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Increasing the fatigue strength of high-strength steel grades

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Abstract. The paper considers the issue of increasing the fatigue strength of high-strength steel grades. Based on the results of experimental measurements of the fatigue strength limit (σ_{-1}) of spring steel grades, we analyzed the effect of tensile strength, ratio of the yield strength during shear and the fatigue strength limit. The absence of statistical relationship between fatigue strength limit and tensile strength ($\sigma_{-1} \neq f(\sigma_u)$) was established. The ratio τ_t/σ_{-1} is the stress concentration coefficient (SCC), which is closely related to the tensile strength of steel. From the theoretical analysis, it follows that in the presence of the same morphological type and size of non-metallic inclusions (NMI) in steel, relationship of SCC with the strength properties of steel is functional. Spread of its actual values is associated with the presence of various morphological types and sizes of NMI in the metal. Each morphological type of NMI is characterized by corresponding physical and mechanical properties (modulus of elasticity, tensile strength and various SCC). SCC increases both with an increase in the strength of steel and with an increase in diameter (thickness) of NMI. It was established that the intensity (rate) of the increase in SCC depends on the size and elastic modulus E_{MNI} of NMI (ratio of mass fractions of SiO_2 and Al_2O_3 oxides in NMI). The average intensity of the change in SCC obtained by processing experimental data corresponds to similar indicators for NMI: 13 % SiO_2; 87 % Al_2O_3 (4.0 µm thick); 20 % SiO_2, 80 % Al_2O_3 (5.0 µm thick); 25 % SiO_2; 75 % Al_2O_3 (7.0 µm thick). According to the obtained connections, dimensions of NMI and their morphology are approximately indicated, which make it possible to increase the fatigue properties of spring steels grades in the tensile strength range from 1200 to 2000 MPa. To increase the fatigue life of steel (especially in high-strength condition), it is recommended to use the technology of aluminum-free metal deoxidation during smelting. At the same time, a favorable morphology of NMI with SCC less than 1.0 is provided. Formation of a fine-grained structure of steel after heat treatment is obtained in the absence of aluminum during deoxidation with small additives of vanadium, niobium or titanium.

Keywords: strength properties of steel, yield strength, stress concentration coefficient, non-metallic inclusions, fatigue strength

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Увеличение усталостной прочности сталей высокопрочных марок

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Аннотация. Рассматривается вопрос увеличения усталостной прочности сталей высокопрочных марок. По результатам экспериментальных измерений предела усталостной прочности (σ_{-1}) стали пружинных марок проведен анализ влияния временного сопротивления, отношения предела текучести при сдвиге и предела усталостной прочности. Установлено отсутствие статистической связи предела усталостной прочности и временного сопротивления ($\sigma_{-1} \neq f(\sigma_в)$). Отношение τ_t/σ_{-1} есть коэффициент концентрации напряжений (ККН), который находится в тесной связи с временным сопротивлением стали. Из проведенного теоретического анализа следует, что при наличии в стали неметаллических включений (НВ) одного морфологического типа и одинаковых размеров связь ККН с прочностными свойствами стали функциональна. Разброс фактических его значений связан с наличием в металле НВ различных морфологических типов и размеров. Каждый морфологический тип НВ характеризуется соответственными физико-механическими свойствами (модулем упругости, пределом прочности и различным ККН). Коэффициент концентрации напряжений возрастает как с ростом прочности стали, так и с увеличением диаметра (толщины) НВ. Установлено, что интенсивность (скорость) повышения ККН зависит от размера НВ и от модуля упругости $E_{НВ}$ (соотношение массовых долей оксидов SiO_2 и Al_2O_3 в НВ). Средняя интенсивность изменения ККН, полученная путем обработки экспериментальных данных, соответствует аналогичным показателям для НВ: 13 % SiO_2; 87 % Al_2O_3 (толщиной 4,0 мкм); 20 % SiO_2, 80 % Al_2O_3 (толщиной 5,0 мкм); 25 % SiO_2; 75 % Al_2O_3 (толщиной 7,0 мкм). По полученным связям примерно указаны размеры НВ и их морфология, позволяющие повышать усталостные свойства сталей пружинных марок в диапазоне временного сопротивления от 1200 до 2000 МПа. Для повышения ресурса усталостной прочности стали (особенно в высокопрочном состоянии) рекомендовано использовать технологию безалюминиевого раскисления металла при выплавке. При этом обеспечивается благоприятная морфология НВ с ККН не более 1,0. Формирование мелкозернистой структуры стали после термической обработки получают при отсутствии алюминия при раскислении, небольшими добавками ванадия, ниобия или титана.

Ключевые слова: прочностные свойства стали, предел текучести, коэффициент концентрации напряжений, неметаллические включения, предел усталостной прочности

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Introduction

The fatigue strength stands as a critical parameter for metals and alloys, profoundly influencing their potential applications as structural materials across diverse industrial sectors [1; 2]. Among the spectrum of structural metal alloys, steels persist as the most prevalent choice for fabricating a wide range of metal products and structures, especially those subjected to heavy-duty operations. In instances such as rail and spring steels enduring dynamic and fluctuating loads [3; 4], the fatigue strength assumes paramount importance, directly dictating the operational lifespan of metal products [5; 6]. It's noteworthy that fatigue strength isn't solely contingent upon the chemical and phase compositions of steel or its structural configuration [7; 8], but also on factors such as dimensions, non-metallic inclusion morphology, and operational conditions of the metal products [9; 10]. Notably, strain hardening emerges as a viable method to influence fatigue strength positively [11 – 13]. Consequently, enhancing steel's fatigue strength remains a pressing research imperative in contemporary materials science endeavors [14].

Materials and methods

The known relationship $\sigma_{-1} = 0.5\sigma_u$ (where σ_{-1} is fatigue strength and σ_u is tensile strength) is valid for steel with the tensile strength not exceeding 900 MPa [15; 16]. However, as the strength surpasses this threshold, the actual values of fatigue strength significantly deviate from the calculated ones [17; 18] (Fig. 1). This study focuses on exploring the correlation between fatigue strength and tensile strength in spring steel using regression analysis methods. The specific values of tensile strength (σ_u) and fatigue strength limit (σ_{-1}) used in this study are extracted from [19 – 23] (refer to the Table).

The statistical regression model $\sigma_{-1} = 0.028\sigma_u + 566.4$ is inadequate. Fisher's criterion, at 0.206, falls below the significance value (0.657), indicating a low statistical significance. Additionally, the correlation coefficient stands at a meager 0.120.

The results of regression analysis reveal a lack of a meaningful relationship between the function and the parameter. Notably, there's a noteworthy trend: as the tensile strength of steel escalates, the disparity between actual and calculated results widens.

Consequently, it can be inferred that the factor affecting the reduction of fatigue strength, contingent upon the tensile strength of the metallic matrix (MM), is subject to alteration. Steel products are typically designed considering the fatigue strength of steel. Under these circumstances, it becomes challenging to fully utilize the available strength potential (indicated by high σ_t and σ_u levels), thereby limiting the potential to reduce the material intensity of metal structures.

The papers [18; 24] demonstrate that in the non-metallic inclusion – metallic matrix (NMI – MM) system subjected to external impacts, shear stress occurs at their interface within the MM, while NMIs, acting as stress concentrators, have the potential to amplify the effects of these impacts.

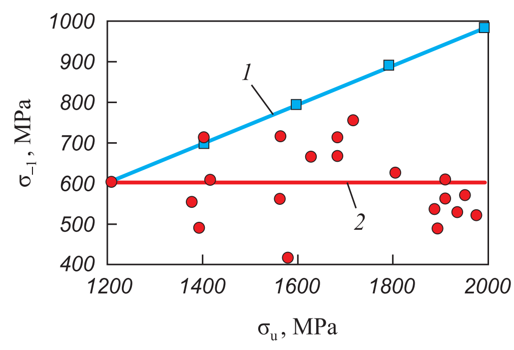

Fig. 1. Dependence of fatigue strength limit on tensile strength of spring steel:
1 – $\sigma_{-1} = 0.5\sigma_u$ (■, theory); *2* – $\sigma_{-1} = 0.028\sigma_u + 566.4$ (●, fact)

Рис. 1. Зависимость предела усталостной прочности от временного сопротивления пружинной стали:
1 – $\sigma_{-1} = 0{,}5\sigma_u$ (■, теория); *2* – $\sigma_{-1} = 0{,}028\sigma_u + 566{,}4$ (●, факт)

Mechanical properties of spring steel grades

Механические свойства сталей пружинных марок

Steel grade	Heat treatment	Source	σ_t, MPa	σ_u, MPa	σ_{-1}, MPa	E^*, hPa
60G	quenching 800 °C, tempering 380 °C	[20]	1180	1370	529	204
65G	n/a	[20] [22] [22]	1220 1280 1440	1470 1420 1690	578 647 725	215
55S2	quenching 880 °C, tempering 400 – 460 °C	[19]	1050 1300 1690	1200 1400 1710	598 720 769	196
60S2	quenching 860 °C, oil, tempering 400 – 550 °C n/a	[19]	n/a 1370	1380 1580	490 421	212
60S2A	isothermal quenching, 330 °C, 1 h, tempering 300 °C quenching, oil, tempering 420 °C quenching, oil, tempering 400 °C	[21]	n/a	1680 1810 1900	686 637 500	212
50KhFA	quenching 850 °C, oil, tempering 175 °C quenching 860 °C, oil, tempering 500 °C	[20] [21]	1590 1430	1630 1570	666 725	218
60S2KhA	quenching, oil, tempering 400 °C Isothermal quenching, soaking 290 °C isothermal quenching, soaking 290 °C, tempering 325 °C	[21]	1830 1720 1430	1980 1950 1920	540 568 578	196
60S2KhFA	quenching, oil, tempering 415 °C isothermal quenching, soaking 290 °C isothermal quenching, soaking 290 °C, tempering 325 °C	[21]	1810 1780 n/a	1900 1960 1920	549 588 613	191

N o t e s . * – data from the paper [23].

Once the stress level attains or surpasses the yield strength under shear (τ), the local regions of the NMI – MM interface activate the Frank-Read sources [16 – 18]. This activation induces local plastic deformation within the metal. With the escalation of dislocation density in these zones, initial cracks begin to propagate, eventually reaching a critical size, thereby instigating material fracture.

The magnitude of resultant shear stresses is assessed using the following equation [18; 24]:

$$\tau = \sigma_u \frac{E_{NMI}}{E_{MM}} \frac{d}{l_s}, \tag{1}$$

where τ is shear stress; σ_n is external tensile stress; E_{NMI} and E_{MM} are modulus of elasticity of the NMI and the MM, respectively; d is diameter (thickness) of the NMI; l_s is the sum of maximum lengths of the zone of shear stresses in the MM at the boundary with NMI.

Consequently, the factor $\frac{E_{NMI}}{E_{MM}} \frac{d}{l_s}$ represents the stress concentration coefficient (SCC). The equations governing the fatigue strength limit are expressed as follows: $\sigma_{-1} = \frac{\tau_t}{SCC}$ or $SCC = \frac{\tau_t}{\sigma_{-1}}$.

In instances where compressive stresses affect the NMI – MM system, shear stresses arise at their interface. However, their magnitude is significantly lower compared to tension scenarios [18]. Henceforth, only tensile forces are further considered.

A close statistical association is evident between the yield strength and tensile strength in spring grade steels (Fig. 2). The relationship is mathematically expressed as $\sigma_T = 1.08\sigma_u - 312$, presenting the regression model's statistical parameters as follows: a standard error of 104.5 MPa; a correlation coefficient of 0.94; Fisher's criterion standing at 100.86, with a significance level of $9 \cdot 10^{-8}$. The dependences of the strength limit, yield strength under shear, and tensile strength of the steel are derived from the equation $\tau = 0.7 - 0.75\sigma_T$.

When τ is divided by σ_T using the corresponding values of σ_u, a statistical model of the Stress Concentration Coefficient (SCC) dependency on steel strength is obtained (Fig. 3).

The model appears as follows

$$SCC = 0.00167\sigma_u - 1.04 \tag{2}$$

with statistical parameters indicating a Pearson coefficient is 0.70; a standard error of 0.31; and Fisher's criterion measuring 15.98, showing a significance level of 0.00093.

Consequently, the SCC exhibits a fairly strong statistical association with the tensile strength of steel. It suggests that as the strength properties increase, so does SCC.

For specific thicknesses of NMIs (d) and their particular morphology, the equation is formulated as follows [18]

$$SCC = \frac{E_{NMI}}{E_{MM}} \frac{d}{l_s} = 2 \frac{E_{NMI}}{E_{MM}} \frac{\tau_u^{MM}}{\sigma_u^{NMI}}, \tag{3}$$

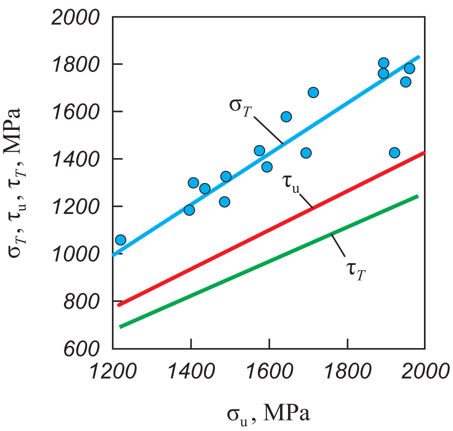

Fig. 2. Dependences $\sigma_T = f(\sigma_u)$; $\tau_u = f\sigma_u$; $\tau_T = f\sigma_u$ for spring steel grades

Рис. 2. Зависимости $\sigma_T = f(\sigma_u)$; $\tau_u = f\sigma_u$; $\tau_T = f\sigma_u$ для сталей пружинных марок

where τ_u^{MM} represents the MM strength limit during shear and σ_u^{NMI} denotes the tensile strength of the NMI.

RESULTS AND DISCUSSION

The theoretical analysis suggests that when identical NMIs of the same morphological type and the same size coexist within the steel, the relationship between SCC and the steel's strength properties becomes functional. However, the observed variability in the actual SCC values (Fig. 3) is linked to the presence of diverse morphological types and sizes of NMIs within the metal. The morphology of internally formed NMIs during the steel's deoxidation process is contingent upon the ratio of oxygen to aluminum dissolved within it [25 – 27]. These endogenous NMIs exhibit varying physical properties, which are notably influenced by the proportion of SiO_2 and Al_2O_3 basic oxides present in them. This variation spans from plastic aluminosilicates to brittle globules, which remain non-deformable during the rolling process, up to yielding pure alumina [28]. Each morphological type

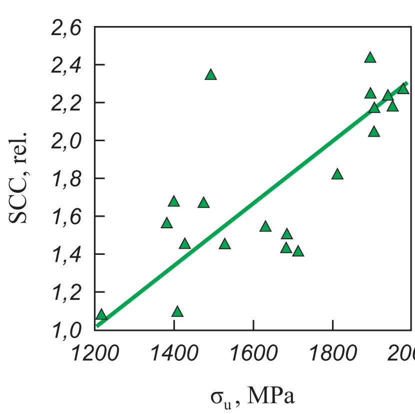

Fig. 3. Dependence of SCC on tensile strength of steel

Рис. 3. Зависимость ККН от временного сопротивления стали

of NMI exhibits specific physical and mechanical properties, such as modulus of elasticity (E_{HMI}), tensile strength (σ_u^{NMI}) resulting in diverse SCC.

Fig. 4 illustrates the derived relationships depicting the dependency of SCC on the tensile strength of steel concerning three potential elemental compositions of NMIs, %, along with sizes of 4.0, 5.8 and 7.0 μm:

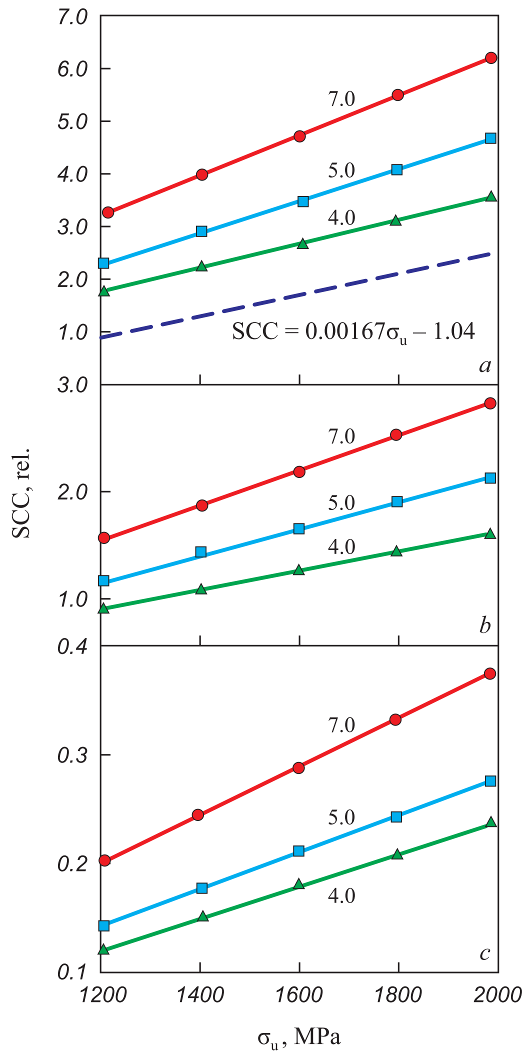

Fig. 4. Calculated dependences of SCC on tensile strength of steel for alumosilicate NMI with different concentrations of SiO_2 and Al_2O_3 oxides in them:
a – 10 % SiO_2, 90 % Al_2O_3, *E* = 350 hPA;
b – 25 % SiO_2, 75 % Al_2O_3, *E* = 320 hPA;
c – 80 % SiO_2, 20 % Al_2O_3, *E* = 100 hPA;
solid lines – calculated values;
dashed line – experimental values;
numbers indicate thickness (diameter) of NMI (μm)

Рис. 4. Расчетные зависимости ККН от временного сопротивления стали для алюмосиликатных НВ с разными концентрациями в них оксидов SiO_2 и Al_2O_3:
a – 10 % SiO_2, 90 % Al_2O_3, *E* = 350 ГПа;
b – 25 % SiO_2, 75 % Al_2O_3, *E* = 320 ГПа;
c – 80 % SiO_2, 20 % Al_2O_3, *E* = 100 ГПа;
сплошные линии – расчетные значения;
штриховая линия – экспериментальные значения;
цифрами обозначена толщина (диаметр) НВ (мкм)

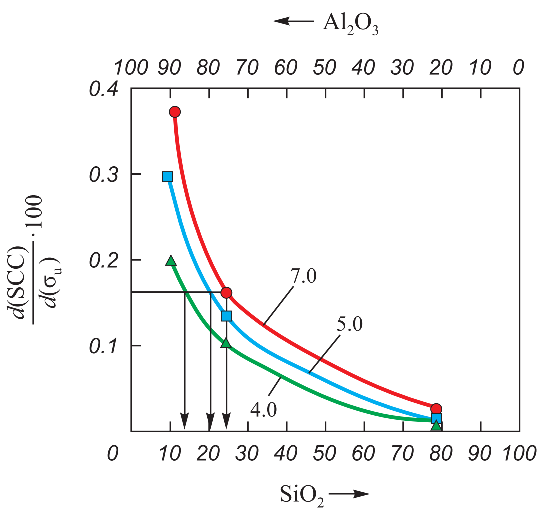

Fig. 5. Dependence of the rate (intensity) of increase in SCC on the ratio of mass fractions of SiO_2 and Al_2O_3 oxides in NMI

Рис. 5. Зависимость скорости (интенсивности) увеличения ККН от соотношения в НВ массовых долей оксидов SiO_2 и Al_2O_3

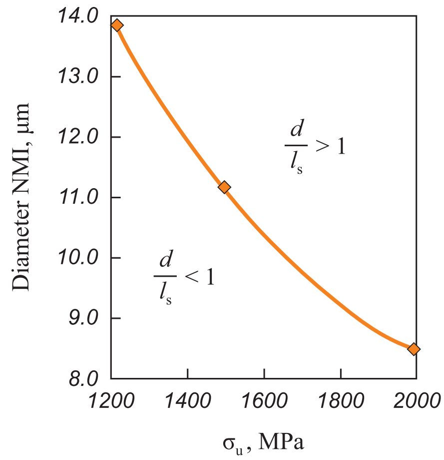

Fig. 6. Dependence of the limit diameter of NMI (60 – 65 % SiO_2; 35 – 40 % Al_2O_3) on tensile strength of steel at $d/l_s = 1$

Рис. 6. Зависимость предельного диаметра НВ (60 – 65 % SiO_2; 35 – 40 % Al_2O_3) от временного сопротивления стали при $d/l_s = 1$

Group	SiO_2	Al_2O_3	*E*, hPa
1	10	90	350
2	25	75	320
3	80	20	100

Aluminosilicates falling within groups *1* and *2* of high-modulus NMIs, surpassing the typical modulus of elasticity within the MM (with an average value of 205 hPa, as indicated in the Table). Conversely, aluminosilicates categorized under group *3* demonstrate low-modulus traits.

SCC escalates proportionally with the increase in both steel strength and the diameter (or thickness) of the NMI. The rate of this rise in SCC depends on the size and elastic modulus E_{NMI} of the NMI, dictated by the ratio of mass fractions of SiO_2 and Al_2O_3 oxides within the NMI (Fig. 5). It's noteworthy that the average rate of change in SCC, calculated from experimental data using Equation (2), corresponds to analogous indicators for NMIs: 13 % SiO_2; 87 % Al_2O_3 (4.0 μm thick); 20 % SiO_2, 80 % Al_2O_3 (5.0 μm thick); 25 % SiO_2; 75 % Al_2O_3 (7.0 μm thick).

For example, in the context of producing spring grade steels by smelting and deoxidation processes (as indicated in the Table), where diverse high-modulus NMIs are formed, these inclusions significantly impact fatigue indicators. To enhance the steel's fatigue strength limit, it becomes crucial to ensure the formation of NMIs with a modulus of elasticity not exceeding that of MM ($E_{NMI} \le E_{MM}$) and a thickness (d) that does not surpass l_s.

As per [18], achieving involves the formation of NMIs in steel, comprising at least 60 – 65 % SiO_2, with the total content of high-modulus oxides like Al_2O_3, MgO not surpassing 35 – 40 %. These NMIs, when produced under these conditions, exhibit ductility at the heating temperature for metal rolling, allowing for easy deformation, resulting in the formation of thin filaments. For example, during rail rolling, aluminosilicate NMIs are generated within the rail head, measuring approximately 4.0 – 6.0 μm in diameter and having an average length of 40 – 50 μm. Fig. 6 illustrates the calculated maximum diameter (or thickness) for NMIs with the specified chemical composition and various levels of tensile strength within the MM.

Hence, as long as the NMI thickness does not exceed 8.5 μm (maintaining a $d/l_c \le 1$, $E_{NMI}/E_{MM} \approx 1.0$ [18], the SCC remains below 1.0, even with MM strength reaching 2000 MPa. In this context, the fatigue strength of the considered steel must be equal to or exceed the yield strength of the metallic matrix during shear.

Conclusions

To enhance the fatigue endurance of steel, particularly in high-strength conditions, employing aluminum-free metal deoxidation technology during smelting proves beneficial. This approach facilitates the creation of a desirable NMI morphology, ensuring that the SCC remains below 1.0. Achieving a fine-grained structure in steel post heat treatment is feasible by deoxidizing without the inclusion of aluminum, instead incorporating minimal amounts of vanadium, niobium, or titanium.

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M. V. Temlyantsev – analysis of the relevance of research on the problem, systematization of information and data in the problem area.

V. V. Bukhmirov – elaboration of the content of sections, selection of references.

В. В. Павлов – создание идеи статьи, проведение теоретических исследований, анализ и научное обоснование полученных данных, формулировка выводов.
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