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A DUCTILE FAILURE CRITERION

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ABSTRACT

The strength of a material might be thought of as one of the factors that determines the point at which plastic regions locally appear in a given piece of material. In order to pursue this idea use was made of the stress intensity factor. After inserting one notch in a carbon steel rectangular tension test specimen, the test strip was subjected to a tensile test. Experimental measurement was made in accordance with the degree of load by rendering visible the plastic regions appearing at the tip of the notch. A regression equation was derived from the experimental values of the widths of the plastic regions. A relation was then ascertained between K_I and the widths of the plastic regions. By means of this relation it can be shown that when the width of the plastic region has a value of zero, the value of K_I may be thought of as the parameter for the strength of the material, indicating the point at which the material undergoes ductile failure.

1. INTRODUCTION

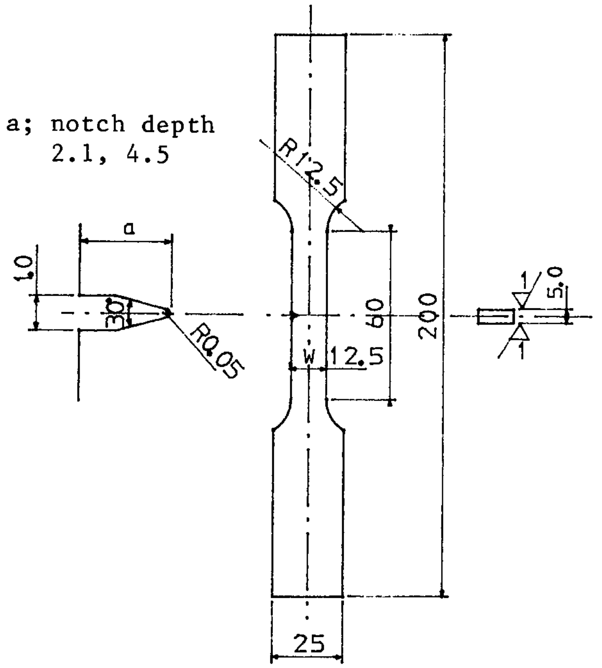
When as a result of the application of a load a plastic region breaks out on a portion of some component, it becomes impossible to use that component. If there were a technique to predict this condition shortly before its occurrence, the technique would have great practical usefulness. The clue to discovering such a technique is to be found in the phenomenon that the transformation into a plastic region always originates within an elastic region.

By utilizing a certain property that corresponds to the yield stress, "yield stress stripes" [1] or "stretcher strains," it is possible to make direct observation of the condition of an elastic-plastic region. By observing the pattern of the yield stress stripes as observed by the naked eye, it was attempted to trace the propagation of a plastic region originating in the midst of an elastic region. A tensile load was applied to a notch that was inserted in a carbon steel rectangular tension test specimen. Direct visual examination was then made of the properties of the plastic region as it developed at the tip of the notch. The experimental values were then correlated with the stress intensity factor.

2. THE TEST SPECIMEN AND THE METHOD OF EXPERIMENT

Figure 1 displays the shape and the dimensions of the test specimen. The dimensions of the notch-tip portion correspond to the value of a JSME, S-001 [2]. Fig. 2 is an enlarged photograph of the notch tip portion of a test specimen. The border of the notch is very smoothly finished. Table 1 [2] displays the chemical composition of the material. A common market variety S50C steel strip was used. The tensile test yielded a value of 350 MPa as the yield stress for this material. The test specimen was vacuum annealed after machine processing. In order to make observation of its surface with the naked eye, a number 2000 emery paper was used to finish it to a fine smoothness. The R_{max} value of the surface texture was determined to be less than 0.1 μm.

The tensile test was carried out using an Instron-type material testing machine. A video camera was used to make a continuous recording of the yield stress stripes appearing in the vicinity of the notch tip; the data were recorded at a magnification of ten. For the sake of expediency in observing the phenomena, the speed of the test machine's cross-head was set at 0.1 mm per minute. A strain gauge type of extensemeter was used to measure the displacement of the test specimen.



all dimensions in mm

Fig. 1 The shapes and dimensions of specimens.

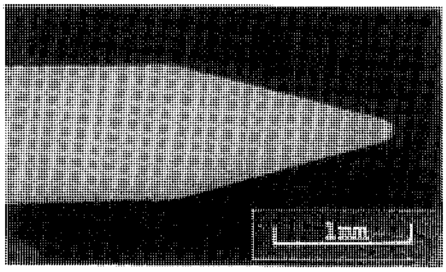


Fig. 2 Detail of a notch tip.

Table 1 Chemical composition of the specimens in percentage.

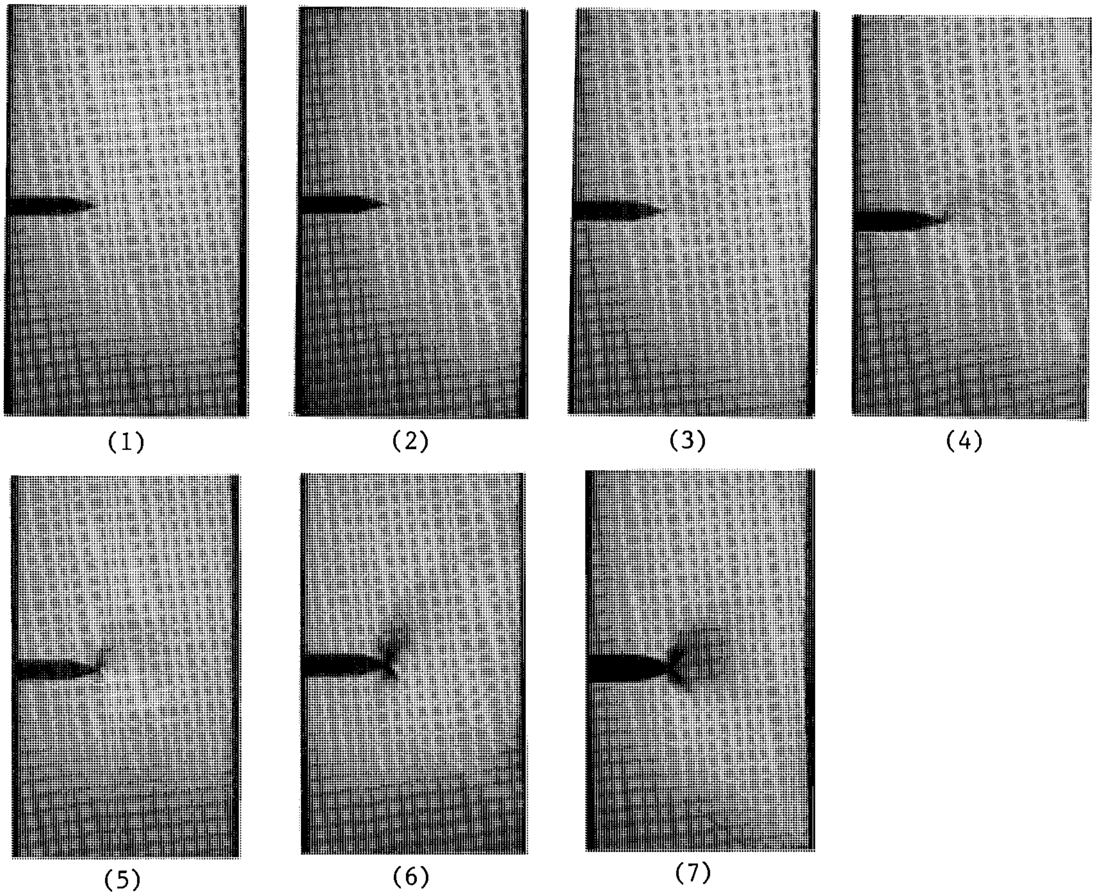
C	Si	Mn	P	S
0.53	0.17	0.61	0.29	0.16

3. EXPERIMENTAL RESULTS AND EXAMINATION

3.1 Yield Stress Stripes

Figure 3 is a sequential recording of the evolution of yield stress stripes for a specimen with a: 4.8 mm notch. The photographs reveal that as tensile load is increased the yield stress stripes break out, grow, and transform into orange peel patterns. The test specimen finally snaps at the notch tip portion. Initially, as in frames (1) - (4) of Fig. 3, the yield stress stripes have a round shape. As the load increases the yield stress stripes continue to grow until they face the notch tip and change into an open configuration as shown in frames (5) and (6) of Fig. 3. At about this time the yield stress stripes near the notch tip change into an orange peel pattern. The orange peel patterns gradually spread until finally a crack starts to appear at the notch tip as in frame (7) of Fig. 3. The crack enlarges and the test specimen snaps at that point.

The place where the yield stress stripes appear may be regarded as the plastic region where the mechanical properties allow slipping to occur. The location where the yield stress stripes are seen in frames (1) - (3) of Fig. 3 is the plastic region brought about by the tensile load. The plastic region in frames (1) and (2) of Fig. 3 may be thought to pertain to a small-scale yield state.



(1) (2) (3) (4)

(5) (6) (7)

Fig. 3 Propagation of the yield stress stripe patterns in the notch tip region [3].

3.2 The Diagram of the Load and Displacement

Figure 4 shows the load-displacement curves and indicates the points where the photographs of Fig. 3 were taken. The numbers given in frames (1) - (7) of Fig. 4 correspond in the same order to the numbers recorded in Fig. 3. The positions given in the load-displacement diagram corresponding to the yield stress stripes in frames (1) - (4) of Fig. 3 form an ascending straight line, indicating a direct ratio between load and displacement. The point where the load-displacement line becomes nonlinear (just after frame (4)) corresponds to the moment when the yield stress stripes surround the notch tip in an open configuration.

A crack started to become visible just at the moment when the load reached its highest value. As the crack becomes larger the line in Fig. 4 veers markedly down to the left.

From the experimental results of Fig. 4 and Fig. 3 it is possible to ascertain the dimensions of the plastic zone and the corresponding load. The relation between these two is an important mechanical property of the elastic-plastic zone originating at the notch tip. It is very easy to ascertain this relationship by observing the yield stress stripes.

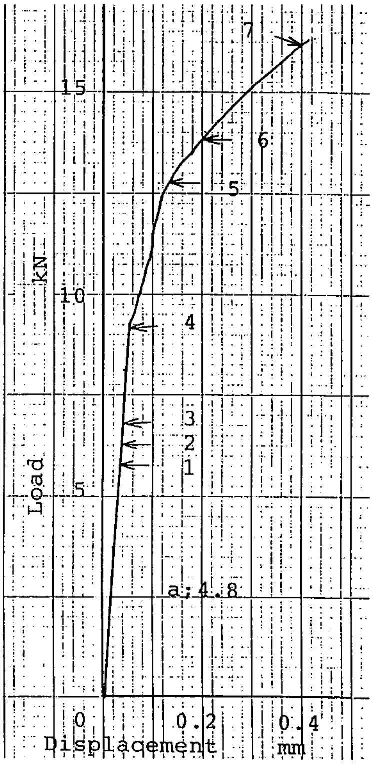


Fig. 4 Propagation of the yield stress stripe patterns as shown by the load displacement curves.

3.3 The Size of the Plastic Zone

The plots in Fig. 5 record the effect of the tensile load on the size of the plastic zone, r_p, as measured by visual observation of the yield stress stripes. The plastic zone is larger for deeper notch depths due to the greater stress intensity for longer crack lengths. Fig. 5 indicates that the depth of the notch serves as a parameter which shifts the plastic zone size - load relationship.

The following regression equation was obtained by making a regression analysis of the experimentally measured values of r_p, the widths of the plastic region in relation to load.

$$r_p = 0.664P - 7.71 \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$r_p = 0.655P - 4.59 \quad \ldots\ldots\ldots\ldots \quad (2)$$

In these equations P represents the load in unit terms of kN, while r_p is represented in millimeters. In the first equation r_p is 2.1 mm, and in the second equation it is 4.5 mm. The perimeter of the dotted line describing the experimentally measured values represented by the points in Fig. 5 corroborates the regression equation or a 95% confidence limit for that equation.

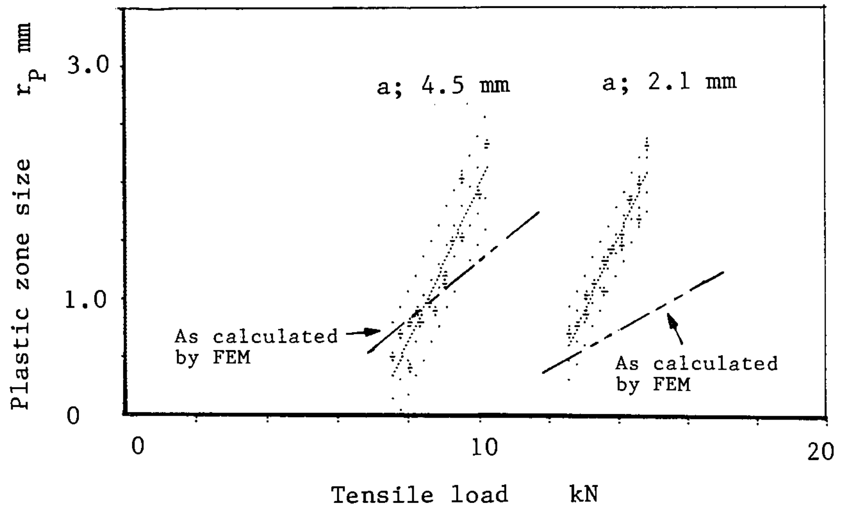


Fig. 5 The relation of the plastic zone size to tensile load.

The widths of the plastic areas were calculated according to load by means of finite element analysis. The results of those calculations are illustrated by the phantom line in Fig. 5. If the notch depth 'a' is 2.1 mm and the widths of the plastic area are small, the experimentally measured values approximate very closely the values obtained by finite element analysis. When the notch depth 'a' is 4.5 mm, the lines crossed in the middle. It is thinkable that this is due to a relation between the values of 'a' and W.

The stress intensity factor, K_I, is usually used for expressing the intensity of the stress field near a notch tip. For the geometry used in this investigation, K_I is appoximately determined from

$$K_I = Y\sigma\sqrt{a} \quad \ldots\ldots\ldots\ldots \quad (3) \quad [4]$$

$$\text{with } Y = 1.99 - 0.41\frac{a}{W} + 18.7\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4$$

$$(1.99 = 1.12\sqrt{\pi})$$

where σ is the far-field stress, 'a' is the notch depth, and W is the width of the specimen. Equation (3) illustrates that K_I is directly proportional to the applied load.

Upon ascertaining K_I in relation to σ in equations (1), (2), and (3), the relation between K_I and r_p was obtained as represented in the illustration given by Fig. 6.

As the value of K_I increases the width of the plastic zone also increases. Fig. 6 reveals that there is a systematic relation between the values of K_I and r_p.

The straight line in Fig. 6 is expressed by the following equations:

$$r_p = 0.39\ K_I - 7.65 \quad \ldots\ldots\ldots\ldots \quad (4)$$

$$r_p = 0.17\ K_I - 4.30 \quad \ldots\ldots\ldots\ldots \quad (5)$$

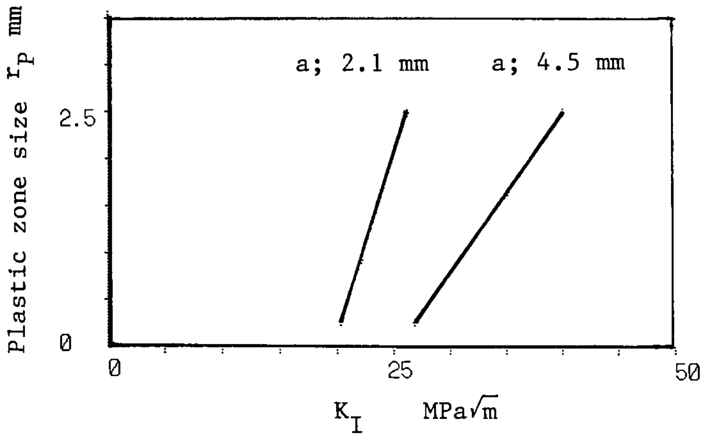


Fig. 6 The relation of the plastic zone size to K_I.

Equation (4) is valid when a is 2.1 mm, while equation (5) applies when a is 4.5 mm. Equations (4) and (5) express the relation between K_I and the growth of the plastic regions. According to these equations, when $r_p = 0$, the value of K_I, being the limit at which plastic regions appear in separate locations, functions as a parameter for the strength of the material. This value constitutes K_{Ip}. K_{Ip} represents the limit at which the material undergoes ductile failure. Whereas K_{Ic} indicates the point at which a crack will appear in a material, K_{Ip} represents the limit at which a ductile material will start to failure. K_{Ic} is requisite to detect a fatigue crack in the experimental strip [5], whereas the detection of K_{Ip} does not indicate that there is a fatigue crack in the test specimen.

4. CONCLUSION

Experimental measurement was made of the widths r_p of the plastic regions which appeared when a tensile load was applied to the tip of a notch made in a carbon steel rectangular tension test specimen. It was ascertained that there is a relation between the experimentally measured values r_p based on the regression equation and the stress intensity factor K_I. By means of that relation it was established that when r_p is 0, the corresponding value of K_I may be regarded as a parameter for the ductile strength of the material, indicating its breaking point.

5. REFERENCES

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