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EVALUATION OF FRACTURE ROUGHNESS USING TWO KINDS OF FRACTAL DIMENSION MEASUREMENTS

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ABSTRACT

This paper introduces the basics of fractal measurements. The fracture surface roughness and the toughness of a series of steel samples were analyzed using two kinds of fractal dimensions.

Fracture surface profiles were obtained by means of the cross vertical sections through the fracture surface of steel samples coated with copper in order to protect the surface. With image processing, the fractal dimension of numerous profiles was measured by Euclidean erosion and dilation through the distance map. This 1D fractal dimension measure described the roughness of fracture surfaces and was correlated with the fracture toughness of the materials.

We also applied mathematical morphology fractals to analyze the grey level images of fracture surfaces of steel samples examined by SEM , which were treated as three - dimensional surfaces. The grey level morphological method was based on a series of dilations on this surface and plotting area of the resulting set of surfaces versus the structuring element size. It was demonstrated that the 2D fractal dimension measure was strongly correlated with both roughness and fracture toughness.

Key words: fracture, fractal dimension, roughness, toughness.

INTRODUCTION

There has been great interest in describing and quantifing complex surfaces - non-planar surfaces, such as fracture surfaces of materials. The materials surface roughness and irregularity were investigated using the fractal dimension by E.E.Underwood [1986,1990], J. C. Russ [1991,1992] and many others.

The concept of fractal dimension was introduced by Mandelbrot in early 1960s. For some curves the measured length is a function of the size of measuring unit used to estimate the length and the apparent length becomes infinite as the size of measuring unit approaches zero. The fractal dimension D is used to describe irregular self-similar curves. Self-similarty means that the curve has the same apparent visual shape and configuration under any magnification. Fractal geometry is being used in materials science, because it can be applied to describe non-linear structures. In fractal geometry noninteger dimensions occur and are characterized by self-similarity, scale invariance and discontinuities on all scales [Mecholsky, 1989,1991,1992].

Complex surfaces, such as fracture surfaces of materials may also have self- similar characteristics and can be analysed as self-similar processes suitable for mathematical description by fractal dimensions. We are interested in the roughness of fracture surface of materials, specially in the self- similar case where the surface looks the same in a statistical sense under any magnification.
In our test two different methods were used to measure the fractal dimension of fracture surfaces of materials.
First experimental procedure was to cut vertical sections through the fracture surface of materials generating irregular profiles whose roughness, shape, and configuration were related to those of the fracture surface and statistically presented the characteristics of materials fracture surfaces. We analyzed the profile fractal dimension to describe the fracture surface roughness.
As second method, texture analysis was used . The 2D fractal dimension was directly obtained from surface images examined with a scanning electron microscope (SEM) which were considered as a three - dimensional surfaces. Its texture was analyzed in order to measure the fractal dimension based on the mathematical morphology technique [Peleg, 1984].
Thus, two kinds of fractal dimensions were compared in our experiments.

MATERIAL AND METHODS

A. Experimantal materials and procedure

The steel grade DIN 17100 (st. 50) samples were used to produce fractures. When the impact toughness test temperature was continually changed from the room temperature to -60° C, 8 samples with different impact toughness were obtained, as shown in table 1.

Table 1. Sample number (N) and its impact toughness (T) in J with its test temperature (t)

N	1	2	3	4	5	6	7	8
T (J)	138.28	61.78	43.64	34.81	32.36	26.48	21.58	9.81
t (°C)	room	0	-10	-20	-30	-40	-50	-60

The higher the impact toughness was, the rougher and more complex the surface of fracture was. This means that roughness of the fracture surface increased with increasing the toughness. Surface of the sample 8 with the lowest impact toughness was very flat, according to its brittle crack at low temperature.
After a series of fracture samples was prepared, the surfaces were first examined with a scanning electron microscope. Several images of fracture surfaces were imaged by SEM and analyzed by grey level image processing.
Next, the fracture surfaces were coated with copper in order to protect the surface. Then four vertical sections were cut through both two parts of fracture surfaces of every sample in different directions (cross direction). The intersections in fours of each sample were mounted in bakelite, with the profile facing the side to be polished by 1μ diamond.
A number of profiles from all intersection samples was obtained using optical microscope. Next, the profiles were digitized using a CCD camera connected to a GOP Images Processing System running a MICRO-GOP software package. Then the grey level images of profiles were changed to binary profile lines.
Furthermore, digitized fracture profile images were transfered to a Unix computer system and were analyzed by the morphological operations (see in section B).
The fracture images from SEM were transfered into a Unix computer system too, and the grey level images of steel fracture surfaces were analyzed with the grey level mathematical

morphology methods (section B).
The 1D fractal dimension of fracture profiles and 2D fractal dimension of fracture surface were calculated for each sample and the relationship between fractal dimension and toughness was established. The correlations were compared and results discussed.

B. Computer Program

The image processing was divided into two parts both based on mathmatical morphology [Serra, 1982].
First, we measured binary profiles in order to estimate the length of profiles. We have utilized that the perimeter of an object was proportional to the area of the object divided by the mean width of the object. We did not need to estimate absolute values of the perimeter, since our primary interest laid in the 'change' in perimeter over different scales. True fractals were characterized by having a infinite perimeter. There were constraints on the term of perimeter, since the total length of perimeter L must obey the following expression :

$$L= K * S^H \qquad (1)$$

where S is a length of measuring unit, K is a constant, and H is a slope of line. When plotting the Richardson plot: Ln(L) vs. Ln(S) (1), this is also known as the Richardson equation [Mandelbrot, 1982]. The fractal dimension D can now be derived from the equation D = 1 - H.
The Richardson plot of Ln(L) vs. Ln(S) details change in measured length of the profile line as a function of scale. Construction of a plot for a fracture surface requires a line that is representative for the fracture surface and a range of scales for measuring that line.
One way of measuring the profile length by image processing was to dilate successively the profile line, to create a series of bands or Minkowsky sausages along the profile. The Minkowsky fractal dimension was then simply obtained by counting the area of the sausage as a function of the number of dilations. An efficient way of doing this was to use the Euclidean Distance Map (EDM) [Russ, 1992]. This assigned a value to each pixel in the image which was its distance from the nearest pixel of the opposite type (feature or background). By thresholding the EDM it was possible to perform true Euclidean morphological dilations, and hereby avoiding orientation biases, because of the anisotropy of the 'normal' morphological operations.
The second part of the image processing was based on grey-scale morphology. Two-dimensional grey level image was analysed as a three-dimensional surface whose height at each point represented the grey level at that point, and the idea was to make an estimate of the surface area A measured at different scales E (different sizes of measuring units). The area of a fractal surface behaves according to the expression [Mandelbrot, 1982]:

$$A = K * E^H \qquad (2)$$

where K is a constant, E is the scale or size of measuring unit, and D (= 2 - H) is the fractal dimension.
By performing series of grey-scale erosions and dilations on the grey level image, a 'blanket' of thickness 2E [Peleg, 1984] will cover the original surface. If we call the upper part of the blanket (the original image dilated E times) U_E, and the lower blanket (E times erosion) L_E, the volume V_E of the blanket is calculated by the summation:

$$V_E = \Sigma_{i,j} [U_E(i,j) - L_E(i,j)] \qquad (3)$$

An estimate of the surface area A(E) can be found as $A(E) = V_E/2E$. Analogous to the method applied to the elevated profiles, this volume divided by E (area of the measuring unit) was plotted as a function of E on log-log basis. The slope of this plot gave the surface fractal dimension. We have used a slightly different approach also presented by Peleg et al. [Peleg, 1984]. Instead of calculating A(E) as above, Peleg calculated the surface area as follows

$$A(E) = (V_E - V_{E-1})/ 2 \qquad (4)$$

According to Peleg, subtracting V_{E-1} from V_E isolated just those features that changed from scale E-1 to scale E. This should give better measures for fractal surfaces.

RESULTS AND DISCUSSION

A. Fractal dimension of profiles

More than 20 profile line images were obtained from 4 intersections (two directions) of each sample. Typical profiles from the fracture of higher and lower toughness are shown in figures 1 and 2. They vary from the more irregular and rougher to the flat.

In order to relate the fractal dimension D to the machanical properties of fractures, the mean fractal dimension measured from all profiles of each sample is plotted against their fracture toughness values examined from the impact test and shown in Fig.3.

The fractal dimension increased with increasing toughness value (i.e increasing roughness of fracture surfaces).

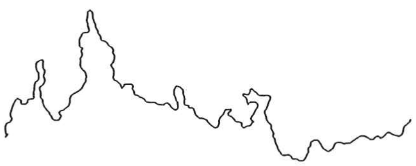

Fig.1 Profile of sample 1

Fig.2 Profile of sample 8

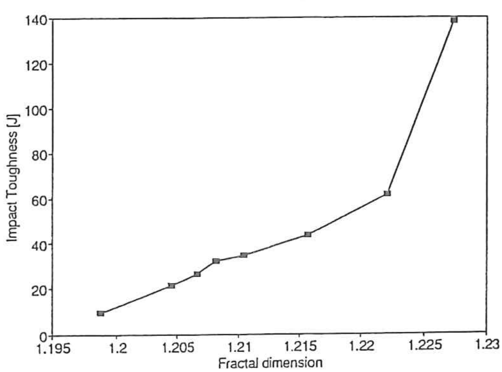

Fig.3 Relationship between the 1D fractal dimension of fracture profiles and toughness

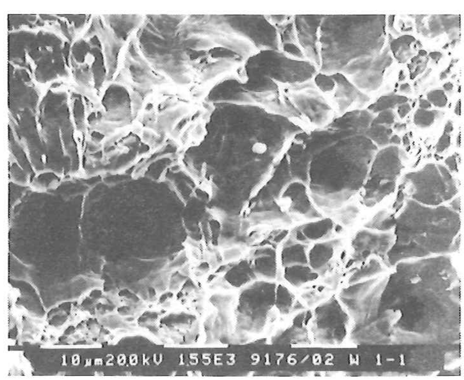

Fig.4 Fracture surface of sample 1

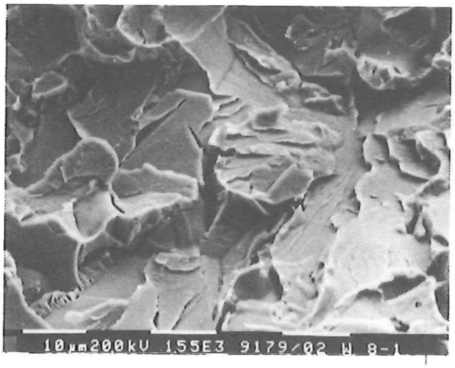

Fig.5 Fracture surface of sample 8

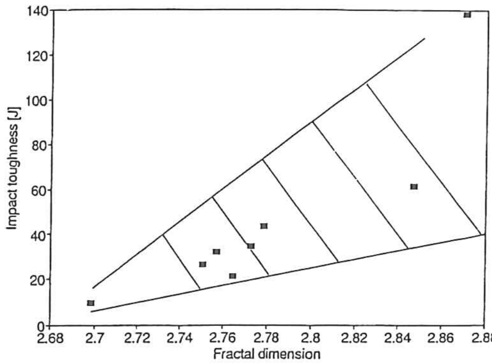

Fig.6 Relationship between the 2D fractal dimension of fracture surface images and toughness

From Fig.3 we can see, the plot was linearly increasing from sample 8 to sample 2 due to the same kinds of fractures (brittle fracture). However, from sample 2 to sample 1 the toughness was greatly increased because the type of fracture was varied from the brittle crack to the ductile crack. The increase of the fractal dimension of sample 1, as shown in Fig.3, was not expectantly high compared with the one of toughness value. The reason may be that the fractal geometry did not greatly vary when the type of fracture was transfered from the brittle crack to the ductile one.

B. Fractal dimension of surfaces

The grey level images of different fracture surfaces examined by SEM are shown in figures 4 and 5. Several images were prepared for each sample.

The texture in the images was found to consist of many small pattern elements. An elementary pattern in the texture structure was able to generate the whole texture pattern. Therefore, the self-similarity was included in the texture analysis.

2D fractal dimensions of fracture surfaces obtained from the texture image measure using mathematical morphology against toughness values are shown in Fig.6. Comparing Fig.6 with Fig.3, it is clear that the shape and variability of these two curves are strongly similar.

This result demonstrates that the 1D fractal measured from fracture profiles and the 2D fractal from images of fracture surfaces are similarly correlated with fracture toughness.

The clear trend was obtained, despite the fact that the dimension of the 1D form was not expected to be exactly one less than the 2D dimension of the surfaces since many factors may cause a difference between two kinds of fractal dimensions:

Because the 2D fractal of the fracture surfaces was obtained from the SEM images of surfaces, we were finding the fractal dimension of the image surface and not the true fractal dimension of the fracture surface. There were to be expected little differences between the image surface and the true fracture surface, this would have an affect on the fractal values. Nevertheless, the fractal dimension from the image of the fracture surfaces can still be used to describe the fracture characteristics, according to our test results.

The image location in the fracture and the intersection (profiles) position in the fracture for each sample may vary and they may present different characterictics of the fractures.

Image processing and transfer procedure and also the computer error of measurement may be the second reason.

To summarize, the two kinds of fractal dimensions both had strong relationships with the fracture roughness and toughness, that is, with the fracture mechanical properties of materials.

CONCLUSIONS

This test represents a limited result of evaluation of fracture properties of materials using fractal analysis based on two different methods (two kinds of dimension analysis). It may be concluded that:

1, Two kinds of fractal dimension form, 1D or 2D, were both able to describe and quantify fracture surface (roughness). Fractal values were meaningful for evaluation of fracture toughness of materials.

2, When increasing the roughness and complexity of fracture surfaces of materials, the fractal dimensions 1D and 2D were also increased. They were similarly related directly to the mechanical properties of fracture.

3, The texture pattern measure technique based on mathematical morphology can quickly and nondestructively provide fractal dimension from grey level images of fracture surfaces of materials. This 2D fractal dimension measure method was feasible for detection complex surface characteristics and was comparable with the 1D fractal dimension using Erosion & Dilation method through the fracture profiles of materials.

In addition to this principal use of the new parameters for studying fracture properties of materials, we developed different related measures of self-similarity and techniques through fractal geometry research, it is desirable to reveal the geometry regularity of fracture surface structures of materials.

REFERENCES

Fahmy Y, Russ JC, Koch CC. Application of fractal geometry measurements to the evaluation of fracture toughness of brittle intermetallics. J Mater Res, Vol. 6, No. 9, Sept. 1991:1856-61.

Mandelbrot BB.The Fractal Geometry of Nature. San Francisco, CA: Freeman, 1982.

Mecholsky JJ, Passoja DE, Feinberg-Ringel KS. Quantitative Analysis of Brittle Fracture surface using Fractal Geometry. J Am Ceram Soc, 72[1], 1989: 60-65.

Mecholsky JJ. Relationship between Fractal Geometry and Fractography. J Am Ceram Soc, 74[12], 1991: 3136-38.

Mecholsky JJ, Plaia JR. Fractal analysis on fracture surface of glass using replication techniques. J Non-crystalline Solids, 146, 1992: 249-255.

Peleg S. Multiple Resolusion Texture Analysis and Classification. IEEE Trans PAMI-6, No.4, July 1984: 518-523.

Russ JC. Characterizing and Modelling Fractal Surfaces. J Comput Assist Microscopy, Vol.4, No. 1, 1992:73-126.

Russ JC. The Measurements and Analysis of Images. Comput Assist Microscopy. 1990: 330-349.

Serra J. Image Analysis and Mathematical Morphology. Academic Press, London, 1982.

Samarabandu J, Acharya R, Hausmann E, Allen K. Analysis of Bone X-Rays Using morphological Fractals. IEEE Trans, Vol. 12, No. 3, Sept. 1993: 466-470.

Underwood EE, Banerji K. Fractals in Fractography. J Mater Sci & Eng 80, 1986: 1-14.

Underwood EE. Evaluation of overlaps in fracture surfaces. Micro 90, ASTM STP 1094, 1990: 340-353.

Underwood EE. Treatment of Reversed Sigmoidal Curves for Fractal Analysis. Micro 90, ASTM STP 1094, 1990: 354-364.