Cast iron is used as material for motor and pump casings due to its superior casting characteristics. In addition, it is used for cylinder liners and pistons exposed to high temperatures because its strength does not deteriorate even at high temperature conditions. For parts made of cast iron, examples of brittle fracture damage induced by thermal stress are reported. However, there are few failure examples where cracks lead to fracture. Therefore, a study was conducted to clarify the transition process of stationary crack to brittle dynamic fracture induced by thermal stress. All processes of fracture phenomena were recorded by an ultra-highspeed video camera. The position of the crack tip was determined from image data, and the propagation velocity of the crack was surmised. Then, the authors measured the surface roughness of the fracture process zone caused by crack propagation. Furthermore, the stress intensity factor which is a condition for a crack to propagate was obtained by calculation using the load data value of the specimen.

1. Introduction

The cast iron is used as components such as the cylinder liner or the cylinder cover of the diesel engine installed as the main engine of the ship. Especially, inside temperature of the cylinder cover and the cylinder liner is very high, and outside temperature of these is low. It is the situation that the thermal stress is always generated in these materials. As a result, fatigue cracks by the thermal stress are often seen in component materials of the diesel engine.

Accordingly diesel engine makers and research institutes are studying the thermal stress of the cylinder cover and the cylinder liner forming the combustion chamber[1]. In addition, they perform analysis about the thermal stress using a finite element method.

But there are very few damage examples to reach a fracture by the thermal stress because the growth rate of the fatigue crack is very slow. However, there are some failure examples that the crack extended to fracture in cast iron.

Therefore authors have started this study to clarify the brittle fracture phenomenon that was broken by thermal stress. As the first stage, we experimented in the brittle fracture phenomenon using a specimen of the cast iron which was brittle material, and confirmed that the cast iron was broken by the thermal stress. At the same time, we took photographs of the fracture phenomenon and crack propagation state with the ultra-highspeed video camera, and collected data through this experiment.

This report describes the experiment method of the brittle fracture phenomenon by the thermal stress effect at first, and displays the image of the process of the photographed brittle fracture phenomenon with the ultra-highspeed video camera. Next it explains the crack propagation velocity and roughness of the fracture surface, and the stress intensity factor that is calculated based on collected load data.

2. Experiment

2.1 Specimen

The specimen was made of the cast iron FC200 that was continuously cast using a wire cutting electrical discharge machine. Figure 1 shows the size and shape of the specimen, and thickness is 4.5mm. There are two pinholes of 12.5mm and 20mm in diameter to fix the specimen at both ends. And the initial crack of 0.25 mm (width) 25 mm (length) is induced by an electric discharge machining at a center of the specimen.

In order to obtain the necessary signal to trigger of the ultra-highspeed camera, an insulating coating was applied to the finished specimen surface. Furthermore two layers were applied in consideration of falling of an insulation effect by a surface heating by a gas torch burner.

To obtain the trigger signal from a circuit interruption by the crack propagation, the crack tip of the specimen was
painted a conductive coating of a few millimeters wide. The conducting wires were fixed on this paint surface by putty, and ends of the wires were attached to the trigger input of the ultra-highspeed video camera system. Conducting wires were covered by the fireproof putty to protect from the heat of the burner.

Ultra-highspeed video camera system used in this experiment is the world's most advanced equipment, and it is possible to take sharp images at very short time in conjunction with pulsed laser.

Fig. 1 Specimen Shape

2.2 Experimental equipment
The experiment was carried out using a fatigue-testing machine show in figure 2, and the load that acts on the specimen was measured continuously by a load cell. Because the load cell can move freely up and down, restraint of both ends of the specimen became easy to use this machine. The surface temperature of the specimen was measured with non-contact infrared thermometer.

In addition, the ultra-highspeed video camera system show in figure 3 was used to photograph the crack of the brittle fracture caused by the thermal stress to propagate at very high speed.

Fig. 2 Experimental equipment

<Specifications of ultra-highspeed video camera system>
* Resolution: 312×260 pixels (256 gradation)
* Shooting Speed: from 30 frames per second up to 1 million frames per second
* Number of record images: 102
* Manufacturer: SHIMADZU CORPORATION

2.3 Experimental methodology
The testing procedure is described below.
(1) The upper pinhole of the specimen was restrained to the load cell using an upper restraint pin, and the lower pinhole of the specimen was fixed to a jig of a base plate using a lower restraint pin.
(2) The height of the load cell went up 0.9996mm after the lower restraint pin was pulled out, and the hole of the jig and the specimen matches when the specimen expands 0.9996mm by heating.

\[ \delta = \alpha \Delta T L \delta : \text{thermal expansion length (mm)} \]
\[ \alpha = \text{Coefficient of thermal expansion}^{(2)} = 11.9 \times 10^{-6} / \degree K \]
\[ \Delta T = 280 \degree K \]
\[ L = 300 \text{mm} \]
\[ \delta = \alpha \Delta T L = 11.9 \times 10^{-6} / \degree K \times 280 \degree K \times 300 \text{mm} = 0.9996 \text{ (mm)} \]
(3) The upper and lower part of the specimen was heated with the gas torch burner show in figure 4, and the surface temperature of the specimen increased until 300°C.
(4) When the length of the specimen expanded 0.9996mm, the lower restraint pin was inserted in the pinhole, and the jig and the specimen were completely restrained.
(5) When the specimen was completely restrained, the heating was stopped.
(6) The specimen was cooled with the atmosphere, and a surface temperature of the specimen decreases to room
temperature by progress of time. The tensile stress that was increased with the decrease in temperature was measured continuously by the load cell.

(7) When the surface temperature of the specimen fell to about 200 degrees Celsius, the specimen was fractured by excessive tensile stress.

(8) Photographs that were taken with the ultra-highspeed video camera system showed the brittle fracture phenomenon of the specimen caused by the propagation of the crack. As the trigger signal that was starting photography with the ultra-highspeed video camera system, the progress of the crack was used.

![Fig.4 Heating of specimen](image)

3 Experimental Results

3.1 Photographs of brittle fracture

It was confirmed that the cast iron of brittle materials was fractured by the tensile stress due to the thermal stress in this experiment. The crack of the specimen propagating at high speed was captured with the ultra-highspeed video camera system at 31,250 frames per second.

Figure 5 shows the part of ultra-highspeed photographs of the dynamical propagating crack induced by the thermal stress. The crack tip propagates from the initial crack that was induced by an electric discharge machining, and the crack propagation direction was confirmed to be perpendicular to the direction of the load.

These photographs show that plastic deformation does not occur during the crack propagate in the specimen, and the specimen separates by the propagation of crack. The white circle in the photograph shows the crack tip.

![Crack Tip](image)
3.2 Crack propagation velocity

The position of the crack tip was decided from image data captured by the ultra-highspeed video camera system, and the propagation velocity of the crack was surmised. Incidentally, the starting point was made the place where the position of the crack tip had been confirmed at first. It also assumed that the crack propagate horizontally during propagation, we determined the location of the crack tip by distance from the edge of the specimen.

Figure 6 shows the crack tip position and the crack propagation velocity during the crack propagation. Left vertical axis shows the distance from the initial crack tip, and right vertical axis shows the crack propagation velocity. This figure shows that the crack propagation velocity was slow initially, it becomes the maximum in the middle stage, and it becomes the slow again before the fracture at the terminal of specimen. The maximum value of the crack propagation velocity is 57.04m / s.

3.3 Fracture surface roughness

Because the difference of the fracture surface could not distinguish using the fractographic study by the microscope image, we measured the surface roughness of the fracture process zone caused by the crack propagation.

The laser focus displacement meter shown in Figure 7 was used to evaluate the roughness of the fracture surface. Evaluation resolution of the crack surface with the displacement meter is 10μm pitch in the x and y direction, and the precision of z direction is 2μm.

Figure 8 shows the conceptual diagram of the measurement of the fracture surface roughness. Because this displacement meter can measured x direction and y direction, it is possible to measure two dimensional space.

The surface roughness is given in an equation (1). This equation can obtain the arithmetic mean deviation of the profile of each measurement point on the fracture surface.

\[
R_a = \frac{1}{\ell} \int_{x}^{x+\ell} \left| z_m(x) - z_{ave} \right| dx
\]  

(1)

From the result of the calculation of the fracture surface roughness of each measurement point, we determined the distribution of the fracture surface roughness. Because the entire fracture surface is the inclined or curved surface in this case, the influence is considered. To accurately measure the surface roughness, the standard surface Zs has to be
tilted itself\(^3\).

In this measurement, the plane that was composed of four triangles assumed as the standard surface. As shown in figure 9, these triangles are formed by connecting the four corners and center of the regular square indicating the roughness measurement range.

The fracture surface roughness was measured like this way by the unit of 10,000 \(\mu m^2\). The roughness of surface for the sloping standard surface was calculated using equation (2), and the calculation value is assumed to be a value of roughness at the center point.

\[
R' = \frac{1}{(y_2 - y_1)(x_2 - x_1)} \int_{y_1}^{y_2} \int_{x_1}^{x_2} f_a(x, y) - z(x, y) \, dx \, dy
\]

\(\mu m\)

\[\Delta x = x_2 - x_1 = \Delta y = y_2 - y_1 = 100\]

Figure 10 shows the result of the calculation. The surface roughness of the initial crack induced by the electric discharge machining is very smooth, and maximum roughness of brittle fracture surface is 56 \(\mu m\).

Figure 10 shows the surface roughness on the contour. The red color shows the peak of the roughness of the fracture surface, and blue color shows the valley of it. The surface roughness of the early stage crack and the later stage crack were compared, and a significant difference was not found. In this experiment, it is thought that the brittle fracture by the thermal stress was generated from the early stage of the crack.

3.4 Generation of thermal stress

When the temperature of the specimen decreases, the tensile load by the thermal stress is generated in it. The value of the load of the specimen was measured with the load cell at intervals of 200 milliseconds.

Figure 11 shows the relation between the tensile load and the time obtained from the data collected in the data logger. The horizontal axis of Figure 11 indicates time, and the vertical axis shows the tensile load. The temperature of the specimen decreases with progress of the time, and tensile load increases approximately linearly on the cooling effect of thermal stress. The specimen was fractured at 109 seconds showing the maximum load (61132.4N), and the load falls to zero immediately. It was approximately 200 degrees Celsius when it measured the temperature of the specimen at the time of the fracture with the non-contact infrared thermometer.

3.5 Stress intensity factor

The stress intensity factor that was a condition for the crack to propagate was obtained by the calculation using the value
of the load data of the specimen. We calculated using the formula for finding the stress intensity factor of a uniform tensile load of crack in one side of the strip. Equation (3) is used to calculate the stress intensity factor $K_I$.

$$K_I = \frac{\sigma}{\pi} \cdot F(\alpha)$$  \hspace{1cm} (3)

$$a = a/W$$

$$F(\alpha) = 1.12 - 0.231 \alpha + 10.55 \alpha^2 - 21.72 \alpha^3 + 30.39 \alpha^4$$

Here, $\sigma$ is stress, $a$ is length of the initial crack, $F(\alpha)$ is correction factor, and $W$ is the width of the specimen. Each value is substituted in equation (3) and calculated.

$$\sigma = 61132.4N \div (50 \times 4.5mm) = 271.6996 \text{ N/mm}^2$$

$$\sigma = 271.6996 \text{ MPa}$$

$$\alpha = a/W = 25mm/50mm = 0.5$$

$$F(\alpha) = 1.12 - 0.231 \alpha + 10.55 \alpha^2 - 21.72 \alpha^3 + 30.39 \alpha^4$$

$$= 1.12 - 0.231 \times 0.5 + 10.55 \times 0.5^2 - 21.72 \times 0.5^3 + 30.39 \times 0.5^4$$

$$= 1.12 - 0.1155 + 2.6375 - 2.7150 + 1.8994 = 2.8264$$

$$K_I = \frac{\sigma}{\pi} \cdot F(\alpha)$$

$$= 271.6996 \times (3.14 \times 25 \times 10^{-3})^{1/2} \times 2.8264$$

$$= 271.6996 \times 0.28018 \times 2.8264$$

$$= 215.1591 \text{ MPa} \cdot \text{m}^{1/2}$$

4. Conclusions

The following facts are confirmed by the result of the experiment to generate the thermal stress in the cast iron and to break in brittleness.

(1) The cast iron of the brittle material was fractured by the pure thermal stress.

(2) When the value of the tensile stress was small, the crack propagation speed was slow. When the stress increased and the brittle fracture was generated, the crack propagation speed was very fast.

(3) We found the crack propagation velocity from the movement distance of the crack tip position in the photography image. The maximum propagation velocity of the brittle fracture in this experiment was 57.04m/s.

(4) Result of the measuring roughness of the brittle fracture surface, the maximum roughness is 56μm.

(5) The value of the stress intensity factor to show the degree of the stress of the crack tip was decided by the calculation using load data. As a result of the calculation, the intensity factor $K_I$ decided 215.16MPa·m$^{1/2}$.

In this experiment, we confirmed that the brittle fracture of cast iron occurred under the effect of thermal stress, and revealed the process of brittle fracture.

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References


