

Miniaturizing Solid State Additive manufacturing Literature Review

By: Michael Lynn



January 16, 2023

Rotoforge Project

# Abstract

Solid state additive manufacturing (SSAM) promises economical closed loop fabrication of freeform multimaterial 3d structures with forged quality properties directly from raw and recycled material in a single step process under ambient conditions. Most present day techniques operate at large size scales in the inch range or larger. This inhibits application of SSAM and its incredible capabilities to the worlds of electronics, robotics, much of aerospace and a wide variety of other fields in deep need of more flexible, reliable and economical manufacturing techniques. This literature review discusses the present state of the art in SSAM, some of the limitations of the current techniques, and the challenges associated with miniaturization. We then discuss some possible solutions to the challenges of miniaturization presented by recent advancements in general physics, micro BLDC technology, and micromanufacturing tools.

# 1.Introduction

A pen on a piece of paper

Description automatically generated with low confidenceThe history of tool use in humans may well predate written and spoken language. [1] Among the first tools ever created was the humble wedge. Through many generations of evolution and reimplementation, what once was a simple element of force concentration wielded by hand has become the modern machine tool. Through the application of force via rotation to a cutting edge a modern mill can rapidly and precisely shear away virtually all materials known to humans, to create fine geometries, tight tolerances and high quality end use parts. The primary mechanism of conventional machining is rapid plastic deformation of material by a concentrated force applied via a sharp cutting edge on a rotating tool. As the cutting edge strikes the work piece, pressure builds at the interface eventually exceeding the flow stress of the work piece material resulting in slip fault formation and ultimately sliding of atomic planes in the work as a chip forms on the rake of the tool. The chip continues to slide up the rake of the tool until it eventually breaks, and the process repeats for each subsequent tool rotation. The process of machining has been described in detail through a combination of physical models, classical descriptions, and molecular dynamics simulations. It is, by all accounts a well understood process. In conventional machining, the work of plastic deformation generates heat which is dissipated mostly into the chip as it forms. On occasion, under conditions of excessive chip loading, work piece material will weld to the cutting tool and to surrounding surfaces under and around the cut region. This situation was noted by early developers of friction welding processes. And thus, from problems in subtractive machining, was a new manufacturing method born, friction stir welding and friction processing. In essence, the cutting tool in conventional machining is replaced by a relatively blunt element intended to penetrate the work material and encourage heating due to plastic deformation and thorough mixing of the work materials to facilitate intimate contact and bonding between deformed material atoms. Most recently methods such as additive friction stir deposition (AFSD) and additive friction extrusion deposition (AFED) have applied similar methods of severe plastic deformation and friction assisted bonding, to the world of 3D printing and freeform fabrication of metals. Through continuously feeding a sold material into a rotating tool, and therein deforming the solid material against a surface to facilitate friction assisted heating and bonding between subsequent layers, 3D objects can be built up with properties comparable to wrought metal. These are examples of the contemporary field of solid-state additive manufacturing (SSAM) and are among the processes of interest in our discussion of the state of the art, and its limitations. In subsequent sections we will explore these techniques and their relationship to machining in greater detail and examine how their size and scale effects their applicability to broad classes of problems, as well as how some of these shortfalls may be overcome.

## Limitations of Solid State Additive Manufacturing

The largest limitation in solid state additive manufacturing at the present time is free form feature resolution. This largely due to the size and scale of the machinery deployed in the process, and the complexification of the relevant physics and material behavior as excess power budget decreases, and feature size shrinks. To produce a functional desktop scale metal, plastic and ceramic heterogenous 3D printer with solid state additive manufacturing a substantial enhancement in knowledge of the underlying process physics will be in order. This will be discussed in subsequent sections of this review. But first we will introduce the reader to what SSAM is, what the current state of the art looks like, and what has thus far determined the size and scale of current generation systems.

### What is Solid State Additive Manufacturing(SSAM) and its Relation to Machining

Additive Manufacturing(AM), or 3D printing, is the building of freeform geometries by successive addition of materials layer by layer. SSAM is the application of solid state material deformation to facilitate the AM process. That is, using continuous plastic deformation of feed stock material, via heat, friction, kinetic energy, rotation, and pressure, to perform the successive addition of layers for 3D printing. Similarly, Machining, or subtractive manufacturing(SM) as it has come to be known, is the process of using applied pressure to a rotating wedge to induce shear in a workpiece and thus facilitate the removal of material, layer by layer in the form of chips, to obtain the final desired geometry. At first glance the techniques seem quite disparate in application and outcomes, however, the fundamental process physics are essentially the same, and this fact has lent to increasing crossover between methodologies, and process products. In the present day, the boundary between AM and SM has become blurry, as additive technologies like Meld’s additive friction stir deposition(AFSD) print bulk density components from machining chip wastes using continuous rotation, and conventional mills and lathes are used for sheet extrusion as in high shear extrusion machining(HSEM). There exists evidence for such crossover, arguably as far back as the invocation of high speed machining (HSM) where the optimization of cutter speed and table feed rates in conventional SM results in a state of rapid and continuous plastic deformation in the work piece, reducing cutting forces and facilitating continuous chip production and removal, followed by greatly reduced tool wear and enhanced productivity. In short, one could reasonably describe SSAM as machining in reverse.

### Current State of the Art in Solid State Additive Manufacturing

SSAM takes many forms, including AFSD, additive friction extrusion deposition (AFED), cold spray additive manufacturing (CSAM), Ultrasonic Additive Manufacturing (UAM),Hybrid Extrusion and Bonding (HYB) and many more. At the present time, resolution is typically limited to track widths greater than 10 mm and layer heights of greater than 0.4 mm. This is generally a result of the scale of machinery used in the processes at present. AFSD, AFED, and UAM,HYB, and CSAM all involve large thrust loads due to processing large mass flows of material, this produces a need for a high degree of rigidity in the motion system and complicates feature scale down. Further, virtually all extant SSAM techniques utilize relatively blunt deformation apparatus. For example, AFSD directly presses the feedstock material, in the form of ~1/2” square rod through a keyed shoulder and onto an underlying surface; AFED, presses a 1/2” round rod into a rotating die, which then softens the material and facilitates extrusion through the hole in the die and onto the build platform. CSAM, being a gas actuated process, relies on nonturbulent flow conditions to facilitate high particle velocities, this necessitates a minimum de-laval nozzle diameter, typically above 1mm at the throat. UAM utilizes giant bulk metal foils, and large contact presses to facilitate intimate contact for ultrasonic bonding to take place.

Crucially, most present day published SSAM techniques essentially rely on the basic process physics of bulk metal forming, derived generally from large scale extrusion and welding operations, this limits their ability to scale down as a result of a variety of complicating size effects, seen historically with micro forming techniques. Increased surface area to volume ratio, 1/r scaling of tool surface speed, increased effective flow stress for materials at near the grain size scale, large thermal gradients due to short paths, relatively large thermal conductivities, and small working masses all conspire to frustrate attempts at direct scale down of extant SSAM processes to a size relevant for electronics manufacture, or meso/microfabrication.

At present some reliable examples of continuous plastic deformation at meso and micro scale are generally found in machining, and micro friction stir welding (uFSW), particularly in high speed machining (HSM) and high strain extrusion machining (HSEM). In these techniques one may find methods of building for a smaller scale in SSAM.

### c) Size and Scale of Solid State Additive Manufacturing

## 1.2 Challenges in Miniaturizing Solid State Additive Manufacturing

### a) Power Density

### b) Surface Area and Friction Scaling

### c) Flow Stress and Pressure Requirements

# 2. Solutions

## 2.1 Implications of the Shear Viscosity to Entropy Density Ratio

### a) Scale Invariance in the Hard Spheres Model

### b) Commutability of Force and Pressure in Determining the Shear Viscosity

### c) Commutability of Shear and Heat in the Entropy Relation

## 2.2 Recent Advances in Micro BLDC Motor technology

### a) RPM Capabilities

### b) Specific Power Density

### c) Closed Loop Control

## 2.3 Small Scale Manufacturing Technologies

### a) Micro Mill/Drill Ends

### b) Micro Extrusion Nozzles

### c) Micro Material Feeders

### d) Small, Rigid Motion Control Frames

# 3. Discussion

# 4. Conclusion

# 5. Bibliography