SECTION 2

THERMAL AND FAST REACTOR MATERIALS

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FRACTAL MODEL OF ESTIMATING QUALITY OF COLD WORKED FUEL CLADDING TUBES

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A possibility was considered concerning estimation of grain anisomery in the structure of fuel cladding tubes of corrosion-resistant 026Cr16Ni15Mo3Nb steel of austenitic class rolled according to two flow charts: regular and intensive technologies using fractal formalism. Role of grain boundary hardening during cold plastic deformation was analyzed by studying the effect of the fractal dimension of grains D and their boundaries Dg on $\sigma_{0.2}$, σ_w, and δ_5. The best correlation among those that were considered was observed between relative elongation and fractal dimensions of the grain structure ($R^2 = 0.90$). The smallest correlation was observed with the yield stress ($R^2 = 0.64$). It is because of variation of plastic flow processes towards a decrease in the degree of hardening in the material rolled according to the intensive technology. Cold deformation results in refining of the average grain size from 15.50 to 15.42 μm. In this case, extent of the grain boundary length L increased by 17.62% at an iteration step δ commensurate with the average grain size which is indicated by a change in the fractal dimension according to $L \sim \delta^{1-D}$. Degree of the grain structure inhomogeneity was estimated using ratios of self-similarity of regions of fractal dimensions of the structure. The obtained results on the level of mechanical properties of fuel cladding tubes made of austenitic steel indicate advantage of the intensive technology over regular one that was confirmed by results of fractal modeling.

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INTRODUCTION

Quality requirements to nuclear fuel element materials used in nuclear power engineering including structure and mechanical properties are ever toughening in the connection with intricate conditions of their operation [1]. Tubes made of austenitic chromium-nickel steel and chromium-nickel-molybdenum steel, for example, 03Cr18Ni11, 03Cr17Ni14Mo3Nb, occupy a special place among the critical purpose materials. Treatment of various types is used to improve material service characteristics [2] in connection with current requirements.

Cold-worked thin-walled tubes of 026Cr16Ni15Mo3Nb steel of austenitic class are used for the most critical units of power plants [3]. Due to the multi-parameter and multi-criteria nature of the technology used for production of tubes from 026Cr16Ni15Mo3Nb steel, their structure is characterized by chemical and structural heterogeneity. Anisotropy, anisomery, grain number, grain boundaries are structural characteristics that have a significant effect on mechanical properties of austenitic alloy steel. In this case, Geometric configuration of the grain shape is not usually taken into account because of transformation of grains after plastic working which is insufficiently taken in consideration by conventional techniques of quantitative metallography.

According to the present-day concepts, surface of many materials is of fractal nature which [4] is the most common case in nature [5]. It may happen that the neglect of fractal dimension [6] of the metal structure elements can introduce an error in establishing a relationship between structure and properties [7].

In order to take into account influence of "deformity" of grain structure in thin-walled tubes of structurally sensitive 026Cr16Ni15Mo3Nb steel after cold rolling on their mechanical characteristics, it was proposed to apply the Mandelbrot's fractal formalism [8]. Practical implementation of this formalism allows one to regularize conditionally incorrect problems of metal science [9]. The use of fractal (fractional) dimensions in materials science has made it possible to determine average grain size in metals [10], predict mechanical properties of low-carbon steel after heat treatment [11], estimate residual life of aircraft structures [12], develop a fractal accelerator based on a corrugated plasma waveguide [13], etc. Application of the fractal theory confirms a more accurate estimation of quality characteristics of various materials (cast iron rolls of cold rolling mills [14], metals [15], concretes [16]) due to their ranking which contributes to stabilization of the multi-parameter technology of their production.

The abovementioned and many other publications indicate prospects for using fractal modeling to describe structural transformations of materials.

1. MATERIAL AND TECHNIQUE

Chemical composition of the tube steel under study meets requirements of TU 14-1-1641 (Table 1).

Experimental samples of 5.8×0.3 mm tubes of 026Cr16Ni15Mo3Nb steel manufactured both by the regular (current) technology and intensive technology (with intensive plastic deformation in the working passes) must meet requirements of Technical Condition. In this connection, all tubes were tested for compliance with this technical specification in industrial production conditions.

Table 1

Chemical composition of 026Cr16Ni15Mo3Nb steel

Element content, wt.%						
C	Si	Mn	Cr	Ni	Mo	Nb
0.017	0.06	0.82	16.48	15.59	2.57	0.45
S	P	N	V	Co	Cu	–
0.01	0.01	0.012	0.094	0.005	0.06	–

A standard flowchart for the production of cladding tubes requires application of a significant number of cyclic operations at main units and a large number of auxiliary operations. In the manufacture of tubes, the existing schedule includes 8 cycles and 220–230 operations. To reduce the production cycle, improve the set of mechanical properties and reduce structural heterogeneity, an intensive technology of tube processing has been implemented [3]. In this case, the diagram of stressed state in the deformation zone was altered. The intensive technology consists in the use of two-row deformation schemes at KhPT cold tube rolling mills using two pairs of rolls arranged in series (four-high stands) and KhPTR cold tube rolling (roller) mills with a two-row separator. Simultaneous reduction of billets in two pairs of rolls (rollers) determines a specific cyclic force interaction of two deformation zones, which significantly changes plastic flow of the rolled material towards a decrease in the degree of hardening, makes it possible to more fully use the metal plasticity resource and practically halve cycle city of the tube production process [3].

Microstructure and mechanical properties of the cladding tubes produced by both technologies have been studied (Fig. 1).

Mechanical properties of tubes rolled according to two flow charts are given in Table 2. Microstructure of finished tubes is shown in Fig. 1.

Table 2

Mechanical properties of fuel rod cladding tubes

Deformation variant	Tube dimensions (diameter × wall), mm	Temperature, +20 °C		
		$\sigma_{0.2}$, N/mm^2	$\sigma_в$, N/mm^2	δ_5, %
intensive	5.8×0.3	320…365	610…620	46…48
regular	5.8×0.3	335…345	600…610	43…45
TU 14-3-550	not less			
	–	–	520	37

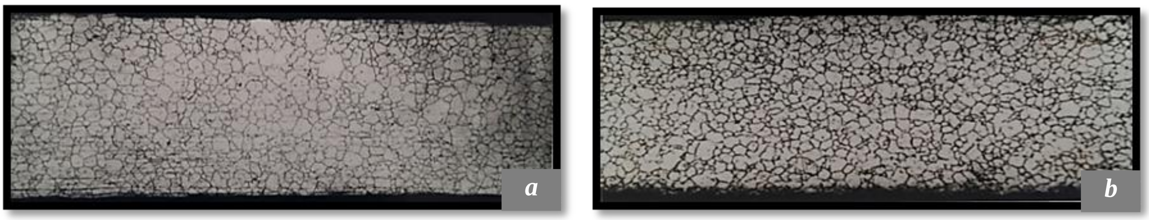


Fig. 1. Microstructure of finished (5.8×0.3 mm) tubes: regular technology (a); intensive technology (b) ×100

Austenitic grain size was measured using an RPA installation and metallographic examination of thin sections was made using a Neophot-21 microscope. Average grain size corresponded to size numbers 9–10 in tubes rolled using regular technology and size numbers 10–11 in tubes rolled using intensive technology according to GOST 5639 [17].

2. THE TECHNIQUE OF FRACTAL ANALYSIS

To determine fractal dimension of austenitic structure in the tubes obtained by the two rolling variants described above, a patented technique was used [18] according to the following scheme (Fig. 2).

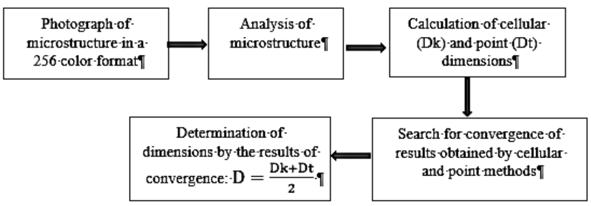


Fig. 2. General scheme of determining fractal dimensions

The developed technique was computer implemented. It is based on determining the convergence of values of the Hausdorff cellular dimension (1) [19] and point (2) [20] dimension:

$$D = -\lim_{\delta \to 0} \frac{\ln N(\delta)}{\ln \delta}, \tag{1}$$

where N (δ) is the number of cells of δ size by which the investigated fractal element is covered.

The point dimension was determined as follows:

$$\tilde{N}(\delta) = \sum_{m=1}^{K} (1/m) P(m, L), \tag{2}$$

where $\tilde{N}(\delta)$ is the average value of the number of cells of δ size that contain m points of the fractal (pixels for a computer).

The results of calculating the fractal dimension of the grain structure (see Fig. 1, a) are shown in Fig. 3.

Dependence 1 in Fig. 3 describes the fractal dimension of boundaries of austenite grains calculated by the cellular method and dependence 2 describes their point dimension. Dependences 3 and 4 are cellular and point dimensions of austenite grains, respectively.

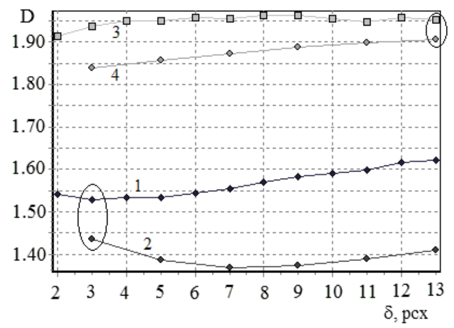


Fig. 3. Dependence of the fractal dimension on the cell size δ (in pixels)

It follows from Fig. 3 that the best convergence of values of fractal dimensions is observed at the 3rd step of iteration for grain boundaries:

$D_g = (D_k + D_t) = (1.528+1.434) = 1.481$

and at the 13th step of calculations for grains:

$D = (1.951+1.907) = 1.929$.

3. RESULTS AND DISCUSSION

When controlling structure in tubes, a great importance is attached to the grain size which is determined by a strictly regulated complex of properties, especially mechanical properties, which are largely ensured by the grain structure of metal.

This is because of the fact that many of the properties are structurally sensitive, for example, $\sigma_в$, $\sigma_{0,2}$, δ_5, long-term strength, electrical resistance, tendency to intergranular corrosion, etc. The processes of precipitation of carbides occurring at operating temperatures of the reactor are also associated with grain size and the extent of the grain boundary. In their turn, these processes significantly affect nature of creep and high-temperature strength.

The study of efficiency of the fractal model of grain structure in estimating mechanical properties ($\sigma_{0,2}$, $\sigma_в$, and δ_5) of 5.8×0.3 mm cladding tubes was carried out by comparison of its fractal dimensions with the results of conventional Euclidean (diameter, area) and statistical (number of grains, dispersion, coefficient of variation) characteristics of the structure.

Quantitative estimation of microstructure of the cladding tubes rolled according to the regular and intensive technologies was carried out by conventional methods using an Epiquant structure analyzer with subsequent computer processing. The study results are shown in Table 3.

According to the procedure of quantitative analysis of structure (GOST 5639), in the case of determining the grain size in an anisomerous structure, average dimensions (diameter, area of the grain) are not characteristics of its estimation. For example, it was found that the maximum grain size decreased with intensive processing technology by only 10% (from 50 to 45 μm) compared to the regular technology. In this case, average austenite grain size during transition from the regular technology to the intensive one decreased only by (15.50–15.42) μm = 0.08 μm or 0.52% which is practically leveled by the values of root-mean-square deviation of its sizes 8.63 and 8.10 μm within the experiment. The decrease in scatter of the grain size values is evidenced by the coefficients of their variation: 0.56 for the regular and 0.53 for intensive technologies, respectively (see Table 3).

According to the ASTME system, average grain size in 112 5.8×0.3 mm tubes produced by intensive technology changed by ½ number (from 9 to 8.5). According to GOST 5639, grain size in the metal of tubes rolled using intensive technology also decreased to 8–9 numbers in comparison with numbers 8–10 in the metal of tubes rolled using regular technology. This is probably due to a more uniform development of recrystallization processes in metal with an increase in the degree of plastic deformation in passes.

In the region of large deformations, density of dislocations and excess of dislocations of the same sign are so high that a large number of primary recrystallization centers are rapidly formed which involves the entire volume of metal during annealing,

Large degrees of deformation is one of conditions for obtaining a more uniform grain structure upon subsequent annealing. A graph of grains size distribution in cladding tubes rolled according to two technological schemes is given in Fig. 4.

The data presented indicate less blur of the curve (1) in the case of rolling tubes by the intensive technology which also indicates a decrease in the austenite anisomery.

Within the experiment, number of grains changed by only 0.50% in 1 mm^2 and it also changed insignificantly (by 0.75%) in a unit of volume (1 mm^3).

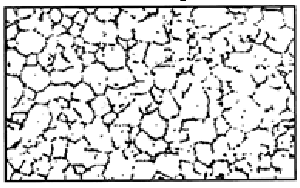
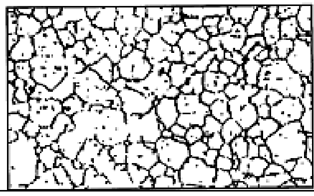
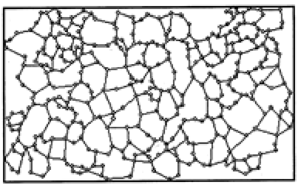
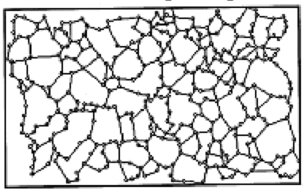
The obtained geometric and statistical estimates of anisomerous austenitic structure within the experiment indicate their insufficient sensitivity to changes in mechanical properties of the cladding tubes in the studied parameter range.

In this regard, in order to search for more effective estimates of anisomerous structure of cladding tubes, it was proposed to apply the fractal theory. Effect of fractal dimension of austenite grains and their boundaries on mechanical properties, i.e. their role in hardening of grain boundary, was estimated in this work. This choice of characteristics was determined by the fact that the effect of grains and their boundaries on plasticity, toughness, and crack resistance of metal is very significant [1, 2]. In addition, grain boundaries not only prevent crack initiation but also inhibit their development giving rise to an additional energy dissipation [21].

Figs. 5 and 6 show graphs describing relationship between fractal dimensions of austenite grains and their boundaries and mechanical properties of the cladding tubes made of 026Cr16Ni15Mo3Nb steel. An increase in the fractal dimension of grains is associated with a decrease in grain size, i.e. with an increase in compactness of filling the considered two-dimensional space of the thin section. Tubes with higher strength characteristics rolled using the regular technology correspond to a grain size number 9, and those with lower strength characteristics correspond to a grain size number 10.

Table 3

Computer processing of the structure in 5.8×0.3 mm tubes

Regular rolling technology		Intensive roling technology	
Structure of initial plane section 		Structure of initial plane section 	
Structure after computer processing 		Structure after computer processing 	
Number of grains, pcs	110	Number of grains, pcs	111
Maximum grain size, μm	50.00	Maximum grain size, μm	45.00
Average diameter of flat section, μm	15.50	Average diameter of flat section, μm	15.42
Dispersion, μm	8.63	Dispersion, μm	8.10
Coefficient of variation	0.56	Coefficient of variation	0.53
Total area of grains, mm^2	0.02895693	Total area of grains, mm^2	0.02907737
Number of grains in 1 mm^2, pcs	3798	Number of grains in 1 mm^2, pcs	3817
Number of grains in 1 mm^3, pcs	234062	Number of grains in 1 mm^3, pcs	235821
Average grain size number (GOST 5639)	10	Average grain size number (GOST 5639)	9
Average grain size number (ASTME 112)	9	Average grain size number (ASTME 112)	8.5

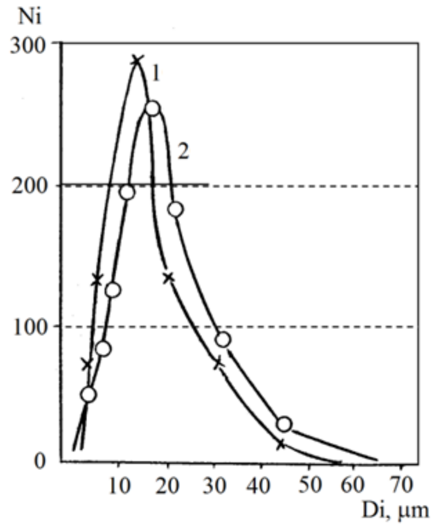


Fig. 4. Grain size distribution in 5.8×0.3 mm tubes rolled by intensive (1) and regular (2) technologies

For tubes rolled using the intensive technology, higher properties were recorded in those sections that corresponded to a lower grain size number 8 compared to the size numbers 9 and 10. A decrease in the grain size leads to an increase in their length L per unit area, which is fixed using their fractal dimension and confirmed by the following relation [8]:

$$L = L_0/\delta^{D-} , \qquad (3)$$

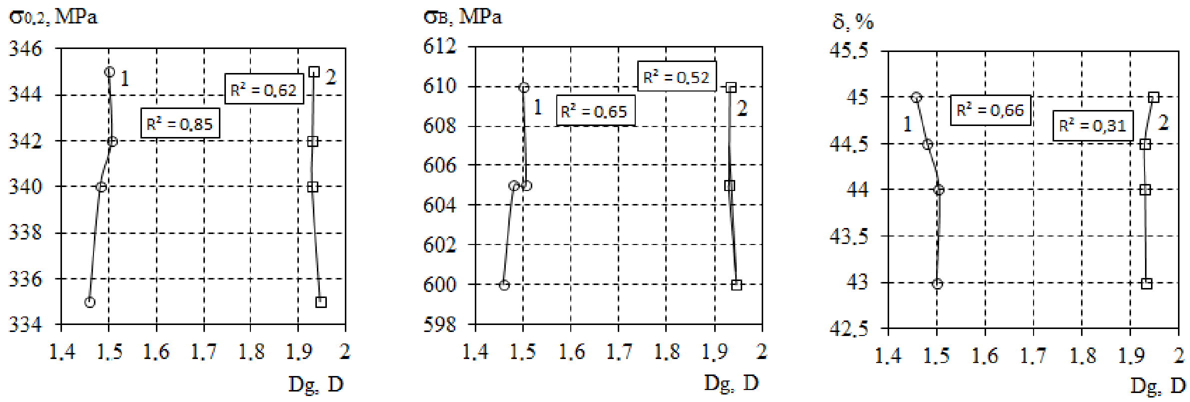
where L is the extent of the grain length calculated by conventional method using a palette with a step δ. At $\delta \to 0$, fractal dimension D of the curve L_0 becomes equal to one. As the grain size decreased from number 10 to number 8, fractal dimension of their length increased from 1.458 to 1.633. In this case, length of the grains estimated by formula (3) increased. For metal of tubes rolled according to the regular technology, length of the grain boundaries was 74.034 mm/mm^2, and for the tubes rolled according to the intensive technology, length of the grain boundaries was 89.868 mm/mm^2 and the difference in their length was 17.62%. An increase in length of the grain boundaries per unit area was due to the specific cyclic force interaction of two deformation zones which leads to a smaller decrease in the degree of hardening by changing the processes of plastic flow of the material being rolled. From this point of view, fractal dimension of the grain boundaries can be an indicator of a change in the length L of grain boundaries due to the influence of plastic deformation.

As a result of analysis of the relations given in Figs. 5 and 6, fractal models for predicting mechanical properties of tubes (4–6) at +20 ^{0}C were obtained.

$$\sigma_{0.2} = -2420.91+859.36 \cdot D+739.61 \cdot Dg, \quad R^2=0.64; \quad (4)$$

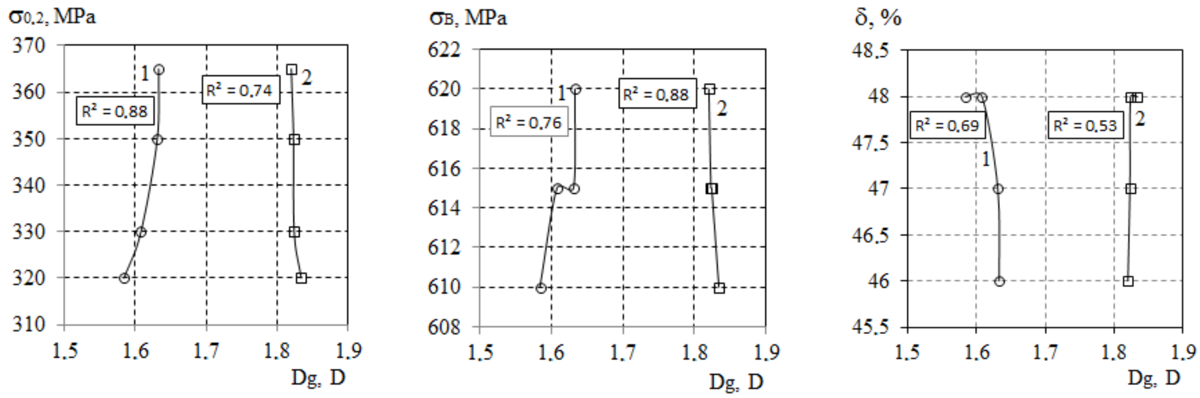
$$\sigma_B = 150.00+105.31 \cdot D+169.06 \cdot Dg, \quad R^2=0.84; \quad (5)$$

$$\delta = 314.49-95.73 \cdot D-57.33 \cdot Dg, \quad R^2=0.90. \quad (6)$$



a *b* *c*

Fig. 5. Relationships between fractal dimension of grain boundaries Dg (1), grains D (2) and yield point (a); ultimate strength (b); relative elongation (c) of cladding tubes rolled according to the regular technology



a *b* *c*

Fig. 6. Relationships between fractal dimension of the grain boundaries Dg (1), grains D (2) and yield point (a); ultimate strength (b); relative elongation (c) of cladding tubes rolled using intensive technology

Based on analysis of the coefficients of fractal models (4–6), it was found that contribution to the grain boundary hardening of austenite grains for strength characteristics of the cladding tubes made of 026Cr16Ni15Mo3Nb steel after cold rolling was 38...54% and it was 46...62% for their boundaries (Fig. 7). Contribution of the grain size was 63% for the plasticity characteristics (δ), and, respectively, contribution of their boundaries was equal to 0.37%. This was largely due to alteration of the plastic flow processes in the rolled material towards a decrease in the degree of hardening when using the intensive technology [3].

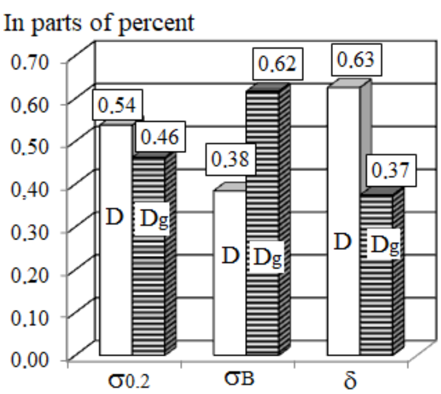


Fig. 7. Estimation of contribution of austenite grains and their boundaries to grain boundary hardening using the fractal theory

Heterogeneity of anisomerous microstructure was estimated in this study using fractal formalism (Fig. 8). The coefficient of self-similarity of the microstructure was determined from the ratio of fractal dimensions of the regions of austenite grains and their boundaries.

It follows from the graph shown in Fig. 8 that the region of self-similarity of grain boundaries Dg (2) is the most sensitive to a change in anisomery of grains in the tube metal (2). It ranged from 0.972 to 1.031 indicating the prospects for its application to estimation of structural heterogeneity in comparison with the self-similarity of grains.

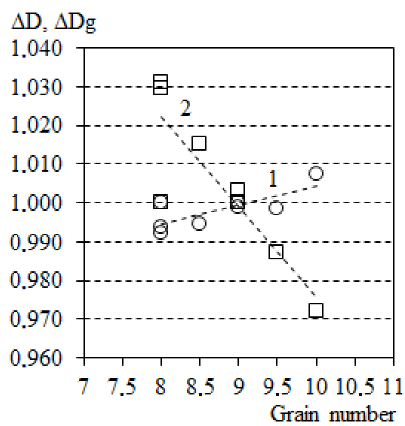


Fig. 8. Relationship between the grain size according to ASTME 112 and ratios of their fractal dimensions

Comparative analysis of the effect of cold plastic working of fuel cladding tubes on their mechanical properties using conventional and fractal structure estimates indicates the prospects for using the fractal approach. It follows therefrom that the fractal dimension can be used as an indicator of structural transformations of anisomerous structure the tube metal and mechanical properties of the tubes.

CONCLUSIONS

Application of the fractal theory in modeling the anisomerous structure and properties of the fuel cladding tubes made of austenitic 026Cr16Ni15Mo3Nb steel is useful in the following.

1. Assessment of the degree of influence of cold deformation on microstructure by assessing its contribution to grain-boundary hardening based on dynamics of changes in the fractal dimension of the grain structure.

2. Assessment of inhomogeneity of the grain structure by comparing the regions of its self-similarity.

3. Forecast of strength and plastic properties ($\sigma_{0.2}$, $\sigma_в$, and δ_5) according to fractal dimensions of the grain structure ($R^2 = 0.64...0.90$).

4. Application of the fractal approach as an alternative in quality control of the cladding tubes when sensitivity of conventional estimates of anisomerous structure is insufficient to establish a correlation with mechanical characteristics.

The obtained results in terms of level of mechanical properties show advantage of the intensive technology and the prospects of its application in connection with the problems of operability of fuel element cladding in reactors iwhere the cladding loses its plastic and strength properties by the campaign end.

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ФРАКТАЛЬНАЯ МОДЕЛЬ ОЦЕНКИ КАЧЕСТВА ХОЛОДНОДЕФОРМИРОВАННЫХ ТРУБ-ОБОЛОЧЕК ТВЭЛ

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Рассмотрена возможность оценки разнозернистости структуры труб-оболочек твэл из коррозионно-стойкой стали аустенитного класса 026Х16Н15М3Б, прокатанных по двум технологическим схемам – действующей и интенсивной, с применением фрактального формализма. Проанализирована роль зернограничного упрочнения при холодной пластической деформации на примере исследования влияния фрактальной размерности зерен D и их границ Dg на $\sigma_{0,2}$, $\sigma_в$ и δ_5. Установлено, что наилучшая корреляция среди рассматриваемых характеристик наблюдается между относительным удлинением и фрактальными размерностями зеренной структуры ($R^2 = 0,90$), а наименьшая – с пределом текучести $R^2 = 0,64$, что обусловлено изменением процессов пластического течения прокатываемого материала по интенсивной технологии в сторону снижения степени упрочнения. Холодная деформация приводит к измельчению среднего размера зерен с 15,50 до 15,42 мкм. При этом увеличивается протяженность длины границ зерен L на 17,62% при шаге итерации δ, соизмеримым со средним размером зерна, что фиксируется изменением фрактальной размерности согласно $L \sim \delta^{1-D}$. С помощью соотношений областей самоподобия фрактальных размерностей зеренной структуры оценена степень ее неоднородности. Полученные результаты по уровню механических свойств оболочек твэл из аустенитной стали указывают на преимущество интенсивной технологии перед штатной, что подтверждается результатами фрактального моделирования.

ФРАКТАЛЬНА МОДЕЛЬ ОЦІНКИ ЯКОСТІ ХОЛОДНОДЕФОРМОВАНИХ ТРУБ-ОБОЛОНОК ТВЕЛ

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Розглянуто можливість оцінки різнозернистості структури труб-оболонок твел з корозійно-стійкої сталі аустенітного класу 026Х16Н15М3Б, прокатаних за двома технологічними схемами, яка діє зараз та за інтенсивною технологією, із застосуванням фрактального формалізму. Проаналізовано роль зернограничного зміцнення при холодній пластичній деформації на прикладі дослідження впливу фрактальної розмірності зерен D і їх границь Dg на $\sigma_{0,2}$, $\sigma_в$ і δ_5. Встановлено, що найкраща кореляція серед розглянутих спостерігається між відносним подовженням і фрактальними розмірностями зеренної структури ($R^2 = 0,90$), а найменша – з межею плинності $R^2 = 0,64$, що обумовлено зміною процесів пластичної течії матеріалу, що прокатаний за інтенсивною технологією, в сторону зниження ступеня зміцнення. Холодна деформація призводить до подрібнення середнього розміру зерен з 15,50 до 15,42 мкм. При цьому збільшується протяжність довжини границь зерен L на 17,62 % при кроці ітерації δ порівнянним із середнім розміром зерна, що фіксується зміною фрактальної розмірності згідно з $L \sim \delta^{1-D}$. За допомогою співвідношень областей самоподібності фрактальних розмірностей зерен структури оцінено ступінь її неоднорідності. Отримані результати за рівнем механічних властивостей оболонок твел з аустенітної сталі вказують на перевагу інтенсивної технології перед штатною, що підтверджується результатами фрактального моделювання.