about 5 Hz to get a real-time load-line displacement value, and are also stored in order to be processed after the end of the test, if necessary. A high resolution 4000x3000 pixels 12 bits black and white camera is used, together with a high quality and luminous objective lens. In order to increase the speed, the image can be clipped within the camera. The nominal range is fixed to 20 mm, so one pixel corresponds to 5 μm. However, thanks to the sub-pixel interpolation of the DIC technique, the resolution is much better (tests on a static sample give a value close to 0.3 μm). Fig. 3 shows an overview of the equipment used for high temperature fracture toughness testing: oven, objective, camera and co-axial lighting (thanks to a semi-reflecting mirror). The knife edges are filmed through a vertical slit in the oven (Fig. 4). Fig. 5 specifies the direction of view regarding to the knife edges and Fig. 6 shows an example of the image given by the camera, with the two subsets (in red) and the clipping area (in green).

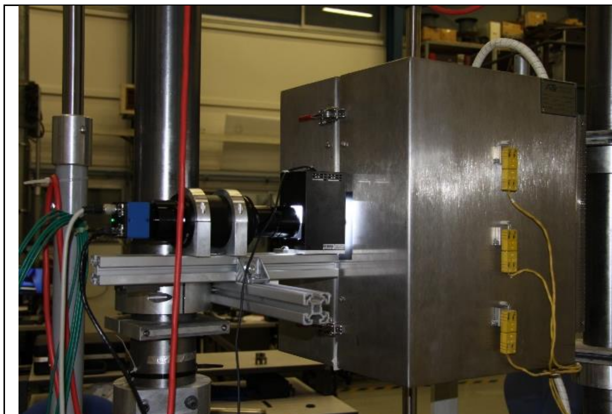

Figure 3: View of the testing equipment

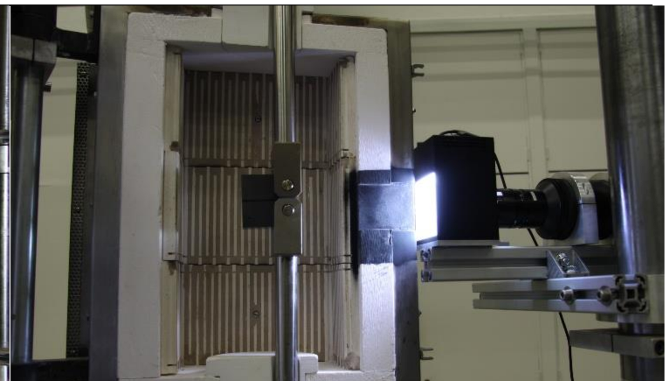

Figure 4: View of the CT specimen inside the oven

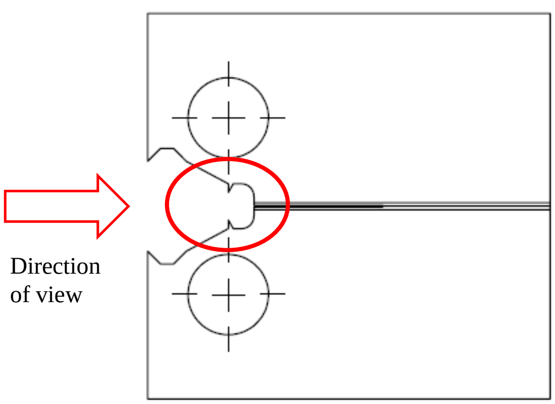

Figure 5: Location of the knife edges on a CT specimen

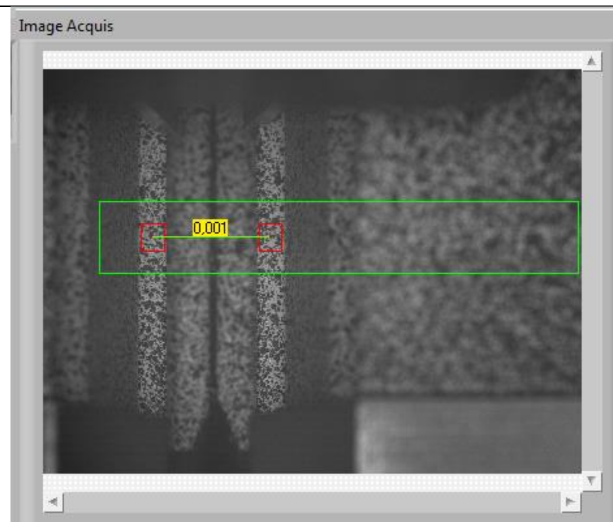

Figure 6: View of the knife edges area showing the irregular black pattern and the two subsets

4.2 Preliminary room temperature tests

Room temperature tests were conducted on large CT specimens made of alloy 600. This material is very ductile and the specimens are big, so a clip-gage extensometer with a large range is necessary. Moreover, it is possible to use the clip-gage and the DIC together during the test (see Fig. 5), so the accuracy of the DIC method can be checked. Three specimens where tested, of which two beyond the maximum range (12.5 mm) of the clip-gage. The load versus LLD curves are shown in Fig. 6. The curves corresponding to specimen B1-12 are lower than the others, due to a larger initial crack depth (75 mm instead of 72 mm). Fig. 7 shows the J-R curves derived from these tests. For the specimens B1-9 and B1-12, the crack growth values come from the clip-gage measurements, whereas for the specimens B1-10 and B1-11 (red and green marks), the values come from the DIC measurements. The agreement between the J-R curves is very good, but the scatter of the crack extension from the DIC measurements is larger, particularly before the crack initiation. It should be noted that the slope of the parallel to the blunting line is equal to four times the flow stress. With this definition, the J_{Ic} value is close to 700 kJ/m^2.

Figure 7: View of the testing equipment for room temperature tests on CT60 specimens

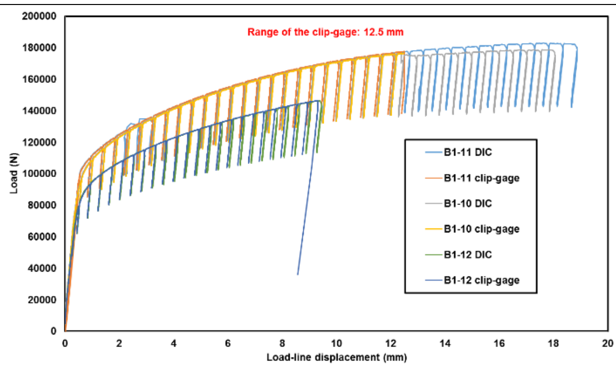

Figure 8: Load versus LLD curves of the three CT60 specimens tested at room temperature

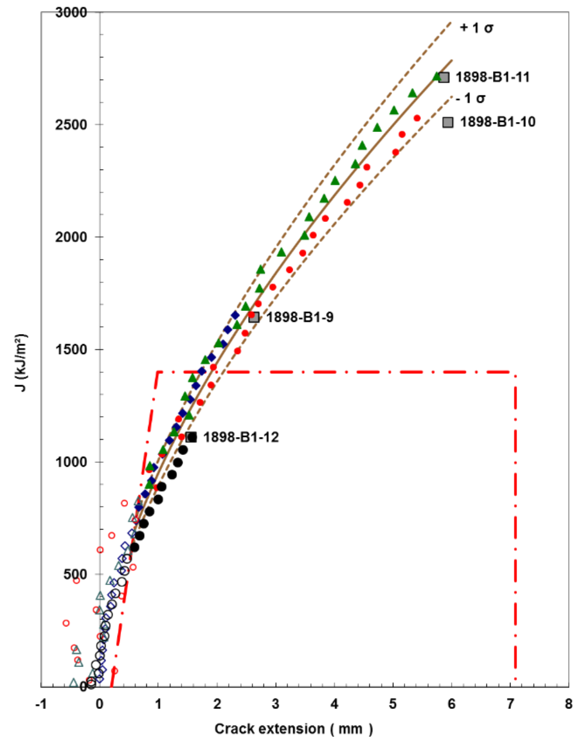

Figure 9: J-R curves for the CT60 specimens tested at room temperature

4.3 Preliminary high temperature tests

A test was conducted at 350°C on a CT25 specimen made of ferritic steel. Fig. 10 shows the load versus LLD curve whereas Fig. 11 shows the corresponding J-R curve. Once again, the crack length calculated before the crack initiation is not very stable and shows large fluctuations. After the crack initiation, the scatter is reduced. It was discovered that at low load, due to the tensioning of the load-line, the specimen can move significantly towards or backwards respectively to the camera, and that can defocus the images. It was decided to add a focusing system, based on an analysis of the image contrast and a stepper motor below the camera. If necessary, the re-focus is done during the hold time for load relaxation that precedes each unload/reload sequence.

Moreover, the infrared radiation degrades the image that becomes pale with low contrast. To fix this problem, a blue filter was added in front of the lens and an anti-turbulence device was placed between the lens and the oven.

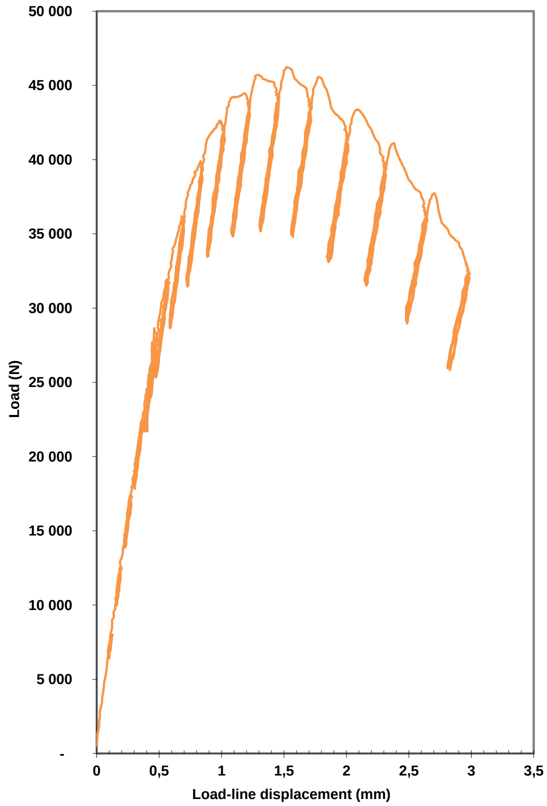

Figure 10: Load versus LLD curve of the CT25 specimen tested at 350°C

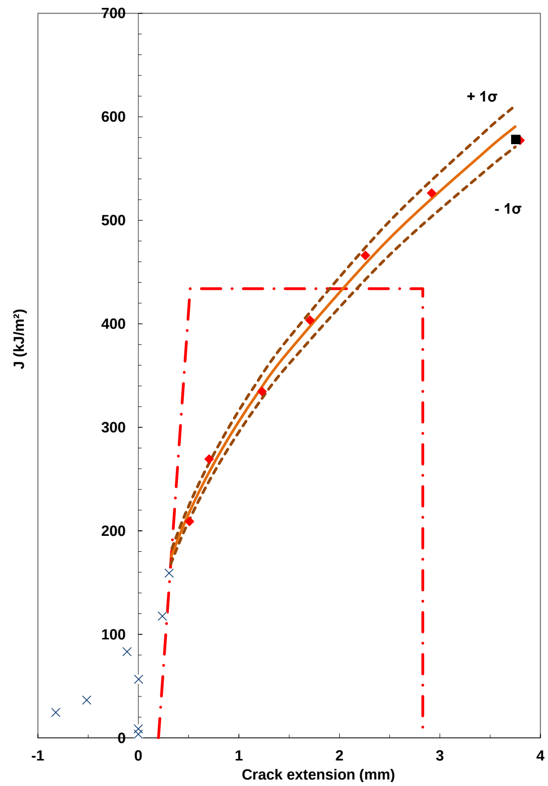

Figure 11: J-R curve of the CT25 specimen tested at 350°C

4.4 Final room and high temperature tests

To check the efficiency of the measures taken to improve the quality of the images, room and high temperature (330°C) tests were conducted on a low alloy steel. Three CT25 specimens were tested at each temperature. At room temperature, Fig. 12 shows the load versus LLD curves whereas Fig. 13 shows the corresponding J-R curves. At 330°C, the corresponding curves are given in Fig. 14 and Fig. 15. At both temperatures, the agreement between the three J-R curves is very good, and the scatter on the crack extension is very reduced, particularly at 330°C. Moreover, the agreement between the crack extension measured optically at the end of the test and the final crack extension calculated using the DIC extensometer measurements is excellent.

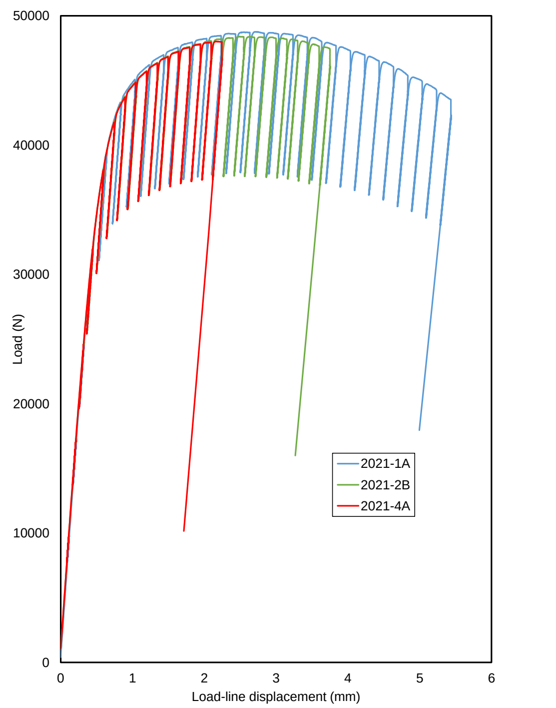

Figure 12: Load versus LLD curves of the CT25 specimens tested at 20°C

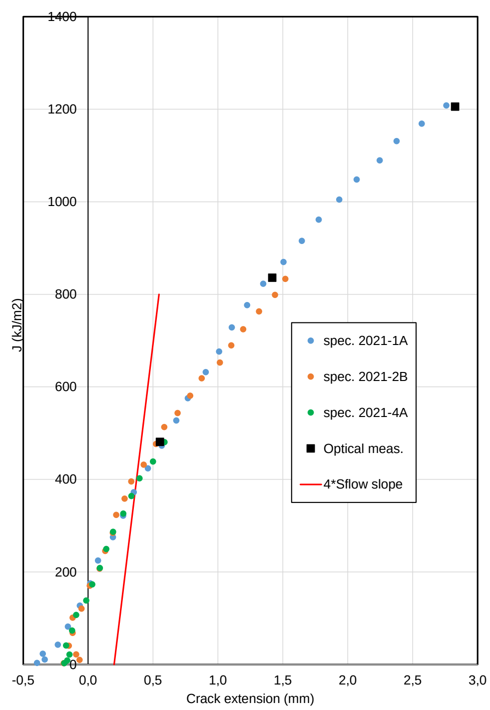

Figure 13: J-R curves of the CT25 specimens tested at 20°C

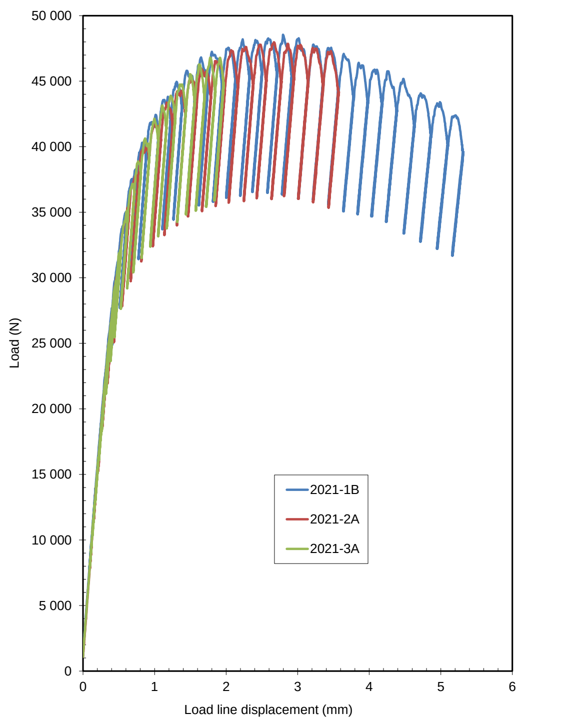

Figure 14: Load versus LLD curves of the CT25 specimens tested at 330°C

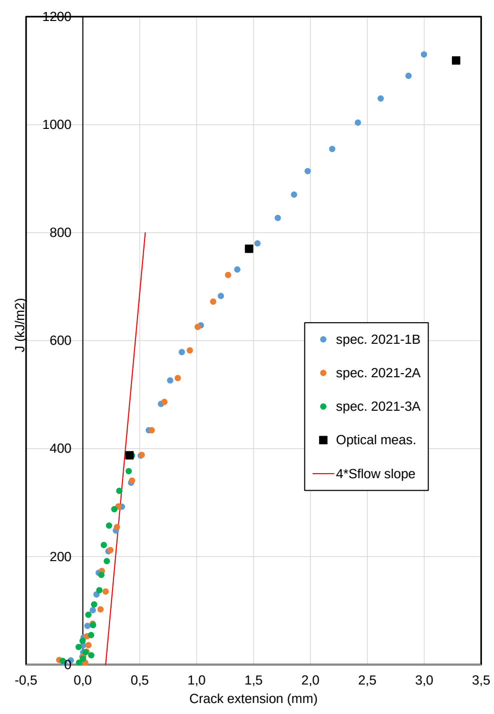

Figure 15: J-R curves of the CT25 specimens tested at 330°C

5 CONCLUSIONS

A new method to conduct single specimen fracture toughness tests by the unloading compliance method has been developed. This method uses the DIC technique to get the load-line displacement during the test, by measuring the gap between the knife edges of the specimen.

The DIC method has some advantages:

- No need of high temperature mechanical extensometers,
- Very high temperature (e.g. 750°C) tests are practicable,
- It allows for large LLD measurements (for large CT specimens and/or very ductile materials).

But it has also some limits listed hereafter:

- The system is sensitive to the optical environment (lighting, reflections, quality of the objective lenses, quality of the spray painting),
- At elevated temperature, the images can be altered by red and infrared radiations and by air turbulences,
- The image sampling and the image processing are time consuming and a DIC extensometer is slower than a mechanical clip-gage,
- The image can be altered by vibrations or blurred by rapid displacements of the specimen (this can be improved by increasing the lightning to reduce the exposure time),
- It is difficult and hazardous to control the hydraulic machine with it, so the periodic unloads must be controlled with the ram displacement.

Preliminary tests at room temperature and at high temperature shown that the technique gives useable results. In order to improve the accuracy, some improvements were made regarding elevated temperature tests (blue filter and anti-turbulence device) and possible defocusing during the tests (real time analysis of the image contrast and addition of a stepper motor below the camera). New tests conducted after these improvements gave very good results, comparable to those obtained with mechanical extensometers at room temperature.

Work is on-going to improve the speed of the image processing and to further reduce the air turbulences.

6 REFERENCES

[1] Abbassi, T., Mistou, S., Pantale, O., and Zghal, A., 2015, “FE simulation and full-field strain measurements to evaluate the necking phenomena”, *Procedia Manufacturing*, Vol. 2, pp. 500-504

[2] ASTM E 1820-11 (2011). “Standard test method for measurement of fracture toughness”, *American Society of Mechanical Engineers*

[3] Fagerholt, E., ∅stby, E., Borvik, T., and Hopperstad, O.S., 2012, “Investigation of fracture in small-scale SENT tests of a welded X80 pipeline steel using Digital Image Correlation with node splitting”, *Engineering Fracture Mechanics*, 96, pp. 276-293

[4] Vavrik, D., and Jandejsek, I., 2014, “Experimental evaluation of contour J integral and energy dissipated in the fracture process zone”, *Engineering Fracture Mechanics*, 129, pp. 14-25