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Evaluation of mechanical properties in medium carbon steel with a point mode electromagnetic sensor

He Cunfu, Huang Yan, Liu Xiucheng*, Wu Bin

College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, 100124, China

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ABSTRACT

This paper reports the evaluation of mechanical properties of medium carbon steel based on a novel sensor. The novel point mode electromagnetic sensor with compact configuration and concentrated magnetic flux characteristics has attracted wide attention in recent years. The point mode electromagnetic sensor consists of exciting coil, receiving coil and needle permalloy core embedded into the coil. Response surface methodology was adopted to explore the relationships between the structure paramerters of core (contact radius and height of the cone) and magnetic field intensity based on finite element analysis. The analysis results showed that the contact radius and cone height of the core had important influences on magnetic field intensity. The influence of the cone height was lesser than that of the contact radius. Moreover, the mathematic model was verified effectively by testing magnetic field intensity of different cores based on scanning techniques. Mechanical properties experiment results measured by using a novel sensor showed that a linear correlation exists between the values of amplitude for fundamental and the hardness of samples.

1. Introduction

Crankshaft of the ship and blisk of engine are key devices. Mechanical properties of narrow space and complex curved surfaces in the above two devices, such as hardness, depth, and residual stress, are widely concerned. In recent years, many researchers have focused on nondestructive testing (NDT) of the mechanical and physical properties of materials as an alternative to destructive methods [1–3]. Micromagnetic testing techniques are one of nondestructive technologies and include Magnetic Barkhausen Noise [4–6], incremental permeability analysis [7,8], and eddy current detection [9–14], which are used to monitor the product quality in production lines based on the conductivity and permeability of measured materials.

A variety of electromagnetic sensors has been developed for nondestructively evaluation of defect, load and mechanical properties of structures. Ye et al. [15] devised novel eddy current probe to generate rotating field without mechanically rotating the probe, and the probe offered high inspection speed and was sensitive to defects of all orientation. Delabre et al. [16] proposed a method for designing flexible eddy current sensor for evaluation of the electrical conductivity during inspection of defects. To conduct wireless structural health monitoring (SHM) to the metal infrastructures, Annamdas et al. [17] developed a novel system based on electromechanical piezo-impedance and electromagnetic contact sensing to gather the information of load. In addition, the electromagnetic sensors are also adequate for SHM application in composite materials such as carbon fiber reinforced plastics (CFRP) [18] which are widely used in aerospace field. Savin et al. [19] designed a sensor with a metamaterial lens to nondestructively characteristic the damages of carbon fiber reinforced plastics by the phase.

As for the mechanical properties evaluation in ferromagnetic materials, Sorsa et al. [20,21] established a Magnetic Barkhausen Noise measurement system, used a magnetic yoke to excite the magnetic field, and coupled it into a sample. It was capable of evaluating fatigue damage based on the amplitude of Magnetic Barkhausen Noise in low-carbon structural steel caused by the changes in the dislocation density in the case of high-cycle fatigue damage. Zhu et al. [22,23] proposed a H-shaped EM sensor consisting of five coils, one common primary excitation coil, and four secondary flux sensing pick-up coils. It has been reported that typical decarburization layers of a rail sample can be distinguished. Rumiche et al. [24] developed an electromagnetic sensor composed of primary excitation coil, secondary coil, and the array of Hall

* Corresponding author.
E-mail address: xiuchliu@bjut.edu.cn (X. Liu).

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sensors which could be used to evaluate the microstructures of carbon steels by measuring magnetic properties. EM sensor can detect the changes in magnetic properties because the percent of ferrite, grain size, and hardness of material are different. Hao et al. [25] proposed a potential online nondestructive method based on multi-frequency electromagnetic sensor and established the relationship between the sensor output and the decarburized layer thickness.

The main structures of detected objects mentioned above are planers or rods. Nondestructive testing remains a challenge in the complex ferromagnetic structure, which requires the complicated morphology or narrow-space testing capability of detection systems. Meyendorf et al. [26] established a system in which the sample holder and the end of electrode were connected to the amplifier of exciting signals. When the electrode tip contacted sample surfaces, the closed circuit was formed. Then an alternating electrical current was coupled into pin type electrode and Magnetic Barkhausen Noise was excited due to a magnetic field of sample surfaces and collected by the Barkhausen Noise Coil. Although the method might be used to determine the mechanical properties of the edges of testing samples, the testing process involving an indispensable step to electrify the sample was inconvenient. Amiri et al. [27] proposed point probes composed of primary coil, needle core, and secondary coil. The special structure made the flux concentrated at the needle tip and the flux density of the inspected material reached the saturation state. The samples with different hardness could be measured based on magnetometer mode. The sensor could detect mechanical properties in narrow space, but the whole structure is too bigger to be integrated into the detection system. Therefore, it is necessary to develop sensors with compact structures and high sensitivity to the magnetic signals, which reflected the mechanical properties induced by the objects to be detected.

In this paper, a novel point mode electromagnetic probe was presented. The point probes could excite localized and concentrated magnetic field and was characterized by compact configuration. It could be integrated into the online detection system to assess the mechanical properties. In order to explore the exciting magnetic field intensity, the geometric configurable parameters of the needle core were explored firstly. As a collection statistical and mathematical tool, the response surface methodology was used to establish the approximate function between magnetic field intensity and geometric configurable parameters based on numerical results. Afterwards, the point probe performances including the spatial distribution range and magnetic field intensity were experimentally characterized by the scanning testing system. Finally, mechanical properties of medium carbon steel were measured by using a novel sensor. A relationship between the sensor output signal and mechanical properties were established.

2. Design of point mode electromagnetic sensor

2.1. Numerical model of excitation magnetic circuit

The point mode electromagnetic probe with compact configuration and concentrated magnetic flux characteristics (Fig. 1) was more attractive. The exciting coil (84 turns of 0.3 mm insulated copper wire) was wound on the end of a permalloy core with the height of 15 mm and the inner and outer radii of 4 mm and 4.6 mm. The exciting coil was driven by a Virtual Oscilloscope (HS3) to generate the magnetic field and the permalloy core had the high magnetic permeability. It was found that the needle structure was of the minor importance to magnetic field intensity. The numerical model of the point mode electromagnetic probe was established and magnetic field intensity was analyzed by the response surface methodology based on the central composite design.

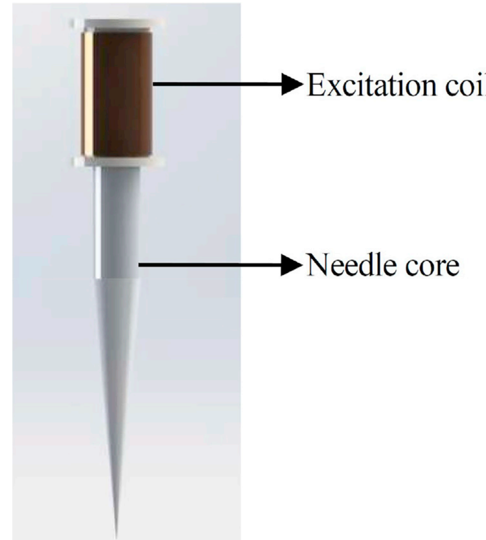

Fig. 1. Schematic diagram of excitation magnetic circuit of the point mode electromagnetic probe.

In order to obtain the magnetic field intensity of different probes, electromagnetic numerical simulation of localized concentrated and spatial point mode electromagnetic probe should be performed. The finite element method (FEM) has been widely used in electromagnetic simulation. The computational domain, boundary conditions, and mesh generation were discussed below.

As shown in Fig. 2a, the entire model includes the excitation coil, core of permalloy and the air domain. In order to improve the computation efficiency, the entire model of sensor is treated as 2D problem in the *r*-*z* plane. Axisymmertic boundary is assigned to the z-axis and magnetic insulation are applied for the rest three edges of the calculation area. The 3D configuration of the entire model is shown in Fig. 2b, the core has a needle-like shape.

The permalloy core and the exitation coil are key parts. In order to guarantee the precision of the model, the mesh setting should be reasonably realized by means of limiting the element size. The maximum and minimum values of the element were respectively selected as 0.02 mm and 0.001 mm. The air domain was meshed in predefined extremely fine model. The adaptive algorithm with free triangular mesh was adopted in the whole model. The mesh refinement of the top of the core is shown in Fig. 3(a) and the final grid number of each design is presented in Table 2.

Direct current fed into the exitation coil was about 1 A. The magnetic field intensity distribution was computed by the stationary solver. The typical analysis results (the contact radius is 0.07 mm and the height of the cone is 15.96 mm) are presented in Fig. 3(b). The magnetic flux density *B* is the highest in the position near the exitation coil and the lower at the tip of core.

2.2. Evaluation method of excitation magnetic circuit

In this paper, in order to explore magnetic field intensity of point mode electromagnetic probes, the model between the magnetic flux density and structure parameters of the core was established.

Various experimental designs such as Box-Behnken design (BBD), central composite design (CCD), and Doehlert designs are widely used. According to Eq. (1), the central composite design (CCD) is chosen to determine the number of numerical simulations and the design includes the following three parts:

a) A full factorial or factorial design;