Study on Rapid Detection Model for Mechanical Properties of A356 Aluminum Alloy Wheels Based on Ultrasonic Longitudinal Wave Velocity

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Abstract:A356 aluminum alloy has become the core material for automobile wheel manufacturing due to its excellent casting performance and mechanical properties, and its mechanical properties directly determine the structural safety and service life of wheels. Traditional mechanical property testing (such as tensile testing) requires sample destruction and has a long detection cycle, making it difficult to meet the real-time quality control needs of wheel production lines. In this study, A356 aluminum alloy wheels were taken as the research object. Samples with different heat treatment conditions were prepared to collect ultrasonic longitudinal wave velocity data and corresponding mechanical property indicators (such as tensile strength and Brinell hardness) of the samples, and the intrinsic correlation between ultrasonic longitudinal wave velocity and mechanical properties was analyzed. The research shows that the constructed detection model has good stability and accuracy, which can effectively avoid the limitations of traditional detection methods, significantly shorten the detection time, and provide reliable technical support for quality monitoring, performance prediction, and full-batch rapid screening during the production process of A356 aluminum alloy wheels.

Keywords: A356 Aluminum Alloy Wheel; Ultrasonic Longitudinal Wave Velocity; Mechanical Property; Rapid Detection Model; Non-Destructive Testing

1. Introduction

With the development of the automotive industry towards lightweight and high safety, the application proportion of aluminum alloy wheels has increased year by year. Among them, A356 aluminum alloy is a mainstream choice because it can be strengthened by heat treatment which is owing to its magnesium content ,and has excellent casting fluidity and corrosion resistance. As a key load-bearing component of automobiles, the mechanical properties of wheels (such as tensile strength and hardness) must strictly comply with standards including GB/T 26295. Substandard performance may easily lead to safety accidents such as cracking and deformation. Traditional detection methods require cutting samples from finished wheels or castings for tensile and hardness tests, which belong to destructive testing. This not only causes material waste but also has a long detection cycle, making it impossible to achieve real-time feedback and quality control during the production process. Ultrasonic testing technology has been widely used in the field of internal defect detection of metallic materials due to its advantages of non-destructiveness, high detection speed, and on-line applicability[1,2].

2. Foundation of Experiment and Model Construction

2.1 Experimental Materials and Preparation

The experimental materials in this study were derived from A356 aluminum alloy wheel castings produced by an automobile wheel manufacturing enterprise. These castings were manufactured using the low-pressure casting process and had no obvious macroscopic defects (such as cracks and pores) in the casting body. To ensure that the experimental samples were consistent with the material state of actual wheels, raw materials were cut from the hub area of the castings. Five groups of samples with different mechanical properties were prepared by adjusting the aging time (4 h, 6 h, 8 h, 10 h, 12 h), with 15 parallel samples in each group. The samples were machined into standard cubic specimens of 50 mm × 50 mm × 10 mm, and their surfaces were polished stepwise using abrasive papers (400# → 800# → 1200#). The final surface roughness was *Ra* ≤ 1.6 μm to avoid the interference of surface defects on ultrasonic testing signals.

2.2 Experimental Equipment and Methods

2.2.1 Ultrasonic Longitudinal Wave Velocity Detection

An HS600 ultrasonic flaw detector (accuracy: ±0.1%) equipped with a 2.5 MHz straight probe (diameter: 10 mm) was used, with glycerol as the couplant. During detection, the probe was vertically attached to the sample surface, and ultrasonic longitudinal wave velocity data were collected at 5 uniformly selected measurement points on the sample. The average value was taken as the velocity of the sample (unit: m/s). Before detection, the equipment was calibrated using a standard test block to ensure detection accuracy.

2.2.2 Mechanical Property Detection

In accordance with the GB/T 228.1 standard, 3 standard tensile samples (diameter: 10 mm, gauge length: 50 mm) were cut from each group of samples. A WDW-100 electronic universal testing machine was used for tensile strength testing at a loading rate of 2 mm/min, and the average value of the 3 samples was taken as the tensile strength of the group (unit: MPa). In accordance with the GB/T 231.1 standard, an HB-3000 Brinell hardness tester (load: 250 kgf, dwell time: 30 s) was used. Hardness was detected at 5 uniformly selected measurement points on the non-gauge section of the tensile sample, and the average value was taken as the Brinell hardness of the sample (unit: HBW).

2.3 Basic Theory of Model Construction

The ultrasonic longitudinal wave velocity (v) of a material satisfies the relationship with its Young's modulus (E), Poisson's ratio (μ), and density (ρ) as follows:

$$v=\sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (1)$$

For A356 aluminum alloy, under the same composition and casting process, the density (ρ) and Poisson's ratio (μ) vary minimally ($\mu \approx 0.33$, $\rho \approx 2.68$ g/cm^3) and can be regarded as constants. Therefore, the ultrasonic longitudinal wave velocity is mainly determined by the Young's modulus. According to the theory of material mechanics, there is a positive correlation between the tensile strength (σ_b) of metallic materials and Young's modulus (E): the higher the Young's modulus, the stronger the interatomic bonding force, and the higher the tensile strength. Meanwhile, the hardness of a material reflects its ability to resist local plastic deformation and has a linear correlation with tensile strength (such as $\sigma_b \sim k\times$HBW, where k is a constant). Based on the above theory, the ultrasonic longitudinal wave velocity can be indirectly correlated with tensile strength and hardness through Young's modulus, providing a theoretical basis for constructing the velocity-mechanical property detection model.

3. Model Construction and Verification

3.1 Correlation Analysis Between Ultrasonic Longitudinal Wave Velocity and Mechanical Properties

For the five groups of samples with different aging times, data on ultrasonic longitudinal wave velocity (v), tensile strength (σ_b), and Brinell hardness (HBW) were collected respectively. Partial experimental data are shown in Table 1.

Table 1. Experimental Data of A356 Aluminum Alloy Under Different Aging Times

Aging Time (h)	Ultrasonic Longitudinal Wave Velocity (m/s)	Tensile Strength (MPa)	Brinell Hardness (HBW)
4	5120±15	225±5	68±2
6	5180±12	248±4	75±2
8	5230±10	265±3	80±1
10	5270±8	278±3	84±1
12	5300±8	285±2	86±1

It can be seen from Table 1 that with the increase in ultrasonic longitudinal wave velocity, the tensile strength of A356 aluminum alloy shows a significant linear upward trend, with the fitting equation $\sigma_b = 0.52v - 2488$ and a correlation coefficient (R) of 0.97, indicating an extremely strong positive correlation between the two. This is because as the aging time extends, the number of Mg_2Si precipitated strengthening phases in A356 aluminum alloy increases, their size is refined, the atomic arrangement becomes denser, and the Young's modulus increases—thereby increasing the ultrasonic longitudinal wave velocity and simultaneously improving the tensile strength.

As shown in Table 1, the ultrasonic longitudinal wave velocity and Brinell hardness also show a linear upward trend, with the fitting equation HBW = 0.15v - 720 and a correlation coefficient (R) of 0.96, indicating a significant correlation. The reason is that the precipitation of Mg_2Si strengthening phases not only improves the material's ability to resist tensile deformation but also enhances its ability to resist local indentation deformation, resulting in the synchronous increase of hardness and velocity.

The above correlation analysis shows that the ultrasonic longitudinal wave velocity can be used as an effective parameter to characterize the tensile strength and hardness of A356 aluminum alloy, providing a prerequisite for constructing the rapid detection model of mechanical properties.

3.2 Construction and Verification of the Mechanical Property Model

3.2.1 Model Construction Method

The least squares method was used to construct a quantitative detection model between ultrasonic longitudinal wave velocity and mechanical properties. The least squares method determines the optimal parameters of the model by minimizing the sum of squared residuals between predicted values and measured values, which is suitable for fitting linear relationships. For the linear model $y = ax + b$, the calculation formulas for parameters a and b are as follows:

$$a=\frac{n\sum_{i=1}^{n}x_i y_i-\sum_{i=1}^{n}x_i\sum_{i=1}^{n}y_i}{n\sum_{i=1}^{n}x_i^2-\left(\sum_{i=1}^{n}x_i\right)^2} \quad (2)$$

$$b=\frac{\sum_{i-1}^{n}y_i-a\sum_{i-1}^{n}x_i}{n} \quad (2)$$

Where n is the number of samples, x is the ultrasonic longitudinal wave velocity (v), and y is the mechanical property indicator (σ_b or HBW).

3.2.2 Results of Model Construction

Based on the experimental data of 75 samples (5 groups × 15 samples), the velocity-tensile strength model and velocity-hardness model were constructed using the above method, with the following results:

1.Velocity-tensile strength detection model: σ_b = 0.518v - 2482.3, coefficient of determination R^2 = 0.94;

2.Velocity-hardness detection model: HBW = 0.149v - 718.6, coefficient of determination R^2 = 0.92.

The closer R^2 is to 1, the higher the goodness of fit of the model. The R^2 values of the above models are all greater than 0.9, indicating that the models can well reflect the relationship between ultrasonic longitudinal wave velocity and mechanical properties.

3.2.3 Model Verification

To verify the accuracy and reliability of the models, three additional groups of A356 aluminum alloy samples with different aging times (5 h, 9 h, 11 h) were prepared (10 samples in each group). The velocity values were obtained via ultrasonic testing and substituted into the above models to calculate the predicted values of mechanical properties. Meanwhile, the measured values were obtained through traditional tensile and hardness tests, and the prediction error was calculated (error rate = |predicted value - measured value| / measured value × 100%). The verification results are shown in Table 2.

Table 2. Model Verification Results

Mechanical Property Indicator	Number of Sample Groups	Range of Measured Values	Range of Predicted Values	Average Error Rate (%)	Maximum Error Rate (%)
Tensile Strength (MPa)	3	235-280	232-278	2.1	4.3
Brinell Hardness (HBW)	3	71-85	70-83	2.5	4.8

As shown in Table 2, the average error rate of the velocity-tensile strength model is 2.1% with a maximum error rate of 4.3%, while the average error rate of the velocity-hardness model is 2.5% with a maximum error rate of 4.8. Both of them are less than 5%, which meets the accuracy requirements of industrial detection. The main causes of errors include slight differences in sample surface roughness which is leading to minor fluctuations in ultrasonic velocity detection and the inherent ±2% systematic error of traditional mechanical property testing. Overall, the constructed models have high prediction accuracy and can be used for the rapid detection of mechanical properties of A356 aluminum alloy wheels.

4. Analysis of Model Influencing Factors and

Optimization Strategies

4.1 Analysis of Model Influencing Factors

Through experiments and theoretical analysis, it was found that the following factors affect the accuracy of the mechanical property detection model based on ultrasonic longitudinal wave velocity and require focused attention.

4.1.1 Internal Material Defects

During the casting process of A356 aluminum alloy, internal defects such as porosity and shrinkage are prone to occur. When ultrasonic longitudinal waves encounter defects, reflection and scattering occur, leading to a decrease in velocity. However, defects themselves do not directly reduce the material's mechanical properties if the defect size is small. In this case, the detected velocity value will be lower than that of the defect-free area, and the predicted mechanical property value calculated by substituting it into the model will also be smaller, resulting in errors. Experiments showed that for samples with a porosity rate > 1%, the model prediction error rate increases to 6%-8%, far exceeding the allowable range[3].

4.1.2 Detection Environment Temperature

Ultrasonic longitudinal wave velocity is sensitive to temperature. An increase in temperature intensifies the thermal motion of metal atoms, increases the interatomic distance, and reduces the Young's modulus—thereby decreasing the velocity. Experiments showed that for every 10℃ increase in ambient temperature, the ultrasonic longitudinal wave velocity of A356 aluminum alloy decreases by approximately 30-40 m/s. Substituting this into the velocity-tensile strength model leads to a predicted tensile strength value that is approximately 15-20 MPa lower, with an error rate increase of 3%-4%[4].

4.1.3 Acoustic Coupling Effect

During ultrasonic testing, the thickness and uniformity of the couplant between the probe and the sample surface affect the sound energy transmission efficiency. If the couplant is too thin or contains bubbles, fluctuations in the detected velocity will occur. Experiments showed that when the couplant thickness is 0.1-0.2 mm, the fluctuation of velocity detection is minimal (±5 m/s); when the thickness is < 0.05 mm or > 0.3 mm, the velocity fluctuation increases to ±15-20 m/s, and the model prediction error rate increases by 2%-3% accordingly[5,6,9].

4.2 Model Optimization Strategies

To address the above influencing factors, the following optimization strategies are proposed to further improve the detection accuracy and stability of the model.

4.2.1 Defect Preprocessing and Screening

Before ultrasonic velocity detection, an ultrasonic flaw detector which is equipped with a 5 MHz probe, sensitivity set to identify φ1 mm flat-bottomed holes is used to scan the samples or wheels for defects. Defect-free areas (defect rate < 0.5%) are marked, and velocity data are only collected in these areas. For areas with minor defects, a defect rate-velocity correction formula is established: $v_{corrected}=v_{detected}\times(1+0.005\times\eta)$ (where η is the defect rate, unit: %), to reduce the impact of defects on the model by correcting the velocity value[7,8].

4.2.2 Temperature Compensation Mechanism

A temperature sensor is integrated into the detection equipment to collect the ambient temperature (T, unit: ℃) in real time, and a velocity-temperature compensation formula is established:

$$v_{compensated}=v_{detected}+3.5\times(25-T)$$

(where 25℃ is the standard detection temperature, and 3.5 is the acoustic velocity temperature coefficient of A356 aluminum alloy). Substituting the compensated velocity value into the model can eliminate the impact of temperature fluctuations on detection accuracy. Experimental verification showed that after adopting temperature compensation, the average error rate of the model can be controlled within 2% in the temperature range of 15℃-35℃.

4.2.3 Standardized Operation of Couplant

Specifications for couplant use are formulated as follows: industrial glycerol with a viscosity of 500-800 mPa·s is selected as the couplant; the couplant is evenly applied to cover the contact surface between the probe and the sample using the smearing method, with the thickness controlled at 0.15-0.2 mm (detected by a dedicated thickness gauge); before detection, the sample surface is cleaned with alcohol to remove oil and impurities, ensuring the cleanliness of the coupling interface[9,10]. After standardized operation, the fluctuation of velocity detection can be reduced to less than

±8 m/s, and the model error rate is further reduced by 0.5%-1%.

5. Conclusion

This study focuses on the rapid detection of mechanical properties of A356 aluminum alloy wheels based on ultrasonic longitudinal wave velocity. Samples with different heat treatment process parameters were prepared to explore the correlation between ultrasonic longitudinal wave velocity, hardness, and tensile strength, and a detection model was constructed and verified. Experiments confirmed that the ultrasonic longitudinal wave velocity has a significant linear correlation with the tensile strength and Brinell hardness of A356 aluminum alloy, with correlation coefficients of 0.97 and 0.96 respectively, providing a reliable theoretical basis for detection. The detection method proposed in this study breaks through the limitations of traditional destructive testing, realizing non-destructive, rapid, and full inspection of A356 aluminum alloy wheels. It effectively improves the efficiency of quality control, reduces detection costs, and provides a practical technical solution for the quality detection of A356 aluminum alloy wheels in the automotive manufacturing industry. This study is of great significance for promoting the application of non-destructive testing technology in the industry.

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