Determination of the Boundaries of the Non-Magnetic Phase of the Dual-Phase Magnetic Material of the Starter-Generator Rotor

Vyacheslav Vavilov[1], *Flyur* Ismagilov[1], *Oksana* Yushkova[1], *Egor* Pronin[1,*] and *Alexey* Zherebtsov[1]

[1]Ufa University of Science and Technology, Ufa, Russia

Abstract. Dual-phase magnetic material - a magnetic material in which, by processing, localized non-magnetic areas can be obtained to control the direction of the magnetic flux. Such properties can significantly improve the output characteristics of a number of topologies of electrical machines, as well as neutralize a number of the main disadvantages inherent in traditional designs of electrical machines. This paper presents a numerical study of the strength characteristics of the rotor of an electric starter-generator with permanent magnets with a dual-phase magnetic material. The optimal boundaries of racks for processing in the non-magnetic phase are determined.

1 Introduction

The development of the electrical industry has led to a rapid expansion of the use of electrical machines and power electronics [1,2] in various industries. At the same time, the automotive and aviation industry makes serious demands on the output characteristics of electrical machines [3,4]. Every year, the requirements become more stringent, which leads to the complication of the design and manufacture of electrical machines [5]. It should also be noted that it will become practically impossible to achieve breakthrough results in the specific characteristics of electrical machines by traditional means and methods in the near future without the use of new approaches to the design and development of new promising materials [6, 7]. One of these materials is a dual-phase magnetic material, the local areas of which, after a certain treatment, acquire non-magnetic properties, which makes it possible to control the direction of the magnetic flux [7].

Currently, increased attention is paid to the production of dual-phase magnetic materials using nitriding. The bottom line is this: the area, which should retain its magnetic properties, is protected from the nitriding process, while the planned non-magnetic area remains completely open to diffuse surface changes in a nitrogen-rich environment. For the non-magnetic region, there is a significant decrease in magnetic characteristics and a significant increase in strength properties. At the same time, in the magnetic region, an insignificant drop in electromagnetic properties is observed, but a rather noticeable drop in

---

[*] Corresponding author: pronin.ea@ugatu.su

strength properties, which should be taken into account when designing electrical machines with dual-phase magnetic materials [8, 9].

This article presents a study of the influence of the boundaries of the location of the non-magnetic phase in the rotor legs with internal permanent magnets on the strength characteristics of the rotor.

2 Model under study

As an object of study, a starter-generator with internal permanent magnets is used. The choice of the type of electrical machine is due to the high specific and output characteristics of electrical machines of this type [10]. This is confirmed by the works, where a comparison was made of electrical machines with permanent magnets with other topologies, where electrical machines with internal permanent magnets showed their incomparable advantage [11, 12].

The case of processing a central non-magnetic rack between permanent magnets is considered (Fig. 1).
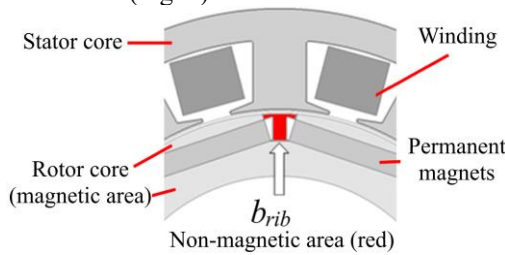

Fig. 1. Non-magnetic area (red color).

As a reference point, the result of the calculation of an electrical machine is taken, with a rotor speed of 6000 rpm with a rotor made of traditional electrical steel, providing the necessary electromechanical characteristics. Then, an electrical machine with a rotor made of a dual-phase magnetic material is calculated, its strength characteristics are evaluated at various values of the boundaries of the non-magnetic section. The use of a dual-phase magnetic material increases the safety factor of the material, which makes it possible to increase the rotor speed due to the available safety factor. The study is carried out in software using the finite element method.
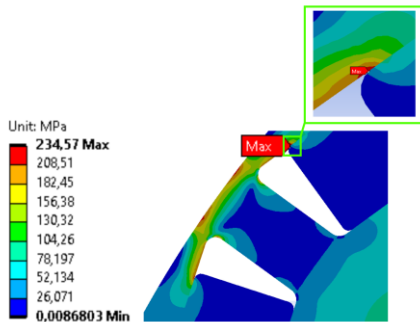
3 Strength calculation

The results of the strength calculation of the rotor of an electrical machine at 6000 rpm are shown in Fig. 2.
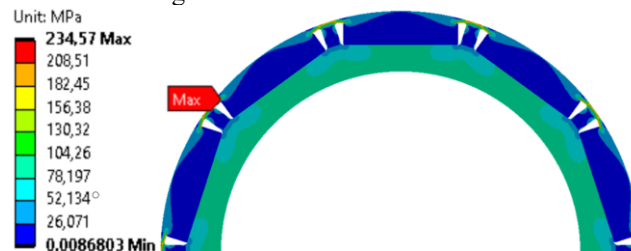
Fig. 2. Strength calculation results (rotor).

As can be seen from a more detailed examination (Fig. 3), the highest stresses are observed in the upper region of the rotor and amount to 234.6 MPa.

**Fig. 3.** Detailed examination of the most loaded area.

The general results of the calculations performed are summarized in Table 1.

Table 1. Strength calculation results.

Parameters	Traditional electrical steel
Yield strength, MPa	344.7
Maximum stress, MPa	234.57
Safety factor	1.47

As can be seen from the calculation results, traditional electrical steel provides the necessary safety factor, but at the lower boundary.

The highest stresses are observed in the area of contact between the edge of the permanent magnet and the magnetic core of the rotor: in the area of the transition of the magnetic phase into the non-magnetic one. An increase in strength in this area can be achieved by using a dual-phase magnetic material, however, it is necessary to determine the processing boundaries (Fig. 4) so that the magnetic phase does not fall on the most stressed area.
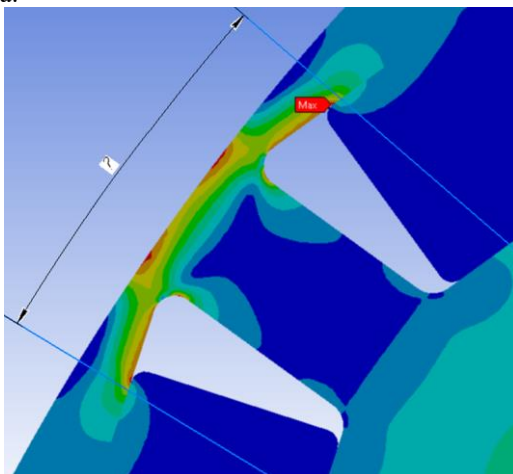
Fig. 4. To the definition of processing boundaries.

The boundaries of the section with a non-magnetic phase, the stresses in it and the safety factor are determined. The assessment is carried out according to the characteristics from Table 2. The results of the calculation are summarized in Table 3.

Table 2. Characteristics of dual-phase magnetic material [7].

Parameters	Dual-phase magnetic material	
	Magnetic phase	Non-magnetic phase
Yield strength, MPa	276	565.4
Maximum stress, MPa	161.61	233.89

Table 3. Factors of safety factor depending on the boundaries of material processing.

Parameters	Boundaries of non-magnetic area (in angular dimension, degree)						
	8.4	8.6	8.8	9	9.2	9.4	9.6
Maximum stress in non-magnetic phase, MPa	208.51	208.51	234.57	234.57	234.57	234.57	234.57
Maximum stress in the magnetic phase, MPa	208.51	234.57	234.57	234.57	208.51	182.45	156.38
Safety factor (magnetic phase)	1.32	1.18	1.18	1.18	1.32	1.51	1.77
Safety factor (non-magnetic phase)	2.71	2.71	2.41	2.41	2.41	2.41	2.41

As can be seen from the calculation results, unlike traditional electrical steel, a dual-phase magnetic material, due to the selection of optimal processing boundaries, withstands specified loads with a width (in angular measurement) of a non-magnetic section of 9.4 degrees or more. It should be noted that even a tenth of the angle when determining the boundaries of a dual-phase magnetic material has a significant impact on the strength characteristics of an electrical machine. In view of the foregoing, the most optimal for the electrical machine under consideration is the size of the boundary of the non-magnetic section of 9.6 degrees.

4 Conclusion

This article investigates the influence of the boundaries of the non-magnetic phase sections of a dual-phase magnetic material in the rotor of an electrical machine with internal permanent magnets on the strength characteristics of the rotor. Calculations were made for electrical machines with a rotor made of traditional electrical steel and with a rotor made of dual-phase magnetic material. The optimal boundaries of non-magnetic sections in a rotor made of a two-phase magnetic material are determined, which make it possible to obtain an increase in the safety factor of the material in the most loaded section.

References

1. I. Yamalov, R. Urazbakhtin, S. Sharafutdinov, I. Zubkov, L. Levchenko, A. Sultanov, A. Varyukhin, M. Urakseev, To the question of the approach to the aviation modern and advanced electrical machines electronics units design for-mation. 2021 Int. Conf. on Elec. Comp. and Syst. (ICOECS) (2021) doi: 10.1109/icoecs52783.2021.9657316

2. A. Barzkar, M. Ghassemi, Electric power systems in more and all elec-tric aircraft: A review. IEEE Access **8**, 169314-169332 (2020) doi: 10.1109/ACCESS.2020.3024168

3. P. Ramesh, N.C. Lenin, High power density electrical machines for electric vehicles—Comprehensive review based on material technology. IEEE Trans on Magn., **55**(11), 1-21 (2019) doi: 10.1109/TMAG.2019.2929145

4. E. Sayed, M. Abdalmagid, G. Pietrini, N.M. Sa'adeh, A.D. Callegaro, C. Goldstein, A. Emadi, Review of electric machines in more-/hybrid-/turbo-electric aircraft. IEEE Trans on Trans Elec, **7**, 2976-3005 (2021) doi: 10.1109/tte.2021.3089605

5. M. Van der Geest, H. Polinder, J.A. Ferreira, D. Zeilstra, Optimization and comparison of electrical machines using particle swarm optimization. 2012 XXth Int Conf on Elec Mach (2012) doi: 10.1109/ICElMach.2012.6350058

6. F. Wu, A.M. El-Refaie, Towards fully additively-manufactured per-manent magnet synchronous machines: Opportunities and challenges. 2019 IEEE Int Elec Mach & Drives Conf (IEMDC) (2019) doi: 10.1109/IEMDC.2019.8785210

7. A.M. El-Refaie, Role of advanced materials in electrical machines. CES Trans on Elec Mach and Syst., **3**(2), 124-132 (2019) doi: 10.30941/CESTEMS.2019.00018

8. S. Huang, M. Zou, W. Zhang, V. Rallabandi, L. Dial, S. Buresh, J. Zierer, A. Jassal, F. Johnson, Development of dual phase soft magnetic laminate for ad-vanced electric machines. AIP Advances, **13**(2), 025021 (2023) doi: 10.1063/9.0000380

9. F. Ismagilov, V. Vavilov, A. Zherebtsov, A. Miniyarov, E. Pronin, Obtaining a dual-phase magnetic material based on electrical silicon steel sheet, J. of Magn. and Magn. Mat., **557**, 169457 (2022) doi: 10.1016/j.jmmm.2022.169457

10. S. Sakunthala, R. Kiranmayi, P.N. Mandadi, A study on industrial mo-tor drives: Comparison and applications of PMSM and BLDC motor drives. 2017 Int Conf on Ener, Com, Dat. an and Soft. Comp. (ICECDS) (2017) doi: 10.1109/ICECDS.2017.8390224

11. E.D. Ganev, A. Salam, Advanced Electric Drives for Aerospace Elec-tric and Hybrid Propulsion. 2019 AIAA/IEEE Elect. Air Tech. Sympo. (EATS) (2019) doi: 10.2514/6.2019-4399

12. B. Wang, Y. Liu, G. Vakil, T. Yang, Z. Zhang, Feasibility of Permanent Magnet Fault Tolerant Machines for Aircraft Starter/Generator Systems. 2020 Int. Conf. on Elec. Mach. (ICEM) (2020) doi: 10.1109/ICEM49940.2020.9270965