Effects of Temperature Gradient on Fracture Toughness

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ABSTRACT

The main aim of this research is to clarify the fracture criterion for crack initiation in the non homogeneous materials. Three point bend tests were conducted on PMMA specimen to determine the fracture toughness of this material at different temperatures by keeping the temperature of the entire specimen uniform. Fracture toughness values (as a function of temperature) were determined. Similar specimens were also tested for fracture toughness while held at a certain temperature gradient. Temperature gradient tests were made to simulate fracture properties of the non homogeneous material. It was found that crack initiation at the crack tip occurred at a higher fracture toughness value, compared to the uniform temperature test, when the temperature ahead of the crack tip increased gradually and the crack initiation at the crack tip occurred at a lower fracture toughness value, compared to the uniform temperature test, when the temperature ahead of the crack tip decreased gradually.

KEY WORDS: fracture criterion, crack initiation, non homogeneous materials, fracture toughness, temperature gradient.

1 INTRODUCTION

Limited natural energy resources like oil, coal, etc. are not going to suffice for a longer period of time, to fulfill our needs of power production and consumption. Therefore, nuclear energy is considered to be one of the alternate sources of energy, which seems to fulfill our energy needs for a very long time in the future. Unfortunately this particular source of energy along with its inherent economic benefits and reliability, has also brought many disasters with it. Present study is an effort to achieve preventive measures to avoid most likely accidents in the nuclear industry.

In nuclear reactor pressure vessels, high neutron radiation over the prolonged periods of time causes radiation embrittlement of the pressure vessel walls. The amount of radiation flux at the inner surface of the pressure vessel walls is very high compared to the outer surface. Correspondingly the degree of radiation embrittlement, experienced by the inner surface is of far higher order compared to the outer surface. In other words, embrittlement caused, varies gradually from inner to outer surface. No fracture criterion has yet been reported for a situation when a crack is sitting in a non homogeneous material.

Whether this crack initiation is determined by the material property just at the crack tip or it is due to a total effect of change in the material property in the crack tip vicinity is of crucial importance to be well understood.

In present research the temperature gradient serves to create the non homogeneous properties in the material.

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2 EXPERIMENTAL PROCEDURE

2.1 Material and specimen

Polymethyl metacrylate (PMMA) specimen were used in the experiments conducted. The reason to use PMMA was that it is a very brittle material and its fracture toughness depends on temperature change. So we can consider the fracture of PMMA in the frame work of linear elastic fracture mechanics (LEFM). Fig.1 shows the shape of specimen used in this research. The crack tip is located in the specimen at a distance of 40 mm from the notched edge with an a/w ratio of 0.5. A notch of 5mm was cut in the specimen and the pre-crack was introduced by fatigue crack process on material testing machine.

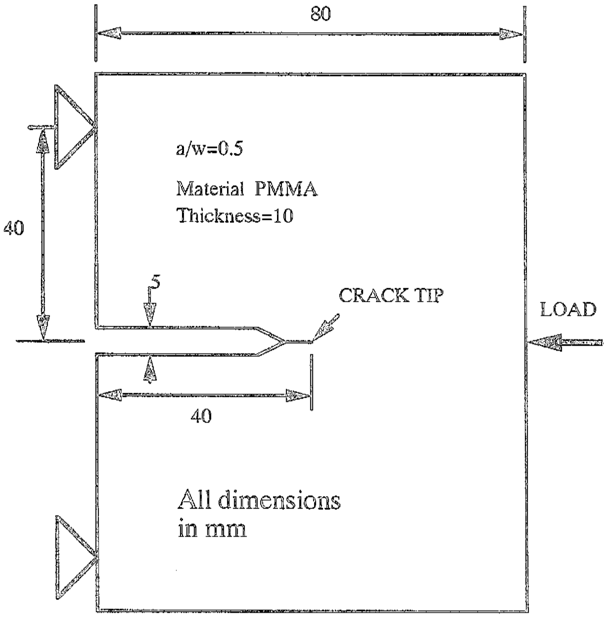

FIG.1 SPECIMEN USED FOR EXPERIMENTS

2.2 Uniform temperature test

As shown in Fig. 2, this test was made after whole the specimen was kept emersed in to a mixture of methyl alcohol and liquid nitrogen for about 20 minutes to ensure that the specimen experienced a uniform temperature condition. Specimen was loaded to break down, measuring the fracture load and fracture toughness values were calculated from the maximum load. Three to four specimens were tested for each temperature.

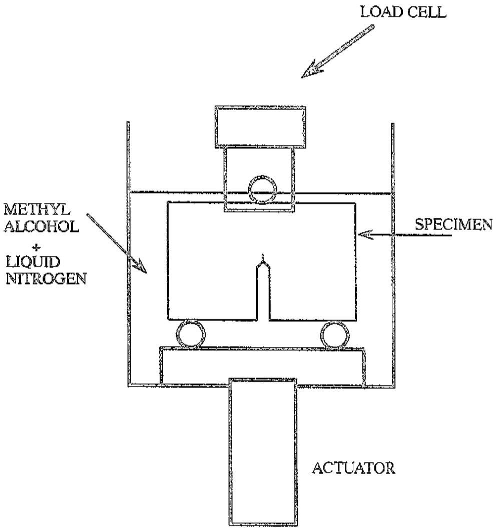

FIG.2 UNIFORMTEMPERATURE TEST

2.3 Temperature gradient test
(notched edge cooling)

Tests were performed as shown in Fig. 3. Specimen was partially emersed in to a mixture of methyl alcohol and liquid nitrogen to achieve required temperature at the crack tip. Temperature measurements were obtained by pasting thermocouples on the specimen surface. Though the the fracture toughness values of the specimen were calculated using maximum fracture load, strain gage was also pasted near the crack tip to measure fracture toughness values for additional reliability. Crack tip lies in the middle of the specimen, 40 mm from the notched edge.

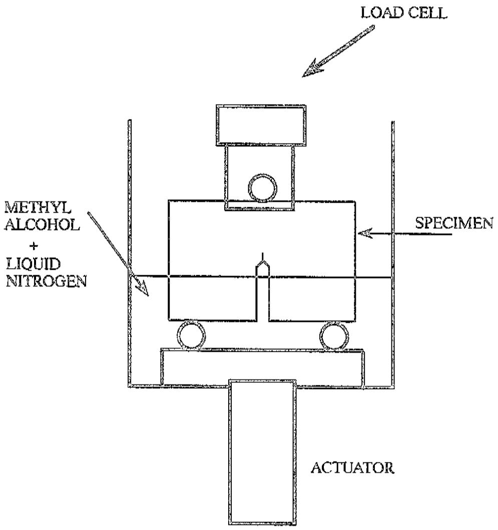

FIG. 3 NOTCH EDGE COOLING

2.4 Temperature gradient test
(load edge cooling)

Tests were performed as shown in Fig. 4. Specimen was partially emersed in to a mixture of methyl alcohol and liquid nitrogen to achieve required temperature at the crack tip. Temperature measurements were obtained by pasting thermocouples on the specimen surface. Though the the fracture toughness values of the specimen were calculated using maximum fracture load, strain gage was also pasted near the crack tip to measure fracture toughness values for additional reliability. Crack tip lies in the middle of the specimen, 40 mm from the notched edge.

In this case specimen was placed on the testing jig with its notched edge facing upwards. In this way temperature ahead of crack tip dropped gradually.

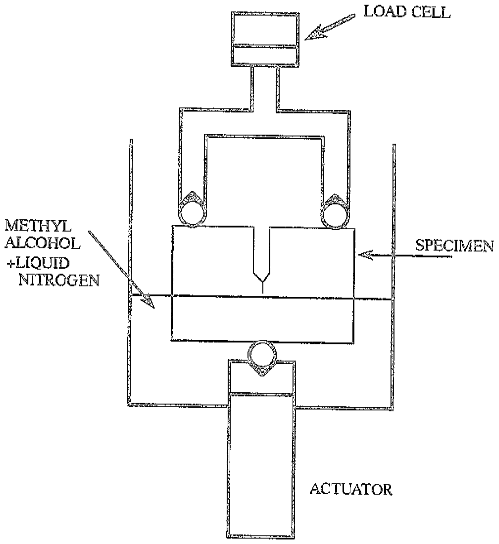

FIG.4 LOAD EDGE COOLING

2.5 Temperature distribution in temperature gradient tests.

Temperature distribution for both of these temperature gradient tests is shown in Fig. 5 and 6. Curves show a linear change in temperature, which was obtained by keeping the specimen surfaces to be covered with heat insulation during the experiment.

3 RESULTS

3.1 Uniform temperature test

Fig. 7 elaborates the uniform temperature test which shows the temperature dependence of fracture toughness for PMMA. In Fig.4 fracture toughness remains nearly uniform in the lower temperature range of -60 °C to -30 °C. The fracture toughness shows nearly uniform behavior in the temperature range of -5 °C to 20°C in the higher temperature range. Moreover fracture toughness increases gradually in the temperature range of -30 °C to -5 °C. The temperature -15 °C lies in the middle of this rising curve, therefore we decided this point to be the crack tip temperature for temperature gradient tests as described in the following sections of this report.

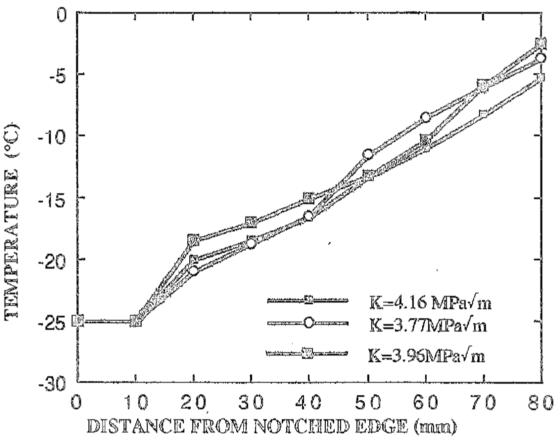

FIG. 5 TEMPERATURE DISTRIBUTION IN THE SPECIMEN

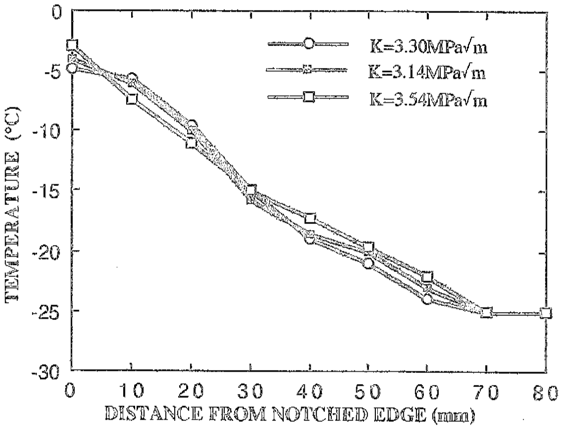

FIG.6 TEMPERATURE DISTRIBUTION IN THE SPECIMEN

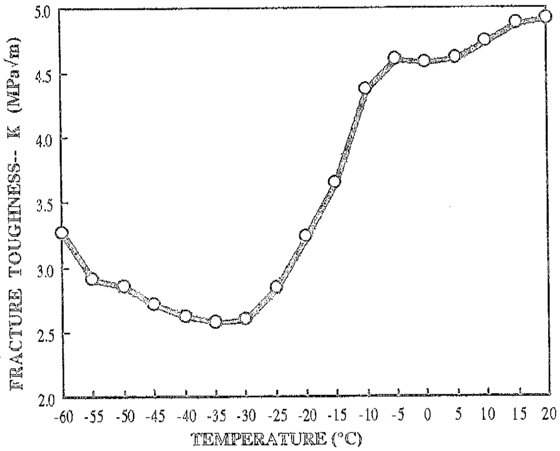

FIG.7 TEMPERATURE DEPENDENCE OF FRACTURE TOUGHNESS FOR PMMA

3.2.1 Temperature gradiend test (notch edge cooling)

Fig. 8 shows the results of this test when the crack tip temperature was mantained at -15 °C. In this case temperature in the region ahead of crack tip increased gradually. The crack tip is located at a distance of 40 mm from the notched edge of the specimen. Fracture toughness value at this point in uniform temperature test was of an amount of 3.66 MPa√m, while the fracture toughness value for temperature gradient test is about 3.96 MPa√m, which shows a significant increase when compared to uniform temperature test. The difference is of the order of 0.30 MPa√m. Fracture toughness value for temperature gradient test is marked by a square in the figure.

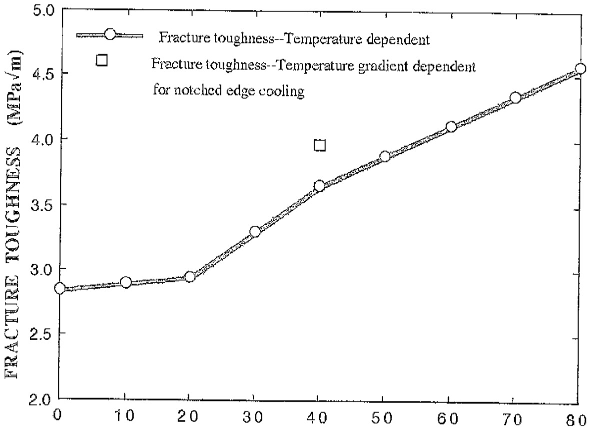

FIG.8 TEMPERATURE GRADIENT DEPENDENT FRACTURE TOUGHNESS COMPARED WITH UNIFORM TEMPERATURE TEST

3.2.2 Temperature gradient test (load edge cooling)

Results for this second case of temperature gradient test are shown in Fig. 9. In this case temperature decreased gradually ahead of the crack tip. Crack tip temperature was mantained at -15 °C. Fracture toughness value recorded at the crack tip in this case was 3.32 MPa√m, which was 0.34 MPa√m less than the value observed in the uniform temperature test. Fracture toughness value for temperature gradient test is marked by a triangle in the figure.

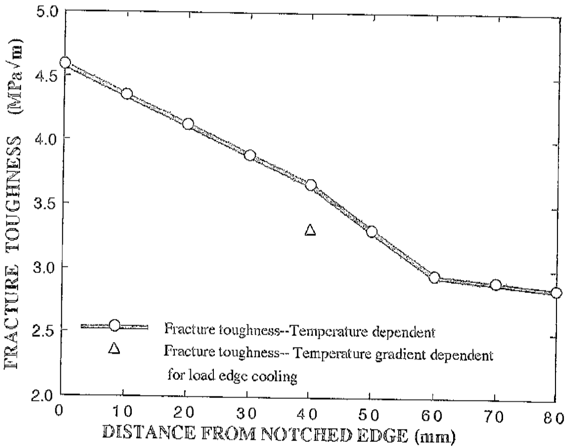

FIG.9 TEMPERATURE GRADIENT FRACTURE TOUGHNESS COMPARED TO UNIFORM TEMPERATURE TEST RESULTS

3.2.3 Thermal stresses in the temperature gradient tests

Fig.5 and 6 show the temperature distribution in the specimen for six different temperature gradient tests. In both of these figures temperature changes linearly from one edge to the other. Since the temperature change is not represented by true straight lines in these figures, it was assumed that there were some thermal stresses involved. And fracture toughness due to these thermal stresses was present but its amount was nearly negligible.

4 DISCUSSION

Looking in to the results obtained from uniform temperature test and the temperature gradient tests, it is evident that there is a certain factor controlling the fracture toughness at the crack tip for temperature gradient tests. This is a finite area (process zone) ahead of the crack tip responsible for the crack initiation. Process zone is generally recognized to exist ahead of the crack tip and material behavior in the process zone is responsible for the crack initiation. Damage of this process zone depends on the material property of the process zone. As the material properties ahead of the crack tip are no more uniform in temperature gradient tests, that is why, we observe a difference in the fracture toughness there.

When uniform temperature tests are performed the specimen material behaves homogeneously. Fracture toughness value at every point in the specimen ahead of the crack tip is same. In this case crack initiates at a certain rate. In temperature gradient tests the situation is quite different, the rate of crack initiation now depends on the particular condition involved. Fracture toughness value at every point ahead of crack tip is gradually increasing when the temperature ahead of crack tip increases, posing a certain amount of resistance which delays the process of crack initiation and consequently gives a higher value of fracture toughness. When the temperature ahead of crack tip is decreasing, it means that the fracture toughness ahead of the crack tip is decreasing and it accelerates the process of crack initiation, which means a smaller value of fracture toughness.

So it is concluded that the process zone plays a very important role in the determination of fracture toughness when the specimens are tested under a temperature gradient.

ACKNOWLEDGEMENTS

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