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A Research on Surface Crack Identification and Location of Selective Laser Melting Specimen

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Abstract
The parts formed by selective laser melting technology tend to have some defects such as cracks and pores. The laser ultrasonic testing technology can use surface wave to detect the surface cracks. However, the anisotropy and residual stress of the SLM parts will affect the propagation of the surface wave and generate a lot of noise, causing identification difficulties. To identify and locate the crack more accurate, the laser ultrasonic signals received need denoising process. In this paper, we use stationary wavelet threshold denoising method to reduce the noise and we find out the best denoising parameters for the laser ultrasonic signals. By this mean, we get relatively accurate results of the surface crack identification and location.

Keywords: *Selective Laser Melting (SLM), Surface Crack Identification, Laser Ultrasonic, Stationary Wavelet Transform (SWT)*

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I. INTRODUCTION

Selective Laser Melting (SLM) is an important technology of metal additive manufacturing. It lays metal powder and then melts it with high-energy laser, the molten metal cools layer by layer, gradually accumulating into solid body [1]. It can be applied to many kinds of metal materials such as nickel based alloy 718 (Inconel 718), which is a widely used high temperature alloy [2]. However, SLM products often have some defects such as cracks and pores, which means it is necessary to carry out non-destructive testing (NDT) [3].

Laser ultrasonic testing technology, a kind of NDT, is widely used in defect detection because it realizes non-contact testing and can be carried out in high temperature, high pressure and radioactive environment [4]. It generates ultrasonic waves by thermoelastic effect whose principle is that when the surface of the metal is irradiated by high-energy laser, part of the laser's energy is absorbed and converted into heat energy, leading to the local metal's thermal expansion and forming a stress field which triggers the ultrasonic waves. Among these waves, surface wave carries most of the laser ultrasonic energy, spreads along the surface of the parts and has been mainly applied to detect the surface cracks.

In this paper, we use surface wave to detect the surface crack of SLM specimen. Due to its manufacturing characteristics, SLM products have obvious anisotropy and residual stress, which will affect the propagation of surface wave and generate a lot of noise, greatly increasing the difficulty of the detection. So the signals received by the sensors need to be denoised. Although the band-pass filtering can remove some noise, it is difficult to determine the cut-off frequency of the filter and it's easy to lose some important information. Compared with band-pass filtering, wavelet threshold denoising is more suitable for the laser ultrasound signals and has been widely used. However, the traditional wavelet denoising has down-sampling and up-sampling processes in signal decomposition and reconstruction, which may bring some errors. So in this paper, stationary wavelet transform (SWT) is used instead of wavelet transform to decompose and reconstruct the signal. We put forward a quantitative evaluation of the denoising results to find out the best denoising parameters so that we can get more accurate identification and location results of the surface crack.

II. PRINCIPLE AND METHOD

2.1 GEOMETRIC MODEL

We use pulse echo method to detect the surface crack, as shown in figure 1, there is an artificial gap with a certain depth in the surface of the test specimen to simulate a surface crack. When using the line laser source which is parallel to the crack, the three-dimensional problem can be simplified to a two-dimensional problem whose principle is shown in figure 2. When the surface wave passes the receiving point of the sensor, we can get a transient pulse signal R, and as the surface wave spreads forward, if there is a crack in its path, part of the surface wave will be reflected by the crack and we can get an echo signal RR when the reflected wave passes the receiving point [5]. We can calculate the distance L between the crack and the receiving point by the following formula

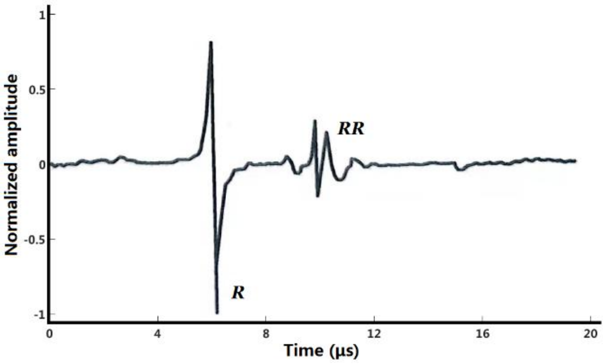
$$L = \frac{c_R \Delta t}{2} \qquad (1)$$

where Δt is the time difference between the two pulse signals, cR is the surface wave velocity, which can be measured experimentally or calculated by the formula [6]

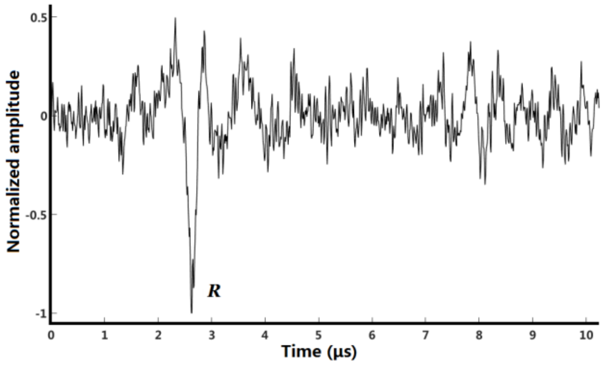
$$c_R = \frac{0.87 + 1.12\mu}{1 + \mu}\sqrt{\frac{G}{\rho}} \qquad (2)$$

Where μ is Poisson ratio, ρ is density, and G is shear modulus. For Inconel 718, μ is 0.3, ρ is 8.24g/cm3, G is 77.2GPa, and cR is 2839.5m/s.

Generally speaking, for isotropic metal specimens, the waveforms of signal R and RR are clear and distinguishable, as we can see from figure 3(a), both the surface wave and its echo are easy to identify. By contrast, for SLM specimens, the anisotropy and residual stress of the medium will obviously affect the propagation of the surface wave, generating amounts of noise. As shown in figure 3(b), only signal R is distinguishable while signal RR can't be directly identified due to the noise.



(a) Isotropic metal specimen



(b) SLM specimen

Fig. 3. Laser ultrasonic signal

To solve this problem, this paper uses the following method to analyze and process the signal. Consider the laser ultrasonic signal as a time-domain sequence X whose length is m. It can be regarded as the sum of useful signal S and random noise W

$$S = s[0],\quad s[1],\quad \cdots,\quad s[m-1]$$
$$W = w[0],\quad w[1],\quad \cdots,\quad w[m-1]$$
$$X = S + W = x[0],\quad x[1],\quad \cdots,\quad x[m-1]$$

Intercept X with a rectangular window whose length is n, and set the start of the window as r, so the intercepted signal is

$$S_r = s[r],\quad s[r+1],\quad \cdots,\quad s[r+n-1]$$
$$W_r = w[r],\quad w[r+1],\quad \cdots,\quad w[r+n-1]$$
$$X_r = S_r + W_r = x[r],\quad x[r+1],\quad \cdots,\quad x[r+n-1]$$

where 0≤r≤m-n. When r varies between 0 and m-n, if the intercepted signal Xr does not contain surface wave signal, Sr will be approximately 0, and the volatility of Xr depends on the noise Wr. If Xr contains surface wave R or its echo RR, due to Sr has volatility, the volatility of Xr is determined by Sr and Wr. We can use variance to describe the volatility of Xr

$$\begin{aligned} D(X_r) &= D(S_r + W_r) \\ &= D(S_r) + D(W_r) + 2Cov(S_r, W_r) \end{aligned} \quad (3)$$

Where D(Xr) is the variance of Xr, and Cov(Sr, Wr) is the covariance of Sr and Wr. Noise W can be considered as a stationary random signal, which means its statistical characteristics are independent of the start of the window and D(Wr) will be constant. In general, the noise W is not correlated with the useful signal S, which means the covariance Cov(Sr, Wr) will be 0. In conclusion, we can get

$$D(X_r) = D(S_r) + const \qquad (4)$$

Considering that the passing time of the surface wave is very short, too large n will lead to the dispersion of volatility and reduce the time-domain distinguishability, and too small n will make D(Xr) vulnerable to random errors. So the window length n should be equivalent to the presentation time of the surface wave. For example, when the sampling frequency is 100MHz and n=100, the D(Xr) curve of the signal in figure 3(b) is shown in figure 4. It can be seen that there are two peaks in the figure, the high peak corresponds to the primary surface wave R, and the low peak corresponds to the echo RR.

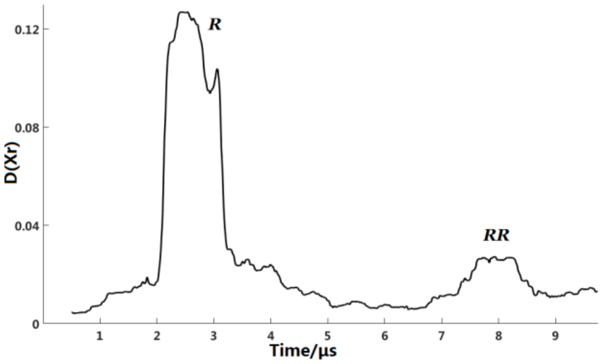


Fig. 4. D(Xr) curve of laser ultrasonic signal

For further signal analysis, we need to denoise the laser ultrasonic signal. When the useful signal is known, the signal-to-noise ratio (SNR) is usually used to evaluate the denoising result. However, since the useful signal S in this study is unknown, the SNR cannot be calculated, we need other methods to evaluate the denoising result.

Suppose that the denoising signal is $\hat{S}$ and the noise removed is $\hat{W}$

$$X = \hat{S} + \hat{W}$$

$$\hat{S} = \hat{s}[0], \quad \hat{s}[1], \quad \cdots, \quad \hat{s}[m-1]$$

$$\hat{W} = \hat{w}[0], \quad \hat{w}[1], \cdots, \quad \hat{w}[m-1]$$

According to the previous discussion, $D(\hat{W}_r)$ should be constant, which is called condition 1; Besides, $Cov(\hat{S}_r, \hat{W}_r)$ should be 0, which is called condition 2. This condition is equivalent to

$$D(X_r) - D(\hat{S}_r) - D(\hat{W}_r) = 0 \quad (5)$$

When there is no surface wave received, the volatility of useful signal S is small and the D(Sr) will approach to 0, which means the better the denoising result is, the smaller $D(\hat{S}_r)$ in no surface wave interval should be. Under the condition 1 and 2, it is to say the constant corresponds to $D(\hat{W}_r)$ should be as large as possible. In summary, the following evaluation methods are established to evaluate the denoising result:

1) Calculate $D(\hat{W}_r)$ and take the mean value of $D(\hat{W}_r)$ as the constant

$$const = \frac{\sum_{r=0}^{m-n} D(\hat{W}_r)}{m-n+1} \qquad (6)$$

Take a small positive number a, we consider that it conforms to the condition 1 when formula (7) is satisfied

$$A = \frac{\sum_{r=0}^{m-n} [D(\hat{W}_r) - const]^2}{m-n+1} < a \qquad (7)$$

2) Calculate D(Xr) and $D(\hat{S}_r)$, take a small positive number b, we consider that it conforms to the condition 2 when the formula (8) is satisfied

$$B = \frac{\sum_{r=0}^{m-n} [D(X_r) - D(\hat{S}_r) - D(\hat{W}_r)]^2}{m-n+1} < b \quad (8)$$

3) When the denoising result conforms to the conditions 1 and 2, the larger the const in formula (6) is, the better the denoising result is.

III. STATIONARY WAVELET THRESHOLD DENOISING

In this paper, we use SWT to decompose the time signal into wavelet domain, and process the wavelet coefficients with threshold function, then reconstruct the time signal by inverse stationary wavelet transform (ISWT).

Let $f(t)$ be a time signal, its wavelet transform is

$$WT_f(2^j, b) = 2^{\frac{-j}{2}} \int_{-\infty}^{+\infty} f(t)\psi\left(\frac{t-b}{2^j}\right)dt \qquad (9)$$

When $b=k\cdot 2j$, $k, j \in \mathbf{Z}$, formula (9) is discrete wavelet transform; When $b=k$, the formula is stationary wavelet transform [7]. SWT only discretized the scale parameter, while the translation parameter b still varies according to the continuous integers, so it is more suitable for the signal which contains mutation.

Stationary wavelet threshold denoising involves several parameters, such as the wavelet basis, the number of the decomposition, the threshold function and so on. These parameters determine the denoising result. According to the evaluation methods in previous section, we take the laser ultrasonic signal of the SLM specimen as the analysis object X and find out the best combination of the parameters for this signal. We can get the best denoising result when using rbio2.6 wavelet, four layers of decomposition, fixed threshold method and soft threshold function. The denoising result is shown in figure 5, it basically satisfies the conditions and formula (4).

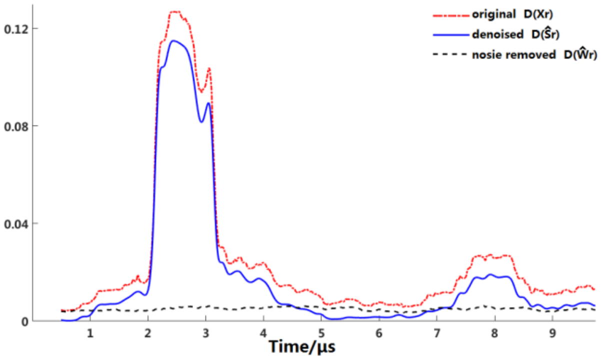
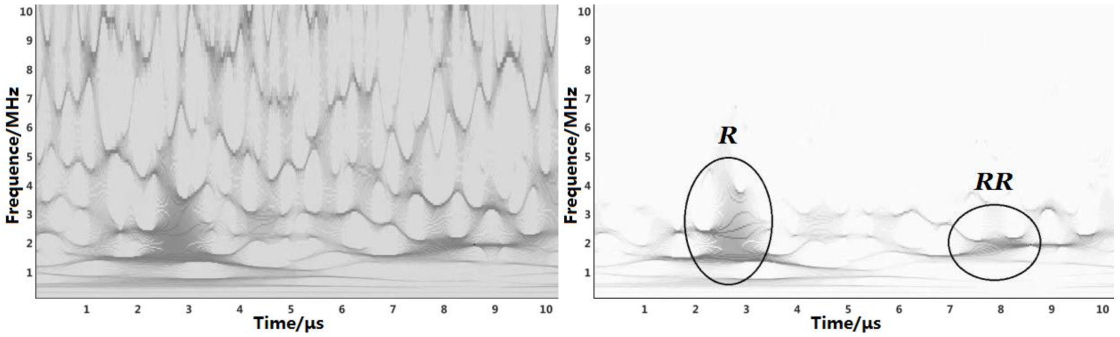


Fig. 5. $D(X_r)$, $D(\hat{S}_r)$ and $D(\hat{W}_r)$ curve

It can be seen from figure 5 that $D(\hat{S}_r)$ has two peaks at 2.5μs and 8μs, indicating that the volatility of the signal around these moments increases suddenly, which means probably the surface wave passed. To confirm this, we analyze the signal in time-frequency domain. As shown in figure 6, before denoising, there is a lot of noise interference in the signal, and it is unable to affirm whether there is the surface wave echo *RR*. After denoising, the noise is greatly reduced, and it can be seen that there are frequency components about 2MHz at 2.5μs and 8μs. Considering that the main frequency of the surface wave in this experiment is about 2MHz, it can be determined that the two peaks are caused by the surface wave *R* and its echo *RR*. Finally, the distance *L* between the crack and the sensor receiving point can be calculated by formula (1).



(a) before denoising (b)after denoising

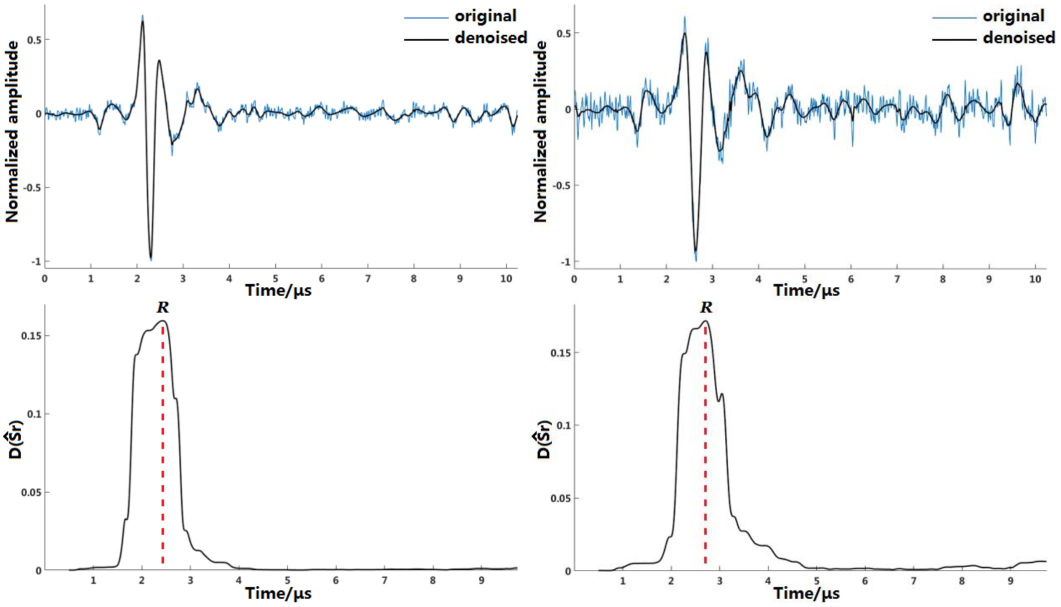
Fig. 6. Time-frequency analysis

IV. Experiment

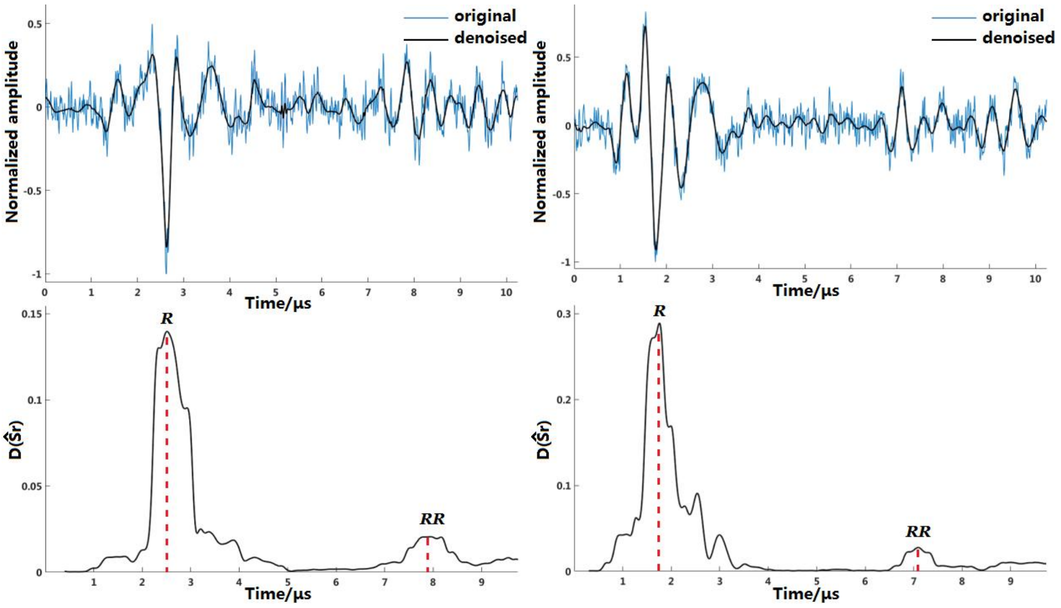
In this experiment, we test four Inconel 718 SLM specimens whose sizes are 30×10×8mm. As shown in figure 1, simulated cracks with the width of 0.2mm and the depth of 0.1mm, 1.0mm and 1.5mm were processed on the surface of three specimens. The laser we use is 178W power, 1064nm wavelength and 11ns pulse width.

By pulse echo method, and stationary wavelet threshold denoising method, we obtain the denoised signals. Then we can identify the crack by time-frequency analysis and locate it according to the time difference between the two peaks of the variance curve. In this experiment, the distance between the crack and the sensor receiving point is 8mm.

The experiment results are shown in figure 7 and sheet 1. When the crack depth is 1.0mm or 1.5mm, the method we use is effective to identify the surface crack and locate it accurately. When the crack depth is 0.1 mm, the method can't detect its existence. Comparing figure 7 (a) and (b) we can see that the two signals are almost same, which is mainly because that as the crack depth decreases, the surface wave echo energy reduces, more and more energy is lost in the forms of transmission and scattering, causing the echo is too weak to be detected.



(a) no crack (b) crack depth 0.1mm



(c) crack depth 1.0mm (d) crack depth 1.5mm

Fig. 7. Laser ultrasonic signals of different specimens

Table 1. Experiment results

Crack depth (mm)	Identification	Peak to peak Δt (μs)	Crack location L (mm)	Error
0.1	No	--	--	--
1.0	Yes	5.47	7.72	3.5%
1.5	Yes	5.35	7.60	5.0%

In terms of location accuracy, there is a small error between the calculation and the actual distance. Besides the systematic error, the causes can be mainly attributed to the following points:

1) Formula (2) is used to calculate the theoretical velocity of the surface wave propagating in isotropic medium. However, anisotropy and residual stress of the SLM specimens may lead to the difference between the actual velocity and the theoretical value. To improve the accuracy, the further study may design additional experiments to measure the actual velocity of the surface wave.

2) The variance curve $D(\hat{S}_r)$ is a kind of short-time analysis method, its time-domain distinguishability is limited, which tends to causing small error in Δt.

V. CONCLUSION

In our study, the surface cracks with depth great than or equal to 1.0mm are identified and located successfully. The results are within the allowable error range. For the small cracks with the depth of 0.1mm, it is unable to identify and locate them by these methods because the echo energy is too low to be detected, and upgraded methods should be considered in further research.

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