Evaluation of medium factor influence on car materials fatigue resistance

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Abstract. Parts and components of a car are subjected to various types of operational loads, causing the construction materials destruction. are vibration loads in corrosive environment are the most dangerous ones, they can increase the probability of road accidents. The article considers the influence of corrosive medium on the patterns of fatigue resistance of automotive structural steels. The factors affecting the resistance to fatigue failure have been detected. Corrosive medium makes it difficult to determine the moment of macrocrack onset and estimate the pre-onset period. However, using the curves of changes in the current deflection under sample cyclic loading, one can set down the moment of crack onset and determine its growth rate. This allows us to justify the choice of materials for car parts and elements at the design stage, extend its life-span, reduce car and processing techniques material consumption, taking into account its service conditions.

Key words: structural materials, corrosive medium, fatigue cracks, deflection curves, cyclic durability.

Introduction

Parts and assemblies of a car are subjected to various types of operational stresses, that increases its damageability and leads to road accidents, which is especially dangerous in corrosive environment [9,10].

Structural performance characteristics change at all stages of the metallurgical breaking range [15, 16, 19, 25]. High cost of metallic materials for car production gives a strong stimulus to increase reliability and life span of a car. Therefore, material fatigue characteristics studies [29] take priority in modern automotive industry, they help to optimize material choice at developing stage, to reduce metal consumption and to determine advanced technological processing methods [5, 6, 16, 24].

This involves studying the kinetics of metals and alloys fatigue fracture in corrosive environment, including determination of the crack onset protensity and the rate of their further growth, which allows to choose the material meeting operational requirements and, therefore, to prevent its destruction, and to reduce maintenance costs. However, the study of the process of material fatigue destruction is complicated by the duration and conditions of tests. At the same time, in the process of developing the part manufacturing technology it is important to take into account factors that affect its durability.

The purpose of the work carried out in NSTU named after R.E. Alekseev is to assess the influence of environmental factors on the fatigue resistance of automotive materials, that will help justify the choice of materials, increase the resource, reduce material consumption and develop manufacturing technology for producing car parts and elements, which will consider operating conditions.

The object of research is automotive structural materials.
The subject of research is revealing of automotive structural materials behavior in the fatigue failure process, taking into account factors of cyclic loading conditions.

The influence of environmental factors in the tests
When designing automobiles, metal parts and elements from various structural materials obtained by various types and modes of processing are currently used. An important factor affecting their operational properties, in addition to the nature of the material, its structure and the quality of its surface, is the factor of the operating environment. Stress concentrators on the surface of the material contribute to the fatigue cracks onset and development. Under cyclic loads all processes in the surface layers of metal associated with the fatigue cracks onset are advanced, and all structural damage processes are activated at the surface.

In the automotive industry various alloys and structural steels are widely used. However, information on the influence of types and modes of their technological processing on their mechanical properties in corrosive media insufficient, which highlights the necessity of optimal design solutions and accurate use of technological processes in order to ensure the performance characteristics of parts and structures.

Therefore, the task of increasing the fatigue reliability of automotive parts with a possible decrease in metal consumption is urgent. Its solution involves the study of fatigue damage kinetics of automotive materials in corrosive environment, determination of the pre-crack period and the rate crack growth.

The solution to this problem will allow detecting the material that objectively meets operational requirements, which, in turn, will reduce the probability of structural damage under cyclic loads in corrosive environment and reduce repair costs.

As a rule, corrosion significantly accelerates fatigue processes in materials [11, 26], leading to a continuous decrease in durability in the multi-cycle region of fatigue curves that do not reach the breaking point.

Tests of smooth samples from steel 15KHN5DMF according to the scheme of zero clear bending at 167; 16.7 and 1.67 MHz frequencies showed [3] that sea water to a lesser extent affects the pre-crack period, but reduces the period of crack development. Comparison of the growth process of short and long cracks on steels A53CL1 [27] and St. JIS SNCM439 [21] revealed an acceleration short cracks growth up to 10 times against long ones.

With decrease in loading frequency, decrease in the durability in the medium is observed for the following materials: 15KHN5DMF [3], 422 SVS410 [20], low-alloy Cr-Mo steel [22], high-strength AISI 4340, 12Ni-5Cr-3Mo, 10Ni-Cr-Mo Co and martensitic steel with 18% Ni [23], 200 [26], 33NiCr [11], Nimonik-105 and IN738C alloys [28]. However, there is evidence that the effect of the loading frequency on the resistance to steel corrosion-fatigue fracture has non-monotonic character, for example, En56C and A533B-1 [17], austenitic steels 316L and 316S16 [31]. Sometimes there is a limit frequency [2] below which the development rate of a corrosion-fatigue crack in 12Kh2N steels either increases slightly or decreases.

The shape of the loading cycle does not have significant effect on the structural materials fatigue resistance in working environments at low voltages [11, 14], but its effect is enhanced at high voltages. The durability of the samples with a sinusoidal form of loading is less than with rectangular or trapezoidal forms. Thus, studies of 15KHN5DMF steel samples during a sinusoidal cycle in sea water by clear zero bending revealed [3] that a fatigue crack onset and growth proceed 10–90% more actively than during a trapezoidal cycle. This effect increases with the degree of cyclic deformation.

With an increase in the asymmetry of the loading cycle the resistance to material corrosion fatigue decreases the greater, the lower the stress intensity at the crack tip [11] is, the threshold stress intensity coefficient [18] and the difference between the crack growth rate in sea water and air [30] are decreased. However, for ship-hull steel 10KHSND for clean bending of frequent 35 Hz in natural sea water, increase in the asymmetry coefficient of the loading cycle does not affect crack onset and growth, but leads to decrease in their number.

An important factor is the degree of medium corrosiveness [11]. So, hydrogenation of metals, especially in high-strength steels with increased sensitivity to hydrogen embrittlement, is often decisive for alternating loading. The study of 08Kh17T and 12Kh18N10T stainless steels at a 2.5 Hz zeroing cycle showed [1] that in hydrogenated medium, the crack growth rate is a magnitude higher than in air.
The study of heat-resistant alloy Inconel-718 alloyed with molybdenum steel X20CrMo13 and titanium BT1-0 revealed [4] that one of the ways to increase metal products service life during fatigue in the medium is to use materials with high threshold stress intensity coefficients or technologies that increase it.

The simultaneous effect of alternating load and medium slows down the corrosion fatigue development due to the destruction of the passive film [13]. Due to the adsorption or adsorption-electrochemical effects of the medium, the initial phase of corrosion fatigue, as in corrosion cracking, is determined by local damage to the passive layer of the material surface. Direct microscopic observation of the working surface of the sample dangerous section [9] proved that corrosion-resistant failure begins in point damages, which occur mainly in non-metallic inclusions on resistant slide bands, the metal of which is most activated and is an anode for nearby surfaces. Then, these damages deepen, the metal thermodynamic activity increases due to the localization of stresses and the intensity of electrochemical processes. Clogging of pittings is obstructed by secondary corrosion products, slowing down oxidation under alternating loading.

It is a source of many corrosion-fatigue microcracks appeared on the surface of the samples without previously induced cracks, they locate close to each and exert cumulative effect on the distribution of the mechanical stresses fields. In this case, the cracks are not straight, but significantly branched.

Thus, according to reference data it difficult to determine the moment of macrocrack onset and estimate time interval before it.

Crack development [8, 14] is described by the “kinetic diagram of fatigue failure”. It represents dependence curve of the “crack growth rate” $\frac{da}{dN}$ to the “magnitude of the stress intensity coefficient” (SIC). The 2nd section of the KDFF is described by the Paris – Erdogan equation [8]:

$$\frac{da}{dN} = C \Delta K^n$$

where $a$ is the length of the crack, m; $N$ is the number of loading cycles; $C$ is the coefficient; $n$ is the exponent in the equation; $\Delta K = K_{\text{max}} - K_{\text{min}}$ is the SIC range, MPa $\sqrt{M}$.

The complete KDFF is complicated, therefore, its numerous descriptions are observed in the form of analytical dependencies that take into account the asymmetry of the cycle and describe the crack growth rate. The peculiarities of the KDFF configuration of many metals and alloys in corrosive media are studied in detail by A.N. Romanov [12].

However, the advantage of such kinetic approach is obvious only when macrocracks already exist in metal, the plane of their development is perpendicular to the direction of normal stresses, and the stress intensity at their peak can be controlled. The surface of smooth samples without previously induced cracks have many corrosion-fatigue microcracks, they locate close to each and exert cumulative effect on the distribution of the mechanical stresses fields. Therefore, it is almost impossible to assess the intensity of stresses at the crack peaks using existing methodological approaches. In addition, often the cracks are curved and significantly branched, which makes it extremely difficult to apply the basic hypotheses of fracture mechanics to the analytical description of fatigue kinetics in corrosive medium.

In the course of experiment using the optical observation scheme for the cylindrical sample fatigue surface (Fig. 1), it was ascertained [8, 26] that the deflection curves represent an integral characteristic of destructive changes under alternating material loading.

![Figure 1](image.png)

**Figure 1.** The scheme of studying the sample fatigue surface: 1 - sample; 2 - a microscope; 3 - stroboscopic lamp; 4 - strobe; 5 - phase synchronizer
It was shown [5, 24] that hardening is immediately observed in materials after annealing, accompanied by intense sliding in almost all grains, as evidenced by deflection decrease (Fig. 2) [5]. Then deflection stabilizes, which is associated with the developed slip along the secondary bands, the intersection of the bands, and ends with a macrocrack that grows until the sample ruptures.

Technologically hardened materials behave differently, their deflection increases immediately (Fig. 3), which corresponds to the appearance of rare slip bands in some grains.

Further, during the deflection stabilization phase, compacted sliding along the primary and secondary planes is observed. The phase of increased deflection growth is characterised by the surface crack onset with the length of about 1.0 mm [6].

The outcomes and their consideration.
The results of mathematical processing of a typical deflection curve in corrosive environment (3% aqueous solution of sea salt) under symmetrical cantilevered bending with the rotation of a model cylindrical sample from a technologically hardened B63 at $\sigma_a = 250$ MPa are appended in the table.
Table 1

The results of mathematical processing of a typical deflection curve in a corrosive environment with symmetrical cantilever bending with the rotation of a model cylindrical sample from technologically hardened brass B63 at \( e_a = 250 \) MPa.

| \( \sigma_0 \), MPa | \( \varepsilon_{op} \), % | \( N_p \), cycle | \( N_{s, mp} \), cycle | \( N_p - N_{s, mp} \), cycle | \( l_z \), mm | \( V_{mp} \), mkm/ cycle |
|-------------------|-----------------|----------------|-----------------|-----------------|-----------|-----------------|
| 300               | 0               | 341000         | 270000          | 71000           | 3.66      | 5,15 x 10^{-2}  |
| 300               | 25              | 115000         | 80000           | 35000           | 3.34      | 9,54 x 10^{-2}  |
|                   |                 |                |                 |                 |           |                 |
| B63, cold-rolled, air |                 |                |                 |                 |           |                 |
| 300               | 0               | 51000          | 40000           | 11000           | 3.10      | 48,2 x 10^{-2}  |
| 300               | 25              | 68100          | 54000           | 14100           | 3.31      | 23,5 x 10^{-2}  |
|                   |                 |                |                 |                 |           |                 |
| B6, cold-rolled, corrosive medium |                 |                |                 |                 |           |                 |

**Note:**
- \( \sigma_0 \) – stress, MPa;
- \( \varepsilon_{op} \) – tensile strength ZD 10/90;
- \( N_p \) – deformation rate \( 5.6 x 10^{-4} c^1 \), %;
- \( N_{s, mp} \) – full durability, c;
- \( N_p - N_{s, mp} \) – number of cycles before crack onset, cycle;
- \( l_z \) – the length of the sample’s pure fatigue fracture, mm;
- \( V_{mp} \) – crack growth rate, mkm/cycle.

Full durability \( N_p \) and durability before crack onset \( N_{s, mp} \) when cold-rolled brass is tested in air, (3.41.105 and 2.7.105 cycles, respectively) is higher than that of cold-rolled brass with a deformation of 25% (1.15.105 and 8.104 cycles, respectively). However, the crack growth rate in cold-rolled B63 (5.15-10² mkm / cycle) is vice versa lower than that in cold-rolled and deformed by 25% (9.54-10² mkm / cycle).

In the medium both full cyclic durability and durability before macrocrack onset is lower, and its growth rate is higher than in air, which confirms the conclusions [7–9, 11].

When tested in a medium, the full durability and the durability before crack onset of cold-rolled brass with additional deformation of 25% (6.81 x 10⁴ and 5.4 x 10⁴ cycles, respectively) higher than that of just cold-rolled one(5.1 x 10⁴ and 4.0 x 10⁴ cycles, respectively). On the contrary, the crack growth rate is higher for cold-rolled B63 (48.2 x 10² mkm / cycle) compared to cold-rolled brass with additional deformation of 25% (23.5 x 10² mkm / cycle).

**Conclusion**

Medium influence, its aggressiveness, frequency, form and asymmetry of the loading cycle on the resistance to fatigue failure has been revealed and estimated.

It has been established that materials and types of automobile parts processing, whose pre-onset crack resource constitutes the larger part of their “life” till the final destruction, are preferable, that allows to detect a crack in the course of regular technical inspection and improve the maintainability of a car.

It has been proved that the sample deflection curves make it possible to track the moment of fatigue crack onset and determine its growth rate, which is especially important in corrosive medium, since direct observation of the sample surface is impossible.

Using the data obtained, it is possible even at the design stage to make the optimal choice of material and manufacturing technology, and at the maintenance stage to prevent the destruction of structural elements and parts that are subjected to operational cyclic loads.
Bibliography

[1] Vitvitsky V.I., Levitsky M.O., Duryashin et al. // Phys. – Chem. fur. materials. - 1981. - 17, - No. 3. - S. 107-108.
[2] Magdenko A.N., Sadichenko V.I. The influence of the cycle shape on the growth rate of a corrosion crack in 12Kh2N steel at low-cycle fatigue. // Phys.-Chem. fur. materials. - 1984. - No. 5. - S.102-103.
[3] Maksimovich G.G., Kozharuk A.V. The origin and development of low-cycle fatigue cracks in steel 15KHN5DMF in sea water. // Phys.-chem. fur. materials. - 1984. - No. 5. - S. 16-20.
[4] Nironovich I.A. // Phys.-Chem. fur. materials. - 1980. - 18, 5. - No. 5. - S. 22-25.
[5] Pachurin G.V., Gushchin A.N., Galkin V.V., Pachurin V.G. The theoretical basis for increasing the operational durability of stamped metal products: textbook. A manual for university students / NSTU. N. Novgorod. 2006. - 173 p.
[6] Pachurin G.V. Fatigue resistance at different temperatures of annealed and hardened brass L63 // International Journal of Experimental Education. - 2014. - No. 3-1.- S. 119-126.
[7] Pachurin G.V. The role of surface structure in corrosion fatigue of deformed metal materials // Modern problems of science and education. 2014. No. 1; URL: http://science-education.ru/ru/article/view?id=11907 (accessed: 08/10/2018).
[8] Pachurin G.V. Corrosion Durability of Deformation-Hardened Metal and Alloy Products: A Training Manual. - 2nd ed., Ext. - St. Petersburg: Publishing House "Lan", 2014. - 160 p.
[9] Pachurin G.V., Kudryavtsev S.M., Soloviev D.V., Naumov V.I. The body of a modern car: materials, design and production: Textbook / Ed. G.V. Pachurina. - 3rd ed., Revised. and add. - St. Petersburg: Publishing House "Lan", 2016. - 316 p.
[10] Pachurin G.V., Galkin V.V., Pachurin V.G. Durability of hardened metals and alloys: a training manual / G.V. Pachurin, V.V. Galkin, V.G. Pachurin. Stary Osokl: TNT, 2017. - 228 p.
[11] Pohmursky V.I. Corrosive fatigue of metals. - M.: Metallurgy, 1985. - 207 p.
[12] Romanov A.N. // Phys.-Chem. fur. materials. - 1980. - 16. - No. 2. - S. 27-30.
[13] Sinyavsky Sun., Valkov V.D., Budov V.M. Corrosion and protection of aluminum alloys. - M.: Metallurgy, 1986. - 368 p.
[14] Terentyev V.F., Petukhov A.N. Fatigue of high strength metal materials. - M.: IMET RAS - TsIAM, 2013.515 s.
[15] Filipov A.A., Pachurin G.V., Kuzmin N.A. et al. Quality assessment of rolled steel for cold forging // News of higher educational institutions. Ferrous metallurgy. - 2018. - Volume 61. - No. 7. - S. 551-556.
[16] Filipov A.A., Pachurin G.V., Kuzmin N.A. The method of forming the structural and mechanical properties of rolled steel for the planting of rod products // Ferrous metals. - 2018. - No. 4. - S. 36-40.
[17] Atkinson L.D., Lindley T.S. The influence of the frequency [loading] and temperature on the growth of a fatigue crack under the influence of a medium in steels [at stresses] below KISSC. // Influence Environment Fatigue Conf., London, 1977. - S. 65-74.
[18] Chen Daolun, Wang Zhongguang, Jiang Xiaoxia, Ai Suhua, Shi Changxu. Fatigue crack growth in rolled two-phase steel // Steel Res. - 1989. - 59. - No. 7. - S. 319-322.
[19] Filipov A.A., Pachurin G.V., Naumov V.I., Kuzmin N.A. Low-Cost Treatment of Rolled Products Used to Make Long High-Strength Bolts // Metallurgist. 2016. Vol. 59. Nos. 9-10. January. S. 810-815.
[20] Komai Kenjiro, Kanasari Hiroshi. Corrosion fatigue crack growth of a martensitic stainless steel in NaCl solution. // Bull. JSME. - 1985. - 28. - No. 236. - S. 202-208.
[21] Nakai Yoshikazu, Akagi Hedenari, Kitamura Yasuhiro, Ohji Kiyotsugu. The growth of short surface cracks in high-strength low-carbon steel under cyclic loading in a 3.5% NaCl solution. // Nihon Kikai Takkai rhombunsu. A = TgankJar.Soc.Mesh. Eng. A. - 1989. - 55. - No. 516. - S. 1724-1731.
[22] Nishiyama Satashi, Abe Takayuki, Mashuda Chitoshi, Hirukawa Hisashi. Characteristics of corrosion fatigue and the influence of the frequency on it for low alloy steels in salt water during rotation by bending. // Nihon Kikai Takkai Rhombus Trans. Jap. Soc. Mesh Eng. 1985. A51. No. 461. S.156-160.
[23] Nagai Kin-ichi. Corrosion resistance and fracture mechanics. // Yessetsu Gakkashi, J.Jap. Well. Soc. 1976. 55. No. 11. S.926-937.
[24] Pachurin G.V., Goncharova D.A., Filipov A.A. and etc. Development of fatigue test technology of sheet automo-bile materials // Eastern-european jour-nal of enterprise tech-nologies ISSN 1729-3774. - Vol 5, No 12 (95). - 2018. - S. 31-37.
[25] Pachurin G.V., Shevchenko S.M., Filippov A.A. and etc. Defining Role Metal Performance for cold bolt upsetting (bolt head) // International Journal of Mechanical Engineering and Technology. - 2018. - No. 9 (4).
[26] Pachurin G.V. Life of Plastically Deformed Corrosion-Resistant Steel // Russian Engineering Research. - 2012. - Vol. 32. - No. 9-10. - S. 661-664.
[27] Pei Hongxun, Yang Jigjun, Ke Wei. The growth of short cracks in A537CL1 steel under cyclic stress in a 3.5% NaCL solution. // Jin-shu-snabao = Acta met. sin -1988. - 24. - No. 6. - S. B393-B397.
[28] Pettit D.E., Ryder J.T., Krupp W.E., Hoeppner Scarlin R.V. Influence of loading frequency and medium on crack growth during high-temperature fatigue of nickel-based alloys. // Adv. Res. Strength Fract. Mater. 4th Int. Conf. Fract., Waterloo, 1977. New York E.A. - 978. - S. 349-857.
[29] Schmidtmann Eugen, Wirths Dieter Aachen. Influence of loading frequency on crack propagation characteristics in high-strength 33NiCrMo145 steel under conditions of pulsating tension in various media. // Arch Fisenhuttenw. - 1973. - 49. - No. 10. - S. 483-437.
[30] Sumita Masae, Maruyama Norio. The propagation of fatigue cracks in the Ti-6Al-4V alloy in sea water at low LC values. // Tetsu to Hagane, J. Iron and Steel Inst. Jap. - 1989. - 74. - No. 9. - S. 1854-1861.
[31] Smethurst E., Waterhouse R.B. Effect of frequency on the fretting fatigue behavior of two austenitic stainless steel implant materials in Hanks solution. // Proc. 2th Int. Conf. Mesh Behav. Mater, Boston, Mass., 1976. - S.1, 1976. - S. 695-699.