Influence of the Stress State on Size and Feature of Dimples on Ductile Fracture Surfaces

J. XIE and Y. W. SHI

Department of Mechanical Engineering, Xi'an Jiao-tong University, Xi'an, PRC

ABSTRACT

The dimple feature was analyzed by SEM photography of fractured surfaces ahead of crack tip in the specimens with different crack length. The mean diameter of dimples was measured by using the mean linear intercept method. The experimental results showed that the feature and size of dimples was different when the specimens were in the state of plane-stress and plane-strain. Tear dimples occurred in the case of plane-stress, and equiaxed dimples plane-strain state, and combination of tear and equiaxed dimples in the condition of mixture of plane-stress and plane-strain. The process model of tear dimples formed was given.

KEYWORDS

Dimple; ductile fracture; stress state.

INTRODUCTION

As well-known, the ductile fracture of structural steel is a process of void initiation, growth and coalescence. If it is possible to put off the void initiation and restrain the void growth, ductility of the material could be improved. Therefore, considerable work on void initiation and growth has been carried out (Goods et al., 1980, Wilsdorf, 1983). However, the final stage of the void growth and its effect on the feature of dimples on the fracture surface has been rarely studied. The kinetics of void growth could be described in terms of Rice-Tracey's model (Rice and Tracey, 1969).

$$dR/R=0.558d\varepsilon \sinh(1.5\sigma m/\bar{\sigma}) \tag{1}$$

where R is the actual size of void, $d\varepsilon$ the increment of plastic strain, σm the mean stress, and $\bar{\sigma}$ the Von Mises equivalent stress. The critical void growth at fracture initiation Rc/Ro is obtained by integrating Eqn.(1), i.e.

$$Ln(Rc/Ro)=0.558(\varepsilon_c-\varepsilon_o)\sinh(1.5\sigma_m/\bar{\sigma}) \qquad (2)$$

where Ro and ε_o are the initial size of the void and the initial plastic strain, respectively, ε_c is the plastic rupture strain.

Some experimental results showed that the Rc/Ro values decreased with increasing the stress triaxiality $\sigma_m/\bar{\sigma}$, and a statistical consideration have led to a reverse trend (Pineau, 1981).

Dimple is believed to be half of a void through which fracture has occurred. The dimple indicates the deformation history and the form of void coalescence. Also the dimple reflects the ductile behavior of crack extension of materials. Size of the dimples seems to be largely influenced by the stress state (Kumar et al., 1983, Ranganath et al., 1987), and the relation in a cast steel could be described by (Biel et al., 1987) instead of Rice-Tracy's model

$$Dc/Do=5.45\sqrt{\varepsilon_c}\exp(1.5\sigma_m/\bar{\sigma}) \qquad (3)$$

where Dc,Do are the diameter of dimple and inclusion respectively. Some results seem to show that the dimple size increases with stress triaxiality level (Ranganath et al., 1987).

In the present work, the mean diameter of dimple was measured, and the feature of dimple was analyzed in the state of plane-stress, plane-strain and mixture of plane-stress and plane-strain. Additionally, the form processes of dimple were described.

EXPERIMENTS

The material tested was a weld metal of an API X52 pipeline steel made by submerged arc welding with H08Mn2Si welding wire. Chemical composition and mechanical properties of the weld metal are given in table 1. Three-point bend specimens were used and fatigue cracks were produced for all of the test pieces before test. Specimen geometry in detal is shown in Fig.1.

Table 1 Chemical composition and mechanical
properties of the weld metal

a. Chemical composition (w.t.%)

C	Mn	Si	P	S	Cu
0.13	1.22	0.22	0.028	0.014	0.04

b. Mechanical properties

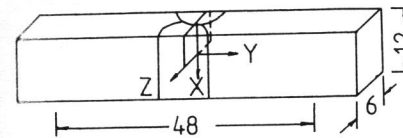| Yield stress (MPa)	Ultimate strength(MPa)	Elongation(%)
475	632	26.5

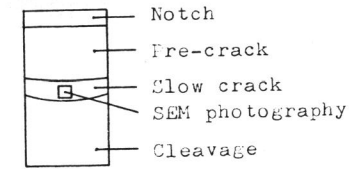Fig. 1 Geometry of specimen.

Fig. 2 Photographed position.

Three-point bend specimens were unloaded after the loading beyond maximum load, then broken in the liquid nitrogen temperature. The fractured surfaces of specimens were observed and photographed using a scanning electron microscope JSM 35C. The position taking photography is shown in Fig.2. The mean diameter of dimples was obtained in the way of mean linear intercept (MLI) method (Pickering, 1975). A number of line segments were marked out arbitrarily on the SEM photography. If L is the length of line segment, diameter of the dimple is given by

$$Dc=1.75(L/N) \qquad (4)$$

The mean diameter of dimples $\overline{Dc}$ is the average of Dc values for all of the line segments on the SEM photography.

RESULTS AND DISCUSSION

The relationship between the size of dimple and crack length (a/W) was obtained by measuring the mean diameter of dimples at the crack tip of mid-thickness on fractured surface for the specimens with different (a/W) values as shown in Fig.3. It can be seen that three regions could be divided by the different mean diameter of dimples in the curve. They are region A with identical size of dimples, region B in which size of dimples decreases with increasing the (a/W) values, and region C with identical size of dimples which is smaller than that in region A.

If the crack length approaches zero, i.e. at the top surface of specimen, it is in the case of plane-stress state. Therefore, It is inferred that the plane-stress state is dominated at crack tip for the specimens with very small (a/W) values (Muscati and Turner, 1977). As the result region A in Fig.3 is in the case of plane-stress state. For deep crack (a/W=0.5), It is indicated that the specimen midsection at crack tip is in the state of plane-strain when specimen thickness B≥25δi (Robinson and Tetelman, 1975). In this the specimen thickness B is 6 mm, δi 0.13mm, so that the region C in Fig.3 is in a state of plane-strain, and region B is considered as a mixture of plane-stress and plane-strain. Based on the analysis previously, the stress triaxiality in region C is higher than that in region B in which the stress triaxiality increases with increasing the (a/W) values. It implies that the size of dimple increases with decreasing stress triaxiality level, and is a constant in the case of plane-stress.

Same results could be obtained by analyzing the variation of mean diameter of dimples along thickness of the specimens with deep crack (a/W=0.52), as shown in Fig.4. The midsection at crack tip is in the plane-strain state, and side surface of specimen plane-stress state. It means that the stress triaxiality level decreases as the positions of interest approach to the side surface of specimen. The mean diameter of dimples increases and up to a constant at the positions near the side surface of specimen.

The dimples could be classically divided into three groups on the basis of dimple features: (1) equiaxed dimple; (2) shear dimple which is elongated and often found in shear-lip zone; (3) tear dimple which is also elongated and has the appearance of parabolas pointing to the direction of crack initiation on both fractured surfaces of specimen. It is worth noticing the feature of dimples in different regions in Fig.3. In region A which is in a state of plane-stress there exist elongated dimples which resemble slim parabolas and point toward the site of crack initiation at the crack tip, i.e. tear dimple. There exist equiaxed dimples in region C which is in a case of plane-strain. In region B which is in a mixture state of plane-stress and plane-strain there are combinated dimples by equiaxed and tear. The phenomenon can also be seen in Fig.4, that is, equiaxed dimples exist at the midthickness of the specimen, and the proportion of equiaxed dimple decreases as the positions of interest approach to the side surface of specimen.

It merits attention that the long dimension of tear dimples in region A in Fig.3 is in the direction of X axis at which the stress σ_x is the smallest comparing to the stresses σ_y and σ_z (Fig.1), and zero on the top surface of specimen. Generally, the long dimension of tear dimples should be in agreement with the direction at which the stress is greater, i.e. Z axis, but it is not in the case. The forming processes of tear dimple are described as follows.
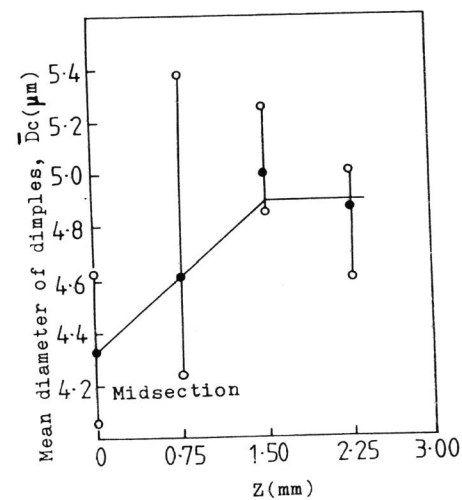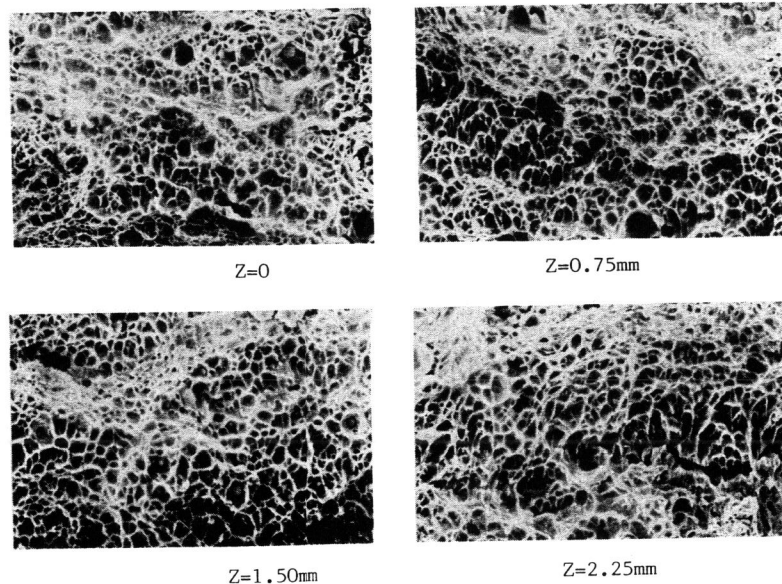

(a) $\overline{D}c$-a/W curve

1 2 3 4

(b) SEM photography

10μ
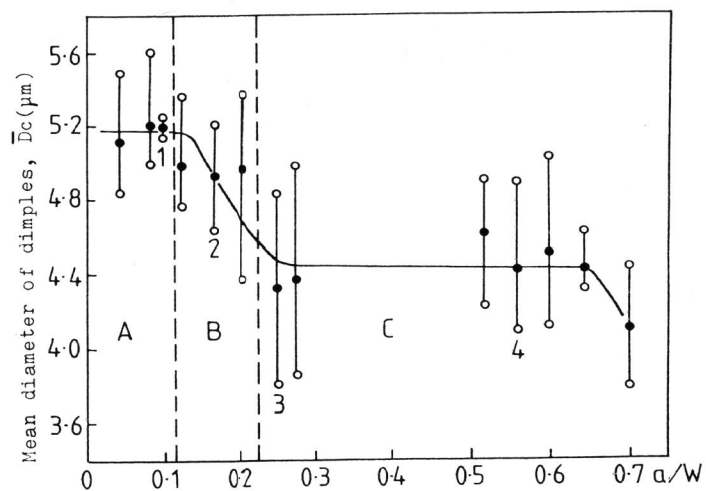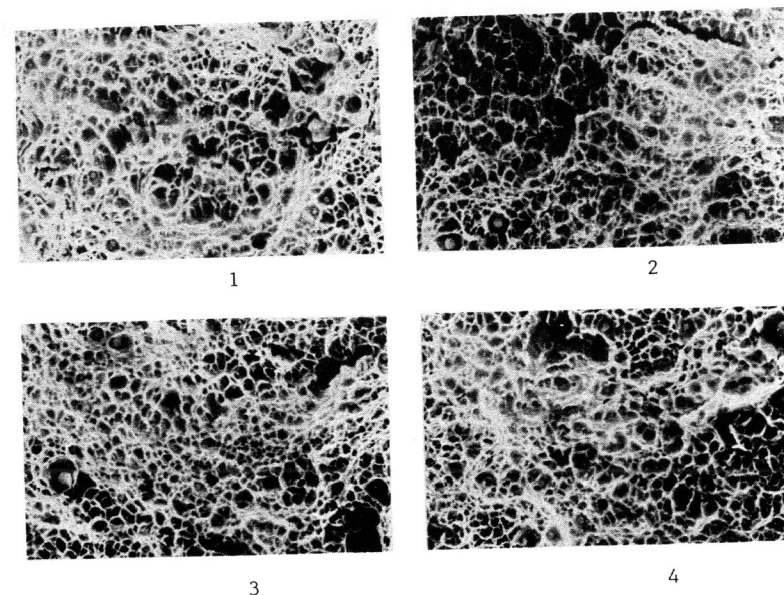
Fig. 3 Variation of mean diameter of dimples with a/W.

(a) Change of mean diameter of dimples with position through thickness

Z=0

Z=0.75mm

Z=1.50mm

Z=2.25mm

(b)   SEM photography

10μ

Fig. 4   Mean diameter of dimples as a function of position
in the specimen (B=6mm, a/W=0.52).

Fig. 5   Formation of tear dimples.

In region A, crack length (a/W) is very small and the stress in the direction of X axis σx (zero for unnotched specimen) is much smaller than σz, so that the region A is in a state of plane-stress or quasi-plane-stress. The long dimension of void is in the direction of Z axis and short dimension X axis during the void growth (Fig.5,a). The behavior of which the void is elongated in Z axis is not gone on until the void grows large enough to contact the crack tip (Fig.5,b). There is a angle of 2θ between the two flanks when crack and void linked up together. The stress σy can be decomposed into two componts σ_T and σ_L. The component of stress σ_L, which is parallel to the crack flank, makes the angle of 2θ enlarged, and other one σ_T which is perpendicular to the crack flank makes the broken void (or dimple) elongated (Fig.5,c). And elongating of the broken void is easy because the internal surface of the broken void is free and the size of the broken void does not change in the direction of Z axis in this condition. As the angle of 2θ increases further, the component σ_T increases. The greater the σ_T values, the more intensive the effect of elongating of broken void. At last the void is separated into two parts, and becomes elongated parabolas dimples (Fig.5,d). This is a reason that the tear dimples are elongated in the direction of X axis in which the stress σx is the smallest for the specimens in region A in Fig.3. For the equiaxed dimples in region C, the void is simultaneously separated in two parts and there is not a process of elongateing, since the stress σx almost becomes as large as the stress σz for deep crack specimens.
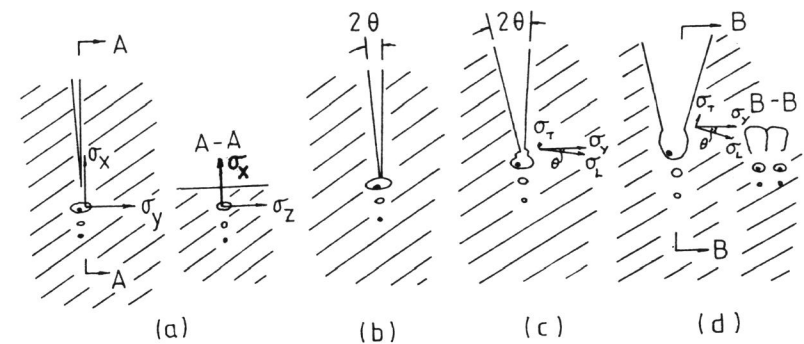
The area of tear dimples elongated is larger than that of equiaxed dimples, so that the mean diameter of tear dimples is larger than that of equiaxed dimples. It means that the more the equiaxed dimples, the smaller the mean diameter of dimples. As the consequence, this is the reason that the mean diameter of dimples is the largest in region A in which the tear dimples elongated dominate, and the smallest in region C in which the equiaxed dimples dominate. With increasing (a/W) values the proportion of equiaxed dimples increases and the mean diameter of diameter decreases in region B, as shown in Fig.3.

Generally speaking, the size of dimples depends on : (1) the number of void nucleated; (2) the plastic strain before void coalescence. The former which is a function of size, number, and distribution of inclusions is unchanged for the same materials. The latter depends on the stress state (or stress triaxiality level) in accordance with the analysis mentioned above. As a coseqence it may not give the conclusion that the size of dimple (or critical void growth at fracture) increase with the stress triaxiality ignoring the effect of plastic strain based on Eqn.(2), and (3).

CONCLUSIONS

(1) Size of the dimple depends on the stress triaxiality for the same materials. The mean diameter of dimples increases with decreasing stress triaxiality level and up to a constant in a state of plane-stress.
(2) Feature of the dimples depends on the stress state. Tear elongated dimples dominate in the case of plane-stress, and all of the dimples are equiaxed in the condition of plane-strain. It is a mixture of tear and equiaxed dimples in a state of mixture of plane-stress and plane-strain.
(3) The forming processes of tear elongated dimples indicate that the broken voids are elongated by the component of stress σy after void grows large enough to contact a crack tip.

REFERENCES

Biel, M.U., and L.S.Golaski(1987). The role of stress triaxiality and
  microstructure in ductile fracture of low carbon cast steel. In: Mecha-
  nical Behaviour of Materials-5 (M.G.Yan, et al., ed.), pp.333-339.
  Pergamon Press.
Goods, S.H., and L.M.Brown (1979). Acta Met., 27, 1-15.
Kumar, A.N., and R.K. Pandey (1983). Micromechanics of fracture in micro-
  alloyed steel. In: Mechanical Behaviour of Materials-4(J. Carlsson, and
  N.G. Ohlson, ed.), pp.1109-1115. Pergamon Press.
Muscati, A., and C.E. Turner (1977). Post-yield fracture behaviour of
  shallow-notched alloy steel bars in three point bending. In: Fracture
  Mechanics in Engineering Practice (P.Stanley ed.), pp.289-304. Applied
  Science Publisher, London.
Pickering, F.B. (1975). The Basis of Quantitative Metallography. Northway
  House, London.
Pineau, A. (1981). Review of fracture micromechanisms and a local approach
  to predicting crack resistance in low strength steel. In: Advances in
  Fracture Research (D.Francois, et al., ed.), Vol.2, pp.553-577. Pergamon
  Press.
Ranganath, V.R., A.N.Kumar, and R.K.Pandey (1987). Influence of notch tip
  state of stress on the fracture characteristics of a HSLA steel. In:
  Mechanical Behaviour of Materials-5 (M.G.Yan, et al., ed.), pp.309-316.
  Pergamon Press.
Rice, J.R., and D.M. Tracey (1969). J. Mech. Phys. Solids, 17, 201-217.
Robinson, J.N., and A.S.Tetelman (1975). Int. J. Fract., 11, 453-468.
Wilsdorf, H.G.F. (1983). Mat. Sci. Eng., 59, 1-39.