Exchange Effects in the Invar Hardening: $Fe_{0.65}Ni_{0.35}$ as a test case

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An increase of the critical resolved shear stress of Invar alloys (Invar hardening) with a lowering temperature is explained. The effect is caused by a growth of the exchange interaction between dangling $d$-electron states of dislocation cores and paramagnetic obstacles (e.g., Ni atoms in FeNi alloys) which occurs below the Curie temperature. The spins of the two electrons align along the magnetization due to the exchange interaction with the surrounding atoms of the ferromagnetic. The exchange interaction between the dislocations and obstacles is enhanced in Invars due to a strong growth of the magnetic moments of atoms under the action of elastic strains near the dislocation cores. Parameters characterizing the exchange interaction are determined for the case of the $Fe_{0.65}Ni_{0.35}$ Invar. The influence of the internal magnetic field on the dislocation detachment from the obstacles is taken into account. The obtained temperature dependence of the critical resolved shear stress in the $Fe_{0.65}Ni_{0.35}$ Invar agrees well with the available experimental data. Experiments facilitating a further check of the theoretical model are suggested.

I. INTRODUCTION

It was in 1897 when Guillaume first revealed unusual properties of ferromagnetic FCC iron-nickel alloys with the content close to $Fe_{0.65}Ni_{0.35}$. The alloys appeared to be characterized by an extremely low thermal expansion in a wide range around the room temperature. This is because of this property of having an invariant volume under varying temperature that this alloys have been named Invars. It was shown later on that many other physical and mechanical properties of Invars also strongly differ from those of other ferromagnetics. We mention here among the others: volume magnetostriction, specific heat, elastic constants, electrical resistivity, pressure dependence of the magnetization and the Curie temperature. Such an anomalous behavior is observed only in the nearest vicinity of the content specific for Invars and may strongly depend on the temperature, pressure, magnetic field and so on (see, e.g., review [1], and proceedings of the centennial symposium on the Invar effect [2]). Many unusual properties of Invars can be understood if one considers a possibility of continuous transitions between the collinear ferromagnetic spin state to a non-collinear configuration ([3,4] and references therein).

Plastic properties of Invars are also anomalous. It is known for long (see, e.g., [5]) that the critical resolved shear stress (CRSS) of any alloy grows with lowering temperature. This growth is explained by a decreasing probability of dislocation detachment from obstacles induced by thermal fluctuations. The same trend is observed in Invars but this growth in Invars is at least order of magnitude stronger than in non-magnetic FCC alloys, and several times stronger than even in FeNi alloys with non-Invar contents [6–12]. It is emphasized that this anomalously strong temperature dependence of CRSS in Invar alloys, named Invar hardening, starts only below the Curie temperature. This fact indicates an active role of the magnetic order in formation of plastic properties of Invars.

Unique properties of Invars resulted in their extremely broad application in numerous fields of technology. This certainly creates a special interest in studying their plastic properties. Several models suggested for an explanation of the Invar hardening will be critically discussed in Section II of this paper. We try to demonstrate in that section that these models are unfortunately not sufficient for understanding the effect.

Section III describes the model which we propose for an explanation of the Invar hardening. It is based on specific features of the exchange interaction between the electrons forming bonds of dislocations with obstacles. This exchange interaction in Invars appears to be much more important than widely discussed elastic and electrostatic interactions.

II. MODELS OF INVAR HARDENING

All the models, proposed with the aim to explain the Invar hardening, take into account the anomalously strong dependence of the local magnetization of Invars near edge dislocations on the local pressure. Krey [13] showed that the direct interaction between local magnetizations near the dislocations is weak. It is three orders of magnitude smaller than the corresponding elastic interaction. Other magnetic mechanisms, e.g., magnetic interaction of the dislocations
with defects, are also very weak. That is why all the models disregard magnetic mechanisms and account only for exchange interactions varying with a change of the Invar magnetization.

It was proposed by Echigoya et al. ([9]) that Invar hardening is caused by the so-called magnetic friction in the course of dislocation motion. According to this model the part of exchange energy, associated with a dislocation, dissipates when the dislocation moves. It leads to an additional friction, which does not depend on the dislocation velocity. However, there are some doubts as for the effectiveness of this mechanism. The dislocation energy, including its exchange self-energy, is conserved when moving in a translationally invariant crystal. A dynamical deceleration of dislocations is possible only due to its interaction with various elementary excitations, such as phonons, conduction electrons, spin waves and so on. Such processes lead to a viscous friction which increases with the dislocation velocity and becomes zero for resting dislocations. There is also a magnetic friction in ferromagnetics caused by interaction of dislocations with magnons. The calculation ([14]) shows that this friction is extremely small even when the dislocation velocities are close to the speed of sound. As for the slowly moving dislocations observed in experiments ([6–12]) (their velocity is 8 to 9 orders of magnitude smaller than the sound velocity), for them the magnetic friction is negligibly small and cannot anyhow affect the plasticity.

Flor et al. ([11]) connect the Invar hardening with the increasing activation energy for the kink motion, which is caused by an increase of their exchange energy. It is, however, known ([5]) that the motion of a dislocation in any FCC alloy is controlled by the dislocation detachment from the obstacles rather than by the kink motion. This makes the starting point of the model ([11]) not quite reliable.

An interesting model for the Invar hardening was proposed by Retat ([11]) who assumed that the spins of the electrons localized near the dislocation core are antiparallel to the spins of the electron in the neighboring atoms. This spin orientation realizes, according to ([11]), the minimum of the energy. If the dislocation moves to the neighboring equilibrium state so swiftly that spins do not have time to relax, then the core spins become parallel to those of the neighboring atoms. The exchange interaction results in an increase of the dislocation energy and in an effective growth of the Peierls barrier. This explains, according to Retat, the Invar hardening.

This mechanism can be effective if dislocation velocities are, at least, about several cm/s. Such and even larger velocities are achievable only under strong pulse loads of pure metals when the dislocation deceleration is due to a viscous friction ([12]). However, the experiments ([6–12]) are carried out under static loads and only slowly moving dislocations appear due to their thermally activated detachment from obstacles. Simple estimates lead to the conclusion that their velocities are less than 10⁻⁴ cm/s, i.e., four orders of magnitude smaller than required for the mechanism ([11]) to work.

Domain walls also play a part in pinning dislocations in Invars. Magnetostriction near the domain walls of the ferromagnetics results in long range strains, ([16]), hindering the dislocation motion. That is why creation of domains at temperatures below the Curie temperature may lead to an increase of CRSS in ferromagnetics, and might have, in principle, produced the Invar hardening.

Unfortunately, there are several reservations as for the role of the domain walls in the Invar hardening. First, the additional strains produced by the walls (~ 1 MPa) are two orders of magnitude smaller than the CRSS observed in Invars ([6–12]). Second, these strains are proportional to the coefficients of the linear magnetostriction, and in Invars these coefficients do not essentially differ from those in other ferromagnetics ([17]), meaning that the fact that this type of hardening is specific only for Invars cannot be understood in this way. Third, the Invar alloys are soft magnetic materials with low values of the coercive field ([18]). This indicates a weak pinning of the domain walls by all the lattice defects including the dislocations. Fourth, direct measurements ([11]) of the influence of the domain walls on CRSS in Invars do not favor their participation in the Invar hardening.

Domains characterized by the magnetic momentum along the external magnetic field grow. This grows diminishes the number of domains walls pinned by dislocations. Therefore, the dislocation path length also grows in the magnetic field. This leads to an increasing plasticity of the ferromagnetic in a rather weak (~ 0.01 T) magnetic field ([19]). However, the experiments ([11]) show that the 0.04 T field, quite sufficient to essentially reduce the number of domain walls, does not have any influence on CRSS. We have no other choice as to conclude that domain walls hardly play any part in the Invar hardening.

We see that existing models do no provide a convincing explanation of the plastic properties of Invars. We will try in the next section to formulate an alternative model. The important feature of this model is a strong temperature dependence of the exchange interaction between dislocations and solute atoms (Ni atoms in case of FeNi alloy) which allows one to explain the anomalous plastic properties of Invars.
III. ROLE OF THE DISLOCATION–OBSTACLE EXCHANGE INTERACTION IN THE INVAR HARDENING

We are going to present in this section our explanation of the effect of Invar hardening. When carrying out the discussion and numerical estimates we will mainly refer to the Fe$_{0.65}$Ni$_{0.35}$ alloy, although our model with minor, mainly numerical, corrections is applicable to Invars with other contents as well.

The theory of plastic properties of alloys usually considers two main types of the dislocation interaction with defects — elastic and electrostatic [4]. The elastic interaction arises if the size of the impurity atoms differs strongly from the host atoms and a strain field is created in their vicinity. Then they interacts with the strain fields of dislocations. The electrostatic interaction in metals is due to the electric fields created due to a redistribution of charges near a dislocation, which acts on the charge distributions near defects.

Both types of the interaction are expected to be very weak in Invars, since atoms constituting them have very close sizes and chemical properties. For example in Fe$_{0.65}$Ni$_{0.35}$ Invar, the size of Ni (1.24Å) is hardly distinguishable from that of Fe (1.28Å in FCC lattice). Therefore, one should not expect any strain field around Ni atoms and, no tangible elastic interaction of dislocations with Ni atoms is possible. Ni atoms do not also create additional charges, since they are characterized by the same valence and electro-negativity as Fe atoms, making the electrostatic interaction between the dislocations and Ni atoms also negligible.

However, Invar alloys are characterized by a strong spin inhomogeneity. Calculations [20, 22] of the density of states with oppositely directed spins demonstrate that different atoms in Invar alloys possess unsaturated d-states with differing values of the localized magnetic moments. For example, Fe atoms in Fe$_{0.65}$Ni$_{0.35}$ Invars have a 2.5µ$_{B}$ magnetic moment, in contrast to 0.7µ$_{B}$ typical of Ni atoms [23]; here µ$_{B}$ is the Bohr magneton. As a result, localized spin states are associated with Ni atoms. The authors consider, so called, “chemical” interaction of the dangling $d$-bonds of a dislocation cores and impurities. Their calculation shows that the interaction can be very strong, up to 1 eV. This type of interaction is specific for the edge dislocations and is absent in the case of the screw dislocations. The screw dislocations can hardly form such bonds, which manifests itself in their much higher mobility observed in the experiments [8, 10]. The structure of chemical bonds is known to be largely controlled by the exchange interaction (see, e.g., [25]). It is the exchange energy which makes the difference between the chemical bonds formed by electrons with parallel and antiparallel spins. Depending on the sign of the exchange interaction - positive (ferromagnetic) or negative (antiferromagnetic) - the bond with either parallel or antiparallel spins becomes bonding, whereas the chemical bond with the opposite spin configuration becomes antibonding.

We have recently demonstrated [26–32] that considering the role of the exchange interaction in formation of the bonds between obstacles and edge dislocations plays a crucial role in the dislocation dynamics under the influence of a magnetic field. Such an approach allowed us, in particular, to understand the microscopic mechanisms of the electro- and magnetoplastic effects. Here we are going to apply similar ideas for an explanation of the Invar hardening.

The exchange interaction between the electrons in the dangling bonds of the dislocation core and the solute atom can be conventionally described as

$$U_{dk} = -2J(S_dS_k)$$

where $J$ is the exchange integral, while $S_d$ and $S_k$ are spin vectors related to the dislocation and defect electron spins. In a magnetic medium these vectors tend to orient along the common magnetization vector. Then using the molecular field approximation one can substitute them by their average values and rewrite equation (1) as

$$U_{dk} = -U_0 - 2JS_dS_k\sigma^2(T).$$

where $\sigma(T)$ is the temperature dependent relative magnetization.

The term, $U_0$, of the interaction (1) does not disappear even at $T > T_c$. It is a smooth function of the temperature near $T_c$ and accounts for the correlations between the orientations of the interacting spins which remain nonzero even in the paramagnetic state. It is quite sufficient for our purposes to represent this smooth function by a constant $U_0$. A similar equation has been deduced in reference [33].

Interaction between defects can be also described by this type of equation. For example, the interaction between vacancies in α-Fe grows from 0.24 to 0.30 eV when transiting from the para- to the ferromagnetic state [24]. This growth is well described when assuming interaction potential [24] with $U_0 = 0.24$ eV and $2JS_dS_k = 0.06$ eV.

It is specific for the Invar alloys that the magnetic moments of atoms depend anomalously strongly on the pressure [23, 33], decreasing under a positive pressure and increasing under a negative pressure. The dangling bonds of the edge dislocations are situated in the region of the missed semi-plane, i.e., they are under the action of a negative pressure. The same can be said about the Ni atoms whose electrons interact with the dislocation dangling bonds. The negative pressure results in a growth of both values of the spins $S_d$ and $S_k$ and, hence, the linear approximation for the pressure dependence of the atomic moments near the dislocation axis, results in
with \( i = d, k \). Here \( S_i^0 \) is the spin value at zero pressure \( p \). \( \alpha \) is a material constant. In the region of the missed semi-plane the pressure near the dislocation is [37]

\[ p = -\frac{\mu(1 + \nu)}{3\pi(1 - \nu)} \]

where \( \mu \) is the shear modulus and \( \nu \) is the Poisson coefficient. Now substituting equations (2) and (4) into (2) one gets the exchange interaction of dislocations with atoms in the form

\[ U_{dk} = -U_0 - \delta U g^2 \sigma^2(T) \]

where

\[ \delta U = 2JS_d^0 \sigma_k^0, \]

and

\[ g = 1 - \frac{\alpha \mu(1 + \nu)}{3\pi(1 - \nu)}. \]

When considering conventional ferromagnetics one can describe the relative magnetization using the Curie-Weiss model according which

\[ \sigma(T) = \begin{cases} \sqrt{1 - \frac{T}{T_c}}, & \text{at } T \leq T_c \\ 0, & \text{at } T > T_c \end{cases} \]

(6)

with \( T_c \) being the Curie temperature. However, the temperature dependence of the relative magnetization \( \sigma(T) \) in Invars deviates from the Curie-Weiss equation (3). This deviation is caused by the coexistence of several magnetic states whose energies are very close to the energy of the ground ferromagnetic state [4]. The most important deviation occurs near the Curie temperature where \( \sigma(T) \) does not go to zero but acquires small (0.15 to 0.20) values and rapidly decreases at higher temperatures [1]. Here we are interested in the range below the Curie temperature where we expect an influence of the magnetic ordering on plasticity. In this temperature range using equation (6) is a rather rough but reasonable approximation. Even at higher temperatures close to \( T_c \) this approximation does not cause an essential error since the relative magnetization is small and the energy (2) is proportional to \( \sigma^2(T) \), making the corresponding correction even smaller.

According to (3) the temperature dependence of the interaction energy is the stronger the more the value of \( g \) deviates from one. This value essentially differs from one only for Invar alloys with anomalously large parameter \( \alpha \). For example, the Fe\(_{0.65}\)Ni\(_{0.35}\) alloy is characterized by \( \alpha = -1.1 \times 10^{-11} \) (dyn/cm\(^2\))\(^{-1} \) [36]. Using the values \( \mu = 6.35 \times 10^{11} \) dyn/cm\(^2\) and \( \nu = 0.3 \), one gets \( g = 2.38 \). It is known [35] that the slightest deviation of the alloy content from the composition Fe\(_{0.65}\)Ni\(_{0.35}\) results in a decrease of the absolute value of the parameter \( \alpha \) by an order of magnitude or even more. As a result \( g \approx 1 \) in non-Invar compositions and, hence, for these alloys the potential [3] depends on the temperature much weaker. We believe that this is the principle cause of the anomalously strong temperature dependence of CRSS in Invar alloys.

According to the data available in reference [9] the value \( \tau_c \) of CRSS depends on the Ni concentration as \( c_{2.3}^\alpha \). Such a dependence corresponds to the solid solution hardening model proposed by Labush [2] according which the CRSS at \( T = 0 \) (i.e., the stress necessary to move a dislocation through a random array of obstacles in the glide plane) is

\[ \tau_{c0} = \frac{c_{2.3}^\alpha f_m^{4/3} w^{1/3} C}{a^{4/3} b (4T_l)^{1/3}}. \]

(7)

Here \( b \) is the magnitude of the Burgers vector, \( T_l \approx \frac{1}{2} \mu b^2 \) is the line tension of the dislocation, \( a^2 \) is the area of a lattice cell, \( w \) is the range of the dislocation - obstacle interaction force, \( f_m = U_{dk}/w \) is the maximal interaction force; \( C = 0.36000 \) for a repulsive interaction, and \( C = 0.27956 \) for an attractive interaction.

If one also accounts for thermal activation processes, equation (5) becomes

\[ \tau_c(T) = \frac{c_{2.3}^\alpha f_m^{4/3} w^{1/3} C}{a^{4/3} b (4T_l)^{1/3}} \left[ 1 - \left( \frac{T}{T_0} \right)^2 \right]^{\frac{3}{2}}, \]

(8)

4
where \( T_0 \) is a characteristic temperature at which \( \tau_c(T) \) becomes zero. The characteristic temperature \( T_0 \) is proportional to the interaction energy between the dislocation and the obstacle \[1\]. As shown above \[3\], this energy itself depends on the temperature in the ferromagnetic state and, hence, the characteristic “temperature” may be represented as

\[
T_0(T) = \begin{cases} 
T_{0p} \left[ 1 + \frac{\delta U}{U_0} g^2 \sigma^2(T) \right], & \text{at } T \leq T_c \\
T_{0p}, & \text{at } T > T_c
\end{cases}
\]

where \( T_{0p} \) is the value of the parameter \( T_0 \) in the paramagnetic state.

Now we are in a position to consider the influence of the internal magnetic field on plastic properties of Invar alloys. There is a spontaneous magnetization \( M \) of about 1 to \( 2 \times 10^3 \text{A/m} \) which corresponds to an internal magnetic induction \( B \sim 1 \text{ to } 2 \text{T} \). This field is strong enough to influence plastic properties of crystals (see our papers \[24, 22\] and references therein). It has been demonstrated in these papers that effective concentration of obstacles participating in the dislocation pinning depends on the magnetic field. We believe that a similar mechanism is responsible for the influence of varying magnetization on the CRSS in Invars.

According to this approach the binding energy of the bond between a dislocation and a paramagnetic obstacle strongly depends on its multiplicity. In the paper \[24\] we assumed that the singlet state of the bond possesses energy which is lower than in a triplet state, which corresponds to the negative (antiferromagnetic) sign of the parameter \( J \) in equation \( \{\} \). According to our model an external magnetic field may induce singlet to triplet transitions and lead to an increased population of the \( T \) state with lower binding energy and, hence, to an increased probability of the dislocation detachment from the obstacles. The crystal plasticity may, as a result, grow.

The Invar alloys which we discuss now are ferromagnetics and it is more natural to assume that the exchange parameter \( J \) in equation \( \{\} \) is now positive (ferromagnetic). Then the triplet state will have a larger binding energy, and magnetic field induced transitions to the singlet state will facilitate detachment of the dislocations. This process can be described by the same equations as in \[24\]. The opposite sign of the exchange energy does not have any consequences for these equations, since they relate to the dynamics of the system in the resonance region, where the exchange energy is negligible. But, contrary to the antiferromagnetic case, we assume that the dislocation bond is initially formed in one of three \( T \) states with equal probability \((1/3)\). We should also keep in mind that the difference between the magnetic field \( \mu_0 H \) and the induction \( B \) is important in ferromagnetics \((\mu_0 = 4\pi \times 10^{-7} \text{kg}\cdot\text{m}^3\text{sec}^{-4} \text{A}^{-2} \) is magnetic constant). Solving equations presented in reference \[24\], we look for the probability \( \rho_T(B) \) that, on having passed the resonance region under the action of a magnetic induction \( B \), the system remains in one of the three triplet states:

\[
\rho_T(B) = \frac{1}{1 + \frac{B^2}{B_0^2}}
\]

where

\[
B_0 = \sqrt{6(1 + \frac{T_1}{\tau})(1 + \frac{T_2}{\tau})B_m},
\]

\[
B_m = \frac{\hbar}{\sqrt{6g\mu_B T_1T_2}}.
\]

Here \( \Delta g \) is the difference of the \( g \) factors of the two electrons forming the radical pair (dislocation – obstacle bond); \( T_1 \) and \( T_2 \) are the transversal and longitudinal relaxation times characterizing the radical pair. The typical value of the characteristic field \( B_0 \) can be estimated to be from several tenths to one Tesla.

An obstacle is capable of pinning a dislocation in a ferromagnetic only if the bond between them is in a binding triplet state. If the radical pair is excited to its singlet state, the dislocation passes such an obstacle freely without “seeing” it. One may say that the effective concentration \( c_{ac}(B) \) of active obstacles is proportional to \( \rho_T(B) \). This concentration, \( c_{ac}(B) \), is now to be used instead of \( c_{at}(B) \) in equation \( \{\} \). The temperature dependence of this effective concentration arises due to the temperature dependence of the local magnetic field which in the Lorentz model reads

\[
B_M(T) = \frac{1}{3} \mu_0 M(0)\sigma(T).
\]

Substituting it into equation \( \{\} \) one gets

\[
c_{ac}(T) = \frac{c_{as}(0)}{1 + \left( \frac{\mu_0 M(0)\sigma(T)}{3B_0}\right)^2}
\]
where $\mu_0 M(0)$ is the saturation magnetization of the ferromagnetic at $T = 0$.

Comparing equation (10) with our results obtained earlier [26] one can conclude that the effective concentration of the active obstacles does not in fact depend on the sign of the exchange parameter $J$. Therefore, the fact that the Invar magnetic ordering is not purely ferromagnetic but rather a superposition of collinear and noncollinear states [3,4] does not play a role here. This rather complex structure produces a temperature dependent local magnetic moment which is to be used in equation (10).

Equations (8) and (10) determine the temperature dependence of the CRSS. If we take the $Fe_{0.65}Ni_{0.35}$ Invar alloy, then $T_c = 503K$ [1], $\mu_0 M(0) = 0.14T$ [13], $b = 2.5 \times 10^{-10}m$, $w = \sqrt{3}b = 4.3 \times 10^{-10}m$, $a^2 = \sqrt{3}b^2/3 = 3.6 \times 10^{-20}m^2$, $C = 0.27956$. The values of the other parameters: $T_{0p} = 980K$, $U_0 = 0.15eV$, $\delta U_0 = 0.10eV$, and $B_0 = 0.36T$, are obtained by fitting equation (8) to the experimental data [9].

Fig. 1 exhibits a good agreement of the theory and experiment for these values of the parameters. It is worth mentioning that the values itself are also quite reasonable. The above characteristic field $B_0 = 0.36T$, which corresponds to the typical values of the magnetic induction at which dislocations effectively detach from obstacles, lie between the value $B_0 = 0.49T$ obtained for aluminum [27,28] and $B_0 = 0.22T$ for copper [29]. The $U_0$ and $\delta U_0$ values are close to those (0.24 and 0.06 eV) obtained for vacancies in $\alpha$-Fe [34]. The absolute value of $U_{dk}$ varies at low temperature within the range from 0.15 to 0.72 eV, which coincides with the typical range of the energies of the dislocation – obstacle interaction [37].

IV. CONCLUSIONS

As has been demonstrated in the above section the Invar hardening can be explained by the temperature dependence of the exchange interaction energy in the system of dislocations bound to obstacles. Estimates for $Fe_{0.65}Ni_{0.35}$ Invars show that at reasonable values of the parameters there is a quantitative agreement between the experimental data and the theory.

It has been emphasized in the previous section that the main characteristics which really strongly distinguish between Fe and Ni atoms are their magnetic moments. This has lead us to the conclusion that a special attention should be paid to the exchange energy contribution to the edge dislocation – obstacle interaction. It is demonstrated in this paper that our approach provides a reasonable quantitative description of the Invar hardening.

Our model represents, as far as we know, the first attempt to consider the influence of the internal magnetic field on plasticity. Since the major part of construction materials are various steels, which are ferromagnetics, these results may be of an importance for developing a microscopic theory of plastic properties of steels.
There are also several other consequences of this model which, being experimentally verified, may serve as additional independent confirmation of the validity of our model. These are:

1. CRSS grows with a decreasing temperature due to the increase of the dislocation – obstacle interaction \( U_{dk} \).
   We expect that such a behaviour of \( U_{dk} \) should also show up in the amplitude - independent internal friction of dislocations. It was shown in reference [39] that the internal friction \( Q^{-1} \) in alloys varies inversely proportional to \( U_{dk} \). That is why, one may expect a rapid fall of the quantity \( Q^{-1} \) at \( T < T_c \), when the energy \( U_{dk} \) starts growing (see fig. 2). The temperature dependence of the internal friction \( Q^{-1} \) is expected to be stronger than linear in contrast to conventional nonmagnetic alloys.

2. This paper connects the Invar hardening with a strong increase of the magnetic moments created by the \( d \)-electrons in atoms in the vicinity of the dislocation cores. This, as shown in reference [40], causes a strong \( s-d \)-scattering of the conduction electrons and makes the principal contribution to the dislocation electric resistivity. Hence, one may expect that the anomalous increase of the magnetic moments of atoms near the dislocation cores will result in an anomalously strong dislocation electric resistivity, as compared to other ferromagnetic metals.

3. A strong temperature dependence of CRSS in the \( \text{Fe}_{0.65}\text{Ni}_{0.35} \) Invar alloy is explained by a large value of the parameter \( \alpha \) in the dependence of the magnetic moments on the pressure. Another Invar alloy – \( \text{Fe}_{0.72}\text{Pt}_{0.28} \) – is characterized at the room temperature by the parameter \( \alpha \) which is factor of 2.2 larger than in \( \text{Fe}_{0.65}\text{Ni}_{0.35} \). Hence, the Invar hardening in this alloy may be expected to be much stronger than in \( \text{Fe}_{0.65}\text{Ni}_{0.35} \).

4. The model proposed in this paper demonstrates the importance of the internal magnetic field in formation of the plastic properties of ferromagnetics. Strong fluctuations of the local magnetic field due to the fluctuations of the magnetization near the Curie temperature (see, e.g., [41]) may cause an enhanced detachment of dislocations from obstacles and an increase of plasticity at this temperature. The fluctuations of the magnetization on the paramagnetic side of the transition are twice as large as on the ferromagnetic side [41].

![FIG. 2. The expected qualitative shape of the temperature dependence of the amplitude independent internal friction of dislocations in Invars — solid line. The dashed line shows this dependence in nonmagnetic alloys.](image)

In Invars, characterized by an anomalously large magnetic susceptibility, these fluctuations may be especially strong on both sides of the phase transition temperature. Hence, asymmetric peaks, with a larger high temperature shoulder, may appear in the temperature dependence of the plasticity of Invars near the Curie temperature. The internal friction of dislocations, which strongly depends on the magnetic field [42], may serve as a convenient technique of studying such peaks. One may expect asymmetric peaks in the temperature dependence of the internal friction near the Curie temperature (see fig.2).
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