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Nondestructive testing of additively manufactured material based on ultrasonic scattering measurement

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ABSTRACT

To improve ultrasonic testing capability for additively manufactured materials, extreme value statistics is employed to calculate the experimental confidence bounds of structural noise, which can be treated as time-dependent thresholds for ultrasonic C-scan image segmentation. A 316L stainless steel sample manufactured by selective laser melting is used for ultrasonic scattering measurements with a focused transducer. Compared with the fixed threshold used in the traditional C-scan image segmentation, the time-dependent threshold can effectively distinguish the flaw echoes from the background of structural noise. The optical microscopy measurement results show that the present method can avoid both missed detections and false positives.

1. Introduction

Additively manufactured (AM) parts can be produced by selective laser melting (SLM) process with mechanical properties comparable to those of conventional cast parts [1]. However, the macroscopic flaws (e.g. isolated pores, cracks, and lacks of fusion) can destroy the mechanical properties of SLM additively manufactured metallic material [2]. To comply with the high safety standards, quality assurance is pursued using ultrasonic inspection. Rieder et al. [1] and Lévesque et al. [3] have presented online inspection methods for AM materials using contact transducer underneath the build-platform and non-contact laser ultrasonics, respectively. The offline inspection methods are also developed with phased array [1] and conventional C-scan approach [2]. However, the ultrasonic inspection for AM materials is still a challenge because flaws will go undetected when the reflected echoes from the flaws are hidden by undesirable structural noise in ultrasonic waveforms.

The structural noise is known as the ultrasonic backscattering signal, which is constituted by coherent scattering waves travelling back to the transducer in the opposite direction of the incident ultrasonic wave [4]. The scattering of ultrasonic wave is caused by acoustic impedance differences existing within the propagation medium, which has a significant detrimental effect on nondestructive testing applications [5]. Due to the need to achieve better testing quality, the ultrasonic structural noise has been an active research topic for the past decade [6]. Moreover, the fact that the ultrasonic backscattering signal carries important information on the geometric and elastic properties of the material microstructure, which leads to intensified interest in ultrasonic scattering measurements and modeling [7].

If there are no porosity and nonmetallic phase in the propagation medium, the structural noise can be also recognized as the grain noise. The first realistic model of grain noise was developed by Rose [8]. Han and Thompson [9] extended Rose's work to the scattering in hexagonal polycrystalline materials with duplex microstructures. The grain noise model for polycrystals with arbitrary crystallite and macroscopic texture symmetries was developed by Li and Rokhlin [7]. However, all of these works are in frequency domain, which can be used in material characterization but are hardly applicable to flaw detection. Recently, Ghoshal and Turner [10] have developed a time-dependent grain noise model called singly-scattered response (SSR) model, which produces equivalent results and behaviors as the model in the frequency domain. The theoretical SSR model assumes that the ultrasonic waves scatter only once from the microstructure, and includes the three parts: experimental calibration, backscatter coefficient, and the transducer beam pattern [10].

More recently, Song et al. [11] developed a forward backscattering model to estimate the upper bound of grain noise based on the SSR model [10,12] and extreme value theory [13]. The upper bound can be regarded as the time-dependent threshold in ultrasonic inspection and used to locate the flaws automatically; however, the previous SSR model [12] is not applicable for the strongly-scattering stainless steel alloy fabricated by SLM, whose structural noises are attributed to not only the columnar grain, but also the inherent porosity, texture and residual stress. Additionally, the effect of grain noise's non-zero spatial

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average on the theoretical bound is ignored [11].

In this work, we highlight the experimental bounds of structural noise from SLM stainless steel, in which the ultrasonic waves are considered multiple scattering. A predictor-corrector algorithm for measuring the experimental bounds is given in terms of the extreme value statistics; both the spatial standard deviation and spatial average of structural noise are taken into consideration. Finally, the experimental bounds are used in ultrasonic inspection, and the present method is verified with a 316L stainless steel sample fabricated by SLM.

2. Method

When the ensemble was obtained by collecting waveforms at different spatial locations on the sample, the spatial average and standard deviation of an ensemble of collected ultrasonic waveforms are [14].

$$\mu^{\exp}(t) = \frac{1}{N}\sum_{i=1}^{N} V_i(t), \tag{1}$$

$$\sigma^{\exp}(t) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} V_i^2(t) - \left(\frac{1}{N}\sum_{i=1}^{N} V_i(t)\right)^2}, \tag{2}$$

where i denotes the i-th waveform in the ensemble containing a total of N normally distributed waveforms and $V_i(t)$ is the time-dependent amplitude (typically a voltage) of the i-th waveform. The spatial average and standard deviation at time t refer to the concentration and dispersion of backscattering data from different lateral transducer positions, and they are denoted by the superscript exp to emphasize that they are experimentally measureable parameters. Notice that $V_i(t)$ are assumed to be distributed in a Gaussian manner at all depths, even in the focal zone [15].

Based on the fundamental assumption that $V_i(t)$ belongs to a normal distribution, the extreme value statistics [13] can be introduced to describe the relationship between the maximum/minimum amplitudes in the ensemble $A_{\max}^{\exp}(t) = \max\{V_i(t)\}$ or $A_{\min}^{\exp}(t) = \min\{V_i(t)\}$, spatial average $\mu^{\exp}(t)$ and spatial standard deviation $\sigma^{\exp}(t)$. More strong assumptions are used here: (1) the polycrystalline materials should be strictly statistically homogeneous; (2) there are no vertical offsets to the baseline signal; (3) the effects of measurement system (e.g. electromagnetic interference, averaging time, scanning speed, etc.) can be neglected; (4) the separation between two consecutive transducer positions should be large enough that the two backscattered signals are fully uncorrelated. All of these assumptions are used to ensure that all the waveforms are independent and identically distributed (IID).

Assuming that $V_i(t)$ are normally distributed and that $A_{\max}^{\exp}(t)$ and $A_{\min}^{\exp}(t)$ obey the Gumbel distribution, then, taking advantage of the useful properties of the Gumbel distribution, the upper bound of $A_{\max}^{\exp}(t)$ and the lower bound of $A_{\min}^{\exp}(t)$ can be given as:

$$\begin{aligned} U^{\exp}(t) &= b_N^{\max}(t) - a_N^{\max}(t)\ln[-\ln((1+\alpha)/2)],\\ L^{\exp}(t) &= -b_N^{\min}(t) + a_N^{\min}(t)\ln[-\ln((1+\alpha)/2)], \end{aligned} \tag{3}$$

where α is the confidence level. The normalization constants $a_N^{\max}(t)$, $a_N^{\min}(t)$, $b_N^{\max}(t)$ and $b_N^{\min}(t)$ can be defined as [13].

$$\begin{aligned} a_N^{\max}(t) &= a_N^{\min}(t) = \frac{\sigma^{\exp}(t)}{\sqrt{2\ln N}},\\ b_N^{\max}(t) &= \left[\sqrt{2\ln N} - \frac{\ln\ln N + \ln 4\pi}{2\sqrt{2\ln N}}\right]\sigma^{\exp}(t) + \mu^{\exp}(t),\\ b_N^{\min}(t) &= \left[\sqrt{2\ln N} - \frac{\ln\ln N + \ln 4\pi}{2\sqrt{2\ln N}}\right]\sigma^{\exp}(t) - \mu^{\exp}(t), \end{aligned} \tag{4}$$

where $\mu^{\exp}(t)$ and $\sigma^{\exp}(t)$ are the time-dependent spatial average and standard deviation curve, and N denotes the number of waveform. In practice, the bounds of structural noise can be used to establish amplitude thresholds to be triggered by a flaw echo. Therefore, Eq. (3) is the primary result of this article.

To reduce the error of the bounds, an ideal reference sample without any flaws is required, but this is unrealistic in practice. Besides, some flaws could be missed if a large scanning step is used to acquire independent backscattered signals. Thus, a predictor-corrector algorithm, or a self-referenced method, is introduced here to establish the bounds with smaller step. First, the predictor step: (1) choose a subset $V_j(t)$ from $V_i(t)$ with a large enough virtual scanning step, where $V_j(t)$ should include at least 1000 independent backscattered signals; (2) use the subset $V_j(t)$ to acquire $U^{\exp}(t)$ and $L^{\exp}(t)$. Next, the corrector step: (1) remove the waveforms $V_j(t) > U^{\exp}(t)$ or $V_j(t) < L^{\exp}(t)$ form $V_j(t)$, which might be flaws echoes; (2) get a new subset $\hat{V}_k(t)$ and use it to acquire $\hat{U}^{\exp}(t)$ and $\hat{L}^{\exp}(t)$. Finally, $\hat{U}^{\exp}(t)$ and $\hat{L}^{\exp}(t)$ can be used to identify flaw echoes in the original ensemble $V_i(t)$. Finally, the experimental bounds can be obtained even when the waveforms scattered from the flaws are used.

To verify the present method, a few numerical examples were given by the Monte Carlo simulations. In the simulations, the number of data generated randomly was n, which means the sample size of subset $V_j(t)$ is n. Assume that the number of data points from the backscattering signal in the ensemble is Mn, and the number of data points from the anomalous flaw echo signal in the ensemble will be $(1-M)n$, where $0 \leqslant M \leqslant 1$. When the scale factor $M = 1$, all data are from the backscattering signal. On the other hand, when $M = 0$, all data are from the flaw echo. The following three conditions are assumed in the simulations: the backscattering data belong to the normal distribution $N_0(0,0.1)$, one half of the anomalous flaw echo data belong to the normal distribution $N_1(-\mu_1,\sigma_1)$, and the rest of the flaw echo data belong to the normal distribution $N_2(\mu_2,\sigma_2)$. The predicted bounds and corrected bounds can be calculated with confidence levels α and $\hat{\alpha}$, respectively. As Fig. 1 shows, the quantile-quantile plots are used to show four different simulation cases. Fig. 1(a) indicates that if the amplitude of flaw echo was dramatically larger than the amplitude of backscattering signal, both the predicted bounds and corrected bounds can identify the flaw easily. The data points within the predicted bounds constitute a new subset. Because all the flaw echo data in the initial subset were removed, the corrected bounds given by the new subset can be made much narrower while maintaining the same confidence level. Fig. 1(b) shows all the flaw echo data can be identified and the simulated amplitude difference between the backscattering data and flaw echo data was only 3.15 dB (lower than the requirement of 6-dB in British Standard EN 12680-1:2003). As shown in Fig. 1(c), when the proportion of flaw echo data at time t is larger than 1%, the presented self-referenced method breaks down, because the flaws are widely distributed at one layer in the sample. Fig. 1(d) shows that the confidence level can be enhanced in the corrector step, and all the flaw echo data can still be identified when the simulated amplitude difference was 5.22 dB (also lower than 6 dB).

3. Experiments

3.1. Preparations

To illustrate the application of the proposed methodology, a 316L stainless steel sample (size 40 mm × 40 mm × 15 mm, mass 196.34 g, volumetric porosity 0.38%) fabricated by SLM was used to conduct the ultrasonic experiments. The volume fraction was measured by the Archimedes method. The sample was produced by Farsoon F271M at a laser power of 180 W; it should be noted that a lower laser power than the usual 225 W was intentionally used to produce more flaws in the specimen. The laser scanning velocity was 1000 mm/s, the hatch spacing was 0.09 mm and the layer thickness was 0.03 mm. All processing occurred in a nitrogen environment with less than 0.1% oxygen to avoid oxidation and degradation of the material during the process [16]. In the SLM process, the sample was heated tautologically by the heat transfer from the uppermost laser all the time, which leads to the residual stresses in the samples. Thus, to prevent the sample from cracking by residual stresses, stress relief annealing was conducted after