Journal of Mines, Metals and Fuels, *71(12D): 22-29; 2023. DOI: 10.18311/jmmf/2023/47981*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

A Review of the Magnetic Field Generation in Ferromagnetic Materials with Applied Stress

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Abstract

The main motive of this paper is to review the generation of magnetic fields in ferromagnetic materials under the application of stress. Mechanical stress, temperature, and magnetic field are three significant factors that influence magnetisation. The magnetisation level depends on the material type, magnetic history, magnetic field strength, strain and temperature. Owing to the external load, the magnetic behaviour of ferromagnetic materials changes extensively through plastic deformation. Hence, the domain structure alters the ferromagnetic material's internal magnetic field. The magneto-mechanical effect, i.e., the alteration of magnetisation of ferromagnetic material with external stress, has been a focal point for many researchers. The concept of magnetism is discussed along with the various parameters that depict the fundamental magnetic properties. Furthermore, Magnetoelastic Sensors (MES), a potential substitute for strain-gauge devices, have been discussed in this paper. The future lines of research have also been highlighted. The use of ferromagnetic materials for various applications in the mining industry has also been highlighted.

Keywords: *Ferromagnetic Materials, Magnetic Field, Magnetoelastic Sensors, Plastic Deformation, Stress*

1.0 Introduction

Mechanical loading influences magnetic behaviour and the degree, kind and direction of the loading impacts its evaluation[1]. Saturation magnetisation or magnetostriction is the term used to describe the magnetically generated strain apparent in all ferromagnetic materials. The magnetisation process changes the dimensions and the shape of ferromagnetic materials. This is termed the magnetostriction effect which was discovered by Joule in 1842. It has enormous industrial importance in robotics, functional structures or adaptive transducers, actuators, sensors and other magnetic components.

Conversely, owing to applied stress, there will be an alteration in the magnetic properties of ferromagnetic materials. This magnetostriction phenomenon is termed the 'piezomagnetic' or the 'Villari effect[2]'. Two categories of magnetostriction may occur under stress in ferromagnetic materials: positive and negative magnetostriction. In positive magnetostriction, the material expands under tension and there is an increase in magnetisation. In negative magnetostriction, the material contracts and the magnetisation decreases when magnetised. Due to its significance in magnetic measurements, the piezomagnetic effect is more considered when evaluating material stresses. Magnetostriction occurs in all pure magnetic substances. Though the direct magnetostrictive effect is minor, properties such as permeability and the hysteresis loop size depend on stress in several materials due to an inverse effect.

Without considerable stress application, a ferromagnetic material consists of numerous domains since the single domain's existence is generally energetically not favourable since the higher magnetostatic

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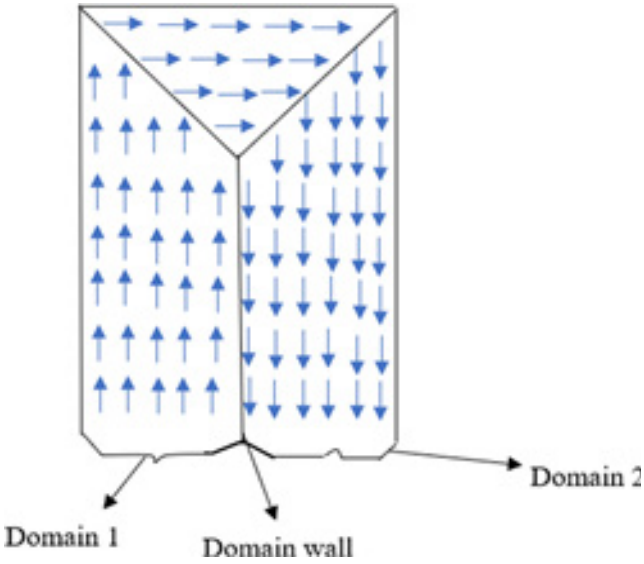


Figure 1. An illustration of domains in ferromagnetic materials without applying stress; Arrows represent magnetic dipoles of the atoms.

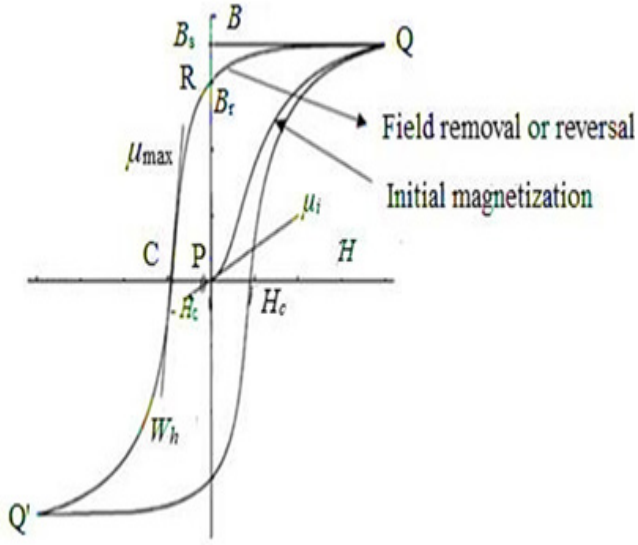


Figure 2. A representative hysteresis loop of a ferromagnetic material.

energy is related to a single domain sample. Multiple domain wall formation in the material will reduce the magnetostatic energy once the magnetostatic energy surpasses the energy essential for forming the domain wall. The complex magnetic domain and its development under external loading is exciting. Domains represent a vital concept in magnetism. A ferromagnetic material not subjected to external stress comprises numerous domains. Each domain has a mutual alignment of magnetic dipole moment in a similar direction (Figure 1). Domain walls are boundaries between regions where dipoles have a specific direction-magnetisation direction change within the wall from one domain to another.

2.0 Assessment of Ferromagnetic Material Properties

The properties of ferromagnetic materials may be measured through the various parameters related to the hysteresis loop or the *B*-*H* curve. The hysteresis loop represents the magnetising force or field intensity (*H*) versus the magnetic flux density (*B*) curve (Figure 2).

In ferromagnetic materials, *B* and *H* are not directly proportional. With increased *H*, the *B* field gradually increases, grows speedily and becomes independent of *H*. It is essential to represent a ferromagnetic material's nonlinear magnetisation behaviour with an applied magnetic field. The six parameters, namely initial permeability, coercivity, maximum permeability, saturation magnetization, remanence and hysteresis effect, can be comprehended from the *B*-*H* curve.

The permeability μ, which depends on *H*, is estimated from the *B* versus *H* curve slope. The slope at $H = 0$ is the initial permeability; μ_i is a material property. The maximum value of μ_i is at the coercivity H_c. Hence, the maximum permeability, μ_{max}, is an additional feature of the hysteresis loop. The saturation flux density, B_s, is the maximum value of *B* and M_S is the subsequent magnetisation called saturation magnetisation.

The curve P-Q shows the initial magnetisation. The curve does not retrace the original path with the reduction of the H field by field direction reversal. The *B* field decreases slower or lags behind the applied *H* field, producing a hysteresis effect. The remanence or the remanent flux density, B_r, has a residual *B* field at zero *H* field. Thus, the material remains magnetised without an externally applied *H* field. The *H* field of magnitude $-H_c$

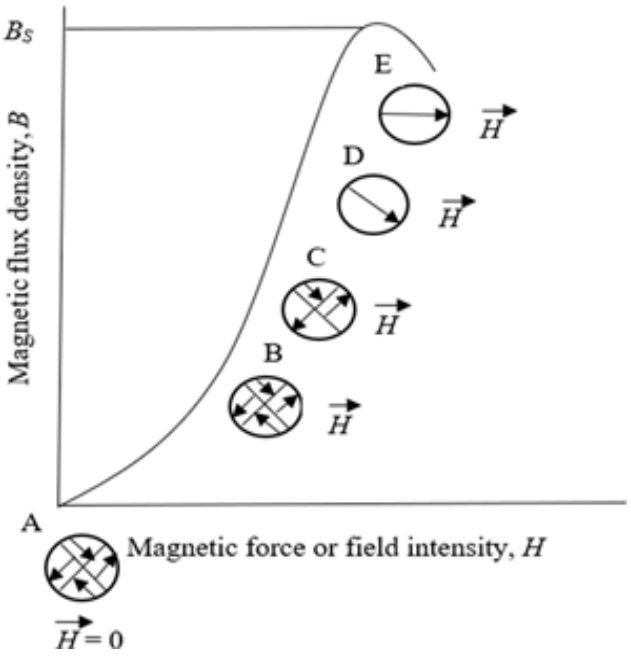


Figure 3. The B-H behaviour for a ferromagnetic material unmagnetised at the beginning (Bs is the maximum value of B).

application must be opposite the original field to reduce the *B* field within the specimen to zero. When the field is applied in the opposite direction, saturation occurs in the opposite sense (related to point Q'). The second field reversal is to the point of initial saturation (Q). The magnetic energy released per unit volume cycling of the material about one loop represents the loop area. The energy lost is dissipated as heat. The hysteresis loss *Wh* is the area bounded by the hysteresis loop. The magnetic domain walls go through an irreversible motion. The rotation of domain magnetisation within the material is also 0irreversible. The domain structures are displayed in the positions (labelled A to E) at points in the *B* versus *H* curve in Figure 3. At first, the constituent domains' moments are randomly oriented, so there is no net *B* field (inset A). With the application of external fields, the domains are oriented in favourable directions (or closely aligned with) the applied field and the dipoles are oriented in directions favourable to the externally applied magnetic field.

Stress with a co-applied magnetic field influences magnetic properties, which have been widely investigated. The experimentations were carried out under an additional magnetic field. The properties assessed were magnetic susceptibility, permeability, remanence and coercivity[3–6]. There hasn't been much discussion in the literature on the different magnetic signals for ferromagnetic metals under stress without an external magnetic field (apart from the Earth's magnetic field).

Considering the above discussion, the report of generating a 0.1 Tesla transient magnetic field throughout the crack's tensile propagation and fracture of low-carbon steel samples appears significant[7-10]. The specimens were demagnetised before testing, but adjacent to the fracture, the fractured pieces were found to be magnetised.

According to Nuti and colleagues[11] observation of the magnetic effect, the general equation of reluctance variation does not need the release of a strong magnetic field. In the necking zone of the specimen, Misra suggested creating a Neel wall configuration phenomenon, which theoretically supported the presence of a strong magnetic field. Comprehensive studies were conducted and the magnetic field created was reported high[12]. They also noted a further increase in magnetic flux before the last fracture. It was mainly caused by an extra flux increase due to a possible realignment of the magnetic domain in the necking zone of the specimen. No magnetic field of any sort could be detected in the studies on comparatively thin steel specimen sheets[13].

A theoretical model concluded that a 0.1 Tesla magnetic field could be generated in necking in cylindrical steel specimens[14]. The dislocation configuration complex through the necking and before tensile fracture triggered the transient generation of the magnetic field. The magnetic field generation in low-carbon steel during tensile fracture depended on the specimen's necking degree[15]. Thin sheets, square, cylindrical and rectangular specimens were investigated. Throughout the tensile process, the stray field of the ferromagnetic sample existed and the variation can well divulge the stress state. The magnetic field generation was reliant on the specimen's cross-section and thickness.

The *in-situ* magnetic characterisations of Fe (3 wt%) and Si steel (non-oriented) were reported [16]. With the help of suitable experimental equipment, magnetic measurements were performed with uniaxial tensile

strains. The measurement of stresses was both in the unloaded states and near and beyond the macroscopic limit of elasticity. The Barkhausen noise was measured, and the *B-H* hysteresis loop was examined. The sensitivity to stress was observed to have qualitative similarities to polycrystalline iron. Lu Li's contribution was substantial in his work on the effect of stress on ferromagnetic material on nickel and stainless-steel specimens [17].

It is a systematic study that employs theory, experimentation, and numerical computation to examine the practical implications of magneto-mechanical effects and nondestructively assess the tensile properties of cold-rolled virgin 304SS specimens[18]. A study[19] describes the fluctuation in the magnetic field that arises from the cyclic stress created in the elastic region of the ferromagnetic sample in the geomagnetic field.

It was shown that when the strain was applied alone, ferromagnetic materials may display modest magnetic signals on their surface[20]. The intricate dislocation structure through the necking and before the tensile fracture produced a strong transient magnetic field that abruptly oriented the magnetisation vectors. It was observed that the fluctuations caused plastic deformation, which in turn affected the magnetoelastic properties of the dislocation structure[21].

Bao[22] tested three distinct steel sheets through tensile tests. The residual magnetic signals underwent a characterisation of the deviation. To reduce the impact of the initial magnetic field, every specimen underwent demagnetisation before loading. During the elastic and plastic stages, the magnetic signal changes over the steel surfaces showed specific properties. In Q235 and 45# sheets of steel, the magnetic field variation displayed a nonlinear correlation with the applied stress during the elastic stage. A linear correlation between magnetic field and stress was detected in Q345 steel. For Q235, the magnetic field variation was intricate during the plastic stage.

A three-dimensional principal stress space model was suggested for the magnetic anisotropic constitutive owing to induced stress for analysing the magneto-mechanical coupling effect of the Magnetic Memory Method (MMM)[23]. A linear interrelation between the magnetic field and magnetisation was employed for the low-intensity magnetic field. Hence, the stress-induced magnetic anisotropy dependency on magnetic permeability was studied in various directions. The stress effect on the surface magnetic field and magnetic permeability were computed following the model. Fatigue bending experiments were performed on four-point notches of single-edge bend specimens[24]. Examining the onset and spread of fatigue cracks was the objective. Measurements of the magnetic memory signal of the metal were conducted throughout the fatigue process. An assessment of the fatigue-related damage to the ferromagnetic material was made. MMM was examined by Bao and co-workers[25] to detect initial failures and the fatigue damage of ferromagnetic specimens, micro-crack and stress concentration. The advanced experimental analyses on the MMM techniques were performed on the factors influencing the detection signals, damage judgment measures and magnetic parameters for evaluating the testing results.

A kinematic hardening model of the susceptibility of ferromagnetic materials to stress, primarily plastic strains was proposed as a macroscopic method[26]. It was assumed that the strained plastic substance was a two-phase system. Kinematic hardening and residual stress are known to be related. Different magnetic qualities of steel varieties were assessed in light of plastic deformation[27]. The specimens were heat-treated at various intervals of temperature before measurement. Magnetism equipment was used to measure the magnetic characteristics. For the specimens examined to determine how plastic deformation influenced the magnetic properties, only AISI 304 steel was approved. As temperature increases, magnetic materials properties alter.

A report[28] examined the effect of loading speed on the stress-induced magnetic behaviour of Q235 steel. Uniaxial tension tests were performed on the steel at different loading rates and stress concentrations. The specimen's magnetic signal fluctuation was examined using a fluxgate magnetometer. The outcome demonstrated that changes in the magnetic signal are influenced by both the tensile loading level and loading speed during the test. A stress-dependent model of magnetic charge was proposed[29].

The impact of fracture size on the stress of 12CrMoV was evaluated using the MMM technique[30]. To imitate surface cracks, several widths and depths of rectangular grooves were pre-cut on the surface of the experimental specimen with the help of equivalent theory. Scanning Electron Microscopy (SEM) was used to analyse the overall fracture morphology. The magnetic properties of the stress state of grade M270-35A non-grain-oriented steel were inspected using the customised measurement setup used for stress-strain[31]. Measurements of electrical resistance, Transmission Electron Microscopy (TEM) and magneto-mechanical properties were made. The loss separation technique was used to investigate core energy losses. As the mechanical load was released, the magnetic characteristics further deteriorated.

3.0 Magnetoelastic Sensors

As sensors become more widely used in various applications, the need for upgraded sensor technologies to detect various physical parameters has grown immensely.

3.1 Theory of Operation

Thick-film ribbons of amorphous ferromagnetic alloy can be manufactured by Magnetoelastic Sensors (MES). These sensors produce longitudinal vibrations that resemble elastic waves with varying strength with time when under the influence of a magnetic field. Measuring the magnetic flux of elastic waves in a magnetostrictive magnetoelastic material is possible. The sensor material modifies these vibrations' amplitude and resonance frequency and the adjacent medium by functioning as a damping agent.

When MES becomes magnetostrictive in a magnetic field, a strain develops in the material. Magnetoelastic sensors work on magnetoelastic inverse magnetostrictive effect. The magnetic susceptibility changes with the application of mechanical stress. Susceptibility and magnetic permeability are correlated. The imposed stress is positively replicated by the changing permeability.

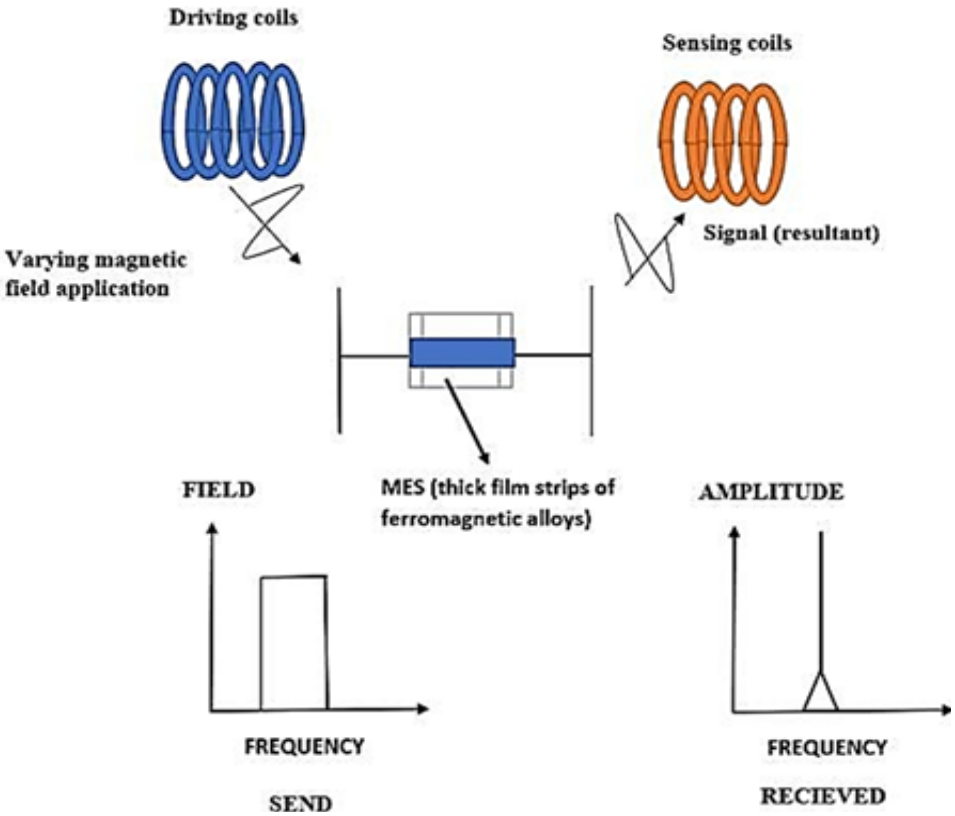


Figure 4. Working devices and primary measuring devices of the magneto-elastic sensor.

Examining the shift in permeability after stress is applied can help with MES inspection[32]. A Villari effect sensor's detecting rod is made of a magnetostrictive material. An alternating current signal is received by an overlapping drive coil. The sensing rod and coils are inductively connected (Figure 4). A signal is produced thereupon, responsive to the permeability of the magnetostrictive sensing rod, which reduces in response to the load applied.

3.2 Application and Advantages

The development of force sensors also utilises the magnetoelastic effect. The effect is employed in sensors for monitoring ball valves, civil engineering, biomedical monitoring and large diesel engines in locomotives[33]. As magnetoelastic sensors are non-contact, they have no mechanical wear and a very long operating life. Even though the magnetoelastic properties of a material are incredibly reliable and will not degrade, magnetoelastic sensors do not require calibration. They are economical and have high tensile strength.

4.0 Ferromagnetic Materials in the Mining Industry

One of the most popular applications is magnetic separators which are large-scale devices that generate a strong magnetic flux. Conveyor belts in the mining industry can move aggregates containing magnetic minerals and these separators can extract and separate those elements. Magnetic separators can employ permanent magnets made of alnico, a mixture of cobalt, nickel and aluminium. Industrial magnets are also employed during mining to get tramp metal off the production line. Magnetic drum separators and suspended plate magnets are magnetic separators utilised in the mining sector. Iron, nickel, cobalt and certain rare earth metals are examples of ferromagnetic materials that are magnetised and susceptible to magnetism.

4.1 Ferromagnetic Materials for Stress-Related Failure in Mining

Ferromagnetic materials are used in various industries, including mining, due to their unique properties and potential applications in stress evaluation and damage detection. When subjected to stress, ferromagnetic materials exhibit changes in their magnetic properties, which can be used to identify and measure stress-related defects and failures. The stress state of ferromagnetic materials in the mining industry has been assessed using various techniques, including magnetic induction intensity, magneto-mechanical effect, magnetic field variations, magnetic stress detection based on EMAT, magnetic Barkhausen noise and the magnetic method.

5.0 Futuristic Areas of Research

There is a significant magnetic shape anisotropy because the specimen's shape affects how the magnetic field is generated. The magnetic domain may reorient as a result of significant plastic deformation. As a result, the phenomenon gains significance for all magnetic devices and components. Their significance has expanded due to the discovery of novel materials with high measurements, such as those obtained using ultrasonic and X-ray or neutron diffraction techniques. The most technologically advanced passive sensors measure residual stress and characterise damage. In practical applications, signal processing methods can adjust the magnetic field for applied stress while considering variations in the surrounding field.

Massive magnetoelastic couplings interact with magnetic material strain and magnetisation and nondestructive evaluation techniques in various metallic materials to identify the onset of microplastic deformations. Future research courses might focus on calibrating applied and residual magnetic field strength and residual stress for various metals.

6.0 Conclusion

An overview of the creation of magnetic fields in stressed ferromagnetic metals is presented in this article. Plastic deformation under stress significantly alters the magnetic behaviour and domain structure of ferromagnetic materials. The magneto-mechanical processes change the internal magnetic field. Understanding the fundamental theories of magnetism and the parameters that represent

the basic magnetic properties is crucial. Because of their unique qualities and prospective uses, ferromagnetic minerals like iron, nickel and cobalt are widely used in many industries, including mining for applications like magnetic separation, tramp metal detection and magnetic surveying. Magnetoelastic sensors have also become a viable substitute for strain-gauge systems, especially in terms of equipment cost and scale of mass production.

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