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REVIEW

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Magnetic Fields and Equipment for Studying the Magnetoplasticity of Metals

Chenjian Dong[1] and **Maksym Kraiev**[2,*]

[1]*School of Automobile and Transportation, Yancheng Polytechnic College, China*

[2]*Rocket and Space Industry, Ukraine*

Abstract: The phenomenon of magnetoplasticity of metallic materials is presented. Methods of magnetic processing using constant and variable magnetic fields are described. The characteristics of constant and alternating magnetic fields used in experimental studies are compared. A method for calculating the magnetic field in the gap between the electromagnet cores is described. The influence of the gap between the cores of an electromagnet and the current strength in the winding of its coils on the induction of the magnetic field has been studied. Schemes of the perpendicular and parallel orientation of the samples and their main axis of deformation relative to the magnetic field lines are presented. The composition of the equipment for creating the effect of magnetoplasticity in laboratory testing of metal samples is described. The types of permanent magnets, electric inductors, and magnetic field concentrators are given. Prospects for the development of experimental research on magnetoplasticity are determined.

Keywords: magnetic field, induction, magnetoplasticity, mechanical test

1. Introduction

Magnetoplasticity has been studied for several decades [1–3], but due to the versatility of manifestations and versatility of use, it remains a hot topic for research. Electromagnetic processes form the basis of interaction at the atomic level of the structure of matter. And the properties of elasticity, plasticity, strength, and creep of metals are determined by the processes occurring at the level of the atomic crystal lattice. All substances are magnetic and are magnetized in an external magnetic field. The magnetic properties of metal alloys depend on the type of magnetism of their structural components in a given state [4].

A metal in a magnetic field is acted upon by ponderomotive forces, which are a source of mechanical stress and cause deformation of the metal. This process belongs to the macroscopic manifestations of the influence of a magnetic field. On its basis, a method for magnetic-pulse stamping of ferromagnetic metals was created. Para- and diamagnetic metals experience a weak (relative to deforming loads) action of ponderomotive forces [4].

At the microscopic level, an external magnetic field changes the magnetic moments of metal atoms. This affects the spin-dependent processes of interaction of atoms of the crystal lattice and hence the mobility of linear and point defects, which in turn forms the strength and plasticity of metal bodies [5]. The effect of a magnetic field on the atomic structure of a metal is used in the technologies of magnetic-pulse hardening and softening, heat treatment, and plastic deformation of metals [6–10]. Also, the magnetic field affects the magnitude of the energy barrier overcome by the defects of the crystal structure during their movement [11–13]. This phenomenon of magnetoplasticity will be the topic of research.

The aim of the study is to describe the magnetic fields used to create the effect of magnetoplasticity of metals, types of tests, and test devices for studying this effect, used in experiments on metals. The material of the article is a generalized overview of information on the study of magnetoplasticity, useful in the development of new forming technologies for scientific and industrial applications.

2. Magnetic Fields, Their Creation, and Application in Mechanical Testing Processes

Magnetic fields are usually divided into weak (by induction up to 0.05 T), medium (0.05 – 4 T), strong (4 – 100 T), and super-strong (over 100 T). The impact of a magnetic field of a material can be pulsed, constant, or variable. Units of pulsed magnetization allow for a short time, for a fraction of a second, to create high-intensity fields up to 32 MA/m. Permanent magnetic fields have a lower intensity up to 16 MA/m, but allow the material to be exposed to the field for a long time.

Constant and variable magnetic fields can be created using permanent magnets, inductors, and electromagnets. A wide selection of permanent magnets makes it possible to create compact research equipment. Various shapes of permanent magnets (cylinder, plate, ring, etc.,) make it possible to test metal samples of various shapes: volumetric cylindrical and flat sheet. Solid neodymium NdFeB, samarium-cobalt Sm-Co, and AlNiCo magnets, which have the highest field strength characteristics, are used. However, the strength of the magnetic field of a permanent magnet is still relatively small, and it is difficult to find a magnet with a field induction on its surface of more than 1 T. Moreover,

*__Corresponding author:__ Maksym Kraiev, Rocket and Space Industry, Ukraine. Email: mkraev79@gmail.com

the strength of the magnetic field sharply decreases with increasing distance from the magnet surface.

Electromagnets consist of magnetic coils with a core. Laboratory electromagnets most often have a solid cylindrical core with a diameter of about 100 mm, which, as will be shown below, ensures uniformity of the magnetic field in the narrow gap between the cores. Using ferromagnetic cores, directional magnetic fields of the required configuration are created. Using the appropriate design, technology, and material of the core, it is possible to form fields of a given shape and provide the required penetration depth, the required degree of localization, etc. [14–18]. The cores are made of soft magnetic materials with low coercive force and low residual magnetic induction. This allows, by changing the current strength in the winding of the coils, to change the created magnetic field from almost zero to the maximum possible value. The best material for the core is Armco-iron, alloys of iron with silicon, cobalt, or nickel.

In electromagnets with a constant magnetic field, a constant electric current flows through the coil windings. The required current value is set using an adjustable power supply with a power transformer. To create an alternating magnetic field, an alternating electric current flows through the winding of the coils. The current frequency converter regulates the frequency of magnetic field oscillations. To create a high-strength alternating magnetic field, a series of high-current electrical pulses are generated at a certain repetition rate. The pulsed current source is equipped with a capacitor bank to obtain high current values.

Calculation of the force characteristics of the magnetic field in the deformation zone requires knowledge of the magnitude of the magnetic flux in the gap between the electromagnet cores or the poles of permanent magnets. In general, the magnetic flux Φ passing through a finite surface S is equal to the product of the magnitude of the magnetic induction vector B and the area of the given surface [4]:

$$\Phi = \iint B \cdot dS \tag{1}$$

In scalar form:

$$\Phi = (B \cdot \Delta S) = B \cdot \Delta S \cdot cos\alpha \tag{2}$$

where α is the angle between the magnetic induction vector and the normal to the S plane.

To measure the parameters of the magnetic field and the magnetic properties of substances, magnetometers are used: oerstedmeters – field strength; inclinators and declinators – field directions; gradiometers – field gradient; teslameters – magnetic induction; webermeters, or fluxmeters – magnetic flux; coercimeters – coercive force; mu-meters – magnetic permeability; kappa meters – magnetic susceptibility, magnetic moment. From the point of view of materials processing, the influence of a magnetic field on a sample of finite dimensions is relevant to consider as a force acting on the metal in a unit of space. This corresponds to the value of magnetic field induction B. Measurement of magnetic induction and magnetic field strength in constant and alternating fields is carried out using teslameters with Hall transducers. Typically, the measurement range of teslameters with Hall sensors is 0–2 T. To measure strong constant magnetic fields with an induction of up to 25 T or alternating fields with a frequency of up to 1 GHz, pulse-wave teslameters are used based on the nuclear magnetic resonance method [19]. Among the less common ones, there are fluxgate teslameters, based on electronic paramagnetic resonance, superconductivity, and "optical pumping" (quantum).

The accuracy of the calculated values of B depends on the uniform distribution of the magnetic field induction lines, which is determined by the shape and size of the gap between the electromagnet cores [20, 21]. When the magnetic induction lines are parallel and the equipotential surfaces are planes, the field is called uniform. Based on the magnetic field circulation theorem, the induction in the air gap between the electromagnet cores is determined by the formula [22]:

$$\mathrm{B} = \frac{\mu_0 NI}{L} \tag{3}$$

where μ_0 – magnetic constant 4×10^{-7} H/m;

N – total number of winding turns, pcs;

I – current strength, A;

L – gap width, m.

The induction in the gap between the cores cannot increase indefinitely as the product NI increases and is limited not by the magnitude of the external magnetic field created by the inductors, but by the magnetic state of the core. The core material has a saturation induction, usually 1.5 – 2.5 T.

The uniformity of the magnetic field in the deformation zone is one of the most important characteristics of magnetic processing and, along with the magnetic field force, determines the quality and efficiency of its application.

Field uniformity is observed when the ratio of the cross-sectional dimensions of the end of the core and the gap between the cores is $a/\delta \leq 0.2$ and $b/\delta \leq 0.2$, i.e., when the cross-sectional dimensions are much larger than the gap (Figure 1 [20, 21]). The instability of qualitative and quantitative results of magnetic processing of the same metals may be associated with a discrepancy in the uniformity of the magnetic field experiments. If these dependencies are not observed, the influence of distortion (bulging) of the magnetic induction lines at the edges of the core becomes significant. The field is no longer uniform. Determining the induction value is possible either by simplifying assumptions regarding the field pattern in the gap or by mathematical processing of experimental data.

Figure 1
Poles that form a uniform magnetic field between the parallel ends of the cores

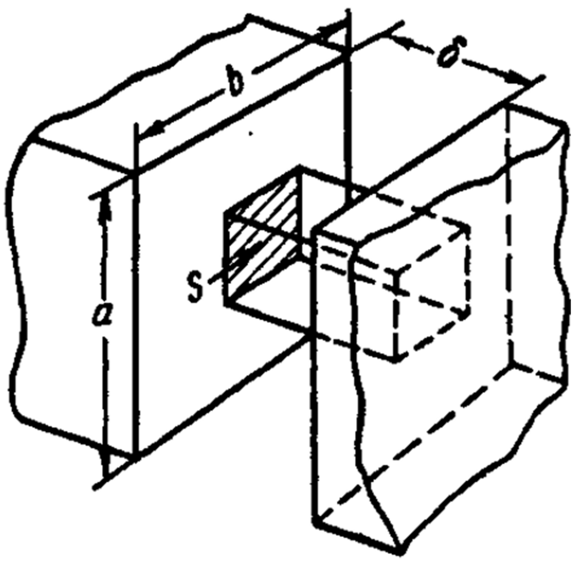


Figure 2
Change in magnetic field induction between electromagnet cores depending on the width of the air gap

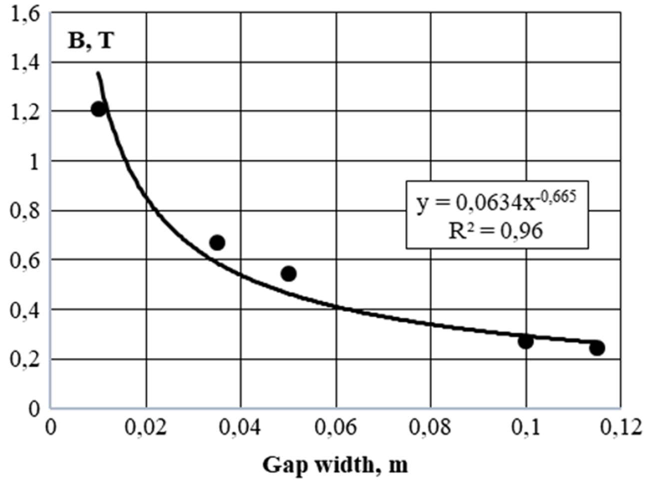
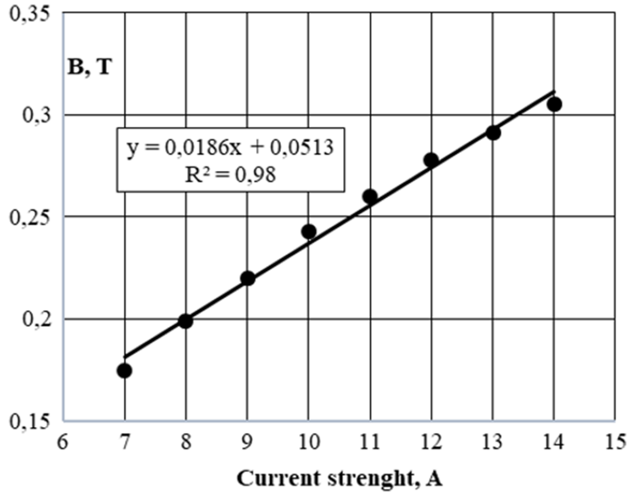


Figure 3
Change in magnetic field induction between electromagnet cores depending on current strength



From formula (3), it follows that the induction of the magnetic field of an electromagnet has a direct dependence on the strength of the current passed through the coils and the distance between the ends of the cores. Therefore, changing the magnitude of the magnetic field induction was carried out by adjusting the current flowing in the coils and changing the size of the gap between the cores.

At a constant current strength (maximum value 14 A for the electromagnet used), the authors of this article conducted a study of the influence of the size of the gap between the round cores of an electromagnet with a diameter of 100 mm on the strength of the magnetic field (Figure 2). The gap size varied from 10 to 115 mm. The magnetic field induction was measured in the central part of the gap in the area of the longitudinal axis of the cores at the same distance between them. The teslameter probe was inserted into the gap perpendicular to the axis of the cores.

As follows from formula (3), the relationship between induction and gap width is a power law. As the gap decreases to 10–30 mm, the strength of the magnetic field increases sharply. A larger gap value is ineffective; the magnetic field strength becomes weak. And increasing the field in large gaps due to the electrical characteristics of the magnet coils is difficult to implement in practice due to the multiple increasing dimensions of the electromagnet itself and the limitations of the magnetic conductivity of its cores. Therefore, it can be assumed that the width of the zone of effective influence of the magnetic field does not exceed 30 mm, which determines the size of the metal samples under study.

To assess the influence of current strength on the magnitude of magnetic induction in the air gap, the authors of this article tested an electromagnet in which the current strength varied from 7 to 14 A (Figure 3). The gap between the magnet cores was constant and equal to 115 mm. This gap size made it possible to place testing equipment for metal deformation, namely a hydraulic press stamp, between the electromagnet cores. As follows from formula (3), the relationship between induction and current strength is linear. The steepness of the graph shows the effectiveness (often the only option) of using high current strength to create a strong magnetic field.

Known methods of magnetic processing are divided according to the use of constant and variable magnetic fields [6, 8, 23–27]: processing methods with a constant magnetic field: processing with subsequent demagnetization or without it, dynamic processing, when the part rotates in a field of constant strength with some acceleration of the rotational speed or with free movement of the sample in the cavity of the inductor; methods of pulsed magnetic processing: single-cycle processing without subsequent demagnetization and multi-cycle processing with holding between cycles.

For magnetic processing, multi-turn inductance coils are used, inside which the sample is placed [28, 29]. The parts are insulated from the inductor turns by a dielectric. During pulse processing, storage capacitors are discharged through the turns of the inductor. In this case, the field strength is no less than 107 V/m, the pulse duration is no more than 0.001 s, and the number of pulses is from 1 to 5 [28]. The magnetic field in the inductor induces eddy currents in the samples and causes repulsive forces between the inductor and the sample. These forces compress the sample throughout its entire volume. As a result, phase and structural changes occur in it.

The plant for magnetic-pulse processing of metals [28] is a pulse current generator consisting of a capacitive storage of electrical energy – a high-voltage capacitor bank, a working element – an inductor and a switching device – a high-voltage controlled spark gap. Using a spark gap, the capacitor bank is discharged onto the inductor. The capacitive storage device is charged for the energy required for a given technological operation using a charger. The operating discharges of the storage device are produced using an ignition device that includes a spark gap. Zagulyaev et al. [30] used a circular coil made of a copper busbar with a cross-section of 10 mm^2 and an internal diameter of 0.03 m as an inductor.

A magnetic field is used not only inside the solenoid but also between the cores of the inductors (Figure 4 [31]).

The pulsed magnetic field equipment [32] includes two parts. The first part is the pulse power supply, which can output the sine wave and square wave. The pulse width and frequency can be adjusted in succession within the range of the fixed one. The second part is a magnetic field generator. This generator includes magnet yokes and current-carrying coils. The cavity size can be adjusted to generate a continuously tunable pulsed magnetic field from 0 T to 2.8 T. Half sine wave pulsed magnetic field was used. The pulse frequency was 1 Hz. In total, 55 pulses were used in each group at room temperature.

An option for local processing of bodies of revolution is described in Kovalevsky and Tulupov's [33]. The part is fixed on a lathe, and a pulsed magnetic field concentrator is installed in the tool holder, which is brought to the surface being processed (Figure 5 [33]).

Figure 4
Schematic diagram of pulsed magnetic treatment system

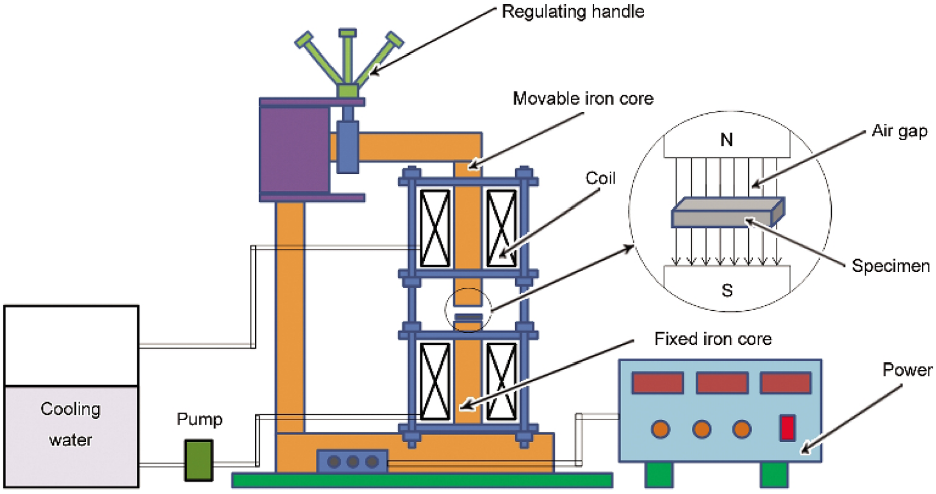


Figure 5
Scheme of processing parts such as rotating bodies with a pulsed magnetic field on a lathe

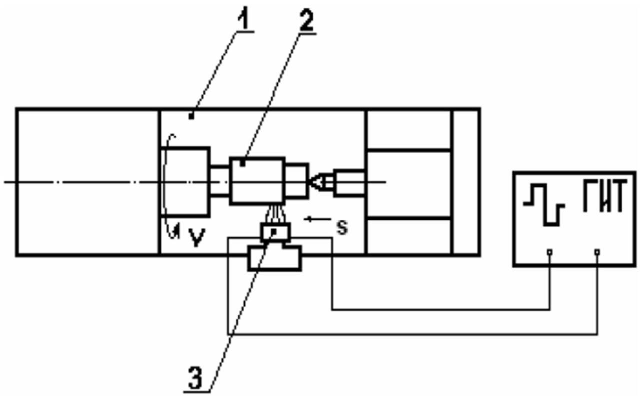
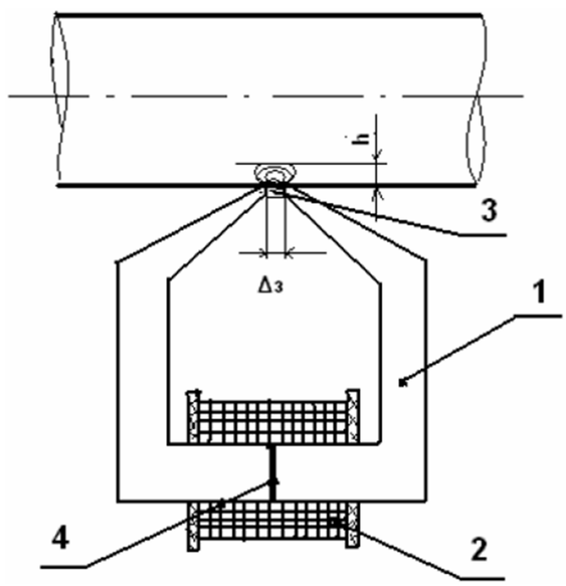


Figure 6
Pulsed magnetic field concentrator



Mechanical (longitudinal feed and spindle speed) and electrical (current and frequency) processing modes are set. The spindle is started, current is supplied to the coil from the pulse current generator, the longitudinal feed is turned on, and the surface of the part is processed. The pulsed magnetic field concentrator (Figure 6 [33]) consists of a composite magnetic circuit having a front and rear gap and coils.

By supplying pulsed currents with alternating polarity, a magnetic field is excited in the magnetic circuit, the force lines of which, concentrating on it and exiting through the front gap, are closed through the surface layers of the part. The depth *h* of penetration of the pulsed magnetic field in the surface layer of the workpiece depends on the size of the front gap. The larger the gap *Δз*, the larger *h*. As the gap increases, it is necessary to increase the current to ensure the required magnetic field strength.

In thermomagnetic processing, a magnetic field is used in the process of hardening and annealing of parts, when the steel undergoes phase and magnetic transformations. The magnetic field influences the quantity and quality characteristics of the released magnetic phases. A magnetic field is more often present during heating and cooling of a part, when the metal has ferromagnetic properties [34–38], but sometimes during exposure at high temperatures [39]. For a noticeable change in the transformation temperature, exposure to fields with an intensity of about 106 Oe is required; magnetic fields with induction of up to 10 T were used in the studies. The intensity of pulsed magnetic fields approaches these values. In this regard, the most suitable for such studies was the martensitic transformation due to its high rate of occurrence, since it is enough to apply a pulsed field with a pulse duration of the order of 10^{-4} s to introduce significant changes in the thermodynamics of the transformation [40]. Let's consider an installation for hardening machine needles in a magnetic field (Figure 7 [41]).

Dosing device 1 ensures that needles are fed into the oven at a set rhythm, individually or in portions. Solenoid 3 serves to hold the

Figure 7
Schematic diagram of the plant for thermomagnetic treatment of needles

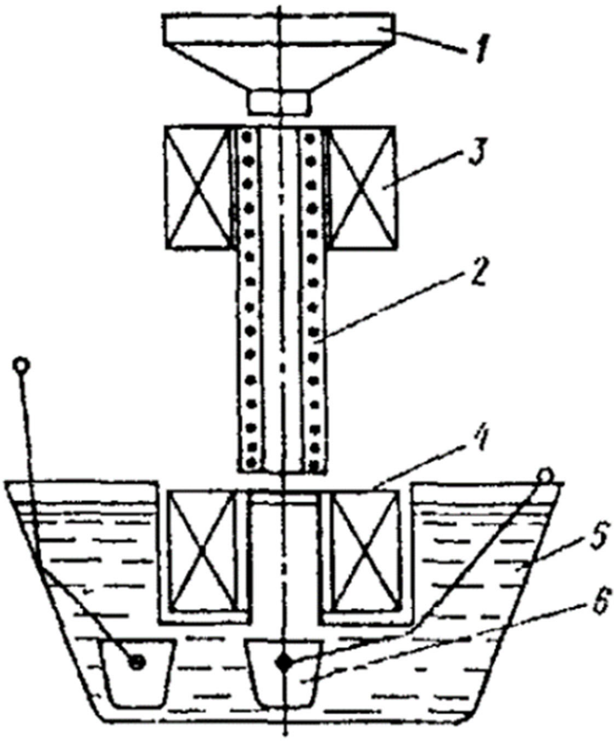
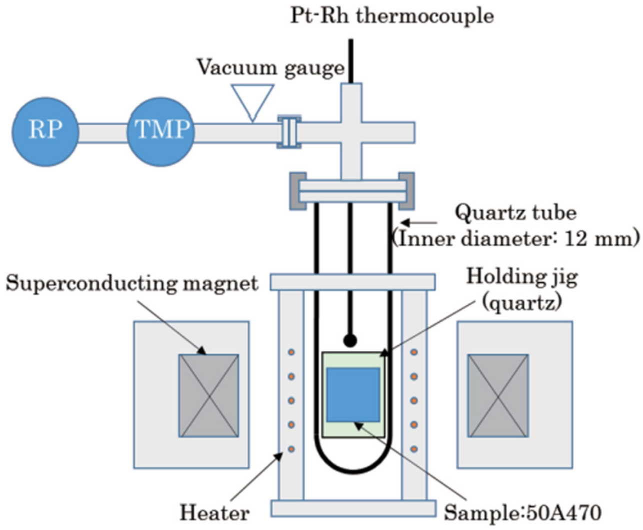


Figure 8
Schematic diagram of magnetic heat treatment apparatus



needles entering the furnace 2 in a vertical position in the upper part of the furnace, where the products are heated as if in a clamped state, since their long axis is oriented in the direction of the magnetic flux inside the solenoid 3. Needles made of U10 steel, when heated to a temperature of ~740 °C, cannot be held in the upper part of the furnace, since they lose their ferromagnetic properties due to the formation of a significant amount of austenite. Freely falling in a vertical position inside the furnace (as in a guide), the needles are additionally heated to a set temperature of 780 °C. To do this, the length of the furnace and the temperature in its cavity are calculated accordingly, providing the required heating rate. The needles enter the quenching tank 5 in a strictly vertical position and, during the process of the appearance of ferromagnetic martensite, are also oriented vertically in a clamped state in the field of the solenoid 4, which, in addition to the orienting function, is also used for the direct purpose of exposure to a magnetic field during quenching [41].

The circuit with heating and simultaneous application of a magnetic field is shown in Figure 8 [42]. The installation allows you to create a magnetic field with induction up to 10 T [42, 43].

Heat treatment in a magnetic field can also occur at low temperatures. Tang et al. [44] used two permanent NdFeB magnets, between which the sample under study was clamped and then the whole thing was placed in a cryogenic plant.

For the manifestation of the effect of magnetoplasticity, a combination of mechanical stresses in the metal and the action of an external magnetic field is necessary. Tests are carried out in constant magnetic fields with an induction of about 1 T [45, 46], which corresponds to the availability of creating inductors with an average field strength. The influence of the magnetic field occurs during the entire time of the test. Variable magnetic fields make it possible to increase the induction up to 2.5 T [32, 47] and even up to 7 T [5], but they act for a short time of 0.05–2.0 s. Pulsed (multiple) switching of the field during the period of sample processing is used. At present, it is impossible to say unambiguously which type of field: constant or alternating is most effective for creating magnetoplasticity conditions. Experiments on the same materials under the same deformation conditions with variations in constant and alternating magnetic fields have not yet been carried out.

Since research has not yet left the laboratories, the most numerous of those descriptors are standard mechanical tests of metal samples. Of these, tensile testing comes first. Here, laboratory tensile machines are used with a block of equipment to create a magnetic field in the sample tension zone. The magnetic field lines (induction) are more often perpendicular to the deformation axis of the sample (Figure 9 [46]), less often they are parallel (Figure 10 [48]).

The same scheme of tests for metal creep, when the samples are kept in a magnetic field, being under a mechanical load with a certain amount of tensile stresses; or tensile fatigue tests [46], when samples are held in a magnetic field while under a cyclic alternating mechanical load.

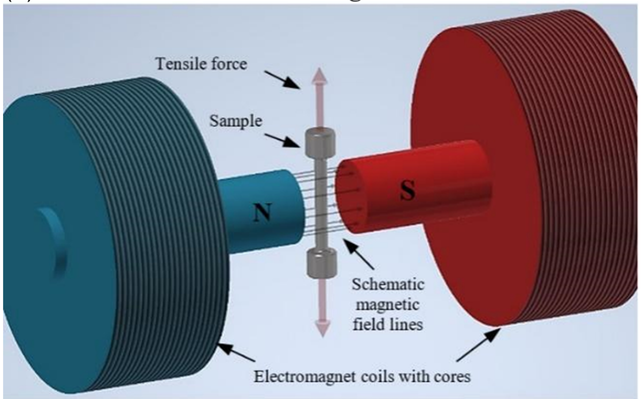
The orientation of the magnetic field lines relative to the main axis of deformation of the samples significantly affects the test result. The majority of positive test results were obtained for the case of perpendicular directions of the magnetic field and deformation of the samples. This is due to the resonance nature of the magnetoplastic effect [49, 50]. At the same time, the equipment has a more complex design, containing electromagnetic coils with cores, versus a relatively simple hollow electromagnetic coil (Figure 10 [48]), where the role of the core is played by the sample itself.

In the case of using an electromagnet with cores, the strength of the magnetic field is limited by the electrical parameters of the coils and the gap between the cores. Placement of the sample and equipment of the tensile testing machine between the coils of the electromagnet prevents the cores from approaching a minimum distance.

To enhance the magnetic field in the deformation zone, its concentrators with different end surface shapes were used [51]. Concentrators are made of mild steel. They are rectangular, and

Figure 9
Scheme of the device for tension samples in a magnetic field, and field lines are perpendicular to the deformation axis. (a) With electromagnet inductor. (b) With permanent magnet inductor

(a) **with electromagnet inductor**



(b) **with permanent magnet inductor**

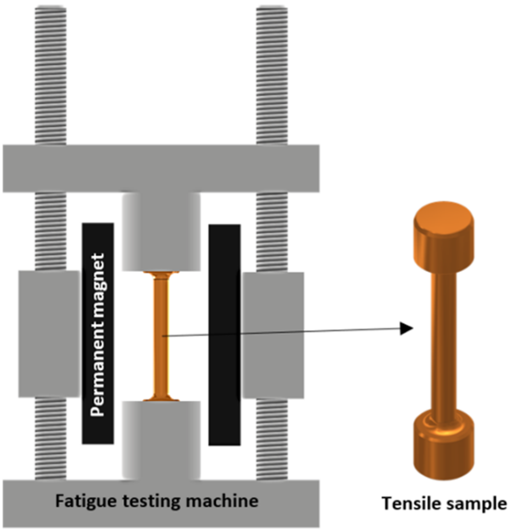


Figure 10
Scheme of the device for tension samples in a magnetic field, and the field lines are parallel to the deformation axis

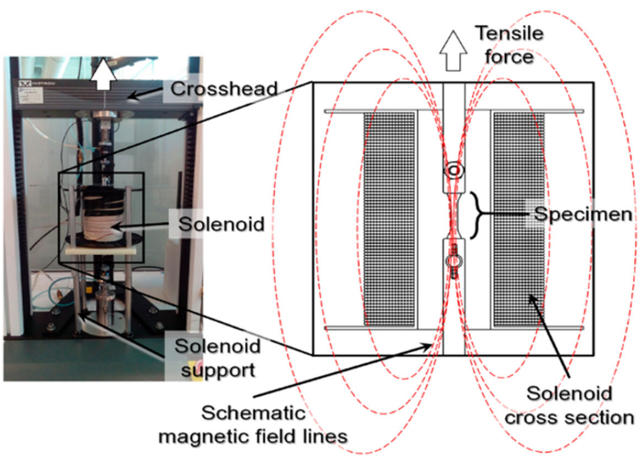
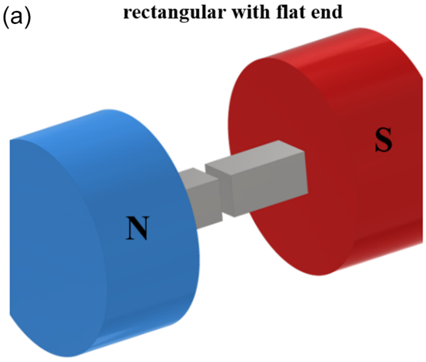
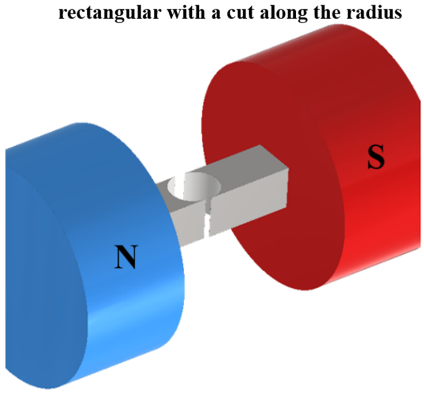


Figure 11
Magnetic field concentrators. (a) Rectangular with flat end. (b) Rectangular with a cut along the radius. (c) Rectangular with hole. (d) Cylindrical wedge-shaped die sandwiched between concentrators

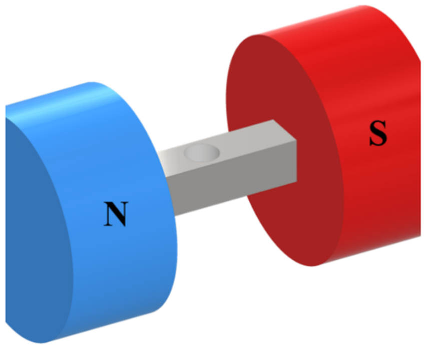
(a) **rectangular with flat end**



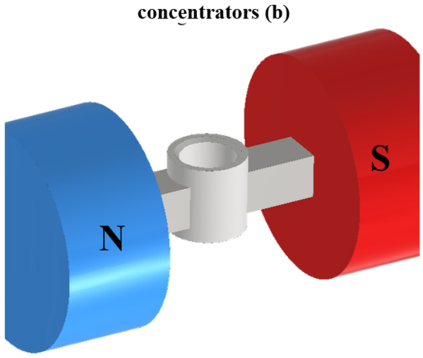
(b) **rectangular with a cut along the radius**



(c) **rectangular with hole**



(d) **cylindrical wedge-shaped die sandwiched between concentrators (b)**



the shape of their ends can be different (Figure 11 [51]) and depends on the shape of the sample and should ensure the creation of a magnetic field of the maximum possible strength.

The maximum magnetic field induction is provided by concentrators with a flat end (type a, Figure 11 [51]). The flat surface of the core ensures the parallelism of the lines of magnetic induction and hence the uniformity of the magnetic field in the gap. In addition, the field in a narrow gap, the width of which is five times smaller than the width of the core (concentrator), can be considered uniform. With the same gap L = D in concentrators of type b and c (Figure 11 [51]), the induction is less by 1.3 and 3.0 times, respectively, compared with type a. The d type concentrator (Figure 11 [51]) can provide a strong magnetic field at the die hole, on par with the type a, by using a hardened die steel. Hardening reduces the magnetic permeability of the steel, which prevents the field from propagating through the die metal and displacing it into the hole. If the die has a high magnetic permeability, this type of concentrator becomes similar to the most inefficient type c (Figure 11 [51]).

The use of concentrators does not solve the problem of uniformity of the magnetic field in the deformation zone. It is rather a technological technique for creating a stronger magnetic field in the deformation zone of the metal.

The effects of magnetoplasticity manifest themselves not only during the plastic deformation of metals but also in the form of relaxation of residual internal stresses after heat treatment of the metal [32, 45, 47]. In these experiments, the samples are exposed only to the magnetic field of the inductor.

At the current stage of research using relatively simple magnetic devices, the results achieved no longer evoke a feeling of novelty, rather they are clarifying. The development of the study of magnetoplasticity lies in the area of confluence with the phenomena of magnetic resonance. The same applies to experimental studies. Therefore, it is of interest to create an installation with cross-constant and variable magnetic fields.

3. Outlooks

Magnetoplasticity has been studied for many materials under separate laboratory mechanical testing conditions. The next stage in the study of magnetoplasticity should be a mathematical description of the change in strength and ductility under conditions of a complex stress-strain state of the metal. Why is it necessary to conduct complex tests for tension, compression, and shear of each of the metals under study? This will allow us to construct a plasticity surface for the selected material under the influence of a magnetic field, which in turn will advance the experiment towards practical application in metal forming processes. It is important to carry out a set of tests in a constant and alternating magnetic field, which will reveal the most effective type of its influence.

4. Conclusion

The magnetic fields used in the study of the effect of magnetoplasticity are described and divided into constant and variable fields. The power characteristics of each type of magnetic field are given.

Schemes and composition of test equipment for plastic deformation of metals using an external magnetic field are presented.

5. Recommendations

The review revealed the existing interest in magnetoplasticity research. At the same time, there is already a development methodology for conducting mechanical tests with the application of an external magnetic field. Further research can be carried out in several directions: increasing the complexity of experimental laboratory test devices, varying the schemes for applying a magnetic field, and achieving resonance phenomena from the influence of a magnetic field.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Chenjian Dong: Methodology, Validation, Writing – original draft, Writing – review & editing, Visualization, Supervision; **Maksym Kraiev:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Project administration.

References

[1] Alshits, V. I., Darinskaya, E. V., Koldaeva, M. V., & Petrzhik, E. A. (2003). Magnetoplastic effect: Basic properties and physical mechanisms. *Crystallography Reports*, *48*, 768–795. https://doi.org/10.1134/1.1612598

[2] Golovin, Y. I. (2004). Magnetoplastic effects in solids. *Physics of the Solid State*, *46*(5), 789–824. https://doi.org/10.1134/1.1744954

[3] Urusovskaya, A. A., Alshits, V. I., Smirnov, A. E., & Bekkauer, N. N. (2003). Effects of magnetic influence on the mechanical properties and real structure non-magnetic crystals. *Crystallography*, *48*(5), 855–872.

[4] Tamm, I. E. (2003). *Fundamentals of the theory of electricity*. Russia: Fizmatlit.

[5] Li, G., Cheng, J., Wang, H., Li, P., & Li, C. (2016). Influence of a high pulsed magnetic field on the tensile properties and phase transition of 7055 aluminum alloy. *Materials Research Express*, *3*(10), 106507. https://doi.org/10.1088/2053-1591/3/10/106507

[6] Bernshtein, M. L., & Pustovoit, V. N. (1987). *Heat treatment of steel products in a magnetic field*. Russia: Mashinostroenie.

[7] Pustovoit, V. N., Dolgachev, Y. V., Salynskikh, V. M., & Stiopka, V. Y. (2018). Kinetics of martensitic transformation in steel under the action of an external magnetic field. *International Journal of Applied Sciences and Technologies "Integral"*, *4*, 224–229.

[8] Krivoglaz, M. A., Sadovsky, V. A., Smirnov, J. B., & Fokina, E. A. (1977). *Tempering steel in a magnetic field*. Russia: Nauka.

[9] Schastlivtsev, V. M., Kaletina, Y. V., & Fokina, E. A. (2007). *Martensitic transformation in a magnetic field*. Russia: Ural Branch of the RAS.

[10] Konovalov, S. V., Gromov, V. E., & Ivanov, Y. F. (2013). *The influence of electromagnetic fields and currents on plastic deformation of metals and alloys*. Russia: Publishing House "Inter-Kuzbass".

[11] Li, G. R., Wang, F. F., Wang, H. M., Zheng, R., Xue, F., & Cheng, J. F. (2017). Influence of high pulsed magnetic field on tensile properties of TC4 alloy. *Chinese Physics B*, *26*(4), 046201. https://doi.org/10.1088/1674-1056/26/4/046201
[12] Alshits, V. I., Darinskaya, E. V., Koldaeva, M. V., Kotowski, R. K., Petrzhik, E. A., & Tronczyk, P. K. (2016). Experimental studies and computer simulations of magnetoplastic effect. In *Progress in Electromagnetic Research Symposium*, 1907–1907. https://doi.org/10.1109/PIERS.2016.7734825
[13] Kraiev, M., Voronkov, E., & Kraieva, V. (2021). Calculation of energy and magnetic susceptibility of Fe atomic system during dislocation motion in magnetic field. *Multidiscipline Modeling in Materials and Structures*, *17*(6), 1183–1192. https://doi.org/10.1108/MMMS-02-2021-0026
[14] Utyamyshev, R. I., & Vrana, M. (2003). *Electronic apparatus for stimulating organs and tissues*. Russia: Energoatomizdat.
[15] Karasik, V. R. (1964). *Physics and technology of strong magnetic fields*. Russia: Nauka.
[16] Knopfel, G. (1972). *Superstrong impulse magnetic fields*. Russia: Mir.
[17] Herlach, F. (1988). *Strong and superstrong magnetic fields*. Russia: Mir.
[18] Lagutin, A. S., & Ozhogin, V. I. (1988). *Strong pulsed magnetic fields in a physical experiment*. Russia: Energoatomizdat.
[19] Grosz, A., Haji-Sheikh, M. J., & Mukhopadhyay, S. C. (2017). *High sensitivity magnetometers*. Switzerland: Springer.
[20] Gordon, A. V., & Slivinskaya, A. G. (1960). *DC electromagnets*. Russia: Gosenergoizdat.
[21] Slivinskaya, A. G. (1972). *Electromagnets and permanent magnets*. Russia: Energy.
[22] Lomonosov, V. Y., Polivanov, K. M., & Mikhailov, O. P. (1990). *Electrical engineering*. Russia: Energoatomizdat.
[23] Malygin, B. V. (1989). *Magnetic hardening of tools and machine parts*. Russia: Mashinostroenie.
[24] Sarraf, M., Kataria, S., Taimourya, H., Santos, L. O., Menegatti, R. D., Jain, M., . . . , & Liu, S. (2020). Magnetic field (MF) applications in plants: An overview. *Plants*, *9*(9), 1139. https://doi.org/10.3390/plants9091139
[25] Ren, Z., Lei, Z., Li, C., Xuan, W., Zhong, Y., & Li, X. (2020). New study and development on electromagnetic field technology in metallurgical processes. *Acta Metallurgica Sinica*, *56*(4), 583–600. https://doi.org/10.11900/0412.1961.2019.00373
[26] Hou, Y., Gao, Z., & Li, C. (2022). Solidification processing of metallic materials in static magnetic field: A review. *Metals*, *12*(11), 1778. https://doi.org/10.3390/met12111778
[27] Eskin, D. G., & Mi, J. (2018). *Solidification processing of metallic alloys under external fields*. Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-319-94842-3
[28] Alifanov, A. V., Burnosov, N. V., & Chudakova, I. L. (2011). Pulse magnetic hardening cutting tools technology. Woodworking: Technologies, equipment, management of the 21st century. In *Proceedings of the VI International Eurasian Symposium*, 255–260.
[29] Weiss, D., Murphy, B., Thompson, M. J., Henderson, H. B., Rios, O., Ludtka, G. M., . . . , & Kesler, M. S. (2021). Thermomagnetic processing of aluminum alloys during heat treatment. *International Journal of Metalcasting*, *15*, 49–59. https://doi.org/10.1007/s40962-020-00460-z
[30] Zagulyaev, D. V., Konovalov, S. V., & Gromov, V. E. (2010). Change in microhardness of technically pure aluminum A85 in a pulse magnetic field. *Bulletin of CSU*, *12*(193), *Physics, 7*, 21–24.
[31] Ma, L., Liang, Z., Wang, X., Zhao, W., Jiao, L., & Liu, Z. (2015). Influence of pulsed magnetic treatment on microstructures and mechanical properties of M42 high speed steel tool. *Acta Metallurgica Sinica*, *51*(3), 307–314.
[32] Hou, M., Li, K., Li, X., Zhang, X., Rui, S., Wu, Y., & Cai, Z. (2020). Effects of pulsed magnetic fields of different intensities on dislocation density, residual stress, and hardness of Cr4Mo4V steel. *Crystals*, *10*(2), 115. https://doi.org/10.3390/cryst10020115
[33] Kovalevsky, S. V., & Tulupov, V. I. (2006). Surface treatment by pulse magnetic field of machine parts. *Tool Reliability and Optimization of Technological Systems*, *19*, 181–185.
[34] Pustovoyt, V. N., Kuzmina, V. A., & Dolgachev, Y. V. (2016). Structural features pearlite transformation in a magnetic field. *Scientific and Technical Bulletin of BSU*, *2*, 97–100.
[35] Papadatu, C. P., Bordei, M., & Ciortan, S. (2019). Effects of the non-conventional treatment in magnetic field applied on a steel for gearings. *IOP Conference Series: Materials Science and Engineering*, *485*, 012020. https://doi.org/10.1088/1757-899X/485/1/012020
[36] Li, P. X., Zhang, Y., Wang, W. Y., He, Y., Wang, J., Han, M., . . . , & Li, J. (2021). Coupling effects of high magnetic field and annealing on the microstructure evolution and mechanical properties of additive manufactured Ti–6Al–4V. *Materials Science and Engineering: A*, *824*, 141815.
[37] Kolano-Burian, A., Zackiewicz, P., Grabias, A., Wojcik, A., Maziarz, W., Szlezynger, M., . . . , & Hawelek, L. (2021). Effect of Co substitution and thermo-magnetic treatment on the structure and induced magnetic anisotropy of $Fe_{84.5-x}Co_xNb_5B_{8.5}P_2$ nanocrystalline alloys. *Materials*, *14*(12), 3433. https://doi.org/10.3390/ma14123433
[38] Titenko, A. N., Demchenko, L. D., Perekos, A. O., & Gerasimov, O. Y. (2017). Effect of thermomagnetic treatment on structure and properties of Cu–Al–Mn alloy. *Nanoscale Research Letters*, *12*, 285. https://doi.org/10.1186/s11671-017-2052-6
[39] Sobolev, A. S., & Pudov, V. I. (2013). Increasing the wear resistance of tool steel products. *Bulletin of TSU*, *18*(4), 1794–1795.
[40] Milyutin, V. A. (2017). *The influence of a strong magnetic field on the evolution of structure and crystallographic texture during the annealing of deformed and amorphous ferromagnetic metal alloys*. Doctoral Dissertation, M.N. Mikheev Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences.
[41] Pusgovoyt, V. N., & Kholodova, S. N. (2003). Deformation-free hardening heat treatment of small rod parts in a magnetic field. *Bulletin of DSTU, T.3*, *3*(17), 338–343.
[42] Kinoshita, T., Kohara, K., Shimoji, H., Sato, T., & Todaka, T. (2018). Effects of magnetic field applied during heat treatment on magnetic properties of non-oriented electrical steel sheets. *Journal of the Magnetics Society of Japan*, *42*(3), 83–89.
[43] Kinoshita, T., Shimoji, H., Aihara, S., Sato, T., & Todaka, T. (2019). Effect of heat treatment under high magnetic field on crystallographic orientation and magnetic properties of non-oriented electrical steel sheets. *IEEE Transactions on Magnetics*, *55*(2), 1–5.

[44] Tang, L., Yan, X., Jiang, Y., Li, F., & Zhang, H. (2020). Effect of magnetic field coupled deep cryogenic treatment on wear resistance of AISI 4140 steel. *Advances in Materials Science and Engineering*, *2020*(1), 2589283. https://doi.org/10.1155/2020/2589283

[45] Pokoev, A. V., Osinskaya, J. V., Shakhbanova, S. G., & Yamtshikova, K. S. (2018). The magnetoplastic effect in aluminum alloys. *Bulletin of the Russian Academy of Sciences: Physics*, *82*(7), 870–873. https://doi.org/10.3103/s106287381807033x

[46] Gu, Q. J., Huang, X., Xi, J., & Gao, Z. (2021). The influence of magnetic field on fatigue and mechanical properties of a 35CrMo steel. *Metals*, *11*(4), 542. https://doi.org/10.3390/met11040542

[47] Zhang, X., Zhao, Q., Cai, Z., & Pan, J. (2020). Effects of magnetic field on the residual stress and structural defects of Ti-6Al-4V. *Metals*, *10*(1), 141. https://doi.org/10.3390/met10010141

[48] Soria-Hernández, C. G., Palacios-Pineda, L. M., Elías-Zúñiga, A., Perales-Martínez, I. A., & Martínez-Romero, O. (2019). Investigation of the effect of carbonyl iron micro-particles on the mechanical and rheological properties of isotropic and anisotropic MREs: Constitutive magneto-mechanical material model. *Polymers*, *11*(10), 1705. https://doi.org/10.3390/polym11101705

[49] Alshits, V. I., Darinskaya, E. V., Koldaeva, M. V., & Petrzhik, E. A. (2016). Resonance magnetoplasticity in ultralow magnetic fields. *JETP Letters*, *104*, 353–364. https://doi.org//10.1134/S0021364016170045

[50] Kraiev, M. (2023). Analysis of the magnetoplasticity of steel by constructing the absorption spectrum of mechanical energy at magnetic resonance. *Multiscale and Multidisciplinary Modeling, Experiments and Design*, *6*, 573–577. https://doi.org/10.1007/s41939-023-00167-8

[51] Kraiev, M. V., & Kraieva, V. S. (2018). Aluminum extrusion in a constant magnetic field. *Conference Series: Modeling and Development of Metal Forming Processes, 24*, 74–79.

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