Research on Laser Ultrasonic Testing of 316L Stainless Steel Mean Grain Size Based on Wavelet Threshold Denoising

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Abstract

This paper investigated a mean grain size characterization method based on laser ultrasonic. The 316L stainless steel samples with different mean grain size were conducted with different heat treatments and times, and each sample was observed by SEM and tested by laser ultrasonic. Due to the state of the sample surface, complexity of equipment and environment, the ultrasonic signal contains a lot of noise. Proposes a method to calculate the ultrasonic attenuation coefficient based on the signal after wavelet threshold denoising. Using db3 as the wavelet basis function, the signal is decomposed and denoised 5 times and then recombined. The attenuation coefficients of the amplitudes in the time domain and frequency domain of the original signal and the denoised signal are calculated. The results show that wavelet threshold denoising can improve the signal-to-noise ratio of the signal and the calculation accuracy of the average grain size.

1. Introduction

Austenitic stainless steel has been widely used in nuclear power, petroleum, natural gas, aerospace and other fields due to its excellent corrosion resistance, resistance to creep at high temperature and good weldability [1-3]. Grain size is one of the important structural parameters that affect the quality of alloy materials, and has great effect on mechanical and physical properties of metal materials. It is a **significant** parameter that needs to be controlled in practical production process [4-7].

Traditional grain size measurement methods use optical or electron microscope to obtain the grain size accurately, which are destructive and not all parts of sample can be observed. Laser ultrasonic technology is a non-contact and nondestructive testing technology. Based on the thermal bombing and ablation mechanism, the pulsed laser focuses on the surface of the sample to generate ultrasonic waves. When ultrasonic waves propagate in polycrystalline materials, the inhomogeneity of elasticity and density will lead to the change of propagation of velocity in each microcrystal, resulting in ultrasonic scattering [8], and then leads to the ultrasonic attenuation of velocity and energy. The velocity of ultrasonic wave depends on the characteristics of the material, such as the elastic coefficient of monocrystal and the anisotropy of polycrystal. Ultrasonic velocity is suitable to characterize the relative change of microstructure composition of materials. The difference of ultrasonic attenuation can be used to evaluate the size and configuration of microstructure.

Since White [9] first used laser to generate ultrasonic wave in elastomer, laser ultrasonic testing technology has been widely used to detect the microstructure of metal materials as a nondestructive testing method in recent years. S. SUNDIN [10] fitted the attenuation of ultrasonic longitudinal wave excited by laser with the mean grain size of low carbon steel, and discovered that the mean grain size of low carbon steel can be greatly characterized by the attenuation of ultrasonic longitudinal wave. Thomas Garcin [11] used ultrasonic attenuation to evaluate the grain size of Inconel 718 alloy which grew abnormally during the process of Solid solution. Yin AM, He Fei [12,13] and others calculation attenuation of ultrasonic energy to evaluate the grain size of low carbon steel. In order to improve the accuracy of

detection, Li Xiongbín [14] and others proposed to use multi-scale ultrasonic attenuation coefficient to evaluate the mean grain size of 304 stainless steel, and effectively improve the fitting accuracy. However, the establishment of the mean grain size evaluation model of large grain size span still needs to be studied and completed deeply.

In this paper, the ultrasonic attenuation calculation by laser ultrasonic was fitting with the mean grain size of the sample obtained by metallographic method. The mean grain size calculation model of 316L stainless steel was established, and then use wavelet threshold denoising to denoise the ultrasonic signal and optimize the fitting model.

2. Experimental Materials And Methods

2.1 Experimental materials

Rolling plate of 316L was selected to be the experimental material, and the thickness of plate is 2mm. The chemical composition is shown in Table 1. In order to eliminate the influence of chemical composition, hot rolling process and dislocation on the laser ultrasonic signal, the 316 plates of same batch were cut into 60 samples of size 100mm×200mm.

Table 1 Composition of 316L stainless steel

Composition	Cr	Ni	Mo	Mn	Si	O	Cu	N	S	C	Fe
Content(%)	16.97	12.28	2.39	1.24	0.46	0.05	0.01	0.01	0.006	0.003	Bal.

Grain size of the sample was controlled by heat treatment conditions of different temperature and time of solid solution. The temperature of solid solution was 900C ~ 1150 °C, the time of solid solution was 5 ~50min. Then air-cooled to room temperature. The heat treatment temperature of 316 plate is shown in Table 2, and the gradient of heat treatment time is same at each temperature as shown in Table 3.

Table 2 Heat treatment conditions

Sample	Solution temperature (°C)	Cooling method	Solution time (min)
316-1	900	AC	5/10/15/20/25/30/35/40/45/50
316-2	950		5/10/15/20/25/30/35/40/45/50
316-3	1000		5/10/15/20/25/30/35/40/45/50
316-4	1050		5/10/15/20/25/30/35/40/45/50
316-5	1100		5/10/15/20/25/30/35/40/45/50
316-6	1150		5/10/15/20/25/30/35/40/45/50

2.2 Laser ultrasonic testing system in laboratory

The laser ultrasonic testing system in laboratory as shown in Figure 1 was adopted in this research. The pulse laser is a Q-switched Nd: YAG laser. Pulse time width is 12ns, pulse energy is 200mJ, wavelength is 532nm, and energy of continuous laser is 100mW. Laser ultrasonic receiving system is an ultrasonic probe with the frequency of 10MHz.

Polish the surface of the sample, the pulse laser excited by laser hits on the surface of the sample, and receive the ultrasonic wave through interferometer which is placed on the other side of the sample. After interferometer received ultrasonic vibration, input to differential circuit, where the differential circuit is

equivalent to a high-pass filter. The low frequency noise such as vibration of sample table, sample vibration and ultrasonic in the air can be eliminated, and then the high frequency signal which has been processed was passed to oscilloscope and computer for data storage. Each sample was sampled for 3 times, and the average value of 128 times of ultrasonic waves excited by laser was selected for each sample to eliminate the error of ultrasonic signal acquisition.

2.3 Method of determination of mean grain size

After heat treatment, using optical microscope to determine mean grain size. Samples of size 8mm×7mm were obtained by wire cutting, and use the Metallographic inlay machine to mosaic the samples in a group of 5. The surface of the sample was burnished step by step with CW200-CW2000 water sandpaper, used polishing cloth and 1um polishing powder to polish samples, washed with anhydrous alcohol and blown dry. Then the corrosion was carried out in an aqueous solution of hydrochloric acid and nitric acid with a volume fraction of 1:1:1. After corrosion for 40 s, the sample was washed and dried with anhydrous ethanol, and the mean grain size of the sample was tested by scanning electron microscope. Then the corrosion was carried out in an aqueous solution of hydrochloric acid and nitric acid with a volume fraction of 1:1:1. After corrosion for 40 s, washed and dried the sample with anhydrous ethanol, and the mean grain size was determined by scanning electron microscope.

In this paper, the mean grain size is measured by Secant method. The transverse line of the microstructure diagram of the sample is crossed, the length of the horizontal line is measured by Image J software, the number of horizontal lines passing through the grain size is calculated, finally mean grain size is obtained. In order to avoid the randomness of a horizontal line and repeated measurement of the same grain by too many horizontal lines, five equal distance horizontal lines are drawn on the microstructure diagram, and the distance between the adjacent horizontal lines is more than twice mean grain size.

3 Experiment Results And Discussion

3.1 Grain size

The mean grain size measured by electron microscope is shown in figure 2. The grain size increases as the temperature and time of solid solution increase. There are a large number of twinning. The calculated results of mean grain size of the sample are shown in Table 4

Table 3 Mean grain size of sample

Sample number	Mean grain size/ μm	sample	Mean grain size/ μm	sample	Mean grain size/ μm
1-1	13.77	3-1	17.76	5-1	35.28
1-2	15.44	3-2	17.55	5-2	56.80
1-3	14.78	3-3	19.60	5-3	40.64
1-4	13.96	3-4	17.84	5-4	49.14
1-5	14.54	3-5	18.59	5-5	58.31
1-6	15.67	3-6	19.32	5-6	48.00
1-7	16.54	3-7	18.18	5-7	88.38
1-8	13.52	3-8	19.43	5-8	67.56
1-9	13.66	3-9	18.82	5-9	62.18
1-10	17.76	3-10	25.33	5-10	68.41
2-1	14.82	4-1	21.14	6-1	67.31
2-2	16.69	4-2	20.64	6-2	64.04
2-3	16.30	4-3	23.46	6-3	79.33
2-4	16.43	4-4	24.58	6-4	67.33
2-5	17.70	4-5	22.07	6-5	105.49
2-6	17.63	4-6	21.31	6-6	79.33
2-7	15.24	4-7	31.48	6-7	83.17
2-8	15.76	4-8	33.69	6-8	93.28
2-9	17.08	4-9	33.15	6-9	81.82
2-10	15.82	4-10	37.77	6-10	68.63

From the microstructure of figure 2 and the mean grain size of Table 3, it can be seen that the grain size does not increase significantly with the extension of holding time when the temperature of solution is 900C. When the temperature is 950C and 1000 °C, the grain size increases to a certain extent at different temperatures and changes little with time. When the temperature is 1050°C, 1100°C and 1150°C, the mean grain size increases from 13.66 μm to 105.49 μm . This indicates that the main factor affecting the growth of austenite grain is temperature, followed by the holding time at this temperature. The law of constant temperature growth of 316L austenite grain is in accordance with Avrami's law, that is, the grain size is a power exponential function of temperature and a parabolic function of time [15]. The process of grain growth is that the larger grains absorb the smaller grains, the total area of grain boundary and the total interfacial free energy of the material decreases gradually. When the solution temperature is relatively high, for example, at 1100°C, large grains appear in the sample abnormally. With uneven grain size and large dispersion width of grain size, this is due to the abnormal grain growth of the sample caused by long holding time.

3.2 Amplitude attenuation method

The attenuation of ultrasonic wave refers to the ultrasonic wave propagation in the medium, ultrasonic energy decreases with the increase of the propagation distance. The attenuation of energy is generally measured by the change of the amplitude of continuous echo. Ultrasonic attenuation is mainly divided into two parts: absorption and scattering attenuation. The influence of the change of grain size on ultrasonic attenuation is mainly focus on scattering attenuation. The attenuation coefficient of ultrasonic wave can be calculated to characterize the grain size of the material, then the physical properties of the material can be tested.

Using amplitude attenuation analysis method to measure the attenuation coefficient. The amplitudes (longitudinal coordinates) of the first bottom echo 1p and the second bottom echo 3P as shown in figure 3a were extracted from each group of ultrasonic data. Corresponding wave peak (or trough) was selected as the amplitude was selected, amplitude data which have been extracted substituted into the

attenuation coefficient calculation formula respectively, finally attenuation coefficient was obtained [16]. The attenuation coefficient was obtained by average attenuation coefficient of 9 tests.

There is often a great deal of noise in the signals due to the influence of the measurement process, personnel operation and other factors in actual measurement. In order to improve the accuracy of signal calculation of ultrasonic attenuation coefficient, it is necessary to denoise the signal [17]. MATLAB provides a smooth function used for data smoothing specially. If the smoothness of the signal is not high, it indicates that there are abundant high-frequency molecules in signal. After smooth processing, the high-frequency molecules in the signal are effectively suppressed, and the curve will become relatively smooth. The original signal is processed by smooth, the signal after smooth process as shown in figure 3b. The amplitude of the first and second bottom echo of the processed signal were brought into the formula to calculate the ultrasonic attenuation coefficient.

$$\alpha = \frac{1}{2L} \lg \left| \frac{A_2}{A_1} \right| \quad (1)$$

where α represents ultrasonic attenuation coefficient, A_1 and A_2 represent the amplitude of the second echo 1P and the first echo 3P, L is the thickness of the samples.

In order to obtain the information in frequency domain of signal. The complete waveforms of first echo 1p, second echo 3p and third echo 5p were selected in figure 3, Origin software was used to process echoes extracted from ultrasonic signals by fast Fourier transform (FFT) as shown in the following formula.

$$X(\omega) = \int_{-\infty}^{\infty} x(t) \exp(-j\omega t) dt \quad (2)$$

The amplitude of each echo is extracted and substituted into the formula (3) to calculate the ultrasonic attenuation coefficient.

$$P = Ae^{-\alpha x} \quad (3)$$

Where P represents amplitude, α is attenuation coefficient, and x represents propagation distance of ultrasonic. The ultrasonic attenuation coefficients in time and frequency domain are shown in Table 5.

Table 4 Ultrasonic attenuation coefficient in time domain and frequency domain

Sample	Attenuation coefficient/dB/mm			Sample	Attenuation coefficient/dB/mm		
	Original signal	Smooth	Frequency domain		Original signal	Smooth	Frequency domain
1-1	0.0655	0.0459	0.136	4-1	0.0668	0.0416	0.155
1-2	0.0738	0.0462	0.152	4-2	0.0665	0.0564	0.147
1-3	0.0637	0.0485	0.122	4-3	0.0738	0.0570	0.162
1-4	0.0671	0.0486	0.129	4-4	0.0811	0.0672	0.185
1-5	0.0619	0.0467	0.124	4-5	0.0645	0.0498	0.151
1-6	0.0562	0.0397	0.125	4-6	0.0700	0.0584	0.165
1-7	0.0765	0.0478	0.138	4-7	0.1085	0.0982	0.265
1-8	0.0682	0.0402	0.132	4-8	0.1037	0.0916	0.253
1-9	0.0613	0.0439	0.123	4-9	0.0652	0.0387	0.157
1-10	0.0723	0.0478	0.162	4-10	0.1075	0.0934	0.252
2-1	0.0568	0.0409	0.110	5-1	0.0909	0.0772	0.212
2-2	0.0643	0.0519	0.121	5-2	0.1093	0.0998	0.256
2-3	0.0617	0.0425	0.124	5-3	0.1164	0.0949	0.299
2-4	0.0590	0.0496	0.111	5-4	0.1038	0.0933	0.234
2-5	0.0550	0.0432	0.099	5-5	0.1331	0.1251	0.303
2-6	0.0647	0.0435	0.130	5-6	0.1195	0.0995	0.279
2-7	0.0571	0.0428	0.108	5-7	0.1029	0.1161	0.266
2-8	0.0567	0.0430	0.106	5-8	0.1304	0.1251	0.312
2-9	0.0570	0.0379	0.131	5-9	0.1628	0.1212	0.348
2-10	0.0659	0.0503	0.131	5-10	0.1538	0.1314	0.361
3-1	0.0626	0.0484	0.121	6-1	0.1155	0.1339	0.294
3-2	0.0672	0.0435	0.147	6-2	0.1344	0.1372	0.308
3-3	0.0621	0.0476	0.142	6-3	0.1461	0.1359	0.351
3-4	0.0548	0.0435	0.119	6-4	0.1187	0.1160	0.296
3-5	0.0585	0.0447	0.119	6-5	0.1559	0.1504	0.375
3-6	0.0667	0.0545	0.141	6-6	0.1847	0.1421	0.470
3-7	0.0686	0.0528	0.137	6-7	0.1630	0.1187	0.357
3-8	0.0682	0.0535	0.128	6-8	0.2013	0.1602	0.438
3-9	0.0612	0.0458	0.131	6-9	0.1812	0.1490	0.413
3-10	0.0797	0.0642	0.177	6-10	0.1846	0.1238	0.382

Using holding time of 5, 10, 15, 20, 25, 30, 35, 40, 45 minutes of sample at different temperature of solid solution as a standard linear fitting formula. The ultrasonic attenuation coefficient calculated from Table 4 linearly fitted with the mean grain size calculated from Table 3, it is found that there is a linear relationship between ultrasonic attenuation coefficient and mean grain size, and the fitting figure is shown in figure 4.

From figure 4, It can be seen that the ultrasonic attenuation coefficient increases with the increment of grain size. After smooth process, the ultrasonic attenuation coefficient has a better degree of fitting with the mean grain size. The linear fitting formula of grain size and attenuation coefficient calculated from amplitude attenuation of original signal, amplitude attenuation of smooth signal and amplitude attenuation in frequency domain are shown as follows respectively.

$$d = 612.01 \times \alpha - 19.865 \quad (4)$$

$$d = 655.11 \times \alpha - 13.137 \quad (5)$$

$$d = 245.37 \times \alpha - 14.045 \quad (6)$$

Where d represents mean grain size, α is ultrasonic attenuation coefficient. In order to verify the accuracy of the calculation model established above, the attenuation coefficient calculated by the samples of holding 50min at each temperature of solid solution was substituted into the formula to calculate the mean grain size, and the error of the mean grain size calculated by ultrasonic method and metallographic method were calculated as shown in Table 6.

Table 6 Mean grain size and error calculated by laser ultrasonic attenuation

Sample	Grain size (μm)	Attenuation analysis method base on original signal		Attenuation analysis method base on smooth signal		Attenuation analysis method base on Frequency domain	
		Calculated value(μm)	Error (%)	Calculated value (μm)	Error (%)	Calculated value(μm)	Error (%)
1-10	17.76	24.38	37.29	18.18	2.35	25.70	44.74
2-10	15.82	20.47	29.37	19.82	25.25	18.10	14.40
3-10	25.33	28.91	14.14	28.92	14.18	29.39	16.01
4-10	37.77	45.93	21.59	48.05	27.22	47.79	26.52
5-10	68.41	74.26	8.55	72.94	6.63	74.53	8.95
6-10	68.63	93.11	35.67	67.97	0.97	79.69	16.11

As it can be seen from Table 6, the average error of amplitude attenuation calculated from original signal is 24.43%. After smooth process, the average error of signal calculation is 12.77%, and the average error of amplitude attenuation in frequency domain is 21.12%. When the grain size is small (less than 30um), the average error calculated by amplitude attenuation method are 26.93%, 13.93% and 25.05% respectively, and when the grain size is large (greater than 30um), the average error is 21.93%, 11.60% and 17.20% respectively. It can be seen that the characterization accuracy of mean grain size measured by laser ultrasonic method is relatively high when the mean grain size is large. The characterization accuracy of grain size after smooth process is higher than original signal attenuation and frequency domain attenuation methods.

3.3 Wavelet threshold denoising method

In last section, amplitude attenuation method of the previous three echoes were used to measure attenuation coefficient. However, in actual measurement, the ultrasonic signal receives the influence of noise, such as the stability of the equipment, the change of the testing environment and the inhomogeneity of microstructure. The acquisition of signal in laser ultrasonic testing often contains a lot of high frequency noise, which has a negative impact on the calculation of attenuation. The noise caused by the surface state of the sample can be eliminated by collecting ultrasonic signals from the same sample for many times.

In order to reduce the influence of noise, in this section, a method was proposed to filter out the high-frequency noise in the ultrasonic signal by wavelet analysis so as to enhance the accuracy of ultrasonic test. Both traditional methods of attenuation calculation and Fourier transform have limitations. As a multi-scale expression, wavelet analysis provides both time and frequency domain information of signal at the same time, therefore it is widely used in image and signal processing [18,19]. Wavelet analysis is a method of time-frequency analysis of signals. The time-frequency window of the wavelet basis function varies with the center frequency at any time, so the wavelet transform can meet the requirements of multi-resolution [20]. The basic idea of wavelet transform is to represent the signal through a series of functions [21]. The time-frequency decomposition of energy-constrained signals can be obtained through the family of functions under given conditions. Most of the useful components of the decomposed signal are concentrated in the low-frequency part, set an appropriate threshold to filter out the noisy of high-frequency part, the purpose of denoise was achieved after signal reconstruction.

In this paper, db3 was selected as the wavelet basis function, and the signal was decomposed in five layers. The decomposed signal is shown in figure 5. The signal after wavelet threshold denoising was

processed by smooth and fast Fourier transform, the ultrasonic attenuation coefficients of the obtained signal and the original signal were calculated by the amplitude attenuation method in the last section respectively, as shown in Table 5. The ultrasonic attenuation coefficient calculated from the signal after wavelet threshold denoising is linear fitted with the mean grain size in Table 4 as shown in figure 6.

In the laser ultrasonic experiment, the average value of 128 ultrasonic signals was taken after 128 times of laser excitation at each test point, therefore the influence of operation and facilities of external experimental was significantly reduced. The main function of wavelet threshold denoising is to filter out high-frequency noise. As it can be seen from figure 6, the signal after wavelet threshold denoising has a higher smoothness than the original signal, the amplitude of the signal has changed to a certain extent as well.

Table 5 Ultrasonic attenuation coefficient calculated by amplitude attenuation method after wavelet denoising

Attenuation coefficient/dB/mm			Sample number	Attenuation coefficient/dB/mm		
Attenuation in time domain	Smooth attenuation	Attenuation in frequency domain		Attenuation in time domain	Smooth attenuation	Attenuation in frequency domain
0.0653	0.0460	0.1362	4-1	0.0670	0.0418	0.1548
0.0741	0.0469	0.1516	4-2	0.0668	0.0568	0.1466
0.0640	0.0487	0.1447	4-3	0.0742	0.0572	0.1614
0.0675	0.0492	0.1287	4-4	0.0815	0.0674	0.1847
0.0624	0.0474	0.1238	4-5	0.0647	0.0500	0.1504
0.0566	0.0399	0.1245	4-6	0.0700	0.0586	0.1647
0.0772	0.0482	0.1381	4-7	0.1095	0.0994	0.2647
0.0684	0.0404	0.1319	4-8	0.1045	0.0926	0.2530
0.0616	0.0444	0.1232	4-9	0.0528	0.0414	0.1579
0.0725	0.0478	0.1361	4-10	0.1081	0.0940	0.2521
0.0567	0.0407	0.1101	5-1	0.0915	0.0778	0.2118
0.0644	0.0519	0.1207	5-2	0.1100	0.1007	0.2552
0.0620	0.0432	0.1238	5-3	0.1171	0.0957	0.2994
0.0594	0.0497	0.1110	5-4	0.1049	0.0945	0.2344
0.0547	0.0431	0.0968	5-5	0.1338	0.1344	0.3028
0.0646	0.0435	0.1292	5-6	0.1205	0.1005	0.2794
0.0572	0.0430	0.1080	5-7	0.1038	0.1173	0.2731
0.0568	0.0431	0.1059	5-8	0.1316	0.1267	0.3117
0.0571	0.0380	0.1375	5-9	0.1645	0.1230	0.3707
0.0666	0.0508	0.1305	5-10	0.1552	0.1329	0.3606
0.0626	0.0480	0.1204	6-1	0.1160	0.1350	0.2944
0.0676	0.0494	0.1471	6-2	0.1357	0.1393	0.3075
0.0626	0.0482	0.1417	6-3	0.1479	0.1382	0.3510
0.0547	0.0437	0.1192	6-4	0.1197	0.1175	0.2968
0.0584	0.0447	0.1185	6-5	0.1575	0.1520	0.3761
0.0668	0.0548	0.1405	6-6	0.2093	0.1437	0.4708
0.0692	0.0532	0.1371	6-7	0.1635	0.1189	0.3567
0.0686	0.0542	0.1371	6-8	0.2036	0.1622	0.4382
0.0613	0.0460	0.1309	6-9	0.1840	0.1511	0.4093
0.0799	0.0615	0.1770	6-10	0.1850	0.1244	0.3829

From Fig. 6, the previous 9 samples of each group are taken as the standard to establish the formula for calculating mean grain size. Formulas of mean grain size based on frequency attenuation of original signal after wavelet threshold denoising, the smooth processing signal after wavelet threshold denoising and the attenuation in frequency domain of signal after wavelet threshold denoising are shown as follows respectively.

$$d = 576.30 \times \alpha - 17.088 \quad (7)$$

$$d = 642.49 \times \alpha - 12.818 \quad (8)$$

$$d = 244.45 \times \alpha - 14.126 \quad (9)$$

Where Y represents mean grain size, is ultrasonic attenuation coefficient. The ultrasonic attenuation coefficient measured by the samples held for 50min at different temperatures was substituted into the above formula, and the mean grain size was calculated as shown in Table 6.

Table 6 Mean grain size and error calculated by laser ultrasonic attenuation after wavelet threshold denoising

Sample number	Detection value/ μm	Signal attenuation analysis method after		smooth signal attenuation analysis method after		signal attenuation analysis method in frequency domain after	
		Wavelet denoising		Wavelet denoising		Wavelet denoising	
		Calculated value / μm	error	Calculated value / μm	error	Calculated value / μm	error
1-10	17.76	24.69	0.3904	17.89	0.0075	19.14	0.0779
2-10	15.82	21.29	0.3460	19.82	0.2529	17.77	0.1236
3-10	25.33	28.96	0.1432	26.70	0.0539	29.14	0.1505
4-10	37.77	45.21	0.1970	47.58	0.2596	47.50	0.2576
5-10	68.41	72.35	0.0576	72.57	0.0608	74.02	0.0820
6-10	68.63	89.53	0.3045	67.11	-0.0222	79.47	0.1580

In last section, there is a linear relationship between the mean grain size and the ultrasonic attenuation coefficient when the mean grain size changes obviously, and the ultrasonic attenuation increases with the increasement of the average grain size as it can be seen in Table 7, the attenuation coefficient calculated by wavelet threshold denoising signal also increases with the increasement of mean grain size. The calculation result of wavelet threshold denoising signal is consistent with the conclusion of last section. The mean grain size errors calculated by amplitude attenuation method after wavelet threshold denoising are 23.97%, 10.94% and 14.16% respectively. When the mean grain size is small (less than 30 μm), the errors are 29.32%, 10.47% and 11.73% respectively. When the sample mean grain, size is large (greater than 30 μm), the errors are 29.32%, 10.47% and 11.73% respectively. The average calculation errors are 18.63%, 11.42% and 16.59%. In order to verify that wavelet threshold denoising can improve the accuracy of laser ultrasonic evaluation of grain size, the mean grain size error of the signal calculated after wavelet threshold denoising was compared with the calculation error of center number—the results are shown in Table 8.

Table 8 The model accuracy before and after wavelet threshold denoising

Sample	Attenuation analysis method in time domain		Smooth time domain attenuation analysis method		attenuation analysis method in frequency domain	
	original signal	Wavelet signal	original signal	Wavelet signal	original signal	Wavelet signal
1-10	0.3729	0.3904	0.0235	0.0075	0.4474	0.0779
2-10	0.2937	0.3460	0.2525	0.2529	0.1440	0.1236
3-10	0.1414	0.1432	0.1418	0.0539	0.1601	0.1505
4-10	0.2159	0.1970	0.2722	0.2596	0.2652	0.2576
5-10	0.0855	0.0576	0.0663	0.0608	0.0895	0.0820
6-10	0.3567	0.3045	-0.0097	-0.0222	0.1611	0.1580

As it can be seen from Table 8, the average error of grain size calculated by the model established by time-domain attenuation method was reduced from 24.43% to 23.98% after wavelet threshold denoising of ultrasonic signals; the average error of grain size calculated by signal was reduced from 12.77% to 10.95% after smooth process; and the average error of grain size calculated by frequency domain attenuation was reduced from 21.12% to 14.16%. It can be found that wavelet threshold denoising can improve the precision of grain size through calculation of frequency domain attenuation significantly, and the smoothing method of signal after wavelet threshold denoising can obtain the most accurate grain size calculation.

4. Conclusion

(1) Provide a nondestructive evaluation of mean grain size of 316L stainless steel based on laser ultrasonic testing technology. The attenuation coefficient calculated by amplitude attenuation in time domain and frequency domain have a great fitting with the mean grain size.

(2) When the mean grain size is small (less than 30um), the calculation error of the mean grain size of the sample are 15.86%, 16.31% and 20.98%. When the mean grain size is large (greater than 30um), the calculation errors are 16.21%, 2.46% and 5.78%. The smooth signal and the frequency domain attenuation method have more accuracy when the mean grain size of the sample is large.

(3) The wavelet threshold denoising method is used to filter out the high frequency noise in ultrasonic signal. The calculation error of mean grain size of amplitude attenuation method is reduced from 16.75% to 15.98%. The calculation error of the mean grain size of signal after smooth process is reduced from 13.24% to 11.70%. The calculation error of frequency domain amplitude attenuation method is reduced from 18.26% to 15.91%. It can effectively improve the calculation accuracy of mean grain size.

5. Declarations

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: SY, AY was in charge of the whole trial; JW, ZZ wrote the manuscript; HC, SL assisted with sampling and laboratory testing. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Figures

Figure 1

Laser ultrasonic laboratory testing system

Figure 2

Microstructure diagrams of sample (a)900°C; (b)950°C; (c)1000°C; (d)1050°C; (e)1100°C; (f)1150°C

Figure 3

Ultrasonic diagram

Figure 4

Fitting model of attenuation coefficient and mean grain size

Figure 5

Wavelet threshold denoising signal

Figure 6

Fitting model of signal attenuation coefficient and mean grain size after wavelet threshold denoising