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Analysis of Energy Flow to the Interface Microstructure and Its Effect on Weld Strength in Ultrasonic Additive Manufacturing

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Abstract: Ultrasonic additive manufacturing (UAM) is a process used for the three-dimensional printing of metal foil stock that can produce near-net-shaped metallic parts. This work details the development of an energy-based tool to identify the relationships between input energy, energy stored in the interface microstructure, and the strength of the weld interface in UAM. The stored energy in the grain boundaries of the crystallized grains in the interface microstructure are estimated using the Read–Shockley relationship. The energy stored in the interface is found to be positively correlated with the resulting weld strength. An energy flow diagram is developed to map the flow of energy from the welder to the workpiece and quantify the key participating energies such as the energy of plastic deformation, energy stored in the interface microstructure, energy required for asperity collapse, and heat generation. A better understanding of the flow of energy in UAM can assist in optimizing the process to maximize the portion of energy input by the welder that is used for bond formation.

Keywords: ultrasonic additive manufacturing (UAM); additive manufacturing; process energy map; electron backscatter diffraction (EBSD); microstructure analysis



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1. Introduction

Ultrasonic additive manufacturing (UAM) is a solid-state 3D printing process based on continuous ultrasonic metal welding. The system can typically draw up to around 9 kW for welding and is capable of welding a wide range of material combinations: from soft metals like 3000 series aluminum [1] and higher-strength materials such as 6000 series aluminum [2], steel [3], and titanium [4] to dissimilar materials such as steel and tantalum [5]. The welding or additive stage of the process works by bringing a cylindrical tool piece called the welder, sonotrode, or horn into contact with a metallic foil under controlled pressure. The sonotrode is actuated at a nominal resonance frequency of 20 kHz and connected, using a waveguide, to piezoelectric transducers that work in a push–pull configuration [6,7]. The sonotrode scrubs the metallic foil against pre-deposited metal foils or a baseplate metal beneath. The parameters controlled during welding include the normal force (weld force), amplitude set point of oscillation (weld amplitude), preheat temperature, and speed of rolling (weld speed). Bond formation in UAM occurs as follows: the applied pressure from the welder collapses the asperities of the two foils being welded; the applied ultrasonic vibrations and the resulting severe plastic deformation assist in the plastic flow of the foil material, as well as in the dispersal of oxides and contaminants, enabling nascent metal contact and welding. This figure details the working of the SonicLayer 4000 machine with the two Dukane ultrasonic transducers, each rated to 4.5 kW, used in this study to fabricate metal parts using UAM.

How the strength of UAM joints is affected by different process parameters and operating conditions is not well understood. The different energies involved and their

relative importance to the strength of the weld are also not well understood [8]. The energy of plastic deformation is also found to be a key driver of bond formation and an analytical expression of the relationship between weld strength and this energy was developed in [9]. Plastic deformation is a critical factor for redistributing the oxide layer for mechanical interlocks and it fills the gaps between the mating elements during bond formation in UAM [10]. It is shown in [11] that cycles of mechanical deformation imparted by the welder under pressure can lead to the cracking of the aluminum oxide layer, which can then be dispersed to enable nascent metal contact between the foils and thus bond formation. Imaging techniques like Transmission Electron Microscopy (TEM) have been used to image the oxide layer of aluminum samples welded using UAM [12]. In this work, the energy required to disperse the oxide layer is estimated from TEM measurements of the as-received Al 6061-H18 foil mentioned in [13].

The energy of plastic deformation, which is used to deform the foil material, results in some of the energy E_{disl} being stored in the foil microstructure as dislocations while the remainder is dissipated as heat [14]. It is also shown in [15] that geometrically necessary dislocations (GNDs) are the predominant type of dislocations in UAM and determine the subgrain diameter of the resulting microstructure. While early work in the field used optical microscopy to image the weld interface [16], electron backscatter diffraction (EBSD) is the technique commonly used to visualize the grain orientations, grain boundaries, and subgrain sizes in weld interfaces in UAM [10,17,18]. The weld interface is observed to contain a narrow region of small, mostly equiaxed, recrystallized grains, expected to form from continuous dynamic recrystallization driven by high-strain-rate plastic deformation due to the ultrasonic vibrations and pressure generated [5]. In this work, EBSD is used to characterize the interface microstructure, as it can be used to calculate misorientation angles, the fractions of high- and low-angle boundaries, and the size of subgrains, which can be used to quantitatively estimate the energy stored in the interface microstructure using the procedure in [19]. Previous work on modifying the interface microstructure of as-welded Al 6061 with the heat treatments shown in [20] has shown improvements in fracture stress, which are a direct effect of microstructural changes such as grain growth.

Of the energies participating in the UAM process, the energy required to collapse the asperities and enable nascent metal contact has not been quantified in detail. In this work, an upper bound for this energy is developed analytically. The contribution of this energy to weld strength can help us understand whether pre-weld surface treatments can improve the strength of welds in UAM. In other metal–metal joining processes such as adhesive bonding, resistance welding, and roll bonding, physical or chemical preparations such as wire brushing or chemical etching of the surface are crucial to obtain good bond quality [21], but this is usually not the case for UAM. The work in [22] shows that for the UAM of Al 3003 to copper, changing the roughness of the copper foil from 0.17 to 1.17 μm does not produce a statistically significant increase in mechanical strength, as measured using a push-pin test, and produces only a small increase in the energy of failure for samples with higher roughness. This work expands on this study by quantifying the contribution of the energy required to collapse asperities and studying the impact of pre-weld foil surface roughness on weld strength.

The relationship between the input energy and weld strength has been investigated in prior work by [8], but detailed investigations of the participating energies and their effect on weld strength has not been studied to deduce the impact of changing process inputs. To this end, the different participating energies in UAM are quantified in this work by developing an energy flow diagram, and their correlation with weld strength is investigated, as well as their relationship to process inputs such as the vibration amplitude of the welder or weld amplitude, the traversal speed of the rolling welder or weld speed, the normal force applied or weld force, the preheat applied to the baseplate, and baseplate geometry. The effect of baseplate geometry on the input electrical and mechanical energies is detailed in [23]. The correlations between the strength of joints welded using UAM and the different energies involved are also investigated to better understand the selection of

process inputs to optimize weld strength and also optimize the UAM process by reducing the sources of lost energy, such as losses in the welder and heat conduction to the welder.

2. Materials and Methods: Energy Flow Diagram

All UAM samples were manufactured with a 9 kW SonicLayer 4000 UAM system, shown in Figure 1, from Fabrisonic, based in Lewis Center, Ohio, USA. It was designed with a nominal resonant frequency of 20 kHz. A cylindrical steel sonotrode with a diameter of 96.77 mm (3.81 inch) and a width of 28 mm (1.1 inch) was used to weld the foils. The discussion in this manuscript applies to the welding of any metal combination using UAM, but the data presented are from the commonly welded aluminum alloy Al 6061-H18. The composition of this alloy can be obtained from [24]. The thickness of the 25.4 mm (1 inch) wide foil feedstock is 152 μm . The samples were welded, using a 9 kW UAM welder, onto an Al 6061-T6 baseplate, and the nominal UAM process conditions used were a 32 μm weld amplitude, 5000 N weld force, and 84.67 mm/s (200 in/min) weld speed. The energies participating in the UAM process are listed below.

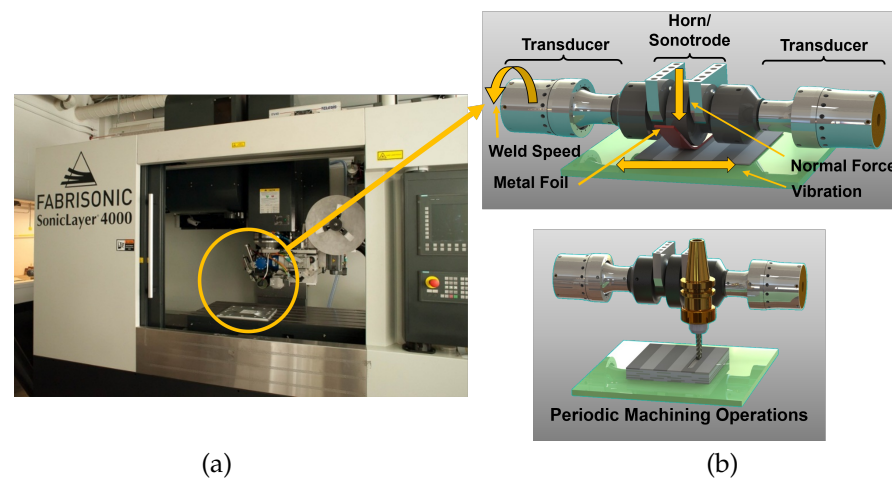


Figure 1. Fabrisonic 9 kW SonicLayer 4000 ultrasonic additive manufacturing system: (a) a cylindrical steel sonotrode attached to 9 kW piezoelectric transducers in a CNC framework; (b) the additive stage, where foils are welded under a combination of normal pressure and 20 kHz vibratory motion from the sonotrode, which rolls at a set speed, and the subtractive CNC stage, which is used to introduce complex internal features and to trim components to near-net shape.

2.1. Welder Losses

The efficiency of the piezoelectric transducers that are part of the weld assembly are estimated to be around 80 and 85% in the work of [25]. The energy lost E_{wloss} per unit of weld length is lost as heat in the transducer and waveguide components and quantifies the efficiency of the welder assembly in transferring the input energy per unit length, E_{ip} , to the welded sample. This efficiency e can be redefined from the expressions in [25] in terms of E_{ip} as

$$e = \frac{\frac{1}{2}\delta F_s}{E_{ip} \cdot |\dot{x}|}, \quad (1)$$

$$= 1 - \frac{E_{wloss}}{E_{ip}}, \quad (2)$$

where $|\dot{x}|$ is the traversal speed of the welder or the weld speed, δ is the welder vibration velocity, F_s is the shear force applied by the welder, and E_{ip} is the ratio between the electrical power draw into the transducers and the weld speed. The welder efficiency e defined in (2) is largely unaffected by the normal force applied by the welder and is found to decrease slightly with increasing weld amplitude.

2.2. The Energy of Plastic Deformation

The energy of plastic deformation is a key driver of bond formation and bond strength in UAM. The work of [9] details a simplified coupled thermal–mechanical model for UAM to estimate this energy per unit length of the weld, E_{pl} , as

$$E_{pl} = \frac{a}{|\dot{x}|} F_s \left(|\dot{\delta}_{welder}| - \int_{-a}^a \frac{\tau(x)}{F_s} |\dot{\delta}_{slip}(x)| w dx \right), \quad (3)$$

where $|\dot{x}|$ is the weld speed, and the values for the contact half-width a , shear force F_s , welder vibration velocity $\dot{\delta}_{welder}$, shear stress $\tau(x)$, and slip velocity of the foil $\dot{\delta}_{slip}$ are estimated from the simplified analytical model of foil deformation. The fraction of the energy that is dissipated as heat is given by the Taylor–Quinney coefficient, β , and a typical value of 0.9 is chosen for aluminum [26]. The remaining energy E_{disl} is stored in the foil microstructure as dislocations.

2.3. Frictional Energy Dissipation

The energy associated with frictional slip, E_f , is calculated in [9], using the coefficient of friction μ , as

$$E_f = \frac{a}{|\dot{x}|} \int_{-a}^a \mu \sigma(x) |\dot{\delta}_{slip}(x)| w dx, \quad (4)$$

where $\sigma(x)$ is the normal stress in the foil material. This energy contributes to the temperature increase near the weld interface. Understanding this temperature rise is also critical to finding acceptable process parameter ranges to embed temperature-sensitive components using UAM, as detailed in [9], where a thermal FE model was validated using in situ infrared measurements of the process temperature.

2.4. Heat Generation

The heat generated Q in the UAM process is mainly from two sources—frictional slip and heat generation from plastic deformation. This heat generation contributes to the increase in temperature during the process. This increased temperature of the foil material can also affect the energy of the plastic deformation by lowering the local yield strength.

$$Q = E_f + \beta E_{pl}, \quad (5)$$

The uniaxial tensile strength of as-received Al 6061-H18 foil was measured at different temperatures. The measurements were conducted using an MTS system to test 0.152 mm thick and 25.4 mm wide Al 6061-H18 foil in a temperature-controlled chamber. The shear strength was then estimated as $1/\sqrt{3}$ of the tensile strength. Its yield strength decreases with an increase in temperature, while its ductility increases. For the range of weld parameters used in this study, from the infrared measurements of in situ weld temperature in [9], it is known that the peak temperature does not exceed 93 °C (200 °F) for the UAM of Al 6061-H18, and hence, from Figure 2, the flow stress is expected to decrease by about 10 %. In order to simplify model calculations, this effect is not modeled in the energy flow diagram. This effect can also be used to demonstrate how an increase in the preheat temperature of the baseplate can result in UAM welds with a higher mechanical strength, as observed in [27], as there is an increase in the energy of plastic deformation available for the same applied vibration amplitude. Further investigation into the effect of the preheat temperature is left for future studies, as it is beyond the scope of this study.

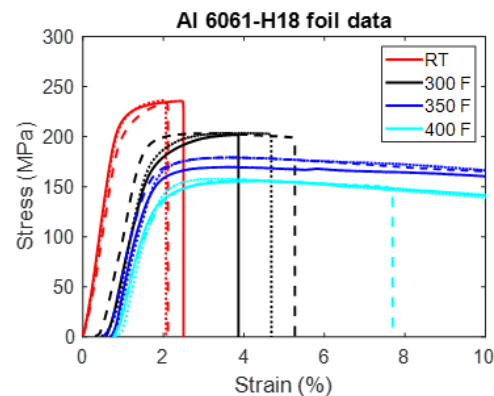


Figure 2. Stress–strain curves from uniaxial tensile testing of as-received Al 6061-H18 foil, conducted at different controlled temperatures of 86 °F (RT or 30 °C), 300 °F (149 °C), 350 °F (177 °C), and 400 °F (204 °C). Replicates are shown using dotted and dashed lines.

2.5. Energy Required for Asperity Collapse

UAM requires the contact of nascent metal surfaces for solid-state bonding to occur successfully, which is enabled by asperity collapse and oxide layer removal [28]. The roughness of the surface needs to be studied to investigate the energy required for the collapse of asperities. The surface roughness profile of a surface can be characterized using different metrics, with the most common statistical measures used being R_a and R_q [29,30]. For a surface with profile $z(x)$, these metrics are given by

$$R_a = \frac{\int |z(x)| dx}{\int dx} = \text{avg}(|z(x)|), \quad (6)$$

$$R_q = \sqrt{\frac{\int |z(x)|^2 dx}{\int dx}}. \quad (7)$$

The surface of the UAM welder is typically textured to increase the grip between the weld foil and the welder. The texture is produced using electrical discharge machining (EDM) to create a roughened texture with an R_a value typically between 11 and 14 μm [31]. This also imparts a rough texture to the deposited foil.

The top surface of the textured sample was characterized using vertical scanning interferometry with a Bruker Contour GT-K optical profilometer, as shown in Figure 3. Vertical scanning interferometry, or VSI, was used as it is better suited to measuring the profile of very rough surfaces when compared to phase-contrast interferometry [32]. The sampled profile of the rough weld foil is shown in Figure 4. The sample was fabricated by welding two layers of Al 6061-H18 foil onto an Al 6061-T6 baseplate. Green light was used instead of the typical white light for the measurements as the narrower bandwidth of illumination creates a substantially longer fringe envelope, which helps to better image samples with large roughness values.

To calculate the energy required to collapse the asperities, a simplified model of the asperities as cuboids with height z is developed, and thus their total volume per unit length of weld foil can be estimated as the product of the width of the foil feedstock w , which is 25.4 mm (1 inch), and its height $z(x)$. The average asperity height can be estimated from the average of the raw profile height data $z(x)$ from the profilometer. Since this method is time-intensive, only one representative sample was imaged, which is shown in Figure 4, and the average asperity height, or R_a from (6), was calculated from measurements using a Mitutoyo SJ210 contact surface roughness gauge.

The upper bound for the energy required to collapse the asperity can be estimated using the failure energy of the bulk material and the volume of the asperities. An up-

per bound for the average energy required for asperity collapse, E_{asp} , can be estimated as follows:

$$E_{asp} = \frac{1}{2} \tau_f \gamma_f w \text{ avg}(|z(x)|) w = \frac{1}{2} \tau_f \gamma_f R_a w, \quad (8)$$

where τ_f is the shear stress at failure, and γ_f is the shear strain at failure. The uniaxial tensile strength value of Al 6061-H18 at room temperature was measured to be 242 MPa from Figure 2. Its shear stress at failure is estimated to be $1/\sqrt{3}$ of the uniaxial tensile strength value, about 140 MPa. The shear strain at failure is not available in the open domain for Al 6061-H18, but is available for a different precipitation-hardened alloy Al 6061-T6, which has a 28% higher tensile strength [33] than that of the Al 6061-H18 foil used (Figure 2). The value for the shear strain at failure of 0.6 was used as an upper bound for the foils welded, using the value for Al 6061-T6 from [34]. This is possible as the fully hardened H-18 temper of 6061 aluminum is expected to have a lower shear strain at failure than the artificially aged T6 temper. The possible error from this overestimation will be the same for all the samples tested so their energies can still be compared.

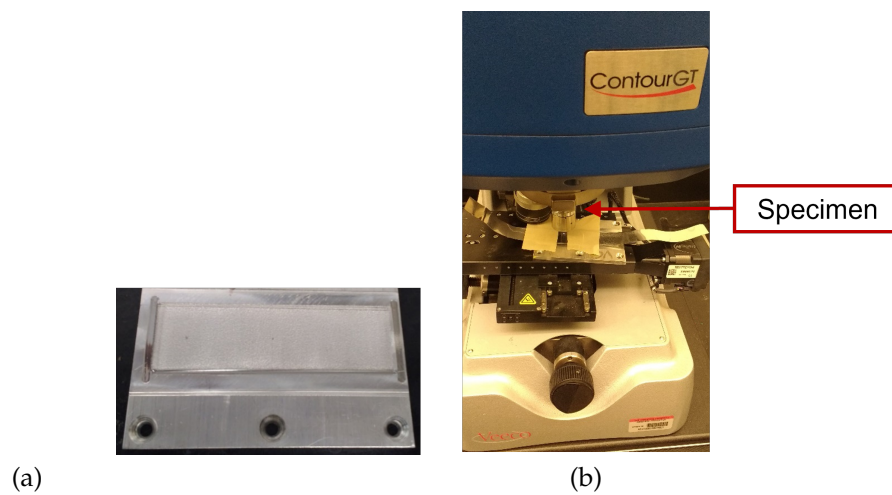


Figure 3. Optical profilometry setup: (a) specimen with 2 layers of Al 6061-H18 foil welded onto a Al 6061-T6 baseplate; (b) Bruker Contour GT-K optical profilometer used for non-contact roughness measurement using vertical scanning interferometry (VSI).

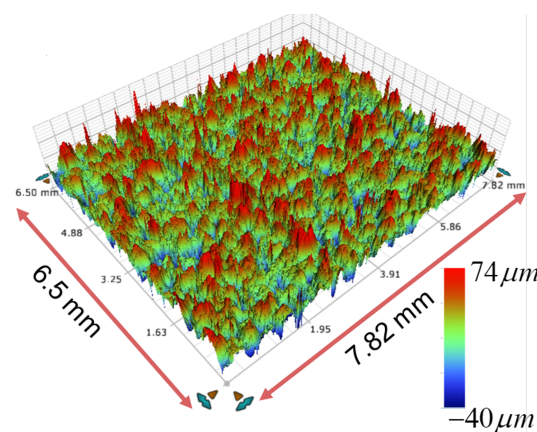


Figure 4. Three-dimensional surface profile of an as-welded Al 6061-H18 foil welded using UAM with the following weld parameters: 28 μm weld amplitude, 5000 N weld force, and 84.67 mm/s (200 in/min) weld speed. The profile was measured using a Bruker GT-K optical profilometer using vertical scanning interferometry.

The impact of the roughness of the foil surface on the shear strength of the resulting welded joint, or weld strength, was investigated in [13]. The R_a values varied from 0.1 μm

for a machined surface to $7.5\ \mu\text{m}$ for a roughened foil surface prepared using the welder in a process called pretexturing. The energy required to collapse the asperities for the $25.4\ \text{mm}$ ($1\ \text{inch}$) wide foil of Al 6061-H18 can be estimated for each case. The energy input in the different cases was observed to be unaffected by the roughness changes. An upper bound for the energy for asperity collapse can thus be estimated by (8) to be $8\ \text{J/m}$ for the samples with an R_a of $7.5\ \mu\text{m}$, which is about 0.06% of the input electrical energy, and $0.1\ \text{J/m}$ for the machined sample with an R_a of $0.1\ \mu\text{m}$.

2.6. Energy Required to Disperse Oxide Layer

The successful welding of aluminum foils using UAM requires the breaking up and dispersal of the oxide layer. TEM imaging of the UAM weld interface [2] showed that the oxide layer is completely dispersed due to the normal and shear deformation occurring in the UAM process. The energy required to break up the oxide layer can be estimated from the thickness of the oxide layer and the failure strain of the aluminum oxide using the method detailed in [13]. The failure strain value for aluminum oxide was obtained from [35]. The welded sample of Al 6061-H18 was sectioned using a FEI Helios DualBeam FIB machine and a Technai 20 TEM microscope was used to produce Figure 5. The thickness of the oxide layer for Al 6061-H18 was measured, using TEM, to be less than $20\ \text{nm}$.

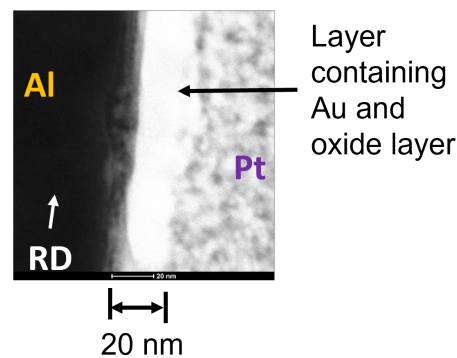


Figure 5. TEM measurements of air-grown oxide layer of as-received Al 6061-H18 foil at room temperature using a Technai 20 TEM machine, reproduced from [13]. The thickness of the oxide layer is found to be less than $20\ \text{nm}$. RD denotes the rolling direction of the welder. To the left is the as-received foil, and to the right is the deposited platinum and gold. The bright segment in the middle contains the oxide layer of the Al.

The brittle oxide film is expected to deform elastically until failure, and hence the energy required for the mechanical failure of the oxide layer per unit length, E_{oxide} , is estimated from the properties of alumina oxide to be about $4.7\ \text{mJ/m}$, as the ratio of the power required for oxide dispersal is $0.4\ \text{mW}$, from [13], and the weld speed value is $84.67\ \text{mm/s}$ ($200\ \text{in/min}$). In comparison to the typical input electrical power of $2000\ \text{W}$ needed to successfully weld Al 6061-H18 using a weld force of $5000\ \text{N}$, the energy required for this step is found to be very small. Hence, as long as a sufficient normal force and weld amplitude are applied to the metal foils to initiate welding and disperse the oxide layer, the energy required for this step is not expected to require a significant fraction of the energy available during the process.

2.7. Energy Stored in the Microstructure

The energy stored in the grain boundaries is estimated in the work [19] for samples prepared using different vibration amplitudes, from 23 to $32\ \mu\text{m}$. Although it only represents a small part of the input energy, it is important to understand how aspects of the microstructure of the weld interface, such as the degree of recrystallization and the volume of recrystallized grains around the weld interface, are affected by the process parameters. The energy stored in grain boundaries can be used as a metric to quantify these effects.

Changes to the microstructure of the post-weld sample due to the UAM process can be quantified using the process detailed in [19], where EBSD images are processed using the MTEX toolbox in MATLAB to identify grain boundaries.

The weld interface, shown in Figure 6 with dashed lines, is identified by a high concentration of small, equiaxed, recrystallized grains with a high density of high-angle grain boundaries (HAGBs). The bulk material is largely unaffected and contains mostly elliptical grains that are elongated in the direction of rolling, which are a characteristic of the as-received rolled foil stock. The histogram of misorientation angles is also found to have a peak of around 40–50 degrees near the interface, characteristic of a random distribution of recrystallized grains.

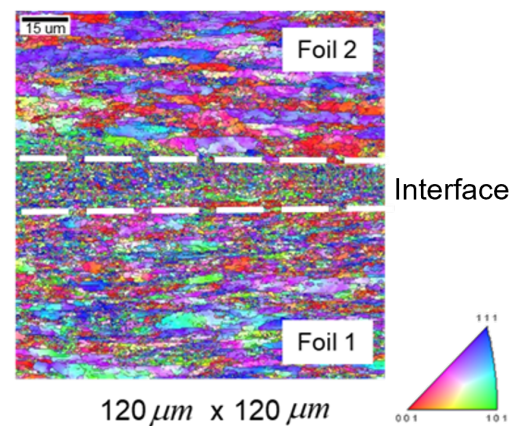


Figure 6. Inverse pole figure (IPF) from the EBSD analysis of a 2-layer Al 6061-H18 UAM sample fabricated on an Al 6061-T6 baseplate, reproduced from [19]. The colors in the figure indicate the grain orientation at each point and the dashed lines indicate the estimated boundaries of the weld interface.

The Read–Shockley relationship is then used to estimate the energy stored in the grain structure. The expression is given as

$$S = \sum_{\theta} \Omega_{GB} \cdot \gamma_{GB} \cdot \begin{cases} \frac{\theta}{\theta_m} (1 - \ln \frac{\theta}{\theta_m}), & \text{if } \theta \leq \theta_m \\ 1, & \theta > \theta_m \end{cases} \quad (9)$$

where θ is the angle of misorientation between a boundary pixel and its neighboring pixels, γ_{GB} is the grain boundary energy density of aluminum ($=0.324 \text{ J/m}^2$ [36]), and Ω_{GB} is the cross-section's area.

3. Weld Strength Measurements in Shear

UAM samples have a thin laminated construction, with subsequent layers usually welded onto previous ones, and this provides a challenge for their mechanical characterization. In previous work, characterization has been limited to push pin testing [37] and peel testing [1], which provided a means of comparing the interfacial strength of UAM builds, but these were not benchmarked against bulk properties. A fixture was developed in [38] to characterize the absolute shear strength of a specific weld interface in a UAM build, as shown in Figure 7c. This method is used to quantify the bond strength of UAM welds in comparison to the strength of the bulk foil material. Full-size samples were constructed using different sets of parameters and surface roughnesses by welding 23 layers of Al 6061-H18 on an Al 6061-T6 baseplate. Test coupons were then cut out of the full-size samples and machined to size, as shown in Figure 7a,b. The same build height was used for all the samples, as previous work by [37] has shown that welds at a further distance from the baseplate can have reduced weld strengths even when fabricated using the same

weld amplitude. This is expected to be due to the change in system compliance or acoustic stiffness with build height.

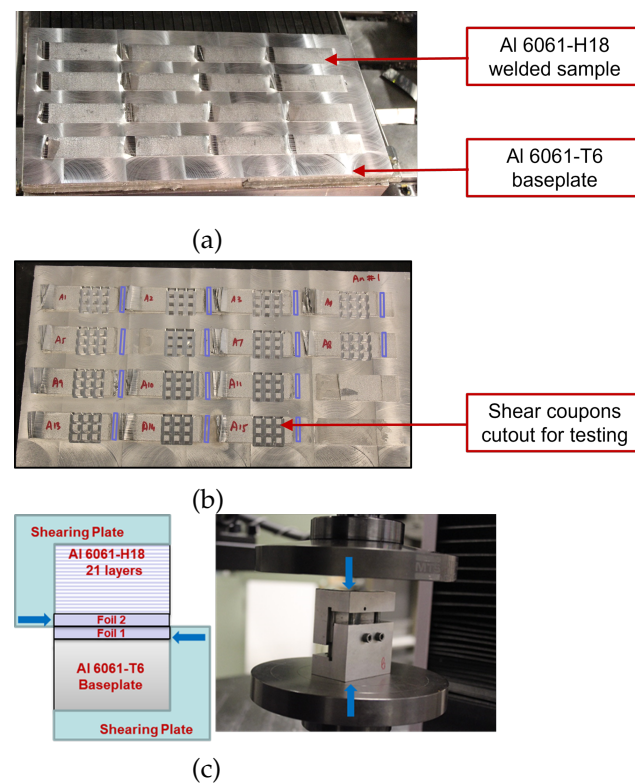


Figure 7. Steps for measuring the shear strength of a foil–foil interface in UAM: (a) 23-layers of Al 6061-H18 welded onto an Al 6061-T6 baseplate; (b) prepared mechanical testing coupons; (c) shear testing rig used with compression plates in an MTS load frame for testing the interface in shear.

The coupons prepared for shear testing, shown in Figure 7b, have a square cross-section with a side dimension of 0.195 mm. The effect of the direction of the shearing force relative to the directions of the foil rolling and welder travel is not expected to significantly affect the test results, since all the observed failures were brittle failures concentrated at the interface. Hence, the bulk material is not expected to contribute to the interface region, where the strength in shear is expected to depend mainly on the local microstructure, with its dynamically recrystallized grains and mechanical interlocking. The effect of the rolling direction could be more pronounced when the thickness of the foil is reduced such that the weld interface width is comparable to the thickness, and future work will investigate the contribution of the test direction to the measured weld strength in shear.

The force–displacement curves for the shear testing conducted on samples with different pre-weld surface roughness values, from an R_a value of 0.1 μm for the machined samples to a maximum R_a value of 7.5 μm , are shown in Figure 8. The geometry of the samples was designed so that the samples would fail by shearing at the foil 1–foil 2 interface, as shown in Figure 7c. The shear area during testing is a square cross-section with a side length of 0.195 mm. The shear stress was obtained by dividing the peak load by the shearing area of the sample. The strength value is normalized to the bulk shear strength of the foil material.

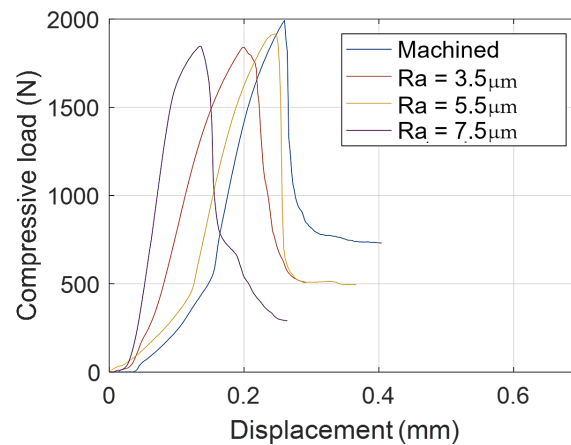


Figure 8. Representative force versus displacement curves of samples in shear prepared using different surface textures between foil 1 and foil 2 before welding. At least two replicates were used to compute the average curve for each surface texture value. The machined sample had an R_a value of 0.1 μm .

4. Energy Mapping of UAM

The participating energies in the UAM process can be related using Figure 9 and the following equation:

$$E_{ip} = E_{wloss} + E_{micro} + E_{disl} + E_{asp} + E_{micro} + \underbrace{Q}_{\beta E_{pl} + E_f} + E_{oxide}. \quad (10)$$

The interface temperature, which is a result of the different sources of heat generation, is coupled to the energy of plastic deformation through the reduction in yield strength of the foil material. The degree of coupling will depend on the type of foil used and its flow–stress relationships. The effect of the different process inputs in Figure 9 on the strength of the welded part can thus be studied from an energetic point of view using the framework developed.

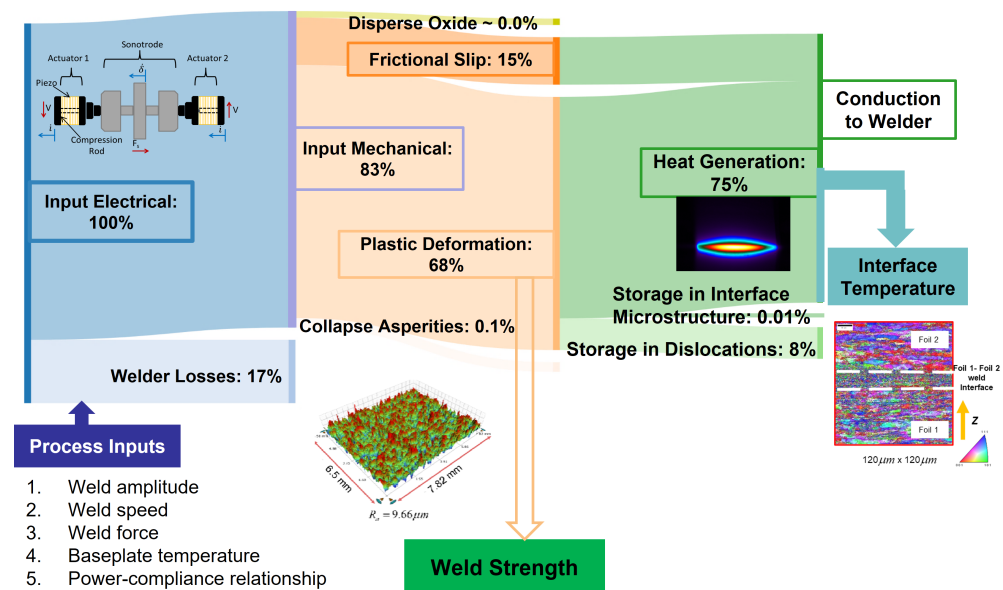


Figure 9. Energy flow of the UAM process, expressed using a Sankey diagram, for Al 6061-H18. Each step from left to right shows the conversion of energy from one form to another, starting from the input electrical energy to the piezoelectric transducers, with the energy normalized to 100%.

The models from the literature used to estimate the energies participating in the energy flow diagram in Figure 9 have limitations, but can be applied to create a good approximation of the UAM of Al 6061-H18. The model for estimating the energy for oxide removal is applicable only for the UAM of metals with brittle oxide layers, such as aluminum. Similarly, the model for estimating the energy of plastic deformation does not account for the hardening of the metal foil without an empirically calibrated parameter, but it can be used for the Al 6061-H18 foil since it is fabricated by inducing the maximum strengthening from cold rolling possible for the 6061 alloy, and further work hardening is not possible despite additional deformation from the UAM process.

Three different studies on the UAM of Al 6061-H18 using different process parameters are summarized in Figure 10 to analyze the correlation between the weld strength and the (a) energy stored in the microstructure; (b) energy required to collapse asperities, where the pre-weld surface roughness for foil–foil welding between the first and second layer is varied; and (c) energy of plastic deformation, where the weld amplitude is varied.

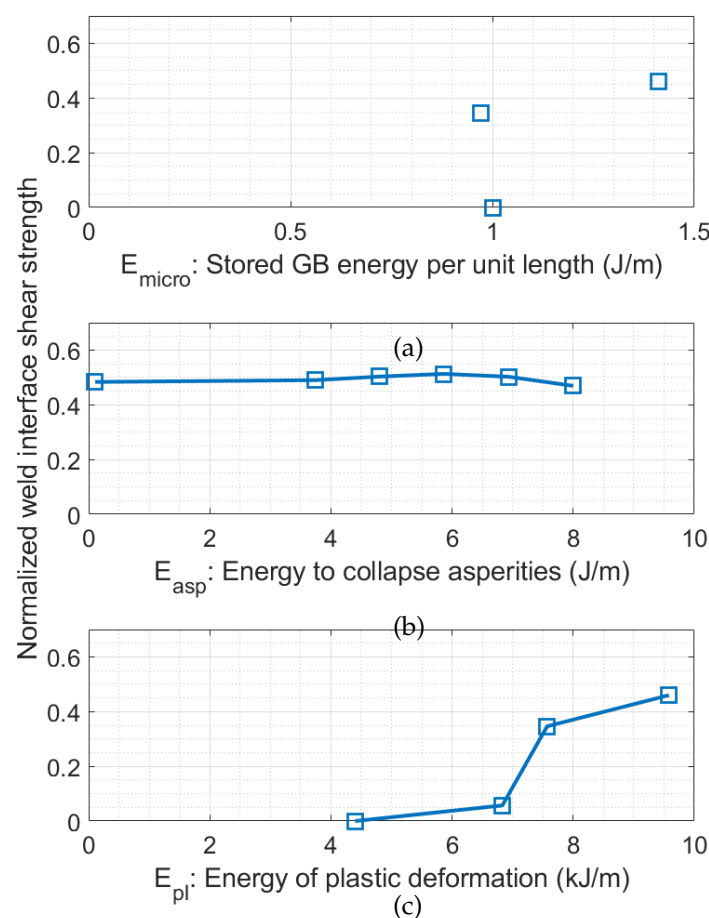


Figure 10. Normalized shear strength of UAM welds as a function of the key participating energies in the UAM of Al 6061-H18 foil: (a) energy stored in the microstructure, where the samples in the study were prepared by welding the foil using weld amplitudes of 23, 29, and 32 μm , a weld force of 5000 N, and a weld speed of 84.67 mm/s (200 in/min); (b) energy required to collapse asperities, where the samples in the study were prepared with different surface roughness profiles, with R_a values ranging from 0.1 μm to 7.5 μm , and welded using a weld amplitude of 32 μm , a weld force of 5000 N, and a weld speed of 84.67 mm/s (200 in/min); (c) energy of plastic deformation, where the samples in the study were prepared by welding the foil using weld amplitudes of 23, 26, 29, and 32 μm , and a weld force of 5000 N, and a weld speed of 84.67 mm/s (200 in/min).

5. Conclusions

A detailed energy flow diagram was developed for UAM to map the energies involved, from the input electrical energy from the transducers to the energy stored in recrystallized grains in the resulting welded microstructure. Simplified analytical models were developed to estimate the energy used to collapse asperities and to disperse the oxide layer. The energies of plastic deformation and heat generation were estimated using the previously developed techniques in [9] and a simplified coupled thermo-mechanical model of the process using analytical and FE modeling. The energy stored in the microstructure was also quantified from an EBSD analysis of the welded samples.

A shear testing rig was used to measure the strength of the welded interface under different process parameters. The corresponding participating energies were estimated and correlated with the weld strength. The energy of plastic deformation was found to have the strongest impact on the weld strength. A threshold energy of plastic deformation is observed in UAM, below which bonding fails, while higher energies result in an up to 50% bulk strength for the weld in Al 6061-H18. The effect of temperature on the flow stress of the Al 6061-H18 foil was also quantified, with a reduction in yield strength of about 10% at the expected weld temperature of around 93 °C (200 °F). The energy stored in the microstructure was also found to strongly increase with a higher weld amplitude, which is caused by the increase in the degree and volume of recrystallized grains in the foil material. Increasing the energy required to collapse the asperities of the foil material was not found to affect the weld strength significantly for the UAM of Al 6061-H18. This is expected to be due to asperities collapsing when a sufficiently high normal force is applied, thus not significantly reducing the energy available for bond formation.

The energy-based framework developed can be used to reduce the energies lost, such as the heat lost to the welder by lowering the conductivity of the welder and the welder losses seen at the transducer by increasing the efficiency of the transducer assembly. This energy-based paradigm can also be used to optimize the process and maximize the portion of input energy from the welder that is used for bond formation.

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