# QUANTITATIVE MEASUREMENT OF STRETCHED ZONE WIDTH BASED ON DIFFERENCES IN FRACTURE SURFACE ROUGHNESS

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ABSTRUCT

A stretched zone is formed as a result of blunting and stretching at a crack tip during fracture process. Consequently, fracture surface becomes fine and smooth. Paying attention to this characteristic, the authors proposed a new method to evaluate the stretched zone width quantitatively, based on differences in the fracture surface roughness. To verify the validity of the proposed method, measurements were carried out on fracture surfaces obtained by elastic-plastic fracture toughness tests of CT specimens cut out of a carbon steel pipe. The fracture surface was observed with a high-resolution scanning electron microscope to measure critical stretched zone width ($SZW_c$) for stable crack initiation quantitatively. The critical stretched zone widths determined by the proposed method were compared with those reported in the references. The comparison led the conclusion that this method enabled us to measure $SZW_c$ quantitatively, which had been difficult to measure in the absence of skilled microscope operators. The method also showed the possibility to estimate the failure load from the fracture surface by using fracture mechanics parameters.

## 1 INTRODUCTION

Major cause for failure accidents of machines and structures is fatigue fracture that is induced by cyclic loading as many cases indicate(Brooks et al.[1]). Fatigue cracks initiated in structural components continue to grow with the cyclic loading, and the fracture process will transform to a rapid fracture, once the remaining area of the components no longer can sustain the applied load. The crack front is elongated during this transition process, and glide plane decohesion will be taken place as pointed out by Spitzig[2], and Beachem et al[3]. The elongated zone came to be called as stretched zone. Many investigators(e.g. Broke[4]) reported relationships between the critical stretched zone width $SZW_C$ measured on specimens fractured with overloading, and critical crack tip opening displacement *CTOD*, or elastic-plastic fracture toughness $J_{Ic}$. Kobayashi et al.[5] investigated the relationship between $SZW_C$ and the fracture mechanics parameters on 21 kinds of steel samples that had yield strength between 17 to 193 kg/mm$^2$ (167 to 1891 MPa). They found that a fairy good relationship exists between the values of $SZW_C$ and $J/E$ that is obtained by dividing the $J$ value by Young's modulus $E$, of the steel concerned. This result suggests that the $J$ values at fracture can be computed from the measured values of $SZW_C$ on fracture surfaces, and that the failure load can be estimated.

However, the measurement of the stretched zones has some problems to be considered (JSME [6]). The stretched zones are not necessarily formed uniformly at the tips of fatigue pre-cracks, and the boundaries are usually obscure because microstructure and inclusions of the material concerned affect the formation of stretched zones. Thus, the accuracy of measuring $SZW_C$ may strongly depend on observers.

The present study proposes a quantitative evaluation method of $SZW_C$ that does not rely on skilled observers, to solve the issue on measuring method of $SZW_C$. Once $SZW_C$ is quantitatively evaluated, the $J$-integral at fracture can be estimated quantitatively from the fracture surface, and the failure load is believed to be estimated from the $J$ value obtained. Here, the authors paid attention to the differences in surface roughness between fatigue and rapid fracture surfaces adjacent to stretched zone for extracting $SZW_C$ effectively. The introduction of roughness parameter for measuring $SZW_C$ is an original idea presented in the present study.

To verify the validity of the proposed method, fracture surfaces were prepared by elastic-plastic fracture toughness tests and the $SZW_C$ was measured by the proposed method. The values of $SZW_C$ determined by the proposed method were compared with those reported in the references. The comparison led the conclusion that this method enabled us to measure $SZW_C$ quantitatively, which had been difficult to measure in the absence of skilled microscope operators.

## 2 PROPOSAL OF MEASURING METHOD OF $SZW_C$ BASED ON DIFFERENCES OF SURFACE ROUGHNESS

A stretched zone is formed as a result of blunting and slipping off a crack tip by overloading. The stretched zone is literally formed by the result of stretching of a crack tip, and thus, the surface is widely known to be smooth and without any specific features. However, fatigue fracture surfaces formed before the rapid fracture are known to show surfaces with small cyclic patterns as typified by striations. On the contrary, the fracture surfaces formed during the rapid fracture are characterized by the fracture morphology such as dimples and cleavage facets. These fracture surfaces are relatively bumpy. The fracture surface morphologies differ in accordance with the fracture modes. Consequently a parameter denoting the surface roughness becomes smaller in stretched zones, and this difference is considered to make it possible to evaluate $SZW_C$ quantitatively. The outline of the proposed measuring method is illustrated in **Fig. 1**. The practical measuring procedures are explained below.

The first step is to measure three-dimensional shape of a fracture surface. Here, the height profiles are measured so as to include a stretched zone and two adjacent fracture surfaces formed during fatigue and rapid fractures.

The next step is to compute the surface roughness based on the three-dimensional data. The surface roughness is computed along the direction parallel to the stretched zone. In other words, the surface roughness in the perpendicular direction to the crack propagation is measured. Since the boundaries of the stretched zones are sometimes obscure as explained in the introduction, the measurements are conducted along the stretched zone. An average roughness $R_a$, is employed as a parameter for the surface roughness. The value shows the deviation from the mean line of height (a filtered wavy curve), and

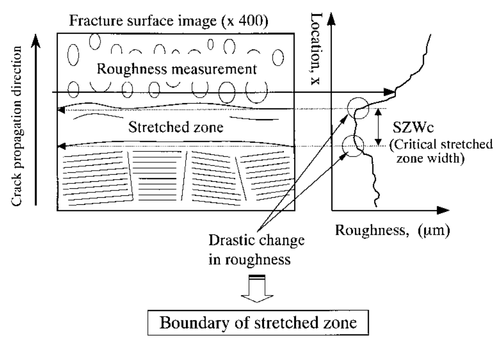


Fig. 1 Oultline of $SZW_C$ measurement by proposed method

also is applied as a parameter to express roughness of machined surfaces commonly.

Surface roughness is to be measured on all measurement lines for obtaining the relationship between the surface roughness and the measurement line. The surface roughness is set to be a function of a measurement point. The differential coefficients are used to determine the boundary of $SZW_C$ from the points where the roughness parameter shows a drastic change, or the differential coefficient reaches an extreme value.

However, some degrees of dispersion in the differential coefficients exist because discrete values are to be treated. As fluctuations in the coefficients may be probable, small fluctuations are eliminated as noises by setting threshold value.

## 3. EXPERIMENTAL PROCEDURE

### 3.1 Fracture surfaces

The fracture surfaces used in this study were ones obtained by elastic-plastic fracture toughness tests for carbon steel pipe of Japan Industrial Standards(JIS) STPG370 in the authors' another study[8]. In the study, two CT specimens differing in crack orientation were used: one machined so that crack orientation would parallel to the longitudinal direction of pipe (C-L specimen) and the other machined so that crack orientation would coincide with the circumferential direction (L-C specimen). The $J$-integral values were summarized in **Fig. 2** and a few data were not qualified as $J_{Ic}$.

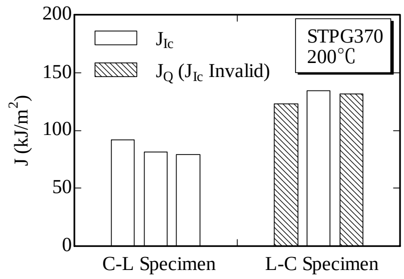


Fig. 2 $J$-integral values for specimens subjected to fracture surface analysis[8].

### 3.3 Measuring method of $SZW_C$

The three-dimensional profile of the fracture surface was measured by a high resolution scanning electron microscope with the secondary electron integration method. The magnification was set to be 400. The reason for selecting the magnification is that the area ratio on a microscope image among the fatigue fracture surface, the stretched zone, and the rapid fracture surface becomes about 2:1:2 and the characteristics on each fracture surface could be clearly observed. The numbers of the sampling data were 300 in the crack propagation direction (in the vertical direction on an observation field), and 400 points in the transverse direction to the former, and then the total 12,000 points were sampled.

After the three-dimensional profile was measured, the surface roughness in the transverse direction was computed. Here, the sample length is set to be 300 μm so as to be identical to the width of the observation field (in the transverse direction). The surface roughness measured here is a mean value in the width of the observation field.

The relationship between the surface roughness and the measuring point was obtained after the surface roughness measurements completed. The surface roughness was assumed to be a function of a position, and the differential coefficients were calculated to decide the boundaries of the stretched zone. The two points where the coefficients change drastically were judged to be the boundaries and $SZW_C$ was computed.

## 4. EXPERIMENTAL RESULT

**Figure 3** shows an example of the computed result of the stretched zone by the proposed method. The measurements were conducted at the center of a specimen thickness. The direction of the crack to propagate is from the bottom to the upper part in the photograph. Therefore, the crack at the bottom of the photograph is a fatigue pre-crack, and the upper region where dimples were observed is the stable crack propagation region. The average roughness measured along the width direction of the photograph is plotted at corresponding locations on the right hand side of the photograph.

The changes in the surface roughness suggest the following results. The dimple region where the stable crack propagated takes the largest value of the surface roughness. The second roughest surface is fatigue fracture surface where striations are observed. The lowest roughness region is the stretched zone. The boundary between the stretched zone and the stable cracking zone is distinguishable clearly even with naked eyes, and the surface roughness shows the most drastic change near the boundaries. The roughness change is also seen at boundaries between the striation zone and the stretched zone, although the change ratio is less remarkable.

To estimate the drastically changing points quantitatively, the surface roughness was set as a function of a location, and the function was differentiated. The differential coefficients are shown in the right side graph in **Fig. 3**. The differential coefficients changes rapidly corresponding with the roughness change shown in the central graph in **Fig. 3**. The stretched zone boundaries are defined as the two extreme values of the differential coefficients adjacent to the smallest coefficient in the stretched zone. These boundaries are shown in the figure. However, the extremes arising from small fluctuations are eliminated as noises according to the method described in Chapter 2.

Although some parts of the stretched zone boundary are formed by dimples and the boundary cannot be expressed by a straight line, a fairy good agreement is confirmed to exist by naked eyes at the boundary to the dimple region. On the other hand, the boundary with the fatigue fracture surface was not well detected because of the dull change in the roughness. The striations were seen even in the area detected as the stretched zone. The width of the stretched zone measured in this manner was 54 μm.

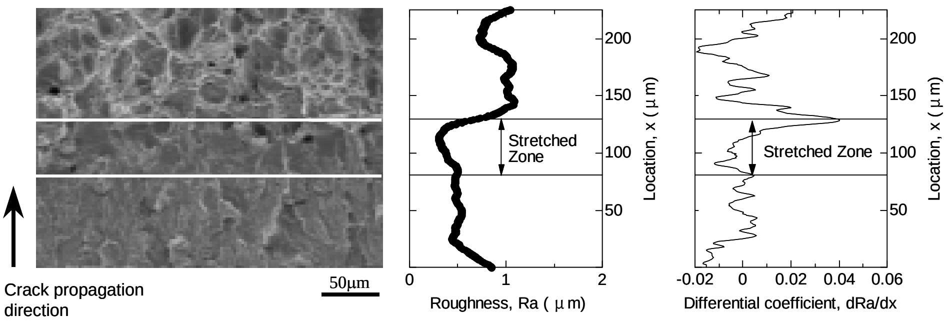


Fig. 3 Quantitative evaluation result of $SZW_c$ by proposed method (C-L specimen, $J_{Ic}$ = 79.1 kJ/m$^2$).

## 5 DISCUSSION

Firstly, the boundary with stable cracking region is discussed. As the fracture surface photograph in **Fig. 3** shows, the boundary is not formed uniformly because of existence of the dimples. In the vicinity of this boundary, rougher fracture surface as typified by dimples exists together with smoother one of the stretched zone. The area ratio of both surfaces changes along the crack propagation direction. Since the surface roughness was measured in the horizontal direction with the sample length equal to the width of the observation area, the roughness change shown in **Fig. 3** appeared.

Secondly, the boundary with the fatigue fracture surface is discussed. This boundary is less pronounced than that of the dimple region. Striations may be a main characteristic in this region to determine the boundary by naked-eye observation. The heights of the striations, however, are of the order of some hundreds nano-meter. The value is too small to be a characteristic value to the surface roughness. Therefore, changes in the surface roughness at boundaries with fatigue cracks are not drastic.

When the fatigue pre-crack was introduced, the stress intensity factor at the crack front was kept as low as about $10\,\mathrm{MPa}\sqrt{\mathrm{m}}$ . In such a condition, the directions of the striations are affected by the crystallographic orientations, and the directions do not coincide with the macroscopic crack propagation direction. Furthermore, the cracks propagate on the different crystal plane from the microscopic standpoint of view. Then the continuous striations are formed only in a certain narrow region. Within such a region, fracture surface becomes flat, but the fracture surface in discussion consists of these regions. Different regions form steps on the fracture surface. Consequently, the roughness parameters in the fatigue fracture surface are larger than those in the stretched zone, and the boundary was detected.

The present study aims to extract $SZW_C$ by relative comparison of the roughness. The absolute values of the surface roughness are not of concern in the measurements. A fact to be emphasized here is that the absolute value of the surface roughness may change with different magnification value, or with different sample length as a natural sequence.

Next, the validity of the measurements of $SZW_C$ is discussed. As described in the introduction, this study aims to assist fracture surface analysis that depends entirely on the observers and to estimate failure load, rather than to extract the stretched zone regions vigorously with an image recognition method. Therefore, the validity of the proposed method was confirmed by using the reported relation between $J$-integral values and stretched zone widths. With respect to the relationship, $J$ - $SZW_C$, Kobayashi et al.[5] reported the following equation.

$$SZW_C = C\,J/E \qquad (1)$$

where, $C$ is a constant. The mean value of $C$ is 89 with the standard deviation for

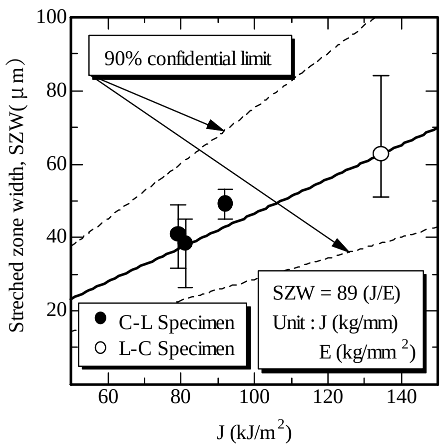


Fig. 4 Relationship between $J$-integral and stretched zone width evaluated by proposed method.

90% confidential limit of 54.7 $\leqq C \leqq$ 143, and $E$ is the Young's modulus in kg/mm$^2$, and the unit for $J$ in kg/mm.

The critical stretched zone widths measured by the proposed method are plotted in **Fig. 4** together with $J_{Ic}$ with respect to the specimen orientation. The measurements were conducted on three locations for each specimen in which the valid $J_{Ic}$ was obtained. The first location was at the center of the specimen thickness, and other two locations were away from the first point to about 1.1mm (corresponding to 1/8 of the specimen) in both sides. Open and solid circles in the figure indicate the mean values of the measured $SZW_C$ for L-C and C-L specimens respectively, and the data dispersions are also shown in the figure with error bars. The relationship of the equation (1) is also drawn in the figure by a solid line.

Although all specimens are sampled from the same material, it is found that some specimens show large scatter, and some do small scatter. The difference in the dispersion is believed to be caused by the local microstructure difference. However, there is dispersion in the relationship of $J$ - $SZW_C$. The broken lines in the figure note the 90% confidential limit for the equation (1). All measured values of $SZW_C$ by the proposed method are located within the confidence limits, and the accuracy of the measurements is concluded to be satisfactory. Therefore, the $J$-integral values can be quantitatively determined from fracture surfaces based on the proposed method as far as the stretched zones are observed. This result implies a possibility for estimating the failure load applied from the $J$ values.

## 6 CONCLUSIONS

The conclusions obtained in the present study are summarized as follows.

1) A new method was proposed to evaluate the critical stretched zone width $\mathrm{SZW_C}$ quantitatively, based on the differences in the roughness on the fracture surface.
2) The measured results of $SZW_C$ according to the proposed method for the fracture surface obtained were compared to the conventional relationship $J$ - $SZW_C$. The values of $SZW_C$ obtained by the proposed method are confirmed to stay in the range of the dispersion reported the reference. Therefore, the present method can be applied to evaluate the $J$-integral values quantitatively from the fracture surfaces whenever stretched zones are observed, and thus, the failure load can be estimated.

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