Chapter 8
Sheet Lamination Processes

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 cross-hatch cutting operation. A schematic of the LOM process can be seen in Fig. 8.1.

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 processes, (c) clamping, and (d) ultrasonic welding. As the use of ultrasonic welding is relatively new, and is an area of considerable research interest, an extended discussion of this bonding approach is included at the end of this chapter.

8.1 Gluing or Adhesive Bonding

The most popular lamination build material has been paper with a thermoplastic coating on one side. This type of adhesive-backed paper is similar to the "butcher paper" used to wrap meat. Paper thicknesses often 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. In one category, there are processes in which the laminate is bonded first to the substrate and is then formed into the cross-sectional shape ("bond-then-form" processes). In another category, there are processes in which the laminate is formed first and then bonded to the substrate ("form-then-bond" processes).

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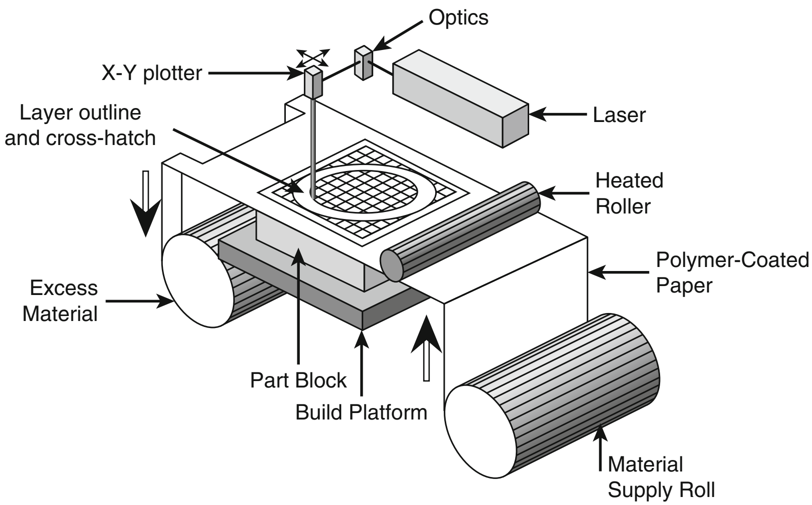

Fig. 8.1 Schematic of the LOM process (based on [1] JOURNAL OF MATERIALS PROCESSING TECHNOLOGY by D.I. Wimpenny, B. Bryden, I.R. Pashby. Copyright 2003 by Elsevier Science & Technology Journals. Reproduced with permission of Elsevier Science & Technology Journals in the format Textbook via Copyright Clearance Center.)

8.1.1 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, where a heated roller melted the plastic coating, causing it to adhere to the previous layer. 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 postprocessed. 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 build-up.

As mentioned above, most people associate paper sheet lamination with the Laminated Object Manufacturing machines introduced in 1991 by Helisys Inc., USA and most recently serviced by Cubic Technologies, USA (after Helisys’ bankruptcy). These LOM systems make use of a CO_2 laser for cutting the laminates. However, similar systems have been developed, including (a) Solid Slicing

Fig. 8.2 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)

Manufacturing (SSM) by Beijing Yinhua, China, (b) Zippy RP Systems by Kinergy PTE Ltd., Singapore; and (c) Paper Lamination Technology (PLT) by Kira Corp. Ltd., Japan. The PLT system makes use of plain paper (no adhesive) as the build material, and a laser printer is used to apply a proprietary resin powder on top of the previously deposited layer or substrate in the regions where bonding is desired. Because the support material is not adhesively bonded, unlike in LOM, the support removal process is easier.

Solidimension (Be'erot, Israel) took the concepts of LOM and further developed them in 1999 into a commercial prototyping system for laminating PVC plastic sheets. Solidimension sells its own machines under the Solido name [2] and it has also sold machines through Graphtec Corp. Japan under the name "XD700" and through 3D Systems under the name "InVision LD 3D-Modeler." This machine utilizes an *x*–*y* plotter for cutting the PVC sheets and for writing with "anti glue" pens, which inhibit bonding in prescribed locations. This machine uses a unique approach to support material removal. Support material is subdivided into regions, and unique patterns for cutting and bonding the excess material are used to enable easy support material removal. An example of this support material strategy can be seen in Fig. 8.2.

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 postprocessing is used to debind and sinter the structure. In most cases tape casting methods are used to produce sheets of material made up of powdered build material (such as SiC, alumina, or other materials) and a polymer binder. These tapes are then used for part construction employing the standard LOM process. Various SiC, alumina, TiC–Ni composite, and other material tapes have been used to build parts.

Specific advantages of LOM and 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; (g) nontoxic, stable, and easy-to-handle feedstock; and (h) low material, machine, and process costs relative to other AM systems.

LOM 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. Each of these limitations, however, has been overcome to some extent using the sheet lamination variations discussed in the subsequent sections of this chapter.

In general, parts produced by paper-based LOM 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 LOM include patterns for sand-casting and 3D topographical maps – where each layer represents a particular elevation of the map.

8.1.2 *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. 8.2) 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

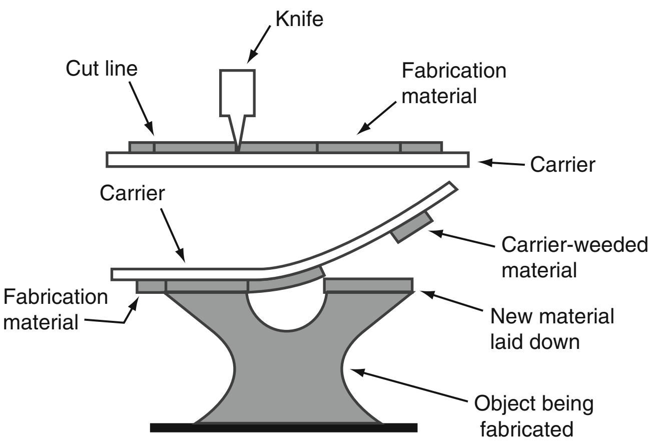

Fig. 8.3 Offset Fabbing system, Ennex Corp. (http://www.ennex.com/fab/Offset/)

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. 8.3.

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 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; and 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. 8.4. 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, introduced in Chap. 5. The CL-100 machine produces parts within its 150 mm (6″) cube work envelope. Up to five types of materials, including materials of differing thickness, can be automatically incorporated into a build. One or more of

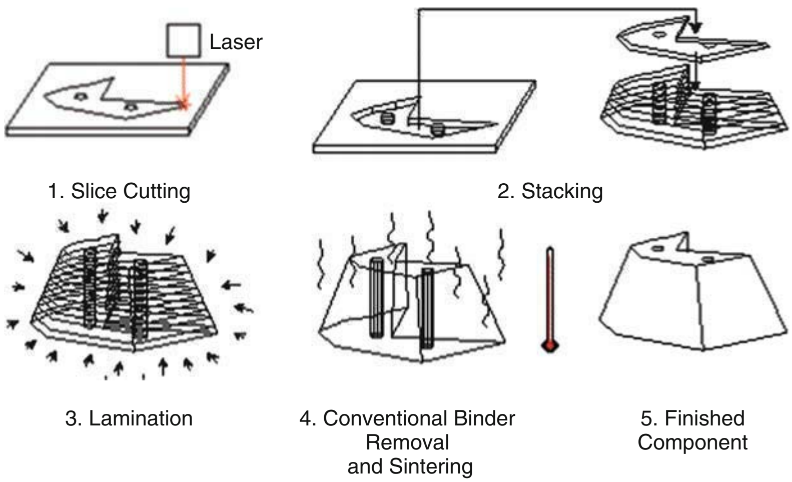

Fig. 8.4 CAM-LEM process (Courtesy CAM-LEM, Inc.)

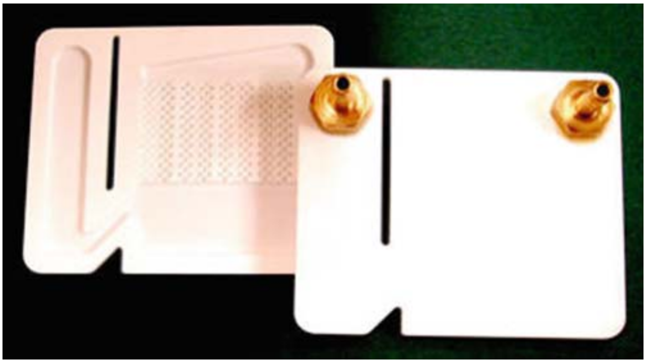

Fig. 8.5 A ceramic microfluidic distillation device cutaway view (*left*) and finished part (*right*) (Courtesy CAM-LEM, Inc.)

these materials may act as secondary support materials to enable internal voids or channels and overhangs. These support materials are later removed using thermal or chemical means. A wide layer thickness range is possible, from 30 μm to 1.3 mm or more. A problem with this process is that thermal postprocessing to consolidate the metal or ceramic powders results in a large amount of shrinkage (12–18%) which can lead to dimensional inaccuracies and distortion. A key application for this technology is for the fabrication of microfluidic structures (structures with micro-scale internal cavities and channels). An example microfluidic structure made using CAM-LEM is shown in Fig. 8.5.

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.

8.2 Thermal Bonding

Several sheet lamination processes use thermal processes for bonding sheet materials. Complex-shaped 3D parts have been made from metallic sheets and foils employing diffusion bonding, laser spot welding, and brazing techniques. Most investigators have adopted the form-then-bond approach for metal part fabrication, as excess metal support materials are very difficult to remove when using a bond-then-form approach.

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. [8] produced laminated steel tooling with conformal cooling channels by brazing laser-cut steel sheets. Similarly, Yamasaki [9] 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 postprocessing 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 metal lamination is primarily in the area of 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) [10]. With SDM, the geometry of the part is subdivided into non-planar segments. Each segment is deposited as an over-sized, near-net shape region and then finished 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, functional requirements, etc. Secondary support materials were commonly used to enable complex geometry to be made and for clearance between mechanisms that required differential motion after manufacture. A completely automated subdivision routine for arbitrary geometries, however, is not possible as 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.

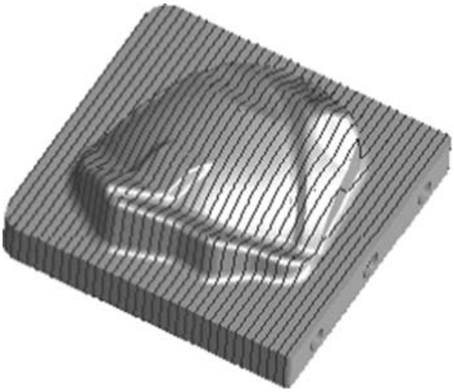

Fig. 8.6 Profiled edge laminate tool (courtesy Fraunhofer CCL)

8.3 Processes Based on 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. 8.6. 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. 8.6). The drawback 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.

8.4 Ultrasonic Consolidation

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. In UC, the object is built up on a rigidly held base plate bolted onto a heated platen, with temperatures ranging from room temperature to a maximum of approximately 200°C. Parts are built from bottom to top, and each

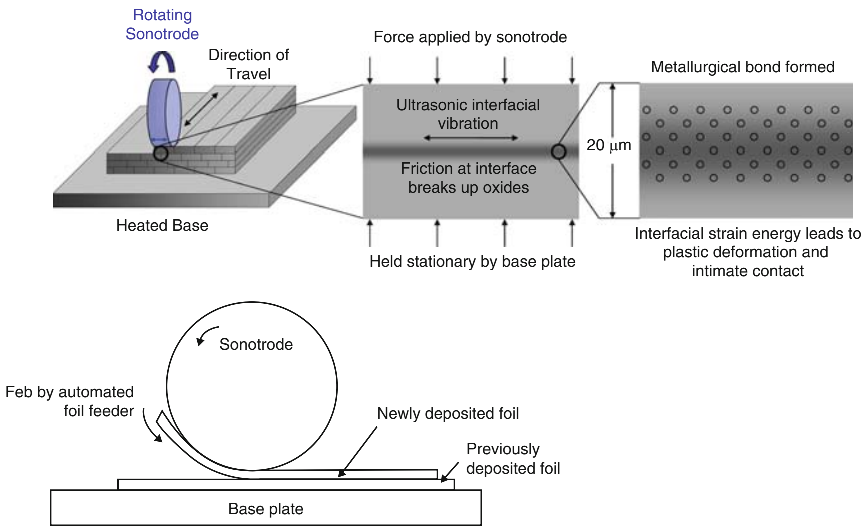

Fig. 8.7 Schematic of ultrasonic consolidation

layer is composed of several metal foils laid side-by-side and then trimmed using CNC milling.

During UC, 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. 8.7. 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 UC. 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, UC 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 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 UC 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 UC 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 UC. However, on-going support material research for UC will hopefully result in an automated support material approach in the near-term.

To better illustrate the UC process, Fig. 8.8a–f illustrates the steps utilized to fabricate a honeycomb panel (272.5 mm by 240 mm by 10.7 mm). The cutaway CAD model showing the internal honeycomb features is shown in Fig. 8.8a. The part is fabricated on a 356 mm by 356 mm by 12.7 mm Al 3003 base plate, which is firmly bolted to a heated platen, as shown in Fig. 8.8b. Metal foils used for this part are Al 3003 foils 254 mm wide and 150 μm thick. The first layer of deposited foils is shown in Fig. 8.8c. 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. 8.8d. After every four layers of deposition, the UC 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. 8.8e. Four layers are deposited, and the final panel is shown in Fig. 8.8f.

8.4.1 UC Bond Quality

There are two widely accepted quality parameters for evaluating UC-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. To determine the LWD of a UC-made part, samples should be cut perpendicular to the bonding interface and evaluated. An example of a microstructure sample made from four layers of Al 3003 tapes by UC is shown in Fig. 8.9. The black areas represent the unbonded regions along the interfaces. In this microstructure, a LWD of 100% occurred only between Layer 1 and the base plate.

8.4.2 UC Process Fundamentals

Since the 1950s, ultrasonic metal welding (UMW) has been implemented as a versatile joining technology in various industries, including in electronics,

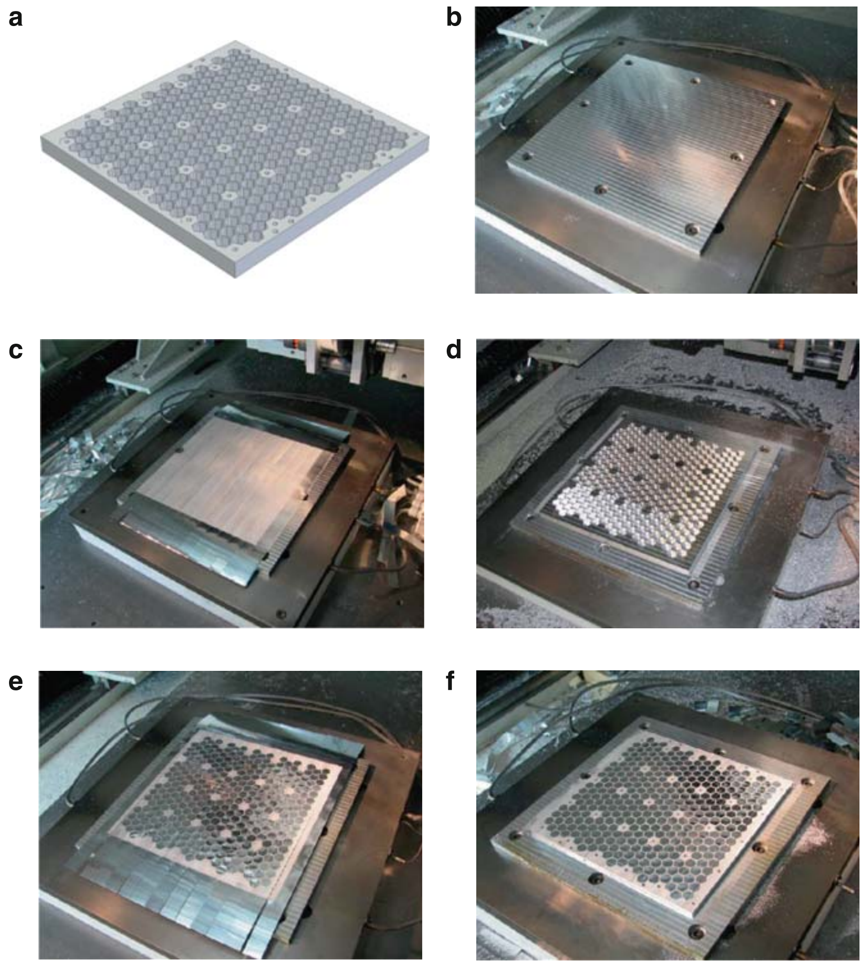

Fig. 8.8 Fabrication procedure for a honeycomb structure using UC

automotive and aerospace industries. Compared to other metal fusion processes, UMWs solid-state joining approach does not require high 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 introduced 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 UC.

Bonding in UMW can be by (a) mechanical interlocking; (b) melting of interface materials; (c) diffusion bonding, and (d) atomic forces across nascent metal

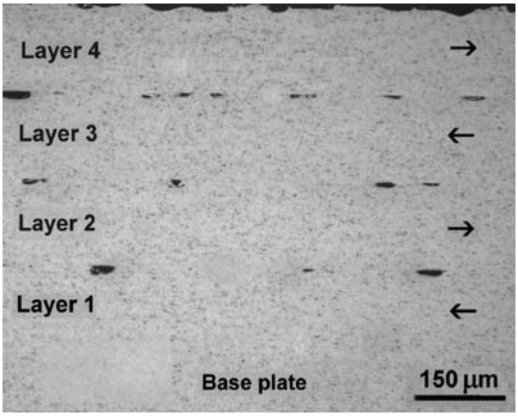

Fig. 8.9 A UC part made from four layers of Al 3003 foils. LWD is determined by calculating the bonded interface divided by the total interface (*arrows* show the sonotrode traveling direction for each layer). "Effect of Process Parameters on Bond Formation during Ultrasonic Consolidation of Aluminum Alloy 3003," G.D. Janaki Ram, Yanzhe Yang and Brent Stucker, Journal of Manufacturing Systems, 25 (3), pp. 221–238, 2006

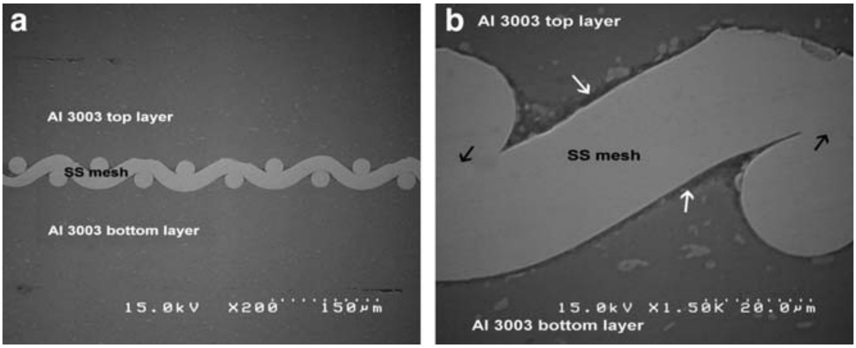

Fig. 8.10 SEM microstructures of Al 3003/SS mesh: (**a**) SS mesh embedded between Al 3003 layers, (**b**) Al 3003/SS mesh interface at a higher magnification. The *white arrows* illustrate the lack of metallurgical bonding between the Al and SS materials. The *black arrows* indicate areas of metallurgical 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

surfaces (e.g., solid-state metallurgical bonding without significant diffusion). In UC, 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 UC process is shown as Fig. 8.10. 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 UC: (a) generation of atomically clean metal surfaces, and (b) intimate contact between clean metal surfaces. Both conditions can be satisfied by plastic deformation of foil surfaces due to combinations of ultrasonic excitation and application of normal forces during UC. 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 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 UC-compatible when employing chemical or mechanical techniques for removing the surface oxide layers just prior to welding.

Some amount of plastic deformation at the foil interface is critical for UC, to break up surface oxides and overcome surface roughness; forcing the layers into intimate contact across the interface. The magnitude of plastic deformation necessary to achieve effective 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. 8.9) 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. Some of these changes are beneficial for UC, including effects of 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 [11]. 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.

UC 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 is enhanced pronouncedly. Both of these characteristics aid in UC bonding.

8.4.3 UC Process Parameters and Process Optimization

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

8.4.3.1 Oscillation Amplitude

Energy input directly affects the degree of elastic/plastic deformation between mating metal interfaces, and consequently affects bond formation. For a given material combination, oscillation amplitude and frequency of the sonotrode determines the amount of ultrasonic energy available for bond formation. In commercial UC 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 UC, 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 the energy input exceeds a critical level, bonding deteriorates as excess plastic deformation can damage previously formed bonds at the welding interface due to excessive states of stress and/or fatigue.

8.4.3.2 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. From a bond formation point of view, surface oxide layer removal and mating interface plastic deformation are strongly influenced by applied normal force, as the normal force along with the reciprocal oscillating motion directly determine the magnitude of dynamic stresses at the bond interface during UC. Therefore, more severe stress conditions result from increased normal force. 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.

8.4.3.3 Sonotrode Travel Speed

Welding exposure time has a direct effect on bond strength during ultrasonic welding. In UC 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.

8.4.3.4 Preheat Temperature

Metallurgical bonds can be established at ambient temperature during UC processing. However, for many materials an increased preheat temperature facilitates bond formation. In UC of Al 3003, the LWD of parts increases as the temperature increases from room temperature to 150°C. 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. Finally, for certain materials, such as Cu, enhanced oxide formation at elevated temperatures will impede oxide removal to a greater degree than the enhanced softening that aids plastic deformation, and thus excess heating becomes detrimental to bonding.

In addition to the above process parameters, other factors also affect bond quality. Certain materials and material combinations are inherently better-suited to ultrasonic welding than others. Material properties and state, such as material hardness, surface cleanliness, oxide characteristics, oxide layer thickness, surface roughness, and others, significantly affect ultrasonic weldability. For many materials, optimized process parameters are easy to obtain across a wide range of parameter combinations; whereas for materials with poor ultrasonic weldability, process optimization can be difficult and time-consuming. Although models for UC bonding have been developed, they are not yet robust enough to predict optimum parameters for a given material, and are mostly useful for investigating bonding trends. Thus, just as for many other AM processes, finding optimum process parameter combinations for a given material system may require extensive experimentation.

Metal foil thickness is another important factor to be considered in UC. The most common metal foils used in UC 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 UC 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 UC.

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 UC 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. 8.9). 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.

8.4.4 Microstructures and Mechanical Properties of UC Parts

8.4.4.1 Defects

The most common defects in UC-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. 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 UC results in the breaking of previously formed bonds. Type-2 defects are rare once process parameter optimization has been completed. 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. 8.11). 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.

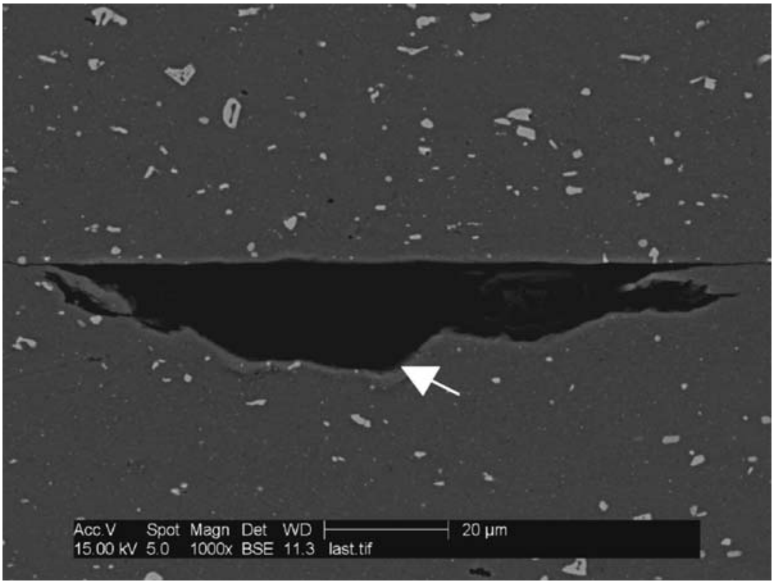

Fig. 8.11 Type-1 UC defect (arrow indicates location of surface oxides)

Type-3 defects are the physical gaps between adjacent metal foils within one layer of deposition, as shown in Fig. 8.12. In UC, the foil width setting within the software determines the offset distance the sonotrode and foil placement mechanism are moved between 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 UC machine, combined with improper width settings cause Type-3 defects.

Defects strongly affect the strength of UC parts. Thus, 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 also be avoided by using surface machining. If a small amount of metal (~10 μm, or the largest roughness observed at the upper-most deposited surface, as in Fig. 8.9) is removed after depositing each layer, the surface roughness of the metal foil is significantly reduced and voids between foils are fewer in number, smaller in size, and easy to be closed by plastic deformation. 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 UC

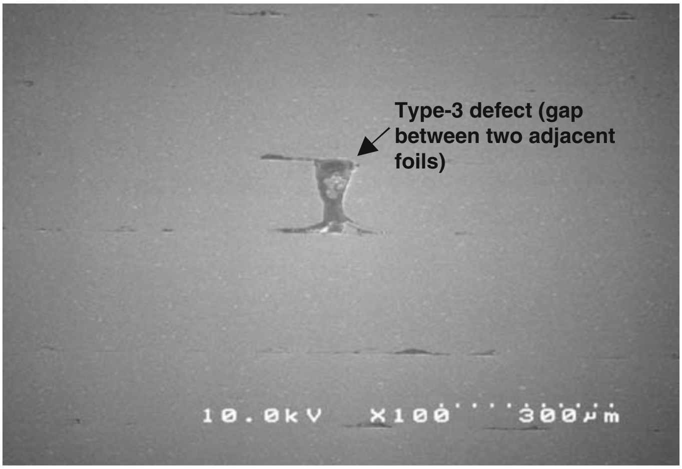

Fig. 8.12 Type-3 defect observed between adjacent foils. (Note the morphology of the Type-1 defects between layers indicate that this micrograph is upside-down with respect to build orientation)

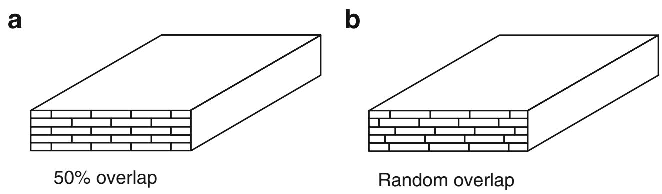

Fig. 8.13 Schematic illustrating (**a**) 50% foil overlap, and (**b**) random foil overlap in UC

part can be arranged so that 50% overlap across layers is obtained, as shown in Fig. 8.13. Although somewhat counter-intuitive, it has been shown that better tensile properties result from a 50% overlap than when random foil arrangements are used.

8.4.4.2 UC Microstructures

A typical microstructure of a UC part made from Al 3003 tapes with representative defects were shown in Figs. 8.9 and 8.12. Figure 8.14 shows the microstructure of two Ni 201 foils deposited on an Al 3003 substrate. These Ni foils exhibit some unbonded regions with several defects. Plastic deformation of Ni foils near the foil surfaces can be experimentally visualized using orientation imaging microscopy, as shown in Fig. 8.15. Smooth intragrain color transition within a few grains at the surface indicates the foil interfaces undergo some plastic deformation during UC processing, whereas the absence of intragranular color transitions away from

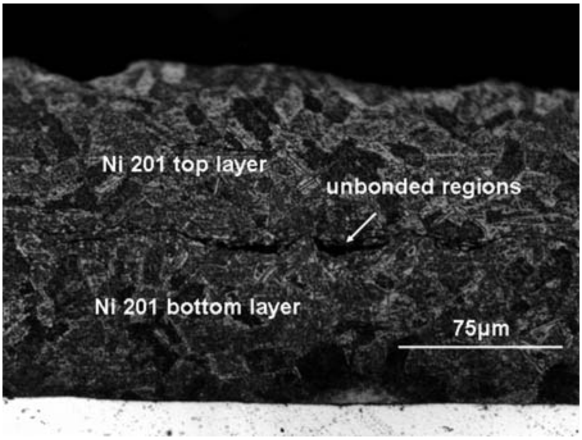

Fig. 8.14 Ultrasonically consolidated Ni 201 foils

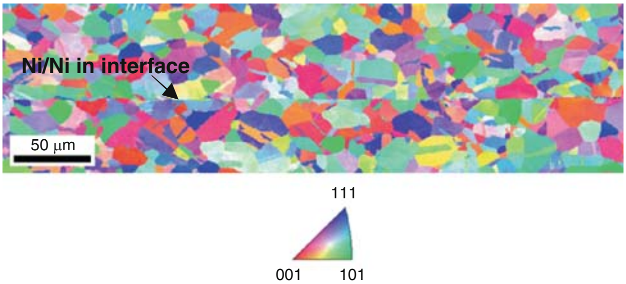

Fig. 8.15 An image of several inverse pole figures of contiguous areas along a well-bonded Ni–Ni interface stitched together. The grains in the image are color coded to reflect their orientation (for color version, see ACTA MATERIALIA by Brent L. Adams, Clayton Nylander, Brady Aydelotte, Sadegh Ahmadi, 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.)

the foil surfaces indicates that the original microstructure is retained in the bulk of the foil.

In addition to UC of similar materials, UC 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 [12].

8.4.4.3 Mechanical Properties

Mechanical properties of UC parts are typically 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 UC are prepared via rolling. Grains within the foils are often elongated along the rolling direction, which is the foil length (longitudinal) direction. As a result, foils are typically stronger along the longitudinal direction, and thus UC parts are typically stronger in the foil longitudinal direction, even when annealed foils are used, unless heat treating is performed after UC. Type-3 defects also lower the strength in the transverse direction when compared with the longitudinal direction. Thus a typical transverse strength for a UC part is about 85% of the published bulk strength value for a particular material whereas the longitudinal strength will often exceed published values for a material. In both the longitudinal and transverse directions, unless heat treatment is performed after UC the ductility of UC-fabricated parts is inferior to published bulk values.

In the z direction, perpendicular to the layer interfaces, UC parts are much weaker than the longitudinal and transverse 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 UC for part fabrication, it is important to consider the anisotropic aspects of UC parts with respect to their design.

Another factor which affects mechanical properties is the interfacial plastic deformation which foils undergo during UC. 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.

8.4.5 Modeling of UC

Since cyclic deformation during UC takes place at 20 kHz, any direct measurement of the strain field, temperature distribution or stress states in real time is incredibly difficult. As a result, researchers primarily use simulations of the UC process to understand these phenomena. Most researchers use a combined friction-based, coupled-field (mechanical and thermal) model. As a result, induced interfacial plastic deformation, work due to friction and geometric-based wave propagation factors have all been identified as key aspects which affect bond quality. Simulation results show that maximum temperatures are below 50% of the melting temperature, thus concurring with experimental results.

One interesting correlation between modeling and experimental results is with respect to the degree of plastic flow which occurs in the presence of an embedded fiber in UC. As can be seen in Fig. 8.16, 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 recent 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.

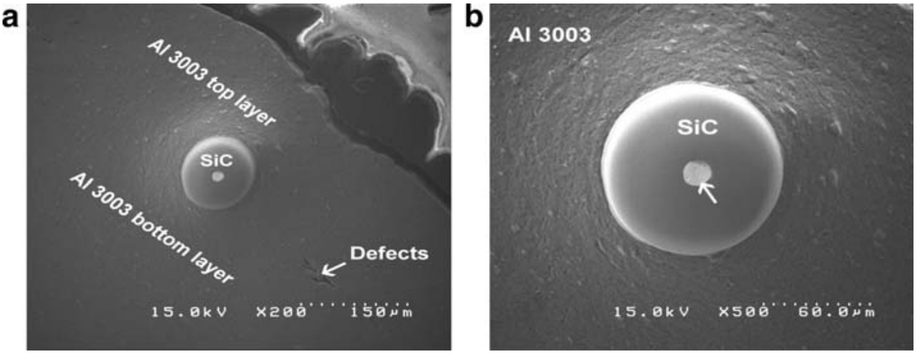

Fig. 8.16 SEM microstructures of Al 3003/SiC: (**a**) SiC fiber embedded between Al 3003 layers showing a lack of defects near the fiber; and (**b**) the same SiC fiber at a higher magnification showing excellent bonding near the fiber. © Emerald Group Publishing Limited, "Use of Ultrasonic Consolidation 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

Using both experimental and modeling results, it has been shown that it becomes quite difficult to bond parts using UC when their height-to-width ratio is near 1:1 [13]. 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.

Some simulations and experimental results appear to indicate that there is some type of threshold ultrasonic energy for each material, which depends on the deformation and yield behavior of the material under varying processing condition. Bonding improves as energy increases up to this threshold, but if the material is exposed to excess ultrasonic energy the trend changes and bonding degrades. A simplified analytical model has been developed to help analyze experimental results with respect to a threshold ultrasonic energy input [14]. Figures 8.17 and 8.18 illustrate the axes and directions associated with this model. In this model, the small volume of material immediately underneath the sonotrode, which is affected by the sonotrode oscillation, is of interest (Fig. 8.18). The width of the contact area along the *X*-axis is equal to the width of the metal foil used, which is ~25 mm.

In this energy model, simplifying assumptions include:

1. There is no slip between the foil being deposited and the sonotrode, and thus the foil upper surface vibrates at an identical displacement, velocity, and acceleration as the sonotrode.
2. The base plate is assumed to be rigid.
3. Only elastic deformation occurs at the sonotrode/foil contact region.
4. The properties of materials are assumed to be constant.
5. All energy delivered to the workpiece is assumed to be used for bond formation, meaning no energy input is attenuated during transmission, lost or used to break

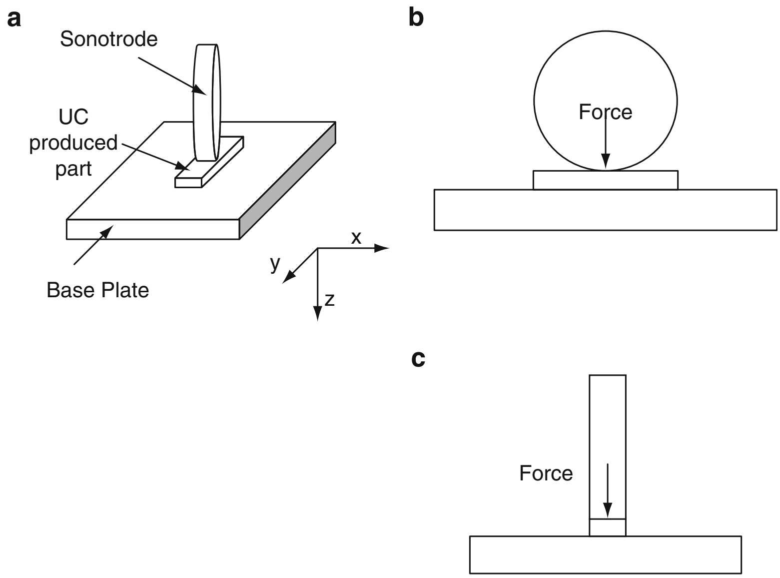

Fig. 8.17 (**a**) 3D schematic of metal foil deposition with UC. (**b**) 2D view on *Y–Z* plane. (**c**) 2D view on *X–Z* plane (© Emerald Group Publishing Limited, "An Analytical Energy Model for the Effects of Processing Parameters on Bond Formation during Ultrasonic Consolidation," Yanzhe Yang, G.D. Janaki Ram and Brent Stucker, Rapid Prototyping Journal 16 (1) 2010.)

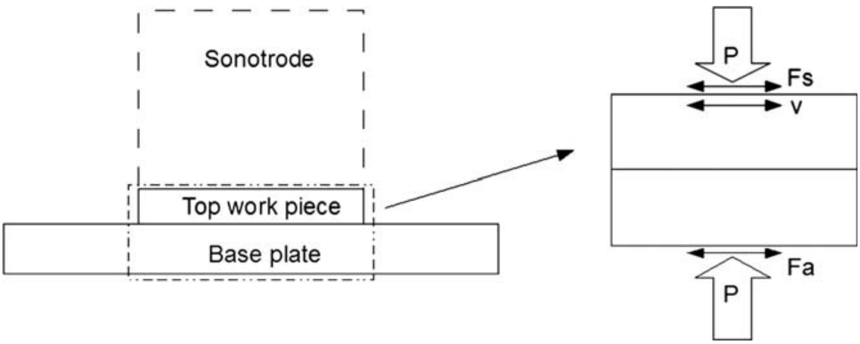

Fig. 8.18 Forces applied on top workpiece and base plate during UC (© Emerald Group Publishing Limited, "An Analytical Energy Model for the Effects of Processing Parameters on Bond Formation during Ultrasonic Consolidation," Yanzhe Yang, G.D. Janaki Ram and Brent Stucker, Rapid Prototyping Journal 16 (1) 2010.)

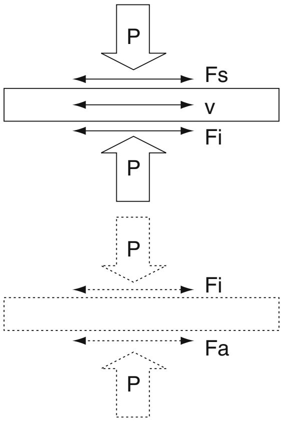

Fig. 8.19 Free body diagram of top workpiece and base plate (© Emerald Group Publishing Limited, "An Analytical Energy Model for the Effects of Processing Parameters on Bond Formation during Ultrasonic Consolidation," Yanzhe Yang, G.D. Janaki Ram and Brent Stucker, Rapid Prototyping Journal 16 (1) 2010.)

previously formed bonds; thus 100% of the input energy becomes transmitted energy.

As seen in Fig. 8.18, normal force P is applied to the top workpiece through the sonotrode, which results in friction (F_s) between the sonotrode and the workpiece. The motion of the sonotrode is assumed to be:

$$\xi(t) = \xi_0 \sin(2\pi ft) \tag{8.1}$$

where $\xi(t)$ is the displacement of the sonotrode and the top workpiece at time t; ξ_0 is the oscillation amplitude preset by the user; and f is the ultrasonic frequency at which the machine is operated, which is 20 kHz.

The velocity and acceleration of the sonotrode and top workpiece are calculated respectively as:

$$v(t) = \xi'(t) = 2\pi\xi_0 f \cos(2\pi ft) \tag{8.2}$$

$$a(t) = \xi''(t) = -(2\pi f)^2 \xi_0 \sin(2\pi ft) \tag{8.3}$$

Interfacial shear force between the top workpiece and the base plate, shown in the free body diagram, Fig. 8.19, is designated F_i. For the top workpiece, the equation of motion is thus:

$$F_s(t) + F_i(t) = m\,a(t) \tag{8.4}$$

where $F_s(t)$ is the friction force between the sonotrode and the top workpiece, which has a value of kP (k is the friction coefficient between the sonotrode and the top workpiece) and always has opposite sign to the velocity of the sonotrode. The mass of the top workpiece is m. Thus (8.4) can be expressed as:

$$F_{\mathrm{s}}(t) + F_{\mathrm{i}}(t) = Ad\rho\, a(t) \tag{8.5}$$

where A is contact area, d is metal foil thickness, and ρ is density of the metal foil.

Determination of the contact length, a, between the foil and base plate along the y direction is computed using (8.6) [15]:

$$a = \sqrt{\frac{PR}{2\pi}\left(\frac{2(\kappa_1 + 1)(1 + v_1)}{E_1} + \frac{2(\kappa_2 + 1)(1 + v_2)}{E_2}\right)} \tag{8.6}$$

where suffixes 1, 2 indicate the two materials in contact, v is Poisson's ration, E is Young's modulus, R is the radius of the sonotrode used, P is the normal force applied by the sonotrode, and κ is known as Kolosov's constant. For the current plane strain condition κ is computed using (8.7):

$$\kappa = 3 - 4v \tag{8.7}$$

Contact area A is computed as:

$$A = 2aw \tag{8.8}$$

where w is the width of the metal foil. Therefore, the equation of motion for the top workpiece becomes:

$$F_{\mathrm{s}}(t) + F_{\mathrm{i}}(t) = 2awd\rho\, a(t) \tag{8.9}$$

The shear force at the interface can be calculated as:

$$F_{\mathrm{i}}(t) = 2awd\rho\, a(t) - F_{\mathrm{s}}(t) \tag{8.10}$$

With determination of the interfacial shear force and reciprocal velocity between metal foils, the energy input, E_0, due to interfacial motion within one single cycle of motion is:

$$E_0 = \int_0^T F_{\mathrm{i}}(t) \times v(t)\,\mathrm{d}t \tag{8.11}$$

where T is the period of ultrasonic motion of the sonotrode, which is 0.00005s. Dwelling duration of the sonotrode at a particular location is determined by the length of contact area divided by the traveling speed of the sonotrode. Given the dwelling duration of the sonotrode, the number of motion cycles while the sonotrode is above the contact area is computed by the dwelling duration divided by the period of one cycle. The total energy, E_t, delivered to the bonding interface is computed using the number of motion cycles times the amount of energy input within a single cycle, E_0.

When comparing results of experimental data between various researchers using different sonotrode diameters and process parameter sets, it appears that, in spite of the significant simplifying assumptions, this simplified energy model is effective for correlating results between disparate research groups and machine configurations. When determining threshold energy for optimum bonding, there is a correlation between LWD and single cycle energy divided by area of contact (E_0/A). As long as the threshold energy for a single cycle is not exceeded, it appears that the greater the amount of total energy utilized, the better the bonding. There also appears to be a correlation between LWD and total energy divided by the square of area (E_t/A^2) when comparing different researchers' results to each other [14]. By including energy compensation terms for foil thickness and temperature, this type of comparison may become even more accurate.

8.4.6 UC Applications

UC 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 are discussed below.

8.4.6.1 Internal Features

As with other AM techniques, UC is capable of producing complex internal features within metallic materials. These include honeycomb structures, internal pipes or channels, and enclosed cavities. During UC, internal geometrical features of a part are fabricated via CNC trimming before depositing the next layer (see Fig. 8.8). 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 bottom (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. The development of an effective support material dispensing system for UC 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.

8.4.6.2 Material Flexibility

A wide range of metallic materials have been used with UC. Theoretically, any metal which can be ultrasonically welded is a candidate material for the UC process. Materials which have been successfully bonded using a UC apparatus 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 [12, 16–19]. Thus, there is significant material flexibility for UC 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. 8.10), which both have been bonded to Al 3003 using UC.

By depositing various metal foils at different desired layers or locations during UC, multi-material 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.

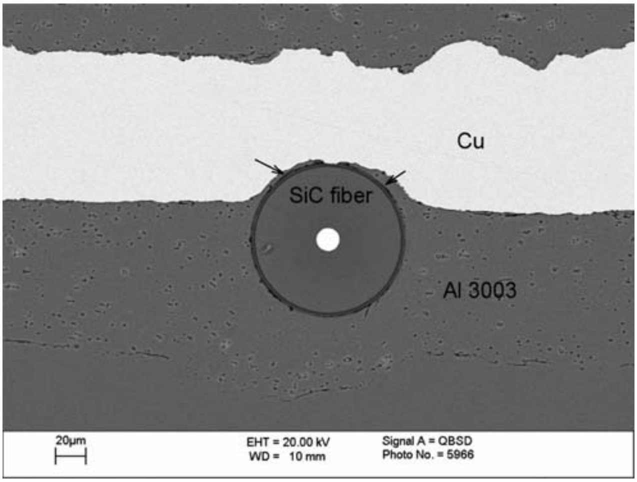

Fig. 8.20 SiC Fiber embedded between copper and aluminum using UC. Black arrows denote regions where the softer Al extruded around the fiber during embedment, resulting in displacement of the fiber away from the interface into the Al base material

8.4.6.3 Fiber Embedment

As mentioned previously, fibers can be embedded between layers using UC (Fig. 8.16). 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. 8.20. 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. 8.16 and 8.20).

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.

UC is a candidate manufacturing process for fabrication of long-fiber-reinforced metal matrix composites. However, to utilize UC 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 UC 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.

8.4.6.4 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. 8.21). Fabrication of smart structures is difficult for conventional manufacturing processes, as they do not enable full 3-dimensional control over geometry, composition and/or placement of components. AM processes are inherently suited to the fabrication of smart structures and UC, in particular, offers several advantages. Primarily due to the fact that UC is the only AM process whereby metal structures can be formed at low temperatures, UC 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 electronics, actuators, heat pipes, or other features at optimum location within a structure [20]. Many types of embedded electronics, sensors, and thermal management devices

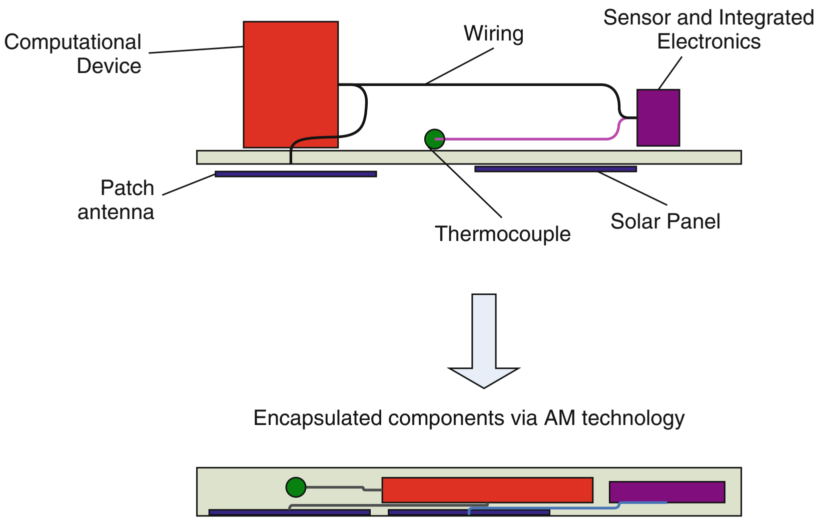

Fig. 8.21 Schematic illustrating the creation of a smart structure using UC

have been inserted into UC cavities. Sensors for recording temperature, acceleration, stress, strain, magnetism, and other environmental factors have been fully encapsulated and have remained functional after UC embedment. In addition to prefabricated electronics, it is feasible to fabricate customized electronics in UC with the integration of direct write technologies (see Chap. 10). By combining UC with direct write, electronic features (conductors, insulators, batteries, capacitors, etc.) can be directly created within or on UC-made structures in an automated manner.

8.5 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 UMW 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.

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.

8.6 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 UC compared to other metal AM processes? Discuss UC and at least three other metal AM processes in your comparison.
5. How might a single cycle energy input and total energy input model help in optimizing the UC process for a new material? Explain in detail how you would design a set of experiments to do this optimization.

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