ELECTRIC CURRENT EFFECT INVESTIGATIONS ON METAL FATIGUE LIFE

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ABSTRACT

The current loading effect on the process of fatigue metal destruction was considered. On the basis of the fatigue dislocation theory and electroplastic effect theory the mechahism of conductivity electrons effect on the fatigue process, explaining fatigue life reduction at DC current passage was proposed. We derived the equation connecting specimen lives at presence and absence of current effect. The result of theoretical and experimental investigation of current effect on electrical copper fatigue life and given. It has been proved that the difference between the specimen lives with current and without it was quite essential and in multicycle region it was from 20% to 50%.

KEYWORDS

Fatigue , electric current, dislocation, theoretical and experimental investigations, life, copper, results.

INTRODUCTION

Problem. Transport facilities electrical equipment is exposed to the effects of dynamic and electrical loads in the process of operation. Especially intensive vibrating and shok effects, non-stationary current loads effect the electrical traction machines of locomotives and thus current conducting element failures are about 20% out of total electrical equipment failures. Taking into account the increased requirements to the traction electrical equipment reliability due to the railway safty provision the investigations of elecIric current passage effect on current conducting element fatigue life is of practical interest.

For example, Troshchenko and Sosnovsky, in their previous works, showed the effect of different operationg factors, including temperature, cycle asymmetry, loading frequency etc on metal fatigue strength. However the electric current effect pertinent to current conducting elements of electrical equipment is inadequately studied. Along side with it, it is necessary to distinguish the work by Isaev et al (1984) in which the current effect was connected with loading cycle asymmetry occurrence resulting in the change of electrical equipment element fatigue strength and the work by Spitsyn and Troitsky (1985) in wich conductivity electrons effect on metal plastic deformation was investigated. However the latter does not deal with the current effect on fatigue strength .

This work deals with the problem to evaluate the current effect on metal fatigue life while neglecting such factors as additional stresses occurrence and change of metal mechanical properties connected with the temperature rise passage of current.

Nature of Current Effect on Fatigue. To describe the physical processes occurring in the conditions of joint mechanical and current loading let us use the fatigue destruction dislocation theory. As is known dislocation movement occurs in metal under the effect of cyclic stresses. With the account of Konaev's work (1991) showing that the plastic deformation under electric current impulse actions is realized on to dislocation due to the direct energy transmition of electrons conductivity, it is possible to assume that the electric current effect stimulates the dislocation movement in metal.

Let us assume conditionally that the direction of DC current coincides with dislocation movement direction at positive cycle voltages. Then if the first quarter of symmetric cycle dislocation displasement have occured under the influence of applied mechanical stress while in the second quarter the conductivity electrons movement energy serves as an additional barrier to dislocation portion return. In the third quarter of the cycle the loading takes place at negative mechanical loading striving to return dislocation to their source. Along side with this a partial dislocation return may occur but the energy of conductivity electrons increases the potential barrier impeding the dislocation return. During the following up cycles the similar processes occur accompanied with dislocations number increase and speed of their displacement.

Thus the analysis of mechanism proceeding from the dislocating theory of fatigue destruction and electroplastic effect allows to assume, that the electric current effect at metal cycle loading leads to the acceleration of fatigue destruction processes.

RESULTS

Analytical Estimation. .For analytical estimation of current effect on fatigue life the energy theory of fatigue destruction utilizing the well known analogy between processes of fatigue destruction and metal melting suggested by Ivanova (1978) is being proposed.

When there is no current let us write down the equation of mechanical loading specific energy before destruction and melting.

$$E_p^m = \frac{\sigma_p^2}{2E} N_p = E_{m} \quad , \tag{1}$$

where σ_p - mechanical stress; E - elasticity modulus ; N_p - loading cycle number before destruction.

At simultaneous current and mechanical loading let us choose the mechanical load similar to that as during the test without current i.e $\sigma_p^{m+i} = \sigma_p$. Then the energy balance may be represented as

$$E_p^{m+i} + E_i = E_{m} \quad , \tag{2}$$

where - E_p^{m+i} specific energy of mechanical loading at joint mechanical and current effects; E_i - current loading specific energy.

Equation (2) may be written as

$$E_p^{m+i} = \sigma_p^2 N_p^i / 2E = E_{m} - E_i \quad , \tag{3}$$

where N_p^i- cycle number before destruction simultaneous effect of vibration and current.

Having divided the equation (3) for (1), after a little manipulation yields the equation connecting the life at test under current and when it is absent

$$N_p^i = \alpha N_p \quad , \tag{4}$$

where

$$\alpha = 1 - E_i / E_{m} \tag{5}$$

Factor α changes from zero to one whereas the critical values assume in these cases

$\alpha \cong 1$,if $E_i << E_{m}$,then $N_p^i \cong N_p$

$\alpha = 0$,if $E_i = E_{m}$,then $N_p^i = 0$

In the first case lives are equal as specific energy of current loading is small and it does not sufficiently influence the fatigue life. From the phisical point of view the second case may be interpreted as instant metal destruction at intensive current loading, i. e. $N_p^i = 0$

Let us represent the specific energy of current energy by means of the full energy

$$E_i = E_i^n / v_0 = Pt / v_0 \tag{6}$$

Substituting power as $P = i^2 R$ into (6),time of load action before destruction $t = \frac{N_p^i}{f}$ as,where f -loading frequency ahd passing over to specific values yields

$$E_i = j^2 \rho N_p^i / f \tag{7}$$

where j - current density;ρ - material resistivity.

Then the equation, connecting spencimens life under current N_p^i with the life without current load N_p yield after substitution (7) into (4) and solving the latter relative to N_p^i

$$N_p^i = \frac{N_p}{1 + k N_p} \tag{8}$$

where

$$k = j^2 \rho / f E_{m}$$

Equation (8) is a fractional linear function the plot of which is a equangular hyperbola with the center in origin of coordinates and one horizontal level asymptote $1/k$.

Only hyperbola semibranch located in the first quarter is of physical meaning as N_p^i and N_p,can be of positive values only. It is characteristic that with the increase of current density the

$1/k$ level decreases and the difference between lives will appear at their reduced values.

The analysis of dependence (8) showed that in the region of cycles small bases ($N_p < 10^5$) the current effect is insignificant and does not execed 5 - 10% while in the region of multicycle fatigue the difference can be great reaching 50% and more.

The increase of vibrating loading frequency results in decreasing of current influence on fatigue which is connected with the time reduction of current load application and thus the mechanical loads contribute greatly to the process of the test specimens destruction. Analysing its influence on the life of ρ and $E_м$ parameters included in the equation (8) it should be noted that they are sufficiently stable material characteristics, electrical copper in particular. When testing other materials the estimation of material specific resistance effect ρ and melting specific energy $E_м$ on fatigue life for designed current density and loading frequency can be fulfilled on the basis of the equation obtained.

Experimental Data. .To comfirm the mentioned assumptions the experimental analyses were carried out at the УВЭ-100/5-3000М vibrational electrodynamic mount.

Comparative single - level tests with and without current passage were accomplished. Specimens current loading were conducted from the ВАК - 1600 ДС lowvoltage source.

A real element of traction electrical machine was subjected to investigations as well as smooth and notched busses made of the ШММ 25x8 GOST 434-78 electric copper. At cycle stresses levels and 2-4 A/mm² current density designed for each experiment the number of cycle up to utter specimens destruction with and without current was recorded in the process of tests. To exclude the temperature effect the test were executed at the specimens temperature of 70 - 100 C° with the employment of loading diagrams excluding the temperature deformation of specimens.

The increase of accuracy and reliability of test data was performed due to use of multispecimen mounts permitting to test from 4 to 16 specimens and also due to the algorithm of results static data processing. The static analysis included: determination of specimens number for the obtaining of the designed accuracy calculation of point assessments and parameters confidence limits of a priori adopted logarithmically normal low of distribution, rejecting the sharply singling-out results on Grubbs's criterion and assessment of randomnesses in discordence of specimens life average values without current N_p and with current N'_p .The results of static analysis are given in the table.

Results of experimental investigations

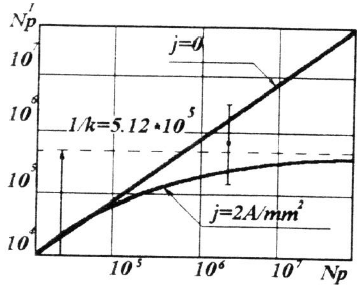
Test specimen	Fatigue life characteristics in numerator - test of specimens without current load in denominator - test of specimens under current Average value and 95% confidence interval $\lg N_{min}$ $\lg \bar{N}$ $\lg N_{max}$	Probability that lives difference $\lg\bar{N}_p - \lg N'_p$ is "random"
Real element	6,076 6,204 6,333	0,088
	5,525 5,856 6,192	
Smooth specimen	6,195 6,229 6,268	0,021
	5,569 5,997 6,318	
Notched specimen	6,477 6,629 6,782	0,033
	6,394 6,518 6,642	

The analysis of experimental data showed that discordence of life average values happened to be substantial in two cases as probability $P(|\lg N'_p - \lg N_p|) < 0,05$, and in one case during the test of real element these average values are random at significance level of 0.05 and significant at significance level of 0.1.

The great spread in results obtained is connected with the fact that on one hand the specimens made of copper which fatigue characteristics have a great instability were subjected to the test and on the other hand the test were carried out in region of multicycle fatigue characterized by substantial spread of lives.

Comparison of exeperimental and calculated data given in the Figure shows that though the experiment showed significant differences of specimen lives with and without current these differences are less significant than it is predicted according to the theoretical curve (8). Apparently it is connected with the fact that a portion of current loading energy is directed in increase of dislocations density and speed of their movement whereas the other portion leads to the Jole metal heating. The latter leads to the increase of the heat oscillations intensity of the crystal lattice resulting in additional energy decrease which would lead to the increase of density and speed of movement of dislocations.

Conclusion. .The results of the theoretical and experimental investigation allow to conclude that electric current effect at cyclic loading leads to the acceleration of fatigue destruction processes and thus it must be taken int account during calculations and tests for the fatigue of electrical equipment current conducting elements.



Current loading effect on fatigue of copper specimens. (The point indicated the average value and 95% confidential interval of smooth specimen lives).

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