MAGNETIC PROPERTIES, SPINODAL DECOMPOSITION AND COLD DEFORMATION IN FeCrCo ALLOYS

Franc Vodopivec,
Institute of Metals and Technology, Ljubljana, Slovenia

LATE PAPER
22nd International Conference on Microelectronics, MIEL'94
30th Symposium on Devices and Materials, SD'94
September 28. - September 30., 1994, Rogla, Slovenia

Key words: permanent magnets, FeCrCo alloys, FeCrCo magnets, magnetic properties, spinodal decomposition, cold deformation, material ductivity, heat treatment, material microstructure, magnetic remanence, coercitivity field strenght

Summary: In technical iron-chromium cobalt alloys the microstructure of ferromagnetic phase α is obtained with addition of suitable alloying elements preventing the formation of phases γ and σ. Alloys have pour ductility by ambient temperature. Magnetic properties depend upon the proper combination of spinodal decomposition, deformation and aging. All magnetic properties are improved by cold deformation. The greatest remanence is obtained by appr. 60% of deformation. The coercivity grows proportionally to the deformation and to the decrease of the distance between particles of phase α_1, while the remanence grows proportionally to the allongement of particles of this phase.

Magnetne lastnosti, spinodalno razmešanje in hladna deformacija v zlitinah FeCrCo

Ključne besede: magneti trajni, FeCrCo zlitine, FeCrCo magneti, lastnosti magnetne, razmešanje spinodalno, deformacija hladna, raztegljivost materiala, obdelava toplotna, mikrostruktura materiala, remanenca magnetna, poljska jakost koercitivna

Povzetek: V tehničnih zlitinah železa, kroma in kobalta je potrebno z dodatkom sekundarnih legirnih elementov preprečiti nastanek faz γ in σ in doseči mikrostrukturo iz feromagnetne faze α. Zlitine imajo zelo majhno duktilnost pri temperaturi ambienta. Magnetne lastnosti so pri pravi sestavi odvisne od kombinacije temperature spinodalnega razmešanja, stopnje deformacije in procesa staranja. Vse magnetne lastnosti se izboljšujejo z naraščanjem stopnje deformacije. Največja remanenca je dosežena pri ca. 60% deformaciji. Koercitivna sila raste proporcionalno z zmanjšanjem razdalje med delci faze α_1, remanenca pa proporcionalno s podaljškom zrnate faze.

1. Introduction

The property of permanent magnetism is obtained in iron-chromium-cobalt alloys through the spinodal decomposition of the solid solution of both alloying elements in the ferromagnetic phase α Fe in two spinodal components. During this decomposition the matrix α_2 is enriched in chromium and particles α_1 are enriched in cobalt. Both components have the same α ferromagnetic lattice, however a different lattice parameter because of the difference in composition. Both phases accommodate with elastic stresses which increase the hardness and stabilise the externally imposed uniform orientation of Weiss domains the more, the greater is the difference in composition, which is increased through a proper aging. Better magnetic properties are obtained by a combination of heat treatment and cold deformation by wire drawing, which produces a spinodal structure aligned and allonged in the deformation axis /1-18/. On principle, good magnetic properties are obtained also by a very slow cooling in magnetic field. By the technically acceptable cooling in magnetic field, which gives the required properties to AlNiCo alloys, several times smaller coercivity is obtained in a $Fe_{28}Cr_{16}Co$ alloy than combining heat treatment and cold deformation. The initial microstructure consists of coarse grains of phase α (fig. 1) obtained by annealing the alloy at 1200°C and quenching. The microstructure should be free of phase σ, which makes the alloys unductile and of the non ferromagnetic phase γ. Already the thin grain boundary layer of phase γ in fig. 2, decreases the magnetic properties by appr. 20%. The proper microstructure is obtained in technical alloys, containing elements stabilisers of the phase σ , f.i. carbon, nitrogen and manganese through a proper addition of aluminium or titanium, which prevent also the formation of phase σ. Twinning makes the monophase coarse grained microstructure virtually undeformable at room temperature, therefore the wire drawing deformation is performed by increased temperature, when deformation by sliding occurs.

In this paper a short and simplified presentation of the relationship between the spinodal decomposition, the deformation and the magnetic properties will be given. The microstructure and the ductility were presented earlier /26/. Unpublished findings will be discussed as well as already published data /19-25/. In the paper the denomination phase will be used for the spinodal components although physically both components are not

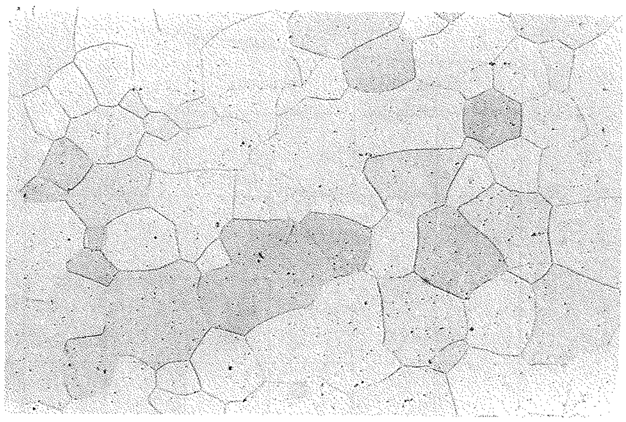

Fig. 1: *mag. 50x, $Fe_{28}Cr_{16}Co$ alloy. Microstructure after 30 min. of annealing at 1200°C and quenching.*

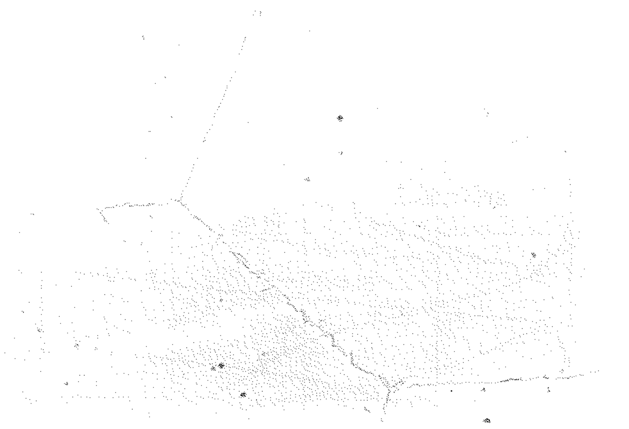

Fig. 2: *mag. 500x. A thin layer of phase γ at the boundaries of α grains.*

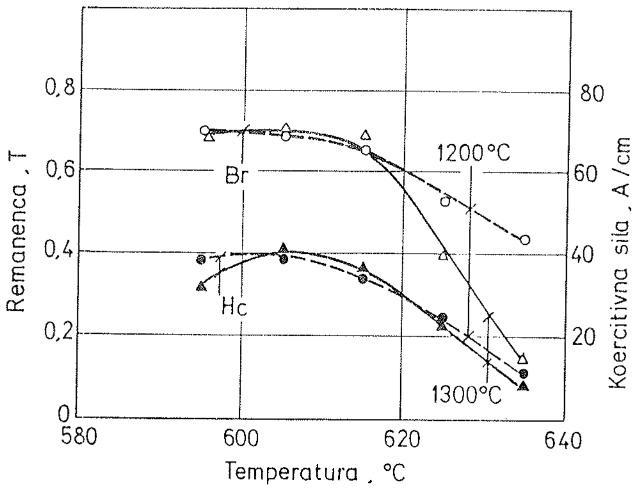

Fig. 3: *$Fe_{31}Co_{10}Co$ alloy. Influence of the 30 min. annealing for spinodal decomposition on coercitivity and remanence. Homogenisation temperatures 1200 and 1250°C.*

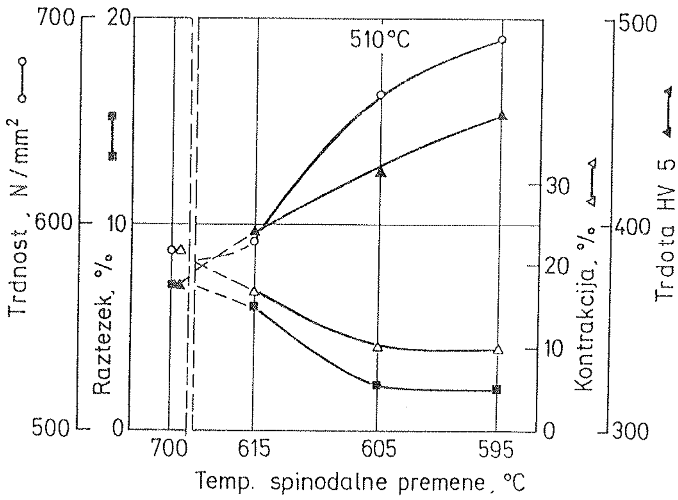

Fig. 4: *The same alloy as in fig. 3. Influence of the 30 min. annealing for spinodal decomposition on hardness and ductility.*

real phases, since they are separated through a chemical gradient and not by a phase boundary.

2. Spinodal Decomposition and Magnetic Properties

The size and the number of particles of phase α_1 as well as their composition depend upon the spinodal decomposition temperature and time. Fig. 3 shows that very similar coercivity and remanence are obtained by the alloy $Fe_{30}Cr_{15}Co$ by 30 min. of annealing in temperature range from 615 °C to 595°C. By higher temperature the magnetic properties decrease very fast. By low spinodal temperature the hardness is increased and the ductility diminished (fig. 4). Experience shows that a sufficient ductility is obtained if the spinodal temperature is above 620°C. A similar effect of spinodal temperature on the ductility was found also for the alloy $Fe_{28}Cr_{16}Co$. By short annealing time the spinodal structure is stable below appr. 620°C. By the temperature of 630°C, which was found as optimal for ductility and magnetic properties after wire drawing deformation, the best properties are obtained by a 30 min. annealing (fig. 5). After the wire drawing deformation the alloys are submitted to a 12 hr. aging in temperature range from 600 in 500°C. During the aging the difference in chemistry between both phases, the accommodating stresses, coercivity and energy product are increased, while remanence shows a slight decrease at initial aging temperature (fig. 6).

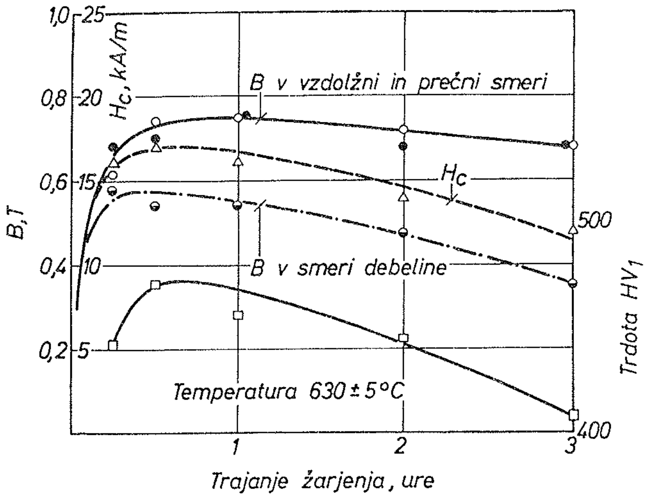

Fig. 5: $Fe_{30}Cr_{10}Co$ alloy. Effect of annealing for spinodal decomposition at 630°C on coercitivity, remanence and hardness. The alloy was homogenised at 1200°C and quenched.

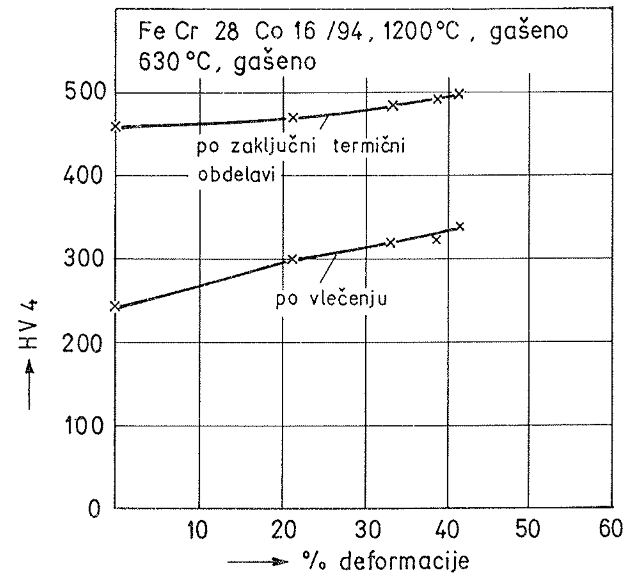

Fig. 7: $Fe_{28}Cr_{16}Co$ alloy. Effect of deformation by wire drawing on hardness before and after aging. The alloy was initially annealed at 1200°C, quenched, reannealed 30 min. at 630°C and quenched.

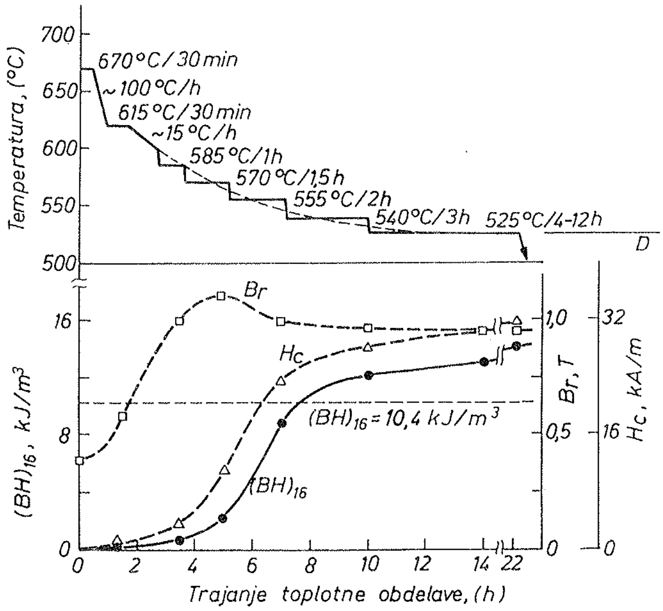

Fig. 6: $Fe_{30}Cr_{10}Co$ alloy. Evolution of magnetic properties and hardness by controlled slow cooling (aging). The alloy was initially annealed at 1200°C, quenched, annealed for 30 min. at 620°C and quenched.

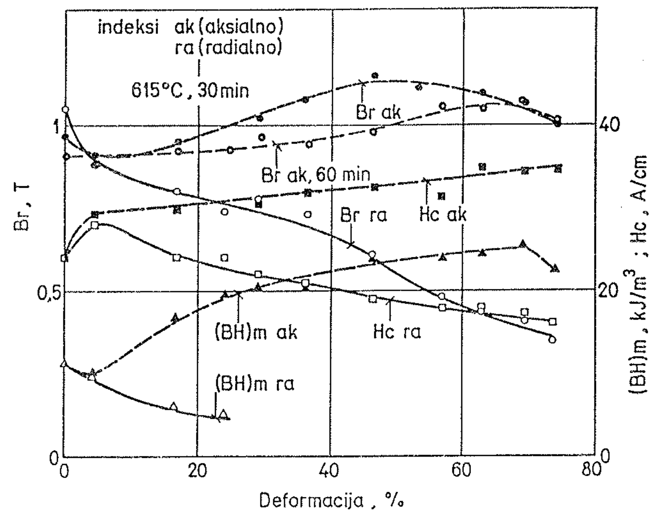

Fig. 8: $Fe_{32}Cr_{10}Co$ alloy. Influence of wire drawing deformation on magnetic properties in axial (ak) and radial (ra) directions. Initially the alloy was annealed at 1200°C, quenched, reannealed 30 min. at 615°C and quenched.

3. Deformation and Magnetic Properties

The wire drawing deformation is carried out at increased temperature. This should be, however, below that which could affect the spinodal decomposition and the dynamic as well as static softening processes. By wire drawing deformation a low strain hardening is obtained (fig. 7), appr. proportional to the degree of deformation. It is interesting that after aging, which is started at a temperature appr. 200°C above the wire drawing temperature, the strain hardening is conserved. The deformation increases the magnetic properties in axial direction and diminishes these properties in radial direction (fig. 8). Correspondingly, the shape of the demagnetisation curve becomes more rectangular (fig. 9). A careful evaluation of experimental findings showed that the remanence grows proportially to the square of the ratio between the initial (di) and the final (da) diameter of the deformed rod (fig. 10), while the coercivity is increased proportionally to this ratio (fig. 11) and it is appr. proportional to the strain hardening. The relationships in fig. 10 and 11 can be explained supposing that the change in magnetic properties in dependence of the deformation is connected to the modification of the shape of the particles of

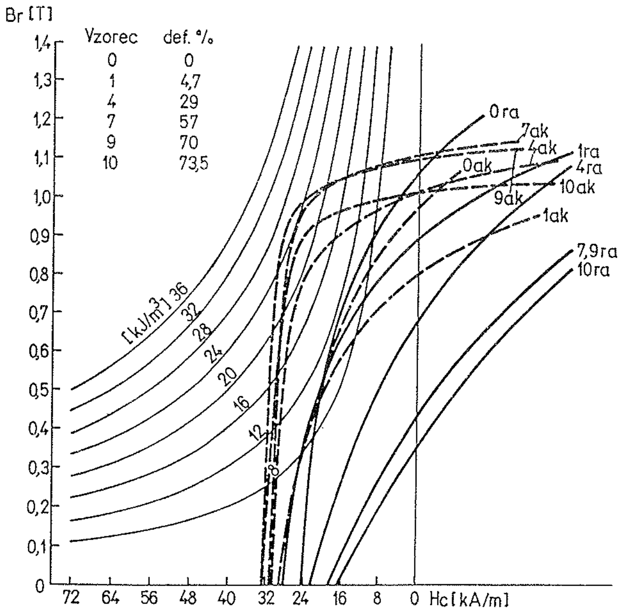

Fig. 9: *Alloy form fig. 8. Influence of the deformation degree on the shape of the demagnetisation curve in axial and radial directions.*

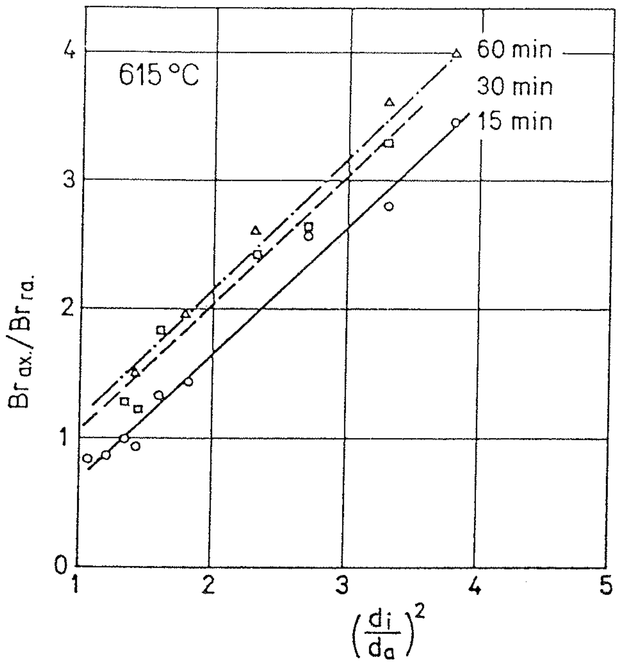

Fig. 10: *Alloy from fig. 8. Relationship allongement-remanence.*

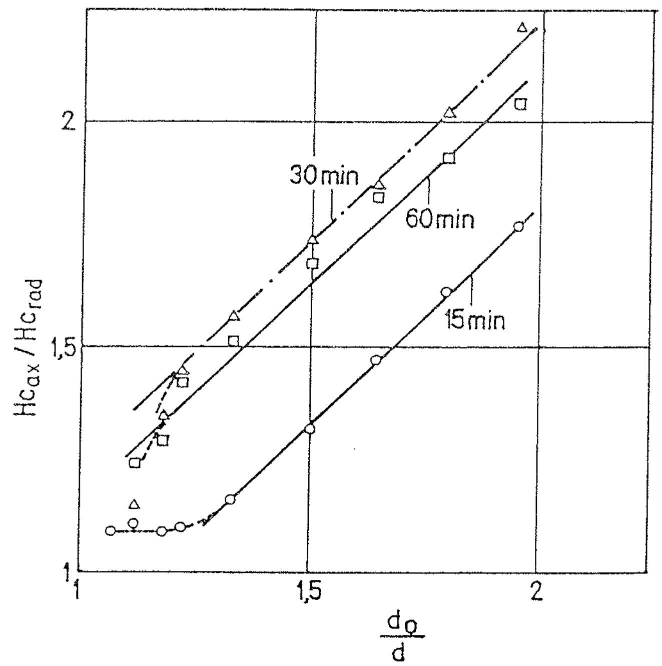

Fig. 11: *Alloy from fig. 8. Relationship decrease of rod thickness-coercitivity.*

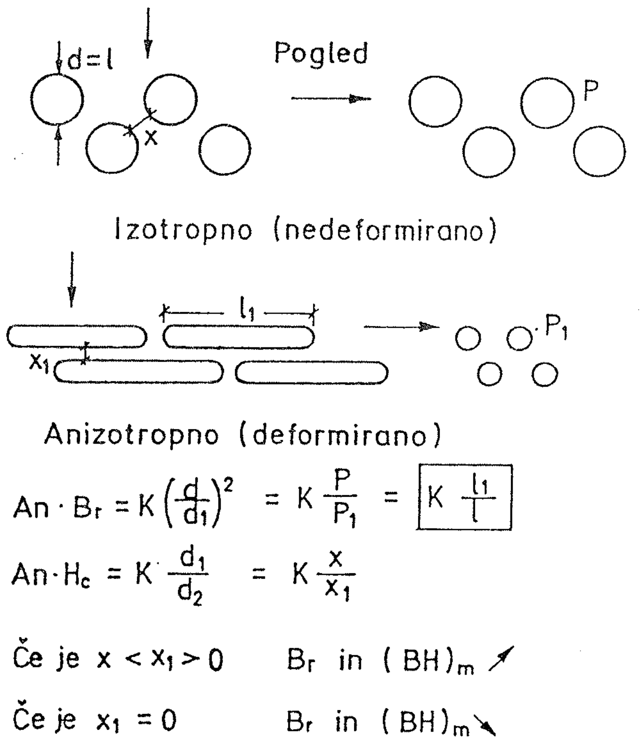

Fig. 12: *Schematically representation of the dependence of the shape of particles of phase $\alpha 1$ and the remanence and the coercitivity.*

phase α_1. These particles are initially spherical and are deformed in the same way as the matrix of phase α_2, because the change in chemistry has no significant effect on the hardness of both phases through solid solution hardening. Shematically, the effect of the shape change of particles of phase α_1 is shown in fig. 12. The coercivity is the higher the smaller is the distance between particles of phase α_1, it increases thus with the gradient of chemistry between both spinodal phases. The effect of deformation on coercitivity is similar to the effect of the lowering of the spinodal temperature. The remanence depends upon the ratio length over diameter of particles of phase α_1, which is proportional to the wire drawing allongement and to the ratio of the initial over final diameter of the deformed rod.

Let us suppose that one Weiss domain occupies a volume of one particle of phase α_1 with the corresponding part of the matrix of phase α_2 /15/. If the allonged particles of phase α_1 approach below a critical distance or even a mutual contact is established, the shape and the size of Weiss domains is changed, and the remanence, which depends upon their size, is diminished also. Indirectly this explanation is confirmed by the fact that the greatest remanence is obtained by a 45-50% deformation after 30 min. of spinodal decomposition at 630°C, while after 60 min. of spinodal annealing at the same temperature the highest remanence is obtained by appr. 65% of deformation. By isothermal annealing the number of particles of phase α_1 (N) is diminished accordingly to the parabolic law $N \approx Kt^{0.2}$ (t - annealing time) and parallelly their size is increased also.

4. Conclusion

In the technical iron-chromium-cobalt alloys is necessary through the addition of secondary alloying elements obtain a microstructure of the ferromagnetic phase α. This microstructure gives, however, after homogenisation and quenching a very poor ductility at ambient temperature. By a selected chemistry of the alloy the magnetic properties depend strongly upon the combination of the temperature of spinodal decomposition, the wire drawing deformation and the aging process. All magnetic properties are improved by the deformation. The highest remanence is found by appr. 60% of wire drawing deformation. The coercivity grows proportionally to the decrease of the distance between α_1 particles, while remanence increases proportionally to the allongement of these particles.

The support of the Ministry of Science and Technology of Slovenia is gratefully a knowledged.

5. References

/1/ H. Kaneko, M. Homma and T. Minowa, IEEE Transactions on Magnetics Mag. 12 (1976) 977-979.

/2/ G.Y. Chin, J.T. Plewes and B.C. Wonsievicz, J.Applied Physics 49 (1978) 2046-2048.

/3/ M. Okada, G. Thomas, M. Homma and H.Kaneko, IEEE Transactions on Magnetics Mag. 14 (1978) 245-252.

/4/ B.C. Wonsievicz, J.T. Plewes and G.Y. Chin, IEEE Transactions on Magnetics Mag. 15 (1979) 950-956.

/5/ S. Yin, G.Y. Chin and B.C. Wonsievicz, IEEE Transactions on Magnetics Mag. 16 (1980) 139-146.

/6/ M.L. Green, R.C. Sherwood, G.Y. Chin, J.H. Wrenick and J. Bernardini, IEEE Transactions on Magnetics Mag. 16 (1980) 1053-1055

/7/ T. Minowa, M. Okada and M. Homma, IEEE Transactions on Magnetics Mag. 16 (1980) 529-533.

/8/ W. Erwens, Techn. Mitt. Krupp-Forsch. Ber. 40 (1982) 109-116.

/9/ F. Zhu, P. Haasen and R. Wagner, Acta Metall. 34 (1986) 457-463.

/10/ S. Yin and N.V. Gayle, IEEE Transactions on Magnetics Mag. 16 (1980) 526-528.

/11/ S. Yin, V. Gayle and J.E. Bernardini, IEEE Transactions on Magnetics Mag. 16 (1980) 1050-1052.

/12/ T.S. Chin, C.Y. Chang and T.S. Wu, IEEE Transactions on Magnetics Mag. 18 (1982) 781-788.

/13/ T.S. Chin, C.Y. Chang, T.S. Wu, T.K. Hsu and Y.H. Chang, IEEE Transactions on Magnetics Mag. 19 (1983) 2035-2037.

/14/ H. Kaneko, M.Homma, N. Nakamura, M. Okada and G. Thomas, IEEE Transactions on Magnetics Mag. 13 (1977) 1325-1327.

/15/ H. Zijlstra, IEEE Transactions on Magnetics Mag. 14 (1978) 661.

/16/ M. Homma, M. Okada, T. Minowa, E. Hirikoshi, IEEE Transactions on Magnetics Mag. 17 (1981) 3473.

/17/ K. Chrost and J. Kladaš, J. Magn. Magn. Mater. 80 (1989) 359.

/18/ S. Jin and G.Y. Chin, IEEE Transactions on Magnetics Mag. 23 (1987) 3187.

/19/ F. Vodopivec, M. Pristavec, J. Žvokelj, D. Gnidovec and F. Grešovnik, Z. Metallkunde 79 (1988) 648.

/20. F. Vodopivec, D. Gnidovec, B. Arzenšek, M. Torkar and B. Breskvar, J. Magn. Magn. Mater. 81 (1989) 369.

/21/ F. Vodopivec, D. Gnidovec, B. Arzenšek, M. Torkar and B. Breskvar, Železarski Zbornik 23 (1989) 73.

/22/ F. Vodopivec, D.Gnidovec, J. Žvokelj, D. Kmetič and A. Rodič, Z. Metallkunde 81 (1990) 877.

/23/ F. Vodopivec, D. Gnidovec, M. Kmetič, A. Rodič and B. Breskvar, Železarski Zbornik 24 (1990) 91.

/24/ F. Vodopivec, D. Gnidovec, M. Torkar and B. Breskvar, Informacije MIDEM 22 (1992) 3.

/25/ F. Vodopivec, J. Žvokelj, B. Breskvar, D. Gnidovec, A. Rodič , M. Torkar, Z. Metallkunde 85 (1994) 207.

/26. F. Vodopivec: 45. Posvetovanje o metalurgiji in kovinskih gradivih in 2. Posvetovanje o materialih, Portorož, oktober 1994

Prof.dr. Franc Vodopivec,
Institute of metals and Technology,
Lepi pot 11, 61000 Ljubljana, Slovenia
tel. + 386 61 125 11 61
fax. + 386 61 21 780

Prispelo (Arrived): 18.11.1994 ***Sprejeto (Accepted): 22.11.1994***