

## PLASMA SPRAYING OF HARD MAGNETIC COATINGS BASED ON SM-Co ALLOYS\*

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**Abstract.** Our research is focused on the formation of hard magnetic coatings by plasma spraying an arc-melted Sm-Co powder. We have studied basic magnetic characteristics depending on the components ratio in the alloy. A sample with a 40 wt.% Sm coating exhibits the highest coercive force (63 kOe) as compared to near-to-zero coercive force in the starting powder. X-ray structure analysis of the starting alloy and the coating reveals that the amount of SmCo<sub>5</sub> phase in the sprayed coating increases occupying up to 2/3 of the sample. We have also studied temperature dependence of the coating and have been able to obtain plasma sprayed permanent magnets operating within the temperature range from -100 to +500 °C. The technique used does not involve any additional thermal treatment and allows a coating to be formed right on the magnetic conductor surface irrespective of the conductor geometry.

The RCo<sub>5</sub> rare earth metal – cobalt alloy is one of the many intermetallic compounds having a low-symmetry hexagonal structure, high magnetic crystallographic anisotropy, relatively high Curie temperature, and strong magnetic saturation. Magnetic moments of rare-earth metals and cobalt act in parallel therefore RCo<sub>5</sub> compounds are preferred materials for permanent magnets.

Philips manufacturers have used a standard SmCo<sub>5</sub> compound to produce a magnet yielding the following parameters: 8.7 kG,  $H_c = 8.4$  kOe,  $(BH)_{\max} = 18.5$  MGOe.

The energy of SmCo<sub>5</sub>- based permanent magnets has now approached its theoretical limit while their coercive force has never been beyond 15...20 kOe. The low coercive force can be attributed to powder defects caused by oxidation of cracks in grinded material. Another contributing factor is the growing size of crystals in the process of sintering and thermal treatment. These factors reduce the Curie temperature of the alloy and affect stability of permanent magnets at operating temperatures 100...300 °C [1].

Hence higher coercive forces have to be provided in order to improve stability of permanent magnets when used at elevated temperatures. Plasma spray technology is capable

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of producing coatings with a fine crystalline structure and ensures very low oxidation during the technological process (below 0.2%).

In our study, we have applied plasma spray technique to obtain highly coercive permanent magnets based on samarium-cobalt alloy powders. This approach is advantageous in that the whole process can be handled as a one-step operation, which combines formation of a 50  $\mu\text{m}$  to 10 mm thick permanent magnet of a predetermined configuration, thermal treatment and fixing of this magnet onto an irregular surface or magnetic conductor.

The powders were prepared in a laboratory and were made of alloys produced by electric arc melting in an inert gas medium (argon, helium and a mixture thereof). Coarse and fine grinding in inert atmosphere yielded particles sized 50 to 80  $\mu\text{m}$  with a different content of samarium (33,37,39,40,42 wt%) in the original alloy. Powders like these cannot be aerated therefore we had to come up with a specially designed powder feeder [2] and plasmatron [3].

A 2.5 cm thick powder layer was plasma sprayed onto a water cooled copper substrate in a chamber with inert atmosphere. By varying the spraying distance, powder and cooling liquid consumption, and speed of mutual movement of plasma jet and the target surface we were able to change the rate of cooling of melted particles on the surface in a controlled manner and thus to control the structure of the coating material.

The coating structure under study was found to be free of inclusions and micropores. The sample density was as high as 99.9% the cast alloy.

The most volatile component of the alloy, Sm, evaporates at the high plasma jet temperatures required for powder melting, therefore the resultant plasma sprayed coating will have the chemical composition, structure and magnetic characteristics as shown in Table 1 below.

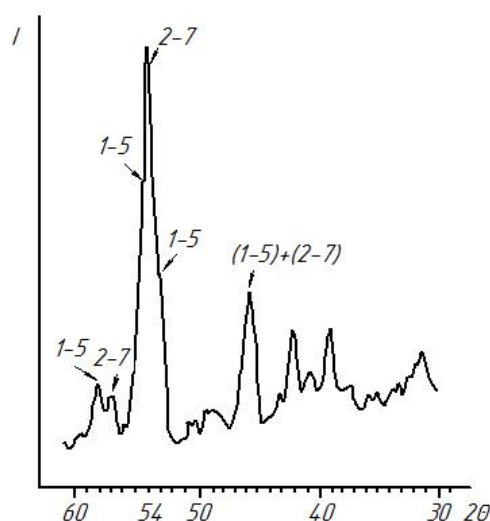
**Table 1.** Magnetic characteristics of coatings.

Sm weight content in alloy, %	Coercive force $H_c$ , kOe	Saturation magnetization $\sigma_m$ , $\text{G}\cdot\text{cm}^3/\text{g}$	Residual magnetization $\sigma_r$ , $\text{G}\cdot\text{cm}^3/\text{g}$
33	10	36	26
37	6	61	37
39	12	44	33
40	63	39	33
42	33	35	26

It is a known fact that the  $\text{SmCo}_5$  phase with a hexagonal structure has the highest magnetic anisotropy and coercive force. Apparently, in the sprayed sample where the initial Sm content in the alloy is 40% and the coercive force is 63 kOe, the  $\text{SmCo}_5$  phase will be predominant. Coercive force of the initial alloy is close to zero therefore we can expect that the  $\text{Sm}_2\text{Co}_7$  phase will prevail as a result of the melt freezing.

To prove our theory, the initial alloy and the plasma sprayed coating were subject to X-ray structural analysis.

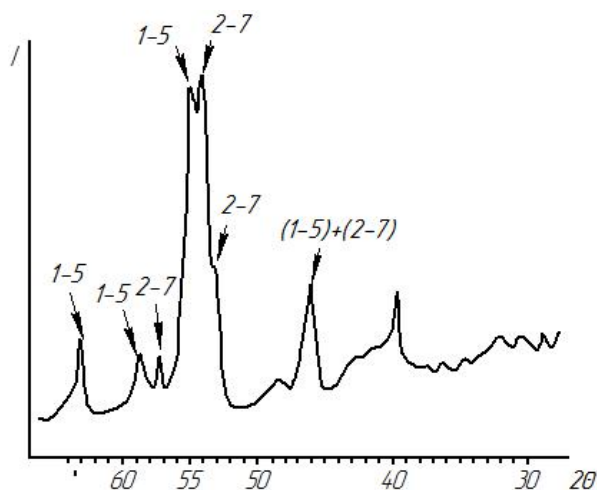
In the X-ray chart for the initial 40 wt% Sm alloy (Fig.1) there is a pronounced narrow reflection peak at  $2\theta = 53^\circ$  that refers to the  $\text{Sm}_2\text{Co}_7$  phase and  $\text{SmCo}_5$  shoulders located on the slopes, which is typical of inhomogeneous crystalline alloy.



**Figure 1.** X-ray graph of the initial 40 wt% Sm alloy: 1-5 –  $\text{SmCo}_5$ ; 2-7 –  $\text{Sm}_2\text{Co}_7$ .

The diffraction pattern shows that more intense curves of the  $\text{Sm}_2\text{Co}_7$  and  $\text{SmCo}_5$  phases occur at  $2\theta$  angles from  $35^\circ$  to  $60^\circ$ , the strongest curves of these compounds being very closely spaced to each other. This happens because there is a resemblance between the structures of these compounds and the interplanar spacing is small. Overlapping of the most intense lines of various phases does not help phase analysis and affects its accuracy. And yet, since the curves corresponding to reflection from the basal and prism planes do not overlap, we are able to register presence of a second phase when its content is more than 5...10%.

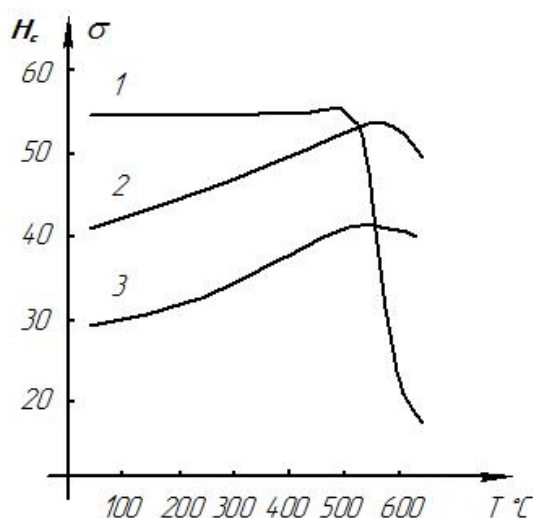
Figure 2 is a diffraction pattern of the sprayed coating. This pattern indicates that the sprayed coating contains ~37 % samarium suggesting that 3% Sm has evaporated in the process. The  $\text{SmCo}_5$  phase dominates occupying about 2/3 of the sprayed coating, the rest belonging to the  $\text{Sm}_2\text{Co}_7$  phase.



**Figure 2.** Diffraction pattern of sprayed coating: 1-5 –  $\text{SmCo}_5$ ; 2-7 –  $\text{Sm}_2\text{Co}_7$ .

The above evidence supports our assumption that a coating based on initial 40 wt% Sm alloy will exhibit high coercive force.

Figure 3 illustrates the results of our study on the effect of thermal treatment temperature on stability of magnetic characteristics of a plasma sprayed coating.



**Figure 3.** Magnetic characteristics as a function of temperature:  
 1 – coercive force; 2 – saturation magnetization, 3 – residual magnetization.

One can see that the coercive force remains unaffected until the temperature reaches 500 °C while the residual magnetization changes from 30 to 40 G·cm<sup>3</sup>/g and the saturation magnetization grows from 40 to 53 G·cm<sup>3</sup>/g. This behavior of magnetic characteristics is maintained in the temperature range up to 500 °C under repeated thermal treatment cycles, which proves high thermal stability of magnetic properties of plasma sprayed permanent magnets.

Thermal treatment of a sprayed coating on a product in-situ is not always practical. We have refined and adjusted the parameters of spraying in order to obtain magnetic characteristics close to those of thermally treated coatings (Table 2).

**Table 2.** Adjusted parameters of spraying process.

Parameter	Unit	Value
Cathode-anode voltage, $U$	V	75
Arc current, $I$	A	250
Plasmatron arc discharge power, $W$	kW	18,75
Powder consumption $q_n$	g/sec	1,5
Size of powder particles, $q_{pp}$	μm	50...80
Argon plasma forming gas consumption, $q_a$	l/sec	1,5
Helium transporting gas requirements, $q_g$	l/sec	3
Spraying distance $L$	mm	80
Speed of mutual movement, $V$	mm/s	10
Cooling liquid requirement, $q_l$	l/min	3

As shown by X-ray phase analysis, under the above discussed spraying conditions the volume share of SmCo<sub>5</sub> phase grows along with its crystalline anisotropy, which entails an increase in Curie temperature, residual magnetization, and saturation magnetization.

Magnets of this type have a demagnetization curve of the hysteresis loop close to a rectangular shape with the maximum magnetic energy  $W_{\max}$  reaching 9.6 MGOe [4].

Based on our studies we have been able to obtain plasma sprayed highly stable permanent magnets featuring high coercive force up to 60 kOe,  $6.2 \cdot 10^3$  G residual induction and 0.0005 %/degree stability of residual magnetization, which makes them suitable for devices operating in the temperature range from -100 to +500 °C. These magnets are thin (with a high demagnetization factor) and no glue technology is required whatsoever to fix them on magnetic conductor surfaces of an awkward geometry.

A 1 mm thick magnet was sprayed onto a gyroscope rotor end. The so sprayed rotor as part of a gyroscope has successfully gone through the entire test program and has been recommended for commercial application.

The wide scope of potential application of such magnets includes small-size dc motors, on-board measuring instruments as well as various purpose devices for space research programs.

## References

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