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Physics of Condensed Matter Section (ФКС-09)

Heterodiffusion in ferromagnetics in the pulsed magnetic fields

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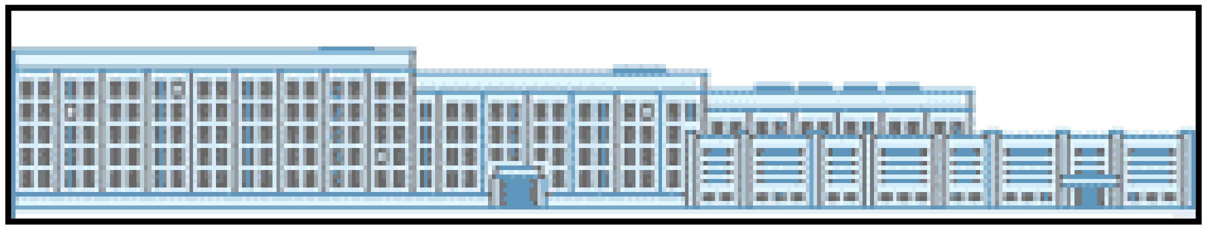

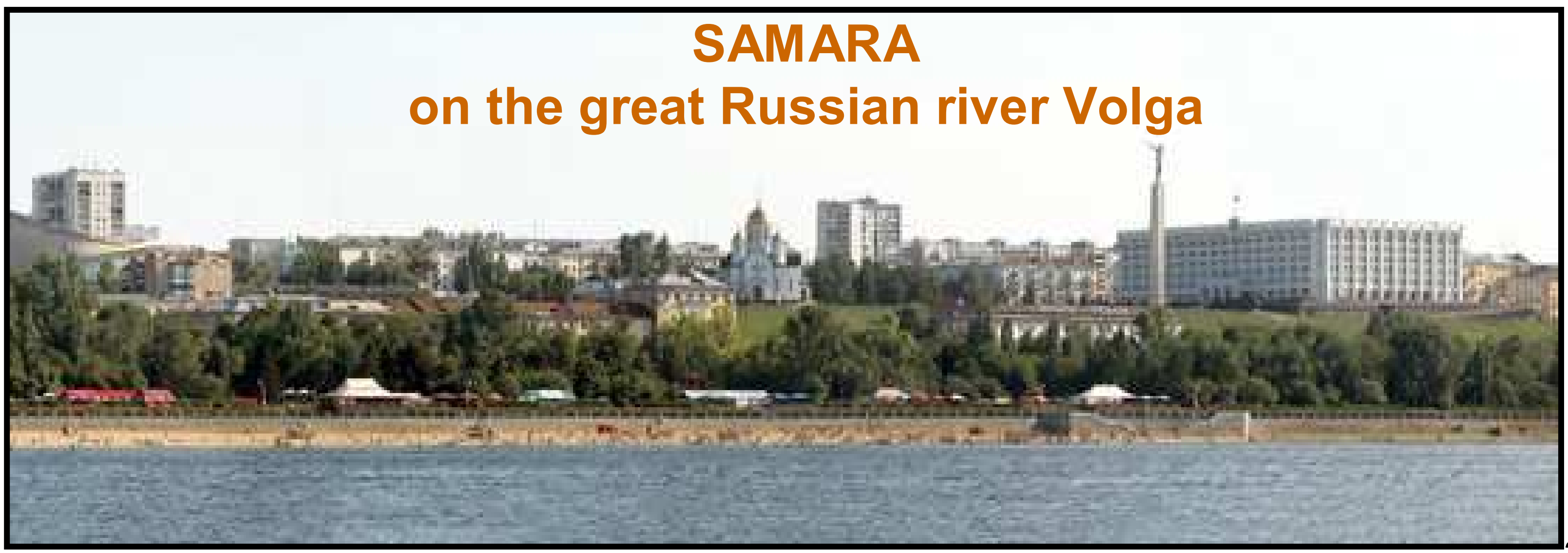

Prepresented data are received together with the 5-th course students of physical faculty of Samara State University
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Motivations

- The problem of impurity atoms behavior diffusing in solids at the increased temperatures under the magnetic fields effect can be qualified as fundamental
- Now electron-spin interaction among the defects in nonmagnetic and magnetic solids is the important and interest problem of the modern solid state physics, physics of durability and spintronics (MPE- and MDE-effects)
- Al heterodiffusion in alpha-Fe under the action of the pulse magnetic field gives the information about interaction among the structural and magnetic (moving domain walls) defects
- The data about of heterodiffusion in solids in variable magnetic fields are rather limited

Content

- Magnetoplastic and magnetodiffusion effects (MDE).
- Aims of the present work - the experimental research of amplitude, frequency and temperature dependences of the heterodiffusion coefficient of Al, Be in Fe under the influence of external pulsed magnetic field
- Experimental technique
- Main experimental results
- Discussion and Conclusion: Physical mechanisms

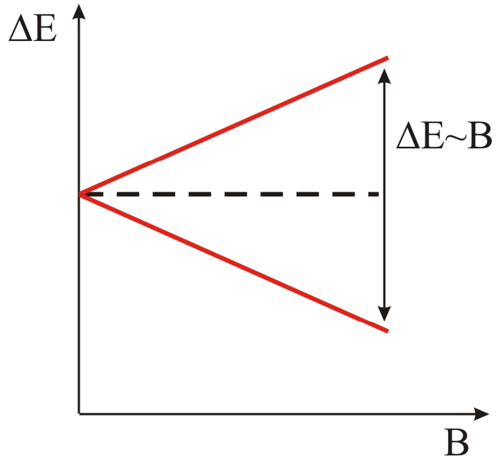
The degree of the external pulsed magnetic field (PMF) influence on the diffusion process can be determined by

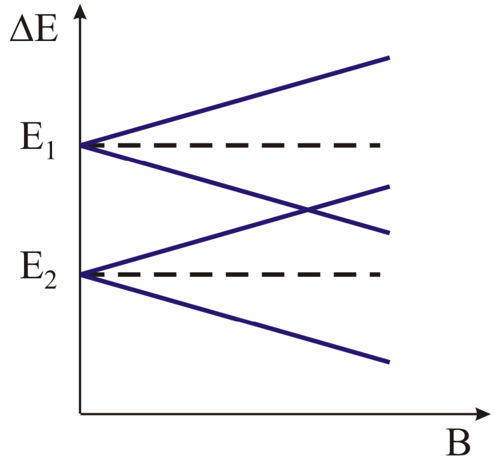
- 1) The magnetic properties of the diffusing impurity atoms in solid solutions and, as the experiments in magnetostatic fields show [1], by
- 2) The magnetic properties of the diffusion matrix proper
- 3) Structural condition and defects of the diffusion matrix proper
- 4) The data about of heterodiffusion in solids in variable magnetic fields are rather limited.

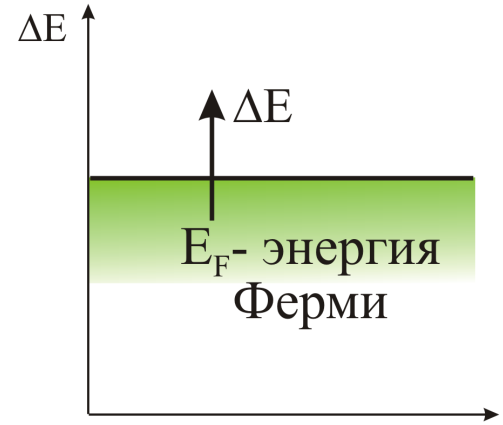
[1] V.F. Mazanko, A.V. Pokoev, V.M. Mironov, D.S. Herzriken, D.V. Muronov, D.I. Stepanov, G.V. Lutsenko.: *Diffusion Processes in Metals under the Action of Magnetic Fields and Pulse Deformations*, volumes I and II (Mashinostroenie-1, Moscow 2006) (in Russian).

"Weak" and "strong" magnetic fields

Different criteria for «strong» MF







Classical limit

$$\Delta E = \mu_B \beta B > kT$$

Quantum limit

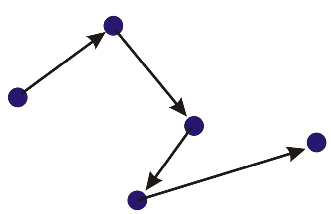
$$\Delta E = \mu_B \beta B > E_1 - E_2$$

Ultraquantum limit

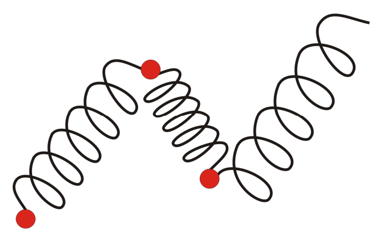
$$\Delta E = \mu_B \beta B > E_F$$

In metals there is an additional «kinetic» criteria $\varpi\tau >> 1$

ω-cyclotron frequency of electrons, τ-relaxation time of electrons



B=0



B удовлетворяет условию ωτ>>1

Literature experimental data on the influence of an alternating MF on the diffusion and diffusion-controlled processes

In work [2] the author revealed the acceleration of the sintering process of ferromagnetic particles as compared with the isothermal annealing without the alternating MF effect, but the all regularities of diffusion had not been established.	[2] M. Eudier: Symp. on Powder Metal. London. (1956), p. 346.
The effect of the alternating MF produced on the diffusion processes at sintering of iron powders is mentioned in work [3]. Is established, that the variable magnetic field with frequency 1 Hz with amplitude of intensity 1 kOe accelerates process of sintering of powders, and also it increases shrinkage and hardness of sintered powder	[3] Yu.I. Boiko, Yu.I. Klinchuk, V.M. Kuts and I.T. Chizhikova: Poroshk. Metall. No. 12 (1989), p. 14 (in Russian).
Available are the statements that alternating MF also has its influence on a mutual diffusion in solid [4]	[4] L. Xiaotao, C. Jianzhong, W. Xiaoming, G. Yanhui and J. Zhang: Scripta materialia Vol. 52 (2005), Issue 1, p. 79.
…. and liquid phases [5]. …..but full regularities of diffusion and full its physical nature had not been established in all cases.	[5] Y. Han, B. Chunyan, B. Qixian, G. Shijie, W. Shuhan and C. Jianzhong: Materials Letters Vol. 60 (2006), Issue 15. p. 1884.

Literature experimental data on the influence of an alternating MF on the diffusion and diffusion-controlled processes (continuation)

It is interesting, that in all cases this authors observed the increase of the growth constant of intermetallide phases in a variable magnetic field	Frequency of alternative magnetic field of 20, 10 Hz with induction of 0.12 and 0.5 T correspondently
In our woks of 2006-2007 years [6,7] it is for the first time revealed that the frequency and amplitude of the PMF intensity within the interval of 0,2-8 Hz influence the diffusion coefficient (DC) of Al in Fe at the one fixed temperature of 730 °C - MDE.	[6] M.A. Verzhkovskaya and A.V. Pokoev: Bulletin of the Russian Academy of Sience: Physics Vol. 70 (2006), p. 1100 (in Russian). [7] M.A. Verzhkovskaya, S.S. Petrov and A.V. Pokoev: Bulletin of the Russian Academy of Sience: Physics Vol. 71 (2007), p. 1674.

Chemical composition of α-Fe

Chemical composition of samples (wt. %)					
C	Si	Mn	S	P	Cu
0.008	0.13	0.25	0.020	0.010	0.16

Samples

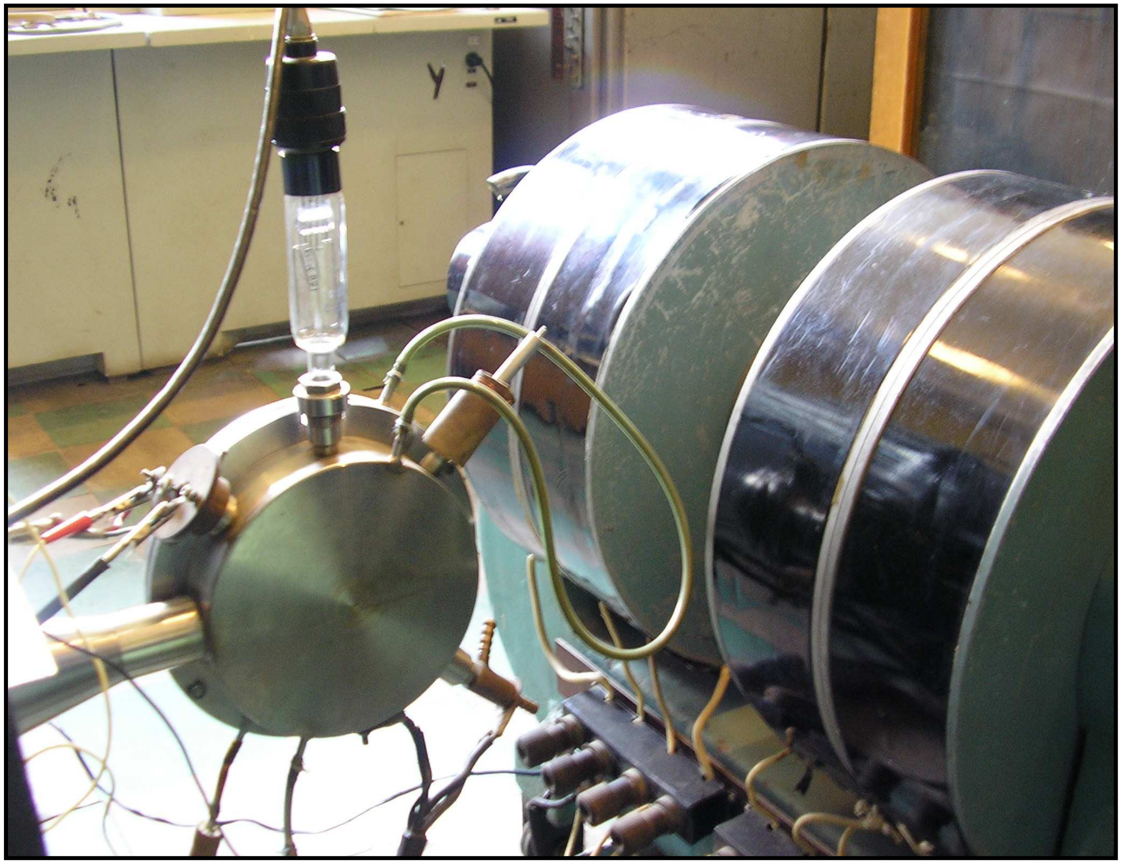
poly- α-Fe: cylinder (d=10 mm, h=10 mm);

anneal at 1400°C , 10^{-3} Pa , 2 h, d_3= 0.5-1 mm;

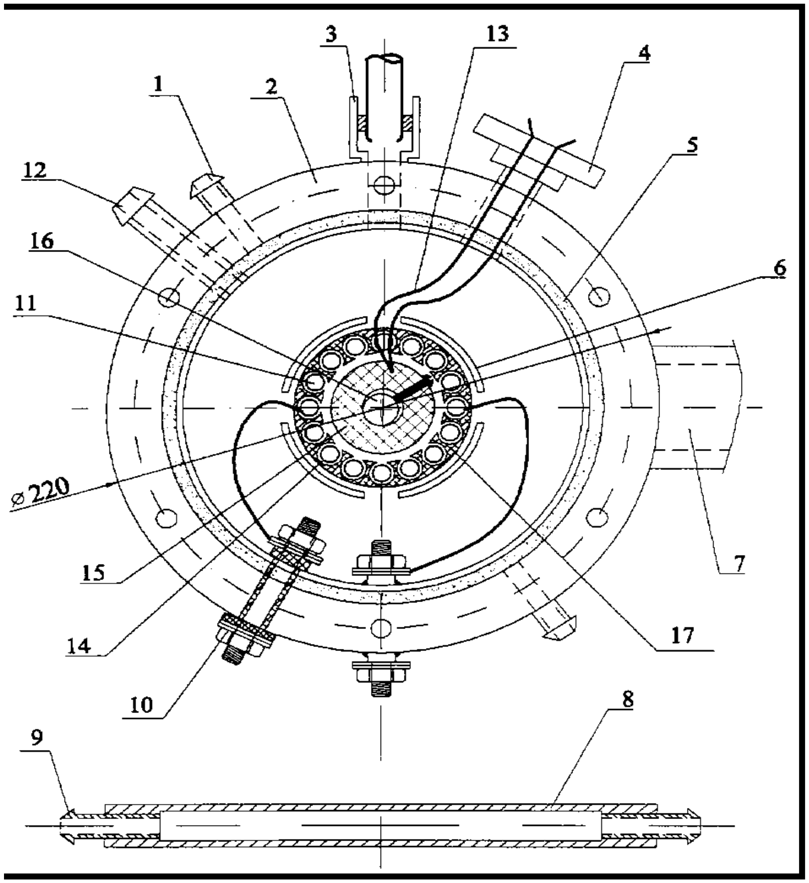
Al-films: 0.12-0.24 μm, thermal evaporation

Method of investigation: X-ray diffraction

Experimental set up



Scheme of vacuum chamber for heat treatments in PMF



1- штуцер для охлаждения корпуса камеры холодной водой,

2 - камера представляет собой цилиндрический цилиндр с фланцем (non-magnetic steel body),

3 - штуцер для манометрической лампы для измерения вакуума (vacuum tube for measuring of vacuum),

4 - ввод для термопары,

5 - кольцо вакуумной резины, для герметичности контакта корпуса и крышки (vacuum-tight contact),

6 - стальной стакан для установки нагревателя,

7 - вакуумопровод для откачки камеры (vacuum tube for spooling),

8 - съемная торцевая крышка (removable water-cooled cover),

9 - штуцер для охлаждения крышки камеры холодной водой,

10 - ввод для питания нагревателя,

11 - пазы на нагревателе для спирали,

12 - штуцер для ввода инертных газов,

13 – термопара (thermocouple),

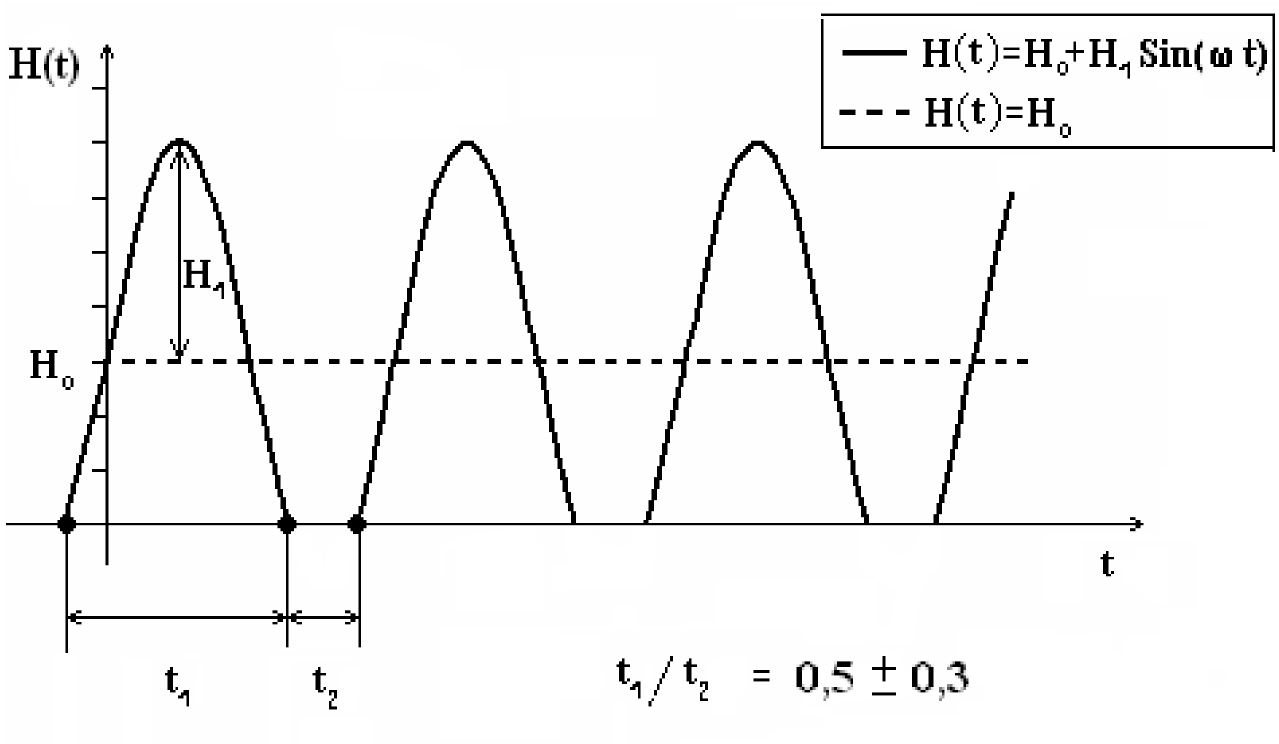
14 - спираль из вольфрамовой или молибденовой проволоки диаметром 0,3-0,5 мм (Mo-wire),

15 - стальная немагнитная оправка (non-magnetic keeper),

16 – образец (spacimen),

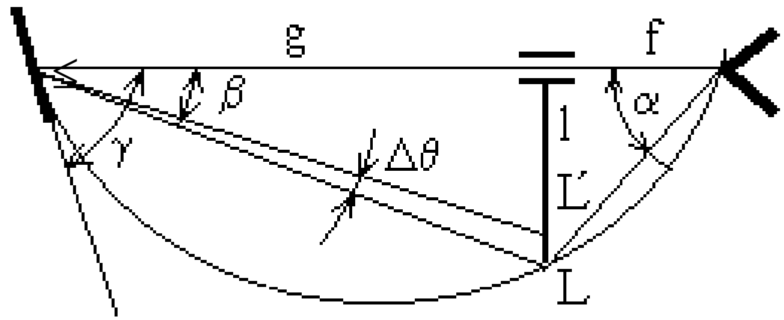
17 - нагреватель в виде керамического цилиндра диаметром 29 мм (heater).

Pulse Shape of Magnetic Field



$$H(t) = \begin{cases} H_0 + H_1 \sin(2\pi f t), & 0 < t < t_1, \\ 0, & t_1 < t < t_1 + t_2 \end{cases}$$

Geometry of rontgenography in PKЭ X-ray camera



Co K_{α}, g=184 mm, (310)Fe, θ=80.6 °

$$c_{Al} = \frac{a_0 \cos^2(\pi - 2\theta)}{2b \cdot g \cdot tg\theta}\Delta l, \quad a_0 = 2.8664 \ \mathring{A} \ (Fe)$$

$$D = \frac{h^2}{\pi \cdot t \cdot c_{Al}^{\ 2}} \left(\frac{V_{Fe}}{V_{Al}}\right)^2$$

$0.8 < c_{Al} < 3.2$ at.%, $1.0 < \Delta l < 4.0$ mm, $4 < t < 17$ h

Δ D/D ~ 6-12 %, D – volume DC

Experimental results

Frequency of PMF - $0 < f < 8$ Hz;

Amplitude of harmonic component of PMF intencity -

$H_1 = 0 \div 557.2$ kA/m (7 kOe);

Value of constant component of PMF intensity, kA/m (kOe) –

Ho=39.8 (0.5), 59.6 (0.75), 79.6 (1.0), 159.2 (2.0), 238.8 (3.0)

Temperature interval - $730 < T < 820$ °C

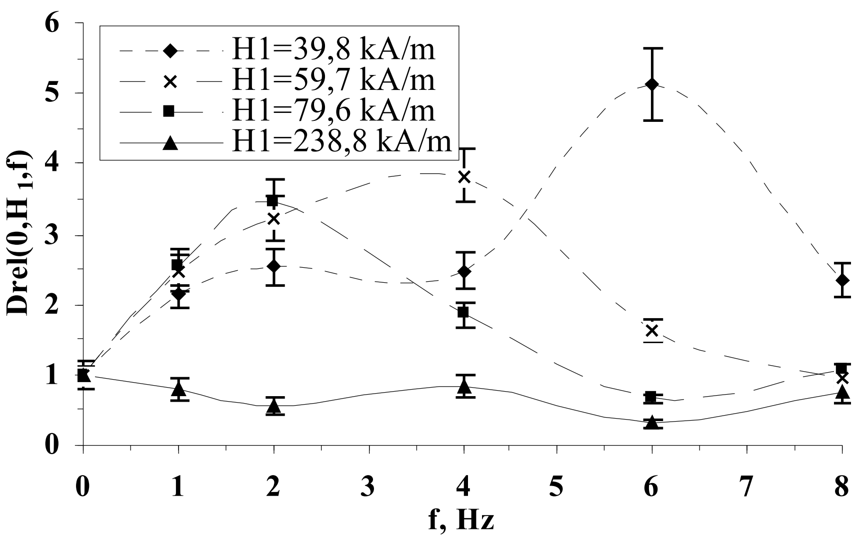
Relative diffusion coefficient have been measured:

$$D_{rel}\ (H_0, H_1, f) = D_H(H_0, H_1, f) / D_{H=0}$$

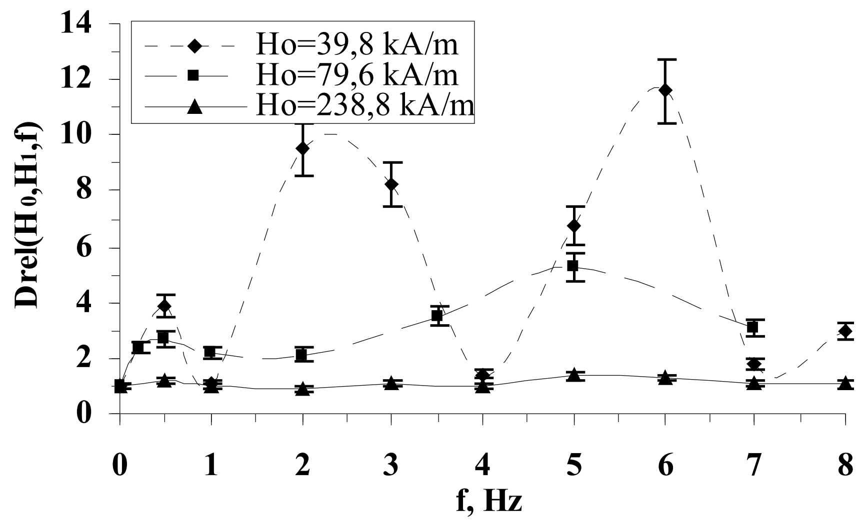
Two series of specimens:

1) $H_0 = 0$, $H_1 \neq 0$ and
2) $H_0 = 0$, $39.8 < H_1 < 541.3$ kA/m

Frequency dependences of the relative DC of Al in Fe in PMF at 730 °C: a - PMF contains only "harmonic" component H_1 (H_0=0); b – PMF contains both constant component H_0 and "harmonic" component H_1

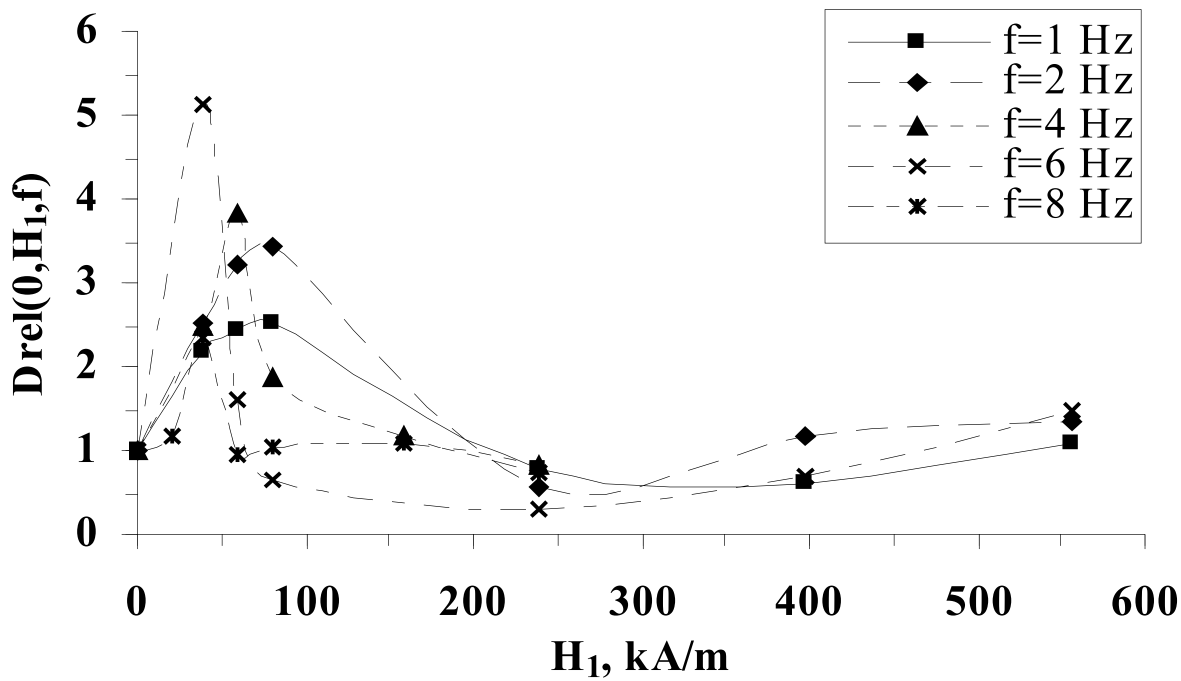


a $(H_0=0, H_1 \neq 0)$



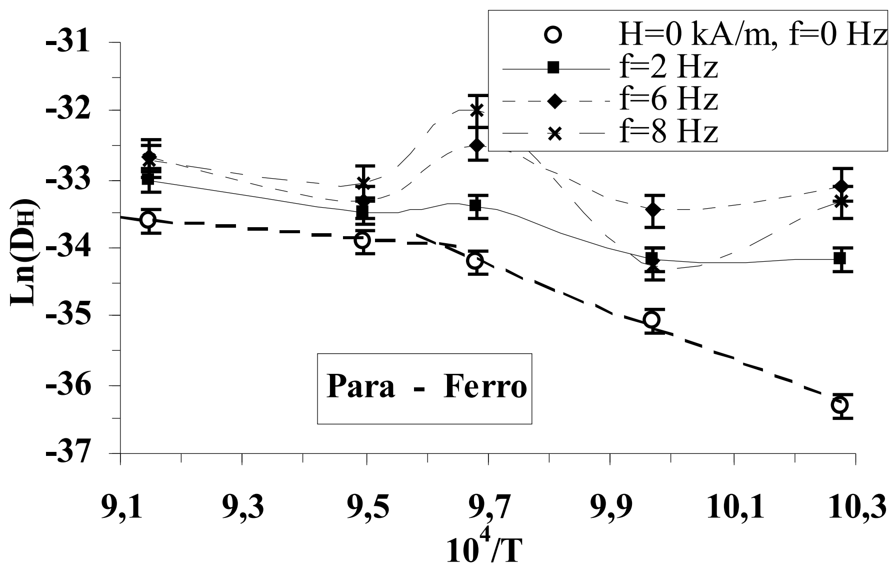
b $(H_0 \neq 0, H_1 \neq 0)$

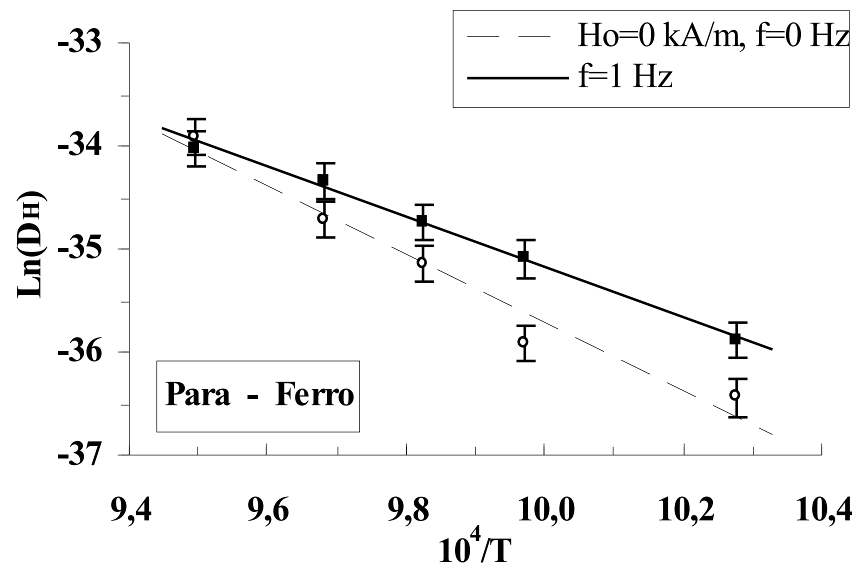
Graphs for amplitude-and-field dependences of the relative DC of Al in Fe (in PMF)



$H_0 = 0, H_1 \neq 0$

Graphs of Temperature Dependences of the Relative DC of Al in Fe $Ln(D_H(H_0,H_1,f))=f(1/T)$

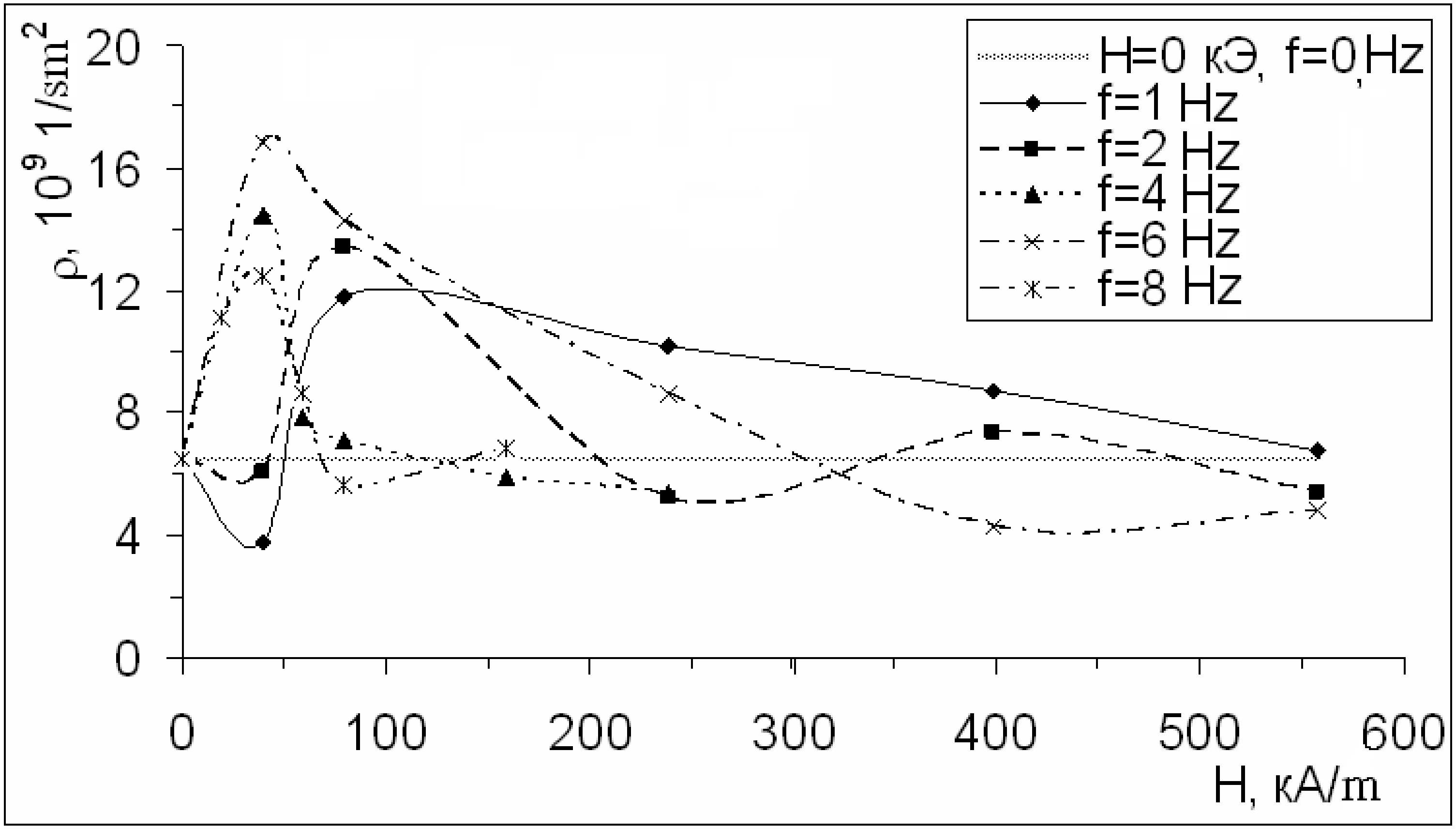




$H_0=0$ and $H_1 = 39.8$ (0.5) kA/m (kOe)

$H_0 = 79.6$ (1.0) and $H_1 = 119.4$ (1.5) kA/m (kOe)

Dependence of the X-ray dislocation density on the amplitude of the magnetic field in Fe at 730 ºC under different frequencies of the PMF



The physical reasons of PMF influence on heterodiffusion

1. Mechanism of direct interaction of moving domain walls with impurity atoms;
2. Mechanism of magnetoelastic interaction of moving domain walls at magnetic remagnetization with dislocations, saturated by impurity atoms in a various degree;
3. Mechanism of magnetoelastic interaction of impurity atoms with an elastic field of concentration distribution of impurity in a diffusion zone.

Diffusion equations in pulsed magnetic field

$$j = -D\frac{\partial n}{\partial x} + n\langle v \rangle_F, \qquad \langle v \rangle_F = uF$$

$$\langle v \rangle_F = \frac{D}{kT}\left(F_{Пр-ДС} + F_{Пр-(Д+ДС)} + F_{Пр-ДЗ}\right)$$

$$j = -D\frac{\partial n}{\partial x} + n\frac{D}{kT}\left(F_{Пр-ДС} + F_{Пр-(Д+ДС)} + F_{Пр-ДЗ}\right)$$

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \frac{\partial}{\partial x}\left[n\frac{D}{kT}\left(F_{Пр-ДС} + F_{Пр-(Д+ДС)} + F_{Пр-ДЗ}\right)\right]$$

Mechanism of interaction of diffusing impurity atoms with moving domain walls

- $v_F = F_x D/(kT)$ – diffusion velocity of impurity atoms, p_m – magnetic moment of the impurity,
- $v = v(f)$ – velocity of the domain wall under the variable PMF action

1. If $v << v_F$, the efficiency of capturing of the impurity by the domain wall will be low, i.e. the atom can "jump out" from the potential hole of the area domain wall.

2. If $v \sim v_F$, then the impurity can be trapped by the domain wall.

3. If $v >> v_F$, then the domain wall can drag the impurity.

Mechanisms of magnetoelastic interaction between dislocation and field driven motion of domain walls

- *Force of magnetic interaction with magnetic moment of dislocation:* M – magnetic moment of dislocation; I – magneticity; b – Buergers vector ; H –magnetic field intensity; δ – the width of domain wall. For Fe in PMF: I(730 °C)≈7.7·105 A/m, b≈3·10-10 m, δ≈3·10-3 m, H≈5.6·10⁴ A/m and therefore: $F_1 \sim 10^{-6}$ N/m.

$$F_1 = M \cdot \text{gradH} \cong Ib^2/\delta\,H$$

- *Force of magnetoelastic interaction of dislocations with domain boundaries:*

β – magnetostriction constant, E – elastic module. For Fe: β(730°C)~4·10^{-6}, E~2·10^{11} N/m^2 and therefore:

$$F_2 \cong \beta E b$$

$F_2 \sim 10^{-4}$ N/m.

- *Force, necessary to pile up of dislocation from pinning points:*

$$F_3 \cong \frac{U}{bL}$$

U – energy of interaction among dislocation and stoppers, L – the average length of dislocation segment. For Fe U~1·10^{-19} J, L~3·10^{-6} m ($\rho_d \cong 1\cdot 10^7$ sm^{-2}) and therefore: $F_3 \sim 10^{-4}$ N/m.

Thus, $F_1 \ll F_2$ and $F_2 \sim F_3$.

Диффузия Be в Fe в ИМП и ПМП

T, C	t, час	H1, кА/м	f, Гц	Δl, мм	Dср±ΔD, м2/с
730	2-8	39.6	6 В ИМП	0.4	(2.6±0.7) · E-16
730	6	39.6	0 В ПМП	0.3	(2.3±0.7)·E-16
730	6-12	0	0 без МП	0.3-0.7	(6.3±1.1)·E-17

CONCLUSIONS

Effect of alternating MF on diffusion can be manifested across several mechanisms.

Since in the diffusion process always a complex reorganization of the dislocation structure takes place which is connected to interactions with magnetoelastic, dislocation and composition fields.

There is no full analytical theory at present for the description of the kinetics of changes of the diffusion coefficients in PMF.

More experiments and efforts are necessary.

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Thank you for your attention!