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Prediction of the Fracture Location by Tensile Tests of Gray Cast Iron Based on the Dimensional Changes of Graphite Flakes

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ABSTRACT

Gray cast iron has been used as a component in various mechanical parts, such as the blocks and heads of automobile and marine engines, cylinder liners for internal combustion engines, and machine tool bases. It is desirable because of its good castability and machinability, damping characteristics, and high

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performance-to-cost ratio. On the other hand, weak graphite flakes present in gray cast iron serve as stress concentrators and adversely affect the material strength. Therefore, it is crucial to examine the relationship between the distribution of graphite flakes and the strength or fracture of gray cast iron. In this study, tensile tests on gray cast iron were carried out using a plate specimen and observed by scanning electron microscopy, and the microscopic deformation was observed on the specimen surface. Particularly, the change in the size of graphite flakes during the tensile tests was examined, and the observed trend was discussed. The experimental results reveal that the dimensional changes in the graphite flakes vary in the observed area and that the final fracture occurs in an area where a large dimensional change is observed, suggesting that the fracture location or critical parts of gray cast iron can be predicted from the dimensional changes of the graphite flakes at an early stage of deformation.

INTRODUCTION

Gray cast iron has been used in various mechanical parts because of its cost-effectiveness, good castability and machinability, low thermal expansion coefficient, high thermal conductivity, and good damping characteristics. As casting is a manufacturing process that renders a high freedom of shape, fundamental experimental studies of gray cast iron, as well as the design and failure analyses of its components have been typically performed in combination with numerical analyses by using the finite element method (FEM). Wang et al. have proposed a method for predicting the fatigue failure for camshafts in vehicles composed of gray cast iron [1]. They used the crack modeling approach in which the stress–distance relationship is approximated by a function of the remote stress and crack length, and it is best fitted to the actual stress distribution in a particular area analyzed by the FEM. The fatigue limit is then predicted by the stress intensity factor by using the best fit remote stress and crack length. The

accuracy of the predicted fatigue limit is improved, and the effect of the hard surface layer on the limit is successfully considered in the modeling approach. In addition, the combination of experimental and numerical modeling was adopted for failure analysis. Branco et al. investigated the failure mechanisms detected in alloyed cast iron liners of marine engines [2]. Numerical analysis was performed to obtain the stress and temperature distributions during the repeated engine combustion. The analytical results and microstructural observation confirmed that the geometrical improvement of the cooling channel of the liner was not sufficient; replacement of the cast iron into a high-grade one was suggested. Similar investigations have been performed for the fatigue analysis of the diesel engine cylinder head used in a truck [3], fatigue properties of the directional valve bodies for tractor lifters [4], and the resistance of brake discs to thermal fatigue [5]. In addition, researchers have used FEM for the analysis of the cylinder blocks used in maritime diesel engines [6–8]. The effect of the tightening of the cylinder head bolt on the lifetime of cylinder block was investigated, and some practical methods to decrease the static strain along the fillet on the upper deck of the cylinder block, such as change in the depth of the thread engagement and modification of the bead shape, were proposed to extend its lifetime under severe combustion conditions.

On the other hand, graphite flakes distributed in gray cast iron serve as stress concentrators and adversely affect the material strength. Hence, microstructural considerations are imperative during the accurate evaluation of the material strength. Wang et al. have prepared gray cast iron with oriented graphite flakes by the severe plastic deformation process and compared its tensile strength with that of normal gray

cast iron [9]. After the severe plastic deformation process, gray cast iron exhibits a higher tensile strength. Since the thickness of the material is largely reduced by the process, the distribution of graphite is also changed. The higher was the relative reduction by the process, the higher were the tensile strength and elongation. Hence, the improved tensile properties are mainly attributed to the reduction of stress concentrations at the tips of graphite flakes rotated along and aligned to the tensile direction. The fracture of gray cast iron has been discussed from the viewpoint of fracture mechanics. Hornbogen has investigated the fracture toughness and fatigue crack growth of gray cast iron [10]. From experimental observations, the crack growth in cast iron occurs in the following order: 1) Elastic deformation, 2) formation of voids or the opening of graphite flakes near the notch tip, 3) growth of microcracks from several broken graphite flakes, and 4) growth of the main crack from the notch tip coalescing with the initiated microcracks. The above results suggest that graphite flakes are extremely weak in comparison to the matrix and act as stress concentrators. In addition, the deformation around the crack can be evaluated by the opening of graphite flakes. Hertolino et al. have evaluated the fracture toughness of gray cast iron using notched specimens of various geometries [11]. Although the macroscopic crack propagates with the coalescence of several microcracks near its tip, and the stress–strain relationship exhibits nonlinearity, the effect of the specimen geometries is not large. In addition, the authors performed microscopic finite element analysis on the stress concentration at the graphite flakes in two dimensions [12]. In the analysis, graphite flakes were recognized as identically shaped voids with no sustained load. The stress distribution on

the gray cast iron surface is found to be extremely complex because of the interaction of several graphite flakes, and the stress distribution near the tip of each flake is not approximated by the simple equation given by the stress intensity factor for a simple isolated through crack.

With the progress of measurement and processing technologies, the three-dimensional shape of graphite flakes near the gray cast iron surface can be obtained. Velichko et al. have visualized the exact shape of graphite flakes by FIB-tomography technology in which serial slicing was performed using a focused ion beam, and the exposed surface was observed by scanning electron microscopy [13]. All of the images were reconstructed to describe the 3D image. Extremely complicated shapes of the graphite flakes are revealed underneath the surface, and it is easily understood that the stress concentration on the surface cannot be predicted on the basis of their two-dimensional (2D) image acquired on the surface.

We summarize from the above investigations on the strength of gray cast iron that graphite flakes cause the stress concentration and considerably affect the tensile strength. However, the 2D image of the graphite flakes acquired on the surface is not sufficient to evaluate the stress distribution and concentration around the graphite flakes. We also think that the geometrical changes of graphite flakes reflect the deformation of pearlite matrix leading to fracture. The changes also include the effect of very complex shape of graphite flakes below the surface and the mechanical interaction between them on the matrix deformation. In this study, tensile tests on gray cast iron were performed using plate specimens and observed by scanning electron microscopy,

and the microscopic deformation was observed as the dimensional changes of the graphite flakes during the tensile tests. From the dimensional changes of graphite flakes, the fracture region was predicted, and the results were compared with the actual fracture line. The authors have been investigating the small inhomogeneous deformation of materials on the surface and have tried to use it as an indication of latent severe deformation and fracture [14–16]. The present paper is one of a series of researches and the results will be helpful to know an appropriate distribution of graphite flakes in the cast iron to avoid the brittle fracture.

EXPERIMENTAL PROCEDURE

Specimen and Tensile Tests

Two plate specimens of gray cast iron with an identical shape, specimens A and B, were used for tensile tests. Figure 1 shows their shape and size. The specimens were taken from the runner of diesel engine cylinder block by wire cut electrical discharge machining. The length and width of the parallel part were 4 mm and 2 mm, respectively, and the thickness was 1 mm. The behavior of the graphite flakes and fracture in this parallel part were observed. Table 1 summarizes the chemical composition of the test material, and Figure 2 shows an example of the distributed graphite flakes observed on the specimen A surface. Several thin graphite flakes were uniformly distributed and randomly oriented in the pearlite matrix, with widely varying lengths. The gray cast iron was classified as type A according to the ASTM standard. The specimen surface was mechanically polished by using #600 to #2000 emery papers and 9 μm and 3 μm diamond pastes before the tensile tests.

Tensile tests were carried out using a tensile testing device set in an S-3500N scanning electron microscope (Hitachi High-Technologies Corporation, Tokyo, Japan). The tensile displacement between the two loading pins was manually increased by turning a handle, and it was increased in steps (Table 2(a) for specimen A and Table 2(b) for specimen B). The lower increase in the displacement during steps 4 and 6 for specimen A was related to the initiation of severe plastic deformation and large cracks observed in the parallel part of the specimen. Specimen B was fractured at a displacement of 0.42 mm. The maximum values for the nominal stress and nominal strain for specimen A were 183 MPa and 0.09, while those for specimen B were 204 MPa and 0.105, respectively. The nominal strain was evaluated using the final displacement between the two loading pins and the initial length of the parallel part.

Observation Areas and Geometry of the Graphite Flakes

The graphite flakes on the front surface of the parallel part of the specimens were observed during the tensile tests, and those on the back surface were observed before and after the tensile tests. In total, ~2000 graphite flakes were observed on each of the front and back surfaces of specimens A and B. The whole observation area was divided into five areas (denoted as Areas 1 to 5, respectively) with the same rectangular shape (Fig. 3). As one of the large cracks was initiated near the end of the parallel part, the observation area for specimen A was taken to be longer than that for specimen B. The geometry of the graphite flakes in each area was measured and averaged. In specimen A, two large cracks were found at the latter stage of the tensile tests, as indicated by the red lines in Areas 3 and 5 in Fig. 3(a), and the test was terminated at $\delta =$

0.36 mm with the opening of these cracks. Specimen B was completely fractured in Area 3 at $\delta = 0.42$ mm along the red line indicated in Fig. 3(b).

To investigate the behavior of the graphite flakes during the tensile test, the length projected onto the longitudinal direction of the specimen, l_{gL} , and that projected onto the transverse direction, l_{gT} , were measured in addition to the areas of the graphite flakes, S_g , shown in Fig. 4 using the binarized image of the parallel part of the specimen. In the magnified image, internal cracking within the graphite flakes and delamination of the flakes from the matrix were observed. However, such cracking and delamination were not considered in the subsequent results because of the facile fracture of these graphite flakes and the absence of a considerable effect on the fracture of a ductile matrix. The length l_g , width w_g , and angle with respect to the loading direction θ_g were evaluated by Eqs. (1)–(3) using the measured values of l_{gL} , l_{gT} , and S_g , respectively.

$$l_g = \sqrt{l_{gL}^2 + l_{gT}^2}, \quad (1)$$

$$w_g = \frac{S_g}{l_g}, \quad (2)$$

$$\theta_g = \tan^{-1} \frac{l_{gT}}{l_{gL}}, \quad (3)$$

In addition to the above values, the increase rates of the width and length of the graphite flakes in each area were evaluated by Eqs. (4) and (5), respectively, to determine the dimensional changes of the graphite flakes:

$$R_w = \frac{w_m|_{i+1} - w_m|_i}{w_m|_i}, \quad (4)$$

$$R_l = \frac{l_m|_{i+1} - l_m|_i}{l_m|_i}, \quad (5)$$

where w_m and l_m are the average width and length of the graphite flakes in each area, respectively, and i is the number of tensile displacement steps.

RESULTS AND DISCUSSION

Appearance of the Graphite Flakes and Tensile Fracture

Figure 5 shows images of the parallel part of specimen A before and after having attained the maximum displacement, i.e., $\delta = 0.36$ mm. Uniformly distributed graphite flakes were observed in the parallel part of the specimen before the test, and two large cracks were observed at $\delta = 0.36$ mm. The two fracture lines indicated by the red lines in Fig. 3 were traced with reference to these two cracks and the surrounding graphite flakes. Some bending, which was caused by the opening of these large cracks, was observed in Fig. 5(b). Figure 6 shows the images of the parallel part of specimen B. Uniformly distributed graphite flakes were observed in the parallel part of the specimen

before the test, and the final fracture occurred near its center. Other large cracks were observed in the parallel part of the fractured specimen B.

Figure 7 shows the magnified views of the graphite flakes in specimen A before the test and at $\delta = 0.35$ mm. Careful comparison of these two photographs revealed that the majority of the flakes becomes thick in the loading direction (x axis) and that some parts of the matrix, such as those circled by the broken line, become white. This part was considered to have underwent large plastic deformation due to a stress/strain concentration by the two close flake tips. These facts confirm that the graphite flakes are extremely weak and behave as crack-like voids. Therefore, the distribution of graphite flakes near the surface considerably affects the tensile strength of the gray cast iron.

Assuming that the material is linearly elastic, then deformation occurs in proportion to the stress, independent of the shape of the material and the presence of cracks and voids. The deformation in the stress/strain-concentrated regions in the material was greater than that in the other regions, but the large deformation remained linear in relation to the stress until the prevalence of plastic deformation in the material. With reference to the linear elastic fracture mechanics, the stress and strain at the crack tip are represented by the stress intensity factor K [17]. The K value is a function of the remote stress, crack length, crack shape, and boundary condition. In addition, as the crack opening displacement and crack tip opening displacement are also expressed by the K value, the precursory deformation of the fracture is expected to be observed as a dimensional change of the crack.

Considering the fact that the graphite flakes are shaped as crack-like voids and that graphite is extremely brittle, the length and width of the graphite flakes is expected to increase with the tensile load, and the parts experiencing large elastic deformation tend to undergo a transition to plastic deformation, leading to the final fracture. On the basis of these viewpoints, the geometry of each graphite flake was measured during the tensile tests.

Geometries of Graphite Flakes

Figures 8 and 9 show the correlation between the length and width of the graphite flakes on the front and back surfaces of the specimens A and B, respectively. Red marks in the figure indicate that these flakes were either on the fracture lines or were connected to the lines, suggesting that they are involved in the final fracture of the specimen. In terms of the lengths and widths of the graphite flakes, an extremely large distribution was observed; the maximum length and width of the flakes were $\sim 400\text{ }\mu\text{m}$ and $12\text{--}14\text{ }\mu\text{m}$ in specimens A and B, respectively. Although the red marks were distributed on the slightly lower side on the back surface of specimen A (Fig. 8(b)) and on the front side of specimen B (Fig. 9(a)), a significant difference was not observed between the red and white marks. Hence, it is difficult to predict the fracture location from the initial size and shape of the graphite flakes.

Figure 10 shows the average increase rates of the graphite flake widths and lengths in Areas 1 to 5. The rates were evaluated between the displacement values of 0 mm and 0.1 mm for both specimens. The widths and lengths of the graphite flakes considerably increased in Areas 3 and 5 of specimen A and Area 3 in specimen B, in

which large cracks were observed. A large dimensional change was observed in the graphite flakes in the fracture areas.

To elucidate the large dimensional change in the graphite flakes near the fracture line, the average increase rates for the width and length of graphite flakes on the fracture line in Areas 3 and 5 of specimen A were extracted (Figs. 11(a) and 11(b), respectively). The flakes on the fracture line tended to show a large change in each area, and the difference was apparent at an early stage. Figure 12 shows the average increase rates of the width and length of graphite flakes on the fracture line in Area 3 of specimen B. The flakes on the fracture line exhibited a large change in Area 3, the tendency of which was similarly observed for specimen A. These results suggest that the final fracture occurs where a relatively large deformation occurs and that a large deformation at an early stage can be exploited to predict the fracture location.

Microstructural Deformation of Gray Cast Iron

The authors have clarified that the microstructural plastic deformation of the grains on the surface is strongly correlated with the microstructural elastic deformation in a plate specimen of polycrystalline pure titanium [14]. The following deformation process and characteristics were suggested from the experimental results: 1) Inhomogeneous deformation commences under low elastic loading conditions. 2) Plastic deformation first occurs in the area that shows a relatively large elastic deformation. 3) As the deformation of each grain on the surface is strongly affected by the neighboring and subsurface grains, it is typically difficult to predict the microstructural deformation on the surface from the geometrical and crystallographic properties, which can be

estimated on the surface. Similar results have been reported for pure copper [15] and semicrystalline polymers [16].

Figure 13 shows the surface and inward cross-section of gray cast iron subjected to an external tensile load in which a number of graphite flakes are embedded. Because of the extremely weak and brittle graphite flakes, it is reasonable to assume that they are small cracks or crack-like voids of the same shape. At a low tensile load, the matrix is elastically elongated, and the stress concentration occurs at the tips of the flakes and in the other regions where the stresses are locally increased by the mechanical interactions with the neighboring and subsurface flakes, as schematically shown in Fig. 13. With the increase in the external load, plastic deformation commences in the high-stress regions, and its area expands to connect the other neighboring stress-concentrated regions. When the local stress is greater than the yield stress, and the stress–strain relationship is no longer linear under a large external load, the regions of large deformation are considered to still correspond to the high-stress regions. When the linkage of the large deformed region is attained throughout the specimen cross-section, the final fracture occurs there. Considering that the local strain in the material increases in proportion to the local stress, the geometrical changes of graphite flakes reflect the local stress and strain conditions. Hence, the fracture line can be predicted from the geometrical changes of the surface graphite flakes. In fact, a number of interior graphite flakes are present, which can affect the fracture of gray cast iron. However, material deformation occurs more easily on the free surface because of the low deformation constraint by the surrounding solid. Hence, it is sufficient to evaluate the

geometrical changes of the graphite flakes on the surface for the prediction of fracture lines. The dependence of the prediction accuracy on the specimen thickness is an interesting topic. Regarding the reproducibility of the results, the present prediction method has not yet been confirmed. While the number of graphite flakes is very large in the specimen, the results were obtained from two specimens. It is suggested that the reproducibility of the method should be examined with the help of image analysis technology in the future.

CONCLUSIONS

To clarify the microscopic deformation of gray cast iron at an early stage and the correlation of these deformations with the final fracture, tensile tests were carried out with a scanning electron microscope. In this study, graphite flakes on the front and back surfaces of the specimen were observed, and their changes in the width and length during the tensile tests were measured. Inhomogeneous microscopic deformation was observed at an early stage of the tensile tests, and the graphite flakes, which showed a relatively large growth, continued to rapidly grow, contributing to the final fracture. This result suggests that the fracture location or critical parts of gray cast iron can be predicted from the dimensional changes of the graphite flakes at an early stage of deformation.

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NOMENCLATURE

δ	displacement, mm
l_{gL}	length of a graphite flake projected onto the longitudinal direction of the specimen, μm
l_{gT}	length of a graphite flake projected onto the transverse direction of the specimen, μm
S_g	area of graphite flakes, μm^2
l_g	length of a graphite flake evaluated by Eq. (1), μm
w_g	width of a graphite flake evaluated by Eq. (2), μm
θ_g	angle of a graphite flake with respect to the loading direction
w_m	average width of graphite flakes in each area, μm
l_m	average length of graphite flakes in each area, μm
R_w	increase rates of the width of the graphite flakes in each area
R_l	increase rates of the length of the graphite flakes in each area
i	the number of tensile displacement steps

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Table Caption List

Table 1	Chemical composition of gray cast iron (wt.%).
Table 2 (a)	Displacement step for specimen A.
Table 2 (b)	Displacement step for specimen B.

Figure Caption List

Fig. 1	Shape and size of the plate specimen.
Fig. 2	Example of the distributed graphite flakes.
Fig. 3	Area division in the parallel part of the specimen. Red lines denote the large cracks and fracture lines. (a) Specimen A. Areas 3 and 5 include large cracks. (b) Specimen B. Area 3 includes a fracture line.
Fig. 4	Length, width, and angle of a graphite flake, which were evaluated from the longitudinal and transverse lengths, as well as the area of the flake.
Fig. 5	SEM images of the front surface of specimen A. (a) Before the tensile tests. (b) At a displacement δ of 0.36 mm.
Fig. 6	SEM images of the front surface of specimen B. (a) Before the tensile tests. (b) At fracture.

- Fig. 7 Magnified images of the graphite flakes in specimen A.
- (a) Before the tensile tests.
- (b) At a displacement δ of 0.35 mm.
- Fig. 8 Correlation between the lengths and widths of the graphite flakes in specimen A. Red marks denote the graphite flakes involved with the final fracture.
- (a) Front surface of specimen A.
- (b) Back surface of specimen A.
- Fig. 9 Correlation between the lengths and widths of the graphite flakes in specimen B. Red marks represent the graphite flakes involved with the final fracture.
- (a) Front surface of specimen B.
- (b) Back surface of specimen B.
- Fig. 10 Change in the widths and lengths of the graphite flakes between displacement values of 0 mm and 0.1 mm.
- (a) Average increase rate of graphite flake width in specimen A.
- (b) Average increase rate of graphite flake length in specimen A.
- (c) Average increase rate of graphite flake width in specimen B.
- (d) Average increase rate of graphite flake length in specimen B.
- Fig. 11 Change in the width and length of graphite flakes in Areas 3 and 5 of specimen A where large cracks appeared in the last displacement step.

(a) Average increase rate of graphite flake width in Area 3 of specimen

A.

(b) Average increase rate of graphite flake length in Area 3 of specimen

A.

(c) Average increase rate of graphite flake width in Area 5 of specimen

A.

(d) Average increase rate of graphite flake length in Area 5 of specimen

A.

Fig. 12 Change in the width and length of graphite flakes in Area 3 of specimen B where final fracture occurred.

(a) Average increase rate of graphite flake width in Area 3 of specimen

B.

(b) Average increase rate of graphite flake length in Area 3 of specimen

B.

Fig. 13 Schematic showing the main factors affecting the deformation and fracture of gray cast iron.

Table 1

C	Si	Mn	P	S	Cu	Cr	Fe
3.15	1.95	0.79	0.038	0.08	0.72	0.21	Bal.

Table 2 (a)

Step	1	2	3	4	5	6
Displacement δ [mm]	0	0.10	0.20	0.30	0.35	0.36

Table 2 (b)

Step	1	2	3	4	5	Fracture
Displacement δ [mm]	0	0.10	0.20	0.30	0.40	0.42

Figure 1

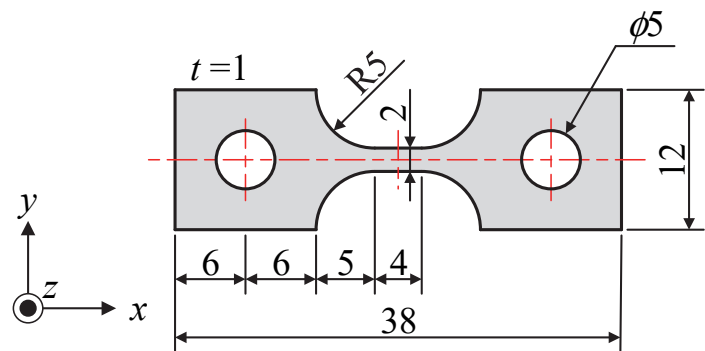


Figure 2

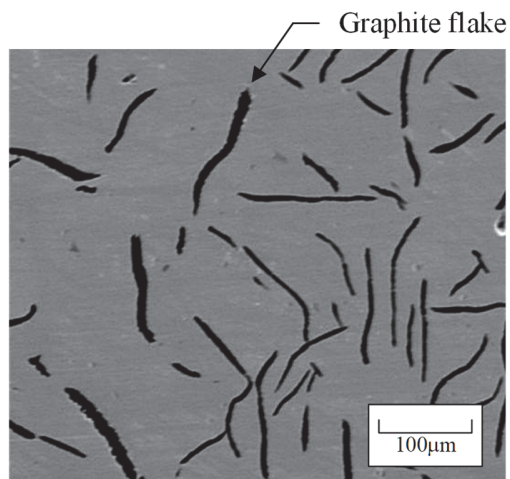


Figure 3 (a)

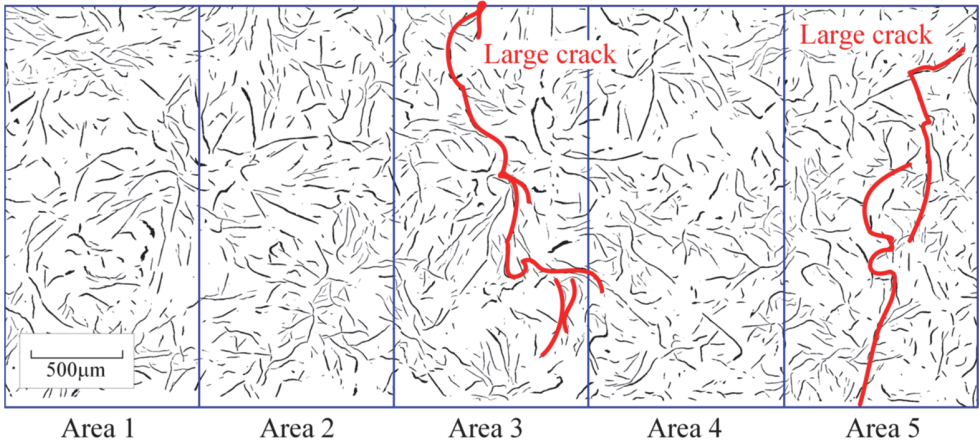


Figure 3 (b)

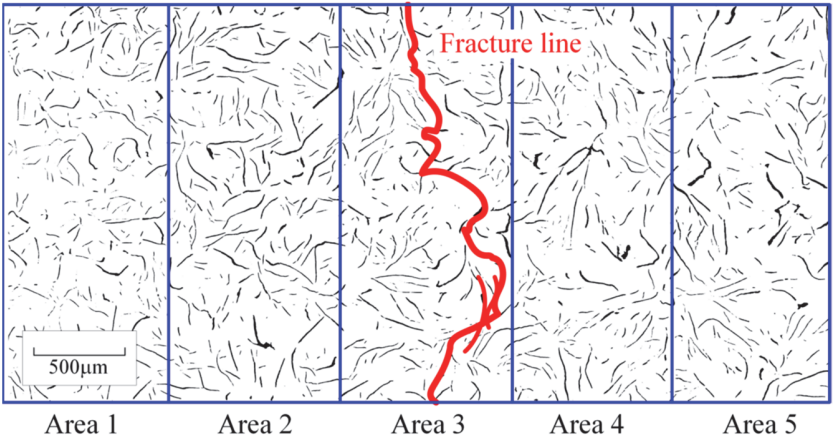


Figure 4

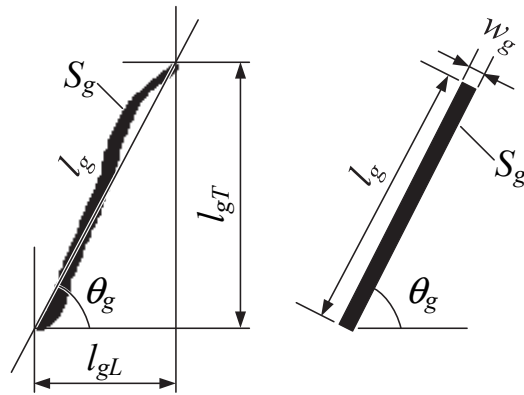


Figure 5 (a)



Figure 5 (b)

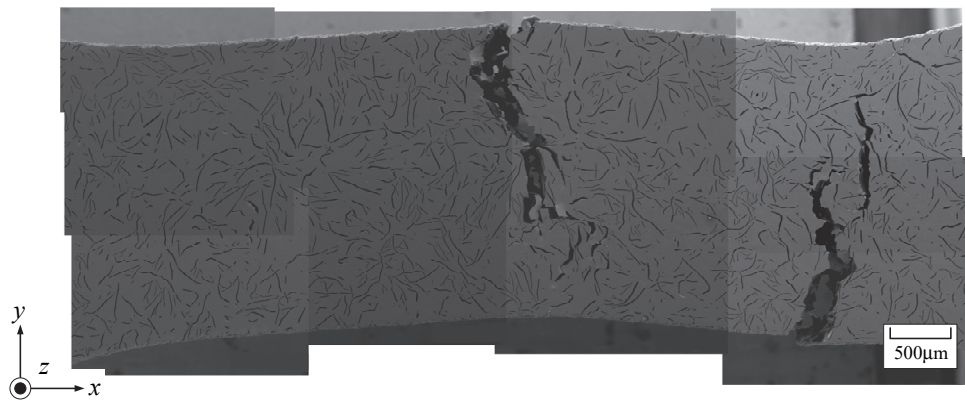


Figure 6 (a)



Figure 6 (b)

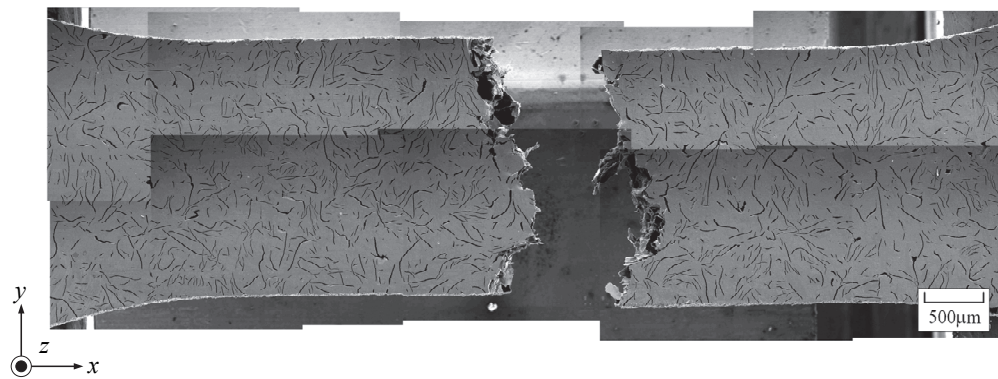


Figure 7 (a)

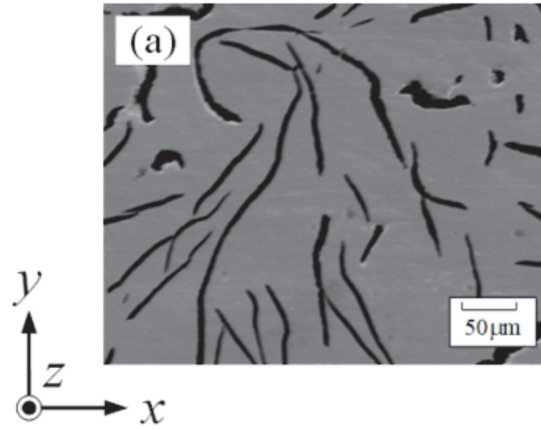


Figure 7 (b)

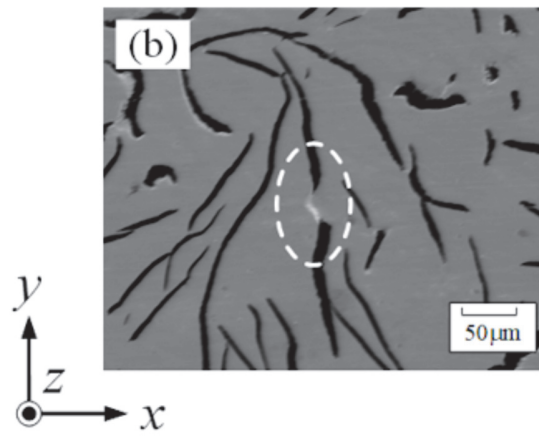


Figure 8 (a)

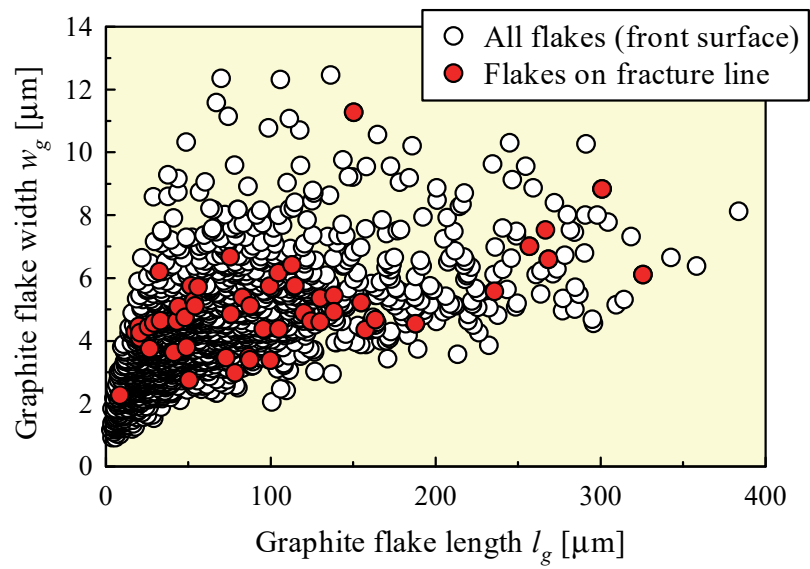


Figure 8 (b)

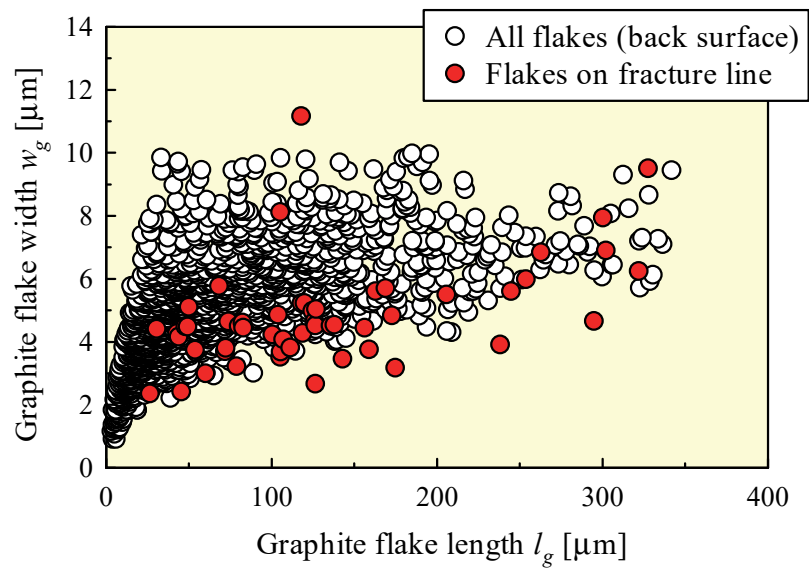


Figure 9 (a)

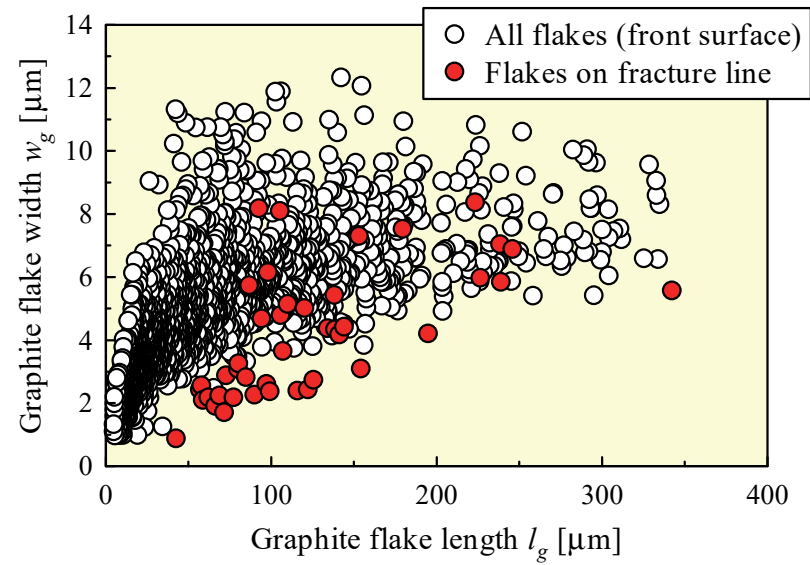


Figure 9 (b)

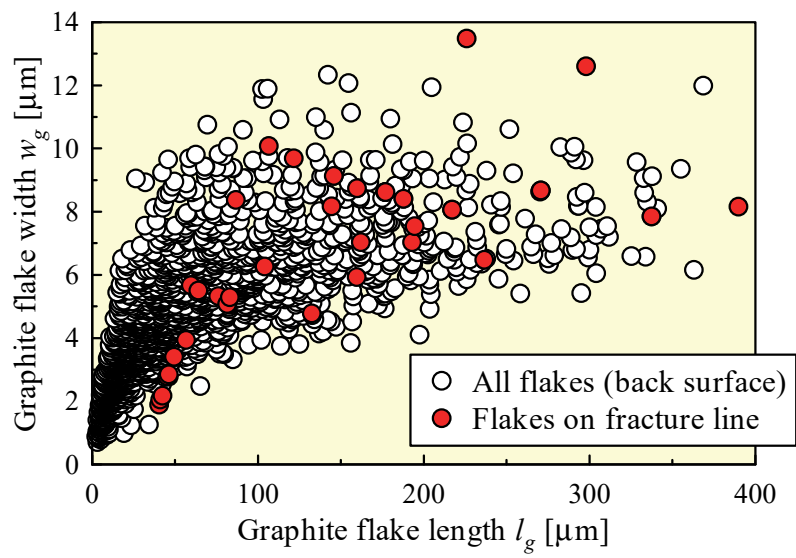


Figure 10 (a)

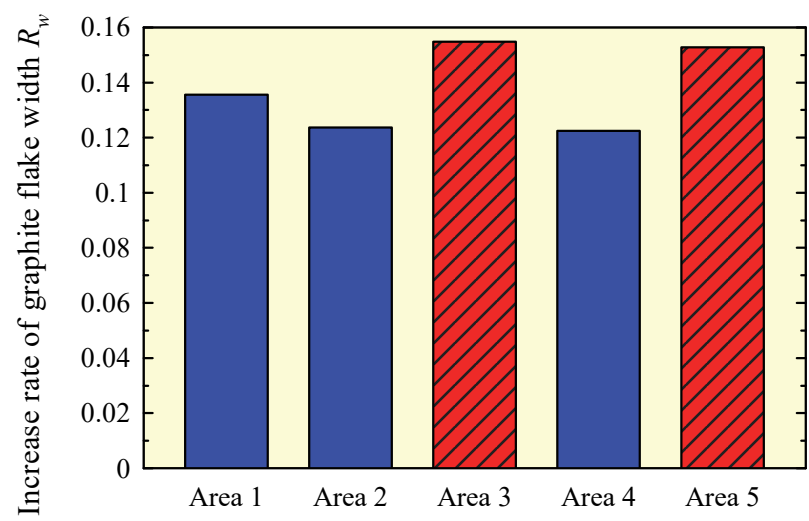


Figure 10 (b)

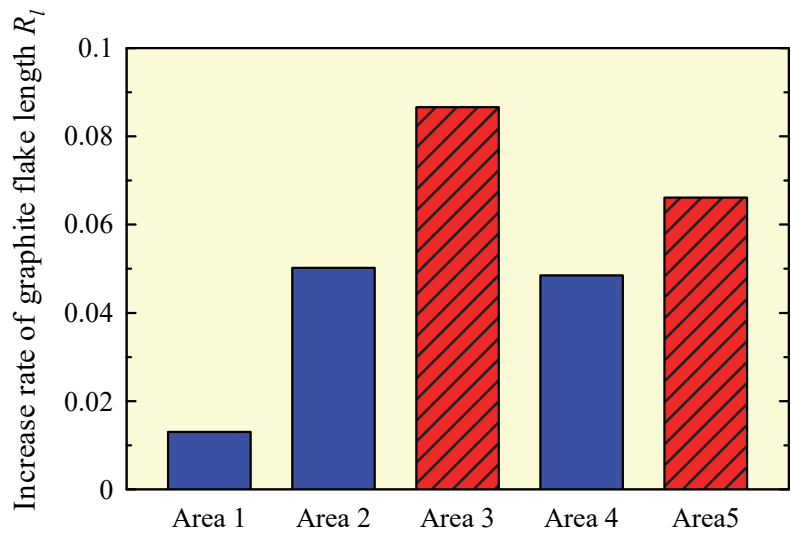


Figure 10 (c)

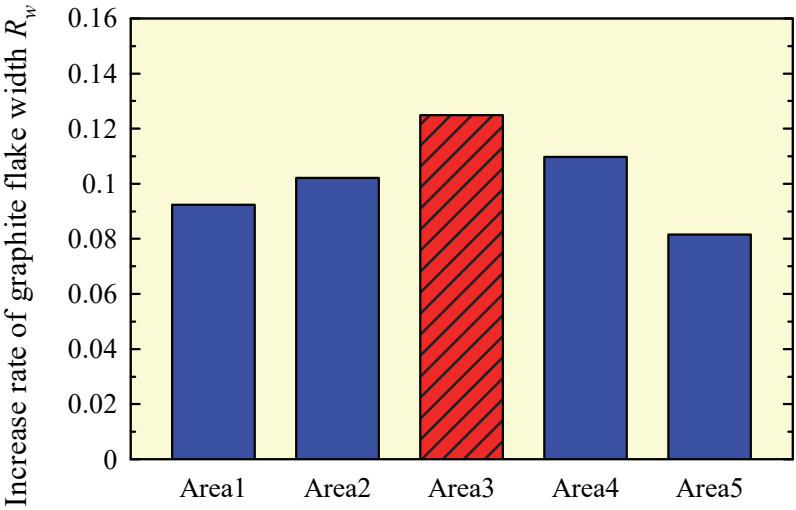


Figure 10 (d)

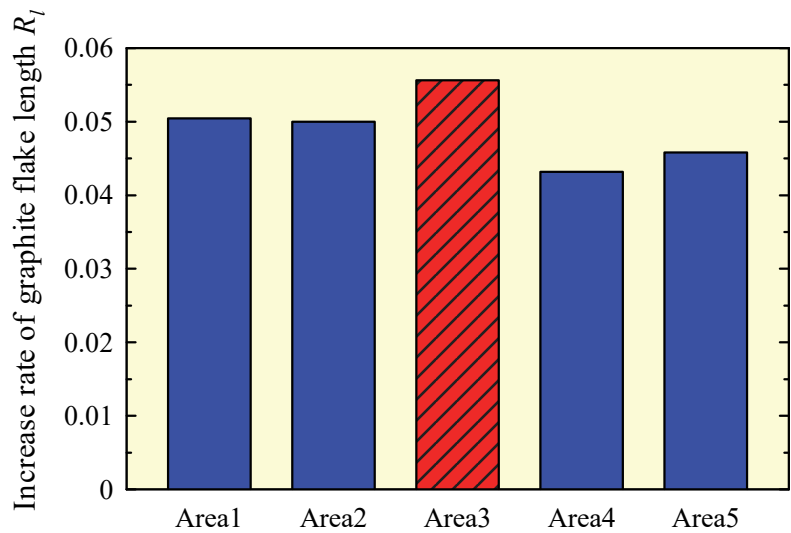


Figure 11 (a)

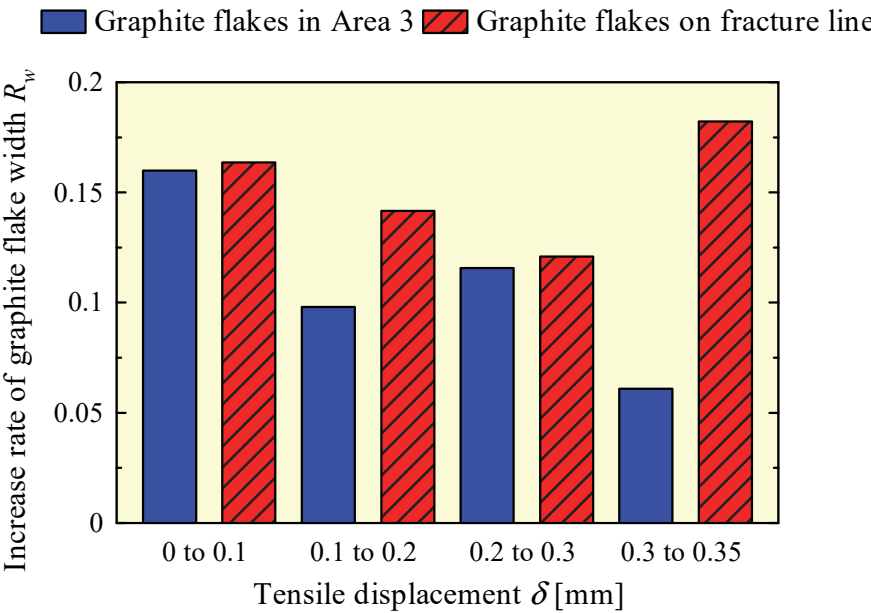


Figure 11 (b)

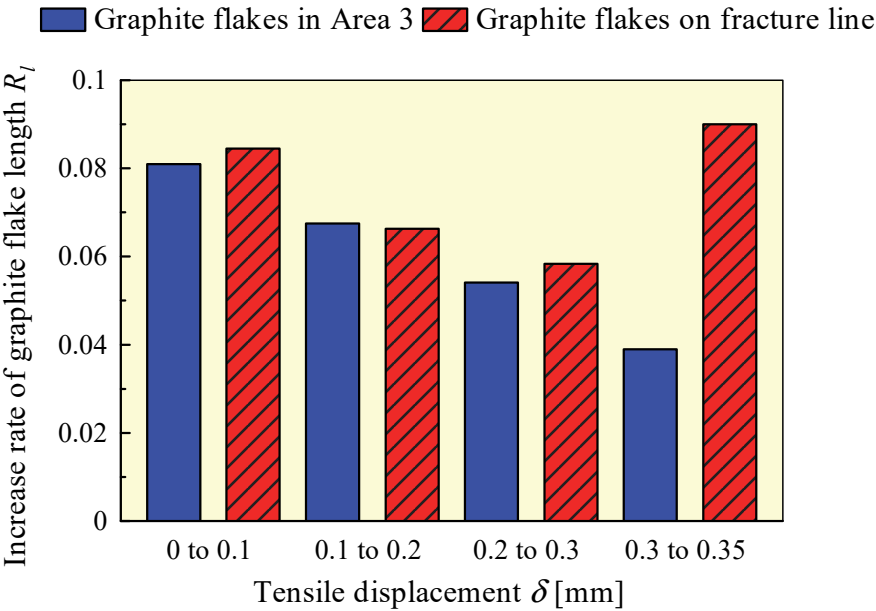


Figure 11 (c)

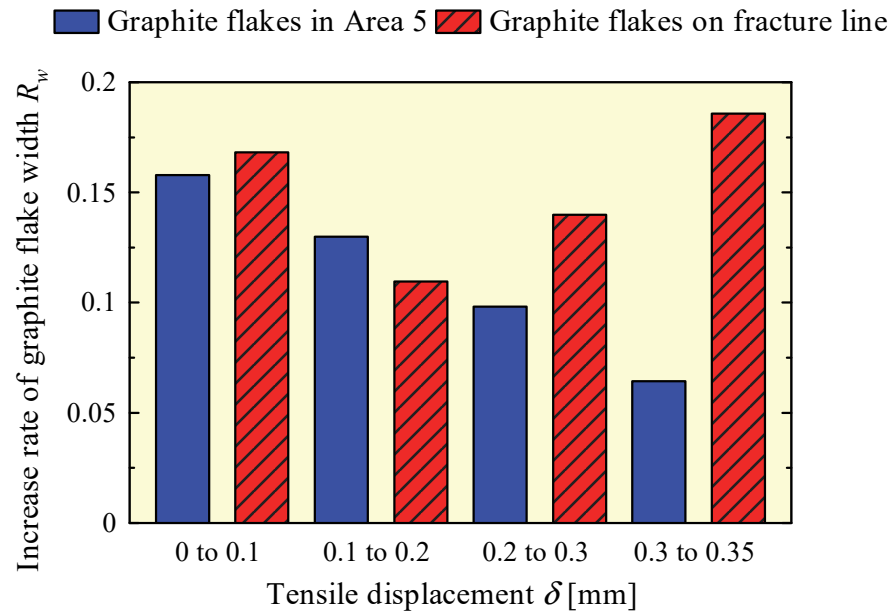


Figure 11 (d)

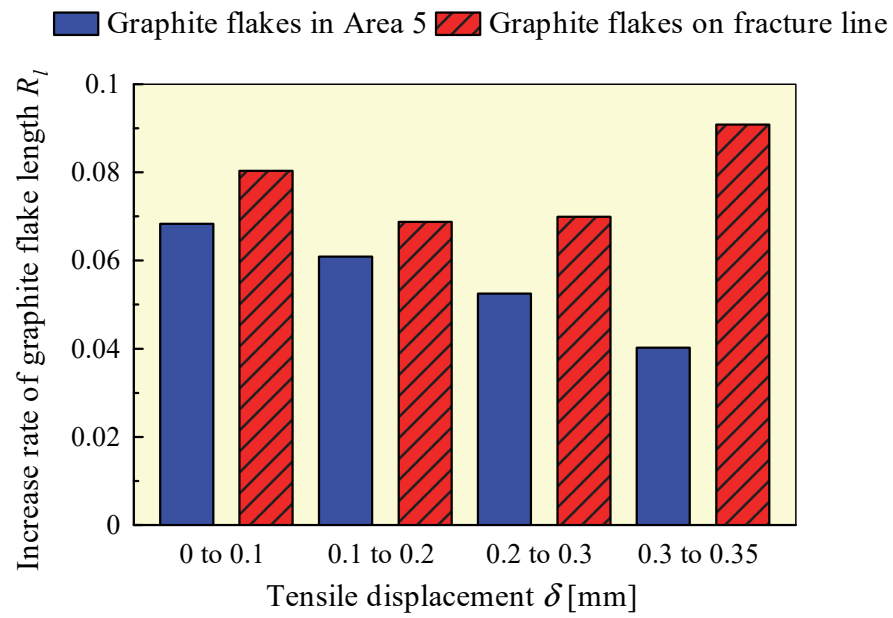


Figure 12 (a)

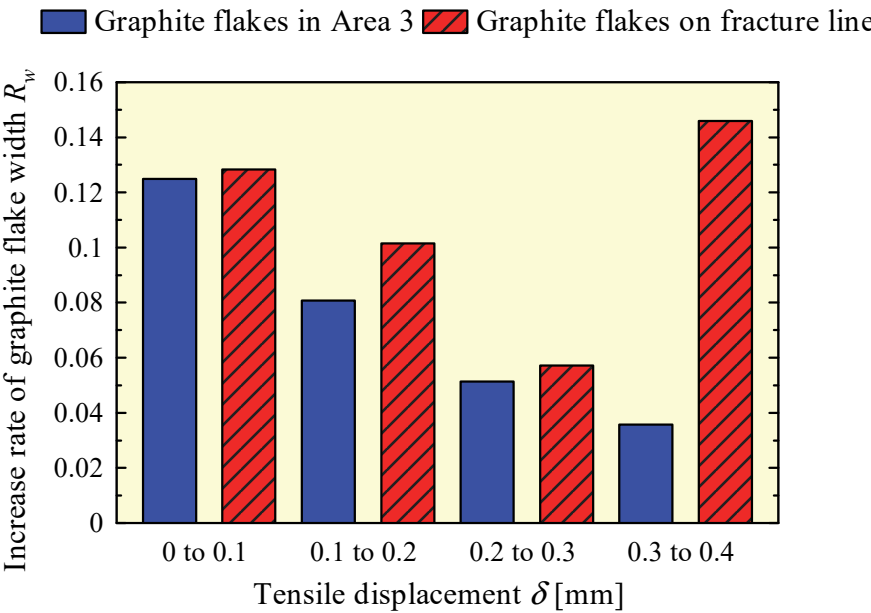


Figure 12 (b)

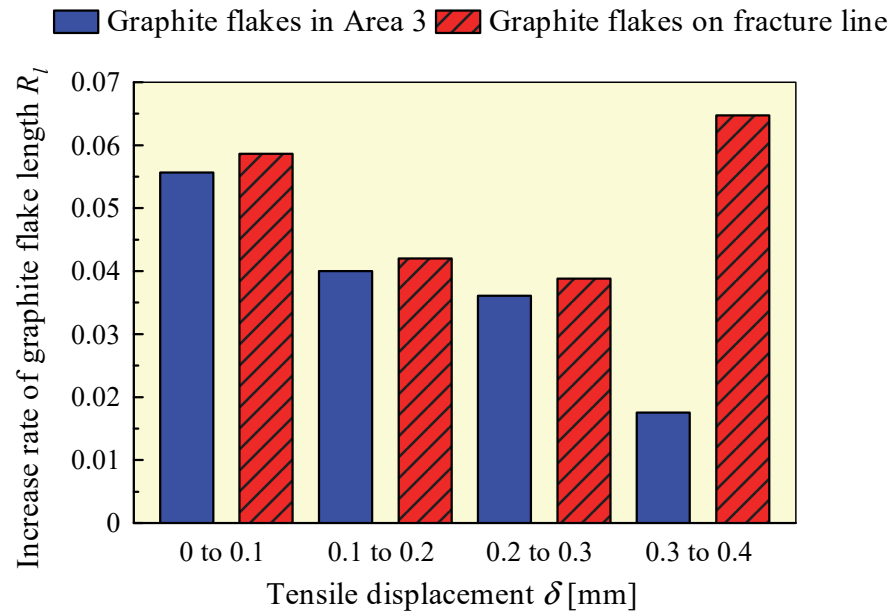


Figure 13

