Effect produced by corrosive environment on fatigue resistance of automotive structural steel

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Abstract. We have studied the influence of corrosive environment on the mechanism of changes in fatigue resistance of automotive structural steels. Analysis of the experimental data has shown that the fatigue resistance of metal materials in corrosive environments is reduced significantly with the increased time of testing. This, in turn, causes a continuous decrease in fatigue curves in the multi-cycle area without reaching the endurance limit. We have identified the factors affecting the resistance to fatigue failure: the medium and its aggressiveness; stress cycle frequency, shape and asymmetry. The presence of a corrosive environment makes it problematic to determine the moment of origin of a macro crack, necessary for the analytical assessment of the time before its appearance. The proposed use of the current sag curves under the sample cyclic loading will allow to fix the moment of the crack origin and to determine the speed of its subsequent propagation. This allows to optimize the choice of structural materials for machines taking into account the operating conditions and to justify the technological manufacturing process in order to reduce material consumption, increase durability and maintainability.

1. Introduction

During operation, the vehicle is subjected to various types of loads, resulting in destruction of its construction materials. The most dangerous loads are vibration in the presence of a corrosive environment [1], increasing the probability of accidents. Therefore, the task of increasing the fatigue resistance of metal materials in corrosive environments and ensuring the performance of vehicle parts and components is one of the most relevant ones in the automotive industry.

The performance indicators of structural materials intended for the manufacture of automotive metal products are formed at all stages of metallurgical processing: from the choice of charge materials for metal smelting to the production of finished parts. The reason for the required increase in the resource and operational reliability is also a high cost of the automotive structural materials. Therefore, experimental studies of the structural materials fatigue characteristics in order to reduce the product metal content, implementation of new processing methods, as well as the selection of competitive material are of high priority in the modern automotive industry.
The solution of this issue involves the study of the fatigue failure of automotive metals and alloys in the presence of a corrosive environment, with the ability to determine the duration of the period before the cracks emergence and the intensity of their further propagation across the structure cross section. This will allow selecting the material that meets the operating requirements, and, as a result, it will prevent its destruction and reduce the financial and time costs associated with the car repair.

Automotive parts are manufactured according to different technologies [2,3,4]. However, the study of material fatigue degradation is complicated by the test duration and conditions. In this regard, the identification of the fatigue behavior mechanisms of the automotive materials manufactured by different technological processes plays an important role. At the same time, in addition to the automotive parts manufacturing technology development, it is important to take into account all factors that affect the operational durability.

2. Materials and methods

In this document the loading factors (cyclic loading scheme, loading frequency, loading cycle form, asymmetry of loading cycle, application severity) have been estimated, which have an impact on the parameters of their fatigue resistance in the corrosive environment (fatigue crack life, fatigue strength, period before fatigue crack nucleation, speed of its further development, intercrystalline or transgranular mechanism of fatigue cracks’ growth, stress-intensity in the apex of fatigue crack) based on examples of research of a wide range of metals and structural materials (15XN5DMF, A53CL1, JIS SNCM439, SVS410, AISI 4340, 12Ni-5Cr-3Mo, 10Ni-Cr-Mo-Co, 200, 33NiCr, “nimonic-105”, IN738C, En56C, A533B-1, 316L, 316S16, 10XCND, BS 817M40, X6CrTi17, X12CrNiTi18-9, Inconel-718, X20CrMo13, BT1-0, ATSpl).

3. Results

The structural materials’ fatigue resistance in a corrosive environment, as a rule, considerably decreases [5]; therefore, the fatigue curves in a multi-cycle area continuously go down failing to reach the endurance limit.

The zero-to-target net knee of the curve (167; 16.7 and 1.67 MHz) of smooth samples made of steel 15XN5DMF has shown that [6] the sea water is to a lesser extent affects the length of the period before the crack origination but reduces the stage of the crack propagation. In this case the comparison of the short and long crack growth kinetics in steel A53CL1 (composition in mass %: C 0.13; Mn 1.48; P 0.012; S 0.005; Si 0.46; Mo 0.016; Cr 0.04; N 0.18; Cu 0.17 and V 0.051) [7] and steel JIS SNCM439 (in mass %: C 0.42; Si 0.24; Mn 0.9; P 0.019; S 0.008; Ni 1.77; Cr 0.78; Mo 0.1) [8] has brought to light a considerable (~10 times) acceleration of the short crack growth when compared to the long ones. The short cracks have an intergranular mechanism while the long ones propagate via the crystal grains.

Loading frequency decrease, as a rule, reduces the endurance capability in the environment, e.g. in steel 15XH5DMF [6] (in the range of 167 to 1.67 MHz), steel 422 (in mass %: C 0.25; Ni 0.77; Cr 12.39; Mo 1.12; V 0.28; W 1.08), steel SVS410 (in mass %: C 0.09; Si 0.38; Mn 0.33; P 0.021; S 0.008; Cr 13.08) [9] (in the range of 10 to 0.1 Hz), low alloy Cr-Mo steel [10] (at frequencies from 30 to 0.03 Hz), high-strength steel AISI 4340, 12Ni-5Cr-ZMo, 10Ni-Cr-Mo-Co and maraging steel with 18% of Ni [11], steel 200 (composition: 18Ni-3.2Mo-0.2Ti-0.1AC-8.5Co-0.035Co) [12] (in the range of 3.3 to 0.017Hz), steel 33NiCr (in mass %: C 0.37; Ni 3.5; Cr 1.35; Mo 0.25; V 0.1; Si 0.3; Mn 0.4) [13] (in the range of 36 to 0.3 Hz), alloys (composition in mass %): nimonic-105 (C 0.2; Cr 14.5; Co 20; Mo 5; Al 1.8; Ti 4.5) and IN738C (C 0.17; Cr 16; Co 8.5; Mo 1.7; W 2.6; Ta 1.7; Nb 0.9; Al 3.4; Ti 3.4; Zr 0.1) [14] (at frequencies from 10^2 to 10^4 Hz).

However, there are other data indicating that the effect of the loading frequency on the corrosion-fatigue resistance of steels is of non-monotonic character, for example, steel En56C (in mass %: C 0.24; Si 0.34; Mn 0.27; Cr 13.38; Ni 0.41; S 0.011; P 0.019) and steel A533B-1 (in mass %: C 0.18; Si 0.26; Mn 1.50; Ni 0.59; S 0.009; P 0.010) [15] when changing frequency from 0.001 to 10Hz, for austenitic steel 316L (in mass %: C 0.03; Cr 17.8; Ni 14.1; Mo 2.5; Si 0.44) and steel 316S16 (in mass %: C 0.02; Cr 18.2; Ni 12.7; Mo 2.1; Mn 1.03; Si 0.59) [16]. In this case in certain instances there is
[17] a limit frequency below which the speed of corrosion fatigue crack formation in steel type 12X2H either slightly increases, or decreases.

The shape of the loading cycle does not significantly affect the fatigue of metal materials in working environments at low stresses [1], however, at high stresses its effect increases. At the same time, the durability of samples tested according to sinusoidal form is weaker than that according to rectangular or trapezoidal form. Thus, the studies of smooth samples of flat cross-section made of steel 15XH5DMF for the zero-to-target net knee curve showed [6] that the occurrence and propagation of fatigue cracks in the sinusoidal cycle in sea water environment is by 10-90% more active than that in the trapezoidal cycle. Moreover, the effect of the cycle shape increases with the level of deformation.

The increase in the asymmetry of the loading cycle leads to a decrease in the material resistance to corrosion fatigue to the greater extent while the stress intensity at the crack tip gets lower [1]. The increase in the cycle asymmetry also leads to a decrease in the threshold stress intensity factor $K_{th}$ [18] and to the difference between the crack growth in the sea water and the air [19]. In the case of ship hull steel 10XSND for the net knee with frequency 35 Hz in a natural sea water environment, the loading cycle asymmetry factor increase does not affect the crack origination and growth but leads to the reduced number of cracks. In high-purity steel grade BS 817M40 (in mass %: P 0.16; S 0.030; As 0.032; Sn 0.019; Sb 0.065), tested [20] for fatigue at $R = 0.1$ and 0.35, up to 35% of the fatigue fracture is attributed to the intergranular constituent and at $R = 0.7$ the percentage of this reaches only $\sim 10\%$.

One of the most important factors affecting the fatigue resistance of materials in the environment is the degree of its aggressiveness [1]. In many cases, hydrogenation of metals, especially in high-strength steels with high sensitivity to hydrogen embrittlement, is decisive for alternating loading.

The study of the cyclic crack resistance of stainless steel grades 08X17T and 12X18H10T at a zero-to-target cycle frequency of 2.5 Hz shows [25] that in a hydrogen-charged (single-normal aqueous solution of sulfuric acid with the addition of 5 ml/l of arsenic dioxide) and pre-hydrogenated medium, the growth rate of fatigue cracks is much higher than that in the air. At the same time, the controlling effect on the crack growth rate is exerted by hydrogenation during fatigue deformation, which is associated with a sharp decline in plasticity in the near-surface layer due to hydrogen adsorption or the embrittling effect of the surface reactions with oxidation and hydrogen release.

On samples made of the heat-resistant alloy Inconel-718, molybdenum-doped steel X20CrMo13 and titanium BT1-0 it is shown that one of the ways to increase the service life of products with the environment fatigue would be the use of materials with high $K_{th}$ or taking measures aimed at increasing it [25]. This reduces the likelihood of deeper cracks formed during fretting.

Studies of the aluminum alloy ATSspl [23] revealed the same sliding and crack formation both in air and in a 3% aqueous solution of sea salt, although in water and especially in a 3% solution of NaCl these are significantly accelerated.

### 4. Discussion

The combined effect of the medium and alternating stress due to the destruction of the passive film [23] and the removal of barriers to the exit of dislocations to the surface accelerates the micro-and sub-micro-deformation of the metal, while passivation inhibits the exit of dislocations, thereby slowing down the corrosion fatigue development.

Due to the adsorption or adsorption-electrochemical effect of the medium, the initial phase of corrosion fatigue, as in corrosion cracking, is determined by a local damage to the passive layer of the material surface. However, if in the first case, the intensity of the trans-crystalline slip increases first, and only then, in the slip bands, juvenile metal planes appear, in the second case, fresh surfaces are immediately formed in clusters of dislocations.

Direct microscopic observation of the working surface of the sample dangerous cross-section [1] showed that fatigue failure in the presence of a corrosive medium begins in the point corrosion damages, occurring mainly in non-metallic inclusions on resistant slip bands, the metal volume of which is most activated, and is an anode for nearby surfaces. Further, these damages deepen and increase the thermodynamic activity of the metal due to localization of stresses and intensification of electrochemical
processes. It becomes difficult to block pittings by secondary corrosion products, slowing down the oxidation progress under alternating loading.

This leads to the fact that the samples without pre-induced cracks will have formed on their surface a plurality of corrosion-fatigue micro cracks, located close to each other, and together affecting the distribution of mechanical stress fields. In this case the cracks are not straightforward, and are much branched.

Thus, according to the literature, all this makes it problematic to determine a macro fracture origination moment for an analytical assessment of the time before its appearance.

The crack development is described (Fig. 1) by the fatigue failure kinetic diagram (FFKD), which is a “curve of dependence of crack growth rate $da/dN$ on the magnitude of the stress intensity factor (SIF).

![Figure 1. Fatigue failure kinetic diagram (according to V.F. Terentyev): $\Delta K_{th}$ – SIF threshold magnitude below which the crack does not extend; $\Delta K_{fc}$ – critical SIF magnitude at which the fatigue failure takes place.](image)

On the left side the diagram is limited by the threshold SIF value $K_{th}$, and on the right side – by the critical SIF value for fatigue $K_{fc}$. FFKD has three phases: 1. crack nucleation, 2. self-similar growth and 3. significant crack growth” [2].

FFKD 2 phase was studied in detail and this is described by Paris-Erdogan equation [2]:

$$da/dN = C\Delta K^n$$

where, $a$ – crack length, $m$; $N$ – number of loading cycles; $C$ – constant factor; $n$ – exponent; $\Delta K = K_{max} - K_{min}$ – SIF magnitude, MPa $\sqrt{M}$.

A complete FFKD has a complex form, so you can understand many attempts made to describe it in a form of unified analytical dependence, including the asymmetry of the loading cycle allowing to describe the crack propagation rate within the entire range $\Delta K$ from $K_{th}$ to $K_{fc}$ (Foreman, Kearny, Erdogan, G.P. Cherepanov, V.D. Kuliev, S.Ya. Yarema, S.I. Mikeshin et al.).

The intensity of the fatigue cracks development acceleration is caused by the type of test medium and increases with the intensity of stresses close to $K_{th}$ threshold value. At the same time, the growth of the fatigue crack in vacuum is much slower than that in the air [24, 26] and, especially, than that in a corrosive environment.

Peculiarities of FFKD configuration in corrosive environments for various structural materials are discussed in detail in the paper [25].

Unlike cracks developing without corrosive media participation, the corrosion-fatigue failure has its own specific features [2], which determine the nature of the driving forces and the kinetics of the corrosion cracks propagation, which cannot be reflected in the traditional analysis of the fracture mechanism. The stress state at the top of the corrosion-fatigue crack can be significantly reduced due to its branching and blunting (corrosion fretting), as well as with the appearance of the crack closure effect,
which contributes to stress relaxation, i.e. the decrease in effective SIF ($\Delta K_{\text{eff}}$), and the closing of cracks reduces the effective SIF magnitude ($\Delta K_{\text{eff}}$). All this affects the failure process.

In comparative tests, when required, for example, to find out the influence of the medium, the stress concentrator, thermal or other processing technology on the fatigue resistance of structural materials, the relative values are often used, for example $\beta_h = \Delta K_{\text{the}} / \Delta K_{\text{th}}$ [2] and others.

The advantage of such a kinetic approach is manifested only when the macro cracks are already present in the metal, the plane of their development is perpendicular to the direction of normal stresses action, and the intensity of stresses at their apex is controllable. In the case of smooth samples without previously induced surface cracks, as shown above, a large number of corrosion-fatigue micro cracks [6] located close to each other and jointly affecting the distribution of stress fields originate at once. Therefore, to assess the stress intensity in the crack top with the involvement of existing methodological approaches is almost impossible. In addition, in many cases the cracks are not rectilinear and are significantly branched [2, 21], which makes it extremely difficult to apply the basic hypothesis of fracture mechanics to the analytical description of fatigue kinetics in the presence of a corrosive medium.

However, it has been experimentally established [2,4,22] that the change sag curves represent an integral characteristic of destructive structural changes under alternating material loading. They make it possible to track the moment of the crack origination and the rate of its propagation, which is important when tested in a corrosive environment, since direct observation of the sample surface is impossible.

Together with metallographic and fractographic analytical methods these allow to optimize the choice of the vehicle structural elements, taking into account the conditions of its operation and manufacturing technology, in order to increase the resource and maintainability, on the basis of identified stages of material destruction.

5. Conclusion

The fatigue resistance of engineering materials in corrosive environment, as a rule, significantly reduces, which brings about a permanent decrease of fatigue curves in the multi-cycle area, failing to reach the endurance limit.

Such factors as: frequency scheme and form of cyclic loading, asymmetry of the loading cycle and environment corrosive power have a great impact on the parameters of fatigue resistance of engineering materials in corrosive environment.

The curves of change of the current deflection in combination with metallographic and fractographic method of analysis enable to perform the optimization of selection of the automobile structural elements on the basis of detection of the materials destruction stages, taking into consideration the condition of its operation and manufacturing technologies, with the goal of increase of the automobile service life and maintainability.

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