The experience of magnets manufacturing from metal powder using a laser

A S Zhukov, B K Barakhtin, V V Bobyr, P A Kuznetsov and I V Shakirov
NRC "Kurchatov Institute" – CRISM "Prometey", Saint-Petersburg, 191015, Russia

E-mail: npk3@crism.ru

Abstract. The structure of hard magnetic and soft magnetic alloys manufactured on a Russian SLM FACTORY init by selective laser melting (SLM) from a spherical powder less than 80 μm in size has been studied. The powder is made by melt atomization from ingots. At various scanning speeds and laser power, additive samples were manufactured to study the structure, magnetic parameters, and also fractal analysis. According to the research results, recommendations were given on changing the melting modes and conducting thermal post-processing of materials. By constructing a hysteresis loop, data were obtained indicating the achievement of magnetic characteristics in additive samples that are close in magnitude to magnets of traditional founding technology. Prototypes of complex-shaped additive magnets have been made.

1. Introduction
The manufacturing of complex shaped magnets from materials of various classes is of practical and scientific interest. Traditional founding limits the geometry of magnets, so alternative methods of making them must be sought. Various methods of high-temperature sintering of powder are known and have been used for more than a dozen years; therefore, their approbation for powders of hard magnetic and soft magnetic alloys seems promising. Improvement of designs and industrial development of sources of concentrated energy fluxes – lasers, electron, ion, plasma beams – led to the development and practical implementation of a method for manufacturing finished products by selective laser melting (SLM) of metal powder raw materials [1-5]. The application of lasers, as the most affordable energy sources, makes it possible to quickly and efficiently build up powder layers using a computer 3D model to obtain a bulk product of almost any shape. At the same time, it is possible to control, diagnose and regulate the technological parameters of laser exposure, minimizes the thermal effect on the product as a whole, thereby suppressing the possibility of changing its geometric dimensions (warpage), the occurrence of residual deformations and stresses, maintaining the chemical composition and improving the performance of the material [6, 7].

A specific feature of the SLM technology is the presence and interaction of solid and liquid phases in the laser spot for a short time [8, 9], in other words, under conditions of thermodynamic nonequilibrium. Local acts of melting and structural-phase transformations realized under thermodynamic nonequilibrium conditions have not been sufficiently studied, although they are widespread in various technological applications with transient conditions [4]. The presence of alloy
components of different morphology gives grounds to consider the resulting additive material as a composite.

Unlike other additive manufacturing processes, SLM and its derivatives make it possible to create real functional products, which, of course, is an indisputable advantage when manufacturing magnets of complex geometric shapes.

The aim of the presented work is to test the SLM method for the manufacture of magnets from powders of hard magnetic (Alnico24) and soft magnetic (80 Permalloy) alloys. The dependences of the curves of magnetization and magnetic induction on the strength of the external magnetic field are used to determine the magnetic characteristics (residual induction, coercivity by magnetization, coercivity by induction, maximum energy product or maximum amount of magnetic energy stored in a magnet), which should correspond to the characteristics of traditional founding magnets.

2. Materials and experimental methods

The required metal powders were produced by atomization of 80 Permalloy (soft magnetic material) and ALNICO24 (hard magnetic material) ingots on a HERMIGA 75/3VI unit. To melt the powders, a Russian SLM FACTORY selective laser melting unit with a solid-state ytterbium laser and a protective nitrogen atmosphere was used. Additive samples were made in the form of cubes with a size of 10x10x10 mm³ (figure 1). The laser power and scanning speed were varied in the ranges 150–189.5 W and 800–1013 mm/s, respectively. The melting modes were varied in order to achieve a satisfactory metallurgical quality so that the energy input in the laser spot (the ratio of the laser power to the scanning speed) for melting was maintained at a level of ~ 0.18 W/mm [8, 9].

![Figure 1. Manufactured additive samples (left) and Russian SLM FACTORY unit (right).](image)

The chemical composition of the obtained SLM samples was measured by the X-ray fluorescence method (table 1).

| Alloy         | Fe  | Cr  | Co  | Ni  | Ti  | Cu  | Al  | Mn |
|--------------|-----|-----|-----|-----|-----|-----|-----|----|
| 80 Permalloy | 15.0| 3.8 | 0.1 | 80.1| 0.1 | 0.1 | –   | 0.9|
| Alnico24     | 53.1| –   | 22.8| 12.7| –   | 2.7 | 7.6 | –  |

Table 1. Chemical composition of the materials.

Structural studies were performed on thin sections by metallographic methods (using a Tescan Lyra 3 scanning electron microscope) with quantitative image processing. Taking into account that the rapid acts of melting and crystallization during SLM are characterized by thermodynamic nonequilibrium, the concept of multifractal analysis of structures was used in data processing. Multifractal analysis of half-tone images of structures was carried out by their black-and-white (binary) maps, which were considered in the form of statistical sets of different dimensions q [10-12]. The measure of ordering \( \delta \)
(with a spread of ± 0.005) and the measure of periodicity K (± 0.03) were calculated from the spectrum of Renyi dimensions. The tendency of δ to zero is a sign of localization of the volume of melting and crystallization with partial or complete amorphization of the structure. The K value characterizes the degree of periodicity and ordering among structural objects.

Br (residual induction), Bd (working point by induction), Hcb (coercivity by induction), Hcm (coercivity by magnetization) and BHmax (maximum energy product, or maximum amount of magnetic energy stored in a magnet) were obtained on hysteresigraphs and milliteslameter in measuring device.

3. Experimental results and discussion
Metallographic studies have shown that the metallurgical quality of the material is unsatisfactory in SLM samples. In the matrix of thin section 80 Permalloy, pores up to 30 µm in size were present, indicating incomplete penetration of the material, and in thin section ALNICO24, there were oxidized grain boundaries, which reduced the strength properties (figure 2). In addition, the finely dispersed structure of the SLM grains did not fully meet the requirements for satisfactory magnetic parameters.

This was also evidenced by the multifractal (figure 3). For example, the structure of the material looked inhomogeneous and disordered in 80 Permalloy samples at low laser powers. It was found that for additive samples in the range of specified laser powers W, the periodicity measure K increased monotonically with increasing power and increased with increasing ordering δ (table 2). An increase in the measure of periodicity indicated the formation of an ordered and regular grain structure.

![Figure 2. Metallurgical defects in SLM specimens of 80 Permalloy (top) and Alnico24 (bottom) at x500 magnification.](image1)

![Figure 3. Multifractal analysis with the construction of the Renyi distribution for the additive sample 80 Permalloy, recorded at x500 magnification.](image2)

| parameters | K  | W  | K  | δ   |
|------------|----|----|----|-----|
|            | 0.28| 110| 0.51| 0.041|
|            | 0.51| 190| 0.47| 0.050|
|            | 0.41| 150| 0.22| 0.020|

It can be conclude, to manufacture a magnetic material with satisfactory characteristics, a coarse-crystalline structure of grains with a minimum number of voids and grain boundaries is required. In
turn, this requires clarification of the SLM modes and additional heat treatment of the samples in order to improve their magnetic (domain) structure.

The laser scanning speed was reduced to 700 mm/s at a maximum power of 189.5 W, after which, in this mode, 4 identical cubic samples were built for each alloy. Technological heating of samples from 80 Permalloy was carried out to a temperature of 1200 °C for 3-6 hours in order to achieve the highest magnetic performance. This improved the magnetic permeability $\mu(H)$ and the magnetization curve $B(H)$ by an order of magnitude (figures 4 and 5, table 3).

**Table 3.** Magnetic parameters of additive samples 80 permalloy.

| parameters | before heat treatment | after heat treatment |
|------------|-----------------------|---------------------|
| Sample No  | $\mu_{\text{max}}$, | $\mu_{\text{max}}$, | $H_c$, | $\mu_{\text{max}}$, | $\mu_{\text{max}}$, | $H_c$, |
|            | $\mu H_n/m$ G/Oe A/m | $\mu H_n/m$ G/Oe A/m |            | $\mu H_n/m$ G/Oe A/m | $\mu H_n/m$ G/Oe A/m | |
| 1          | 3.8 3000 46.9 39.0 31001 3.0 |
| 2          | 4.1 3300 45.7 37.7 30001 3.1 |
| 3          | 3.9 3100 44.6 37.6 29901 2.8 |
| 4          | 3.9 3100 48.7 41.7 33201 2.5 |

**Figure 4.** Magnetic permeability $\mu(H)$ of 80 Permalloy specimens before (top) and after (bottom) heat treatment.

**Figure 5.** Curve of magnetization $B(H)$ of 80 Permalloy specimens before (top) and after (bottom) heat treatment.

The hysteresis loop for a 80 Permalloy sample after heat treatment is shown in figure 6.

As for the additive specimens from the ALNICO24, the following should be noted. In addition to the technological improvement of the conditions for protecting the melted powder from oxidation, the subsequent additional heating of the samples also contributed to the improvement of the magnetic
parameters. This is confirmed by the appearance of magnetic loops after high-temperature long-term heating of the samples (figure 7).

**Figure 6.** An example of magnetic loop of an additive sample 80 Permalloy before and after heating at temperature of 1200 °C for several hours.

**Figure 7.** An example of magnetic loop of an additive sample ALNICO24 after heating at temperature of 1200 °C for several hours.

The summary data on the magnetic characteristics of the studied additive samples in comparison with founding samples are presented in table 4.

| Alloy                     | \( B_r, \text{T} \) | \( \text{BH}_{\text{max}}, \text{kJ/m}^3 \) | \( H_{\text{cb}}, \text{kA/m} \) | \( H_{\text{cm}}, \text{kA/m} \) |
|---------------------------|----------------------|------------------------------------------|-------------------------------|-----------------------------|
| 80 Permalloy (additive)   | 0.63                 | 0.0005                                   | 0.1                           | 0.1                         |
| 80 Permalloy (founding)   | 0.49                 | 0.0047                                   | 0.6                           | 0.6                         |
| ALNICO24 (additive)       | 1.54                 | 23.6                                     | 17.5                          | 17.6                        |
| ALNICO24 (founding)       | 1.13                 | 34.6                                     | 39.8                          | 40.8                        |

Experiments with energy input and heat treatment made it possible to select optimal melting parameters for the indicated alloy grades, which would improve the metallurgical quality of the metal and achieve a small number of discontinuities, as well as a structure with a greater frequency. With optimal melting parameters, prototypes of magnets of complex shape were made (figure 8).

**Figure 8.** Samples of magnets manufactured by SLM.
4. Conclusions
By atomization, it is possible to produce powders of hard magnetic and soft magnetic alloys, suitable for use in SLM technology:

The SLM technology makes it possible to produce both soft magnetic and hard magnetic materials from metal powder.

Multifractal analysis makes it possible to reveal the structural features of additive materials.

To achieve acceptable magnetic parameters, the resulting additive magnetic material must be subjected to additional high-temperature heating.

After selecting the optimal melting modes and carrying out additional heat treatment, using the SLM technology, it is possible to produce magnets of complex shapes with magnetic properties comparable to those of traditional magnets.

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