Material Characterization of Metals Under Ultrasound

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Introduction

Motivation

- To understand the macro dynamics of Ultrasonic Additive Manufacturing (UAM), the effect of ultrasound on material properties should first be understood
- Langenecker discovered an appreciable decrease of stress in metal materials when subjected to ultrasound, which he defined as "acoustic softening" phenomenon[1]. But the underlying principle has been under dispute for decades. This research dedicates to investigate the phenomenon and propose a feasible explanation.

Langenecker 's Experiment

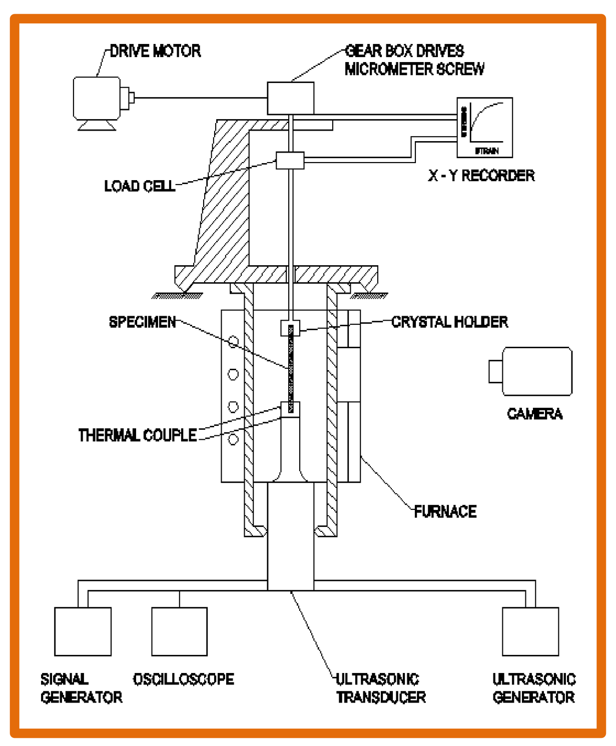

Figure 1. Experiment Apparatus and instrumentation reproduced from Langenecker [1]

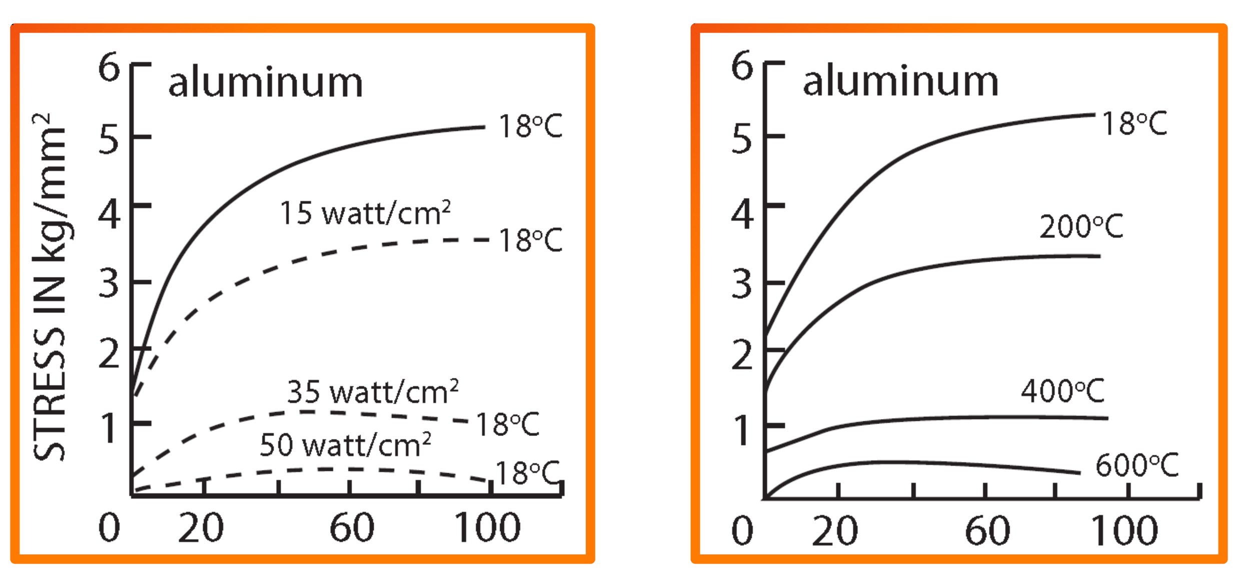

Figure 2. Softening effect of ultrasound (left) and softening effect of temperature(right) of Aluminum reproduced from Langenecker [1]

Different hypotheses of causes to acoustic softening

- **Localized energy absorption in materials**

Langenecker explains acoustic softening by the hypothesis that ultrasonic energy is preferentially absorbed at metal dislocation regions, which are responsible for plastic deformation. The dislocations , "activated" by absorbed energy, can break away from their pinned position and move through crystals, thus facilitating plastic deformation.

- **Superposition of stresses**

Nevill and Botzen put forward the hypothesis that the real yield stress is reached by adding static tensile stress and dynamic(acoustic) stress[2]. The acoustic softening is simply a result of measuring static tensile stress without accounting for acoustic stress. Notice that this hypothesis lies on the assumption that the ultrasonic oscillation is aligned with tension, we propose to modify the oscillation direction to different angles with respect to tension to see if the acoustic softening effect is weakened.

Initial Research

Linear Mathematical Model of Dynamic Response

- Build by hand a linear analytic model, consider the test sample as Euler-Bernoulli beam with linear elastic material properties
- Propose a double transformation procedure to deal with the unique boundary conditions: oscillation at one end and tension with constant strain rate at the other end
- Solve the transformed boundary value problem for dynamic response

Original Model → Double Transformation → Boundary Value Problem

Original Model:

disp $u(x,t) \quad 0 \le x \le L, t \ge 0$

Equation $\frac{\partial^2 u}{\partial t^2} - \frac{E}{\rho}\frac{\partial^2 u}{\partial x^2} = 0$

BC $u(0,t) = X\cos(\Omega t)$, $\frac{\partial^2 u}{\partial x \partial t}(L,t) = \dot{\varepsilon}$

IC $u(x,0) = 0$, $\frac{\partial u}{\partial t}(x,0) = 0$

$$u(x,t) = u_B(t) + u_R(x,t), \quad u_B(t) = X\cos(\Omega t)$$

Double Transformation:

$$u_R(x,t) \quad 0 \le x \le L, t \ge 0$$
$$\frac{\partial^2 u_R}{\partial t^2} - \frac{E}{\rho}\frac{\partial^2 u_R}{\partial x^2} = X\Omega^2\cos(\Omega t)$$
$$u_R(0,t) = 0, \quad \frac{\partial^2 u_R}{\partial x \partial t}(L,t) = \dot{\varepsilon}, \quad u_R(x,0) = 0, \quad \frac{\partial u_R}{\partial t}(x,0) = 0$$

$$u_R(x,t) = u^*(x,t) + \dot{\varepsilon}xt$$

Boundary Value Problem:

$$u^*(x,t) \quad 0 \le x \le L, t \ge 0$$
$$\frac{\partial^2 u^*}{\partial t^2} - \frac{E}{\rho}\frac{\partial^2 u^*}{\partial x^2} = X\Omega^2\cos(\Omega t)$$
$$u^*(0,t) = 0, \quad \frac{\partial u^*}{\partial x}(L,t) = 0, \quad u^*(x,0) = 0, \quad \frac{\partial u^*}{\partial t}(x,0) = -\dot{\varepsilon}x$$

Figure 5. Dynamic response modeling with assumption of linear elastic material

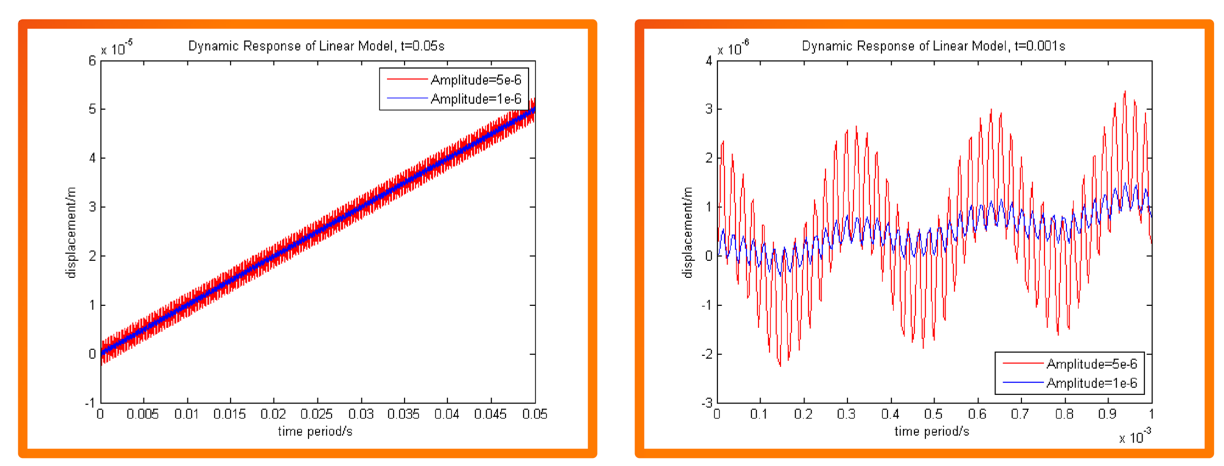

Figure 6. Dynamic response of model

Nonlinear Finite Element Model of Materials

- Build Finite Element material model with consideration of nonlinear (plastic) deformation using the same set of parameters as Langenecker
- Characterize the material behavior ***without*** considering localized energy absorption in micro scale

Table 1. Part of model specification used in simulation

Diameter	Length	Mass Density	Young's Modulus	Poisson's Ratio
1.5 mm	30 mm	2700 kg/m^2	69.3 GPa	0.33

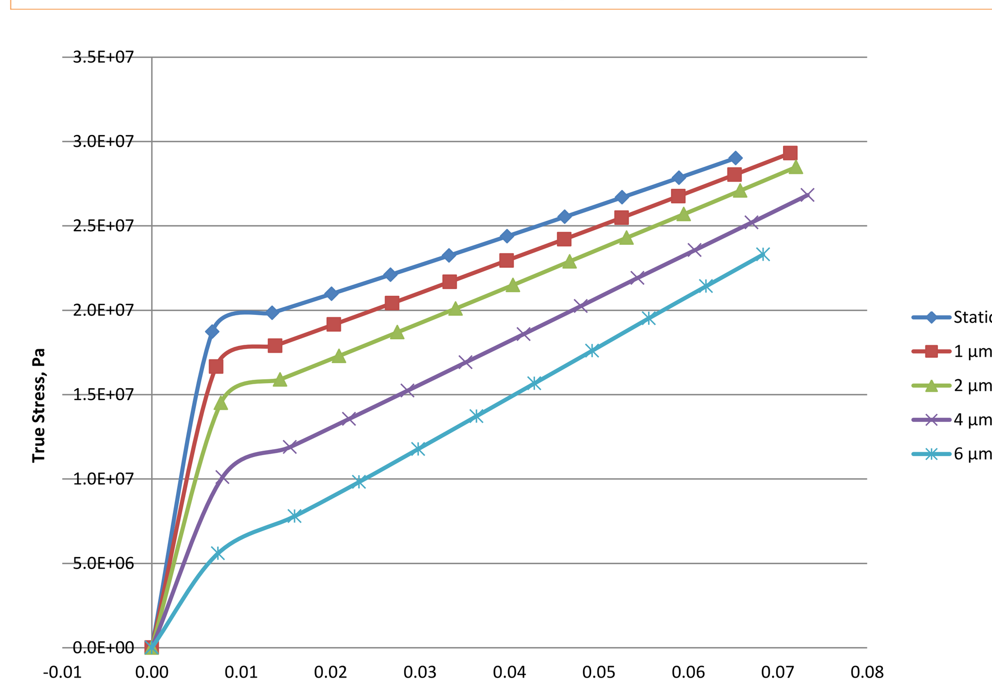

Figure 4. Stress strain curves with varied ultrasonic intensity

Experiment

Reproduce Langenecker's experiment by modifying commercial Instron Tensile test machine and attaching to a Branson 2000 Series Ultrasonic welder. Instron machine apply tension at one end and Branson welder apply ultrasonic oscillation at the other end

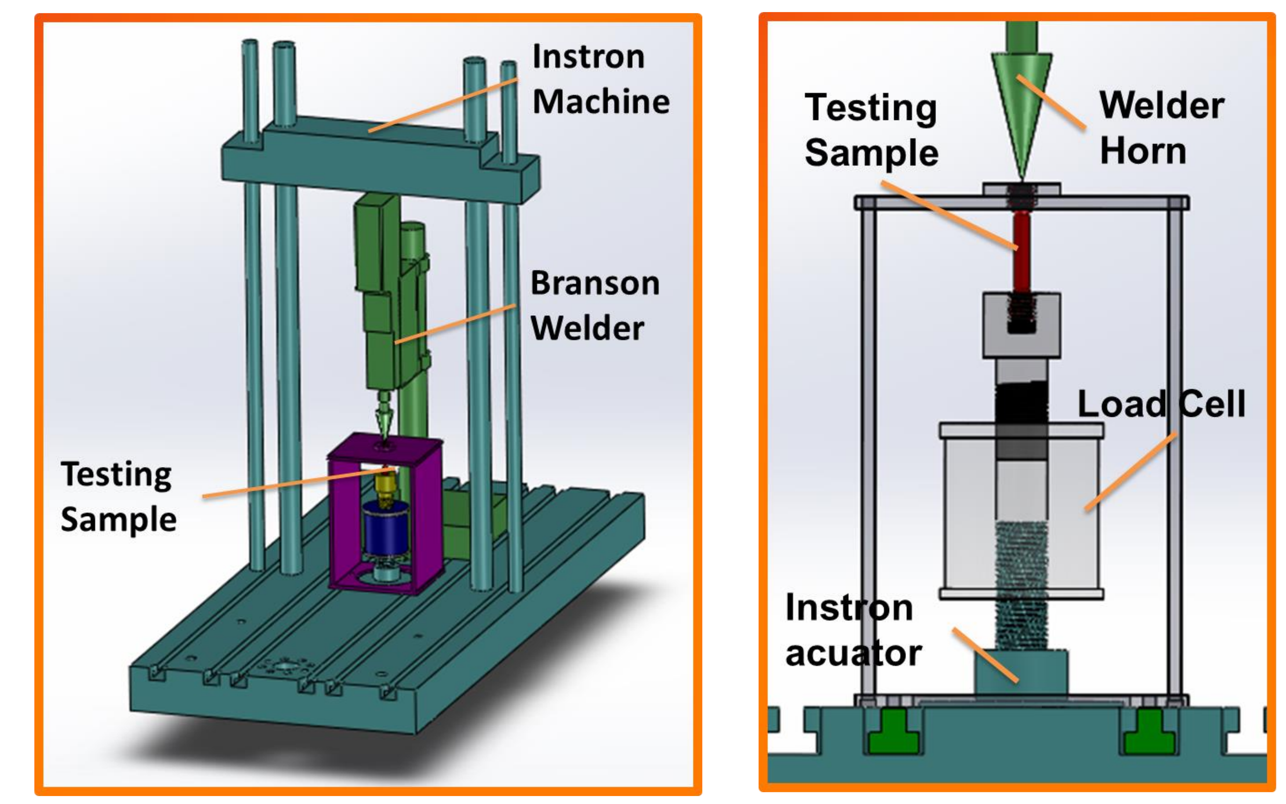

Figure 3. Experiment apparatus and test sample installation

In conducting the experiment, we need to

- Redesign and manufacture ultrasonic horn to conical shape with feasible dimensions, strength and tune the horn to resonate at 20 kHz
- Design and manufacture frame with feasible strength, avoid resonance at 20 kHz
- Design and manufacture actuator to adjust the direction of ultrasonic oscillation by adjusting the posture of ultrasonic welder.

Conclusions

- The stress strain curves obtained using finite element method are analogues to curves obtained from Langenecker's experiment, which suggests that dynamics could be the cause
- The linear elastic analytical model shows that changing of ultrasound intensity/amplitude does not change the mean value of strain/stress, i.e., linear elastic deformation of metals is not affected by ultrasound.

Future Work

- Continue experimental work and compare the data with existing data in papers
- Based on the linear model, build non-linear analytical model of dynamic response, plug in material plasticity data obtained from experiments to model the plastic deformation of metals
- Rebuild the FEM model with material plasticity data obtained from experiment and compare results with that of analytical model

References

[1] B. Langenecker, "Effect of sonic and ultrasonic radiation on safety factors of rocket and missiles," AIAA Journal, 1963.

[2] Nevill, G. E., & Brotzen, F. R. (1957). The effect of vibrations on the static yield strength of a low-carbon steel. Proceedings of Am. Soc. for testing materials, (pp. 751-758).

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