https://doi.org/10.46813/2026-161-140

UDC 620.175.2:669.15

ACHIEVING AN OPTIMAL BALANCE OF PROPERTIES IN 40KHMFA STEEL USING A MULTIFRACTAL APPROACH

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The resistance of 40KhMFA steel to sulfide stress cracking (SSC) was investigated for the production of dual-purpose pipes with enhanced strength and corrosion resistance through optimization of heat treatment regimes. The effect of quenching followed by long-term tempering (from 660 to 740 °C in 20 °C increments) for 5, 30, 60, and 90 min on changes in mechanical properties was studied. Structural evaluation after heat treatment was performed using multifractal analysis. Multifractal parameters (D_0, Δ, K, Δf) effectively describe structural transformations in terms of heterogeneity, self-similarity, and ordering of the acicular bainitic-martensitic structure, correlating with properties: a decrease in D_0 increases ductility, while increases in Δ and K contribute to higher strength. With increasing tempering duration, acicular morphology is retained, but carbide coarsening occurs. Regression models with high R^2 values were developed, enabling the prediction of mechanical properties based on multifractal characteristics. The results confirm the superiority of the multifractal approach over traditional quantitative metallographic methods for non-destructive monitoring of structural degradation (corrosion, fatigue) and optimization of heat treatment. The proposed approach will enable the integration of digital systems for predicting the service life of pipes and structural elements in nuclear power engineering. Based on the need to ensure a high level of mechanical properties, the recommended tempering regime for 40KhMFA pipe steel is (700 ± 10) °C with a holding time of 90 min.

INTRODUCTION

The resistance of materials to sulfide stress cracking is a critical issue in the oil and gas industry, where pipeline steels and equipment operate in aggressive environments with high H_2S content. SSC is a form of hydrogen embrittlement caused by the combined action of corrosion, tensile stresses, and the penetration of atomic hydrogen into the metal matrix, which leads to crack formation and premature failure. According to research, low-alloy steels such as 40KhMFA (an analogue of Cr-Mo-V steels) are susceptible to SSC due to their sensitivity to non-metallic inclusions, phase composition, and microstructural heterogeneities [1, 2]. This steel, used for manufacturing dual-purpose pipes with enhanced mechanical and corrosion properties, exhibits high strength (ultimate tensile strength of 800...1000 MPa); however, its resistance to H_2S is strongly dependent on heat treatment, the content of alloying elements (chromium, molybdenum, vanadium), and inclusion control [1–3, 6].

The properties and service life of alloyed steels are largely determined by microstructural features, phase composition, the distribution of alloying elements, and the presence of non-metallic inclusions [1–5]. Non-metallic inclusions such as sulfides and oxides serve as crack initiation sites in H_2S-containing environments, promoting localized corrosion and hydrogen accumulation [1, 2]. Studies show that SSC is activated in acidic environments (pH < 4) at H_2S partial pressures exceeding 0.0034 bar, where atomic hydrogen diffuses into the steel and causes embrittlement [7, 8].

Standardized tests traditionally used to evaluate SSC resistance include NACE TM0177 (Method A for uniaxial tensile testing) and NACE TM0284 (for hydrogen-induced cracking, HIC), which focus on mechanical properties and corrosion resistance [2, 7, 8]. For instance, in low-alloy steels containing more than 1 wt.% Ni, SSC resistance decreases due to the formation of unstable phases [1, 9]. The effect of tempering temperature on the microstructure (e.g., martensite-bainite) and SSC susceptibility has been investigated for Cr-Mo steels; tempering in the range of 700...715 °C was found to optimize the strength–ductility balance and reduce susceptibility to embrittlement [10].

In recent years, digital technologies – such as mathematical modeling, digital twins, and neural networks – have been increasingly employed to predict material behavior under service conditions [6, 9]. Particular attention has been devoted to fractal and multifractal methods for the quantitative assessment of microstructural complexity, corrosion defects, and fracture mechanisms [11–13].

The fractal dimension (D) is widely used to characterize non-uniform corrosion in pipeline steels; for example, in X80 steel, fractal analysis of the morphology of corrosion defects enables the prediction of burst pressure and crack evolution [14–18]. In studies of 316L stainless steel corrosion, fractal analysis has confirmed a clear correlation between fractal dimension and resistance to hypochlorite corrosion [19].

The application of fractals to evaluate the influence of non-metallic inclusions on the mechanical properties of steels such as S355J2 has demonstrated that the fractal dimension correlates strongly with strength and toughness [2]. Similarly, fractal modeling of mechanical properties after ion-plasma chromizing or the deposition of coatings (e.g., TiN) has shown improved wear resistance due to changes in surface structure [20, 21].

The multifractal approach, which extends classical fractal analysis to heterogeneous systems by calculating the singularity spectrum f(α) and generalized dimensions Dq, provides a more detailed evaluation of structural statistical characteristics such as homogeneity, ordering, and regularity [6, 13]. In the context of pipelines, multifractal methods have been successfully applied to the analysis of failure in hybrid composite pipes and to the prediction of mechanical properties [6].

However, the literature still lacks systematic studies employing the multifractal approach specifically for assessing the SSC resistance of steels of the 40KhMFA type, where the bainitic-martensitic microstructure and non-metallic inclusions play a decisive role [20–22]. Traditional methods do not account for the inherently multifractal nature of corrosion processes, which leads to underestimation of the risk of crack initiation [22–24].

The application of multifractal analysis to predict the mechanical properties and sulfide stress cracking resistance of 40KhMFA steel based on microstructural features opens up new prospects for optimizing heat treatment regimes and improving industrial quality control.

MATERIALS AND METHODS OF THE STUDY

The investigated material was 40KhMFA steel with the following chemical composition (wt.%): 0.42 C, 0.59 Mn, 0.26 Si, 0.87 Cr, 0.30 Ni, 0.25 Mo, 0.14 V.

Heat treatment of the specimens consisted of quenching from 860 °C in oil followed by tempering in the temperature range of 660...740 °C (in 20 °C increments) with holding times of 5, 30, 60, and 90 min. The treatments were performed in laboratory electric furnaces; temperature was controlled using a thermocouple embedded in the specimen.

Tensile tests were carried out on standard cylindrical specimens at room temperature. Impact toughness was determined on Charpy specimens measuring 10×7.5×55 mm with a sharp V-notch (or, in selected cases, a U-notch) tested at room temperature. Hardness was measured using Rockwell and Vickers instruments.

The macrostructure was revealed by chemical etching in a saturated aqueous solution of picric acid with the addition of “Sintol” wetting agent. Metallographic sections for microstructure examination were prepared by mechanical grinding and polishing followed by electrolytic polishing in a chromic-acetic electrolyte and final etching in 4% nital. Prior austenite grain size was determined using chemical etching in a saturated picric acid solution with “Sintol” (or “Singol”) additive.

Sulfide stress cracking resistance tests were conducted in accordance with standardized procedures by measuring the time to failure of specimens subjected to a constant uniaxial tensile load of a specified level in a hydrogen-sulfide-saturated environment.

RESULTS AND DISCUSSION

In the production of dual-purpose pipes resistant to sulfide stress cracking, stringent requirements are imposed on mechanical properties, microstructure, and corrosion resistance.

The microstructure of pipe ends made of 40KhMFA steel after quenching and tempering is shown in Fig. 1.

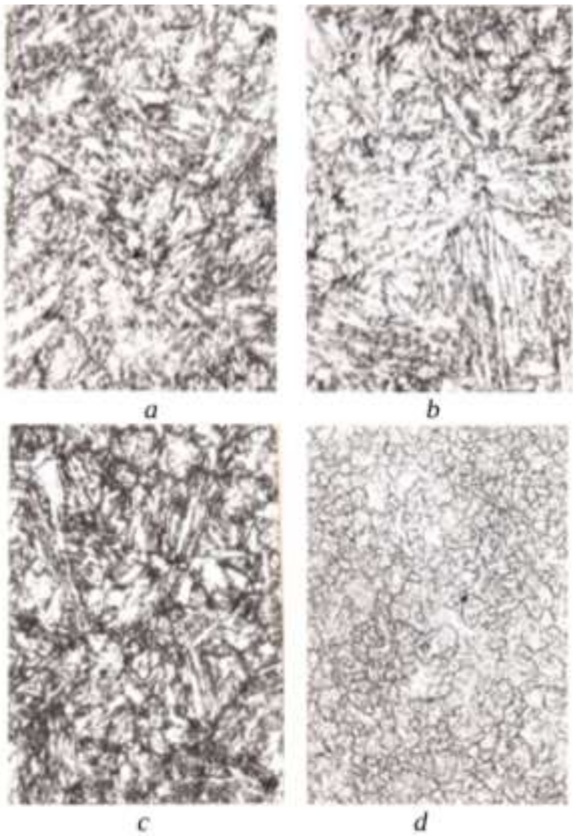

Fig. 1. Microstructure of 40KhMFA steel after heat treatment: a – 630…660 °C; b – 650…670 °C; c – 670…690 °C, ×1250; d – prior austenite grain size, ×400

As the tempering temperature and holding time increase, a systematic decrease in strength characteristics and a corresponding increase in ductility are observed. At higher tempering temperatures, the effect of holding time on the reduction of strength properties becomes less pronounced compared to lower temperatures. In the as-delivered condition, the steel exhibited a tempered acicular bainitic-martensitic structure. With increasing tempering duration, the acicular morphology is retained, whereas noticeable carbide coarsening occurs (Fig. 2).

The results of the mechanical tests are presented in Fig. 3 (the reduction of area after all heat-treatment variants remained in the range of 65...70 % and is therefore not shown in the graphs).

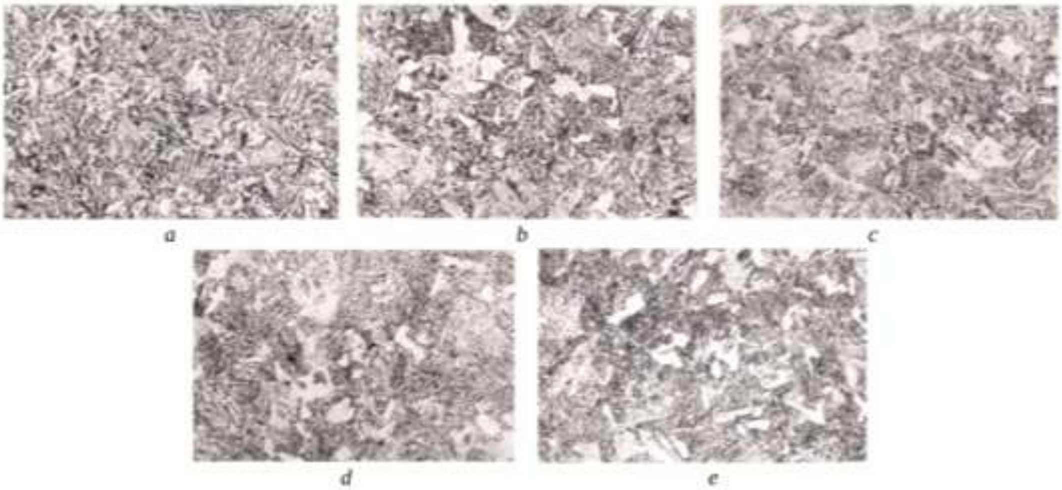

Fig. 2. Microstructure of 40KhMFA steel in the as-delivered condition and after tempering at 700 °C (holding time ×500 magnification): a – as-delivered condition; b – 5 min; c – 30 min; d – 60 min; e – 90 min

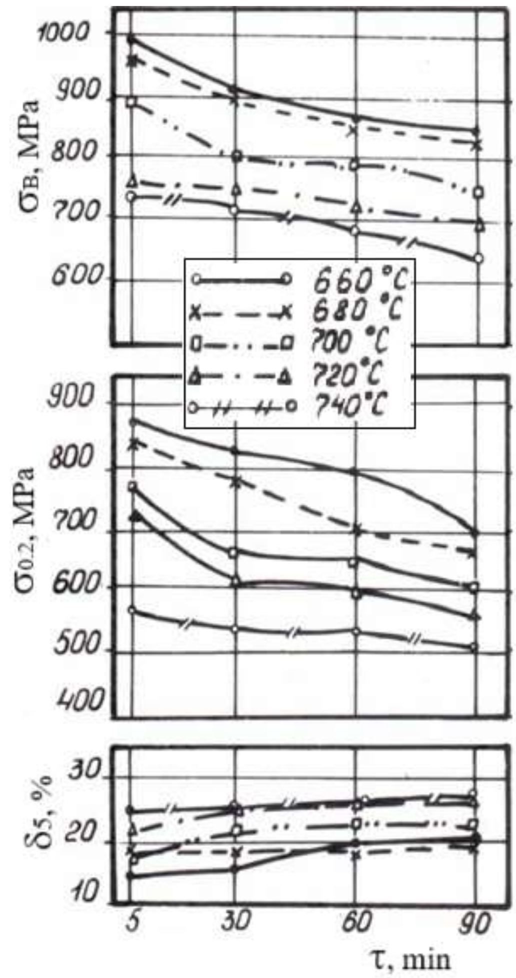

Fig. 3. Effect of tempering temperature and holding time on the mechanical properties of quenched 40KhMFA steel

Analysis of the mechanical properties presented in Fig. 3 reveals the following trends. The graphs illustrate the dependence of mechanical characteristics on tempering temperature and holding time. As the tempering temperature and duration increase, the strength indices (ultimate tensile strength σ_B and yield strength σ_T) systematically decrease, while ductility parameters (elongation δ_5 and reduction of area ψ) increase. This behavior is a classic tempering effect associated with stress relaxation, carbon diffusion, and microstructural transformations, such as martensite decomposition and carbide coarsening.

At higher tempering temperatures (e.g., close to 700 °C), the influence of holding time on strength reduction is less pronounced than at lower temperatures. This is attributed to the accelerated kinetics of diffusion-controlled processes and structural changes at elevated temperatures, resulting in a diminished additional effect from prolonged holding.

The total elongation (δ_5) remains relatively stable within the range of 13...27% across all heat-treatment variants, indicating that the steel retains high ductility regardless of the tempering regime. Although not shown in the graphs, this confirms that 40KhMFA steel maintains favourable plastic properties even after various heat treatments.

The multifractal spectrum was calculated using the Renyi dimension formula (1):

$$D(q) = \frac{1}{q-1} \cdot \lim_{\delta \to \infty} \frac{\ln \sum_{i=1}^{N} p_i^q}{\ln \delta}, \quad (1)$$

where δ – linear size of the square grid cell (box size) that covers the analysed image (corresponds to ε in the classical notation, but in the article the authors use d); p_i – probability that a point (or a portion of the measured "measure" – e.g. pixel intensity, phase area, etc.) of the object falls into the i-th cell; q – moment order (statistical moment exponent), varying continuously in the range from –∞ to +∞.

To evaluate the statistical characteristics of the structural elements, the canonical singularity spectrum f(α) was employed. This spectrum represents the set of Hausdorff dimensions of homogeneous subsets that contribute most significantly to the statistical sum in Eq. (1) for a given value of q.

The f(α) spectrum was derived from the scaling function τ(q) via the Legendre transform:

$$\alpha = d\tau(q)/dq, \quad (2)$$

$$f(\alpha) = q\alpha - \tau(q). \quad (3)$$

Based on the singularity spectrum f(α), the following statistical characteristics were calculated:

– homogeneity, determined from the value of f(α) at q = 200. An increase in this value indicates higher structural homogeneity (in the case of perfect homogeneity, the spectrum degenerates into a single point);

– ordering $\Delta=f(\alpha)|_{q=1} - f(\alpha)|_{q=200}$ and regularity $K=f(\alpha)|_{q=-200} - f(\alpha)|_{q=200}$, which characterise the degree of symmetry violation and the presence of periodic elements. Higher values of Δ and K indicate greater structural ordering and regularity.

Multifractal parameters of bainite and martensite in 40KhMFA steel were calculated using Eqs. (1)–(3); the results are summarised in Table.

Regression equations for predicting the mechanical properties based on multifractal parameters were derived (Eqs. (4)–(6)).

Multifractal characteristics of the microstructure

Metal batch No.	Bainite				Martensite			
	D_0	Δ	K	Δf(α)	D_0	Δ	K	Δf(α)
1	1.81	0.55	1.38	0.05	1.68	0.47	1.35	0.11
2	1.85	0.57	1.44	0.02	1.73	0.49	1.4	0.34
3	1.88	0.73	1.51	0.11	1.72	0.52	1.43	0.39
4	1.91	0.68	1.5	0.17	1.77	0.58	1.45	0.36
5	1.9	0.82	1.56	0.18	1.8	0.55	1.52	0.59
6	1.96	0.79	1.6	0.26	1.83	0.59	1.6	0.68
7	1.97	0.85	1.62	0.29	1.88	0.65	1.7	0.69

Ultimate tensile strength (σ_B) as a function of the multifractal parameters of martensite:

$$\sigma_B = 821.32 - 112.21\ D_0 + 111.26\cdot\Delta + 216.78\ K - 17.24\cdot\Delta f, \qquad R^2=0.95. \qquad (4)$$

Yield strength (σ_T) as a function of the multifractal parameters of bainite:

$$\sigma_T = 695.75 - 469.87\ D_0 - 190.04\cdot\Delta + 573.35\ K + 286.82\cdot\Delta f, \qquad R^2=0.86. \qquad (5)$$

Elongation (δ) as a function of the multifractal parameters of bainite:

$$\delta_5 = 20.99 + 16.35\ D_0 + 28.03\cdot\Delta - 23.15\ K + 5.28\cdot\Delta f, \qquad R^2=0.88. \qquad (6)$$

Analysis of the fractal dimension of bainite shows that D_0 increases from 1.81 to 1.97 (an increase in fractal dimension indicates that the structure becomes geometrically “denser”). The parameters Δ and K also increase (from 0.55 to 0.85 and from 1.38 to 1.62, respectively), reflecting enhanced ordering and regularity with increasing batch number. The parameter Δf(α) rises from 0.02 to 0.29, indicating a progressive increase in multifractality (greater heterogeneity).

For martensite, the fractal dimension D_0 varies from 1.68 to 1.88, Δ from 0.47 to 0.65, K from 1.35 to 1.70, and Δf(α) from 0.11 to 0.69. Martensite exhibits significantly greater scatter in Δf(α), suggesting higher sensitivity of this phase to variations in production conditions or heat-treatment parameters.

Overall, bainite demonstrates higher values of D_0, Δ, and K compared to martensite, which points to a higher degree of structural ordering in the bainitic constituent. As the batch number increases (presumably reflecting differences in heat-treatment regimes or raw-material batches), the microstructure becomes progressively more ordered and multifractal. These structural changes correlate well with the observed evolution of mechanical properties.

The obtained models (see Eqs. (4)–(6)) enable reliable prediction of mechanical properties solely from structural analysis, eliminating the need for direct mechanical testing. This capability is highly valuable for production-process optimization. The high coefficients of determination (R^2), particularly for ultimate tensile strength σ_B ($R^2 = 0.95$), clearly demonstrate the effectiveness of the multifractal approach in modelling both microstructure and resulting properties.

Overall, the results confirm that the optimum tempering regime is dictated by the required balance between strength and ductility: short holds at lower temperatures preserve high strength, whereas longer holds at higher temperatures significantly enhance ductility.

To improve the sulfide stress cracking resistance of 40KhMFA steel intended for dual-purpose pipes with enhanced strength and corrosion performance, the following heat-treatment regime is recommended: quenching from 860 °C in oil followed by tempering at (700 ± 10) °C with a holding time of 90 min.

CONCLUSIONS

The study demonstrates the high effectiveness of the multifractal approach in assessing the SSC resistance of 40KhMFA steel – an essential requirement for its application in the manufacture of dual-purpose pipes possessing enhanced strength and corrosion resistance. Microstructural examination revealed that, in the as-delivered condition, the steel exhibits a tempered acicular bainitic-martensitic structure. As the tempering duration at 700 °C increases, noticeable carbide coarsening occurs, resulting in a systematic decrease in strength characteristics (ultimate tensile strength σ_B and yield strength σ_T) accompanied by a marked increase in ductility (elongation δ_5 and reduction of area ψ within the range of 65...70 %).

The multifractal analysis, based on the Renyi dimension spectrum and Legendre transform, enabled quantitative evaluation of key statistical characteristics of the microstructure, including homogeneity, ordering (Δ), regularity (K), and fractal dimension (D_0). Results obtained for seven metal batches revealed a clear trend of increasing values of these parameters with batch number, with consistently higher values observed for the bainitic phase compared with the martensitic phase. This indicates progressive structural evolution toward greater ordering and multifractality, thereby confirming the high sensitivity of the method to variations in heat-treatment regimes and raw-material quality.

Regression models with high accuracy ($R^2 = 0.86...0.95$) were developed on the basis of the multifractal parameters:

- ultimate tensile strength σ_B is predicted from the martensite parameters;
- yield strength σ_T and total elongation d_5 are predicted from the bainite parameters.

These models enable non-destructive assessment of steel resistance to sulfide stress cracking and significantly improve quality-control efficiency.

To enhance SSC resistance, the following optimum heat-treatment regime is proposed: quenching from 860 °C in oil followed by tempering at (700 ± 10) °C for 90 min. This regime provides an optimal balance between strength and ductility while minimising the risk of corrosion-induced failure in aggressive environments such as oil and gas fields.

Overall, the multifractal approach opens new prospects for precise evaluation and prediction of the behaviour of alloyed steels, thereby contributing to increased material reliability in industrial applications.

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Article received 24.11.2025

ДОСЯГНЕННЯ ОПТИМАЛЬНОГО БАЛАНСУ ВЛАСТИВОСТЕЙ СТАЛІ 40ХМФА МУЛЬТИФРАКТАЛЬНИМ ПІДХОДОМ

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Досліджувалась стійкість до сірководневого розтріскування сталі 40ХМФА для виробництва труб подвійного призначення з підвищеними властивостями міцності та корозії шляхом оптимізації режиму термообробки. Проведено дослідження щодо визначення впливу загартування та тривалого відпуску (від 660 до 740 °С через 20 °С) протягом 5, 30, 60 та 90 хв на зміну механічних властивостей. Оцінка структури після термічної обробки проводилася із застосуванням мультифрактального аналізу. Мультифрактальні параметри (D_0, Δ, K, Δf) ефективно описують структурні трансформації подібно до неоднорідності, самоподібності та упорядкованості голчатої бейнітно-мартенситної структури, корелюючи з властивостями: зниження D_0 підвищує пластичність, тоді як зростання Δ та K сприяє підвищенню міцності. У разі збільшення тривалості відпуску голчастість зберігається, але спостерігається укрупнення карбідів. Розроблено регресійні моделі з високими показниками R^2, що дозволяють прогнозувати механічні властивості на основі мультифрактальних характеристик. Результати підтверджують перевагу мультифрактального підходу над традиційними методами кількісної металографії для неруйнівного моніторингу деградації структури (корозія, втома) та оптимізації термообробки. Запропонований підхід дозволить інтегрувати цифрові системи для прогнозування терміну служби труб, конструкційних елементів у атомній енергетиці. Виходячи з необхідності забезпечити у металі високого рівня механічних властивостей, рекомендований для термообробки трубної сталі 40ХМФА режим відпустки становить (700 ± 10) °С при витримці 90 хв.