UNIT-5

OTHER ADDITIVE MANUFACTURING PROCESSES

5.4 SHEET LAMANINATION PROCESSES

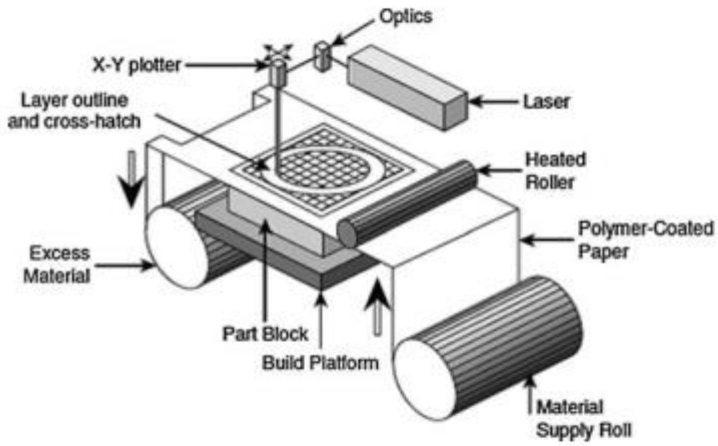

Fig. 9.1 Schematic of the LOM process (based on [1] Journal of Materials Processing Technology by D.I. Wimpenny, B. Bryden, I.R. Pashby. Copyright 2003 by Elsevier Science & Technology Journals. Reproduced with permission of Elsevier Science & Technology Journals in the format Textbook via Copyright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

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 CO2 laser, each sheet representing one crosssectional 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 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.

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-ofconcepts.

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

5.5 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 lasercut 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 formthen-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 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.