# Magnets with gradient microstructure

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## 1. Introduction

Axially symmetric magnets with good mechanical properties in the surface layer and good magnetic properties in the volume of material are essential to manufacture increasing number of modern devices (compressors, high speed engines, turbo-generators, centrifuges etc.). There are many hard magnetic materials used as permanent magnets. The Alnico alloys based on Fe-Al-Ni-Co system are traditional materials for permanent magnets. The magnets based on rare-earth metals (for example, $SmCo_5$, $Nb_2Fe_{14}B$, $Sm_2Fe_{17}N_3$ [1]) are well-known among modern materials. The Alnico magnets can be obtained only with casting methods. They are hard and brittle, difficult to machine after casting and generally they can be machined by grinding only. The alloys based on rare earth metals are relatively expensive, and the technology of their production (by sintering or pressing powders) is complicated. Moreover, they are brittle, which severely limits the field of their applications [1]. At the same time, the magnets of Fe -Cr -Co system draw interest because, due to good ductility, excellent magnetic properties and low cost they are used for the production of permanent magnets of various sizes and shapes, such as wire, tube, bar, strip magnets, etc [2-4]. Their application for the production of high speed rotors for electric motors, however, is limited by the lack of satisfactory mechanical properties, including static and fatigue strength under operating conditions [5]. It is known that mechanical or magnetic properties are dependent on the microstructure of material [6, 7]. Thus, by controlling the microstructure an appropriate level of these properties can be achieved. The microstructure of a gradient type is needed in the case of magnets rotating at high speed, in which the interior with coarse grains provides a high level of magnetic properties, and the fine structure at the surface - good strength of the surface layer. The technologies currently used like casting, powder metallurgy, forging are not capable to ensure the gradient microstructure. However, the severe plastic deformation with the use of various components of the load (e.g. torsion combined with tension or upsetting) at elevated temperatures allows receiving this type of material [8]. Depending on the mode of the deformation chosen, this method allows localizing strain in specific regions and ensures the formation of gradient microstructure with different combination of magnetic and mechanical properties [9, 10]. This work presents the results of influence deformation by tension combined with torsion on the microstructure, magnetic and mechanical properties of the hard magnetic FeCr22Co15 alloy.

A cylindrical sample of FeCr22Co15 alloy, 8 mm in diameter and 44 mm of length, was deformed simultaneously by tension applied to the upper part of sample and torsion applied to the bottom part of sample. The sample was subjected to tension at the rate of $6\cdot10^{-4}\,s^{-1}$ to obtain the deformation of 20 % and torsion at the rate of $8.5\cdot10^{-4}\,s^{-1}$ in 7 rotations. The deformation temperature 750 °C corresponded to the appearance range of the $\alpha+\gamma$ phases. The total degree of deformation, at the distance of half the radius ($R = 2$ mm) of the sample was about 1.34, while at the surface ($R = 3{,}5$ mm) about 2.21.

The microstructure of the pre-deformation state (after quenching from high temperatures and subsequent annealing at 750 °C), consists of large (700 μm) grains of the α phase which contains lamellar, ~20 μm thick, precipitates of the γ phase, Fig 1.

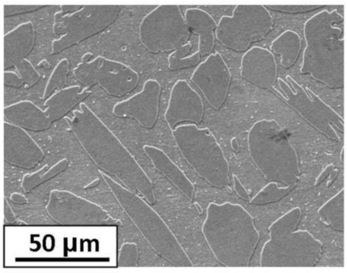

Figure 1. Lamellar structure ($\alpha+\gamma$) of FeCr25Co15 alloy, obtained by heating the solid α solution at 750 °C.

The SEM observations of longitudinal sections of deformed sample showed a gradient microstructure with the highest grain refinement in the zone of intensive deformation (i.e. in the sample surface layer), Fig. 2. The thickness of the fine-grained surface layer was about 3.0 mm (for the sample thickness of 8 mm). The SEM observations of deformed sample showed also the precipitations of intermetallic σ phase. Usually, the appearance of non magnetic σ phase is undesirable because it is hard and brittle, so it worsens the mechanical and magnetic properties of material. The process of σ-phase precipitation, as a rule, is very time-consuming [11]. However, the intensive deformation of Fe-Cr-Co alloys stimulates the precipitation of σ phase by the activation of diffusion processes [9].

The EBSD/SEM measurements of deformed FeCr22Co15 alloy confirmed that more σ phase precipitates formed in the regions of intense deformation (at the surface of the samples). The fraction of σ phase precipitates reached there up to 40 % while inside the material up to 26%. The grain size of α phase in the surface layer of samples reached about 1,0 µm.

The EBSD/SEM measurement showed also, that in the volume of material in the areas of former γ phase the grains of α phase developed with a high density of low angle grain boundaries. The TEM investigations of such areas showed thin plates with low angles of disorientation and very high density of dislocations. Electron diffractions obtained from separate (single) plates exhibited a good solution for both the α phase and the tetragonal martensite. The martensitic transformation of γ phase into $\alpha_{\gamma}$ after quenching from high temperature (800 – 1100 °C) was already observed in the FeCr23Co15 alloy [12]. For the investigated alloy, the strong deformation and cooling from high temperature could probably cause the transformation of γ phase into the $\alpha_{\gamma}$ phase.

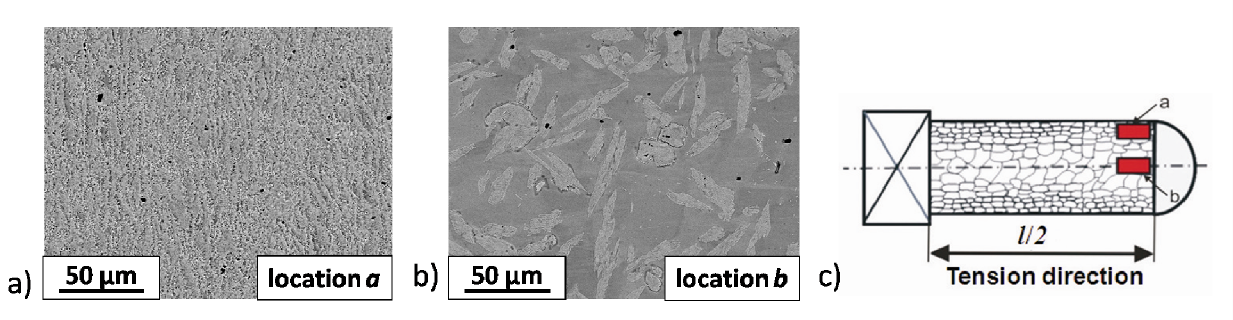

Figure 2. Microstructure of deformed FeCr22Co15 alloy at surface (location a) and in the volume (location b) of sample deformed at 750 °C according to the scheme (c).

Before the magnetic treatment, the deformed sample was subjected to annealing at 1000 °C for 10 min in order to dissolve non-magnetic σ phase. The magnetic measurements were carried out on cuboidal samples with dimensions 3 x 1.7 x 15 mm, which contained both the material from the interior and that from the surface layer of the deformed alloy. The SEM observations of microstructure after the magnetic treatment demonstrated about 30% of $\alpha_{\gamma}$ phase in the α matrix (Fig. 3). The α phase decomposed into the isomorphous $\alpha_1$ and $\alpha_2$ phases, containing ordered and coherent precipitates of sizes about 100 nm.

Table 1 presents the magnetic properties of the alloy after deformation and subsequent magnetic treatment. The table shows that magnetic properties of the deformed alloy are worse than these in the high-coercive state (without deformation). The deterioration of magnetic properties is related primarily to the presence of soft magnetic $\alpha_\gamma$ phase [14]. The microstructure refinement after deformation may also have a negative impact on magnetic properties. This is related to the increased area of grain boundaries. The decomposition of the α solid solution near the grain boundary differs from the decomposition inside the grain, as the precipitates of $\alpha_1$ and $\alpha_2$ phases have different modulation (size), shape and orientation. The changes of precipitate orientation close to the grain boundary reduce the material magnetization and coercive force [9, 10]. On one hand, the $\alpha_\gamma$ phase impairs magnetic properties. On the other hand, it may also appear as a plastic constituent among brittle grains of α phase, which has a positive influence on mechanical properties of the material.

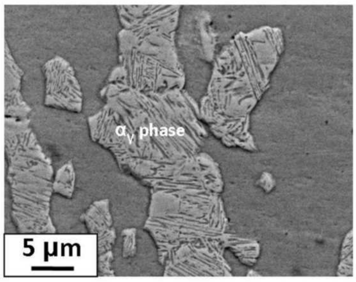

Figure 3. Microstructure of FeCr22Co15 alloy after deformation at 750 °C and subsequent magnetic treatment.

The examination of mechanical properties by the three-point bending method at room temperature shows that the deformed samples after magnetic treatment were sufficiently plastic under the applied load in comparison with the non deformed alloy. The non deformed samples in the high coercive state revealed zero ductility: they cracked in the range of elastic deformation under stress of about 400 MPa [1]. Whereas the deformed samples revealed some ductility: the magnitude of flexure before failure was about 0,3 mm, Table 1. The plasticity of the deformed material can be explained by the presence of $\alpha_\gamma$ phase, which is softer ($HV_{0,01}$ = 350) than the brittle α phase after the magnetic treatment ($HV_{0,01}$ = 420). The increase in the strength is a result of grain refinement and more homogeneous chemical composition of the microstructure.

Table 1. Magnetic and mechanical properties of FeCr22Co15 alloy subjected to tension combined with torsion: coercive force $H_c$ [$kA{\cdot}m^{-1}$], saturation flux density $B_s$ [T], residual flux density $B_r$ [T], maximum compression stress σ [MPa], magnitude of flexure before failure ε [mm]. The alloy properties in the high-coercive state (HCS) without deformation are presented for comparison.

| The state | Hc, kA/м | Br, T | Bs, T | σ, MPa | ε, mm |
|---|---|---|---|---|---|
| Deformation at 750 ºC | 34.30 | 0.78 | 1,08 | 1320 | 0,30 |
| HCS without deformation | 40 | 1,2 | 1,3 | 400 | 0,00 |

## Conclusions

The deformation by tension combined with torsion at elevated temperature of FeCr22Co15 alloy resulted in the formation of gradient microstructure with the minimum grain size (about 1 μm) in the surface layer. The deformation also stimulated the precipitation of intermetallic σ phase, which promoted the refinement of the material microstructure, and caused the martensitic transformation of γ phase into $\alpha_\gamma$. The magnetic treatment of deformed FeCr22Co15 alloy resulted in the dissolution of non-magnetic σ phase and slight increasing the grain sizes of α phase (up to 5 μm). The measurement of magnetic properties showed thedecrease of coercive force of the deformed alloy by14%, saturation flux density by 13% and residual flux density by 34% in comparison with the non deformed alloy. The deterioration of magnetic properties was related primarily to the presence of soft magnetic $\alpha_\gamma$ phase and the microstructure refinement after deformation. On the other hand, the $\alpha_\gamma$ phase appeared as a plastic constituent among brittle grains of α phase, which had a positive influence on ductility, while the grain refinement of deformed alloy provided the increase of strength about 3 times in comparison with the non deformed material.

In this way this unique method of deformation can be used for the production of permanent magnets with gradient microstructure. Other examples of gradient magnets of Fe-Cr-Co system received in the result of intensive deformation are discussed in the publications [9, 10].

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