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FATIGUE FAILURE AS A COMPLEX OF RELAXATION PROCESSES OCCURRED AT THE VERTICES OF THE STRESS RISERS

Abstract. This paper considers the stress-dependent fatigue life of polycrystalline materials and their fatigue failure as a result of the relaxation processes that occurred on the stress risers of various scales: macroscopic stress risers of technological nature (pores, cracks, surface roughness, etc.), and microscopic stress risers at the grain/subgrain boundaries and/or second phase particles. Participation of the relaxation mechanisms plastic (vacancies and dislocation activities, grain boundary sliding) and brittle (cracks) nature in the process of the ‘fish eye’ fatigue crack formation is also addressed. The model described the parabolic dependencies of the densities of elementary carriers of plastic and brittle relaxations on the load change rate (i.e., on the growth rate of the stresses concentrated at the vertices of the stress risers) correlates well to the fatigue life data observed for the surface-modified metallic materials.

Keywords: fatigue life, stress risers, stress growth rate, the ‘fish eye’ fatigue crack, vacancies-assisted plastic relaxation, dislocation activity, surface modification

The main regularities in the formation of microstructures and fracture surfaces have been repeatedly considered at various scale levels of construction and microstructure hierarchies of the products and materials [1-8] as well as using the energy-based approach [9, 10]. However, the concept of the origin and realization of fatigue fractures still needs to be supplemented.
This paper discusses the general regularities of the accumulation of fatigue damages and modern ideas concerning the processes of plastic deformation and fracture of materials, as a complex of relaxation phenomena that depend on the growth rate of the stresses, which are concentrating at the vertices of the technological and microstructural risers. The microstructural risers are known can subdivide the macroscopic applied force into vector components [11, 12]. The action of the stress risers manifests itself in the generation of the corresponding elementary carriers of plastic or brittle relaxations, such as vacancies, dislocations, and/or cracks.

At the presence of a technological defect in the center of a ‘fish eye’ fatigue crack (a riser of a subtraction nature, i.e. pore or crack), the probability of formation of the fatigue crack of such type is maximum in the stage of developed plastic deformations, where straining is associated with the collective activity of plastic relaxation mechanisms. The ‘fish eye’ fatigue crack formation process also changes according to a parabolic dependence on the stress growth rate $V_e$ as the acting stress $\sigma_e$ changes together with the change of the hardening index $n$. When the activity of plastic relaxation mechanisms is weakening at the velocity $V_e$ tending to a maximum, the ‘fish eye’ fatigue crack formation process region overlaps with the region of initiation of brittle cracks. On the contrary, at the velocity $V_e$ tending to a minimum, the rate of the ‘fish eye’ fatigue crack decreases.

This is due to the transition to a less powerful vacancy mechanism of plastic relaxation at the top of the most dangerous riser. This also indicates the direct participation of plastic relaxation mechanisms in the process of the formation of the ‘fish eye’ fatigue crack itself. Additionally, the microstructure in the near-crack area of the metal is changing as well as the features of the fracture surfaces. Especially, when the high-cycle fatigue and mega-cycle fatigue regimes are achieved. In these regimes, the corresponding participating plastic relaxation mechanisms are also changing by limiting themselves to the vacancy mechanism. It is also confirmed by the decrease in the strain hardening coefficient. The above consideration points to the relation between the distinctive features of the relaxation processes that occurred during the fatigue tests with the strain rates and stresses, which regulate the activity
of the separate relaxation mechanisms and their collective activity. This also holds for the fracture process, including the ‘fish eye’ fatigue crack formation.

A couple of papers [11, 12] described the model that leads to a parabolic dependence of the generation of elementary carriers of plastic and brittle relaxations on the rate of change in the macroscopic force (load), i.e. on the growth rate of stresses ($V_{sg}$). The changes in the densities ($\rho$) of such elementary carriers of plastic and brittle relaxations as vacancies (1), dislocations (2), and cracks (3) are shown schematically in Fig. 1.

![Fig. 1. Scheme of parabolic dependences of the densities ($\rho$) of elementary carriers of plastic and brittle relaxation: - vacancies (1), dislocations (2), brittle cracks (3), grain boundaries (4) and cells (5) on the growth rate of the stresses concentrated at the vertices of the stress risers $V_e$.](image)

The processes of accumulation/annihilation of these elementary carriers depend both on the stress level concentrated at the stress risers’ vertices and on the interaction of these elementary carriers (vacancies/dislocations/cracks) and grain boundaries (4) or cells (5) [13, 14]. Fig. 2 shows the changes in the number of concentrators (K) and the strain hardening index (n) plotted dependently on the stress growth rate ($V_{sg}$).
Fig. 2. Scheme of parabolic dependences of the number of the stress risers (K) and the strain hardening coefficient (n) on the growth rate of the stresses concentrated at the vertices of the stress risers $V_e$ at different stages of microstructural formation and fracture on the stages of plastic relaxation, brittle-ductile transition (BDT) and structureless cleavage (SLC).

The correlation of the effective stress ($\sigma_e$) and the strain hardening index (n) at different rates of the stress growth ($V_{sg}$), i.e. in various stages of the microstructure rearrangement under tension is shown in Fig. 3. In Fig. 4, the stress growth rates in all stages of the microstructure rearrangement are compared with the features of the complete curve (Wohler curve) describing mechanical fatigue of polycrystalline materials [15].

Fig. 3. Scheme of the variation of the strain hardening coefficient (n) and acting stress $\sigma_e$ on the growth rate of the stresses concentrated at the vertices of the stress risers $V_e$. 
Fig. 4. Complete fatigue curve (Wohler curve) describing mechanical fatigue of polycrystalline materials and its correlation to the growth rate of the stresses concentrated at the vertices of the stress risers $V_e$.

Taking into account the change in the power and the number of two types of stress risers, i.e. the technological and microstructural stress risers [11], the influence of the surface morphology and near-surface microstructure of the steel samples underwent convenient turning and surface modification using high-frequency mechanical impact loading (ultrasonic impact treatment - UIT) was analyzed in details [16–20]. Following [11, 16, 17], the appearance of a powerful technological stress riser on the sample surface determines not only the position of the fatigue crack initiation site but also the sequence of the relaxation processes occurring on the microstructure stress risers (grain/cell boundaries, second phase particles, etc.) in the nearby area till to the occurrence of the strain localization at the macrolevel and further loss of mechanical stability.

Thus, analyzing the presented curves (Fig.1–Fig.4) and their applicability for describing experimental results [8, 11–13, 16–20] the following conclusions can be drawn:

1. Each stage of deformation of polycrystals, which is associated with the features of stress relaxation, corresponds to characteristic sections on the dependences of $n$ and $\sigma_e$ on the tension rate that have different inclination angles and
lengths. The section length is proportional to $V_{sg}$ (the growth rate of stresses concentrated at the vertices of the stress risers, which number (K) can be a variable (Fig.2, Fig.3).

2. In metallic materials, such staged dependences of n and $\sigma_e$ are due to both the activity of each of the relaxation mechanisms and their cooperative participation associated with the changes in the original grains and their boundaries during the formation of new microstructural elements – dislocation cells. The cell formation is accompanied by the return of the vacancy mechanism to the leading role in the strain accommodation owing to the grain/cell boundaries’ slip. The strain accommodation becomes easier due to severe refinement of the cell size at the developed plastic deformation stage.

3. The number of the sections and their inclination angles correspond to the dependences of n and $\sigma_e$ on the growth rate of stresses concentrated at the vertices of the stress risers $V_{sg}$ for the cases of tension (Fig. 3) and to the complete curve (Wohler curve) describing mechanical fatigue of polycrystalline materials (Fig.4). It is also matching the features of the fracture surfaces, and the observed changes in the structure of the original grains and their boundaries at the stages indicated by II – IV (Fig.4).

4. To construct a truly complete fatigue dependence, the stage ‘I’ in Fig. 4 should be represented following the behavior of $\sigma_e$ in (Fig. 3), i.e. by four ascending sections associated with the tendency of $\sigma_e$ to $\sigma_{br}$ (brittleness stress) in the low-cycle fatigue stage with the successive suppression of plastic relaxation mechanisms and predominance of brittle relaxation (crack initiation). This is accompanied by a significant increase in the growth rate of the stresses concentrated at the vertices of the stress risers $V_e$ (due to decreasing in the number of the stress risers and due to dominance of the most dangerous stress riser. Additionally, the strain hardening index (n) decreases too, and the ‘fish-eye’ fatigue crack is substituted by the appearance of brittle transcrysallite cracks (stage of quick crack propagation without the participation of the subtraction defects (pores, discontinuities)). The number of these transcrysallite cracks also changes following the parabolic relationship (Fig. 1).
5. The probability of formation of a ‘fish-eye’ fatigue crack (often referred to as a brittle crack or the 1-st stage of the crack propagation) is maximal in the presence of a technological riser in its center - a subtraction concentrator (pores, discontinuities). It is maximum in the region of developed plastic deformations and decreases with distance from the center of the stress riser as the activity of plastic relaxation mechanisms is suppressed. This confirms the direct participation of plastic relaxation mechanisms in the initiation of a ‘fish-eye’ fatigue crack.

6. The above consideration is general and can be used for the cases of mechanical fatigue, tribo-fatigue, and other types of tests. It can also be used to predict the durability of the tested materials.

References:
1. V.F. Terentyev, Fatigue strength of metals and alloys, Moscow: Intermet. Engineering: 2002 (in Russian).
2. AA Shanyavsky, Modeling of metal fatigue destruction. Synergetics in Aviation, Ufa: "Monograph" Ltd.: 2007 (in Russian).
3. MV Bannikov, Structural-kinetic mechanisms of destruction of metals in regimes of many and gigacycle fatigue. PhD thesis: Perm: 2004 (in Russian).
4. V.M. Matsevity, K.V. Vakulenko, and I.B. Kazak, On the difference between the mechanisms of destruction of metals under conditions of low-cycle and high-cycle fatigue, Problems of Mech. Eng. 17 (2014) 60–67 (in Russian).
5. VT Troshchenko, Mechanical fatigue of metals. Kiev: Naukova Dumka: 1983 (in Russian).
6. V. T. Troshchenko and L.A. Hamaza. Mechanics of diffuse fatigue damage of metals and alloys. Kiev: Institute for Strength problems NAS of Ukraine; 2016 (in Russian).
7. S.Kotsanda, Fatigue cracking of metals, Moscow:Metallurgy: 1990 (in Russian).
8. O.V. Sosnin, Evolution of structural-phase states in steels under fatigue and mechanical testing under current-pulse action. Dr. Sci.Thesis. Barnaul: 2004 (in Russian).
9. M. Mazari, B. Bouchouicha, M. Zemri, M. Benguediab, N. Ranganathan, Fatigue crack propagation analyses based on plastic energy approach, Computational Mater. Sci. 41 (2008) 344–349, https://doi.org/10.1016/j.commatsci.2007.04.016
10. N. Ranganathan, F. Chalon, S. Meo. Some aspects of the energy-based approach to fatigue crack propagation, Int. J. Fatigue 30 (2008) 1921–1929, https://doi.org/10.1016/j.ijfatigue.2008.01.010
11. P. Yu. Volosevich, Progress Metal Phys. 12 (2011) 367–382 (in Russian),
12. P. Yu. Volosevich, In. 5th Int. Conf. "Fracture Mechanics of Materials and Strength of Structures". Lviv, June 24 - 27. 2014. P. 157–166 (in Russian).
13. P. Yu. Volosevich, Hall-Petch dependence and micromechanisms of plastic deformation. Metallofiz. Noveish. Nechnol. 32 (2010) 413–422 (in Russian).
14. L.N. Larikov, Healing of defects in metals, Kiev: Nauk. Dumka: 1980 (in Russian).
15. L.A. Sosnovsky, Foundations of Tribost-Fatigue, Gomel: Belarus. GUT: 2003.
16. B.N. Mordyuk, G.I. Prokopenko, P.Yu. Volosevych, L.E. Matokhnyuk, A.V. Byalonovich, and T.V. Popova, Improved fatigue behavior of low-carbon steel 20GL by applying ultrasonic impact treatment combined with the electric discharge surface alloying, Mater. Sci. Eng. A 659 (2016) 119–129, https://doi.org/10.1016/j.msea.2016.02.036
17. G.I. Prokopenko, B.M. Mordyuk, P.Yu. Volosevich, S.P. Vorona, T.V. Popova, and N.O. Piskun, The structure and power of 20GL steel for electrospark with nickel and molybdenum and ultrasonic impact treatment, Metallofiz. Noveish. Nechnol. 39, No. 2 (2017) 189–208 (in Russian), https://doi.org/10.15407/mfint.39.02.0189
18. B.N. Mordyuk, G.I. Prokopenko, Yu.V. Milman, M.O. Iefimov, and A.V. Sameljuk, Enhanced fatigue durability of Al-6Mg alloy by applying ultrasonic impact peening: Effects of surface hardening and reinforcement with AlCuFe quasicrystalline particles, Mater. Sci. Eng. A 563 (2013) 138–146, https://doi.org/10.1016/j.msea.2012.11.061
19. B.N. Mordyuk, G.I. Prokopenko, K.E. Grinkevich, N.A. Piskun, and T.V. Popova, Effects of ultrasonic impact treatment combined with the electric discharge surface alloying by molybdenum on the surface related properties of low-carbon steel G21Mn5, Surf. Coat. Technol. 309 (2017) 969–979, https://doi.org/10.1016/j.surfcoat.2016.10.050
20. A.I. Dekhtyar, B.N. Mordyuk, D.G. Savvakin, V.I. Bondarchuk, I.V. Moiseeva, and N.I.Khripta, Enhanced fatigue behavior of powder metallurgy Ti-6Al-4V alloy by applying ultrasonic impact treatment, Mater. Sci. Eng. A 641 (2015) 348–359, https://doi.org/10.1016/j.msea.2015.06.072