Sheet Lamination Processes

9

9.1 Introduction

One of the first commercialized (1991) additive manufacturing techniques was Laminated Object Manufacturing (LOM). LOM involved layer-by-layer lamination of paper material sheets, cut using a CO_2 laser, each sheet representing one cross-sectional layer of the CAD model of the part. In LOM, the portion of the paper sheet which is not contained within the final part is sliced into cubes of material using a crosshatch cutting operation. A schematic of the LOM process can be seen in Fig. 9.1.

A number of other processes have been developed based on sheet lamination involving other build materials and cutting strategies. Because of the construction principle, only the outer contours of the parts are cut, and the sheets can be either cut and then stacked or stacked and then cut. These processes can be further categorized based on the mechanism employed to achieve bonding between layers: (a) gluing or adhesive bonding, (b) thermal bonding, (c) clamping, and (d) ultrasonic welding. As the use of ultrasonic welding involves unique solid state bonding characteristics and can enable a wide range of applications, an extended discussion of this bonding approach is included at the end of this chapter.

9.1.1 Gluing or Adhesive Bonding

The most popular sheet lamination techniques have included a paper build material bonded using a polymer-based adhesive. Initially LOM was developed using adhesive-backed paper similar to the "butcher paper" used to wrap meat. Paper thicknesses range from 0.07 to 0.2 mm. Potentially any sheet material that can be precisely cut using a laser or mechanical cutter and that can be bonded can be utilized for part construction.

A further classification is possible within these processes based upon the order in which they bond and cut the sheet. In some processes the laminate is bonded first to

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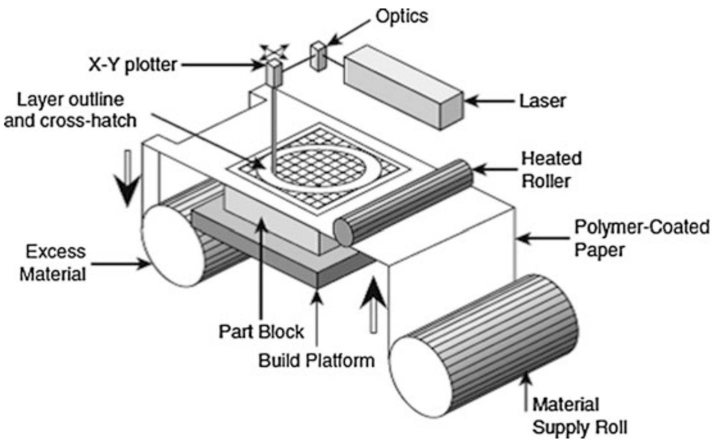

Fig. 9.1 Schematic of the LOM process (based on [1] Journal of Materials Processing Technology by D.I. Wimpenny, B. Bryden, I.R. Pashby. Copyright 2003 by Elsevier Science & Technology Journals. Reproduced with permission of Elsevier Science & Technology Journals in the format Textbook via Copyright Clearance Center.)

the substrate and is then formed into the cross-sectional shape ("bond-then-form" processes). For other processes the laminate is first cut and then bonded to the substrate ("form-then-bond" processes).

9.1.2 Bond-Then-Form Processes

In "bond-then-form" processes, the building process typically consists of three steps in the following sequence: placing the laminate, bonding it to the substrate, and cutting it according to the slice contour. The original LOM machines used this process with adhesive-backed rolls of material. A heated roller passes across the sheet after placing it for each layer, melting the adhesive and producing a bond between layers. A laser (or in some cases a mechanical cutting knife) designed to cut to a depth of one layer thickness cuts the cross-sectional outline based on the slice information. The unused material is left in place as support material and is diced using a crosshatch pattern into small rectangular pieces called "tiles" or "cubes." This process of bonding and cutting is repeated until the complete part is built. After part construction, the part block is taken out and post-processed. The crosshatched pieces of excess material are separated from the part using typical wood carving tools (called decubing). It is relatively difficult to remove the part from the part block when it is cold, therefore, it is often put into an oven for some time before decubing or the part block is processed immediately after part buildup.

Although historically many people continue to associate paper sheet lamination with the LOM machines introduced in 1991 by Helisys Inc., USA and subsequently supported by Cubic Technologies, USA (after Helisys' bankruptcy), new paper-based sheet lamination machines are currently sold by Mcor Technologies (Ireland)

Fig. 9.2 Support material removal for three golf balls made using a Solidimension machine, showing: (**a**) the balls still encased in a central region, being separated from the larger block of bonded material; (**b**) the support material is glued in an accordion-like manner so that the excess material can be pulled out easily as a continuous piece; and (**c**) the balls after complete removal of excess support material (Courtesy 3D Systems)

and Wuhan Binhu (China). These new systems make use of plain paper as the build material, and selectively dispense adhesive only where needed. Because the support material is not adhesively bonded, unlike in LOM, the support removal process is easier. The use of color inkjet printing onto paper by Mcor Technologies enables the production of full-color paper parts directly from a CAD file.

Solidimension (Be'erot, Israel) took the concepts of LOM and further developed them in 1999 into a commercial prototyping system for laminating polyvinyl chloride (PVC) plastic sheets. Solidimension sold its own machines under the Solido name [2] and under other names via resellers. This machine utilized an x–y plotter for cutting the PVC sheets and for writing with "anti glue" pens, which inhibit bonding in prescribed locations. This machine used a unique approach to support material removal. Support material was subdivided into regions, and unique patterns for cutting and bonding the excess material were used to enable easy support material removal. An example of this support material strategy can be seen in Fig. 9.2. Solido machines are no longer offered for sale, however if history is any guide, others may pick up this unique idea and offer similar machines someday.

Bond-then-form sheet lamination principles have also been successfully applied to fabrication of parts from metal, ceramic, and composite materials. In this case, rather than paper or polymer sheets, ceramic or metal-filled tapes are used as the build material to form green parts, and high-temperature furnace post-processing is used to debind and sinter the structure. These tapes are then used for part construction employing a standard sheet lamination process.

Specific advantages of LOM-like bond-then-form adhesive-based processes include: (a) little shrinkage, residual stresses, and distortion problems within the process; (b) when using paper feedstock, the end material is similar to plywood, a typical pattern making material amenable to common finishing operations; (c) large parts can be fabricated rapidly; (d) a variety of build materials can be used, including paper and polymer sheets and metal- or ceramic-filled tapes; (e) nontoxic, stable, and easy-to-handle feedstock; and (f) low material, machine, and process costs relative to other AM systems.

Paper-based sheet lamination has several limitations, including: (a) most paper-based parts require coating to prevent moisture absorption and excessive wear; (b) the control of the parts' accuracy in the Z-dimension is difficult (due to swelling or inconsistent sheet material thickness); (c) mechanical and thermal properties of the parts are inhomogeneous due to the glue used in the laminated structure; and (d) small part feature detail is difficult to maintain due to the manual decubing process.

In general, parts produced by paper-based sheet lamination have been most successfully applied in industries where wooden patterns are often used, or in applications where most features are upward facing. Examples of good applications for paper sheet lamination include patterns for sand casting and 3D topographical maps—where each layer represents a particular elevation of the map.

9.1.3 Form-Then-Bond Processes

In form-then-bond processes, sheet material is cut to shape first and then bonded to the substrate. This approach is popular for construction of parts in metallic or ceramic materials that are thermally bonded (discussed in Sect. 9.3.1) but implementation has primarily been at the research level. One example of a glue-based form-then-bond process is the "Offset Fabbing" system patented by Ennex Corp., USA. In this process, a suitable sheet material with an adhesive backing is placed on a carrier and is cut to the outline of the desired cross section using a two-dimensional plotting knife. Parting lines and outlines of support structures are also cut. The shaped laminate is then placed on top of the previously deposited layers and bonded to it. This process continues until the part is complete. A schematic of the process is shown in Fig. 9.3.

The form-then-bond approach facilitates construction of parts with internal features and channels. Internal features and small channels are difficult or impossible with a bond-then-form approach because the excess material is solid and thus material inside internal features cannot be removed once bonded (unless the part is

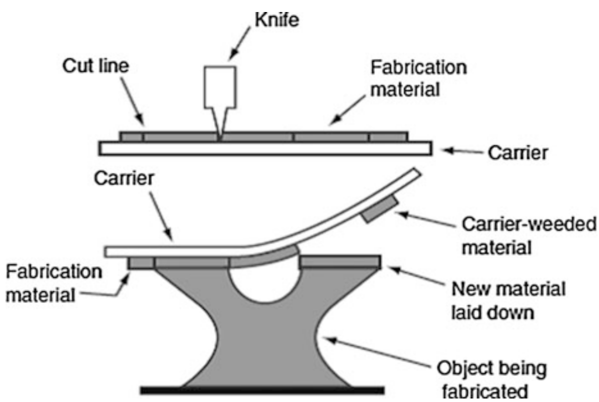

Fig. 9.3 Offset Fabbing system, Ennex Corp (http://www.ennex.com/fab/Offset/)

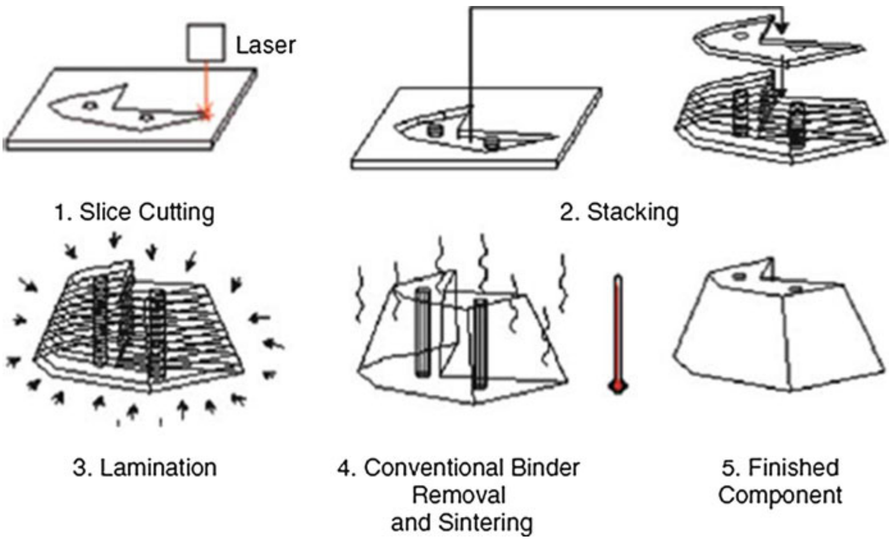

Fig. 9.4 CAM-LEM process (Courtesy CAM-LEM, Inc.)

cut open). Another advantage of form-then-bond approaches is that there is no danger of cutting into the previous layers, unlike in bond-then-form processes where cutting occurs after placing the layer on the previous layer; thus, laser power control or knife pressure is less demanding. Also, the time-consuming and potentially damage-causing decubing step is eliminated. However, these processes require external supports for building overhanging features; some type of tooling or alignment system to ensure a newly bonded layer is registered properly with respect to the previous layers; or a flexible material carrier that can accurately place material regardless of geometry.

Computer-Aided Manufacturing of Laminated Engineering Materials (CAM-LEM, Inc., USA) was developed as a process for fabrication of functional ceramic parts using a form-then-bond method, as shown in Fig. 9.4. In this process, individual slices are laser cut from sheet stock of green ceramic or metal tape. These slices are precisely stacked one over another to create the part. After assembly the layers are bonded using heat and pressure or another adhesive method to ensure intimate contact between layers. The green part is then furnace processed in a manner identical to indirect processing of metal or ceramic green parts made using powder bed fusion, as introduced in Chap. 5. The CL-100 machine produced parts from up to five types of materials, including materials of differing thickness, which were automatically incorporated into a build. One or more of these materials may act as secondary support materials to enable internal voids or channels and overhangs. These support materials were later removed using thermal or chemical means. A key application for this technology is for the fabrication of microfluidic structures (structures with microscale internal cavities and channels). An example microfluidic structure made using CAM-LEM is shown in Fig. 9.5.

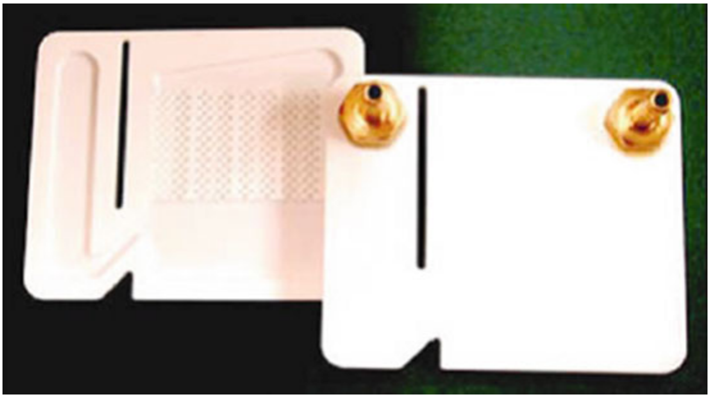

Fig. 9.5 A ceramic microfluidic distillation device cutaway view (*left*) and finished part (*right*) (Courtesy CAM-LEM, Inc.)

Another example of a form then bond process is the Stratoconception approach [3], where the model is sliced into thicker layers. These layers are machined and then glued together to form a part. The use of a multiaxis machining center enables the edges of each layer to be contoured to better match the STL file, helping eliminate the stair-step effect that occurs with increasing layer thickness. This and similar cutting techniques have been used by many different researchers to build large structures from foam, wood, and other materials to form statues, large works of art, and other structures.

9.2 Materials

As covered in the previous section, a wide variety of materials has been processed using a variety of sheet lamination processes, including plastics, metals, ceramics, and paper. A brief survey will be offered identifying the materials and their characteristics that facilitate sheet lamination.

Butcher paper was the first material used in the original Helisys LOM process. Butcher paper is coated on one side with a thin layer of a thermoplastic polymer. It is this polymer coating that melts and ensures that one layer of paper bonds to the previous layer. Since butcher paper is fairly strong and heavy, it forms sturdy parts after a suitable thickness has been fabricated (>5–6 mm typically). After part fabrication, parts are finished as if they were wood by sanding, filing, staining, and varnishing or sealing.

The recently developed Mcor Technologies printers use standard copy paper in A4 or US letter sizes with weights of 20 or 43 lb. Either white or colored paper can be used. The water-based glue binds paper sheets and results in fairly rigid parts although, similar to the Helisys process, a minimum thickness of 5 or 6 mm is required to ensure good strength.

In the metals area, both bond-then-form and form-then-bond approaches have been pursued. Perhaps the most conceptually simple fabrication process is the sheet metal clamping approach, where sheet metal is cut to form part cross sections, then simply clamped together. Other processes use several types of bonding methods. Some researchers were interested in demonstrating the feasibility of some metal sheet lamination process advances, rather than fabricating functional devices, and simply used an adhesive to bond sheets together. In other cases, the adhesive bonded structures were meant to be functional prototypes, not just proof-of-concepts. Aluminum and low-carbon steel materials were most commonly used, unless functional molds or dies were desired, in which case tool steels were used. Thermal and diffusion bonding approaches, on the other hand, tend to provide much more strong parts. Thermal bonding, to be discussed in the next section, has been demonstrated with a variety of aluminum and steel sheets and several types of bonding mechanisms, including brazing and welding. Diffusion bonding, to be covered in Sect. 9.4, has also been demonstrated on a variety of metals and is the important joining mechanism for ultrasonic consolidation, where aluminum, titanium, stainless steel, brass, Inconel, and copper materials have been demonstrated.

In sheet lamination processes, ceramic materials are most often fabricated using bond-them-form processes using ceramic-filled tapes. Tape casting methods form sheets of material composed of powdered ceramics, such as SiC, TiC-Ni composite, or alumina, and a polymer binder. Metal powder tapes can also be used to fabricate metal parts. These tapes are then used for part construction employing a standard sheet lamination process. Various SiC, alumina, TiC-Ni composite, and other material tapes have been used to build parts. A challenge with this process is that thermal post-processing to consolidate metal or ceramic powders results in a large amount of shrinkage (12–18 %) which can lead to dimensional inaccuracies and distortion. This is typical of many conventional powder-based processes, such as powder injection molding, and strategies have been developed to address the effects of shrinkage, although limitations exist.

For polymer materials, the Solidimension example is the most well known and used PVC sheets. Foam blocks have also been used in some research machines, as well as by sculptors who create large sculptures by stacking blocks cut by hot wire or CNC milling. Additionally, some research efforts have successfully demonstrated the automated lay-up of polymer composite sheets. The area of polymer sheet lamination is broad and not very well defined, since it stretches from sculpture to composites manufacturing. This is, perhaps, an area that will see significant attention in the near-term due to its potential.

9.3 Material Processing Fundamentals

As indicated, several types of processes are evident under the general category of sheet lamination. Thermal bonding and sheet metal clamping are covered in this section. In the next section, a more in-depth coverage is provided for the ultrasonic consolidation process.

9.3.1 Thermal Bonding

Many organizations around the world have successfully applied thermal bonding to sheet lamination of functional metal parts and tooling. A few examples will be mentioned to demonstrate the flexibility of this approach. Yi et al. [4] have successfully fabricated 3D metallic parts using precut 1-mm thick steel sheets that are then diffusion bonded. They demonstrated continuity in grain structure across sheet interfaces without any physical discontinuities. Himmer et al. [5] produced aluminum injection molding dies with intricate cooling channels using Al 3003 sheets coated with 0.1-mm thick low-melting point Al 4343 (total sheet thickness 2.5 mm). The sheets were laser cut to an approximate, oversized cross section, assembled using mechanical fasteners, bonded together by heating the assembly in a nitrogen atmosphere just above the melting point of the Al 4343 coating material, and then finish machined to the prescribed part dimensions and surface finish. Himmer et al. [6] also demonstrated satisfactory layer bonding using brazing and laser spot welding processes. Obikawa [7] manufactured metal parts employing a similar process from thinner steel sheets (0.2 mm thick), with their top and bottom surface coated with a low-melting-point alloy. Wimpenny et al. [1] produced laminated steel tooling with conformal cooling channels by brazing laser-cut steel sheets. Similarly, Yamasaki [8] manufactured dies for automobile body manufacturing using 0.5-mm thick steel sheets. Each of these, and other investigators, have shown that thermally bonding metal sheets is an effective method for forming complex metal parts and tools, particularly those which have internal cavities and/or cooling channels.

Although extensively studied, sheet metal lamination approaches have gained little traction commercially. This is primarily due to the fact that bond-then-form processes require extensive post-processing to remove support materials, and form-then-bond processes are difficult to automate for arbitrary, complex geometries. In the case of form-then-bond processes, particularly if a cross section has geometry that is disconnected from the remaining geometry, accurate registration of laminates is difficult to achieve and may require a part-specific solution. Thus, upward-facing features where each cross section's geometry is contiguously interconnected are the easiest to handle. Commercial interest in sheet lamination is primarily in the area of inexpensive, full-color paper parts and large tooling, where internal, conformal cooling channels can provide significant benefits over traditional cooling strategies.

Another process that combined sheet lamination with other forms of AM (including beam deposition, extrusion, and subtractive machining) was Shape Deposition Manufacturing (SDM) [9]. With SDM, the geometry of the part is subdivided into nonplanar segments. Each segment is deposited as an over-sized, near-net shape region and then finish machined. Sequential deposition and machining of segments (rather than planar layers) forms the part. A decision is made concerning how each segment should be manufactured dependent on such factors as the accuracy, material, geometrical features, and functional requirements. Secondary support materials were commonly used to enable complex geometry to be made

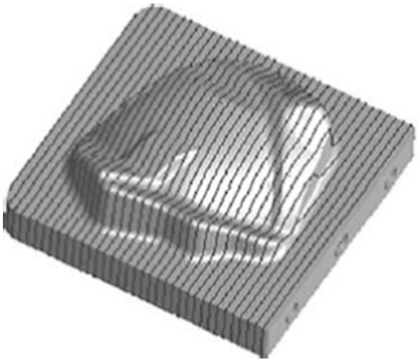

Fig. 9.6 Profiled edge laminate tool (Courtesy Fraunhofer CCL)

and for clearance between mechanisms that required differential motion after manufacture. A completely automated subdivision routine for arbitrary geometries, however, was never developed and intervention from a human "expert" is required for many types of geometries. As a result, though interesting and useful for certain complex multimaterial structures, such a system was never commercially introduced.

9.3.2 Sheet Metal Clamping

In the case of assembling rigid metal laminates into simple shapes, it may be advantageous to simply clamp the sheets together using bolts and/or a clamping mechanism rather than using an adhesive or thermal bonding method. Clamping is quick and inexpensive and enables the laminates to be disassembled in order to modify a particular laminate's cross section and/or for easy recycling of the materials. In addition, the clamping or bolting mechanism can act as a reference point to register each laminate with respect to one another.

When clamping, it is often advantageous to simply cut a profile into one edge of a laminate, leaving three edges of the rectangular sheet uncut. An example of such a "profiled edge laminate" construction is shown in Fig. 9.6. Of course, this type of profiled edge can also be utilized with adhesive and thermally bonded layers as well. The major benefit of this approach is the ease with which the layers can be clamped (i.e., bolting the laminates together through a set of holes, as could be done using the through-holes visible on the right edge of Fig. 9.6). The drawbacks of a profile approach are that clamping forces for most tools would then be perpendicular to the laminate interface, and the laminates might separate from one another (leaving gaps) under certain conditions, such as when pressurized polymers are injected into a mold made from such a tool.

9.4 Ultrasonic Additive Manufacturing

Ultrasonic Additive Manufacturing (UAM), also known as Ultrasonic Consolidation (UC), is a hybrid sheet lamination process combining ultrasonic metal seam welding and CNC milling, and commercialized by Solidica Inc., USA in 2000, and subsequently licensed to Fabrisonics (USA). In UAM, the object is built up on a rigidly held base plate bolted onto a heated platen, with temperatures ranging from room temperature to approximately 200°C. Parts are built from bottom to top, and each layer is composed of several metal foils laid side by side and then trimmed using CNC milling.

During UAM, a rotating sonotrode travels along the length of a thin metal foil (typically 100–150 μm thick). The foil is held closely in contact with the base plate or previous layer by applying a normal force via the rotating sonotrode, as shown schematically in Fig. 9.7. The sonotrode oscillates transversely to the direction of motion, at a constant 20 kHz frequency and user-set oscillation amplitude. After depositing a foil, another foil is deposited adjacent to it. This procedure is repeated until a complete layer is placed. The next layer is bonded to the previously deposited layer using the same procedure. Typically four layers of deposited metal foils are termed one level in UAM. After deposition of one level, the CNC milling head shapes the deposited foils/layers to their slice contour (the contour does not need to be vertical, but can be a curved or angled surface, based on the local part geometry). This additive-subtractive process continues until the final geometry of the part is achieved. Thus, UAM is a bond-then-form process, where the forming can occur after each layer or after a number of layers, depending on the settings chosen by the user. Additionally, each layer is typically deposited as a

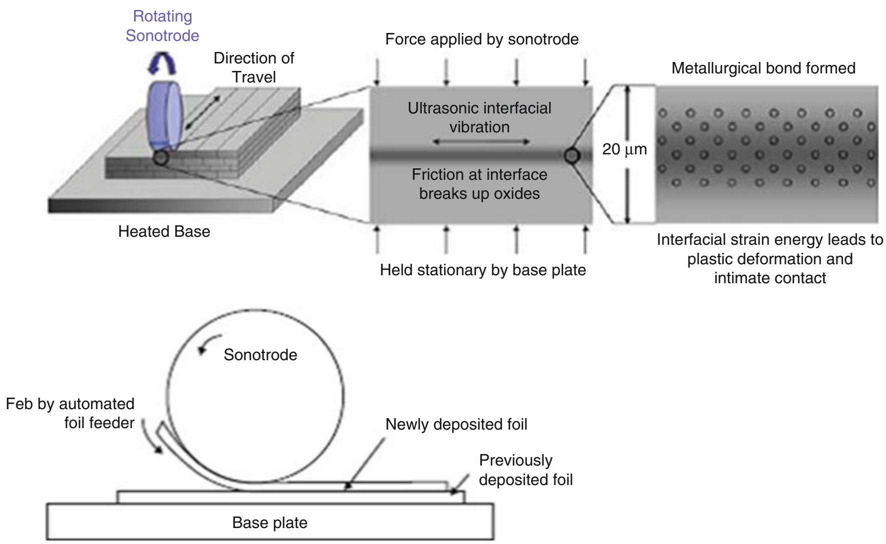

Fig. 9.7 Schematic of ultrasonic consolidation

combination of foils laid side by side rather than a single large sheet, as is typically practiced in sheet lamination processes.

By the introduction of CNC machining, the dimensional accuracy and surface finish of UAM end products is not dependent on the foil thickness, but on the CNC milling approach that is used. This eliminates the stair-stepping effects and layer-thickness-dependent accuracy aspects of other AM processes. Due to the combination of low-temperature ultrasonic bonding, and additive-plus-subtractive processing, the UAM process is capable of creating complex, multifunctional 3D parts, including objects with complex internal features, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors, and instruments. The lack of an automated support material in commercial systems, however, means that many types of complex overhanging geometries cannot be built using UAM. However, on-going support material research for UAM will hopefully result in an automated support material approach in the future.

To better illustrate the UAM process, Fig. 9.8a–f illustrates the steps utilized to fabricate a honeycomb panel (270 mm by 240 mm by 10 mm). The cutaway CAD model showing the internal honeycomb features is shown in Fig. 9.8a. The part is fabricated on a 350 mm by 350 mm by 13 mm Al 3003 base plate, which is firmly bolted to a heated platen, as shown in Fig. 9.8b. Metal foils used for this part are Al 3003 foils 25 mm wide and 0.15 mm thick. The first layer of deposited foils is shown in Fig. 9.8c. Since the width of one layer is much larger than the width of the individual metal foils, multiple foils are deposited side by side for one layer. After the deposition of the first layer, a second layer is deposited on the first layer and so on, as seen in Fig. 9.8d. After every four layers of deposition, the UAM machine trims the excess tape ends, and machines internal and external features based on the CAD geometry. After every 40 layers, the machine does a surface machining pass at the exact height of that layer (in this case the z-height of the 40th layer is 0.15 mm per layer times 40 layers, or 6 mm) to compensate for any excess z-height that may occur due to variability in foil thicknesses. A surface machining pass can occur at any point in the process if, for instance, a build interruption or failure occurs (enabling the build to be continued from any user-specific z-height). After a series of repetitive bonding and machining operations the facesheet layers are deposited to enclose the internal features, as shown Fig. 9.8e. Four layers are deposited, and the final panel is shown in Fig. 9.8f.

9.4.1 UAM Bond Quality

There are two widely accepted quality parameters for evaluating UAM-made structures, which are linear welding density (LWD) and part strength. LWD is defined as the percentage of interface which is bonded divided by the total length of the interface between two ultrasonically consolidated foils, determined metallographically. An example of a microstructure sample made from four layers of Al 3003 tapes by UAM is shown in Fig. 9.9. The black areas represent the unbonded

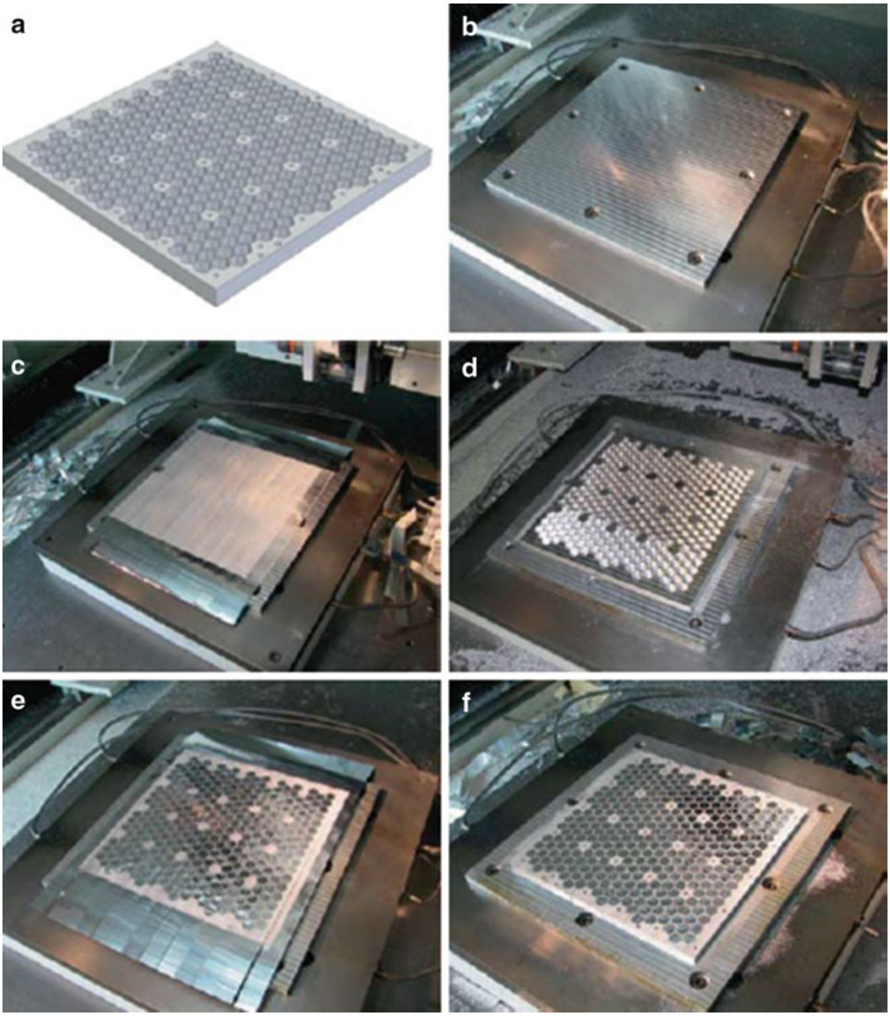

Fig. 9.8 Fabrication procedure for a honeycomb structure using UAM

regions along the interfaces. In this microstructure, a LWD of 100 % occurred only between Layer 1 and the base plate.

9.4.2 Ultrasonic Metal Welding Process Fundamentals

Ultrasonic metal welding (UMW) is a versatile joining technology for various industries, including in electronics, automotive and aerospace. Compared to other metal fusion processes, UMWs solid-state joining approach does not require high

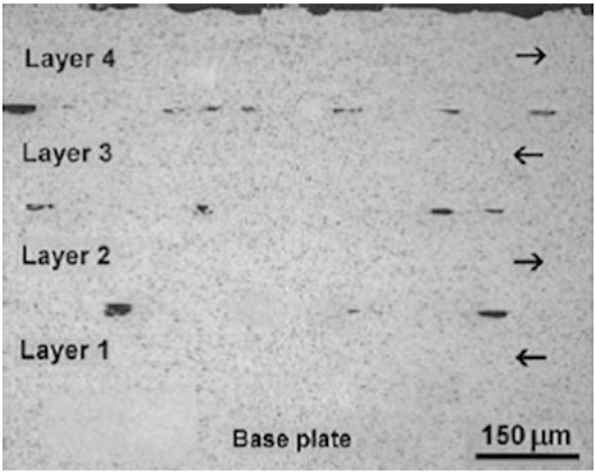

Fig. 9.9 A UAM part made from four layers of Al 3003 foils. LWD is determined by calculating the bonded interface divided by the total interface (*arrows* show the sonotrode traveling direction for each layer). "Effect of Process Parameters on Bond Formation during Ultrasonic Consolidation of Aluminum Alloy 3003," G.D. Janaki Ram, Yanzhe Yang and Brent Stucker, Journal of Manufacturing Systems, 25 (3), pp. 221–238, 2006

temperature diffusion or metal melting; and the maximum processing temperature is generally no higher than 50 % of the melting point of the joined metals. Therefore, thermal residual stresses and thermally induced deformation due to resolidification of molten metals, which are important considerations in thermal welding processes and many AM processes (such as powder bed fusion, beam deposition, and thermal bonding-based sheet lamination processes) are not a major consideration in UAM.

Bonding in UMW can be by (a) mechanical interlocking; (b) melting of interface materials; (c) diffusion bonding; and (d) atomic forces across nascent metal surfaces (e.g., solid-state metallurgical bonding). In UAM, bonding of foils to one another appears to be almost exclusively by nascent metal forces (metallurgical bonding), whereas bonding between foils and embedded structures, such as reinforcement fibers, is primarily by mechanical interlocking. An example of a stainless steel 304 wire mesh embedded between Al 3003 foils using the UAM process is shown as Fig. 9.10. This figure illustrates that the mesh is mechanically interlocked with the Al 3003 matrix, whereas the SS mesh metallurgically bonded to itself and the Al 3003 layers metallurgically bonded to each other. Mechanical interlocking between the Al and SS mesh was due to plastic deformation of Al around and through the mesh. Thus, mechanical interlocking can take place for material combinations between dissimilar metals, or between materials with significant hardness differences. For material combinations of similar materials or materials with similar hardness values, metallurgical bonding appears to be the dominant bond formation mechanism.

Two conditions must be fulfilled for establishment of solid-state bonding during UAM: (a) generation of atomically clean metal surfaces and (b) intimate contact between clean metal surfaces. As all engineering metals contain surface oxides, the oxides must be displaced in order to achieve atomically clean metal surfaces in intimate contact. The ease with which oxide layers can be displaced depends on the

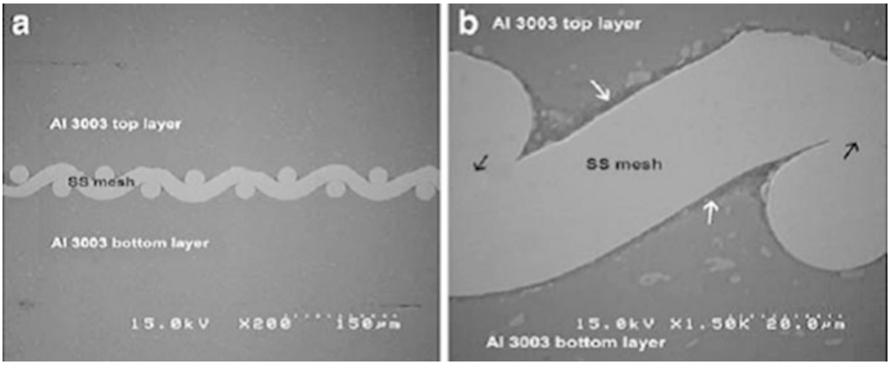

Fig. 9.10 SEM microstructures of Al 3003/SS mesh: (**a**) SS mesh embedded between Al 3003 layers, (**b**) Al 3003/SS mesh interface at a higher magnification. The *white arrows* illustrate the lack of metallurgical bonding between the Al and SS materials. The *black arrows* indicate areas of metallurgical bonding between SS mesh elements. © Emerald Group Publishing Limited, "Use of Ultrasonic Consolidation for Fabrication of Multi-Material Structures," G.D. Janaki Ram, Chris Robinson, Yanzhe Yang and Brent Stucker, Rapid Prototyping Journal, 13 (4), pp. 226–235, 2007

ratio of metal-oxide hardness to base metal hardness, where higher ratios facilitate easier removal. Due to the significant hardness differences between aluminum and aluminum oxide, Al 3003 alloys are one of the best-suited materials for ultrasonic welding. Nonstructural noble metals, such as gold which do not have surface oxide layers, are quite amenable to ultrasonic welding. Materials with difficult-to-remove oxide layers are problematic for ultrasonic welding. However, difficult-to-weld materials have been shown to be UAM compatible when employing chemical or mechanical techniques for removing the surface oxide layers just prior to welding.

Plastic deformation at the foil interfaces is critical for UAM, to break up surface oxides and overcome surface roughness. The magnitude of plastic deformation necessary to achieve bonding can be reduced by decreasing the surface roughness of the interface materials prior to welding, such as by surface machining (which occurred between Layer 1 and the base plate in Fig. 9.9) and/or by removing the surface oxides by chemical stripping or surface finishing. In addition, factors which enhance plastic deformation are also beneficial for bonding, such as using more ductile materials and/or by thermally or acoustically softening the materials during bonding.

Metallic materials experience property changes when subjected to ultrasonic excitations, including acoustic softening, increase in crystallographic defects, and enhanced diffusivities. In particular, metal softening in the presence of ultrasonic excitations, known as the "Blaha effect" or "acoustic softening," means that the magnitude of stresses necessary to initiate plastic deformation are significantly lower [10]. The softening effect of ultrasonic energy on metals is similar to the effect of heating, and can in fact reduce the flow stress of a metallic material more effectively than heating. Thus, acoustic softening results in plastic deformation at strains much less than would otherwise be needed to achieve plastic deformation.

UAM processes also involve metal deformation at high strain rates. High strain rate deformation facilitates formation of vacancies within welded metals, and thus excess vacancy concentration grows rapidly. As a result, the ductility and diffusivity of the metal are enhanced. Both of these characteristics aid in UAM bonding.

9.4.3 UAM Process Parameters and Process Optimization

The important controllable process parameters of UAM are: (a) oscillation amplitude, (b) normal force, (c) travel speed, and (d) temperature. It has been found that the quality of bonding in UAM is significantly affected by each of these process parameters. A brief discussion of each of these parameters and how they affect bonding in UAM follows.

9.4.3.1 Oscillation Amplitude

Energy input directly affects the degree of elastic/plastic deformation between mating metal interfaces, and consequently affects bond formation. Oscillation amplitude and frequency of the sonotrode determine the amount of ultrasonic energy available for bond formation. In commercial UAM machines, the frequency of oscillation is not adjustable, as it is preset based on sonotrode geometry, transducer and booster hardware, and the machine power supply. In UAM, the directly controllable parameter for ultrasonic energy input is oscillation amplitude.

Generally speaking, the higher the oscillation amplitude, the greater the ultrasonic energy delivered. Consequently, for greater energy, more elastic/plastic deformation occurs at the mating metal interface and therefore better welding quality is achieved. However, there is an optimum oscillation amplitude level for a particular foil thickness, geometry, and material combination. A sufficient amount of ultrasonic energy input is needed to achieve plastic deformation, to help fill the voids due to surface roughness that are inherently present at the interface. However, when energy input exceeds a critical level, bonding deteriorates as excess plastic deformation can damage previously formed bonds at the welding interface due to excessive stress and/or fatigue.

9.4.3.2 Normal Force

Normal force is the load applied on the foil by the sonotrode, pressing the layers together. Sufficient normal force is required to ensure that the ultrasonic energy in the sonotrode is delivered to the foils to establish metallurgical bonds across the interface. This process parameter also has an optimized level for best bonding. A normal force higher or lower than the optimum level degrades the quality of bonds and lowers the LWD obtained. When normal force increases beyond the optimum level, the stress condition at the mating interface may be so severe that the formed bonds are damaged, just as it occurs when oscillation amplitude exceeds its optimum level.

9.4.3.3 Sonotrode Travel Speed

Welding exposure time has a direct effect on bond strength during ultrasonic welding. In UAM welding, exposure time is determined by the travel speed of the sonotrode. Higher speeds result in shorter welding exposure times for a given area. Over-input of ultrasonic energy may cause destruction of previously formed metal bonds and metal fatigue. Thus, to avoid bond damage caused by excess ultrasonic energy, an optimum travel speed is important for strong bonds.

9.4.3.4 Preheat Temperature

Metallurgical bonds can be established at ambient temperature during UAM processing. However, for many materials an increased preheat temperature facilitates bond formation. Heating directly benefits bond formation by reducing the flow stress of metals. However, excess heating can have deleterious effects. High levels of metal foil softening can result in pieces of the metal foil sticking to the sonotrode. In addition, in the case of fabrication of structures with embedded electronics, excess temperature may damage embedded electronics. For certain materials, such as Cu, enhanced oxide formation at elevated temperatures will impede oxide removal. Finally, for some materials elevated temperatures cause metallurgical "aging" phenomena such as precipitation hardening, which can embrittle the material and cause premature part failure.

9.4.3.5 Other Parameters

Metal foil thickness is another important factor to be considered in UAM. The most common metal foils used in UAM are on the order of ~150 μm. Generally speaking, bonds are more easily formed between thin metal foils than between thick ones. However, foil damage is a major concern for UAM of thinner metal foils, as they are easily scratched or bent; and thus metal foils between 100 and 200 μm are most often used in UAM.

In addition to material-related constants, process optimization is influenced by the surface condition of the sonotrode, particularly the sonotrode surface roughness. A typical sonotrode in UAM is made of titanium or tool steel. The surface of the sonotrode is EDM roughened to enhance friction between the sonotrode and foil being deposited. However, surface roughness of the sonotrode decreases significantly after extended use. Thus, optimized parameters change along with the condition of the sonotrode surface. Thus it is necessary to practice regular sonotrode roughness measurements and modify process parameters accordingly. Also, the sonotrode surface roughness is imprinted onto the upper-most surface of the just-deposited foil (see upper surface of Fig. 9.9). As a result, this surface roughness must be overcome by plastic deformation during deposition of the next layer. Thus, an optimum surface roughness condition would be one which involves no slip between the sonotrode and the foil being deposited, without significantly increasing the surface roughness of the deposited foil. As slip often increases with decreasing roughness, sonotrode surface roughness is inherently difficult to optimize.

9.4.4 Microstructures and Mechanical Properties of UAM Parts

9.4.4.1 Defects

The most common defects in UAM-made parts are voids. Voids occur either along the interfaces between layers or between the foils that are laid side by side to form each layer. For ease of discussions, defects are classified into three types according to defect origin. Type-1 defects are the voids along layer/layer interfaces due to foil surface roughness and/or insufficient input energy. Type-2 defects are damaged areas, also at the layer/layer interface, that are created when excess energy input during UAM results in the breaking of previously formed bonds. Type-3 defects are found between adjacent foils within a layer.

One can identify defect types by observing the existence of oxide layers on the surfaces of the defects or by looking at the defect morphology. For Type-1 defects, since the metal surfaces have not bonded, oxide layers are not damaged and removed, and can be observed. In addition, Type-1 defects typically have a flat upper surface and a rounded lower surface (where the flat upper surface is the newly deposited, smooth foil and the rounded lower surface is the unbonded upper surface of the previously deposited foil, as seen in Fig. 9.11). For Type-2 defects, since bonding has occurred, oxide layers have been disturbed and are difficult to locate. Type-2 defects thus have a different morphology than Type-1 defects, as they represent voids where the interface has been torn apart after bonding, rather than regions which have never bonded.

Type-3 defects are the physical gaps between adjacent metal foils, as shown in Fig. 9.12. In UAM, the foil width setting within the software determines the offset distance the sonotrode and foil placement mechanism are moved between

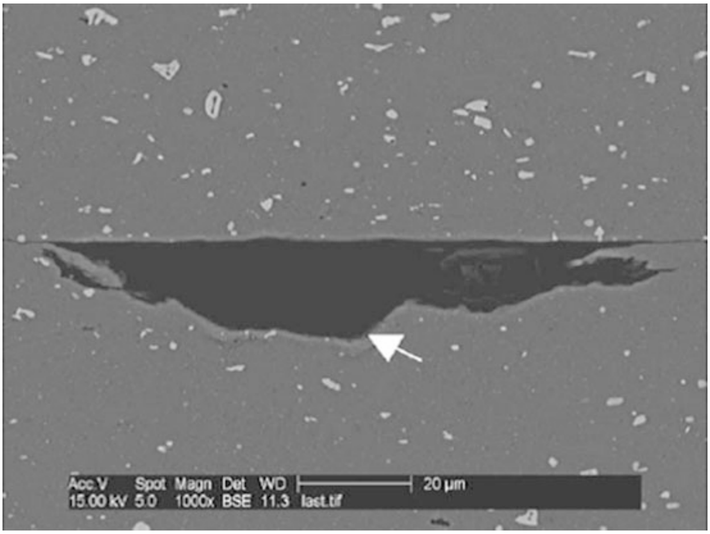

Fig. 9.11 Type-1 UAM defect (*arrow* indicates location of surface oxides)

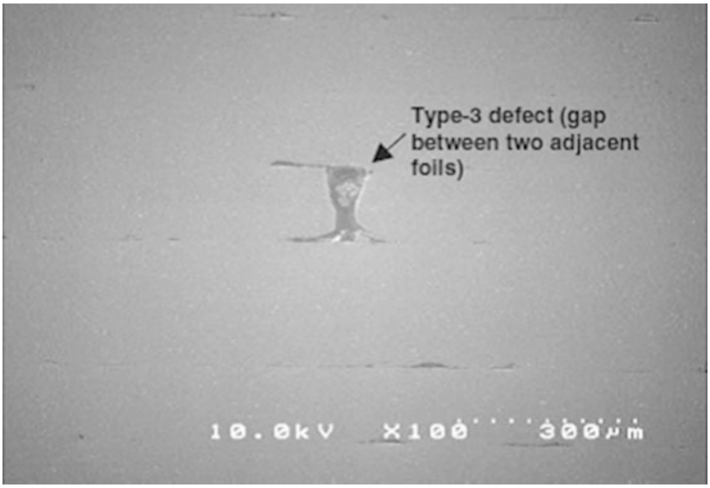

Fig. 9.12 Type-3 defect observed between adjacent foils (Note the morphology of the Type-1 defects between layers indicate that this micrograph is upside-down with respect to build orientation)

depositions of adjacent foils within a layer. If the setting value is larger than the actual metal foil width, there will always be gaps between adjacent foils. The larger the width setting above the foil width, the larger the average physical gap. If the width setting is smaller than the actual width of the foil, gaps will be minimized. However, excess overlap results in surface unevenness at the overlapping areas and difficulty with welding. Thus, positioning inaccuracies of the foil placement mechanism in a UAM machine, combined with improper width settings cause Type-3 defects.

Defects strongly affect the strength of UAM parts. Process parameter optimization (including optimization of width settings) to maximize LWD and minimize Type-3 defects is the most effective means to increase bond strength. With optimized parameters, Type-1 and Type-3 defects are minimized and Type-2-defects do not occur.

Type-1 defects can be reduced by surface machining a small amount of metal (~10 μm, or the largest roughness observed at the upper-most deposited surface, as in Fig. 9.9) after depositing each layer. Post-process heat treatment can also be used to significantly reduce all types of defects.

The degradation of part mechanical properties due to Type-3 defects can be reduced by designed arrangement of successive layers. Successive layers in a UAM part can be arranged so that 50 % overlap across layers is obtained, as shown in Fig. 9.13. Although somewhat counter-intuitive, it has been shown that better tensile properties result from a 50 % overlap than when random foil arrangements are used.

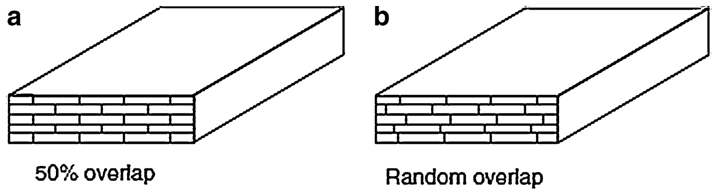

Fig. 9.13 Schematic illustrating (**a**) 50 % foil overlap and (**b**) random foil overlap in UAM

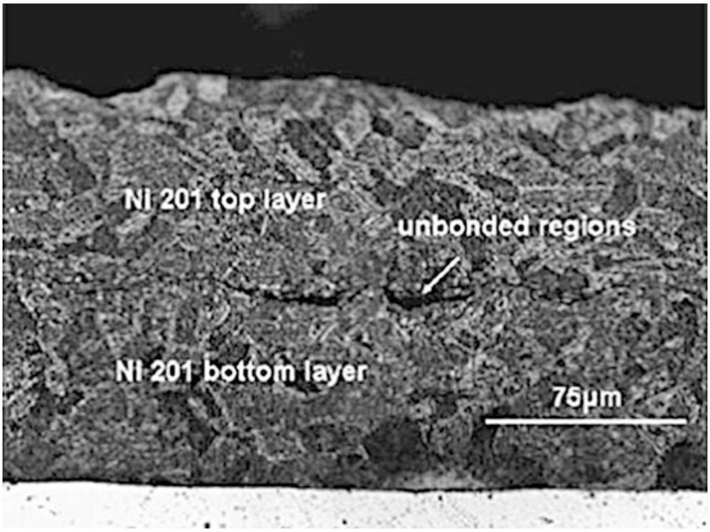

Fig. 9.14 Ultrasonically consolidated Ni 201 foils

9.4.4.2 UAM Microstructures

Typical microstructures from Al 3003 tapes with representative defects were shown in Figs. 9.9 and 9.12. Figure 9.14 shows the microstructure of two Ni 201 foils deposited on an Al 3003 substrate. Plastic deformation of Ni foils near the foil surfaces can be experimentally visualized using orientation imaging microscopy, as shown in Fig. 9.15. Smooth intragrain color transition within a few grains at the surface indicates the foil interfaces undergo some plastic deformation during UAM processing, whereas the absence of intragranular color transitions away from the foil surfaces indicates that the original microstructure is retained in the bulk of the foil.

In addition to UAM of similar materials, UAM of dissimilar materials is quite effective. Many dissimilar metal foils can be bonded with distinct interfaces, with a high degree of LWD and without intermetallic formation [11].

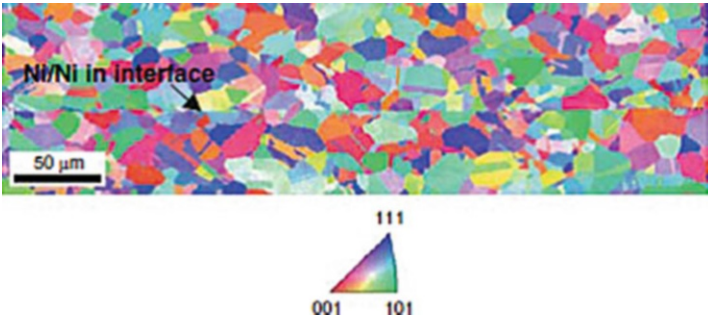

Fig. 9.15 An image of several inverse pole figures of contiguous areas along a well-bonded Ni–Ni interface stitched together. The grains in the image are color coded to reflect their orientation (for color version, see Acta Materialia by Brent L. Adams, Clayton Nylander, Brady Aydelotte, Sadegh Ahmadi, Colin Landon, Brent E. Stucker, G.D. Janaki Ram. Copyright 2008 by Elsevier Science & Technology Journals. Reproduced with permission of Elsevier Science & Technology Journals in the format Textbook via Copyright Clearance Center.)

9.4.4.3 Mechanical Properties

Mechanical properties of UAM parts are highly anisotropic due to the anisotropic properties of metal foils, the presence of defects in particular areas, and the alignment of grain boundaries along the foil-to-foil interfaces. Most metal foils used in UAM are prepared via rolling. Grains within the foils are often elongated along the rolling direction. As a result, foils are typically stronger along the rolling direction, and thus UAM parts are typically stronger in the x-axis than in the y- or z-axes. A typical transverse y-axis strength for a UAM part is about 85 % of the published bulk strength value for a particular material whereas the longitudinal x-axis strength typically exceeds published values for a material. In the *z*-direction, perpendicular to the layer interfaces, UAM parts are much weaker than the x and y properties. This is primarily due to the fact that the bond formed across the foil interfaces, even at 100 % LWD, is not as strong as the more isotropic inter-granular bonding within the foils. Thus, *z*-direction strength values are often 50 % of the published value for a particular material, with very little ductility.

Thus, when considering UAM for part fabrication, it is important to consider the anisotropic aspects of UAM parts with respect to their design. Heat treatment can be used to normalize these properties if this anisotropy results in unacceptable properties.

Another factor which affects mechanical properties is the interfacial plastic deformation which foils undergo during UAM. This plastic deformation increases the hardness of the metal as a result of work hardening effects. Although this work hardening improves the strength, it has a negative effect on ductility.

9.4.5 UAM Applications

UAM provides unique opportunities for manufacture of structures with complex internal geometries, manufacture of structures from multiple materials, fiber embedment during manufacture, and embedding of electronics and other features to form smart structures. Each of these application areas is discussed below.

9.4.5.1 Internal Features

As with other AM techniques, UAM is capable of producing complex internal features within metallic materials. These include honeycomb structures, internal pipes or channels, and enclosed cavities. During UAM, internal geometrical features of a part are fabricated via CNC trimming before depositing the next layer (see Fig. 9.8). Not all internal feature types are possible, and all of the “top” surface of internal features will have a stair-step geometry and not a CNC-milled surface, as the CNC can only mill the upward-facing surfaces of internal geometries. After fabrication of an internal feature is completed, metal foils are placed over the cavities or channels and welded, thus enclosing the internal features.

It has been shown that it becomes quite difficult to bond parts using UAM when their height-to-width ratio is near 1:1 [12]. In order to achieve higher ratios, support materials or other restraints are necessary to make the part rigid enough such that there is differential motion between the existing part and the foils that are being added. The development of an effective support material dispensing system for UAM would dramatically increase its ability to make more free-form shapes and larger internal features. Without support materials, internal features must be designed and oriented in such a way that the sonotrode is always supported by an existing, rigid feature while depositing a subsequent layer. As a result, for instance, internal cooling channels cannot be perpendicular to the sonotrode traveling direction, and honeycomb structures must be small enough that there are always at least two ribs supporting the deposition of the foil face sheets.

9.4.5.2 Material Flexibility

A wide range of metallic materials has been used with UAM. Theoretically, any metal which can be ultrasonically welded is a candidate material for the UAM process. Materials which have been successfully bonded using UAM include Al 3003 (H18 and O condition), Al 6061, Al 2024, Inconel® 600, brass, SS 316, SS 347, Ni 201, and high purity copper. Ultrasonic weldabilities of a number of other metallic materials have been widely demonstrated [11, 13–16]. Thus, there is significant material flexibility for UAM processes. In addition to metal foils, other materials have been used, including MetPreg® (an alumina fiber-reinforced Al matrix composite tape) and prewoven stainless steel AISI 304 wire meshes (see Fig. 9.10), which both have been bonded to Al 3003 using UAM.

By depositing various metal foils at different desired layers or locations during UAM, multimaterial structures or functionally gradient materials can be produced. Composition variation and resultant property changes can be designed to meet various application needs. For instance, by changing materials it is possible to optimize thermal conductivity, wear resistance, strength, ductility, and other properties at specific locations within a part.

9.4.5.3 Fiber Embedment

One of the unique features of UAM is that it enables fiber embedment. As can be seen in Fig. 9.16, bonding near an embedded fiber is much better than bonding away from the fiber for a particular set of process parameter conditions. Plastic flow predicted by modeling done at Sheffield University by Mariani and Ghassemieh (2009) has shown that in some cases there can be one hundred times the degree of interfacial metal flow in the presence of a fiber when compared to bonding of foils without a fiber.

The most commonly embedded fibers are silicon carbide structural fibers within Al matrices (thus forming an Al/SiC metal matrix composite) and optical fibers within Al matrices. Fibers can also be placed and embedded between dissimilar materials, as seen in Fig. 9.17. In the case of dissimilar materials, the presence of a stiff fiber exacerbates the plastic deformation between the stiffer and less stiff material, causing the material with a lower flow stress to deform more than the higher flow stress material. In addition, in contrast to the case of embedment between similar materials where the fiber center is typically aligned with the foil interfaces, the fiber is offset into the softer material (compare Figs. 9.16 and 9.17).

Embedded ceramic fibers are typically mechanically entrapped within metal matrices, without any chemical bonding between fiber and matrix materials. As a result of this mechanical entrapment, friction aids in the transfer of tensile loads from the matrix to the fiber, thus strengthening the part, whereas the lack of chemical bonding means that there is little resistance to shear loading at the fiber/matrix interface, thus weakening the structure for this failure mode.

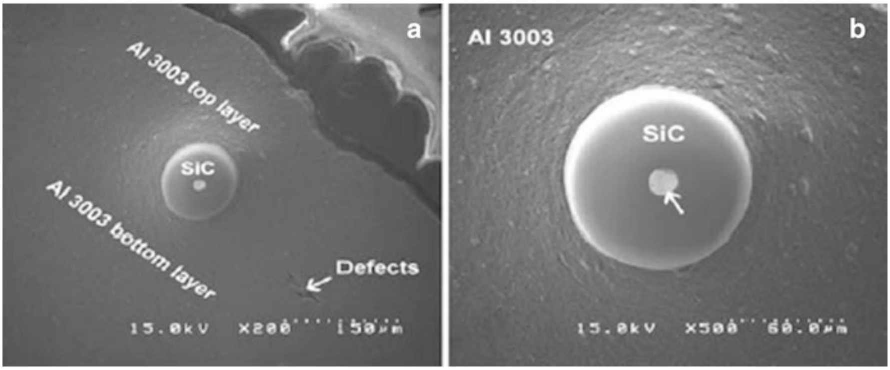

Fig. 9.16 SEM microstructures of Al 3003/SiC: (**a**) SiC fiber embedded between Al 3003 layers showing a lack of defects near the fiber and (**b**) the same SiC fiber at a higher magnification showing excellent bonding near the fiber. © Emerald Group Publishing Limited, "Use of Ultrasonic Consolidation for Fabrication of Multi-Material Structures," G.D. Janaki Ram, Chris Robinson, Yanzhe Yang and Brent Stucker, Rapid Prototyping Journal, 13 (4), pp. 226–235, 2007

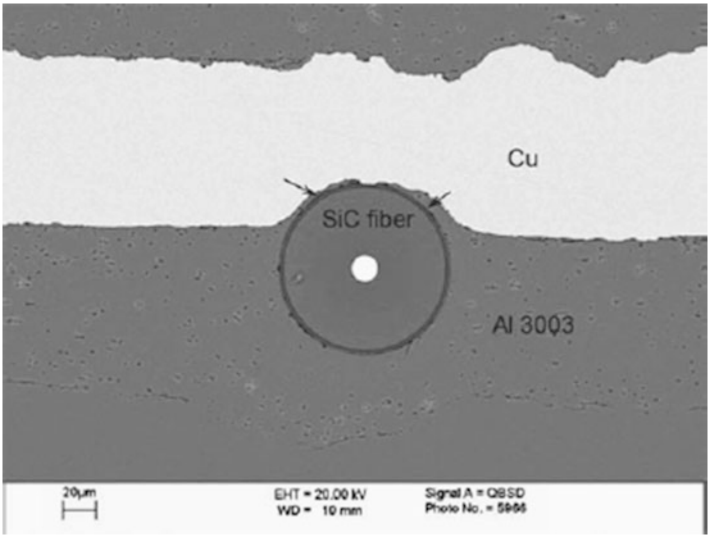

Fig. 9.17 SiC Fiber embedded between copper and aluminum using UAM. Black arrows denote regions where the softer Al extruded around the fiber during embedment, resulting in displacement of the fiber away from the interface into the Al base material

UAM is a candidate manufacturing process for fabrication of long-fiber-reinforced metal matrix composites (MMC). However, to utilize UAM to make end-use MMC parts, several technical difficulties need to be overcome, including automatic fiber feeding and alignments mechanisms, and the ability to change the fiber/foil direction between layers.

Optical fibers have been successfully embedded by many researchers worldwide. Since UAM operates at relatively low processing temperatures, many types of optical fibers can be deposited without damage, thus enabling data and energy to be optically transported through the metal structure.

9.4.5.4 Smart Structures

Smart structures are structures which can sense, transmit, control, and/or react to data, such as environmental conditions. In a smart structure, sensors, actuators, processors, thermal management devices, and more can be integrated to achieve a desired functionality (see Fig. 9.18). Fabrication of smart structures is difficult for conventional manufacturing processes, as they do not enable full three-dimensional control over geometry, composition and/or placement of components. AM processes are inherently suited to the fabrication of smart structures and UAM, in particular, offers several advantages. Primarily due to the fact that UAM is the only AM process whereby metal structures can be formed at low temperatures, UAM offers excellent processing capability for fabrication of smart structures. In addition to traditional internal self-supporting features (honeycomb structures, cooling channels, etc.), larger internal cavities can designed to enable placement of

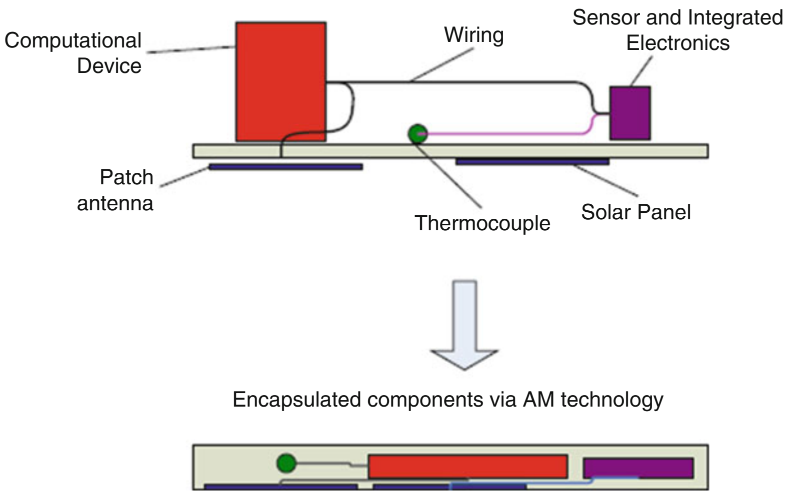

Fig. 9.18 Schematic illustrating the creation of a smart structure using UAM

electronics, actuators, heat pipes, or other features at optimum location within a structure [17]. Many types of embedded electronics, sensors, and thermal management devices have been inserted into UAM cavities. Sensors for recording temperature, acceleration, stress, strain, magnetism, and other environmental factors have been fully encapsulated and have remained functional after UAM embedment. In addition to prefabricated electronics, it is feasible to fabricate customized electronics in UAM with the integration of direct write technologies (see Chap. 11). By combining UAM with direct write, electronic features (conductors, insulators, batteries, capacitors, etc.) can be directly created within or on UAM-made structures in an automated manner.

9.5 Conclusions

As illustrated in this chapter, a broad range of sheet lamination techniques exist. From the initial LOM paper-based technology to the more recent UAM approach, sheet lamination processes have shown themselves to be robust, flexible, and valuable for many applications and materials. The basic method of trimming a sheet of material to form a cross-sectional layer is inherently fast, as trimming only occurs at the layer's outline rather than needing to melt or cure the entire cross-sectional area to form a layer. This means that sheet lamination approaches exhibit the speed benefits of a layer-wise process while still utilizing a point-wise energy source. Many variations of sheet lamination processes have been demonstrated, which have proved to be suitable for many different types of metal, ceramic, polymer, and paper materials.

Future variations of sheet lamination techniques will likely include better materials, new bonding methods, novel support material strategies, new sheet placement mechanisms, and new forming/cutting techniques. As these developments occur, sheet lamination techniques will likely move from the fringe of AM to a more central role in the future of many types of products.

9.6 Exercises

1. Discuss the benefits and drawbacks of bond-then-form versus form-then-bond approaches. In your discussion, include discussion of processes which can use secondary support material and those which do not.
2. Find four papers not mentioned in the references to this chapter which discuss the creation of tooling from laminated sheets of metal. Discuss the primary benefits and drawbacks identified in these papers to this approach to tooling. Based upon this, what do you think about the commercial viability of this approach?
3. Find three examples where SDM was used to make a complex component. What about this approach proved to be useful for these components? How might these beneficial principles be better applied to AM today?
4. What are the primary benefits and drawbacks of UAM compared to other metal AM processes? Discuss UAM and at least three other metal AM processes in your comparison.
5. Develop several different machine architectures for paper sheet lamination processes. Start with the Helisys and Mcor Technologies examples. Investigate form-then-bond and bond-then-form approaches. Include ink-jet printing capability for color part fabrication. Evaluate the pros and cons of each technology and compare with the machine architectures of commercial machines, if you can find them.

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