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Young's modulus distribution of additive manufactured parts measured by laser ultrasonics

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1. Introduction

Additive manufacturing (AM), also referred to as 3D printing or rapid prototyping, has garnered significant attention as a novel processing method. One prominent metal AM technology is powder bed fusion (PBF). In PBF using selective laser melting, a layer of metal powder, approximately 50 µm thick, is deposited onto a base plate and subsequently irradiated with a laser beam to induce melting and solidification. Following each layer's formation, the base plate is incrementally lowered by one layer using an elevator, repeating the process to produce a 3D object of arbitrary shape. Given the layer-by-layer stacking nature of the material, it is expected that the mechanical properties of AM parts will vary between the horizontal and stacking directions. Moreover, while the material is initially formed on a base plate with high thermal conductivity, this property—and consequently the mechanical properties—may evolve as the process progresses. Laser ultrasonics (LU), with its ability to measure mechanical properties within a range of a few millimeters, was employed in this study to investigate whether differences in mechanical properties exist depending on the location and orientation of AM parts.

2. Experimental results

The AM part, with dimensions of 10 × 10 × 10 mm³, was fabricated using a Sodick LPM325 machine with Inconel 718 metal powder supplied by Sanyo Special Steel. The part was produced directly on the base plate and later detached from it using a wire electrical discharge machine, resulting in a final length of 9.5 mm in the building direction (z-direction). To achieve a mirror-like surface, the probe-irradiated surface was polished to a depth of approximately 2.4 mm. A pulse laser and a laser Doppler vibrometer (LDV) were utilized to generate and detect acoustic waves, respectively (Fig. 1). Acoustic waves were generated in thermoelastic mode. The LDV's bandwidth ranged from 50 kHz to 20 MHz. The laser beam (probe) of the LDV was directed at three positions (A, B, and C) as depicted in Fig. 2. The pulse laser's irradiation positions were varied in the x- and z-directions using a galvanometer scanner, resulting in the acquisition of six sets of data. The waveforms obtained from scanning the pulse laser in the x-direction at Position B are shown in Fig. 3, with each waveform averaged 65536 times. Both lateral waves and surface acoustic waves (SAWs) propagated through the AM part. Components within the waveform data, with frequencies between 1.60 MHz and 25.56 MHz, were extracted, and the propagation velocity was determined using a correlation function (Fig. 4). In an isotropic medium, the following equation relates the sound velocities of longitudinal (v_l), transverse (v_t), and Rayleigh (v_r) waves:

$$4\sqrt{1-\left(\frac{v_r}{v_t}\right)^2}\sqrt{1-\left(\frac{v_r}{v_l}\right)^2}-\left\{2-\left(\frac{v_r}{v_t}\right)^2\right\}^2=0 \quad (1).$$

Using eq. (1), the sound velocity v_t was calculated, and from it, Young's modulus (E) and shear modulus (G) were determined using v_l, v_t and the density (ρ) of the AM part (Fig. 5). ρ was determined by the Archimedes' principle (Shimadzu AUW320).

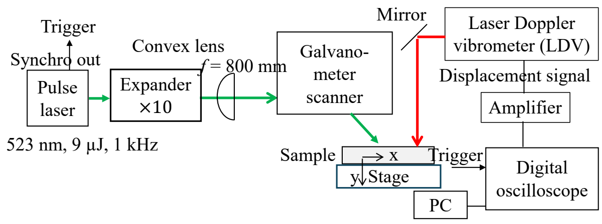

Fig. 1 Experimental setup.

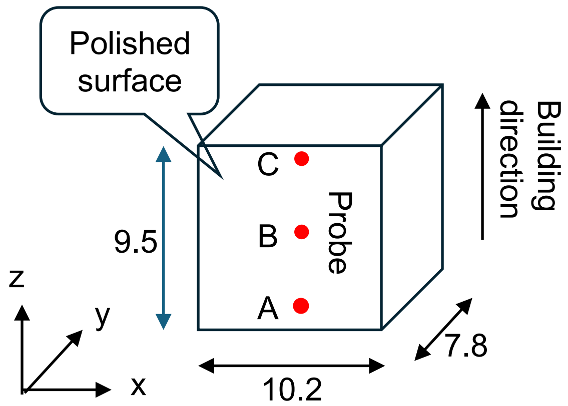

Fig. 2 Schematic of AM parts and positions of probe. Red dots indicate the positions of the LDV's laser beam.

3. Discussion

The sound velocity of the SAW propagating in the x-direction of the AM part was slower than that of the Rayleigh wave in bulk Inconel 718.

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Additionally, the sound velocity of the lateral wave propagating in the x-direction of the AM part was comparable to that of the longitudinal wave in bulk Inconel 718 (Fig. 4). Conversely, the sound velocity of the SAW propagating in the z-direction on the AM part was similar to that of the Rayleigh wave in bulk Inconel 718. However, the sound velocity of the lateral wave in the AM part was slower than that of the longitudinal wave in bulk Inconel 718. Moreover, it was observed that the SAW propagating in the z-direction on the AM part was faster than the SAW propagating in the x-direction. Similarly, the lateral waves propagating in the z-direction were slower than those propagating in the x-direction. These

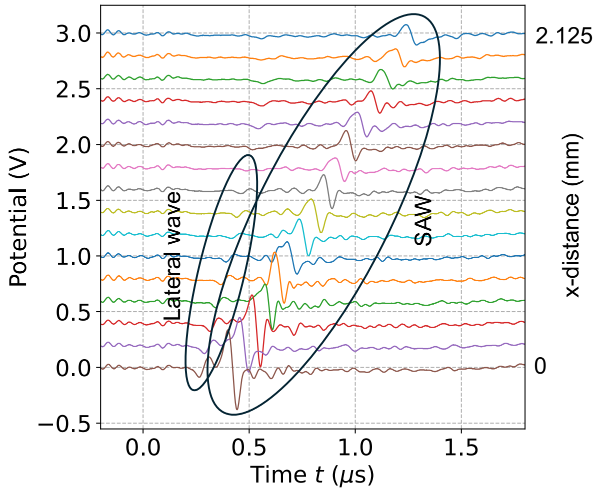

Fig. 3 Lateral and surface acoustic waves propagating on AM parts.

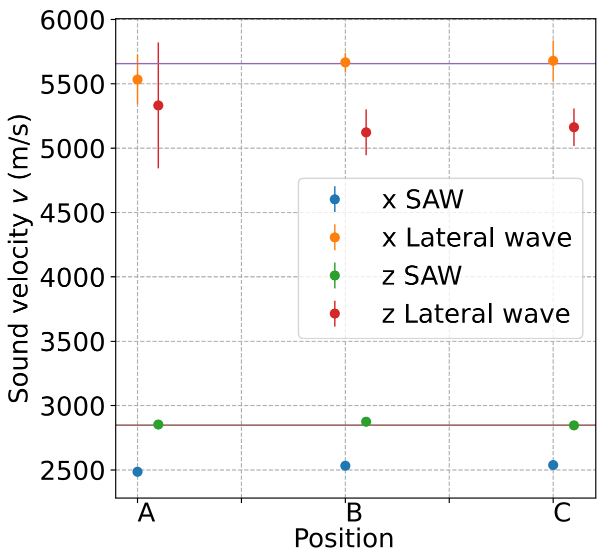

Fig. 4 Sound velocities of lateral and surface acoustic waves propagating on AM parts. Purple and brown lines indicate the sound velocities of the longitudinal and Rayleigh waves, respectively, of a bulk Inconel 718 alloy.

findings indicate significant differences in the mechanical properties of the AM part between the x- and z-directions. As depicted in Fig. 5, both Young's modulus and shear modulus in the z-direction were greater than those in the x-direction. This phenomenon may be attributed to the tendency of AM part crystals to grow preferentially in the z-direction. The values of Young's modulus (E) and shear modulus (G) in the x-direction tended to increase with distance from the base plate. An equation has been developed to relate volume porosity to E. A comparison of the density of Inconel 718 round bar with AM parts in AUW320 indicates a volume porosity of 1.6%. According to equations (1) and (2) in ref. 1, E is calculated to be 194 GPa, which closely approximates E in the z-direction.

4. Results

The mechanical properties of AM parts vary based on their location and orientation. To enhance the reliability of AM parts, it is crucial to perform non-destructive evaluation using LU.

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References

1) J. A. Choren, S. M. Heinrich, M. B. Silver-Thorn, J Mater Sci 48 5103 (2013).

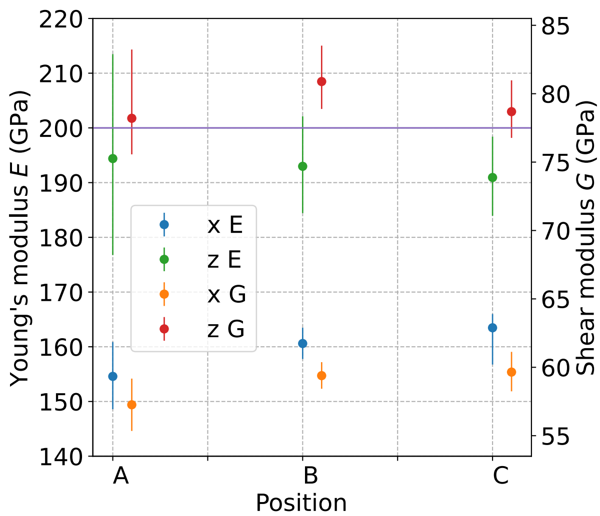

Fig. 5 Position and direction dependence of Young's and shear modulus of AM parts. Purple line indicates E and G of a bulk Inconel 718 alloy.