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INVESTIGATION OF NONLINEAR ULTRASONIC BEHAVIOR OF ADDITIVE MANUFACTURED MATERIAL WITH NRUS AND SHG METHODS.

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ABSTRACT

It has been reported that the layer-on-layer joining process of AM and resulting high temperature gradients produces excessively high dislocations, which can bring a significant impact on the mechanical properties of AM printed components. This research investigates the nonlinear ultrasonic behavior of additive manufactured (AM) materials using nonlinear resonance ultrasound spectroscopy (NRUS) and second harmonic generation (SHG). The specific AM materials to be examined are a 316L specimen manufactured by powder bed fusion (PBF) and a 304L specimen manufactured with Laser Engineered Net Shaping (LENS). As a simulation of post-heat treatment of AM parts, the specimens are annealed for different periods and are examined with the two experimental methods.

Keywords: nonlinear resonance ultrasound spectroscopy (NRUS), second harmonic generation (SHG), additive manufactured materials

NOMENCLATURE

AM	additive manufacturing
NRUS	nonlinear resonant ultrasound spectroscopy
SHG	second harmonic generation
K_0	linear modulus
ε	strain
β	classical quadratic nonlinearity parameter
δ	classical cubic nonlinearity parameter
α	nonclassical hysteretic nonlinearity parameter
$\Delta\varepsilon$	local strain amplitude
Δf	resonance frequency shift
f_0	resonance frequency at an infinitesimal excitation amplitude
A_1	amplitude of the fundamental wave
A_2	amplitude of the second harmonic wave
x	travelling distance between transmitter and receiver
c	plane wave speed of the Rayleigh wave
ω	angular frequency

1. INTRODUCTION

Additive manufacturing (AM) is the process of producing parts by gradually adding material until the final shape is reached. This is a fundamentally different approach than the traditional subtractive manufacturing, where material is removed. AM makes possible a variety of new shapes, materials and microstructures and enables low volume production or mass personalization [1].

Nevertheless, the properties of AM-processed materials are fundamentally different from objects made by traditional methods such as casting or forging. Due to the process AM materials show among others metallurgical defects, residual stresses, dislocations or anisotropic microstructures [1], [7]. In order to be able to use AM-processed materials in structural parts of consumer products, it is imperative to better understand these materials and to develop practical non-destructive material testing methods to ensure the durability of the material.

Currently, the remaining fatigue life is estimated by basic calculations, FEM methods or empirical models, and therefore relies on a projection from known circumstances to the present problem. This approach concentrates on a specific cause for the aging and ignores all possible other causes for a shorter fatigue life. In opposition to this, the method of non-destructive material testing is capable of estimating the remaining fatigue life of the present problem under consideration of all possible influences because the actual material can be tested.

This research aims to evaluate the capability of two main non-destructive material testing methods, NRUS and SHG, to detect defects and predict the remaining fatigue life.

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2. MATERIALS AND METHODS

This research investigates the nonlinear behavior of additive manufactured material. Therefore the techniques of nonlinear resonance ultrasound spectroscopy (NRUS) and second harmonic generation (SHG) are used.

2.1 Theory and Experimental Methods

2.1.1 Stress-Strain Relationship for nonlinear Materials

When the linear stress-strain relationship of Hooke's Law does not apply, additional parameters are introduced be able to also describe classical and nonclassical nonlinear behavior. A one-dimensional constitutive equation which describes nonlinear behavior is given by the stress-strain relationship

$$\sigma = \int K_0(1 - \beta\varepsilon - \delta\varepsilon^2 - \alpha(\Delta\varepsilon + \varepsilon(t)\mathrm{sign}(\dot{\varepsilon})) + \ldots)\, d\varepsilon \qquad (1)$$

where K_0 is the linear modulus, β and δ are the classical quadratic and cubic nonlinearity parameters, α is the nonclassical hysteretic nonlinearity parameter, $\Delta\varepsilon$ is the local strain amplitude and $\dot{\varepsilon}$ is the strain rate with the sign function of the strain rate, $\mathrm{sign}(\dot{\varepsilon})$ [2].

2.1.2 NRUS

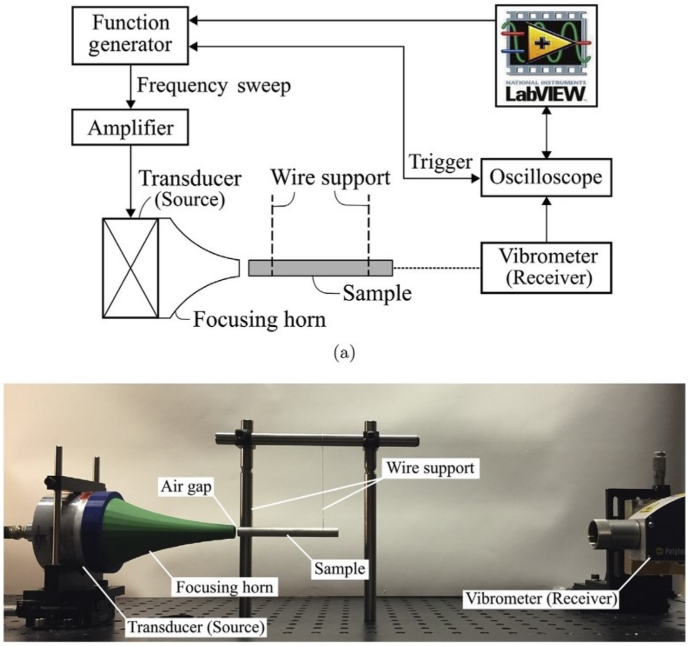
NRUS is a measurement technique which makes use of the varying resonance frequency for changing excitation amplitudes. This effect is due to nonclassical nonlinear behavior in the investigated material which is thought to be caused by soft regions in hard materials, i.e. microcracks, dislocations, etc [3], [4].

The hysteretic nonlinearity parameter α is then determined by the relationship

$$\frac{\Delta f}{f_0} = \frac{f - f_0}{f_0} = \alpha\Delta\varepsilon \qquad (2)$$

where Δf is the resonance frequency shift and f_0 is the resonance frequency at an infinitesimal excitation amplitude [5]. During the measurement the resonance frequency shift is determined and f_0 is linearly extrapolated from the resonance frequency to local strain amplitude measurement readings.

The experimental setup used implements a noncontact NRUS measurement. Thus, both the transmitter and receiver do not interfere the desired free-free boundary conditions. In addition, a possible influence on the measurement results of the bonding of transmitter or receiver is not possible. Figure 1 gives a schematic overview over the experimental setup. The specimen in form of a bar sample is hung on two cords to realize the free-free boundary condition best possible. In extension of the main axis of symmetry of the bar sample the transmitter penetrates the one end of the bar and the receiver measures the axial velocities at the other end of the bar. The excitation is realized with a transducer and an acoustic focusing horn to achieve the largest possible excitation. The receiver is executed in form of a laser vibrometer that measures the out-of-plane velocity at the center point of the cross section at the opposite end of the specimen. For every amplitude a frequency sweep is performed by the function generator. The resulting motion of the specimen is measured by the laser vibrometer and is saved for evaluation by the oscilloscope. To perform these steps for an equally spaced range of excitation amplitudes the process is automated with use of LabVIEW.



(a)

(b)

FIGURE 1: a) SCHEMATIC AND b) PHOTO OF THE NONCONTACT NRUS EXPERIMENTAL SETUP [4].

2.1.3 SHG

This measurement technique makes use of the effect of SHG. Therefore a specimen is penetrated with a monochromatic Rayleigh wave burst. After a specific traveling distance the amplitudes of the fundamental and second harmonic waves are measured. The classical quadratic nonlinearity parameter β is calculated with

$$\beta = 8\frac{A_2}{A_1^2}\frac{c^2}{\omega^2 x} \qquad (3)$$

where A_1 and A_2 are the amplitudes of the fundamental and second harmonic wave (respectively), x is the distance between transmitter and receiver, c is the plane wave speed, and ω is the angular frequency [6].

Figure 2 shows a schematic representation of the experimental setup. The function generator generates a monochromatic burst which is amplified and, through a transducer and a specially designed wedge, results in a Rayleigh wave in the specimen. An air-coupled transducer receives the signal which is then post-amplified and saved for evaluation. This procedure is repeated for a range of traveling distances of the Rayleigh wave.

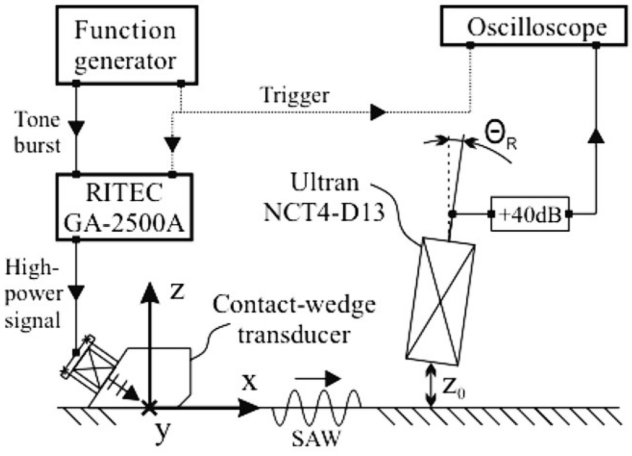


FIGURE 2: SCHEMATIC OF SHG EXPERIMENTAL SETUP [6]

2.2 Material

For this research two AM-materials with different chemical composition and different manufacturing process will be studied. The materials are 316L and 304L and are both variants of stainless steel with low carbon content. The main difference is that 316L has a higher concentration of molybdenum which leads to a slightly better corrosion resistance. The 316L specimen is manufactured by powder bed fusion (PBF). In this process a layer of powder is selectively melted with thermal energy provided by a laser or electron beam. The fused powder combines to the last layer so that a solid body forms layer by layer. The other specimen (304L) is manufactured with Laser Engineered Net Shaping (LENS). This process uses a high-power laser which heats a substrate onto which a powder is placed straightaway. [7]

3. RESULTS AND DISCUSSION

Because there does not exist any results for the AM materials yet the results of another material are presented. These results demonstrate the capability of the NRUS method to detect microstructural changes in the material.

Figure 3 shows the results for a 17-4 PH sample. The samples are thermally aged at 400 °C for 0, 0.1, 1 and 6 hours respectively. All the values are normalized to their respective un-aged value. Both, the values for α and β show a trend over the aging process. [4]

4. CONCLUSION

The example shows, that the NRUS method is able to detect aging processes in the material. The results are similar to the SHG measurements but are more sensitive. [4]

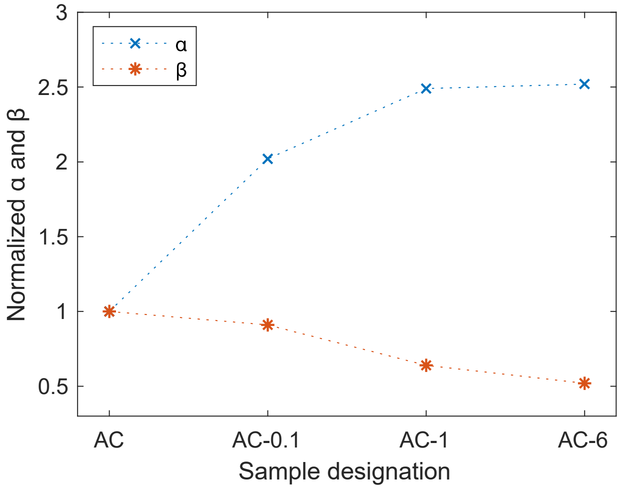


FIGURE 3: COMPARISON OF α AND β FOR INCREASING AGING TIME. ALL VALUES ARE TAKEN FROM [4].

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