A Dovetail Joint for a Segment Permanent Magnet on a Rotor

R Ilyasov, D Dezhin
Department of electrical machines and power electronics, Moscow aviation institute, Moscow, Russia
gusakov.den@mail.ru

Abstract. Specific weight-power parameters (kW/kg, (kW/dm$^3$)) of rotary electric machines depend on the rotational speed of the rotor. Bandage in high-endurance titanium [1] or carbon fiber-based nonmagnetic materials is used conventionally to enhance the rotor strength of magnetolectric excitation high-speed electric machines. Eddy currents induced by tooth harmonics are seen as a major flaw in weighty titanium bandage, while a widened mechanical gap between the rotor and the stator is the principal shortcoming of nonmagnetic bandage, as it reduces magnetic induction values within the gaps. This article discusses a way to increase the rotor top rotational speed (the radial speed) through a dovetail permanent magnet joint solution without using additional titanium or carbon fiber bandage.

1. Introduction
Computational research has been conducted for a fully superconducting combined excitation electric machine [2-7], in which the poles of permanent segment magnets mounted on the rotor (see Fig. 1 below) alternate with ferromagnetic poles where the flow is excited by superconductive windings. Conventional magnetolectric machines, however, can benefit from dovetail magnet solutions too.

![Figure 1. Rotor in cross-section](image)

The permanent magnets 1 within the electrical steel sheet rotor assembly 2 are mounted in closed slots (see Fig. 1 above). The very rotor assembly is, in turn, mounted on the hollow shaft 3 to lighten the weight and to reinforce the structure. As permanent magnets mounted in closed slots generate intense polar leakage flows, the design in question is not used in conventional electric machines. High-coercive permanent magnets, however, satiate thin ferromagnetic bandage, thus limiting polar leakage flows.
Therefore, using a thick bandage to protect permanent magnets mounted on the rotor from the centrifugal force increases the polar flow leakage value. A bandage thickness exceeding 4 or 5 mm increases the bandage section area through which a polar leakage flow passes, which, in turn, reduces the operating flow by multiple times. This is why in comparatively high-speed electric machines the thickness of a ferromagnetic bandage is limited not by the radial speed, but by the polar leakage flow values, generally not exceeding 1.5 to 3 mm. Thus, ways to fasten permanent magnets on a rotor other than by means of bandages should be sought.

On the other hand, a positive contribution of a ferromagnetic bandage to the machine operation deserves to be mentioned – in particular, the bandage keeps permanent magnets from demagnetization by armature demagnetization flow, when portions of the demagnetization flow are shunted to the neighboring ferromagnetic pole and “flow” down the bandage. Moreover, a ferromagnetic bandage in insulated silicic electrical steel sheets keeps a permanent magnet from heating by eddy currents from the stator tooth harmonics.

2. Design of a Dovetail joint

For low-speed electric machines with a radial speed below 40 m/s a 1.5 to 2 mm-thick bandage in electrical steel is enough to keep permanent magnets in place. However, in machines with a radial speed exceeding 80 m/s, the ferromagnetic bandage thickness should be increased substantially, which causes an increased polar leakage flow. Electric machines with a radial speed above 120 m/s are most promising, with additional technological solutions to be used to keep permanent magnets in place and relieve the ferromagnetic bandage.

The dovetail solution is among the technological solutions conventionally used to provide safe coupling of parts. Dovetail joints are most commonly used in aviation to fasten turbine blades on the turbine hub [8], as well as to keep in place copper plates of a DC machine commutator. Please refer to Fig. 2 below for a distribution chart of tensions and contact pressures (shown in vectors) of a dovetail joint, as well as the conventional notations. A dovetail joint consists of a slot and a pin. The base (the neck) operates under tensile strength, which is why the slot is carved in a magnet that is more fragile, while its respective pin makes an integral part of the laminated steel rotor assembly.

One can see in Fig. 2 that the ends of dovetail pins undergo compression; their necks undergo extension, while the maximum contact strengths are applied to the sides of the dovetail at its outer radius. The end of a dovetail should be rounded off with a radius, the tangent to which is perpendicular to a side of the dovetail, to even out the extension strength in the depth of a slot.
Both general and special machine engineering use standardized dovetail spread angles and other parameters to provide unification. Normally, dovetails are ground with custom-made limited-line end mill cutters, while a standard narrow spread angle value multiple to 5° can be chosen as the spread angle. Electric discharge cutting is the most promising processing technique for permanent magnets, which allows carving into hard conductive magnets to form joint slots of practically any shape to a high level of precision. Water jet cutting is another technique for cutting out slots, which is good on hard magnets that have too low conductivity for electric discharge cutting to be used. This is why most rational dovetail parameters, including the slot depths and the spread angles, should be chosen out of many possible combinations.

Laminated assemblies in insulated electrical steel sheets operating in an alternate-current magnetic field are subject to rigorous requirements to the quality of cutting or carving. However, the permanent magnet rotor of a synchronous electric machine is exposed to a direct-current magnetic field, with the exception of a thin layer on the outer cylindrical surface exposed to pulsations of the tooth harmonic magnetic field. For this reason any electrical short-circuiting between the assembly sheets inside the closed slots does not lead to magnetic losses, which allows for mechanical or manual finishing of the inner surfaces of a slot in order to facilitate installation of permanent magnets, including those fitted with additional dovetail pins. The finishing technique in question also safeguards minimum gaps.

Electric discharge cutting is one of the most promising technologies for cutting closed slots in laminated assemblies of electrical steel, with an assembly cut in whole. This cutting technique eliminates any possible protrusion of individual assembly sheets, which may prevent permanent magnets from installation.

3. Analytical estimation of the proposed way of PM mounting

The centrifugal force that acts on the magnet in the radial direction is 15,000 kgf in the example provided by way of illustration, the nominal rotor speed being 12,000 rpm:

\[ F = \Omega^2 \cdot m \cdot r, \]

where \( \Omega \) is the angle rotational speed of the rotor, \( m \) is the weight of the magnet, and \( r \) the radius of gyration of the magnet. The rotor diameter is 188.2 mm in the example, while the thickness of the ferromagnetic bandage covering the slot that contains the magnet is 2 mm. An analysis of the magnetic fields suggests that a 2-mm-thick bandage does not cause an increase in the polar leakage flow and is sufficient to prevent both demagnetizing of the permanent magnet from the armature reaction and its heating from pulsations of the tooth harmonic magnetic field.

The width of a pin neck of a dovetail joint is found from tensile strength conditions from the classical equations below

\[ b = \frac{F \cdot k^2}{N \cdot \sigma_n \cdot L}, \]

where \( k = 1.2 \) is the overspeed index, \( N = 3 \) is the amount of the dovetails per magnet, and \( \sigma_n = 330 \) MPa is the proportionality limit of the electrical steel of the rotor assembly. One must consider the strength vs the overspeed of the rotor of the electric machine when doing computations. The above formula suggests that the impact from the increase of the nominal rotational speed on the top speed is square. Three is the optimal number of dovetail joints, as one of them provides an excessively long console arm, because the material a permanent magnet is made from poorly endures bend and tension, like any other ceramic material. Adding more dovetails makes the slots less deep, yet increases the complexity of the assemblage, as it will take effort to fit parts to multiple surfaces, which, in turn, will impose more rigorous requirements on the manufacture accuracy of the parts to be joined.

The length of a side of a dovetail joint is found from the expression

\[ c = \frac{\sqrt{3} \cdot F \cdot k^2}{N \cdot \sigma_n \cdot L \cdot 2 \cdot \sin(\alpha)} \]

We found through modeling that the factor \( \sqrt{3} \) had to be added to the above formula to provide the same result, despite the fact that the stress values were found to be the same.
The ratio between the side $c$ and the width of the pin neck $b$ of a dovetail joint, depending on the spread angle $\alpha$, can be found from the formulas below

\[
b = \frac{2 \cdot \sin(\alpha) \cdot c}{\sqrt{3}},
\]

\[
c = \frac{\sqrt{3} \cdot b}{2 \cdot \sin(\alpha)}.
\]

Please refer to Table 1 below for standard spread angle values. The Table suggests that the narrower a spread angle, the deeper a slot is. Excessively deep slots are not advised, as it will cause the demagnetization flow from the armature reaction to make its way towards the ferromagnetic pins, thus increasing the demagnetization rate of the magnet on that spot. Short slots with wide spread angles are not advised either, as they cause local concentrations of stresses at acute angles. Following a series of estimation computations, we chose the spread angle $\alpha$ being 25 degrees, the value at which the length of a side surface $c$ is approximately twice the width of the pin neck $b$. 
Table 1. Ratio between side and pin neck width of a dovetail joint, depending on standardized spread angles $\alpha$.

| $2 \cdot \alpha$, deg | $\gamma \alpha$, deg | Pitch | $c/b$ | $b/c$ |
|-----------------------|---------------------|-------|-------|-------|
| 90                    | 45                  | 1/1   | 1.225 | 0.816 |
| 80                    | 40                  | 1/1.192 | 1.347 | 0.742 |
| 75                    | 37.5                | 1/1.303 | 1.423 | 0.703 |
| 70                    | 35                  | 1/1.428 | 1.51  | 0.662 |
| 65                    | 32.5                | 1/1.57 | 1.612 | 0.62  |
| 60                    | 30                  | 1/1.732 | 1.732 | 0.577 |
| 55                    | 27.5                | 1/1.921 | 1.876 | 0.533 |
| 53.13                 | 26.565              | 1/2   | 1.936 | 0.516 |
| 50                    | 25                  | 1/2.145 | 2.079 | 0.488 |
| 45                    | 22.5                | 1/2.414 | 2.263 | 0.442 |
| 40                    | 20                  | 1/2.747 | 2.532 | 0.395 |
| 36.87                 | 18.435              | 1/3   | 2.739 | 0.365 |
| 35                    | 17.5                | 1/3.172 | 2.88 | 0.347 |
| 30                    | 15                  | 1/3.732 | 3.346 | 0.299 |
| 28.072                | 14.036              | 1/4   | 3.571 | 0.286 |
| 25                    | 12.5                | 1/4.511 | 4.001 | 0.25  |
| 22.62                 | 11.31               | 1/5   | 4.416 | 0.226 |
| 20                    | 10                  | 1/5.671 | 4.987 | 0.201 |
| 18.925                | 9.462               | 1/6   | 5.265 | 0.19  |
| 16.26                 | 8.13                | 1/7   | 6.124 | 0.163 |
| 15                    | 7.5                 | 1/7.596 | 6.635 | 0.15  |
| 14.25                 | 7.125               | 1/8   | 6.982 | 0.143 |
| 12.68                 | 6.34                | 1/9   | 7.842 | 1.128 |
| 11.421                | 5.711               | 1/10  | 8.703 | 0.115 |
| 10                    | 5                   | 1/11.43 | 9.937 | 0.101 |

4. Results of strength numeric modeling
A simulation of a rotor with a permanent magnet attached by three dovetail joints was completed based on the analytical computation results. The upper half of the rotor suffices for a model, which reduces the numbers of the mesh nodes and computation time, while the lower half can be substituted with its respective boundary conditions.

The numerical simulation was imported into COMSOL Multiphysics finite element method solver. An analysis of the first results obtained suggests that the von Mises yield criterion for the nominal rotational speed of the rotor of 12,000 rpm) has been generally met, though the corners of dovetail pins bear local strains in excess of the allowed values (330 MPa). Thus, the simulation was perfected by adding bevels to the corners of the pins (i.e., by rounding them off), and by giving a steeper pitch to the longitudinal axes of lateral dovetails while leaving the spread angles and the lengths of the straight
(calculated) areas of the dovetail sides unchanged. With the bevels added to the design, the series of numerical simulations were redone to find the strength, the nominal rotational speed, and the overspeed. Please refer to Fig. 3 below for the results of the modeling for the rotational overspeed of 14,400 rpm, with the radial speed being 142 m/sec. The results for the nominal rotational speed are not shown here, as they fully meet the criterion $\sigma < 330$ MPa.

Fig. 3, c above shows that the criterion $\sigma < 330$ MPa according to von Mises stress is met everywhere, except the local areas at the edges of the magnets, which can be attributed to computations at the conjunctions points of lines and arches, and the numbers of mesh nodes in their vicinities. Fig. 3, d above shows that the vectors of the contact pressures (the red vectors) are highest at those points.

5. Conclusion
An analysis of the results suggests that the dovetails computed analytically to an acceptable accuracy, including their dimensions, spread angles, side lengths, and numbers can hold magnets in place securely at both the nominal rotational speed and the overspeed, with mechanical strains within the bandage not achieving their allowable values.

Thus, the way of securing permanent magnets on the rotor, which allows increasing the top radial speed to values exceeding 140 m/sec without using additional titanium or carbon fiber bandages, or without thickening the ferromagnetic bandage more than 2 mm, has been confirmed and proven to be true.

Using dovetail joints to hold permanent magnets in place in high-speed magnetoelctric synchronous machines can be added to conventional mounting methods, e.g., outer titanium bandage. Whenever there are great divergences between the Young’s modulus values of a bandage material, be it titanium or carbon fiber, and the pin material (electrical steel) of a dovetail, buffer gaps between the pin and the
slot should be provided. As the titanium bandage gets longer due to assuming most of the centrifugal load, the buffer gap disappears, and the dovetails bear the load.

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