Fractal model of structure-properties effect of low carbon steel

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Abstract. Fractal theory has been used for predicting of microstructure (ferrite, pearlite and non-metallic inclusions) effect on mechanical properties (KCV-60, σ0.2, σB, δ) of S355J2 steel. The fractal model which has been obtained may be considered as additive database. The database can be complemented by different treatment modes and microstructure. It has been stated that good response of structure-properties has been obtained for strength characteristics (σ0.2, σB) of S355J2 steel and fractal size of lamellar pearlite. Also, correspondence of elongation to fractal size of ferrite has been obtained. As it has been determined the better correspondence of fractal size of non-metallic inclusions defined to impact toughness of S355J2 steel. The results have been confirmed by effect of low carbon steel microstructure on mechanical properties of the steel. The histogram of microstructure and non-metallic inclusions effect on mechanical properties of S355J2 steel has been plotted.

1. Introduction
Structure of materials forms at open systems with exchange of energy [1]. Therefore, structure elements forms at nonequilibrium conditions and have complicated geometrical shape. Thus, Euclid geometry is not always let the define real structure with required accuracy. But such complicated objects as steel structure at different size scale levels can be easily defined by Mandelbrot’s fractal geometry [2], [3]. For example, at work [4] fractal modelling has been used for evaluation of non-metallic inclusions in steel. At works [5] and [6] fractal modelling of structure and properties of materials has been made. For example, strength/elongation ratio for S235 steel has been searched by means of fractal modelling [7].

At present work fractals theory will be used for structure-properties ratio modelling and impact trend definition for S355J2 steel.

2. Experimental
The chemical composition of low alloyed S355J2 steel are shown at Table 1.

| C  | Mn  | Si  | S   | P   | Cr  | Ni  | Cu  |
|----|-----|-----|-----|-----|-----|-----|-----|
| ≤0.12 | 1.3–1.7 | 0.5–0.8 | ≤0.04 | ≤0.035 | ≤0.30 | ≤0.30 | ≤0.30 |

The steel has been rolled to thick sheets and heat treated. Specimens were cut off at as-rolled condition and after normalization at 900°C and 920°C. Heat treatment let increase the elongation through some decrease of the strength. Mechanical properties of the S355J2 steel are shown at Table 2/
Table 2. Treatment and properties of S355J2 steel.

| #  | Treatment                | YTS, $\sigma_{0.2}$, MPa | UTS $\sigma_b$, MPa | Elongation, $\delta$, % | Impact toughness $KCV-60^\circ$, J/cm$^2$ |
|----|--------------------------|---------------------------|----------------------|-------------------------|------------------------------------------|
| 1  | As rolled                | 390                       | 533                  | 29                      | 15, 20, 28                               |
| 2  | 900°C, 1.5 min/mm        | 360                       | 516                  | 35                      | 337, 331, 332                            |
| 3  | 920°C, 1.5 min/mm        | 346                       | 504                  | 35                      | 281, 235, 245                            |

Fine ferrite-pearlite structure has been obtained as a result of heat treatment (Fig. 1). Structure has been investigated by Neophot-2 light microscope. It should be mentioned that investigated pearlite have had fine-lamellar structure.

Figure 1. Ferrite-pearlite structure and non-metallic inclusions of S355J2 steel, ×1000.

Ferrite grain size has been measured according to standard (GOST 5639). Steel after hot rolling (Treatment 1) has 6-7 grade. Steel after 900°C normalization (Treatment 2) had 9-8 grade, and after 920°C normalization (Treatment 3) had 9-8 grade, also.

Non-metallic inclusions have been detected in structure of the S355J2 steel (Fig. 2). The inclusions have been identified as nondeformed silicates and brittle silicates. Such kind of non-metallic inclusions have strong effect on mechanical properties of the steel and especially on impact toughness [8].

Figure 2. Non-metallic inclusions at structure of S355J2 steel, ×1000.
It should be noted that non-metallic inclusions are quasi-uniformly distributed at the structure of the steel.

3. Discussion
According to grade evaluation there is poor correlation of structure and non-metallic inclusions to mechanical properties (Table 3). Thus, fractal dimensions of the structure and properties have been used. For example, at work [9] strong correlation of multifractal characteristics of ferrite, pearlite, upper and lower bainite, Widmanstatten ferrite and properties of S235 steel has been established. Correlation coefficients were from 0.65 to 0.89. These and other results prove the response of fractal dimension to material properties.

For definition the fractal dimension of the investigated ferrite-pearlite structure a proprietary method has been used [10]. The method is based on convergence of grid [11] and point [12] numerical dimensions of the investigated object. The example of convergence fractal dimensions search for pores size at exlay-concrete is shown at Fig. 3 [10].

![Figure 3. Correlation of fractal dimension to grid size.](image)

The best correlation of pore size $D_t=1.824$ to grid size $l = 6$ pix has been obtained at the six iteration step, calculated by $D_1$ grid and $D_2$ point methods. Background correlation is described by $D_3$ grid and $D_4$ point methods. The best correlation for background is $D_f=1.932$ and also has been obtained at the six step of iteration.

The fractal dimensions of pearlite $D_p$, ferrite $D_f$ and non-metallic inclusions $D_{inc}$ have been calculated. Fractal dimensions of the structure have been compared to properties in order to find the best response (Fig.4).

![Image](image)

Fig. 4. Correlation of (a) yield strength and (b) tensile strength to $D_p$ and $D_f$.
Figure 4. Response of the fractal dimensions of the structure to properties of the S355J2 steel.

Analysis of the Fig.4 and models (1-4) prove the possibility of the predicting of the S355J2 steel properties by fractal method. The good response of elongation to fractal dimension of the ferrite has been found (Fig. 4 b). Also good response of the steel strength to fractal dimension of the pearlite should be noticed (Fig. 4 a). It can be explained by higher strength of the pearlite compared to ferrite due to higher (0.8%) carbon content. Response of the non-metallic inclusions to impact toughness can be explained by peculiarities of the fractal modelling.

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\begin{align*}
\sigma_{0.2} &= 419.05D_p - 411.81, & R^2 &= 0.89 & \text{(Fig. 3 a)} \\
\sigma_b &= 272.71D_p + 11.445, & R^2 &= 0.83 & \text{(Fig. 3 a)} \\
\delta &= -33.398D_F + 89.555, & R^2 &= 0.81 & \text{(Fig. 3 b)} \\
KCV^{50} &= 1420.9D_{inc} - 2296.5, & R^2 &= 0.85 & \text{(Fig. 3 c)}
\end{align*}
\]

The impact trend (structure to properties) evaluation (Fig. 5) has been calculated as a result of the analysis the pair correlation coefficients $R^2$ of the models (1-4).

Figure 5. Impact trend of fractal dimension of the pearlite, ferrite and non-metallic inclusions to properties of the S355J2 steel.

Such approach to structure-properties correlation response let decrease the quantity of the mechanical tests due to effective use of the fractal model for mechanical properties predicting. The model is an additive and can be complemented by new experimental data.

4. Conclusions

It has been established that lamellar pearlite fractal dimension has good response to strength of the S355J2 steel. Also, fractal dimension of the ferrite has good response to elongation. The fractal
dimension of the non-metallic inclusions has better response to impact toughness of the S355J2 steel. Fractal models let the evaluate an effect of the structure components to properties of the steel. The fractal approach let eliminate the models with poor response and complement the database for steel properties predicting.

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