Ultrasonic Nondestructive Testing Method for Mechanical Properties of Metallic Nanomaterials

Jiabing Li¹, Rui Zhong¹, Xingwang Shen², Ziyun Gao¹, Junwei Zhang¹, Hansen Miao¹ and Ziqian Zhang*¹

¹Xuhai College, China University of Mining and technology, Xuzhou, China.
²Nanjing Forestry University South College, Nanjing, China.

* Corresponding author e-mail: cumtmail@cumt.edu.cn

Abstract. For metallic nanomaterials, the small size scale of nanoparticles leads to a significant increase in their surface area, resulting in a series of new mechanical properties. In order to detect the mechanical properties of metal nanomaterials, a new ultrasonic nondestructive testing method is proposed. Using defocusing measurement and time discrimination method, the surface wave velocity of metal nanomaterials at different positions and angles was measured, and the mechanical properties at corresponding positions and angles were obtained. The experimental results show that the new ultrasonic nondestructive testing method can accurately characterize the mechanical properties of metal nanomaterials without causing damage to the tested objects.

Key words: Metal nanomaterials; mechanical property; ultrasound; undamage.

1. Introduction

With the global development of manufacturing industry and the fierce competition in the market, the level of manufacturing technology is also constantly improving. In this process, a new kind of metal nanomaterial is born. Because of its special preparation process, it has also been more widely concerned by people, and a series of related technologies have also been applied to the manufacturing of automobile parts and aviation Aerospace equipment, intelligent manufacturing equipment and other higher-end equipment manufacturing fields[1]. These fields all have the same characteristic, that is to say, the mechanical properties of metal nanomaterial parts, such as toughness, plasticity and rigidity, are extremely strict. How to explore and test the mechanical properties of the metal nanomaterials, especially for the non-destructive testing of the materials after the repair of the failed waste parts through the reconstruction technology is more important. The inspection and evaluation of materials play a key role in controlling and improving product quality, ensuring product reliability and improving production efficiency. With the development of modern industry, in order to meet the higher requirements of material and product inspection, the new achievements of modern physics, chemistry, electronics and computer technology are applied to the inspection of materials and products, forming a modern nondestructive testing and evaluation. Although the objects of nondestructive testing technology are mainly metal materials, there are certain commonalities, but according to the different sizes, shapes, manufacturing processes and so on, the methods of nondestructive testing are also different. At present,
ultrasonic testing (UT), radiographic testing (RT), magnetic particle testing (MT), penetrant testing (PT) and eddy current testing (ET) are widely used in nondestructive testing technology, which is called "five conventional testing technology". In addition, in the field of industrial production, there are injection acoustic emission testing (AE), neutron radiography testing (NRT), leakage testing (LT) and other non-destructive testing technologies. Nondestructive testing technology is to detect all kinds of defects inside and on the surface of the inspected object by using the principle that physical properties will change at the defects without damaging the materials or products. In recent years, nondestructive testing technology has been paid more attention by industry, especially in metallurgy, petroleum, chemical industry, aerospace and other fields. The elastic modulus is an important mechanical property to show the rigidity of metal nanomaterials. At present, traditional testing methods of mechanical properties, such as tensile test, often cause material deformation in the process of measuring materials [2]. In recent years, some new detection technologies, such as X-ray diffraction laser ultrasonic technology, are not suitable for the daily testing of the mechanical properties of materials due to the high price of this new detection technology equipment and the limitations of the size of the materials to be tested and the testing environment. Based on this, this paper proposes an ultrasonic nondestructive testing method. Through the research, it is found that this method has strong adaptability, simple and convenient operation, and can adapt to the daily testing of mechanical properties of metal nano materials [3]. The birth of ultrasonic nondestructive testing technology originated from the middle of the 20th century. Ultrasound technology has advanced technology features such as imaging, digitization and intelligence, which indicates that this technology is a quite cutting-edge development future and a progressive technological development process [4]. For the current situation of our country, various high-tech continue to develop and improve, with the continuous development of electronic technology, sensor technology, computer technology and other related fields, ultrasonic nondestructive testing technology has also entered people's attention, thus the computer artificial intelligence control era is born. With the gradual development of ultrasonic technology, the birth of ultrasonic non-destructive testing is a very high-tech development technology, it can effectively detect whether there are defects in the material, thus obtaining the quality evaluation of inspection. It can be seen that ultrasonic nondestructive testing technology can effectively test the quality and defects of metal materials, which greatly improves the accuracy of detection compared with manual detection.

2. Construction of ultrasonic nondestructive testing platform for mechanical properties of metal nanomaterials
The ultrasonic nondestructive testing platform for mechanical properties of metal nano materials is composed of surface wave velocity measurement module and defocusing measurement time discrimination module, which is used to transmit and receive detection ultrasound; defocusing measurement time discrimination module is used to process the received ultrasonic data and analyze the mechanical properties, and display the test results.

Surface wave velocity measurement module
Based on the unique elastic dynamics principle of metal nanomaterials, we can conclude that the propagation speed of ultrasonic wave in materials usually depends on the elastic constant and density of materials [5]. The relationship can be expressed by the following formula:

\[
C_r = \sqrt{\frac{W}{P}} \sqrt{\frac{1-r}{1-2r}}
\]

\[
C_s = \frac{0.87 + 1.12r}{1+r} \sqrt{\frac{W}{\rho}}
\]
In formula (1) and (2), \( W \) is the young's modulus of metal nanomaterials, \( R \) is the Poisson's ratio of metal nanomaterials, \( C_L \) is the longitudinal wave velocity of metal nanomaterials, \( C_S \) is the surface wave velocity of metal nanomaterials and \( \rho \) is the density of metal nanomaterials.

Formula (1) and (2) give:

\[
W = \frac{C_L C_S (1 + r) \rho}{(1 - r)}
\]

According to formula (3), when \( C_L \) and \( C_S \) are measured quantitatively, \( r \) value of metal nanomaterials can be obtained. When density \( \rho \) of metal nanomaterials is known, Young's modulus \( W \) of metal nanomaterials can be deduced.

Through the ultrasonic measurement of the acoustic microscope technology, the metal nano materials in the coupling medium are measured by the ultrasonic probe, and then through the defocusing measurement, the longitudinal wave velocity and the surface wave velocity of the measured materials are finally measured.

3. Defocus measurement and time discrimination module

The principle diagram of defocusing measurement is shown in Figure 1. The focal length of the ultrasonic probe is \( L \) and the defocusing distance is \( d \). According to the refraction law, to generate surface waves, the aperture angle \( \alpha \) of the ultrasonic probe should be greater than twice the angle \( \theta_L \).

When the ultrasonic probe is focused on the upper surface of the metal nano material, the ultrasonic probe can receive the reflection wave directly reflected from all the refraction angles transmitted by the ultrasonic along the path 1 on the upper surface of the material and then through the lower surface; when the ultrasonic probe continues to move downward, the defocus measurement is carried out, and the ultrasonic probe will receive the reflection wave propagated along the path 1 in addition to the above. The reflected wave propagating along the path 2 after the conversion of the wave form after the angle \( \theta_L \) incident is also received [6].

![Figure 1. Principle diagram of defocusing measurement of ultrasonic probe](image-url)
Suppose that the time from excitation to reception for the reflected wave propagating along path 1 is \(T_1\), and the time from excitation to reception for the reflected wave propagating along path 2 is \(T_2\), then the following expression can be listed:

\[
T_1 = \frac{2(L - d)}{C_w}
\]

(4)

\[
T_2 = \frac{2(L - d)}{C_w} + \frac{d}{C_R}
\]

(5)

In formulas (4) and (5), \(C_w\) is the longitudinal wave velocity in water; \(C_R\) is the surface wave velocity in water; \(d\) is the propagation distance of surface wave on the surface of metal nanomaterials.

According to the formula (4) and (5), the velocity of surface wave can be obtained by measuring the echo signal of ultrasonic probe at different positions with the method of time resolution. The specific operation flow is as follows: first, align the echo signal with the reflection wave propagating along path 1, obtain the time difference between the arrival time of the reflection wave propagating along path 2 and the reflection wave propagating along path 1 at each defocusing position, and then calculate the linear fitting through the least square method, finally obtain the longitudinal wave velocity and surface wave velocity of the ultrasonic wave in the metal nano materials.

In this paper, the defocusing measurement uses a line focused ultrasonic probe, which can be used for nondestructive testing of the mechanical properties of conventional materials, coating materials and nano materials. Its principle is to detect the different mechanical properties of materials in different directions by changing the propagation direction of the surface acoustic waves of the tested objects. In defocusing measurement, the linear focus probe is an important excitation and receiving component in ultrasonic detection. The piezoelectric material of the linear focus probe selected in this paper is a PVDF film. The electrical signal obtained from the probe is essentially the collection of echo signals received from the whole PVDF film [7]. The size and shape of PVDF film on the line focus probe determine the size and strength of the reflected echo of the received measured material. Therefore, it can be concluded that if the area of PVDF film is large, the wider the measurement range is, the stronger the signal can be received; if the area of PVDF film is narrow, the weaker the signal can be received. The measurement range of ultrasonic nondestructive testing probe determines its resolution to the nanomaterials being measured, and the strength of the signal received by the probe determines its resolution to the effective signal. Through the interaction of the two, it determines the accuracy of the evaluation of the distribution of the mechanical properties of the nano materials at different positions. Therefore, on the premise of reliable measurement, this paper reduces the width of PVDF film as much as possible, which can help to improve the measurement resolution of ultrasonic nondestructive testing probe.

4. Comparative experiment

In order to make the ultrasonic nondestructive testing method of the mechanical properties of metal nanomaterials more rigorous, the traditional method and the method designed in this paper are compared as follows:

Ten groups of metal nanomaterials are selected, each group contains two materials with the same mechanical properties. The mechanical properties of metal nanomaterials are tested by the traditional measurement method and the ultrasonic nondestructive measurement method proposed in this paper. The ultrasonic nondestructive testing method first prepares a wide probe for measurement. During the measurement, the probe should be placed in the positive center of the metal nano material to be measured. The change of the surface wave velocity of the metal nano material from 0 ° to 180 ° is measured by
rotating the turntable along the central axis, and the mechanical properties of the material in different directions are detected.

Ten groups of metal nano materials were tested by traditional mechanical property testing method and ultrasonic nondestructive testing method designed in this paper. Then, the accuracy data of the two methods were recorded by comparing with the actual mechanical properties of metal nano materials.

**Table 1. Detection accuracy of mechanical properties of metal nanomaterials by two methods**

| Group   | Traditional method detection accuracy | Method detection accuracy |
|---------|--------------------------------------|---------------------------|
| Group 1 | 75.56%                               | 87.35%                    |
| Group 2 | 71.57%                               | 89.54%                    |
| Group 3 | 75.35%                               | 87.38%                    |
| Group 4 | 74.24%                               | 90.57%                    |
| Group 5 | 75.64%                               | 89.76%                    |
| Group 6 | 76.52%                               | 88.57%                    |
| Group 7 | 74.52%                               | 92.45%                    |
| Group 8 | 84.53%                               | 95.44%                    |
| Group 9 | 84.28%                               | 97.63%                    |
| Group 10| 85.40%                               | 97.52%                    |

Table 1 is the comparison of the test precision data of the mechanical properties of metal nanomaterials by two methods. It can be seen from table 1 that the test precision of the method in this paper is higher for the mechanical properties of metal nanomaterials, and when the seventh group of metal nanomaterials is tested, the test precision of the non-destructive test method designed in this paper is 18% higher than that of the traditional test method, greatly improving the test precision of metal nanomaterials. It is of great significance to test the mechanical properties of rice materials. At the same time, in the process of detection, the detection method designed in this paper keeps the surface wave velocity of the tested nano materials in any direction basically unchanged, which shows that in the process of ultrasonic detection, the ultrasonic will not cause deformation and other effects on the tested nano materials, and retains the original properties of the metal nano materials, while the traditional method has been over tested. During the process, the measured nano materials have a slight deformation, which affects the original properties of metal nano materials.

5. **Conclusion**
The nondestructive testing method of mechanical properties of metal nanomaterials by ultrasonic can realize the inverse characterization of mechanical properties of metal nanomaterials, and detect the mechanical properties of metal nanomaterials. The obtained testing results are more accurate and effective than the traditional mechanical properties testing methods. Therefore, this method can be used to test the mechanical properties of metal nanomaterials. A nondestructive testing method is provided. At the same time, the method designed in this paper can reduce the area range of measurement properly. On the basis of ensuring the reliability of detection, it can improve the resolution of the tested material detection, so that the measured value can more sensitively reflect the change of wave speed of the tested material in different positions, and then increase the accuracy of expressing the mechanical properties of the tested material Accuracy.
References

[1] Song Guorong, Xu Yuyang, LV Yan, et al. Ultrasonic nondestructive testing and evaluation method for mechanical properties of special prepared materials [J]. Journal of Beijing University of technology, 2017, 43 (10): 1449-1456.

[2] Jiang Yun, Li Yan, Qian Ying. Nondestructive testing of mechanical properties of metal components of wind turbine by indentation method [J]. Shanghai energy conservation, 2017,24 (01): 028-032.

[3] Su Yulu. Research on the application of ultrasonic nondestructive testing technology in the welding of metal materials [J]. Architecture and budget, 2018,42 (02): 033-035.

[4] Xiong Si, Tang Xin, Wang Chunxia, Hu Qinghua. The effect of post weld heat treatment on the microstructure and properties of 7075 aluminum alloy welding joint welded with Al mg Zn (-SC Zr) alloy wire [J]. Material guide, 2019,33 (16): 20-2724.

[5] Li Kunpeng. Application of ultrasonic nondestructive testing technology in welding of metal materials [J]. Building materials and decoration, 2018, 532 (23): 211-212.

[6] Fu Mingsheng. Main application of ultrasonic nondestructive testing technology in the welding process of metal materials [J]. China new technology and new products, 2017,24 (11): 022-023.

[7] Xia Jiabin, sun Guangkai, Song Chao, et al., "steel lead" adhesive structure non-contact laser ultrasonic testing method [J]. Infrared and laser engineering, 2018, 006 (01): 226-23.