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Influence of magnetic circuit production for their magnetic properties

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Punching and packing in the process of production of magnetic cores for electrical machines result in the most significant deterioration of their magnetic properties. Specific total losses increase and magnetic polarization curve steepness decreases. This article presents a method that lets measure magnetic properties of cores following different methods of core packing. The effect has been shown of some technological operations in the production process of magnetic cores for electrical machines on their magnetic properties.

1. Introduction

Magnetic steels are the basic material used in production of magnetic cores for electrical machines and their properties significantly influence the quality and cost of the machines. During the production of magnetic cores for electrical machines magnetic properties are deteriorated in the consecutive technological operations. Punching results in unavoidable structure deformations and internal stresses along the punched edges, whereas pressing and different methods of packing (clamping, welding, riveting, etc.) result in introduction of internal stresses [1–9].

The total losses increase mainly in deformed areas, i.e., near punched edges. Micro-feathers form on the punched edges, which may short-circuit the core laminations thus increasing eddy current losses. Hysteresis losses are also strongly influenced by mechanical stresses tangents to side face of magnetic core caused by pressing during the packing of cores, e.g., during the pressing of packs into motor frames as well as by the coating of packs with aluminium alloy [7]. All the above operations contribute to a different degree to deterioration of magnetic properties of those materials and consequently those of the complete magnetic cores.

This paper shows the effect of various methods of stator and rotor core packing on losses and magnetic polarization curve.

The studies have been conducted on magnetic cores of stators and rotors for selected electrical machines. Hitherto, authors have studied effect of magnetic core production technologies on ring-shaped samples [8, 9].

2. Research method

Studies of changes in magnetic properties of both single and packed stator lamellas were conducted with the use of finite difference method (FDM) (Fig. 1). Measurements of total losses were conducted with a wattmeter method according to the IEC 404-2 1996-3 method with the difference that an Epstein frame was replaced by a system of two identical cores (dipolar field magnets) (of the same dimensions and mass) with the external diameter the same as that of the rotor.

Both cores are made as a glued laminate from electrical steels. Each core has two windings: the primary winding—magnetizing and the secondary winding—measuring. Number of turns on all windings in both cores is the same. The primary windings of both cores have a series connection while the secondary windings have a push-pull series connection (Fig. 1). It results in both cores being magnetized to the same extent, but voltages induced in the secondary windings compensate. An arbitrarily selected core is considered a measurement instrument (MI) and the other one a compensate instrument (CI). After the insertion of a MI into the test stator core (TSC), magnetic flux will flow through the air gap δ (the same size as in the motor), then along the stator teeth axis and will be closed by the stator pack yoke (Fig. 2). Because of small anisotropy of non-oriented steels from which stator cores are made it is assumed that the main flux is equally divided after passing the stator teeth and its one half flows to the left while the other half flows to the right. Only those teeth participate in the magnetization which are situated directly below the magnetic pole of the MI (Fig. 2). In order for the magnetic flux density along the tested stator core to be constant it is recommended that the cross-section of magnetized teeth be twice the size of the cross-section of the stator pack yoke under test (Fig. 2).

During the measurement the immobilized MI is placed within the TSC instead of the rotor so that the air gap $\delta = \text{const}$, whereas the other CI is in the air for the whole measurement period. The balance of voltages in the secondary windings becomes disturbed. The measured voltage will be the difference between voltages in the secondary windings of both cores (MI and CI). Its value will be directly proportional to the magnetic polarization J_m of the TSC yoke, number of measurement winding turns z_2, average cross-sectional area of the TSC and frequency according to the

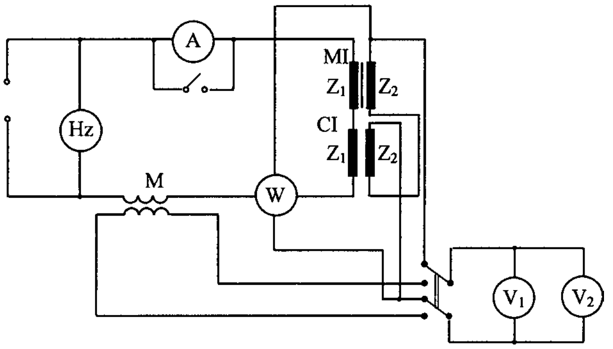

Figure 1 Diagram of measurement circuit. z_1: the primary windings, z_2: the secondary windings, M: the mutual inductance in the circuit, V_1: measures average rectified voltage, V_2: measures r.m.s. voltage, MI: measuring instrument, CI: compensating instrument.

equation:

$$U_2 = 4 \cdot f \cdot \frac{R_\mathrm{i}}{R_\mathrm{i} + R_\mathrm{t}} s \cdot z_2 \cdot J_\mathrm{m} \tag{1}$$

where U_2 is the average value of the rectified voltage induced in the secondary winding, in volts; s is the cross sectional area of the stator yoke; J_m is the peak value of magnetic polarization in the TSC yoke, in teslas; z_2 is total number of turns of the secondary winding of the test core; R_i is the total resistance of the instruments in the secondary winding, in ohms; R_t is the resistance of the secondary windings and mutual inductor, in ohms; f frequency, in hertz; the cross-sectional area of the stator yoke is given by the equation: $s = 2a \cdot h \cdot b$, where a width of TSC yoke, in meters (Fig. 2); h height of TSC yoke, in meters; b stacking factor.

Magnetic polarization value has been calculated from Equation 1 for which specific total loss P_s was then determined. Values of specific total loss, P_s of the test stator core are calculated from the equation:

$$P_\mathrm{s} = \frac{P_\mathrm{c}}{m_\mathrm{a}}; \quad \text{where } P_\mathrm{c} = \frac{z_1}{z_2} P_\mathrm{m} - \frac{(1{,}111 U_2)^2}{R_\mathrm{i}} \tag{2}$$

z_1 is total number of turns of the primary winding of the measurement core; P_m is the calculated total loss of the stator pack, in watts; m_a is the active mass of the stator pack (mass of stator yoke and those teeth who become magnetized).

In aim of determination magnetic curve (J_m vs. H_m) peak value of the magnetic field strength H_m is calculated from the equation:

$$H_\mathrm{m} = \frac{z_1}{4f \cdot M \cdot l_\mathrm{m}} \cdot \frac{R_\mathrm{v} + R_\mathrm{m}}{R_\mathrm{v}} U_\mathrm{H} \tag{3}$$

where M is the mutual inductance in the circuit given in Fig. 1, in henrys; R_m is the resistance of the secondary winding of M, in ohms; R_v is the resistance of the average type voltmeter, in ohms; U_H is the average rectified value of the voltage induced in the secondary winding of M, in volts; l_m is the conventional effective magnetic path length of the TSC in metres.

Peak value of magnetic polarization J_m is calculated from Equation 1.

The described measurement method allows measuring basic magnetic properties on single laminated cores (before and after thermal treatment in the case of silicon-free steels), in clamped, welded, riveted, pressed, glued or aluminium coated cores. Regardless of the above, magnetic anisotropy and specific total loss of the stator may be assessed by turning it from 0° to 180°.

The described measurement method is suitable mainly for comparative studies on how magnetic properties of the stator change in the process of its creation. The flux encounters the locally changing cross-section on its way, which results in different magnetic polarization of the pack in different places. This is a cause of the TSC being differently magnetized in different places. Therefore it is important that the magnetic flux magnetize such a number of stator core teeth that their total cross-section be twice the size of the stator core yoke cross-section. The obtained curves for J_m vs. H_m calculated by using Equations 1 and 3, differ removable from the data obtained from measurements of J_m vs. H_m using an Epstein frame. This comes not only from the effects of the various fabrication steps on the magnetic properties of the test core but it is also caused by the "open magnetic circuit". The value of δ / l_m should be small to reach a good sensitivity of the described device.

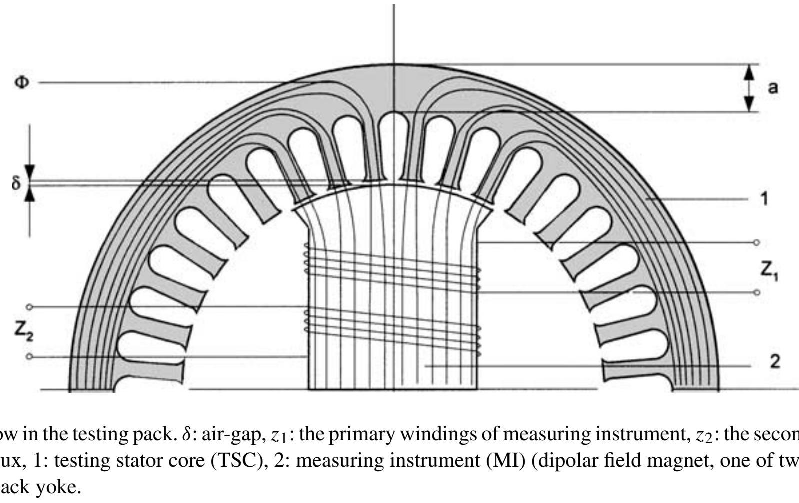

Figure 2 Magnetic flux flow in the testing pack. δ: air-gap, z_1: the primary windings of measuring instrument, z_2: the secondary windings of measuring instrument, Φ: magnetic flux, 1: testing stator core (TSC), 2: measuring instrument (MI) (dipolar field magnet, one of two cores, which act as rotor), a: width of testing stator pack yoke.

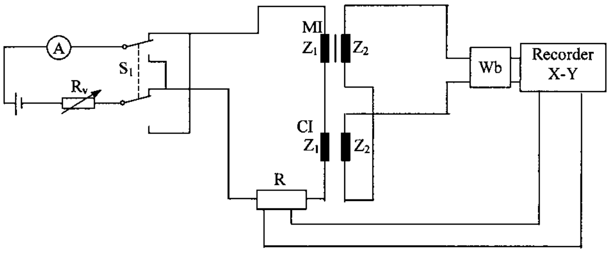

Figure 3 Circuit for d.c. testing of magnetic hysteresis loop (continuous recording method). Wb: fluxmeter, R_V: the internal resistance, 1: measuring instrument (MI), 2: compensating instrument (CI), *R*: resistor.

In order for loose lamellas and stator cores of different shapes and dimensions to be studied, special measurement and compensation instruments should be made for each stator type.

The obtained results of measurements of the effect of consecutive operations of stator manufacturing on their magnetic properties formed the basis for development of the method of inter-operational control for rotor packs as well [10].

Rotor production technology has also significant influence on the value of losses. Changes in magnetic hysteresis curve were conducted at direct current with the method of constant recording according to EN 60404-2 1996 standard with the difference that an Epstein frame was replaced with a system of two identical field magnets (MI and CI) with push-pull connection between secondary windings z_2 and series connection between magnetizing windings z_1. The diagram of the measurement system is shown in Fig. 3. The field magnet cores were C-shaped as glued laminates from non-oriented electrical steels. The rotor core research method is based on the same principle as the stator method with the difference that the rotor pack under investigation is placed within air gap MI with its poles shaped so as to retain an equal circular air gap between the studied rotor pack and electromagnet. During the measurement the rotor core was placed between poles MI, whereas CI without a rotor in the gap was placed in the air. The distance between the MI poles should be sufficient to enable easy placement of the rotor core with 0.3 mm gap left on either side.

3. Results and discussion

Tables I–III and Figs 4–9 show the effect of production of stator cores for Sg80-6A and Sg71-4B engines on the magnetization curve and specific total losses from silicon steel quality EP530-50A (2% Si) as well as from silicon-free steel quality EP650-50 made in Poland. The dimensions of the stator lamellas of Sg80-6A engine were as follows: external diameter—120 mm, internal diameter—80 mm, yoke width—12 mm, number of teeth—36, tooth width—3 mm. In the case of Sg71-4B engine external diameter was 106 mm, internal diameter—58 mm, yoke width 11 mm, number of teeth—24, tooth width—3.0 mm.

TABLE I Measurement of results of magnetic flux density and specific total losses of the Sg80-4B electrical motor stators made from the EB650-50 silicon-free steel after different technological operations

Object of testing	Specific total losses (W/kg) $P_{1.0/50}$	Specific total losses (W/kg) $P_{1.5/50}$	Magnetic polarization (*T*) J_{2500}	Increase $P_{1,.5/50}$ (%)
Epstein 25 cm strips	2.73	6.16	1.64	–
Loose stator lamellas after heat treatment in decarburizing atmosphere	2.94	6.29	1.63	–
Clamped stator	3.20	6.93	1.61	10
Clamped pack pressed into an aluminium alloy frame	3.75	7.80	1.61	24
Pack coated with aluminium alloy	4.47	9.05	1.58	43

TABLE II Measurement of results of stator packs of the Sg80-4B electrical motor made from the EP530-50A silicon steel after different technological operations

Object of testing	Specific total losses (W/kg) $P_{1.0/50}$	Specific total losses (W/kg) $P_{1.5/50}$	Magnetic polarization (*T*) J_{2500}	Increase $P_{1.5/50}$ (%)
Epstein 25 cm strips	2.23	4.83	1.64	–
Loose stator lamellas	2.68	5.93	1.60	–
Clamped stator	2.80	6.14	1.60	5.7
Clamped pack pressed into an aluminium alloy frame	2.89	6.42	1.59	8.3
Pack coated with aluminium alloy	3.56	7.12	1.56	20

TABLE III Measurement of results of stator packs of the Sg71-4B electrical motor made from the EP530-50A silicon steel after different technological operations

Object of testing	Specific total losses (W/kg) $P_{1.0/50}$	Specific total losses (W/kg) $P_{1.5/50}$	Magnetic polarization (*T*) J_{2500}	Increase $P_{1.5/50}$ (%)
Epstein 25 cm strips	2.23	4.83	1.64	–
Loose stator lamellas	2.52	5.21	1.61	–
Clamped stator	2.54	5.67	1.60	4.0
Pack coated with aluminium alloy	2.86	6.06	1.56	16

The research results show that the largest increase in specific total loss is characteristic of aluminium coated stator packs. $P_{1,5/50}$ (at $J_m = 1.5$ T, and 50 Hz) increased by 43% for silicon-free steel while it increased by 20% for silicon-free steel quality EP530-50A. A decidedly more advantageous operation is preliminary clamping of the pack and only then pressing it into the motor frame cast. The increase in losses was visibly smaller but still remarkable. It was 24% for silicon-free steel pack and 8% for silicon steel pack [11].

Stator packs of Sg80-4B engine made of EB650-50 steel and coated with aluminium alloy were subjected to annealing in temperature 450°C for one hour. No change in their magnetic properties was observed after the heat treatment. It resulted from too low annealing temperature, which could not be exceeded in order not to cause permanent deformation of the aluminium frame. Complete removal of the aluminium frame that

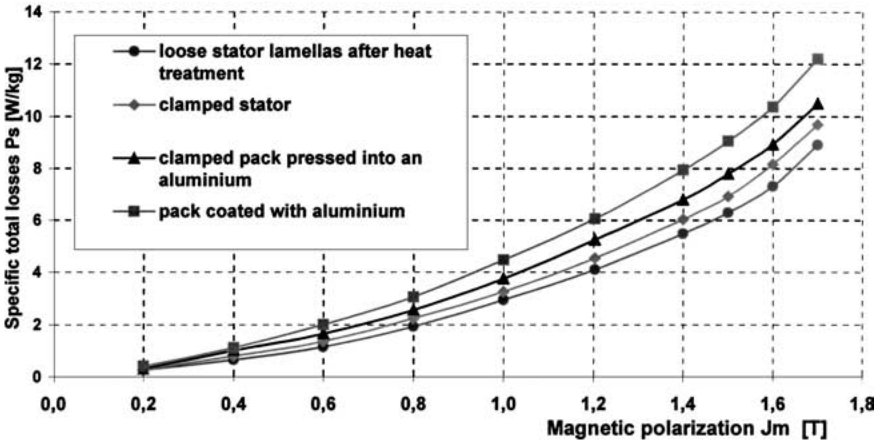

Figure 4 Specific total losses of the Sg80-4B electrical motor (stators) made from EB650-50.

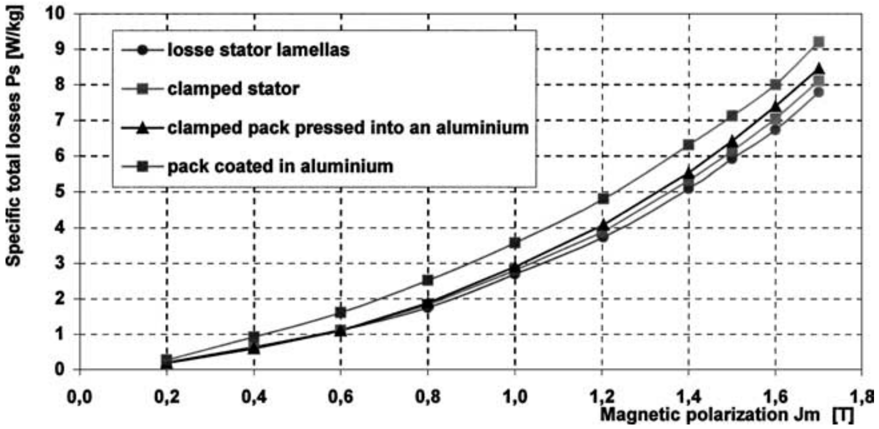

Figure 5 Specific total losses of the Sg80-4B electrical motor stators made from EP530-50A.

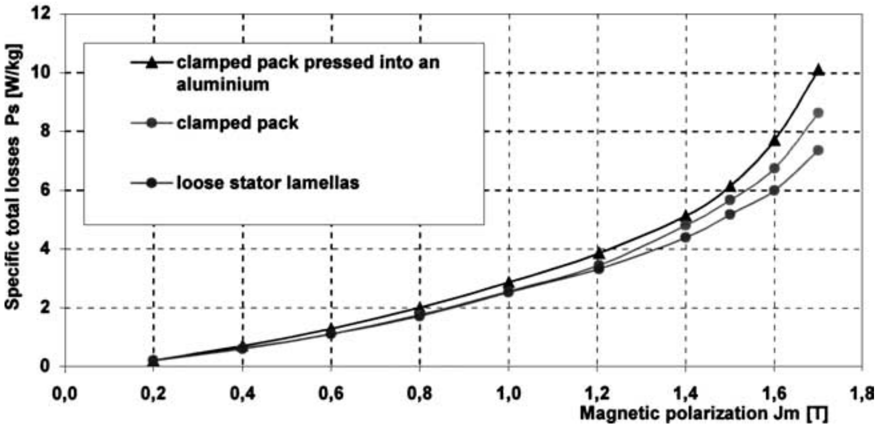

Figure 6 Specific total losses of the Sg71-4B electrical motor stators made from EP530-50A.

had been cast directly onto the pack did not result in restoring its magnetic properties to the initial state, i.e., loose lamella quality. Specific total losses $P_{1,0/50}$ decreased from 4.47 W/kg to 3.18 W/kg. Its is due to (axial and radial) plastic stresses within the stator pack yoke formed as a result of cooling aluminium contraction.

Due to the fact that the coating of packs causes the largest increase in total losses after replacing silicon-free magnetic steel quality EB650-50 by silicon quality EP530-50A, the technology was changed from direct coating of the pack to clamping it and only then pressing it into the aluminium frame that had been cast in advance.

Due to the pressing of lamellas all packing methods result in significant stresses along the stator pack axis [7]. Properly selected pressure should not cause excessive mechanical stresses in the pack. The optimum pressure should decrease the stresses to the minimum but also ensure solid integration of the lamellas into a pack. This is the effect was measured of pressing of the stator pack for motor Sg71-4B made of steel quality EP530-50A on induction B_{2500} and total losses $P_{1,0/50}$ (at $J_m = 1.0$ T and 50 Hz). The measurement results are shown in Fig. 10.

To clarify the effects by Al—compression research was also made on rotors of the motor type Sg80-4B

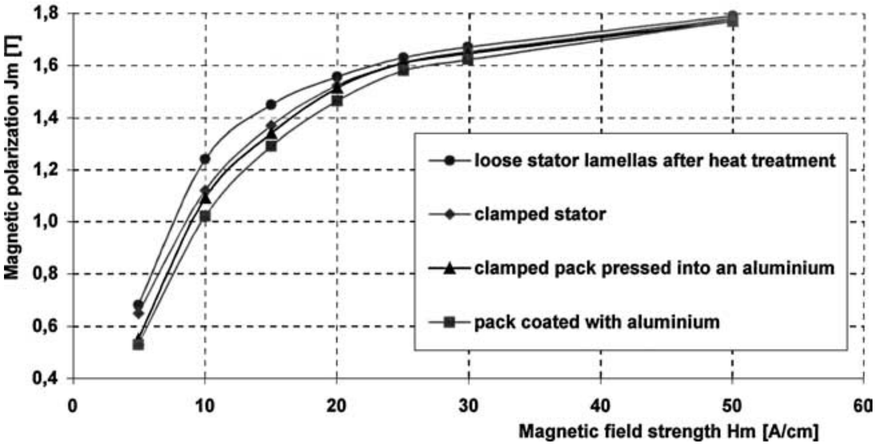

Figure 7 Magnetic polarization of the Sg80-4B electrical motor stators made from EB650-50.

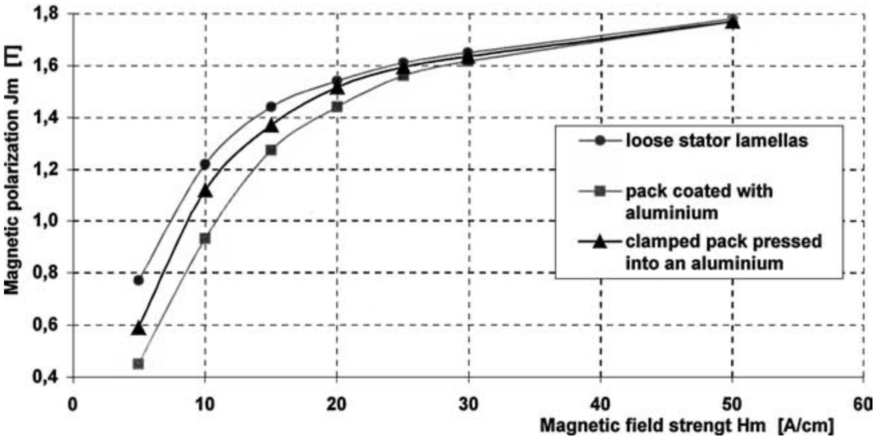

Figure 8 Magnetic polarization of the Sg80-4B electrical motor stators made from EP530-50A.

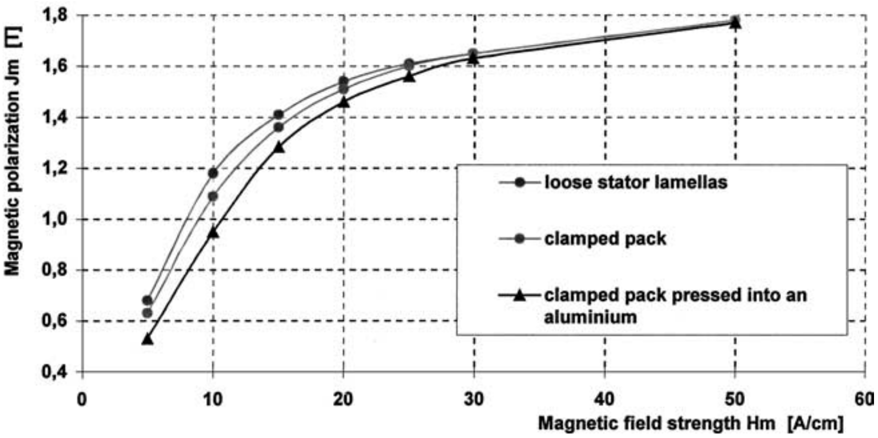

Figure 9 Magnetic polarization of the Sg71-4B electrical motor stators made from EP530-50A.

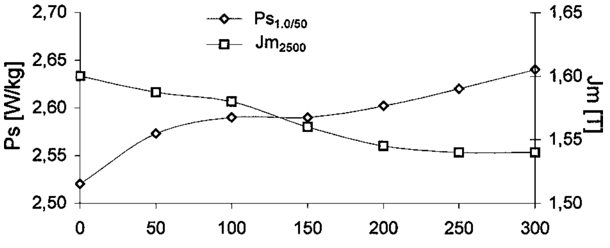

Figure 10 Diagram of magnetic polarization Jm and Ps specific total losses of the stator pack of Sg71-4B made from EP530-50A on the applied pressured.

made of silicon-free steel quality EB650-50. The measurements were done after punching the pack from the raw steel but before decarburizing heat treatment, then after annealing, and after coating with cage-forming aluminium. The results of static hysteresis loop measurements are shown in Fig. 11. External diameter of rotors lamellas—79.4 mm, width tooth—3 mm.

The obtained measurement results showed that coating an annealed packet with aluminium alloy resulted in the 200% increase in hysteresis losses in comparison with an annealed single pack. As in the case of stators, such a large increase in losses and decrease

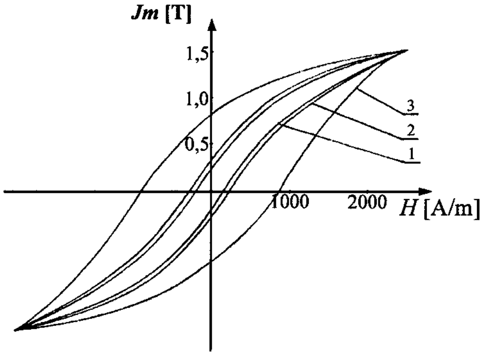

Figure 11 Characteristic of static hysteresis loops of the Sg80-6B electrical motor rotor.

in magnetic polarization in the rotor pack result from internal stresses caused by the cooling aluminium contraction.

4. Conclusion

The obtained research results showed the influence of packing on magnetic properties of stator and rotor cores of electric machines. The results cover the simultaneous effect of punching and packing. The lamellas were not annealed after punching (the only exception being silicon-free steel, which was annealed after punching).

The results of the studies presented above allow the following making the following conclusions:

1. In the manufacturing process of magnetic cores of electric machines, consecutive technological operations result a strong deterioration of their magnetic properties. The internal stresses which are formed, result an increase in specific total losses, decrease in the steepness of magnetic polarization curve, and decrease in magnetic flux density.
2. The effect of the same technological operations varies according to the magnetic steel quality. In the case of silicon steel, which is much harder than silicon-free steel after heat treatment, both clamping and coating it with aluminium alloy increases specific total losses to a lesser extent. Therefore, the results presented above may be useful for a better selection of electrical steel.
3. An appropriate manufacturing method of stators and rotors, as well as a proper electrical steel selection should minimize the loss of advantageous properties present at delivery. However, the manufacturing cycle of stators and rotors to be realized is determined mainly by the economic calculation. The resultant of both elements, i.e. the cost and the magnetic properties obtained should determine the selection of a proper manufacturing cycle.
4. The results of measurements may be taken into account in calculations of magnetic cores (stators and rotors) of electric machines. Taking into account the manufacturing technology of these magnetic cores will permit to improve the accuracy of the calculation results through the substitution of the catalogue data with properties close to the real ones.

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