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Methods for Vibration Reducing in the Structural Elements of Vehicle Electrical Equipment

Abstract. *Methods are presented for increasing the reliability and operational durability of parts of electrical equipment of vehicles subjected to vibration and shock loads, produced by casting, sintering, and cold stamping from thin sheet materials. Additionally, optimization of their structural state, required quality and maintaining the stability of the magnetic properties of parts during operation are considered.*

Streszczenie. *Przedstawiono metody zwiększania niezawodności i trwałości eksploatacyjnej części wyposażenia elektrycznego pojazdów mechanicznych narażonych na obciążenia wibracyjne i udarowe, wytwarzanych metodą odlewania, spiekania i tłoczenia na zimno z materiałów cienkowarstwowych. Dodatkowo uwzględnia się optymalizację ich stanu strukturalnego, wymaganą jakość i utrzymanie stabilności właściwości magnetycznych części podczas eksploatacji.(**Metody redukcji wibracji elementów konstrukcyjnych w wyposażeniu pojazdu elektrycznego)***

Keywords: vibration loads, shock loads, material grain size, electrical equipment of vehicles.
Słowa kluczowe: obciążenia wibracyjne, obciążenia udarowe, wielkość ziarna materiału, wyposażenie elektryczne pojazdów

Introduction

In modern conditions, it is advisable to design, manufacture and modernize electrical equipment taking into account operational factors, namely, it is necessary to ensure the required durability, power supply (the number of electrical equipment and its power), and the elimination of serious accidents.

It should be noted that electrical equipment of air transport operates in more difficult conditions, which include high temperature differences, sudden changes in pressure, significant overloads, exposure to aggressive environments, etc. In some cases, the causes of serious accidents and a decrease in the trouble-free operation of such equipment are vibrations, frequency of switching on, and shock loads. In addition, tangential and normal vibrations cause increased wear of friction elements and lead to instability in the operational characteristics of electrical equipment. Vibration and shock loads have the greatest impact on the service life and operating efficiency of electrical equipment. Under operating conditions, these loads arise during transportation, exposure to operating units, fan blowing of units, and friction.

In the production, repair and operation of electrical equipment of vehicles, first of all, attention is paid to parts that are susceptible to fatigue failure under vibration loads. These are thin-sheet parts made of electrical steels, cast and products produced by powder metallurgy from hard magnetic materials.

Increasing the vibration strength of these parts while maintaining their magnetic properties is an extremely urgent task. This requires improvement of sheet stamping technologies, rational selection of materials and hardening treatment of cast parts and parts produced by casting. In this case, it is necessary to take into account the preservation of the stability of magnetic properties during production and operation under vibration loads.

Therefore, the purpose of the study is to increase the reliability and operational durability of electrical equipment parts of vehicles subjected to vibration and shock loads.

Research materials

The main reasons for reducing the service life and reliability of vehicles electrical equipment are the suboptimal organization of production, as well as parts testing, taking into account the influence of external operating conditions and the interaction of units. The organization of production is associated with the receipt of workpieces, materials, raw materials, and assembly processes. Reliability elements are laid down from the moment of ore processing to the moment of inspection and testing; at all stages of processing materials and workpieces, not only defects are eliminated, but also new ones are introduced that affect the magnetic properties and vibration strength of steels.

Electrical machines and devices use hard and soft magnetic steels and alloys, magnetodielectrics, non-magnetic steels and cast irons. Typical representatives of thin-sheet parts made of soft magnetic materials are shown in Fig. 1.

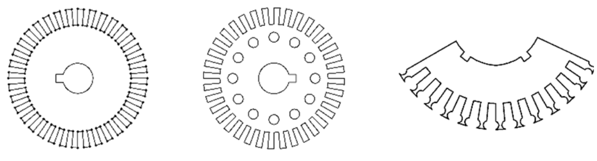

Fig. 1 – Thin sheet parts made of electrical steel: a) armatur. sheet; b) rotor sheet; c) generator stator sheet segment

Vibration strength, including fatigue strength, depends to the greatest extent on the grain size of the alloy material. The optimal structure of hard magnetic alloys is martensite (with soft particles of cementite and carbides).

Technological processing methods that ensure grain refinement, increase in hardness, strength (including fatigue and vibration) of the alloy, simultaneously increase the magnetic field strength.

Control the structure of hard magnetic materials produced by the method of manufacturing parts from melts is implemented in rheo- and texol casting technologies. When producing parts by sintering, it is advisable to use technologies that include additional low-intensity pulse loading [1-3] and methods of hardening by cold plastic deformation. However, the question remains open whether there is an optimal grain size at which the vibration strength of the alloy is maximum. To achieve this, it is proposed to use dependencies d_{opt} , derived from the Yokobori theory [4]. This made it possible to determine the optimal value of the grain size that provides maximum vibration strength:

$$d_{opt} = \frac{(\alpha E)^2 \varepsilon_0}{\tau_i^2} \quad (1)$$

where $\tau\tau$ – stress corresponding to the resistance to dislocation motion; α E – critical value of total stress; ε_0 – width of the maximum apparent voltage range.

The optimal value of the grain size does not correspond to the critical value at which the coercive force of hard magnetic materials increases [5,6]. The grain size corresponds to the dimensions of the submicroscopic structure of the material [7]. Tracking the grain sizes formed in the technological process and under vibration loads is performed using a relationship that is a function of strain rate, temperature and initial metal grain size [8].

(2) $\varepsilon_p = a_1 d_0^{n_1} \dot{\varepsilon}^{m_1} exp\left(\frac{Q_1}{RT}\right) + c_1$;

where $\varepsilon_c = a_2\varepsilon_p$ - average strain value [9]; ε_p – peak strain; a_1 , n_1 , m_1 , c_1 , a_2 – material constants; d_0 – original grain size (mm); $\dot{\varepsilon}$ – strain rate (s^{-1}); Q – activation energy (kJ/mol); R – gas constant; T – metal temperature, K.

To establish the connection between the magnetic properties of a material and the grain size, strain value and strain rate, the magnetization equation [8, 11] is used.

(3) $\mu_r = \frac{N^2}{3RT}\mu_0 \left(\mu_b\right)^2$

where μ_r – relative magnetic permeability; μ_0 – vacuum magnetic permeability, $\mu_0 = 4\pi\cdot 10^{-7}$ (Gn/m); μ_b – Bohr magneton, $\mu_b = 9,27\cdot 10^{-24}$ (a·m^2); N – number of atoms with uncompensated spins per unit volume; T – temperature, K.

Taking the logarithm of equation (3) we obtain the value of the product RT . Substituting the value RT into equation (4) we find the dependence of the relative magnetic permeability on the grain size:

(4) $\mu_r = \frac{N^2\mu_0\left(\mu_b\right)^2}{3\left(-en\varepsilon_p + ena_1 + n_1 end_0 + m_1 en\dot{\varepsilon} + Q\right)}$

The value of deformations $\varepsilon_p < 0,02$ and grain size $d_0 < e$, where e is the exponent. We establish that an increase in deformation leads to a decrease in magnetic permeability, and an increase in grain size leads to its increase. An increase in the strain rate reduces the relative magnetic permeability. Therefore, preference should be given to static methods of deformation of soft magnetic materials.

To determine the peak strain and strain rate, we use the magnetoelasticity equations [12]. In this case, it is much easier to take the limiting strain during elastic deformation as the peak strain.

Let us determine the intensity of deformation of a vibrating thin round plate clamped along the contour ψ (Fig. 2). The equation of the middle surface under elastic and elastoplastic deformation is approximated with a fairly high degree of accuracy by an even fourth-order polynomial. The equation of the middle surface at the moment of time corresponding to the maximum amplitude of oscillations during vibration has the form:

(5) $y_2 = f\left(y_1\right) = a + b_1 y_1^2 + b_2 y_1^4$

where y_2 , y_1 – coordinates of the plates middle surface; a , b_1 , b_2 – constants.

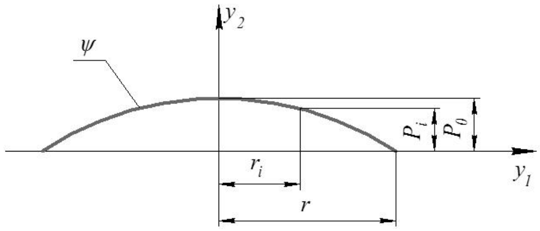

Fig. 2 – Vibrations of a thin elastic plate clamped under a contour ψ (P_0 – maximum amplitude of oscillations during vibration; r – radius of the plate; r_i and P_i – coordinates of the intermediate point in the interval $0 \geq y_2 \leq P$)

Let's consider that when $y_1 = 0$, $y_2 = P_0$; when $y_1 = r$, $y_2 = 0$; when $y_1 = r_i$, $y_2 = P_i$.

From equation (6) and boundary conditions it follows:

$$c_1 = \frac{P_i - P_0}{r_i^2} - \frac{r^2\left(P_i - P_0\right) + r_i^2 P_0}{P_0^2\left(P_i^2 - P_0^2\right)} ;$$

$$c_2 = \frac{P_0^2\left(r_i - r\right) + P_i^2 r}{P_0^2 P_i^2\left(r_i^2 - r^2\right)} .$$

The components of the metric strain tensor have the form:

$$q_{11} = 1 + \frac{\partial P_i}{\partial y_1} ; \ q_{12} = \left(\frac{\partial P_i}{\partial y_1}\right)^2 .$$

While $q_{11}^2 = \left(\frac{\partial P_i}{\partial y_1}\right)^2$ и $q_{11}^2 + 4q_{12}^3 = \left(\frac{\partial P_i}{\partial y_1}\right)^4$.

Getting the deformation values:

$$\varepsilon_{11} = ln\sqrt{1 + \left(\frac{\partial P_i}{\partial y_1}\right)^2} ; \ \varepsilon_{12} = -ln\sqrt{1 + \left(\frac{\partial P_i}{\partial y_1}\right)^2} ,$$

strain intensity

$$\varepsilon_i = \sqrt{\left(\varepsilon_{11} - \varepsilon_{12}\right)^2} .$$

The maximum value of the elastic deformation work:

(6) $A = 0.5\varepsilon_i \cdot \sigma_e$

where A – deformation work; σ_e – elastic limit.

Assume that all the energy of elastic deformation is converted into heat. Then the plate temperature will increase by

(7) $\Delta T = \frac{k\sigma_e}{\rho_0 m_0 c} ln\frac{1}{1-\varepsilon}$

where ΔT – temperature increase; k – thermal equivalent of work; ρ_0 – material density; m_0 – relative mass of thermal conductivity; c – specific heat.

Substituting the found values ε_i and ΔT in equation (3) we determine the change in grain size. A decrease in grain size indicates a deterioration in the magnetic properties of the material. The distribution of grain sizes along the radius of the core disk is shown in Fig. 3.

The coarse-grained structure of silicon electrical steels helps to increase magnetic permeability and reduce eddy current losses. However, large grains significantly reduce the vibration strength of products made from silicon electrical steels. It should also be noted that hard magnetic materials have high magnetic stability. Residual magnetic induction does not decrease over time. The coercive force causing demagnetization is quite large. Additional cold plastic deformation of products after their manufacture increases their magnetic stability. Consequently, vibration effects do not affect the magnetic stability of these materials, however, work hardening and residual stresses are removed. This leads to a decrease in vibration strength.

Figure 3 – Grain size distribution

Regarding soft magnetic materials, it can be noted that vibrations have a negative impact on both operational durability and magnetic properties. The reason for this is the low value of the residual induction, so the relaxation time constant is very small. Soft magnetic materials have high magnetic permeability and low saturation induction, which is necessary for their demagnetization. The coarse-grained structure of silicon electrical steels helps to increase and reduce eddy current losses. However, large grains significantly reduce the vibration strength of products made from silicon electrical steels.

The increased fragility and hardness of these steels are associated with the need to use expensive equipment and technological equipment. In addition, these alloys are characterized by low impact strength and vibration strength. The performance characteristics and vibration strength of electrical and electronic products made from thin-sheet soft magnetic material largely depend on the accuracy of stamping and the size of the burr. Known methods for reducing and eliminating burrs, such as cutting with a stepped punch with transverse upsetting, heating or cooling of workpieces with rounding of the cutting edge of the matrix, lead to hardening and hardening of the surface layer of the workpiece. This significantly increases losses due to hysteresis and eddy currents. In this case, it is more effective to use mechanical error compensators of the "press-stamp" system [5]. High quality indicators and stable magnetic properties are achieved when cutting sheet parts with the implementation of a vibro-plastic effect.

It should be noted that the largest amplitude of oscillations during vibration occurs in the teeth of the segment of vehicle generators. The area of these elements is insignificant. After annealing, it is proposed to perform their local deformation to increase their vibration strength. The presence of a local fine-grained structure prevents the process of dispersion of large grains. During operation, after 10^4 loading cycles, local grain growth of a fine-grained structure occurs with an increase in the magnetic permeability of the material. At the same time, a gradual decrease in vibration strength has virtually no effect on the stability of the magnetic properties of soft magnetic materials and the service life of the product.

It is possible to significantly increase the vibration strength of soft magnetic materials used in electrical products by using amorphous alloys. These alloys reduce heat and electrical losses by an average of 75%.

Practical recommendations and experimental verification

Samples of silicon steels made using the technologies under consideration and traditional ones were tested for vibration strength. The tests were carried out under alternating symmetrical bending, with a load along the fibers. The number of samples is 20 (Table 1).

Table 1 – Vibration strength test results

Material	Manufacturing method	Vibration strength (without destruction)		Number of samples brought to destruction
		Deflection, mm	Number of cycles, 10^6	
Thin sheet electrical steel	Cutting	2	14	11
	Cutting with transverse upsetting of teeth	2	20	15
	Cutting with compensation of the 'press-die' system	2	18	14
	Cutting with the implementation of the vibroplastic effect	2	20	18
Amorphous material	Ultrafast crystallization	2	24	18

The highest vibration strength was shown by samples made of amorphous steel and those obtained by cutting with transverse upsetting. The vibration strength of samples made using traditional cutting technologies was 20-25% lower. The choice of the final option in relation to the cases under consideration is made by determining the optimal reliability while increasing the requirements for production technology.

For example, consider the generator stator sheet (Fig. 1c). The optimal reliability of the generator stator sheet segment is determined by the dependence

(8) $$\alpha_{opt} = 0.805\sqrt{\frac{C_t\lambda_{\max}\left(1-P_1\right)\cdot ln\left(1-P_1\right)^{-1}}{C_p P_1 \tau}} \qquad)$$

where C_p – total costs per part; C_t – costs per vehicle trip; $\lambda_{\max}$ – failure rate value in laboratory conditions [6]; P_1 – probability of achieving the target task; τ – uptime.

The costs of producing thin-sheet parts by cutting, cutting with transverse upsetting, cutting with the implementation of the vibro-plastic effect vary within ±20-25%. The presence of failure rates is minimal for the transverse settlement cutting process.

For other cutting processes it is 40-50% higher. The probability of achieving the target task for all cutting processes and the use of segments from amorphous material lies within $0.8 \le P_1 \le 0.96$ .The value (C_p / C_t) for segments made of amorphous material is 18-20 times lower than the values for parts obtained by cutting. It follows from this that the cutting process with transverse draft of teeth is the most reliable.

The reliability analysis carried out showed the feasibility of manufacturing plates, the teeth of the segments of which, during cutting, are deformed with transverse settlement. It is advisable to strengthen products made from hard magnetic materials using plastic deformation methods that exclude heating of the part. This is waterjet or vibroabrasive hardening. The stability of the magnetic properties of soft magnetic materials under vibration influence under operating conditions is ensured by alloying electrical steels with materials that prevent grain growth during hardening.

Conclusion

The optimal structure (grain size) of hard magnetic steels and alloys has been determined, providing high vibration strength and the required high values of residual magnetic induction. The maximum vibration strength of soft magnetic materials is achieved in the manufacture of parts of electrical machines and devices from amorphous alloys. It is more economically feasible to use cutting methods for manufacturing that preserve the coarse-grained structure of the workpiece material. In this case, it is advisable to produce the elements of the part: teeth, supporting protrusions, which are subject to the greatest degree of vibration, by cutting with transverse compression.

The most effective method for producing thin-sheet blanks with segment teeth is finishing cutting, ensuring transverse upsetting of the segments.

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REFERENCES

1. M. Zagirnyak, V. Drahobetskyi, (2015) New methods of obtaining materials and structures for light armor protection, *International Conference on Military Technologies (ICMT*), Brno, Czech Republic, 2015, pp. 1-6, doi: 10.1109/MILTECHS.2015.7153695.
2. Dragobetskii, V., Zagirnyak, M., Naumova, O., Shlyk, S., & Shapoval, A. (2018). Method of Determination of Technological Durability of Plastically Deformed Sheet Parts of Vehicles. *International Journal of Engineering & Technology*, 7(4.3), 92-99. https://doi.org/10.14419/ijet.v7i4.3.19558
3. V. Drahobetskyi, D. Moloshtan, A. Symonova, A. Nikitina, M. Zagirnyak (2024) Durability and Wear Resistance of Sliding Electric Contacts in Electric Transport, *Przeglad Elektrotechniczny*, pp. 275-278, doi: 10.15199/48.2024.01.57
4. Takeo Yokobori (1970) An Interdisciplinary Approach to Fracture and Strength of Solids. *Wolters-noordhoff scientific publications LTD.* Groningen, p. 264.
5. Hrudkina, N., Aliieva, L., Markov, O., Marchenko, I., Shapoval, A., Abhari, P., & Kordenko, M. (2020). Predicting the shape formation of hollow parts with a flange in the process of combined radial-reverse extrusion. *Eastern-European Journal of Enterprise Technologies*, 4(1 (106), 55–62. https://doi.org/10.15587/1729-4061.2020.203988
6. Markov, O., Gerasimenko, O., Aliieva, L., & Shapoval, A. (2019). Development of the metal rheology model of high-temperature deformation for modeling by finite element method. *EUREKA: Physics and Engineering*, (2), 52-60. https://doi.org/10.21303/2461-4262.2019.00877
7. Kukhar, V., Kurpe, O., Klimov, E., Balalayeva, E. & Dragobetskii, V. (2018). Improvement of the method for calculating the metal temperature loss on a Coilbox unit at the rolling on hot strip mills*, International Journal of Engineering and Technology(UAE),* vol. 7, no. 4, pp. 35-39. https://doi.org/10.14419/ijet.v7i4.3.19548
8. Zhbankov Ya. G. (2014) Modeling changes in the microstructure of metal in the process of hot plastic deformation, *Bulletin of NTU "KhPI",* No. 44 (1087), pp. 34-39.
9. Mirzak V., Bokov V. (2016) The principle of dynamic adjustment as a method of moving the core of thin-sheet section stamping, Konstruiuvannia, vyrobnytstvo ta ekspluatatsiia silskohospodarskykh mashyn: zahalnoderzhavnyi mizhvidomchyi naukovo-tekhnichnyi zbirnyk. Vyp. 46. – Kirovohrad: KNTU, 2016. – S. 245-258., iss. 46, pp. 245-258.
10. Markov, O.E., Kukhar, V.V., Zlygoriev, V.N., Shapoval, A.A., Khvashchynskyi, A.S. & Zhytnikov, R.U. (2020), Improvement of Upsetting Process of Four-Beam Workpieces Based on Computerized and Physical Modeling, *FME Transactions*, vol. 48, no. 4, pp. 946-953. DOI: 10.5937/fme2004946M
11. Dragobetskii, V., Zagirnyak, M., Naumova, O., Shlyk, S., & Shapoval, A. (2018). Method of Determination of Technological Durability of Plastically Deformed Sheet Parts of Vehicles. *International Journal of Engineering & Technology*, 7(4.3), 92-99. https://doi.org/10.14419/ijet.v7i4.3.19558
12. Belas, E., Bogoboyashchyy, V.V., Grill, R., Izhnin, I.I., Vlasov, A.P. & Yudenkov, V.A. (2003), Time relaxation of point defects in p- and n-(HgCd)Te after ion milling, *Journal of Electronic Materials*, vol. 32, no. 7, pp. 698-702. https://doi.org/10.1007/s11664-003-0055-9