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REASONS AND REGULARITIES OF THE INFLUENCE OF MAGNETIC FIELDS ON THE MECHANICAL PROPERTIES AND STRUCTURE OF DEFORMABLE METALS

Background. The strength of metals greatly limits the possibility of obtaining products by plastic deformation. The electromagnetic nature of the processes of structure formation and plastic deformation provided the basis for the application of additional influence of the magnetic field. A fairly large volume of research material has been accumulated on the topic of additional influence of the magnetic field on ferro-, dia- and paramagnetic metals. The researches of recent years have an applied nature of studying the magnetoplasticity of technical alloys. Their generalization will make it possible to move from laboratory research to the development of equipment and technologies for combined pressure processing of metal products in a weak magnetic field.
Objective. Generalization and analysis of the results of laboratory and theoretical studies of the additional application of the magnetic field in the processes of mechanical testing of metals and alloys.
Methods. Literary review of materials of articles, monographs, dissertations.
Results. Reasonable use of a magnetic field for plastic deformation of metals. The explanation of the mechanism of the influence of the magnetic field on the structural elements of metals based on the effect of magnetoplasticity has been made. The description of changes in the mechanical properties of metals and alloys under the additional influence of a magnetic field is given.
Conclusions. The phenomenon of magnetoplasticity has been studied for a wide range of materials such as pure metals and their alloys, including industrial steels and alloys. Various types of positive effects of a magnetic field on the mechanical properties of metals have been established: a decrease in the yield strength and deformation resistance, an increase in strain, relaxation of internal stresses, and a decrease in dislocation density. There is also a reverse, negative effect of the influence of a magnetic field: increased rate of hardening, embrittlement, increased creep of metals. What will be the effect of a magnetic field on a specific metal cannot be guaranteed with high accuracy.
Keywords: Magnetic field; magnetoplasticity; mechanical properties; tension; dislocation.

Introduction

Metals are reliable structural materials due to their high strength and ability to be processed by various methods. The requirements for metal products and the intensification of processing methods continue to increase. The strength of metals greatly limits the possibility of obtaining products by plastic deformation. The impact of a complex of mechanical, electrical or magnetic energy influenced by the rheological properties of the processed metals. A number of new technologies for plastic deformation of metals have been created. Their use is especially important when processing hard-to-deform, alloyed, precious metals and high-value alloys, where even a small increase in the efficiency of the processing process is of great economic importance. The theory is developed towards a description of micro- and nanostructural processes of plastic deformation, atomic and electronic level interactions in metals.

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The rheological properties of crystalline materials are determined by the presence of lattice defects in them, primarily dislocations. The dynamics of their origin and movement under the influence of external stresses determines the mechanical properties of the material. The nucleation and movement of a dislocation is a process of interaction between atoms of the crystal lattice. This interaction of atoms is carried out due to the electrons in their outer shells by changing their structure, redistributing electrons from atom to atom or into the general "electron gas" of the crystal. The bonding of atoms is the result of electrostatic interaction between the nuclei and all electrons of atoms [1].

Problem statemen

Generalization and analysis of the results of laboratory and theoretical studies of the additional application of the magnetic field in the processes of mechanical testing of metals and alloys. Justification of the application of the magnetic field, explanation of the mechanism of the influence of the magnetic field of the structural elements of metals, description of the change in the mechanical properties of metals and alloys under the additional influence of the magnetic field.

Presentation of the main research results

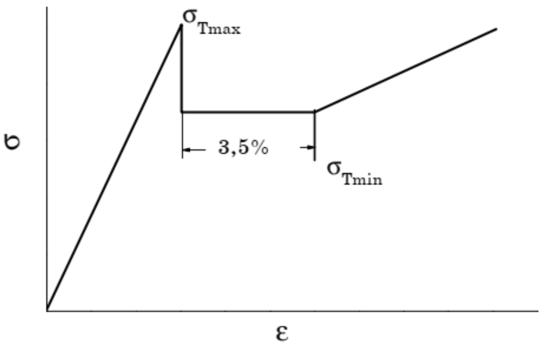
The electromagnetic nature of the processes of structure formation and plastic deformation gave rise to the use of additional exposure to a magnetic field (MF). The beginning of experiments on the use of MF can be considered the mid-twentieth century [2–4], where changes in polymorphic transformations in metals were recorded, which served as the basis for the creation of the first heat treatment technologies with the external influence of MF. A fairly large amount of research material has been accumulated; there are review articles and monographs [5, 6, 11, 15, 18–21, 23] on the topic of additional effects of MF on metals, alkali halide crystals, semiconductors, fullerenes, and polymers.

The research is so numerous that a separate work needs to be devoted to the chronology and systematization of tested materials. However, general conclusions can be formulated based on the opinions of many authors. There are several bright groups of scientists who studied various aspects of the influence of MF: M.L. Bernstein, V.N. Pustovoit – for heat treatment of steels [5–8]; M.A. Krivoglaz, V.D. Sadovsky, V.M. Schastlivtsev, E.A. Fokina – on phase transformations in steels [9, 10]; V.I. Alshits, E.V. Darinskaya, M.V. Koldaeva, Yu.I. Golovin – on the magnetoplasticity of solids [11–15]; V.E. Gromov, S.V. Konovalov, Yu.F. Ivanov – on strength and plastic deformation of metals [11–15]. In addition to groups of scientists, this topic is being studied by many individual researchers, the results of whose work are given in the following description.

Most of the works describe the experimental results of the influence of MF on the mechanical properties of solids. Among them, the most numerous are tensile and compression tests. Changes in the properties of many metals, both in pure form and their alloys, including become. For example: Cu, Ag [16, 17, 23, 28]; Al [16; 17, 21, 23, 28, 29, 33]; Ni, Fe, Co, Ni-Co, Ti, Nb, Mo, Bi, bronze [23]; steel [23–27]. Changes in the mechanical properties of metals under the influence of the MF can manifest themselves in many ways in an increase or decrease in their values, or may not have a significant effect.

The greatest practical interest, based on its wide distribution, is caused by studies of the deformation of iron and its alloys. Tensile tests of technical Fe [23–25] at a strain rate of $2 \cdot 10^{-5}$ s^{-1} showed that when a constant MF (500 Oe) is turned on, the yield strength decreases (Fig. 1) by 30 MPa, and the abrupt change in its value disappears (yield tooth) in the initial period of plastic deformation, the length of the yield plateau is reduced. In the presence of a transverse MF, these effects are significantly less. Longitudinal variable MF (50 Hz, 500 Oe) reduces the value of both the lower and upper yield limits.

The same works [23–25] established that constant MF has little effect on the mechanical properties of technical iron, but noticeably changes the characteristics of pure iron. For example, the elongation increases by 1.7 times. A deformation test under constant load [21] in the presence of constant MF (860 Oe) showed that creep in the case of high purity Fe is accelerated in MF at loads above the yield strength, up to the ultimate strength. MF also affects the increase in total elongation. For example, at a load of 76 MPa, the creep rate at the second stage is $0.9 \cdot 10^{-5}$ s^{-1} without MF and $2.3 \cdot 10^{-5}$ s^{-1} in MF, respectively. At this load, pure iron samples were destroyed in the MP after 25–100 minutes, and without a field in more than 600 minutes. The effect of accelerating creep with the application of a constant MF in the case of samples made of technical Fe is observed only at loads close to the tensile strength of this material. The time to failure at σ = 294 MPa in MF decreases approximately by half. In a weak MF at an intensity of 200 Oe, the effect of its influence on the mechanical properties of iron has not been established. According to the authors of [25], the features of tension and creep of iron in MF are due to the fact that in a constant MF of sufficient strength there are no domain boundaries that serve as places for the accumulation and pinning of dislocations. Therefore, domains do not have an inhibitory effect on the process of plastic deformation, in particular on the acceleration of creep and increasing tensile elongation. The effects are more pronounced in iron that is purer in terms of impurities, since impurity atoms do not block dislocations, and the role of domain boundaries turns out to be more significant.



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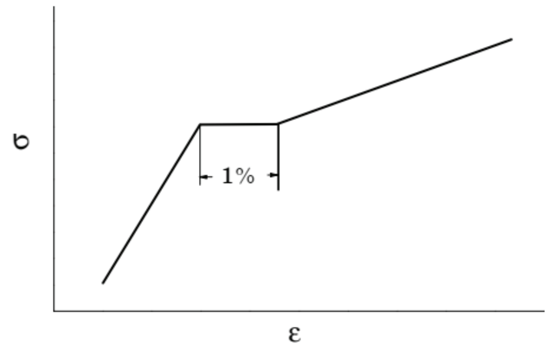
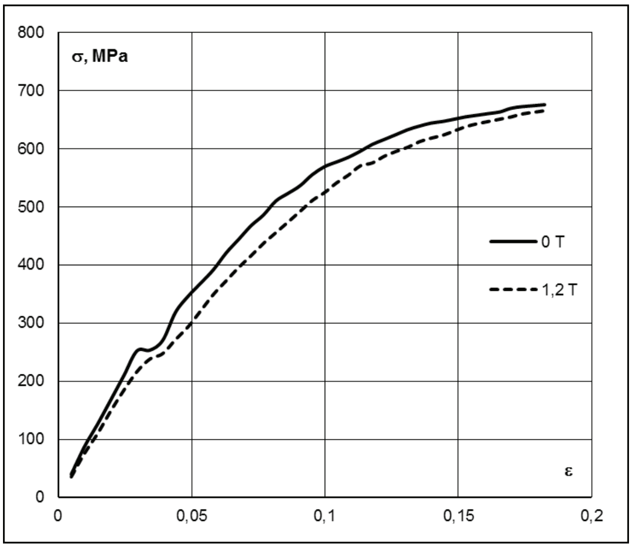


b

Fig. 1. Diagram of the tensile yield area of technical Fe: *a* – without MF ($\sigma_{\text{тmax}}$ = 343 MPa; $\sigma_{\text{тmin}}$ = 274 MPa); *b* – in the longitudinal MF ($\sigma_{\text{тmax}} = \sigma_{\text{тmin}}$ = 245 MPa)

Tensile tests of samples made of St3 (similar S235) steel in constant (500–700 Oe) and alternating (50 Hz, 500–700 Oe) MF were carried out for the first time in [26]. The directions of MF and deformation coincided. The strain rates were 20 and 250 mm/min. Analysis of the stress-elongation curves showed that in MF plastic deformation begins and proceeds at a lower deformation stress. Depending on the deformation rate and MF intensity, the effect of reducing deformation stress lies in the range of 5–10 %. However, the relative elongation decreased by approximately two times. In [27], the tensile curves of St3 steel in a high-strength MF (H = 50 kOe) were also studied. Deformation of pre-annealed samples was carried out at room temperature at a speed of 0.5 mm/min. Tests have shown that in MF the maximum elongation of the sample decreases by 20–30 %, and the hardening increases slightly.

The presented studies motivated us to conduct our own tests, which also yielded positive results. When steels are stretched in a magnetic field with an induction of 1.2 T (Fig. 2), a reduction in deformation resistance of up to 25 % is achieved. The greatest influence is on the deformation of high-strength steels [35].



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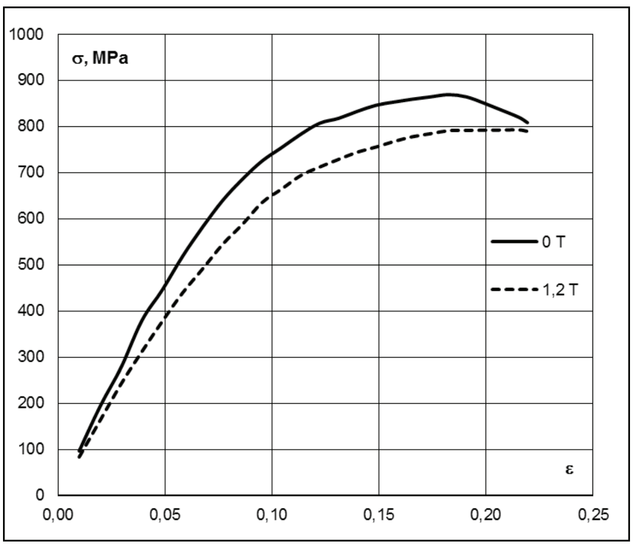

b

Fig. 2. Tensile curves of steels: *a* – S235; *b* – 41Cr4

In addition to ferromagnetic iron alloys, the effect of magnetic fields on paramagnetic alloys has been widely studied. The authors of [33] studied the effect of a pulsed magnetic field with an induction of up to 7 T on the tensile strength of 7055 aluminium alloy (Fig. 3).

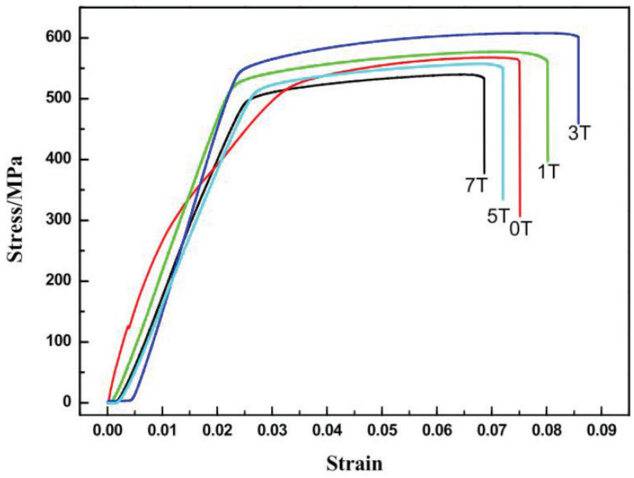

Fig. 3. Tensile curves of alloy 7055 at various values of magnetic induction

The existence of a threshold for exposure to a magnetic field has been revealed; for this experiment, this is a field with an induction of 3 T. As long as the induction is less than the threshold value, its effect on stretch performance is positive. As the induction exceeds the threshold value, the influence of the MF becomes negative. At the peak of the 3 T induction threshold value, the tensile strength and elongation reaches an increase of relative 8 % and 20 % compared to the values of the sample without magnetic field treatment.

A similar experiment with similar results was carried out in tension of titanium alloy Ti6Al4V (TC4) [33]. Here, an induction of 3 T is also the threshold value for the growth of mechanical properties and dislocation density. At an induction of 3 T, the elongation reaches a maximum value, which increases by a relative 24 % compared to the values of the sample without treatment with a MF.

Two-phase titanium alloys, as a Ti6Al4V (TC4) [32], actually contain magnetic elements reacting to a magnetic field positively, which the magnetic elements include titanium and iron. They are able to align under the influence of a magnetic field and form aggreged structures. Magnetic particles inside magnetic materials would be aligned with the direction of an external magnetic field. This phenomenon is clarified by magnetic filler interactions of magnetic particles in a presence of a magnetic field. In the condition of zero magnetic field intensity, magnetic particles may move randomly to other particles because of the van der Waals forces. With a presence of a magnetic field, magnetic dipole energy is large enough to overcome the thermal energy so that magnetic particles tend to align with the direction of the external field. After that, the aligned particles become linear chains [30–32].

There is a fact of instability of test results for the same materials by different authors. This indicates the decisive importance of the thermal and deformation history of the samples, i.e. their structures before testing. Also, an influential factor is the magnetic field itself in the metal deformation zone: its strength, direction of action relative to the axis of the main deformations, duration of exposure. The inconsistency of the results of using MF is still a barrier to recognizing the effectiveness of its use and the practical value of continuing research.

One of the physical quantities that make it possible to assume the causes and mechanism of the influence of a magnetic field on the mechanical properties of a solid [2] can be the energy imparted by the magnetic field to any structural element in a magnetic environment:

$$\Delta U_m \approx \mu_B g B,$$

where μ_B is the Bohr magneton; B – magnetic field induction; g – g-factor.

For weak magnetic fields with induction $B = 1 - 2T$, $\Delta U_m \sim 10^{-5} - 10^{-4} eV$. In [3] a comparison of magnetic energy with the energies that determine the mechanical properties of metals at the macroscopic level is given. The energy required to move a dislocation in steel per atom is $\Delta U_{disl} \sim 10^{-3} eV$, migration energy of point defects (vacancies) – $\Delta U_{p.defects} \sim 10^{-2} eV$, elastic energy of the grain boundary (at a misorientation angle of 3–5°) – $\Delta U_{gb} \sim 10^{-2} - 10^{-3} eV$. According to estimates [1], the activation energy of overcoming the stopper $\Delta U_a \sim 0{,}1 - 1 eV$, exchange energy of dislocation-stopper bond $\Delta U_{ex} \sim 1 eV$. These estimated values indicate that weak MF cannot have a direct effect on the mechanical properties of metals at the macroscopic level. The low energy of the MF leads to the conclusion that the effect of MF on the mechanical properties of solids most likely occurs at the electronic level.

In an ideal crystal, magnetic fields can cause ordering by dipole and magnetic moments, changes in the electronic and phonon spectrum, as well as phase transitions. As for point defects, although they themselves are rarely the cause of material failure, an important factor is their interaction with dislocations. For example, if a defect has a dipole or magnetic moment and elastic anisotropy, then its orientation in the MF will cause a decrease in the flow stress in some planes and an increase in others. In metals, a change in the MF state of the electron gas (which can be considered as a set of point stoppers for dislocations) can affect the plastic properties due to the effect of electron-dislocation interaction [22].

The reason for the change in the mechanical properties of crystalline materials is associated with the manifestation of the magnetoplasticity effect. The magnetoplastic effect (MPE) was first discovered in 1985 at the Institute of Crystallography named after Shubnikov RAS by V.I. Alshits' group [11]. The effect consisted of a displacement of newly introduced edge dislocations in NaCl crystals placed in a constant magnetic field with an induction of up to 1 T; a change in dislocation paths and microhardness was also observed in the crystals. MPE exists for a variety of non-magnetic and magnetic materials, particularly in ionic, ionic-covalent, covalent, molecular and metallic solids. Almost the entire variety of observed physical patterns characterizing this phenomenon in nonmetallic materials has found its explanation within the framework of the concept of spin-dependent electronic transitions in an external MF [23]. According to this concept, MF leads to the evolution of the spin state in the "dislocation-paramagnetic centre (defect)" system, which causes the lifting of the spin ban on certain electronic transitions. The latter radically change the configuration of the system, leading, in particular, to the detachment of dislocations from point defects, which leads to a change in the mechanical properties of the material.

The authors of [33] clearly described the mechanism of magnetoplasticity due to the movement of dislocations. The start of a dislocation motion is controlled by its release from the obstacles. This becomes reasonable under the action of a strong enough mechanical stress. More importantly, the dislocation mobility is the key factor to determine its moving characteristic. When the tensile test is performed under a magnetic field, the influence of the magnetic field on the dislocation, namely, the magnetoplasticity, will take effect. Fig. 4 illustrates the dislocation movement in one period in the presence of a magnetic field and external stress, where the parallelogram plane represents the sliding plane and the shadow represents the region that has slid.

The whole process can be divided into four main steps, as per Fig. 4(a)~(d). Fig. 4(*a*) (step 1) shows the initial state of dislocation. Under the condition of external stress, the dislocation is free from the obstacles and moves forward along the sliding direction indicated by the arrow. The required characteristic time is 10^{-3}~10^{-8} s. The accurate time is determined by the distance (L) between the adjacent obstacles.

Step 2 is the most complicated one during the whole process, which is displayed in Fig. 4(*b*), (*e*) and (*f*). During this period, the dislocation is close to the next obstacle. The relationship between the dislocation and obstacles are determined by L, which is relevant to the radical pair state. When the L is larger than L*(about 10^{-9}m), which is the critical length to distinguish the state of the radical pair, the moving dislocation will pass the S, T resonance area where the electron spin directions are random (Fig. 4(*e*)). In the presence of a magnetic field, when the L is smaller than L*, the free electrons will be stimulated between the dislocation and obstacle (Fig. 4(*b*)). Two free electrons will generate some new radical pairs. The required time to form a radical pair is 10^{-14}~10^{-6} s. The transitory time implies that the free electron stimulation and radical pair formation will be completed instantaneously. Under the Δg mechanism, the radical pairs were impelled to transform from the S state to T0 by an external magnetic field. Further, the magnetic field will influence the electron spin and induce the atomic rearrangement, which directly results in the spin lattice relaxation. Under this condition, the radical pair will transit from a T0 to T+, T–state (Fig. 4(*f*)) [36].

The characteristic time for the atomic arrangement is 10^{-12}~10^{-8} s. In view of the energy difference, the S state of the radical pair implies a higher bonding energy between the dislocation and obstacle when compared to the arbitrary T0, T+, T–state. Therefore, a high coverage of radical pairs in the T state will contribute to the enhancement of the plasticity of the material, which can be achieved in the presence of a magnetic field. The experimental phenomenon is referred to as the MPE. Apparently, the analysis and discussion about MPE is in the quantum scale.

As shown in Fig. 4(*c*) (step 3), the dislocation is hindered and stays at the obstacles. Though the radical pair is at the T state with lower bonding energy, the necessary impulsive energy is still needed. The possible energy resource comes from the stressor, sometimes, heat energy. The relevant characteristic time of this period is 10^{-5} s to ∞. The meaning of "∞" means that if there is not enough energy to stimulate the dislocation movement, the dislocation will stay at the obstacles for long periods.

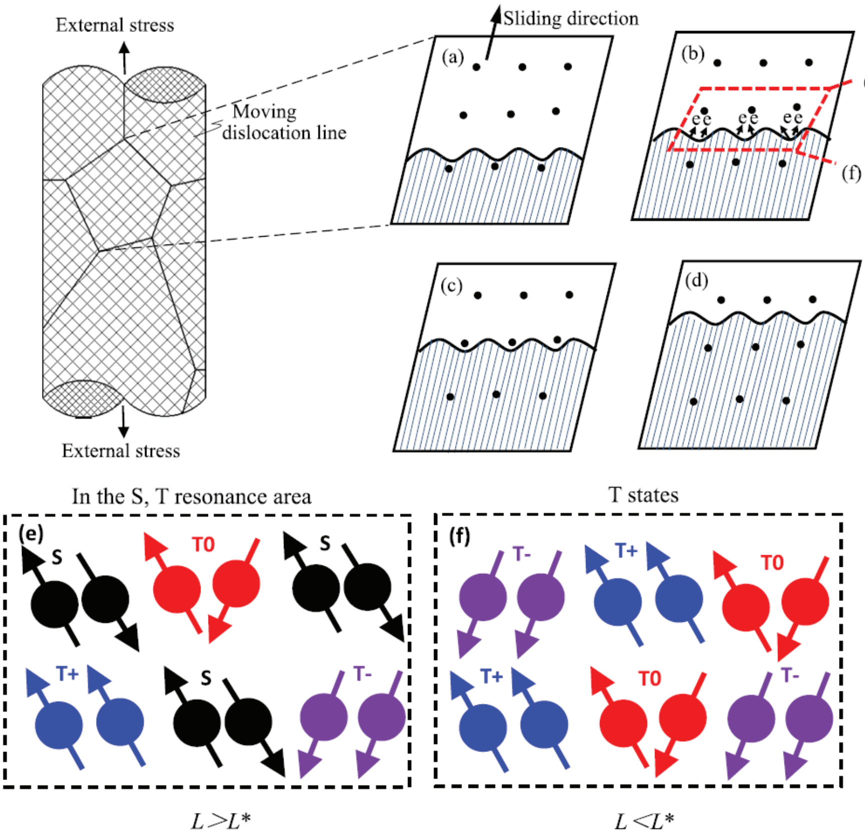

Fig. 4. The schematic of the dislocation movement in the presence of a magnetic field: (*a*) shows surmounting the previous obstacle and moving forward; (*b*) displays the motions close to the obstacles, in the cases of L > L* (*e*) and L < L* (*f*), with L being the distance between dislocation and obstacles, and L* the critical one; (*c*) refers to the stay at the obstacles; (*d*) indicates the surmounting the obstacles and moving forward

In Fig. 4(*d*), when the critical demanded energy is absorbed, the dislocation will depend from the obstacle and move forward. The required time is 10^{-5}~10^{-10} s. One period of dislocation movement will be terminated.

Compared to the characteristic time of the four steps, it can be concluded that step 2, which includes the electron stimulated and atomic arrangement, can end up in momentary time, which meanwhile demonstrates the high efficiency of the magnetic field treatment. Nevertheless, the delay of the dislocations at the obstacle in step 3 is the most time-consuming period. It is regularly the rate-limiting step when performing the tensile test.

The author of this article also made an attempt to explain the effect of a MF on a dislocation core. The change in the total energy of a small fragment of an idealized Fe crystal lattice with a moving edge dislocation has been calculated. Calculations were performed for conditions of external influence of a constant MF and without it. Calculations were carried out using the density functional theory method in the Kohn-Sham version using the GAUSSIAN 09 software package [37]. The movement of a dislocation increases the energy of the Fe atomic system and increases it to an even greater extent in the presence of an interstitial atom. The influence of a MF reduces the energy of a system of atoms in various configurations of their arrangement. The movement of a dislocation increases the magnetic susceptibility of a system of atoms. When a dislocation moves in a MF, either the magnetic susceptibility of a system of atoms decreases or the intensity of its growth decreases. The MF has a positive effect on the uniformity of the distribution of electrons within a system of atoms with distortion of the crystal lattice, especially in the presence of impurity atoms. This result may be one of the justifications for the effect of magnetoplasticity in ferromagnets. The greatest change occurred in the system of pure Fe atoms. Impurity atoms reduce the effectiveness of MF exposure.

A summary of the studied influence of the magnetic field on the process of deformation of metals is presented in Table 1.

Table 1. Results of a study of the influence of a magnetic field on metals

Researched	Determined
Polymorphic transformations in metals and other materials	Changes in the kinetics of polymorphic transformations with the release of ferromagnetic phases, changes in the structure of the resulting phases
Mechanical properties of metals and alloys	The phenomenon of magnetoplasticity in microscopic volumes of material, changes in the strength and plasticity of macroscopic samples at various stages of deformation under conditions of tensile, compression, and creep tests have been revealed
The strength of the magnetic field, its direction relative to the main axis of deformation, constant or pulsed action during processing	Exposure to weak to strong magnetic fields, constant and alternating magnetic fields is effective. A magnetic field perpendicular to the direction of deformation of materials has a greater influence
Dislocation structure of the material	The mechanism of magnetoplasticity based on the interaction of moving dislocations with stoppers. Change in the energy of a system of atoms of a dislocation core in a magnetic field

The mechanism of the effect of MF on metals is determined by various factors and is still insufficiently studied. This is also due to the fact that there is no simple, unambiguous connection between the mobility of individual dislocations and macroplastic deformation characteristics.

Research in recent years has an applied nature in the study of magnetoplasticity of technical alloys. The relevance of the transition to the development of equipment and technologies for combined forming processing of metal products in a weak magnetic field arises.

Conclusions

a) The phenomenon of magnetoplasticity has been studied for a wide range of materials such as pure metals and their alloys, including industrial steels and alloys. Prominent scientists and teams of authors took part in the research, their works are presented in the form of numerous articles, monographs and dissertations. All types of metals are susceptible to the influence of a magnetic field: ferro-, para- and diamagnetic.

b) Various types of positive effects of a magnetic field on the mechanical properties of metals have been established: a decrease in the yield strength and deformation resistance, an increase in strain, relaxation of internal stresses, and a decrease in dislocation density. There is also a reverse, negative effect of the influence of a magnetic field: increased rate of hardening, embrittlement, increased creep of metals.

c) What will be the effect of a magnetic field on a specific metal cannot be guaranteed with high accuracy. The low energy of the magnetic field and its effect on the microstructural, atomic and electronic levels make it difficult to predict the behaviour of the metal.

Acknowledgements

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ПРИЧИНИ І ЗАКОНОМІРНОСТІ ВПЛИВУ МАГНІТНИХ ПОЛІВ НА МЕХАНІЧНІ ВЛАСТИВОСТІ І СТРУКТУРУ МЕТАЛІВ, ЩО ДЕФОРМУЮТЬСЯ

Проблематика. Міцність металів сильно обмежує можливості одержання виробів з використанням пластичної деформації. Електромагнітна природа процесів структуроутворення та пластичної деформації дала основу для застосування додаткового впливу магнітного поля. Накопичено досить великий обсяг дослідницького матеріалу з тематики додаткового впливу магнітного поля на феро-, діа- та парамагнітні метали. Дослідження останніх років мають прикладний характер вивчення магнітопластичності технічних сплавів. Їхнє узагальнення дозволить перейти від лабораторних досліджень до розробки обладнання та технологій комбінованої обробки тиском металевих виробів у слабкому магнітному полі.

Мета дослідження. Узагальнення й аналіз результатів лабораторних і теоретичних досліджень додаткового застосування магнітного поля у процесах механічних випробувань металів та сплавів.

Методика реалізації. Літературний огляд матеріалів статей, монографій, дисертаційних робіт.

Результати дослідження. Обґрунтовано застосування магнітного поля для пластичної деформації металів. Виконано пояснення механізму впливу магнітного поля на структурні елементи металів на основі ефекту магнітопластичності. Наведено опис зміни механічних властивостей металів і сплавів під додатковим впливом магнітного поля.

Висновки. Явище магнітопластичності досліджено для широкого кола матеріалів, таких як чисті метали та їх сплави, у тому числі промислові сталі та сплави. Встановлено різні види позитивного впливу магнітного поля на механічні властивості металів: зниження межі плинності та опору деформації, збільшення відносного подовження, релаксація внутрішніх напружень, зниження щільності дислокацій. Також існує і зворотний, негативний ефект впливу магнітного поля: збільшена швидкість зміцнення, крихка, збільшена повзучість металів. Яким буде вплив магнітного поля на конкретний метал, не можна гарантувати з високою точністю.

Ключові слова: Магнітне поле; магнітопластичність; механічні властивості; напруження; дислокація.

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