FRACTAL ANALYSIS OF FRACTURE SURFACES OF CONSTRUCTIONAL STEELS

A.A. EMELYANOV, L.E. PORTNOV, I.J. PESHMINTZEV and
J.V. POSPELOV
Urals Polytechnical Institute,
Ekaterinburg, Russia

ABSTRACT

Fractal analysis of fracture surface of low-alloyed and medium- alloyed costructional steels was fulfilled. New original method fractal dimension calculation was opened. It was found that fractal dimension of fracture surface of investigated steels was irrespective of their phase composition and strength or plastic properties. Correlation between impact toughness and fractal dimension of fracture surfaces was opened. Obtained experimental results were explained with model, based on modified critical strain energy release rate G_{1c}.

KEY WORDS

Fractal dimension, fracture surfaces, toughness.

INTRODUCTION

As shown by Mandelbrot (1983) the concept of fractals is very useful in identifying of wide variety of the most important phenomena in nature. One of such significant phenomena is fracture. Many investigaters, for example Wright and Karlsson (1983), showed fractal character of fracture surfaces in constructional materials. Dauskardt et al (1990) showed probability of connecting mechanical properties of steels with fractal dimension.

In this work fracture surfaces of some constructional steels were analysed in terms of fractal geometry. The emphasis was made on three questions: (i) relationship of fractal dimension with microstructure parametres, (ii) with mechanical properties and (iii) with fracture micromechanisms.

EXPERIMENTAL PROCEDURES

Chemical composition of investigated steels is shown in Table 1. Steels used for this investigation were melted in an induction furnace and hot rolled to 15x15 mm bars. Low-alloyed steels were subjected to normalization and medium-alloyed steels were normalized and annealed. Mechanical properties were determined by standard experimental procedure. Charpy tests were held for obtaining fracture surfaces.

MICROSTRUCTURE

Common microstructures for investigated steels are shown in Fig. 1.

Table 1. Chemical composition, Wt %.

№	C	Mn	Si	Cr	Ni	Mo	V	Al	S	P
1	0.20	1.12	0.15	-	-	-	-	0.05	0.015	0.012
2	0.20	1.11	0.16	-	-	-	-	0.05	0.070	0.012
3	0.44	1.20	0.10	-	-	-	-	0.05	0.015	0.010
4	0.44	1.19	0.10	-	-	-	-	0.05	0.060	0.010
5	0.07	3.10	0.54	-	4.04	0.63	0.12	0.04	0.016	0.015
6	0.10	0.39	0.13	3.22	2.92	0.52	0.12	0.01	0.016	0.013

Low-alloyed steels have ferrite-pearlite structure. Pearlite content vary from 27 to 76% with increasing carbon content in steel. In steels with increased content of sulphur manganous sulphides are seen, Fig. 1a. Steels №5 and №6 have typical structure of low-carbon martensite and bainite, Fig.1b. X-ray analysis show presence of approximately 5% of retained austenite in these steels.

Mechanical properties of investigated steels are shown in Table 2. Increasing of sulfur content in low-carbon steels decrease plastisity and impact toughness of low-alloyed steels. In general, investigated steels have wide spectrum of mechanical properties, namely: yield strength vary from 330 to 1060 MPa, reduction of area from 14 to 70%, impact toughness (T=20°C) from 0.6 to 1.8 MJ/m^2, and impact toughness (T=-50°C) from 0.15 to 0.7 MJ/m^2.

SEM examination results of fracture surfaces are shown in Fig. 1c,d,e. Under T=20°C all specimens of investigated steels revealed microvoid fracture, Fig. 1c. For low-alloyed steels (№2,4) large amount of manganous sulphides in dimples can be seen, Fig. 1c. Fracture mode changes after testing under - 50°C. Fracture mechanisms of low-alloyed and medium alloyed steels are cleavage and quasicleavage respestively, Fig. 1d,e. So, three mechanisms of fracture are opened in investigated steels: (i) ductile fracture by coalescense of microvoides and brittle fracture by (ii) cleavage and (iii) quasicleavage.

Table 2. Mechanical properties and fractal dimension of fracture surfaces of investigated steels.

№	Tensile strength, MPa	Yield strength, MPa	Elongation, %	Reduction of area, %	Impact Toughness and P +20°C MJ/m^2	P	-50°C MJ/m^2	P
1	540	335	28	70	1.80	1.21	0.60	1.10
2	530	330	24	21	0.60	1.07	0.20	1.06
3	750	445	13	55	1.10	1.19	0.40	1.08
4	740	440	11	14	0.40	1.07	0.10	1.03
5	1200	1060	16	51	0.89	1.15	0.15	1.07
6	1140	1030	17	57	0.85	1.16	0.38	1.12

NUMERICAL SIMULATIONS

The main idea of the concept of fractals is to change real surface (profiles) by some theoretical interpreting surfaces (profiles). These interpreting surfaces are characterised by Hausdorff (fractal) dimensions which are strictly non- integer. Employing these dimensions can help to solve problem of such object classification, which cann't be solved using usual topological dimensions.

Fractal dimension is calculated commonly from the empirical relationship postulated by Richardson between the profile length L and the measuring step ε:

$$L = L_o * \varepsilon^{(1-p)}, \qquad (1)$$

where L_o is a constant and the value of the non-integer exponent P, which is independent of ε, is dependent on the particular profiie being studied. Mandelbrot (1983) subsequently showed that P may be interpreted as the fractal dimension of the profile. For geometrically constructed fractal curves the value of P appears to be characteristic of the degree of roughness of such curves. In physical systems, however, fractal behaviour is confined within limiting dimensions, such as between the size of system being investigated.

One of the main difficulties of practical usage of formula (1) is determination of L_o. Original procedure of fractal dimension P calculation was proposed in this paper.

Fracture surfaces, representing the "classic" fracture modes of transgranular cleavage, quasicleavage and microvoid coalescence were obtained by fracturing charpy U-notch specimens. Fracture surfaces were electrolytically plated with nickel and sectioned normal to their plane. Resulting fracture profiles were mounted, optically polished and lightly etched in 2% nital. Typical profile is showed in Fig. 1f.

Lengthes of fracture surfaces profiles, calculated at different magnifications of optical microscope can be written in terms of formula (1), as:

$$L_1 = L_{01} * \varepsilon_1^{(1-p)} \qquad (2)$$

$$L_2 = L_{02} * \varepsilon_2^{(1-p)} \qquad (3)$$

It is evident that ε is proportional to the magnification of optical microscope. Hence we can calculate P, considering $L_{01}/L_{02} = \varepsilon_1/\varepsilon_2$:

$$P = \log_{\alpha}(L_2/L_1), \qquad (4)$$

where $\alpha = \varepsilon_1/\varepsilon_2$- relation of magnifications ($\varepsilon_1 < \varepsilon_2 << 1$). Calculated P-values are shown in Table 2.

Experimental data analysis shows that fractal dimension P is irrespective of steel phase composition and their strength or plastic properties. Medium-alloyed steels have fractal dimension approximately same as low-alloyed steels. At the same time fractal dimension correlates impact toughness (correlation coefficient is equal to 0.92). The same results were obtained by Dauskardt et al (1990).

This is noteworthy that high values of P are not connected with ductile fracture, or low values - with brittle fracture. So,steels №2,4 represent fracture by ductile microvoid coalescence, but have P - values lower, than in steels №1,3 after brittle fracture by cleavage mechanism.

Authers proposed that fractal dimension of fracture surface was connected with critical strain energy release rate G_{1c}. In the case of straight, "non-fractal" crack propagation $G_{1c} = 2\gamma$, where γ- specific effective surface energy. Dauskardt et al(1990) in their review show that there are a great number of experimental evidence, supporting "fractal" nature of crack propagation. Therefore this experimental result should be taken into account in G_{1c}-criteria.

From formula (4) it is obvious that after decreasing of measuring step size in α-time crack length will increase in α^{p}-time. If crack has straight way (non-fractal nature) its lengthwill increase in α-time. So, it is obvious that length of "fractal" crack will be more than "non-fractal" in $\alpha^{(p-1)}$-time.

Therefore fracture surface section of fractal crack will be more than "non-fractal" in -time. So, we can deduce modified G_{1c} criteria:

$$G_{1c} = 2 * \gamma * \alpha^{2(p-1)} \tag{5}$$

Let's take values of measuring steps and equal to 10^{-8} and 10^{-6} m, respectively. So, $\alpha^{2(p-1)}$ will be equal to $10^{6(p-1)}$. According to Table 2 assume values of fractal dimension P equal to 1.1 for low-energy fracture and equal to 1.2 for high-energy fracture For the first case $\alpha^{2(p-1)}$ will be eoual to 4 and for second case - to 16. In other words, toughness increase is 4-times inthese cases. These results are in agreement with experimental data of impact toughness listed in Table 2.

CONCLUSION

Fractal analysis of fracture surfaces of low-alloyed and medium- alloyed constructional steels was made with new original method of fractal dimension calculation. It was shown that fractal dimension of fracture surfaces was irrespective of their phase composition and strength and plastic properties. Correlation between impact toughness and fractal dimension of fracture surfaces was found. Modified critical strain energy release rate G_{1c} was proposed for experimental results explanation.

REFERENCES

Dauskardt R.H., Haubensak F. and Ritchie R.O. (1990) On the interpretation of the fractal character of fracture surfaces. Acta met. mater., V.38, 2, p.143-159.
Mandelbrot B.B. (1983),The fractal geometry of nature. Freeman, New Jork.
Wright K., Karlsson B. (1983) Fractal analysis and stereological evaluations of microstructure. J. microscopy, 129, p.185-200.

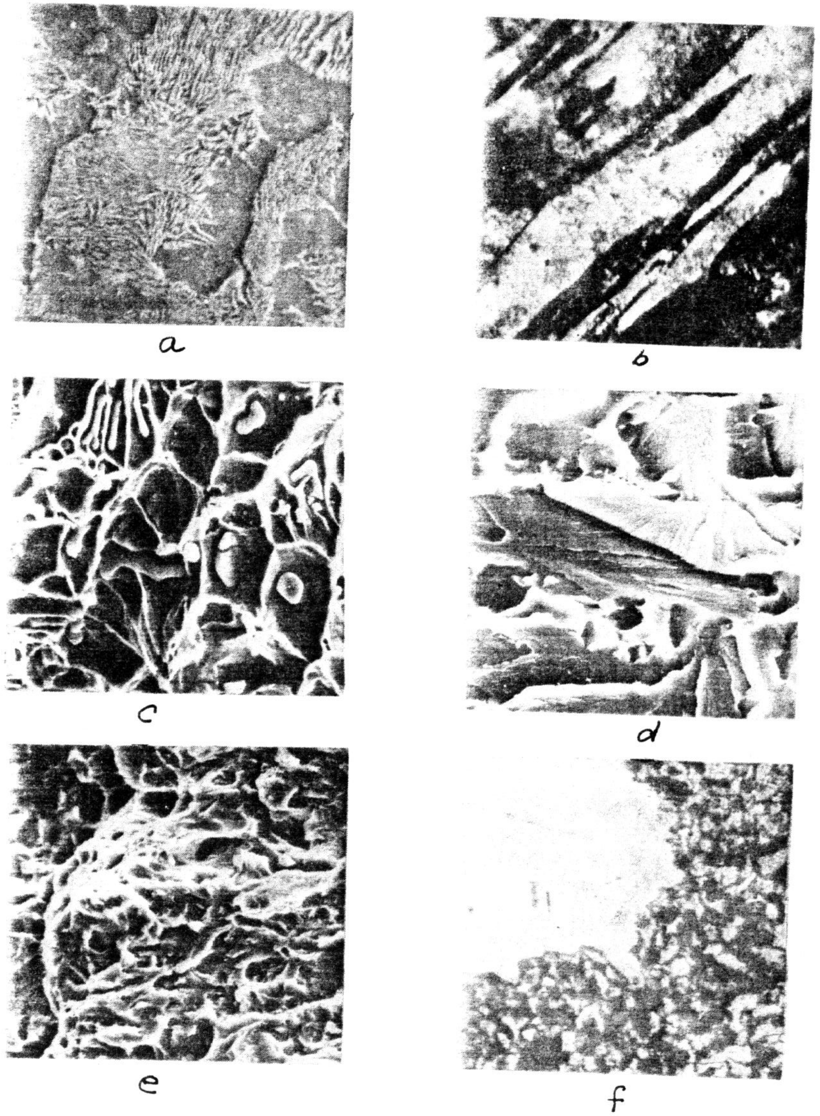

Fig 1. Microstructures of steels №4(a), №5(b), fracture surfaces of steels №2(c), №1(d), №6(e) and fracture profile of steel №3(f). a - x 6000, b - x 40000, c, d, e - x 2000, f - x 600.