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Characterization fine grained low alloy steel 22 NiMoCr 3 7 by magnetic Barkhausen noise analysis

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ABSTRACT

To ensure the quality of mass-produced products, non-destructive material testing (NDT) is required with a method that has high testing speed and accuracy. Products that have undergone heat treatment such as automotive components to obtain a specific hardness value need to be tested to ensure the desired quality. Some parameters such as coercivity and permeability of the ferromagnetic materials, can be used to characterize the shape of the hysteresis curve. The hysteresis curve geometry is related to mechanical hardness, hot working record, and the presence of residual stresses. This paper will present how the coercivity value measurement can be done using the Barkhausen effect, as well as a study of the correlation between the coercivity value and the hardness of a ferromagnetic material using the regression analysis method. Indentation testing has also been done to verify different approaches to obtain hardness value by Barkhausen noise analysis. The research shows that this technique was sufficiently accurate with superior rapid testing and no indentation mark.

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1. INTRODUCTION

Studies of structural performance and materials components are commonly done through a range of analytical techniques including metallography, hardness measurement, mechanical testing, and otherwise. Each method provides different insights into the material's properties and behavior related to variations in the microscopic characteristics. Assessment of the mechanical properties of metal materials specifically for hardness value typically be done using indentation testing such as Vickers or Brinnel method [1], [2]. Even though indentation testing is reasonably reliable for defining the mechanical hardness of the materials, it is often difficult to withdraw enough specimens without impacting the structure performance [3]. On the other hand, when measuring a large number of test objects which have to be carried out at a high tempo such as mass testing of components in the fabrication stage, these two conventional methods are not feasible to utilize [4]. Destructive hardness testing requires more than 8 hours from the sample cutting stage until microscope analysis [5]. To overcome this problem, it is necessary to develop a testing method that is rapid and also highly reliable for the time and cost.

Characterizing the mechanical properties of materials by assessing their magnetic properties is an emerging and promising area of research. This approach leverages the relationship between a specific material’s magnetic behavior and its microstructural and mechanical characteristics. This study utilizes the

Barkhausen noise that occurs when the external magnetic field is exposed to the ferromagnetic material and then validated to conventional hardness measurement by linear regression tool in Nickel-Moly-Chrom (22 NiMoCr 3 7) steel as a testing specimen. Fine-grained alloy steel such as 22 NiMoCr 3 7 is typically used as a structural steel in pressure vessels and automotive components [6]. The development of high-strength steel is widely used as a solution for weight reduction that will improve fuel economy and high passive safety [7]. Heat treatment such as quenching or tempering is frequently done to improve mechanical performance specifically for the load components such as camshaft, gear, and bearing [8]. Grain refinement in this type of steel leads to an increase in yield and ultimate tensile strengths as well as changes in total elongation [9]. Fine-grained alloy steel generally consists of complicated microstructure including grain size and orientation, inclusions, dislocations, size and distribution particles, and other lattice defects which in principle simultaneously influence the magnetization behavior of the material. Table 1 shows the chemical composition 22 NiMoCr 3 7.

Table 1. Chemical composition 22 NiMoCr 3 7 (in weight %)

C	Si	Mn	P	S	Cr	Mo	Ni
0.2	0.24	0.71	0.007	0.009	0.42	0.65	0.86
V	Cu	Sn	Al	N	Co	Ta	Sb
0.01	0.18	0.01	0.016	0.011	0.018	0.01	0.005

The mechanical hardness of a material is described as its ability to resist deformation. Specifically for ferromagnetic materials, variation in mechanical hardness can affect the hysteresis curve characteristics [10]. Harder material may have more rigid structures which potentially leads to better alignment of magnetic domains which forms the hysteresis loop [11]. Based on this, the hysteresis curve pattern has the prospect of being utilized to determine the characteristics of a ferromagnetic material. The parameters that have a direct relation to the hysteresis curve pattern are the value of coercivity, increment permeability, and material magnetic remanence [12]. Literally, by analyzing the hystrometer instrument recording data, the coercivity value of a material can be directly calculated by looking at the intersection of the hysteresis curve on the abscissa axis. However, for mass measurements such as testing of components in the fabrication stage a coercivity value reading technique that is rapid and has high accuracy is needed.

Improvement related to the hardness testing method spans numerous fields such as developing a program to graphically display the hardness value of the object with the help of a charge-coupled camera [13], utilizing eddy current to be used in hardness increase prediction resulting from shot peening work [5], investigation using laser-induced spectroscopy to visualize hardness gradients [14]. On the other hand, research into the application of the Barkhausen effect has been done in the measurement of tensile stress and case depth prediction in medium carbon steel [11], prediction for hardness fluctuation on sheet metal coil under rolling conditions [4], and promoting the hysteresis loop technique for monitoring microstructure change on medium carbon steel [15]. However, there are still a number of issues with the previously used techniques for assessing materials' hardness when performing rapid hardness testing in bulk measurements without compromising accuracy or the structural performance of the component. This study features a fine-grained low alloy steel to empirically analysis the correlation between the coercivity and the hardness value by examining the Barkhausen noise in order to enhance testing speed. This non-destructive hardness determination technique is expected to replace conventional hardness measurement utilized, especially in the automotive component industry which uses many high-strength steels for weight reduction.

2. RESEARCH METHOD

The testing object was alloy steel of 22 NiMoCr 3 7. The specimens to be measured are seven pieces prepared to have a solid cylindrical shape with a length of 50 mm and a diameter of 8 mm. These seven specimens have received different controlled working temperature heat treatments, thus varying in material hardness number. Sample preparation was done by sanding the specimen using 800-grit sandpaper and then polishing it with diamond paste, leaving the sample's surface clean and flat.

The Barkhausen pickup coil is placed near the surface of the specimen to measure the rate of magnetic flux changes on the material's surface. The signal picked up by the surface coil is then passed through a conditioning circuit to improve its quality before further processing. The magnetic noise from the Barkhausen effect would be utilized as an indicator tool when the coercivity condition is reached. The setup that follows is assembled to measure magnetic Barkhausen noise measurements in ferromagnetic materials which offers flexibility for non-destructive applications [16], [17].

The signal obtained from the Barkhausen surface coil is typically very weak and can be susceptible to noise. The signal preamplifier, often an instrumental amplifier, is used to amplify the weak signal before any further processing. This step helps improve the signal-to-noise ratio, making it easier to distinguish the Barkhausen noise from the background noise. The Barkhausen noise signal often contains a range of frequencies, including the fundamental frequency (50 or 60 Hz, depending on the power line frequency) and harmonics, as well as components related to the applied magnetic field. A band-pass filter is used to selectively pass a specific frequency range of interest while attenuating frequencies outside that range. This helps isolate the Barkhausen noise signal from other unwanted frequency components. The high cut-off frequency of the filter is set to avoid aliasing, which occurs when high-frequency components of the signal fold back into lower frequencies due to insufficient sampling rates during analog-to-digital conversion. The high cut-off frequency, often referred to as the Nyquist frequency, plays a crucial role in preventing aliasing during analog-to-digital conversion. The signal that passes through the filter might have an attenuated amplitude due to the band-pass filtering process. A programmable amplifier is used to provide the necessary gain to bring the signal's amplitude within the optimal range for the analog-to-digital converter (ADC). This amplification ensures that the signal fully utilizes the dynamic range of the ADC, enhancing the resolution and accuracy of the measurements.

Magnetic Barkhausen noise is indeed a phenomenon that arises in ferromagnetic materials when their magnetization experiences abrupt changes due to the movement of magnetic domain walls [18]. This movement occurs in response to a smoothly varying external magnetic field. This basic fundamental leads to sensible aspects in detecting material properties and deviation in real-time. By using this setup and signal conditioning circuit, researchers can measure and analyze the magnetic Barkhausen noise phenomenon, which provides insights into the behavior of ferromagnetic materials under changing magnetic fields. This information can be valuable for various applications, such as material characterization, quality control, and non-destructive testing. Figure 1 shows the arrangement of the hystrometer apparatus which is equipped with the magnetic Barkhausen noise measuring instrument.

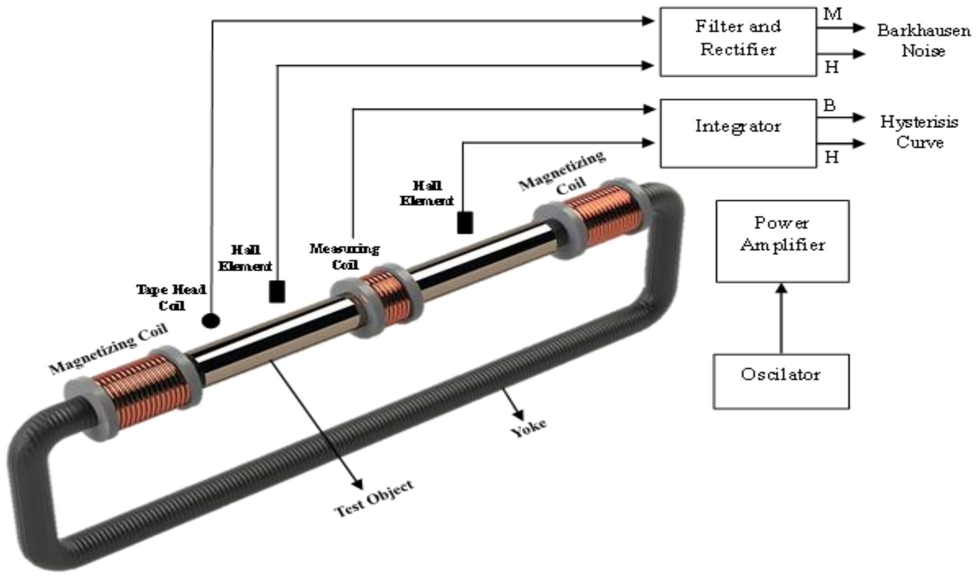

Figure 1. Hystrometer setup equipped with magnetic Barkhausen noise measuring equipment

Hardness measurement verification was made by Vickers microhardness testing. These laboratory methods are based on static force application on a diamond pyramidal indenter. The force given leaves a plastic deformation footprint on the specimen, which is then evaluated to obtain the material hardness number [3]. During Vickers hardness testing, the indenter applied static force and the displacement rate was kept constant. The indenter's surface area was then calculated from the corner-to-corner length of the pyramidal footprints on the specimen by using an optical microscope [19]. The regression formula was developed to obtain the conversion value of the Barkhausen noise data measurement so it can be adopted to achieve rapid estimation of the hardness number of the materials. These conventional methods, individually, or in combination, provide a comprehensive understanding of the microscopic variations in ferrous materials, helping to link microstructural features to macroscopic properties and performance.

3. RESULTS AND DISCUSSION

Figure 2 shows the sample of the hysteresis curve for the first specimen, which is coupled with the magnetic Barkhausen noise curve. The noise reaches its maximum value when the coercivity value is reached. In the magnetization process, the magnetic field strength H used was 50 A/cm. The coercivity value is determined by looking at the magnetic field strength when the Barkhausen noise reaches its maximum.

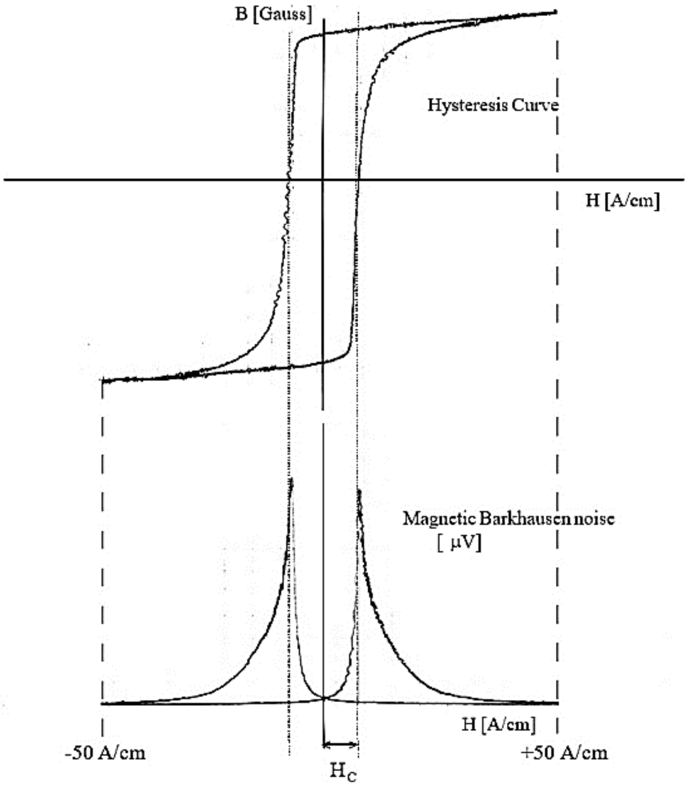

Figure 2. Hysteresis curve and magnetic Barkhausen noise of test specimen number 1

The measurement of magnetic Barkhausen noise is indeed based on Faraday's law of electromagnetic induction. The electrons in the material circulate in a pattern when the specimen is subjected to an electromagnetic field, creating a secondary electromagnetic field. Barkhausen surface coils or Barkhausen pickup coils can be used in the measuring setup to identify Barkhausen noise [20]. This form of coil is particularly designed to enhance the versatility and sensitivity of detecting changes in magnetic flux on the ferromagnetic sample surface, capturing the Barkhausen noise signals more satisfactorily [21]. The signal conditioning circuit is critical in preparing the Barkhausen noise signal for accurate analysis and interpretation. The conditioned signal is prepared for digitization and further processing by maximizing the signal amplitude, isolating the pertinent frequency components, and enhancing the signal-to-noise ratio. This approach considerably improves the effectiveness of magnetic Barkhausen noise measurements for various non-destructive applications [5].

Differences in magnetic response result from microstructural changes. Finer grain material which results from the heat treatment process, increases grain boundary density and gives more resistance to the passage of the magnetic field [22]. Therefore, the magnetic Barkhausen noise will rise with the higher hardness value material that receives heat treatment. The mechanical properties of the material determine the coercivity value of a ferromagnetic test material. The harder the material, the higher the coercivity value. Mechanical deformation and internal stress within the material can also cause domain wall motion and alter the magnetic state of the material [23]. Magnetic Barkhausen noise is a phenomenon observed in ferromagnetic materials when subjected to a smoothly varying external magnetic field that arises from the abrupt movement of magnetic domain walls within the material [24]. An evaluation of a ferromagnetic material's hysteresis loop upon excitation by an external magnetic field yields important information about the material's magnetic characteristics.

Figure 3 shows the mechanical hardness (HV10) obtained from the measurement of microhardness by the Vickers method and the magnetic coercivity value from all seven testing specimens. From the test result, it can be seen that there is a correlation between mechanical hardness and coercivity (hereafter, coercivity can be regarded as magnetic hardness). The greater the mechanical hardness, the greater the coercivity [25]. The representative relationship between mechanical hardness and coercivity can be seen more clearly when plotted into a diagram.

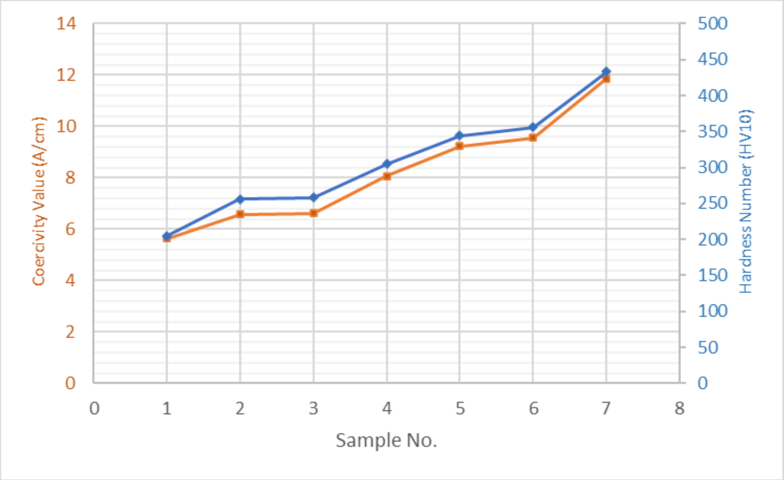

Figure 3. Relationship between mechanical hardness and magnetic hardness

Using the regression method, regression equations as in (1) and (2) were obtained, where Y is the output variable matrix, X is the input variable, b is the matrix of the regression coefficients of the model and e is the matrix of the modeling residual [26].

$$Y = X \cdot b + e \quad (1)$$

$$HV10 = 3.66 \cdot H_C - 1.74 \quad (2)$$

The regression equation above states the equivalency between mechanical hardness (HV10) and magnetic hardness which is obtained from the coercivity value (Hc). Linearity can be found in the relation between hardness and magnetic Barkhausen noise value [7]. The above equation can be used as a transfer function of coercivity quantities into mechanical characteristics. The fitted curve reveals a small error in the relation between Vickers microhardness testing and the magnetic Barkhausen noise test. The Barkhausen noise response from a variety of specimens creates a database to associate with an incremental hardness which then can be used in supervising the process especially when the parameters in the production line have to be adjusted without any destructive test that needs to be performed [5].

Microscopically, in ferromagnetic materials, there are Weiss domains that exhibit magnetic moments divided by crystal structure [10]. Inside each domain, atoms with the same magnetization direction are collected. Although each Weiss domain is a fully magnetized domain, due to the random distribution of domains with a certain magnetization direction the resultative macroscopically for a ferromagnetic material is not magnetic. Neighboring Weiss domains are separated by Bloch walls, where the magnetization inside the domain rotates in the x-y plane [27]. Inside these Bloch walls, the spins of the neighboring domains change their direction gradually continuously in the direction of magnetization of the adjacent domains [4]. Figure 4 shows the illustration of Weiss domains and Figure 5 shows the schematic representation of a Bloch wall.

Consider a ferromagnetic test material that is put into a magnetic field that enlarges gradually and deliberately. In that case, the Weiss domains with an orientation direction closer to the outside magnetic field (more favorable orientation) will enlarge, and on the other hand, Weiss domains with less favorable magnetization orientation will shrink [12]. The enlargement mechanism of Weiss domains takes place by the process of shifting the Bloch walls. This shifting process will be restrained or hindered by the presence of deformation, grain boundaries, and residual stresses [28]. These obstructions can be broken down by a further increase in the magnetizing field and then eventually the Bloch walls will disappear. In the magnetic saturation state, the test material consists of only a single Weiss domain. Figure 6 shows the mechanism of changing the direction of the magnetic of elementary magnets under the effect of changing the magnetic field.

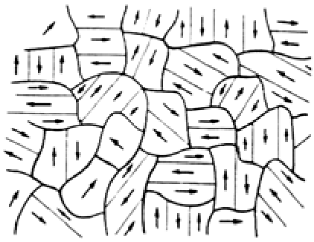

Figure 4. Illustration of Weiss domains

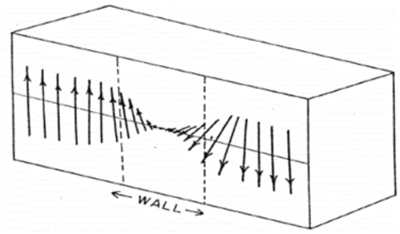

Figure 5. Schematic representation of a Bloch wall

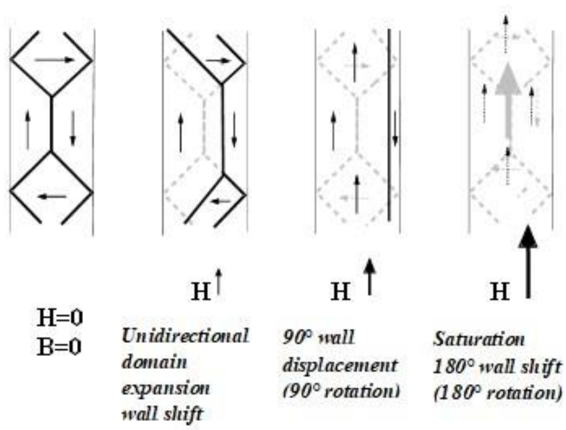

Figure 6. The mechanism of changing the direction of the magnetic of elementary magnets under the effect of changing the magnetic field

The displacement of the Bloch walls does not occur in a continuous mechanical process but will undergo a process of acceleration, braking, arrest, and collapse of the Bloch walls. This non-continuous process of change can be seen as a step-like jump in the hysteresis curve with a magnification window. The change mechanism is known as the Barkhausen effect. This discontinuous process will cause rapid changes in local magnetization and induce eddy currents with a wide frequency band [9]. The eddy current that occurs will then produce a magnetic field that can be measured using a tape head coil sensor on the surface of the test material [29]. The magnetic field produced by the Barkhausen effect is called magnetic Barkhausen noise. The intensity of this noise reaches a maximum when coercivity is reached [30]. The microstructure in the materials such as grain boundary and the stress state will affect the magnetic domains inside the materials [11]. These phenomena describe how magnetic domains in ferromagnetic material are disordered when exposed to the action of an external magnetic field.

Starting from the coercivity measurement process until the regression equation is obtained, it can be referred to as the calibration stage of a non-destructive material testing (NDT) test. Furthermore, the regression equation that functions as a transfer function will be utilized to measure hardness on the test object with the same material at the calibration stage. Surface hardness is an important indicator of the material's resistance to external forces and can be used to evaluate the quality of components or structure integrity [31]. The hardness measurement can be used to predict both the ultimate and yielding strength [3]. We found that Barkhausen noise is a valuable tool in non-destructive testing and evaluation of alloy steel base materials which correlates with providing information about material strength, stress, and microstructure. It is potentially used in automotive industries for quality control, material characterization, and structural health monitoring applications [10]. The automotive industry has been reducing the weight of vehicles which has led to the increased use of advanced high-strength steel [32]. Heat treatment including a rapid cooling process can produce high-strength steels with much lower precious alloying elements [22]. Since conventional indentation methods such as Brinnel, Vickers, or Rockwell will result in indentation marks on the objects which are also time-consuming [5] which made this method only relevant for sampling testing rather than for a bulk mass of workpieces [8]. For hardness testing, the proposed approach would be more advantageous than indentation measurements such as Brinnel and Vickers testing in application bulk hardness monitoring. According to our observations, the Barkhausen noise phenomenon has potential uses in non-destructive testing, quality control, and material characterization. Versatile magnetic testing instruments could be an alternative tool to perform non-destructive evaluation of the hardness measurement. This study approach integrates traditional and innovative methods to provide a thorough characterization of fine-grained alloy steel, emphasizing the potential of magnetic testing as a valuable tool in materials science and engineering.

4. CONCLUSION

In this experiment, two methodologies have been used to look at ferromagnetic materials, namely magnetic studies and mechanical studies. The research confirms that these two fields can be connected empirically using the regression method. Linearity can be found in the relation between hardness and magnetic Barkhausen noise value. In the magnetic field, ferromagnetic metals consist of elementary magnets (or Weiss domains) bounded by Bloch walls. In the mechanical field, metals are composed of crystalline grains mediated by grain boundaries. Magnetic hardness is largely determined by the mobility or flexibility of movement of the Bloch walls, while the flexibility of movement of the crystal grains determines mechanical hardness. The process of Bloch wall movement and grain movement will be hindered by similar mechanisms, for example, due to grain boundaries, dislocation, displacement, and residual stress.

Mechanical hardness measurement of ferromagnetic metal products by utilizing magnetic Barkhausen noise measurements in principle is one of the micromagnetic nondestructive testing of materials group. The Barkhausen effect equipment system could be coupled with a conveyor belt system where test objects passed into a set of magnetic sensors. The hardness of the specimen can be measured rapidly as it passes through the set of sensors. This non-destructive testing method is appropriate in the automotive components manufacturing industry such as in inspection brake components fabrication, stabilizer levers, and other structural parts. At some point, certain vital components of automobiles need to be 100% tested by non-destructive testing methods which play a significant role in mass product testing of automotive components. Assessing mechanical properties through magnetic methods holds significant potential for enhancing material characterization and quality control. Ongoing research and development are likely to expand the applicability and precision of these techniques, making them invaluable tools in various industries. Higher measurement speed with no affected on the structural performance of the testing object were features of the suggested approach in this investigation. Nevertheless, this intended approach was limited to ferromagnetic materials. According to our research, this technique could be enhanced for automated measurement such as in mass material shorting.

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