Fractals Theory Application for Evaluation of Influence of Non Metallic inclusions on Mechanical Properties of S355J2 Steel

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Abstract. Influence of non-metallic inclusions in constructional S355J2 steel on mechanical properties has been evaluated by using fractal theory. Since point evaluation of non-metallic inclusions is fault tolerant to mechanical properties change. Point evaluation of experimental steel grades has been evaluated by 1-2 points. Correlation between mechanical properties of the steel (KV²₀, σ₀₂, σₚᵣ, δ) and fractal dimensions of non-metallic inclusions has been found. Mechanical properties of the steel have been ranking according to influence of fractal dimensions of non-metallic inclusions on the properties. It has been revealed that non-metallic inclusions, evaluated by their fractal dimensions, have strong effect on impact toughness of the steel S355J2 ($R^2 = 0.89$). It can be explained by reducing the metal matrix resistance to crack propagation due to non-metallic inclusions in the matrix. Method of mechanical properties ranging by non-metallic inclusions fractal dimensions allow to vary chemical composition of steel for main parameter obtaining. In this particular case for necessary impact toughness of constructional S355 steel narrower chemical composition of the steel should be chosen.

1. Introduction
As it known, non-metallic inclusions have strong effect on mechanical properties of the steels. Steel consumers, especially railway cars producers, increasing demands to mechanical properties of the steels almost annually. Demands to non-metallic inclusions numbers and sizes regulate by standards and regulatory documentation on the steel rolled and casted products. But the point evaluation of the non-metallic inclusions is semi-quantitate and sometime can’t be used for rapid correspondence to mechanical properties of the steel. Moreover, at industrial steels non-metallic inclusions frequently grow as complexes of different non-metallic inclusions with complicated structure [1, 2]. Such complex morphology of the non-metallic inclusions is featured to non-metallic inclusions of S355J2 steel that can be used for freight railway car sheathing production. For description the objects with complicated structure can be used fractal geometry with promising results [3]. Thus, in [4] the impact of cast iron fractal dimensions to mechanical properties of the cast iron has been shown. It allow evaluate the value of cast iron structure to mechanical properties by means of ranging and use the fractal formalism for multi parametrical technologies. It should be mentioned, that fractal
dimension is a significant factor for agglomeration and dissolution of irregularly shaped non-metallic inclusions [5]. Fractal nature of metals at different size levels has been proved at papers [6-8]. Therefore, fractal approach can be used for evaluation of non-metallic inclusions content influence on mechanical properties of S355J2 steel and ranging by determining factor.

2. Experimental
Chemical composition of investigated steels is presented at Table 1.

| Grade | C    | Mn    | Si    | S    | P     | Cr    | Ni    | Cu   | Al   | N    | Ca   | H    |
|-------|------|-------|-------|------|-------|-------|-------|------|------|------|------|------|
| Grade 1 | 0.100 | 1.610 | 0.560 | 0.002 | 0.009 | 0.030 | 0.020 | 0.040 | 0.032 | 0.006 | 0.0020 | 0.0002 |
| Grade 2 | 0.110 | 1.620 | 0.560 | 0.002 | 0.008 | 0.030 | 0.020 | 0.040 | 0.027 | 0.006 | 0.0021 | 0.0002 |
| Grade 3 | 0.110 | 1.600 | 0.550 | 0.002 | 0.013 | 0.030 | 0.030 | 0.040 | 0.030 | 0.006 | 0.0020 | 0.0004 |
| S355J2  | ≤0.20 | ≤1.65 | ≤0.56 | ≤0.025 | ≤0.025 | -     | -     | ≤0.55 | -    | -    | -    | -    |

Steel S355J2 has ferrite-pearlite structure at as rolled condition (Figure 1). Morphology of non-metallic inclusions and microstructure of the steel has been investigated by light microscopy. Neophot-2 light microscope has been applied.

Contamination of steel by non-metallic inclusions has been measured according to GOST 1778. Cluster of non-metallic inclusions at Grades 1 and 3 distributed non-uniformly thorough entire steel plate thickness. At Grade 2 multiple clusters of fine oxides have been revealed. Oxide clusters have been found on surface and quarter of plate thickness. The center structure of the steel plate has small quantity of oxides. Fine fragments of angular deep-grey inclusions (probably magnesium spinel) have been found at structure of the steel. Typical non-metallic inclusions of steel S355J2 are shown in Figure 2.

Non deforming silicates at all three Grades of S355J2 steel have complex morphology. The sizes of non-deforming silicates determine by point scale (semi-quantity), e.g. 2a(1), 3a(1). Brittle silicates have been determined by point scale 1b(1), 2c(1), as shown in table 2.
Table 2. Point scale of non-metallic inclusions at steel S355J2 according to GOST 1778.

| № grade | Non-deforming silicates, point scale (CH) | Brittle silicates, point scale (CX) |
|---------|----------------------------------------|----------------------------------|
| 1       | 2a(1), 3a(1)                           | 1b(1), 2c(1)                    |
| 2       | 2a(1), 3a(1)                           | 1b(1), 2c(1)                    |
| 3       | 2a(1), 3a(1)                           | 1b(1), 2c(1)                    |

Mechanical properties of S355J2 steel have been specified according to GOST 1497 and GOST 9454 (Table 3).

Table 3. Mechanical properties of S355J2 steel.

| № grade | KV_{20} (J/cm^2) | \sigma_{0.2} (MPa) | \sigma_{B} (MPa) | \delta (%) |
|---------|------------------|-------------------|-----------------|------------|
| 1       | 190-224          | 540-550           | 670-680         | 25.0-30.0  |
| 2       | 162-293          | 400-425           | 509-543         | 29.5-32.0  |
| 3       | 203-258          | 400-440           | 500-540         | 30.0-31.5  |

For Grade 1 steel plate with dimensions 38mm×2240mm×10200mm has been investigated; for Grade 2 steel plate with dimensions 16mm×2000mm×6000mm has been analyzed, and for Grade 3 steel plate with dimensions 16mm×2000mm×6000mm.

3. Discussion
Correlation of non-metallic inclusions content to mechanical properties according standard evaluation (table 2 and table 3) is quite weak. Nevertheless, some papers [9] prove the strong impact of non-metallic inclusions to mechanical properties of constructional steels. Therefore, in the present work the impact of fractal dimension of non-metallic inclusions to mechanical properties of S355J2 steel has been investigated.

Fractal dimension of non-metallic inclusions has been calculated according. The methodology based on convergence of fractal dimensions calculated by cell and point methods. The cell method is based on F. Hausdorff equation (1) [10]:

\[
\text{Fractal Dimension} = \frac{\ln(N)}{\ln(r)}
\]
\[ D = -\lim_{\delta \to 0} \frac{\ln N(l)}{\ln l}, \]  

(1)

where \( N \) is the number of cells with size \( l \), that cover the object. Point dimension has been calculated as ratio (2) [11]:

\[ \tilde{N}(L) = \sum_{m=1}^{K} (1/m)P(m, L) - L^{-D}, \]  

(2)

where \( P(m, L) \) is the probability of \( m \) points of fractal contain inside cell of \( L \) size, and \( \tilde{N}(L) \) is average number of cells that cover the investigated object.

The correlation of mechanical properties and non-metallic inclusions content are shown in Figure 3.

![Figure 3](image)

**Figure 3.** Correlation of mechanical properties of S355J2 steel and fractal dimension \( D \) of non-metallic inclusions at the steel: a – Impact toughness of steel at -20\(^\circ\)C; b – YTS; c – UTS; d – elongation.

Ratio (1) (Figure 3a) analysis shows that impact toughness of steel S355J2 can be predicted by fractal approach \((R^2 = 0.89)\). All other models have relatively low correlation coefficients \( R^2 = 0.14\)-0.34 (3\(\div\)6) to mechanical properties. It can be explained rather low impact of non-metallic inclusions
to strength and elongation in contrast to ferrite-pearlite structure. For example, at [12] high correlation of fractal dimension to mechanical properties of low carbon steel A550 at different heat treatment modes has been shown. The bias of mechanical properties prediction was 7%.

\[
KV^{20} = 185.02D - 97.548, \quad R^2 = 0.89 \quad \text{(figure 3 a)}
\]
\[
\sigma_{0.2} = -261.94D + 916.61, \quad R^2 = 0.34 \quad \text{(figure 3 b)}
\]
\[
\sigma_B = -312.57D + 1114, \quad R^2 = 0.33 \quad \text{(figure 3 c)}
\]
\[
\delta = 6.3291D + 18.612, \quad R^2 = 0.14 \quad \text{(figure 3 d)}
\]

The analysis of equation coefficients (3÷6) gives the range of mechanical properties of steel by means of non-metallic inclusions impact to the properties. It has been revealed that non-metallic inclusions content in steel S355J2 has most effect on impact toughness. It can be explained by decreasing of crack propagation resistance of the metal matrix due to high non-metallic inclusions content in steel. The effect of non-metallic inclusions on impact toughness of steel has been shown in many papers. For example, at [1] has been noticed that uneven movement of vacancies flows, interstitial atoms and matrix atoms near inclusion surface may lead to inclusion shape change. It occurs due to different diffusion rates at surface of inclusion. Surface distortion and internal stresses in inclusion occur unless diffusional flows rates near inclusion will be equalized. Shape change of non-metallic inclusion lead to change of fractal dimension of inclusion.

All other mechanical properties have much lower range rates (coefficient $Y_{\sigma_{0.2}} = 0.47$ etc. (Figure 4)).

As it is shown in Figure 4, the range rate for impact toughness is highest for investigated mechanical properties and equal to 0.72. It may be the evidence of high sensitivity of impact toughness to steel contamination. Therefore, control of non-metallic inclusions in steel is vitally important for high strength rolled plates for freight railway cars production.

4. Conclusions

The possibility of fractal approach for evaluation of steel S355J2 contamination by non-metallic inclusions has been shown. It has been shown that point evaluation of non-metallic inclusions is fault tolerant to change of mechanical properties of steel. It has been proven by point evaluation of non-metallic inclusions content in range 1÷2 point insensitively to mechanical properties. Relevance between mechanical properties of steel S355J2 and fractal dimensions of non-metallic inclusions has been revealed. It helps to predict and ranging properties of steel relative to determining factor. Therefore, investigation the effect of non-metallic inclusions content on impact toughness of constructional steel by means of fractal dimension has advantages compared to point evaluation.
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