

Research Article

The Elastic Constants Measurement of Metal Alloy by Using Ultrasonic Nondestructive Method at Different Temperature

Eryi Hu and Wenjin Wang

School of Mechatronic Engineering, China University of Mining & Technology, 1 Daxue Road, Xuzhou, Jiangsu 221116, China

Correspondence should be addressed to Wenjin Wang; 12551835@qq.com

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The ultrasonic nondestructive method is introduced into the elastic constants measurement of metal material. The extraction principle of Poisson's ratio, elastic modulus, and shear modulus is deduced from the ultrasonic propagating equations with two kinds of vibration model of the elastic medium named ultrasonic longitudinal wave and transverse wave, respectively. The ultrasonic propagating velocity is measured by using the digital correlation technique between the ultrasonic original signal and the echo signal from the bottom surface, and then the elastic constants of the metal material are calculated. The feasibility of the correlation algorithm is verified by a simulation procedure. Finally, in order to obtain the stability of the elastic properties of different metal materials in a variable engineering application environment, the elastic constants of two kinds of metal materials in different temperature environment are measured by the proposed ultrasonic method.

1. Introduction

The elastic constants are significant properties of some new metal alloy materials. Furthermore, the stability of the elastic properties at different temperature will affect the engineering application of the material in a terrible environment condition, such as the aerospace spacecraft design and deep ocean resources development. For instance, the basic vibration frequency of some special construction will change corresponding with the environment temperature. Thus, the metal material with a much more steady elastic characteristic is more popular in the engineering design. On the other hand, sometimes the engineers are interested in the elastic constants of a new metal alloy. Particularly in the reverse engineering area, the material property coefficients must be measured without the destruction of the rare sample components. Thus, the nondestructive evaluation approach is very useful in these material characteristic researches.

The ultrasonic wave method can be introduced into the elastic constants measurement of the metal material. Nowadays, many researchers are using ultrasonic nondestructive testing to evaluate the mechanical characteristics on metallic materials, mainly, due to its accuracy, besides being fast and

very reliable. As we know, the ultrasonic detection methods are very popular in the medical inspection of the human body for a long time. Several researchers have focused on Young's modulus of the bone material or carotid artery measurement by using the ultrasonic technique [1–3]. And then this method is also used in the elastic modulus and other geometrical coefficients detection of other materials, such as alumina ceramics [4]. The ultrasonic method is also introduced into the civil engineering area to obtain the rock's material properties [5–8]. Tavares et al. [9–12] proposed a nondestructive determination method of the elastic properties in shape memory alloy, stainless steel, and plain carbon steel by using ultrasonic measurements. From the previous useful research works, it is found that the detection of the propagating velocity of the ultrasonic wave is the key point in the elastic constants measurement of these different materials [13]. The digital correlation and Fourier transform methods can both be used in the ultrasonic wave flight time extraction; however the precision should be increased by some novel algorithms [14–17].

In this paper, we focus on the elastic constant measurement of metal alloy materials especially in a temperature changing environment. Poisson's ratio, elastic modulus, and

shear modulus will be measured by the ultrasonic wave propagating velocity detection. And then temperature stability of the elastic properties can be provided for the further engineering design application.

2. Principle of the Ultrasonic Measurement Method

As we know, the ultrasonic wave is a kind of elastic waves propagating in the medium with higher frequency. Thus, when the elastic wave is propagating in the isotropic medium without the influence of the volume stress, the wave propagating equation can be expressed as follows:

$$(\lambda + G) \nabla \theta + G \nabla^2 U = \rho \frac{\partial^2 U}{\partial t^2}, \quad (1)$$

where θ is the volume strain and $U = (u, v, w)$ denotes the deformation of one point in the elastic medium. When the propagating elastic wave is an ultrasonic longitudinal wave, the deformation in the elastic medium can be defined as $u = (x, t)$, $v = 0$, and $w = 0$. It is meant that the wave propagating equation can be simplified as follows:

$$\frac{\partial^2 u}{\partial t^2} = V_L^2 \frac{\partial^2 u}{\partial x^2}. \quad (2)$$

Thus, the propagating velocity of the ultrasonic longitudinal wave denoted as V_L is expressed as

$$V_L^2 = \frac{\lambda + 2G}{\rho} = \frac{E(1 - \mu)}{(1 + \mu)(1 - 2\mu)\rho}. \quad (3)$$

On the other hand, when the propagating elastic wave is an ultrasonic transverse wave, the deformation in the elastic medium can be defined as $u = 0$, $v = v(x, t)$, and $w = 0$. The wave propagating equation can be simplified similarly:

$$\frac{\partial^2 v}{\partial t^2} = V_T^2 \frac{\partial^2 v}{\partial x^2}. \quad (4)$$

Following the same process, the propagating velocity of the ultrasonic transverse wave denoted as V_T is expressed as

$$V_T^2 = \frac{G}{\rho} = \frac{E}{2(1 + \mu)\rho}. \quad (5)$$

Combining (3) and (5), the elastic constants of the detected material can be deduced:

$$\mu = \frac{1 - 2(V_T/V_L)^2}{2 - 2(V_T/V_L)^2}, \quad (6)$$

$$E = \frac{V_L^2 \rho (1 + \mu)(1 - 2\mu)}{1 - \mu},$$

$$G = V_T^2 \rho,$$

where ρ is the density of the material, V_L is the ultrasonic longitudinal wave propagating velocity, V_T is the ultrasonic transverse wave propagating velocity, μ is Poisson's ratio, E is the elastic modulus, and G is the shear modulus. From (6), it is found that the elastic constants can be calculated after getting the elastic wave propagating velocities and the material density in a certain experimental environment temperature.

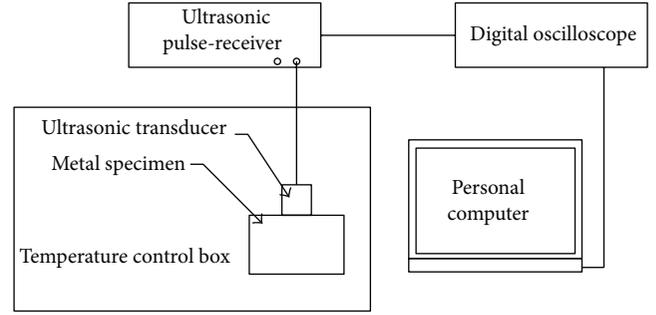


FIGURE 1: Sketch map of the experimental system.

3. Ultrasonic Experimental Measurement System

The schematic diagram of the ultrasonic measurement experimental system is illustrated in Figure 1. The experimental system is constructed by the ultrasonic pulse-receiver, ultrasonic wave transducer, digital oscilloscope, personal computer, detected specimen, and temperature control box. The ultrasonic pulse-receiver is used to excite the ultrasonic transducer and receives the signals reflected from the bottom surface of the detected metal specimen. The type of the ultrasonic pulse-receiver manufactured by Panametrics-NDT is Model 5072PR, and the bandwidth is 35 MHz which is sufficient for this experimental research project. And then, the digital oscilloscope is used for sampling ultrasonic waveform, and the digitized waveforms are stored in the memory of the personal computer. In this experiment, the InfiniiVision 4000X digital oscilloscope is manufactured by Agilent Technologies with 5 GHz maximum sample frequency, so that the single point sampling time period is 0.2 ns. The temperature control box called ZTH100UK(S) is manufactured by Shanghai Zundar. The experimental temperature is controlled by a computer automatically in the range of $-70 \sim 150^\circ\text{C}$, and the temperature controlling precision is about $\pm 0.5^\circ\text{C}$.

The single ultrasonic wave transducer reflect model is used to transmit and receive the ultrasonic waves. In this experiment, two kinds of ultrasonic transducers which can transmit ultrasonic longitudinal wave and transverse wave are fixed on the detected metal specimen, respectively. The main frequencies of the ultrasonic transducers are both 5 MHz. Particularly, the ultrasonic transverse wave transducer is one kind of normal incidence transverse wave transducer, and this single element contact transducer introduces transverse waves directly into the test piece. The special transducer incorporates a transverse wave crystal in a contact transducer case. Rather than using the principles of refraction by the longitudinal wave, as with the angle beam transducers, to produce transverse waves in a material, the crystal itself produces the transverse wave. However, because the transverse waves do not propagate in liquids, it is necessary to use a very viscous couplant when making measurements with the normal incidence transverse wave transducer.

4. Digital Correlation Method for Measuring the Ultrasonic Flight Time

4.1. Basic Principle of the Algorithm. As we know, the ultrasonic transducer is excited by the high frequency electrical pulse, and then the ultrasonic wave propagates in the detected medium. The ultrasonic echo is reflected back by the bottom surface of the medium, and it can be detected by the transducer at the same time. It is known that there is an obvious correlation between the ultrasonic original signal and the echo signal. By using the digital signal analysis method, the similarity of the two signal waveforms can be expressed as the correlation coefficient. Thus, the ultrasonic wave flight time along the propagating direction in the medium can be extracted by this correlation method. In detail, the ultrasonic wave signal sampled and stored in the computer is denoted as $s(t)$. The sections of the original signal and the echo signal are separated and denoted as $s_1(t)$ and $s_2(t)$, respectively, and then the correlation coefficient R_{12} can be expressed as follows:

$$R_{12} = \frac{\int_{-\infty}^{+\infty} s_1(t) s_2(t) dt}{\left[\int_{-\infty}^{+\infty} s_1^2(t) dt \int_{-\infty}^{+\infty} s_2^2(t) dt \right]^{1/2}}. \quad (7)$$

However, the ultrasonic signals recorded by the digital oscilloscope and computer are two series of discrete signals arrays. Thus, the normalized correlation coefficient with the discrete signals is written as

$$R_{12} = \frac{\sum s_1(i) s_2(i) - \sum s_1(i) \sum s_2(i) / n}{\left\{ \left[\sum s_1^2(i) - (\sum s_1(i))^2 / n \right] \left[\sum s_2^2(i) - (\sum s_2(i))^2 / n \right] \right\}^{1/2}}, \quad (8)$$

$(i = 1, \dots, n),$

where n is the calculation length of the signal array and i is the location in the signal array.

In the time domain of signal $s(t)$, there is time delay between the ultrasonic original signal $s_1(t)$ and the echo signal $s_2(t)$. Actually, the time delay is just the flight time of the ultrasonic propagating in the thickness direction for a round trip. In order to obtain the flight time, a circle calculation is applied to get the array of the correlations. In the circle calculation, the maximum correlation coefficient between the discrete data array $s_1(1) \sim s_1(n)$ of $s_1(t)$ and $s_2(1+m) \sim s_2(n+m)$ of $s_2(t)$ should be found to track the time position denoted as m in the signal array. And then if the time sampling frequency is denoted as f , the corresponding flight time T is equal to m/f . Finally, the ultrasonic velocity can be obtained by the following formula:

$$V = \frac{2hf}{m}, \quad (9)$$

where h is the thickness of the detected specimen.

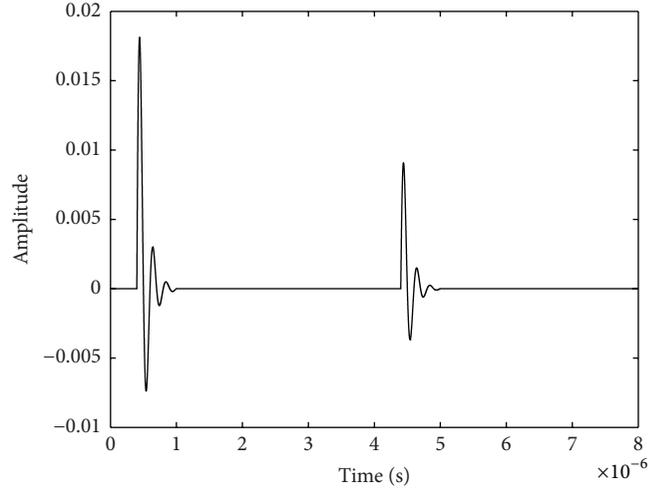


FIGURE 2: The waveform of the simulated signal.

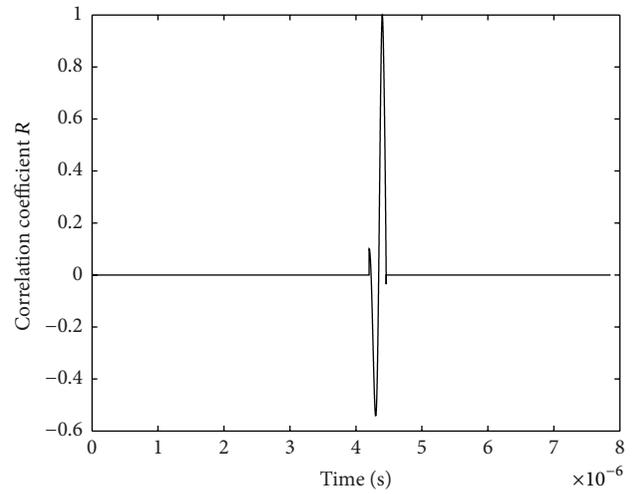


FIGURE 3: The result of the correlation calculation.

4.2. Calculation Example by the Simulation Signal. Firstly, the reliability of the proposed algorithm should be proved by simulation, and the simulated ultrasonic signal is a declined Sinusoidal function

$$S(t) = e^{-kt} \sin(2\pi f_0 t), \quad (10)$$

where k is the declining coefficient of the Sinusoidal function set as 9×10^{-6} and f_0 is the prime frequency of the ultrasonic transducer set as 5×10^6 Hz. The signal sample frequency f is set as 5×10^9 Hz, and the flight time T between the original and the echo signals is set as 4.0×10^{-6} s. The waveform of the simulated signal is shown in Figure 2, and the calculation result of the correlation distribution is shown in Figure 3.

In Figure 3, a significant peak of the correlation coefficients obtained in the circle calculation is found in the time axis, and the flight time corresponding to the correlation peak point is 4.0×10^{-6} s. The calculated result fits well with the theoretical setting value; thus the proposed algorithm is suitable for the ultrasonic signal process in the elastic constants experimental measurement.

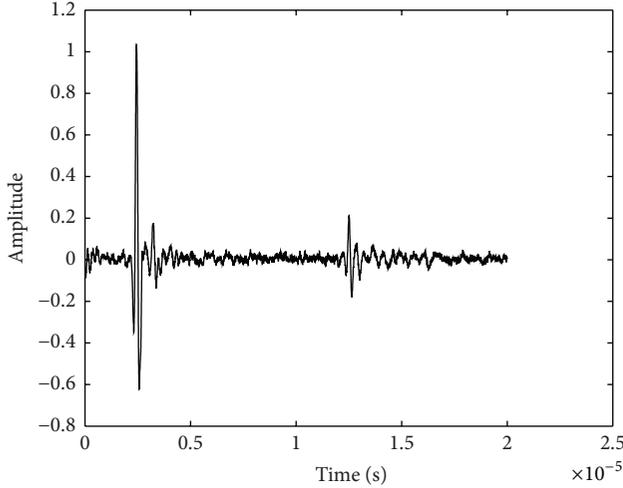


FIGURE 4: The ultrasonic echo signal.

4.3. Calculation Example with the Ultrasonic Signal. Following the previous simulation, now the flight time calculation of the practical ultrasonic signal can be achieved. For instance, the signal shown in Figure 4 is a series of ultrasonic transverse waves with the sampling frequency 5 GHz. It is found that there are high frequency noises in the practical ultrasonic signal. But because the correlation of the noise signal is so small, the effect of this type of noise can be removed in the correlation calculation procedure. By using the proposed method the flight time calculation result is shown in Figure 5. Similarly, there is also a peak value in the correlation coefficient distribution map. Furthermore, the flight time corresponding to this peak is $T = 1.0061 \times 10^{-5}$ s.

5. Experimental Results and Analysis

The experimental specimen is manufactured as a circular column shape, and the cross-sectional area is bigger enough than that of the ultrasonic transducers. In the beginning of the experiment, the couplant is smeared uniformly onto the interface between the specimen and the transducer. The couplant corresponding to the ultrasonic longitudinal wave is one kind of normal lubricating oil, but the couplant corresponding to the transverse wave must be the special viscous media because of the normal incidence transverse transducer's characteristic. The ultrasonic transducers fixed on the experimental specimen are put into the temperature control box, and the experimental environment temperature is increased smoothly in the range of $-20 \sim 70^\circ\text{C}$. The ultrasonic echo signals, which are displayed on the screen of the digital oscilloscope, are manually sampled and stored by the computer with a temperature interval of 10°C . In order to decrease the detection errors, the echo signals are sampled three times in each temperature point. By using the proposed correlation algorithm method, the ultrasonic echo flight time can be extracted, and the average values are used for the elastic constants calculation of the detected metal materials. However, the changing of the volume and density of the experimental specimen is not considered in the experiment.

TABLE 1: The parameters of the experimental specimen.

Specimen material	Diameter (mm)	Thickness (mm)	Density (kg/m^3)
3J53 metal alloy	24.02	19.35	8000.0
New metal alloy	24.04	20.28	8166.1

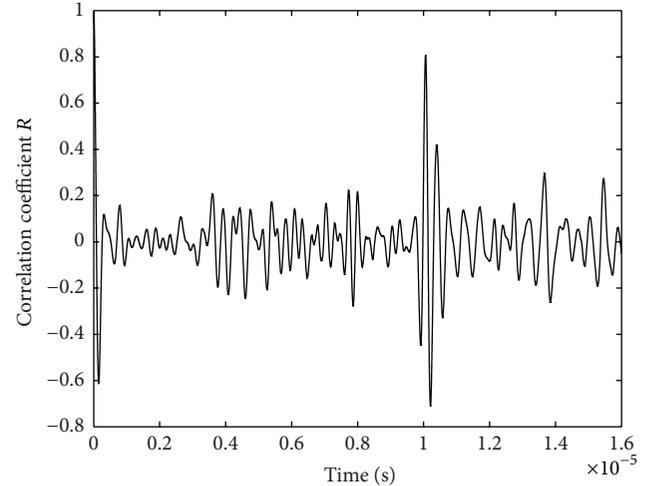


FIGURE 5: The correlation coefficient distribution.

In this study, the ultrasonic nondestructive method is used to measure two kinds of different material specimens' elastic constants. One is named 3J53 in Chinese standard of metal materials, and the other is a new kind of metal alloy which is manufactured by ourselves. And the elastic constants stability of the metal alloys will be researched in different environmental temperature. The parameters of the experimental specimen, such as diameter, thickness, and the density, are shown in Table 1.

After the proposed experimental measurement and data analysis, the calculated Poisson ratio, elastic modulus, and shear modulus of the 3J53 metal alloy material are shown in Figures 6, 7, and 8, respectively. And the calculated results of the new metal alloy material are shown in Figures 9, 10, and 11, respectively.

When the metal materials are used in the variable temperature environment, the presence of metal inside the thermal activation leads to dislocation movement and would inevitably lead to dislocation motion and local small plastic deformation. Thus the metal material intensity and elastic parameters will be variable. Furthermore, the heat-activated fan-shaped deformation rate caused by the temperature can affect the propagation speed of the ultrasound in the metal materials. However, because it is different to describe the behavior of this kind of temperature influence with a simple formula, the complex environmental temperature effect can be studied by this special ultrasonic nondestructive method. For different metal materials, the changing of the elastic parameters is different because of the material internal crystal structure characteristics and the manufacturing procedure. From the calculation results, it is found that Poisson's ratio of the new metal is bigger than that of the 3J53 alloy,

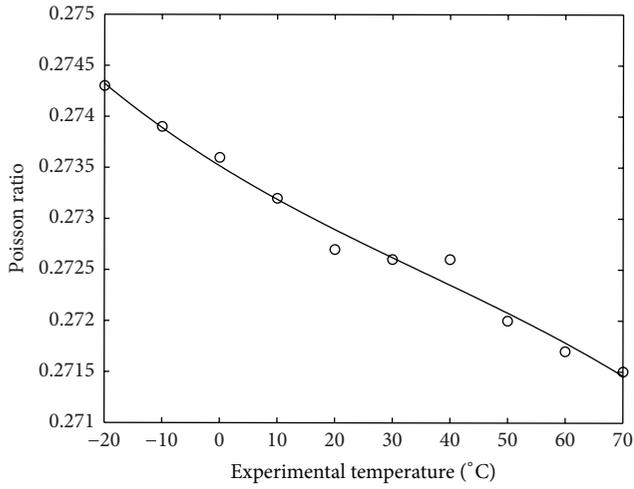


FIGURE 6: Poisson's ratio of 3J53 alloy corresponding to different temperature.

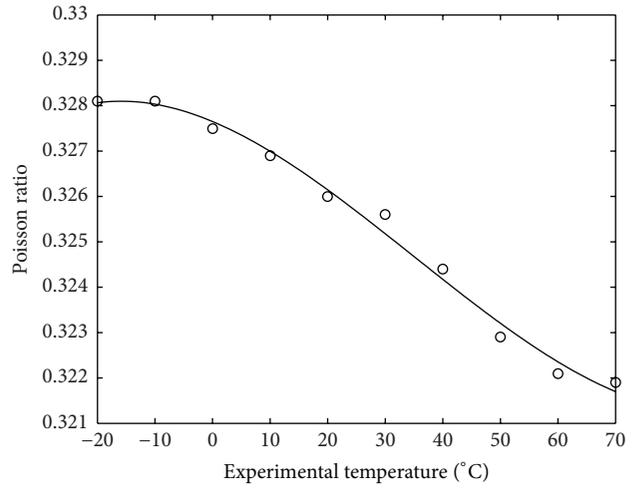


FIGURE 9: Poisson's ratio of the new metal alloy corresponding to different temperature.

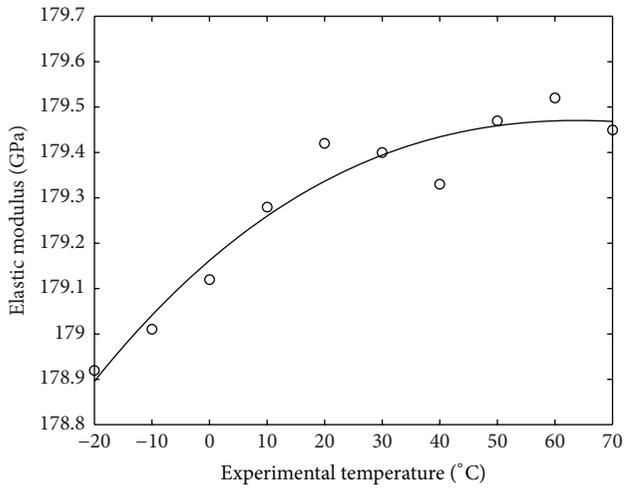


FIGURE 7: The elastic modulus of 3J53 alloy corresponding to different temperature.

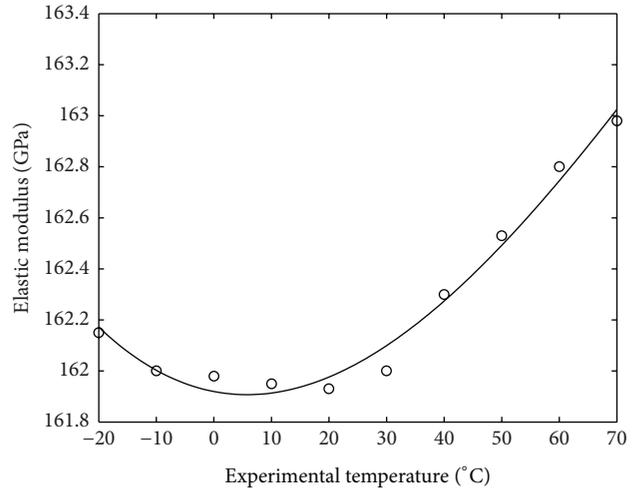


FIGURE 10: The elastic modulus of the new metal alloy corresponding to different temperature.

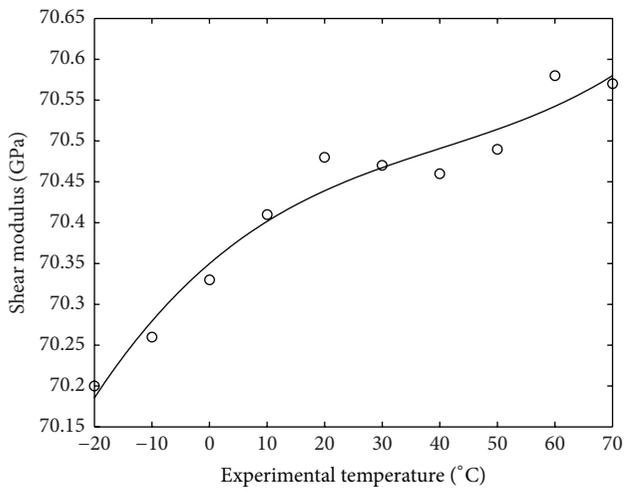


FIGURE 8: The shear modulus of 3J53 alloy corresponding to different temperature.

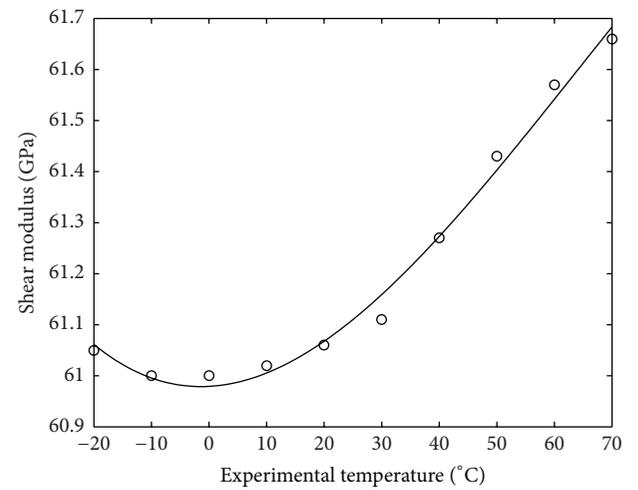


FIGURE 11: The shear modulus of the new metal alloy corresponding to different temperature.

TABLE 2: The maximum changing range of the elastic parameters.

Specimen material	β_μ	β_E	β_G
3J53 metal alloy	2.206×10^{-4}	1.283×10^{-4}	1.417×10^{-4}
New metal alloy	4.645×10^{-4}	2.774×10^{-4}	3.431×10^{-4}

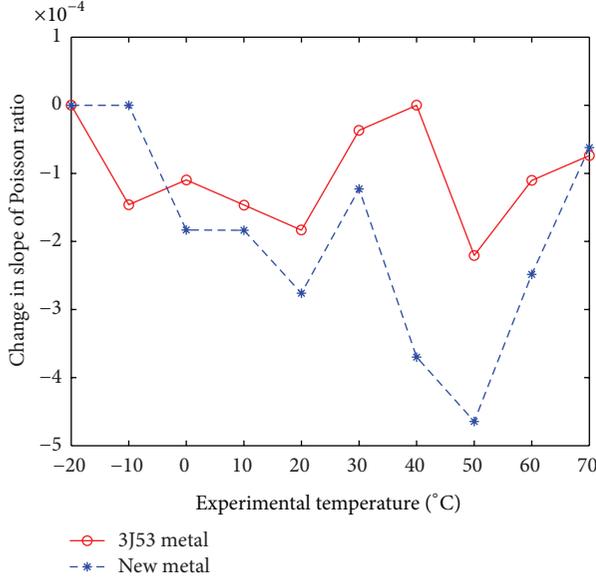


FIGURE 12: The change in slope of Poisson's ratio.

and Poisson's ratios of the two different materials are both decreasing with the increase of the experimental temperature. In the opposite side, the elastic modulus and the shear modulus are increasing with the increase of the experimental temperature. But in the new metal, the elastic modulus and the shear modulus first decrease and then start increasing from 5 to 10 degrees.

The two different materials tested in this study will be used to manufacture primary components in a special frequency detection sensor, so the stability of the elastic parameters plays an important role in the sensor design. In order to give a much more clear difference between the elastic constants of the two kinds of materials with the increase of temperature, a series of new coefficients are defined as follows:

$$\begin{aligned}\beta_\mu &= \frac{\Delta\mu}{\mu \cdot \Delta T}, \\ \beta_E &= \frac{\Delta E}{E \cdot \Delta T}, \\ \beta_G &= \frac{\Delta G}{G \cdot \Delta T}.\end{aligned}\quad (11)$$

The change in slope of Poisson's ratio, elastic modulus, and shear modulus is shown in Figures 12, 13, and 14. The maximum changing range of the measured elastic parameters of the β_μ , β_E , and β_G is shown in Table 2.

It indicates that the change of the elastic constants of the 3J53 metal material is smaller than that of the new metal material. In other words, the elastic property of the 3J53

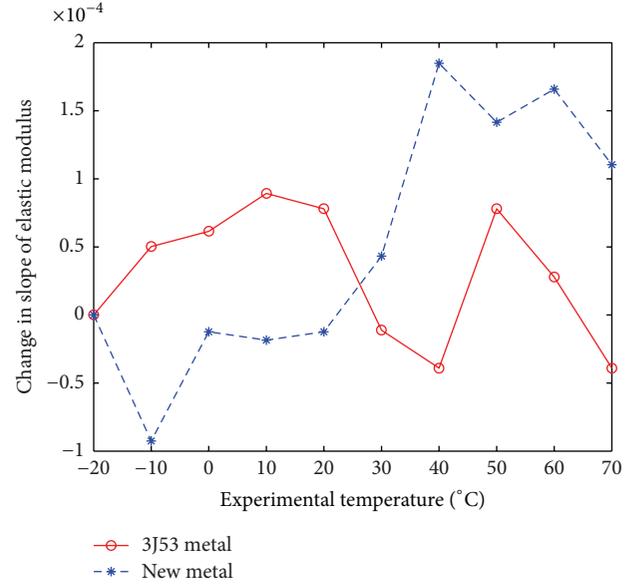


FIGURE 13: The change in slope of elastic modulus.

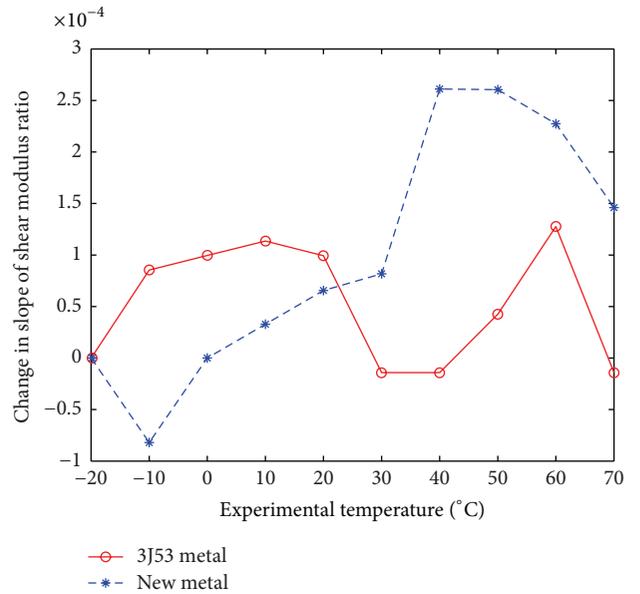


FIGURE 14: The change in slope of shear modulus.

metal material in different environmental temperature is much more steady than that of the new metal material. Thus, the 3J53 metal material is much more appropriate for the engineering application in the temperature changing environment.

6. Conclusion

Through the simulation and experimental analysis, the following conclusions can be drawn. The proposed ultrasonic nondestructive method can be used for the metal material's elastic constants measurement. Based on the velocity extraction of the ultrasonic longitudinal wave and transverse wave by the digital correlation method, the elastic

constants can be calculated conveniently. The feasibility of the correlation algorithm is verified well by the simulation and experimental approach. The application of the ultrasonic nondestructive method for two kinds of metal materials indicates that Poisson's ratio is decreasing with the increase of the experimental temperature, and the elastic modulus and the shear modulus are increasing with the increase of the experimental temperature. Furthermore, the elastic modulus and the shear modulus of the new metal first decrease and then start increasing from 5 to 10 degrees. However, the change of the elastic constants of the 3J53 metal material is smaller than that of the new metal material. Thus, it is much more appropriate for the temperature changing environment.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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