# ANALYSIS OF QUENCH CRACKING IN STEEL BY X-RAY DIFFRACTION

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## ABSTRACT

A method for measuring the energy release rate G for crack propagation in quenched steel specimens is described. The method requires the measurement of microdeformation by X-ray diffraction and of the fracture area after quenching. Application to quenched specimens of 1045 steel shows that reasonable values of G (or the surface energy of fracture) can be obtained by applying the experimental results to Griffith's theory of fracture.

## KEYWORDS

Quench cracking; martensitic transformation; fracture mechanics; strain energy release rate; steel; X-ray diffraction; surface energy.

## INTRODUCTION

The quench cracking phenomena in steel induced by martensitic transformation, which causes severe distortion and a volume expansion (Nishiyama,1978), have been studied in a large number of cases. Many of these studies have been concerned with the estimation of the distortion energy produced by the martensitic transformation, while some works have dealt with the cracking phenomena by some statistical approach (Inoue,1975;Kobasko,1970). However, few works in the authors' knowledge have discussed the quench cracking phenomena from the point of view of fracture mechanics.

In this study an attempt is made to determine the strain energy release rate G according to Griffith's theory, expressed as $G = -\delta U/\delta A$, where U is the elastic strain energy and A is the area of the propagated crack. Here we present an experiment designed in order to allow the calculation of the strain energy per unit area of propagated crack.

## EXPERIMENTAL METHOD AND RESULTS

The basis of the method resides on the measurement of the micro-deformation in quenched steel samples by means of X-ray diffraction (Nishiyama,1978; Warren, 1969). Disc-shaped samples of AISI 1045 carbon steel were machined from stock bar and a radial slit was introduced by spark-cutting, Fig. 1 . The notch tip acted as a stress concentrator from which a crack would extend and measurements of its length could be made readily. Quenching was done from two different temperatures 1073 or 1273°K, into brine held at 273°K, after two hours at the quenching temperature.
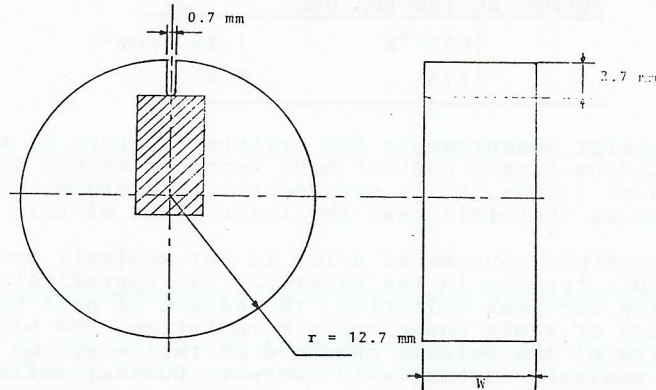


Fig. 1. Geometry of the specimen used in this work.
W oscillates between a minimum value of 4.92 mm
to a maximum value of 15.3 mm.

Inmediately after quenching, the length of the crack produced in each sample was measured; then, microdeformation measurements were carried out by using the (310), (220),and (211) diffraction peaks of martensite. The area of the specimens covered by the X-ray beam is shown dashed in Fig. 1 ; this area was usually traversed by the crack produced by quenching.

Microdeformation reveals itself by a broadening of the diffraction peaks (Warren, 1969; Truckner, 1969). However, the width of the diffraction peaks in our samples were also dependent on the experimental setup (slit width, beam size, etc.) and the degree of splitting of the peaks due to the tetragonal structure of the martensitic unit cell (Cullity, 1978). In order to allow for these two effects on the broadening of the peaks,we first performed a Rachinger correction (Rachinger, 1948) to calculate the actual width of each splitted martensite peak, and then substracted from this the width of a well-annealed sample in which microdeformation should have been reduced to a minimum. The results for 1045 steel samples are shown as a plot of $(\beta_m \cos\theta_m - \beta_f \cos\theta_f)$ versus $\sin\theta_m$ in Fig. 2 ($\beta$ stands for peak width at half maximum, $\theta$ is the Bragg angle, and m and f refer to martensite and ferrite).

The data points in Fig. 2 , were fitted to a linear relationship of the form (Nishiyama, 1978):

$$\beta \cos\theta = k\lambda/t + 2< \epsilon^2 >^{1/2} \sin\theta \qquad (1)$$

in which $\beta \cos\theta = \beta_m \cos\theta_m - \beta_f \cos\theta_f$, t is the number of atomic planes, $\lambda$ is the X-ray wavelength, k is a constant of value close to unity, and $< \epsilon^2 >^{1/2}$ represents the root mean square strain (rmss) in the sample.
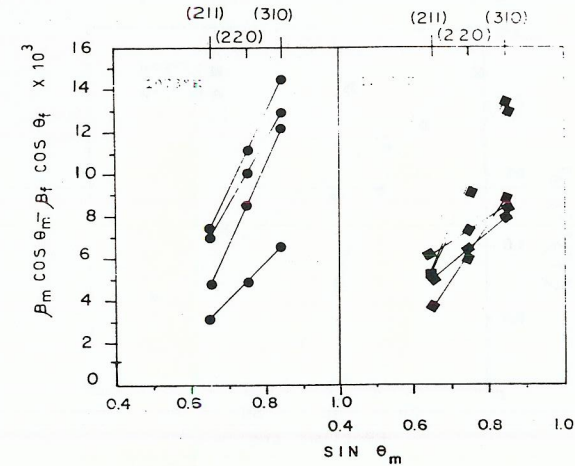


Fig. 2. Plot of $\beta\cos\theta$ vs. $\sin\theta$.

The variation of the rmss with the fracture surface area (crack length times sample thickness) is shown in Fig. 3 . To a large fracture area corresponds a low level of microdeformation, and viceversa. Thus, differences in the fracture area in specimens of this steel are explained by differences in the microdeformation level in each sample.

## DISCUSSION

Having found that there exists a direct relationship between the fracture area and the microdeformation level in our samples, there remains to be seen whether this information may be used for the calculation of the strain energy release rate.

If we assume that the microdeformation, as measured by X-ray diffraction, is a result of the martensitic transformation and that the energy required for crack propagation comes from the release of this elastic microdeformation, then we have at hand a means of relating the energy released by cracks of different fracture area with the change in microdeformation level brought about in different samples by such differences in fracture area.

Furthermore, if the released energy is only used for the crea-tion of new (crack) surface, then we can write:

$$G = 2\gamma = \Delta< \varepsilon^2 >^1/\Delta A_f \cdot V \cdot E/6(1-2\upsilon) \qquad (2)$$

where $\gamma$ is the surface energy of the solid, E and $\nu$ are its Young's and Poisson moduli respectively, $A_f$ is the fracture area and V is the "effective" volume of the sample over which energy was released by crack propagation. Figure 4 shows the plot of $< \varepsilon^2 > \cdot V$ versus $A_f$ for the 1045 steel samples.



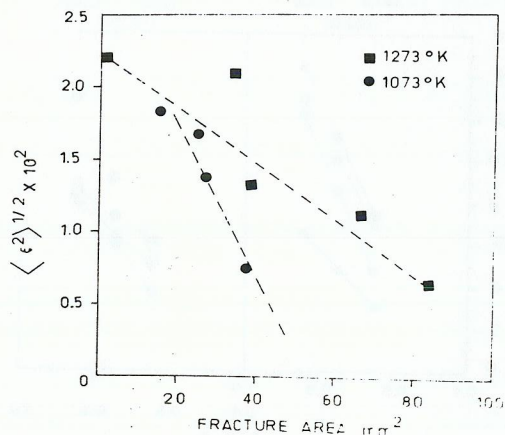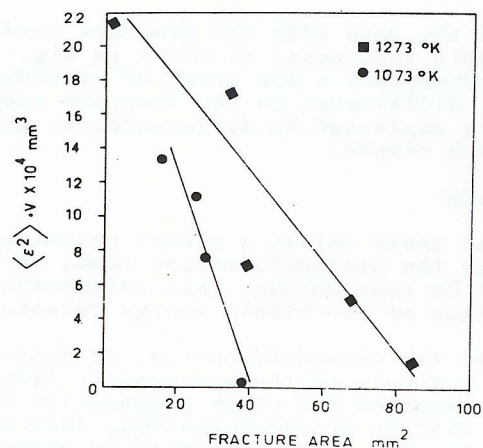Fig. 3. Plot of microdeformation vs. fracture area.



Fig. 4. Plot of $< \varepsilon^2 > \cdot V$ vs. fracture area.

Taking $\Delta< \varepsilon^2 >/\Delta A_f$ from the slopes of the best linear fits to the data in Fig. 4 , and using E = 2.06x10$^5$ MPa, $\nu$ = 0.33 and V approximately equal to the product of the area irradiated by the X-ray beam times twice the penetration of X-rays ($\approx$40$\mu$m), we obtained two values for $\gamma$ from specimens quenched from two different temperatures, as shown in Table 1*.

### TABLE 1  Calculated Fracture Surface Energy for AISI 1045 Steel

| QUENCHING TEMPERATURE | $2\gamma$ |
|---|---|
| 1073 °K | 1.22 J/cm$^2$ |
| 1273 | 0.50 |

Surface energy measurements for brittle fracture in steels of low and medium carbon content have reported values in the range 0.6-60 KJ/m$^2$ ( Hahn,1971); our results, therefore, seem quite reasonable as they fall near the lower limit of this range.

Several possible sources of error in our analysis could be pointed out: texture in the material, the approximate method of allowing for peak splitting, the effect of peak broadening due to lack of truly monochromatic radiation, and others.Howev-er, in view of the results obtained in this work, we believe that our analysis is basically correct. Further refinements in the method of data analysis are under way in order to verify and extend our present results.

### CONCLUSIONS

1. A direct relationship between microdeformation level and fracture area is observed in cracked samples of AISI 1045 steel in the quenched condition. High levels of microdeformation correspond to small fracture areas, and viceversa.

2. The surface energy of fracture or the strain energy release rate, can be calculated by using Griffith's theory of fracture and a linear relationship between the microdeformation level and fracture area in quenched 1045 carbon steel.

### ACKNOWLEDGEMENTS

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*An earlier calculation (Salas, 1982) considered V as the total sample volume.However, we have noticed since then that this is not in agreement with the concept of relaxed microdeformation.

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