Key Engineering Materials Vols. 261-263 (2004) pp 153-158
Online available since 2004/Apr/15 at www.scientific.net

doi:10.4028/www.scientific.net/KEM.261-263.153

Study on Fracture Properties of High-density Polyethylene (HDPE) Pipe

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Keywords: High-density polyethylene (HDPE), Butt-fusion welded joint, Crack opening displacement, Resistance to crack initiation, Multiple specimen resistance curve method, Silicon-rubber replica method, Statistic distribution, Weibull distribution

ABSTRACT

Butt-fusion welding is the main technology to join high-density polyethylene (HDPE) plastic pipes, which are widely used in transport the water, gas and corrosive liquid. Investigation shows that one of the failure modes of HDPE pipe is the crack slowly grows across the thick direction and leads to failure at last, so that it is very important to study the resistance to crack initiation of HDPE pipe and its butt-fusion welded joint. In this study, the elastic-plastic fracture mechanics parameter, crack opening displacement (COD) is used to describe the fracture initiation behaviors for the HDPE materials and its butt-fusion welded joints. The resistance to initiation fracture of HDPE pipe materials and butt-fusion welded joints were investigated at different temperature by using multiple specimen resistance curve method and silicon-rubber replica method. The results show that saturation initial crack COD- δ_{is} of HDPE pipe materials and butt-fusion welded joints decreases with the decreasing temperature. The δ_{is} of butt-fusion welded joints is lower than that of HDPE pipe materials. Investigation also proved that the silicon-rubber replica method is more suitable for HDPE engineering material than the multiple specimen method. At the same time the statistic distribution of the δ_{is} of HDPE butt-fusion welded joint was conducted. The results show that the value of the δ_{is} has the statistic variance inherently. The optimum fitting distribution of COD δ_{is} is Weibull distribution with three parameters.

1. INTRODUCTION

High-density engineering plastic pipe is one of the most important developing aims for the pipe industry presently. It has been applied to transport the water, gas, and corrosive liquid because of its low price, easily installed and good corrosive resistance. Welding technology is the main technology to join engineering plastic pipes, and directly affects the safety application of high-density engineering plastic pipe. It is found that one of the failure modes of HDPE pipe is the crack slowly grows across the thick direction and leads to failure at last. The crack initiation period depends on material properties. Recently, as the application of high-density polyethylene (HDPE) pipe becomes much more popular, it becomes more urgent and necessary to study the resistance to initial fracture properties in order to establish the initiation fracture criterion suitable for HDPE pipe, and to provide the safety assessment procedure based on the fitness for purpose.

General speaking, it is very suitable that using linear elastic fracture mechanics to study the fracture characteristic of brittle polymer, but for tough polymer it must be under special condition, for example, experimental temperature must be lower than –100℃[2,3], so that it is difficult to use linear elastic fracture mechanics for tough polymer. HDPE belongs to tough polymer, so elastic-plastic fracture mechanics were used to evaluate the fracture behaviors of high-density polyethylene pipe and its butt-fusion joints.

In this work, the fracture behaviors of HDPE for the supply of gaseous fuels and its butt-fusion joint were studied at different temperature based on crack opening displacement method. At the same time the statistic distribution of fracture characteristic parameters of HDPE butt-fusion welded joint were conducted also.

2. EXPERIMENTS

2.1 Experimental material

The HDPE pipe and its butt-fusion joint used in this work are commercial products supplied in the form of pipe by Chinaust Plastic Corp. Ltd. Pipe specification is given as follows: the outer diameter of pipe is 200mm, and Standard Dimension Ratio SDR (outer diameter/ pipe thickness) =11. Welding was completed in Chinaust Plastic Corp. Ltd. the sketch of butt-fusion welded joint is shown in Fig.1. Two parts were divided in one butt-fusion joint. Those are fusion zone and base pipe material as shown in Fig.1.

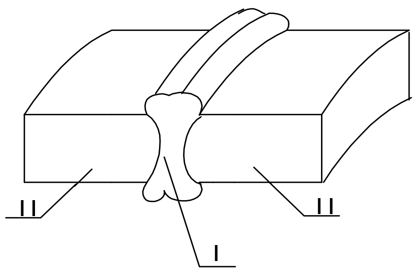


Fig.1 The sketch of butt-fusion weld joint of HDPE

2.2 Experimental specimen

Bars of dimensions 19mm×38mm×200mm, used as single-edge notch specimen (Fig.2) for fracture test, were machined from HDPE pipe and its butt-fusion joint directly. Notching was performed in two steps: first a notch of 15mm depth was cut by the disc saw, and then additional 4mm crack at the tip of the notch was made by a sharp V-blade with radius not more than 25 μ m, and a notch length (a) to specimen width (W) ratio of 0.5 are kept. Notches were cut at different zones shown in Fig.1 respectively.

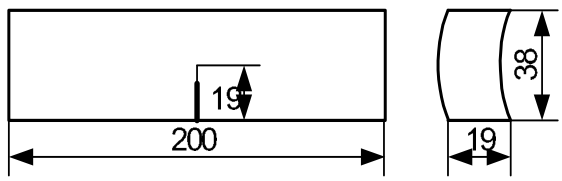


Fig.2 three point bent specimen with prefabricated crack

2.3 Experimental methods

Multiple specimen method and silicon-rubber replica method were used in this study respectively. The COD values that were measured by these two method can describe the resistance to initiation fracture property of HDPE pipe material and butt-fusion joint. The simple introductions about these two methods are as follows.

Multiple specimen resistance curve method is the traditional measurement method for elastic-plastic fracture mechanics including J-integral and COD. The details about the measurement method are described in relevant reference and standard[4,5].

Considering the silicon-rubber replica method, it is one direct measurement method. This method has been used to measure the COD value of metallic materials in order to evaluate resistance to initiation fracture of metallic materials[6]. In this study, this method was used to measure the COD value of HDPE pipe materials and butt-fusion joint firstly in order to evaluate its resistance to initiation fracture. The procedure in details of this method is introduced in reference [6].

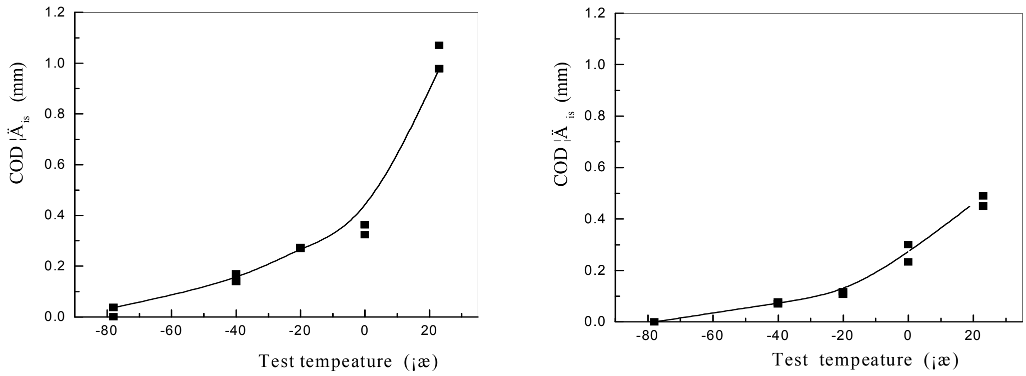
2.4 Statistic distribution method

Because of the variables of the composition of the HDPE welded joint induced by the welding process, the saturation initial crack COD have the statistic variance inherently. So that it is more exact using statistic method to describe the fracture behaviors of its joints.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Effect of temperature on fracture characteristic

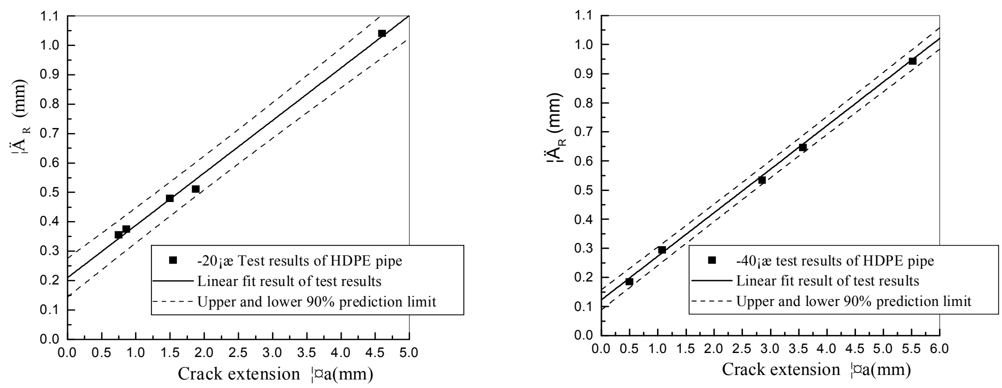
In order to study the effect of temperature on fracture characteristic of HDPE pipe material and butt-fusion joint, fracture test was done at different temperature based on two methods described in 2.3. Experimental results are shown in Fig. 3, and Fig.4 respectively.



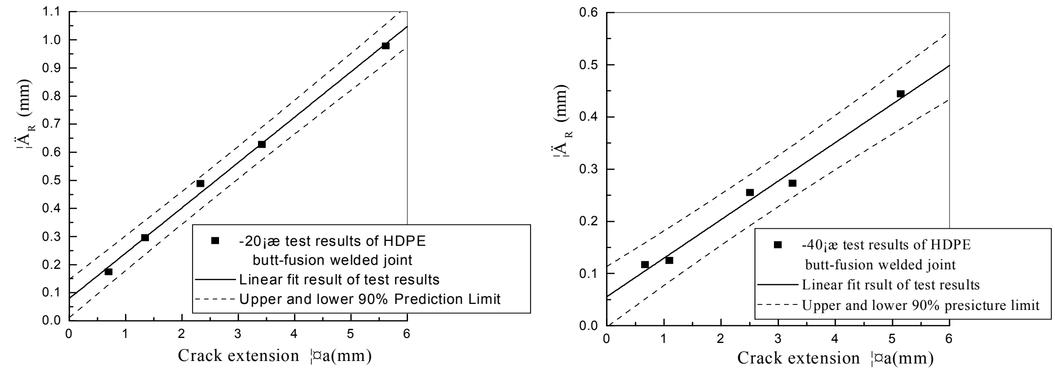
(a) HDPE pipe (b) HDPE butt-fusion joint

Fig. 3 Saturation initiation crack COD δ_{is} of HDPE pipe and butt-fusion at different temperature

Fig. 3 shows the experimental results by using silicon-rubber replica method. As the testing temperature lowered, saturation initial crack COD of each zone such as pipe materials and fusion zone decreases. The effect of temperature on fracture characteristic is due to the greater increasing of materials stiffness with temperature decreasing. As the testing temperature is lowered, stiffness of HDPE materials increased rapidly. The materials have a higher load carrying capacity due to the greater increase in stiffness. For example, for three point bend specimen described in 2.2, its load capacity at 20℃ is 1.2kN, but at –78℃ its load capacity is 2.3kN.



(a) COD versus crack extension of HDPE pipe

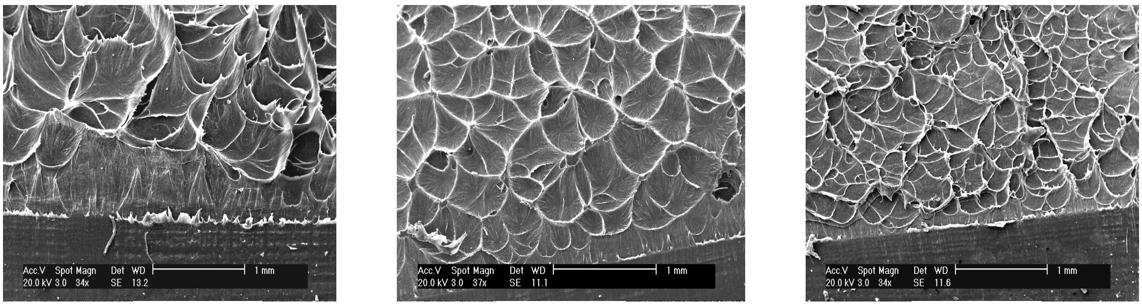


(b) COD versus crack extension of HDPE butt-fusion welded joint

Fig. 4 COD versus crack extension at -20℃ and -40℃

Fig.4 shows the experimental results at different temperature by using multiple specimens resistance curve method. Same results and same law as silicon-rubber replica method were found.

Fracture mode at different temperature is also examined by SEM. Fig.5 shows the results of observation. The fracture surface shows the characteristic dimple-type of a ductile tearing mode. As the testing temperature lowered, the size of the dimples becomes smaller, at the same time the depth of the dimples also becomes smaller, reflecting the decrease in ductility on micro-level.



(a) (b) (c)

Fig. 5 Scanning electron micrographs of fracture surface of HDPE Butt-fusion welded joint
(a) 20℃ (b)-40℃ (c) –78℃

3.2 Effect of welding process on fracture characteristic

Fig.6 shows the comparison of δ_{is} of different zone for the same butt-fusion welded joint. At the same testing temperature, δ_{is} of pipe material is larger than that of heat-affected zone, and δ_{is} of heat-affected zone is higher than that of joint fusion zone. These results are induced by the thermal history during welding process.

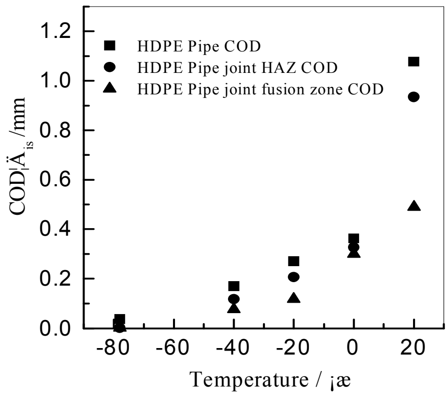


Fig. 6 Comparison of saturation initiation crack COD δ_{is} in different zone

Fracture properties can be expected to be controlled primarily by the degree of crystallinity, even though this parameter is just one of the many factors. In a study on commercial polyethylene, Mandell et al. found a unique correlation between fracture toughness and the degree of crystallinity when the latter is varied because of changing the processing condition such as thermal treatment, chemical composition or molecular weight[7]. The degree of crystallinity is the first structural variable that to be related to fracture properties at different zone of butt-fusion joint. When two pipes welded together, the process that pipes undergo from fusion temperature to room temperature is the same as anneal process. General speaking, the more high anneal temperature is, the more high degree of crystallinity of polymer is, so that the evident difference between butt-fusion joint and pipe material must be existed. For polymer, the degree of crystallinity decided its mechanical properties. Relevant work has been done and discussed in other papers.

3.3 The comparison of two testing methods

Crack opening displacement method is one of the elastic-plastic fracture mechanics. It is first time that using crack opening displacement method to evaluate the fracture characteristic of HDPE in this study. Multiple specimen resistance curve method is one of indirect methods. At first, at least five samples are needed for each temperature by using this method. During the test, P-V curve of each sample must be recorded. The basic mechanical properties, sample dimension and other parameters must also be known at each testing temperature. Then COD characteristic parameters can be gotten by using the relevant expressions and relevant extrapolation.

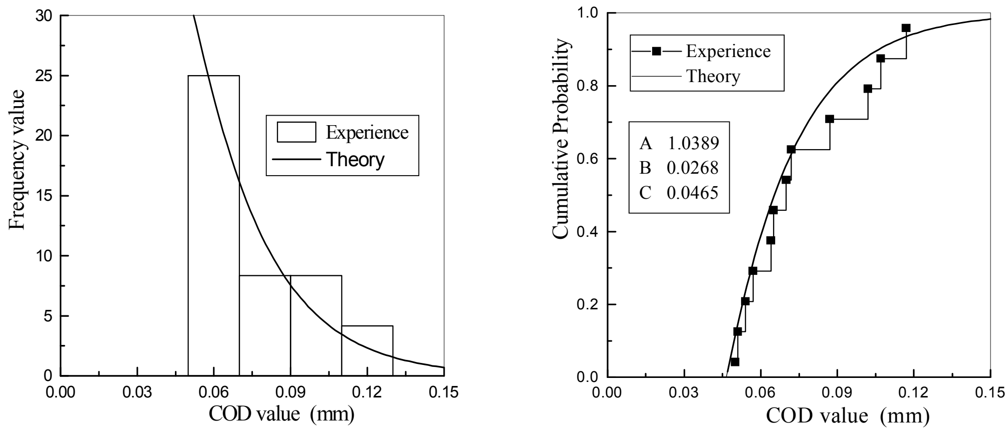
Silicon-rubber replica method is direct measurement method, which is the first time to use this method to evaluate the fracture characteristic of HDPE material. The basic procedure of this method is as follows. First, three point bend test should be done as usual until the specimen was failure. Second, liquid silicon-rubber with catalyst was filled in the crack of specimen. Silicon-rubber replica was brought out after it was solidified. Third, measuring the tip size of silicon-rubber replica using microscope according to relevant standard so that the characteristic COD parameter was obtained. For this method, only one or two samples are enough for each temperature. And P-V curve of each sample need not be recorded. Especially the basic mechanical properties at different temperature and a mass of computation work don't be needed. So using this method can reduce many works, but can get the basic fracture mechanics parameter. Silicon-rubber replica is a simple and feasible measuring method for HDPE materials even other tough polymer.

3.4 The selection of statistic distribution function

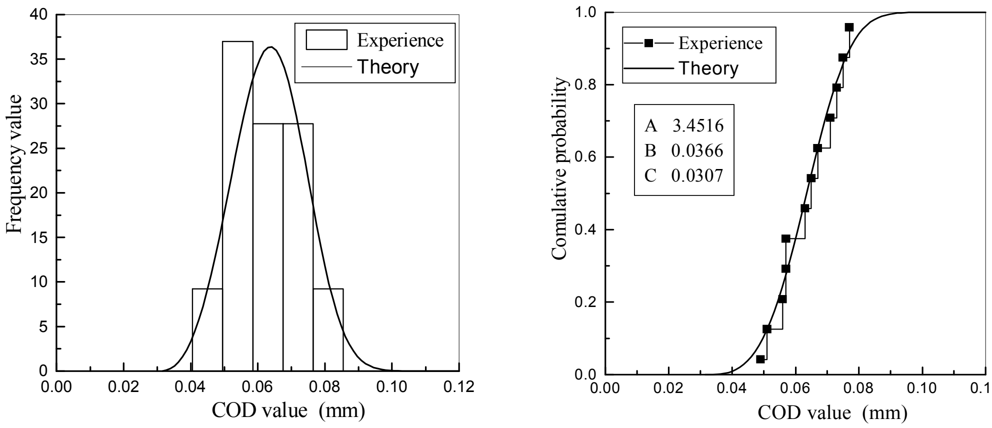
The statistic distribution of fracture characteristic parameters of HDPE butt-fusion welded joint was conducted. Results show that the δ_{is} of HDPE butt-fusion welded joint have the statistic variance inherently. The statistic probabilistic model was set up to fit the distribution function of δ_{is}. Performed several statistic tests such as normal distribution, logarithm normal distribution and Weibull distribution, the results show that the optimum fitting distribution of δ_{is} is Weibull distribution with three parameters. The function of distribution is as follows.

$$F(x) = 1 - \exp[-(\frac{x-C}{B})^{A}] \quad (1)$$

Fig.7 shows the fitting results and the fitting curve.



(a) Experience and theory diagram of δ_{is} at -20℃



(b) Experience and theory diagram of δ_{is} at -40℃

Fig. 7 Experience and theory diagram of δ_{is} for HDPE butt-fusion welded joints at -20℃ and –40℃

4. CONCLUSIONS

The fracture behaviors of HDPE were studied at different temperature. At the same time the statistic distribution of δ_{is} was also conducted. The main conclusions can be summarized as follows.

1. As the experimental temperature is lowered, the value of δ_{is} of HDPE becomes smaller. The fracture mode was ductile tearing at every experimental temperature, but the degree of ductile tearing is different.
2. At the same temperature the value of δ_{is} of HDPE butt-fusion zone is smaller than that of HDPE pipe. This phenomenon has closed relevant with welding heat process.
3. The silicon-rubber replica method is more suitable for HDPE material to obtain δ_{is} than the multiple specimen method by comparing these two experimental methods.
4. The statistic distribution shows that the value of δ_{is} has the statistic variance inherently. The optimum fitting distribution of δ_{is} is Weibull distribution with three parameters.

ACKNOWLEDGEMENT

The authors are grateful for the supporting by National Natural Science foundation of China (50075061). Same appreciation are also given to Chinaust Plastic Corp. Ltd. for their providing all the experimental material including HDPE pipe and butt-fusion joint.

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Advances in Fracture and Failure Prevention
10.4028/www.scientific.net/KEM.261-263

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