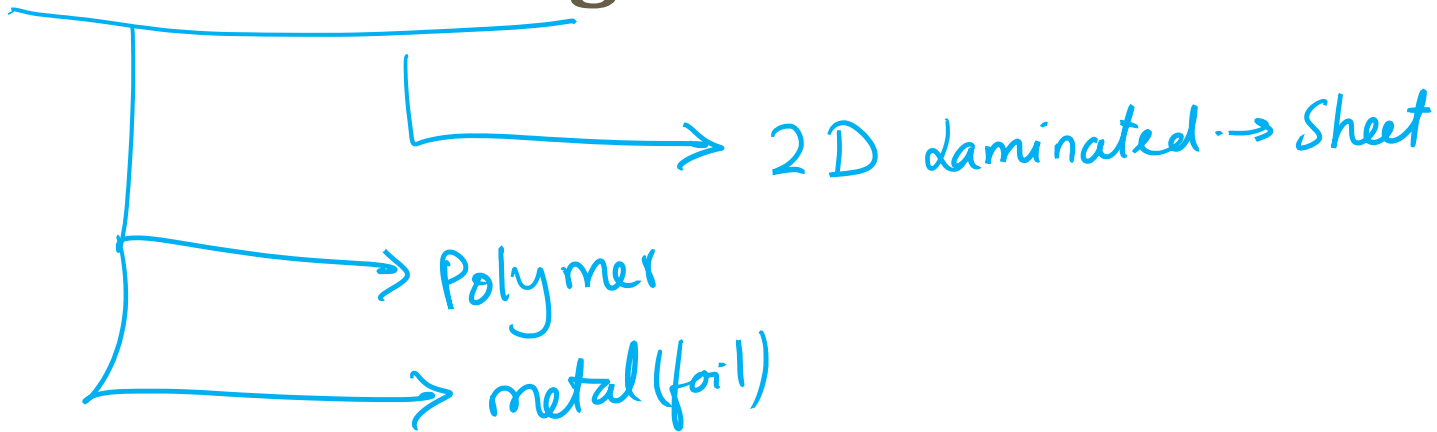


Sheet Stacking Processes $\rightarrow$ RP $\rightarrow$ RM



Dr. Janakarajan Ramkumar

Professor

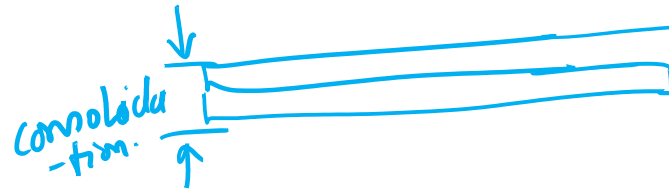
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- **UC Process Parameters and Process Optimization** ✓
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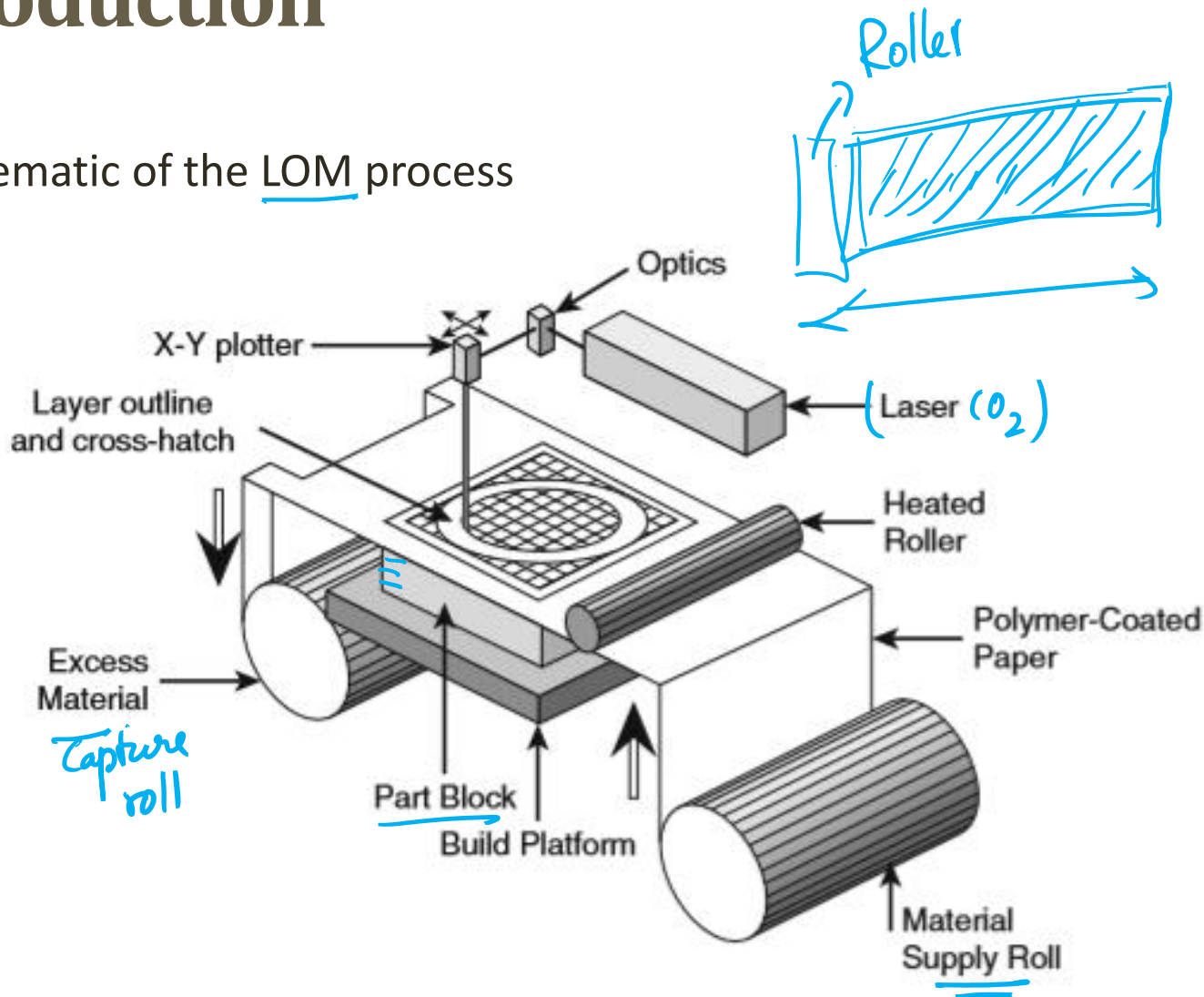
Introduction



- 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 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 cross-hatch cutting operation.

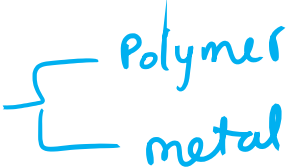
Introduction

- Schematic of the LOM process



Source: Gibson et al. Additive manufacturing Technologies, 2010

Introduction

- 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.
- 

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. ← *layer thickness*
- 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.

Gluing or Adhesive Bonding

- 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).



stick & then you provide
layer information.

Gluing or Adhesive Bonding

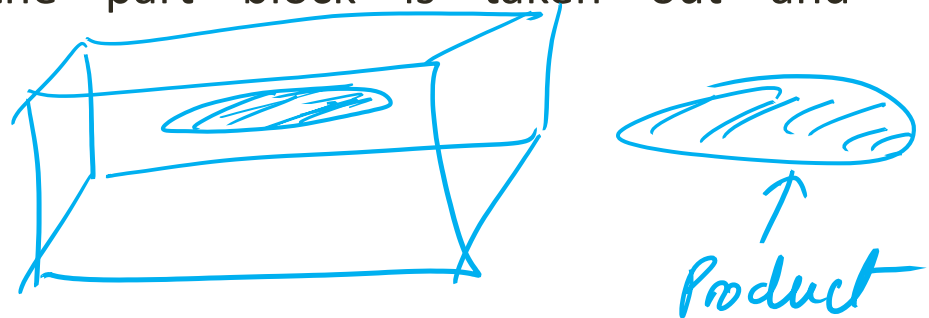
Bond-then-Form Processes

- 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.

Gluing or Adhesive Bonding

Bond-then-Form Processes

- The unused material is left in place as support material and is diced using a crosshatch pattern into small rectangular pieces called 'tiles'- 2D or 'cubes.' - 3D (*Z dimension is very small*)
- 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.



Gluing or Adhesive Bonding

Bond-then-Form Processes

- The crosshatched pieces of excess material are separated from the part using typical wood carving tools (called decubing).

cleavage → uncontrolled crack

- 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.
- The Paper Lamination Technology (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.

Gluing or Adhesive Bonding

Bond-then-Form Processes

- 'InVision LD 3D-Modeler' 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 Figure below.

Gluing or Adhesive Bonding

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;
- (c) the balls after complete removal of excess support material

(courtesy 3D Systems)



Gluing or Adhesive Bonding

Bond-then-Form Processes:

Advantages

1. Little shrinkage, residual stresses, and distortion problems within the process;
2. When using paper feedstock, the end material is similar to plywood, a typical pattern making material amenable to common finishing operations;
3. Large parts can be fabricated rapidly;
4. A variety of build materials can be used, including paper and polymer sheets and metal- or ceramic-filled tapes;
5. Nontoxic, stable, and easy-to-handle feedstock;
6. Low material, machine, and process costs relative to other AM systems.

Gluing or Adhesive Bonding

Bond-then-Form Processes:

Limitations

1. LOM has several limitations, including:
2. Most paper-based parts require coating to prevent moisture absorption and excessive wear;
3. The control of the parts' accuracy in the Z-dimension is difficult (due to swelling or inconsistent sheet material thickness);
4. Mechanical and thermal properties of the parts are inhomogeneous due to the glue used in the laminated structure;
5. Small part feature detail is difficult to maintain due to the manual decubing process.

Gluing or Adhesive Bonding

Pattern → mould → Component

Bond-then-Form Processes

- Each of the limitations, however, has been overcome to some extent using the sheet lamination variations.
- 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.

Gluing or Adhesive Bonding

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 but implementation has primarily been at the research level.

Gluing or Adhesive Bonding

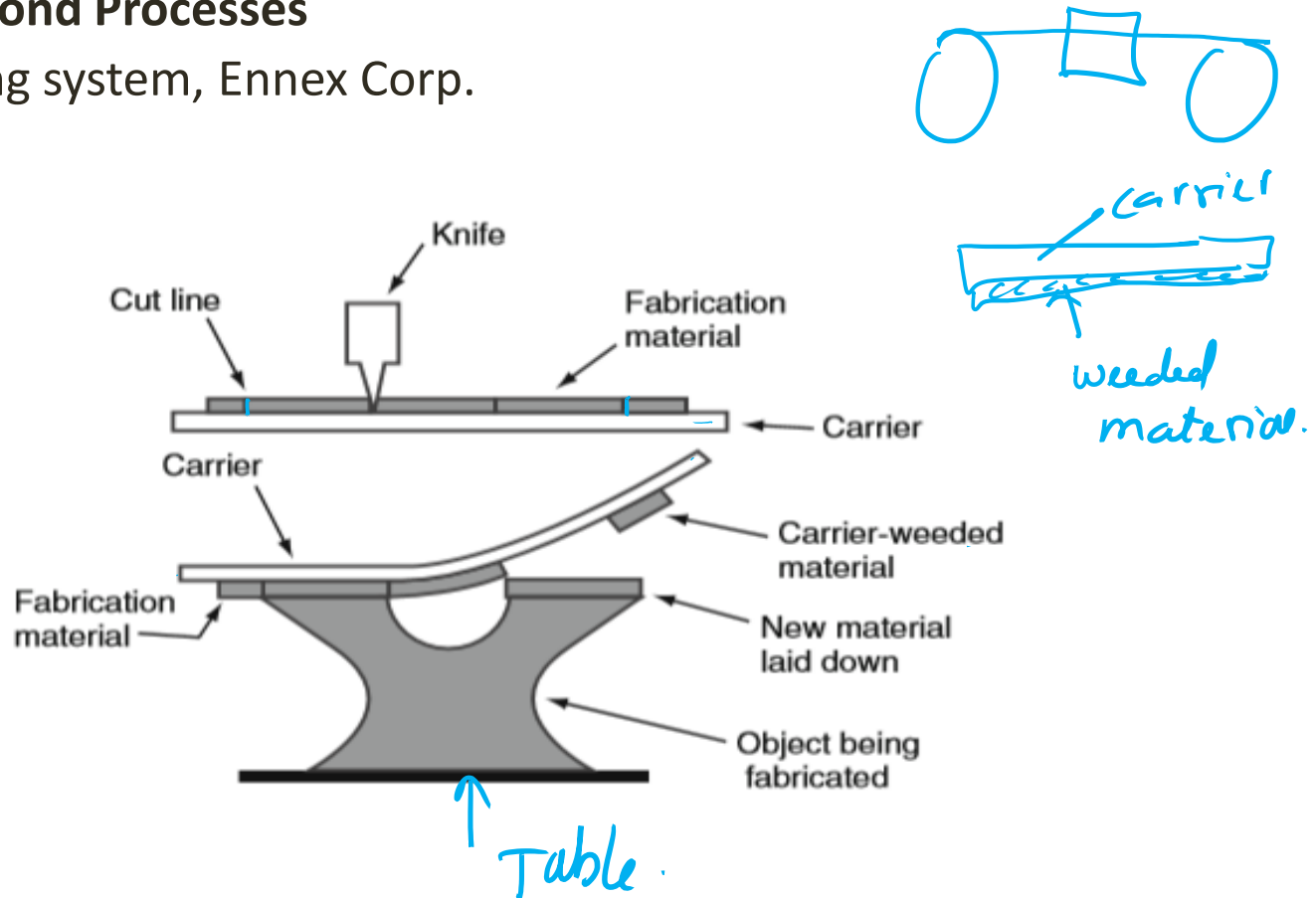
Form-then-Bond Processes

- One example of a glue-based formthen-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.

Gluing or Adhesive Bonding

Form-then-Bond Processes

Offset Fabbing system, Ennex Corp.



Source: Gibson et al. Additive manufacturing Technologies, 2010

Gluing or Adhesive Bonding

Form-then-Bond Processes

Advantages



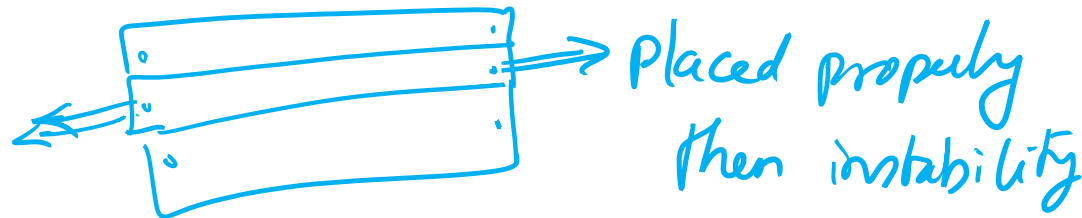
1. The form-then-bond approach facilitates construction of parts with internal features and channels.
2. Internal features and small channels are difficult or impossible with a bond-then-form approach because the excess material is solid and thus material inside internal features cannot be removed once bonded (unless the part is cut open).
3. 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.
4. The time-consuming and potentially damage-causing decubing step is eliminated

Gluing or Adhesive Bonding

Form-then-Bond Processes:
Limitation

Internal feature
de Casing not required.

1. 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.

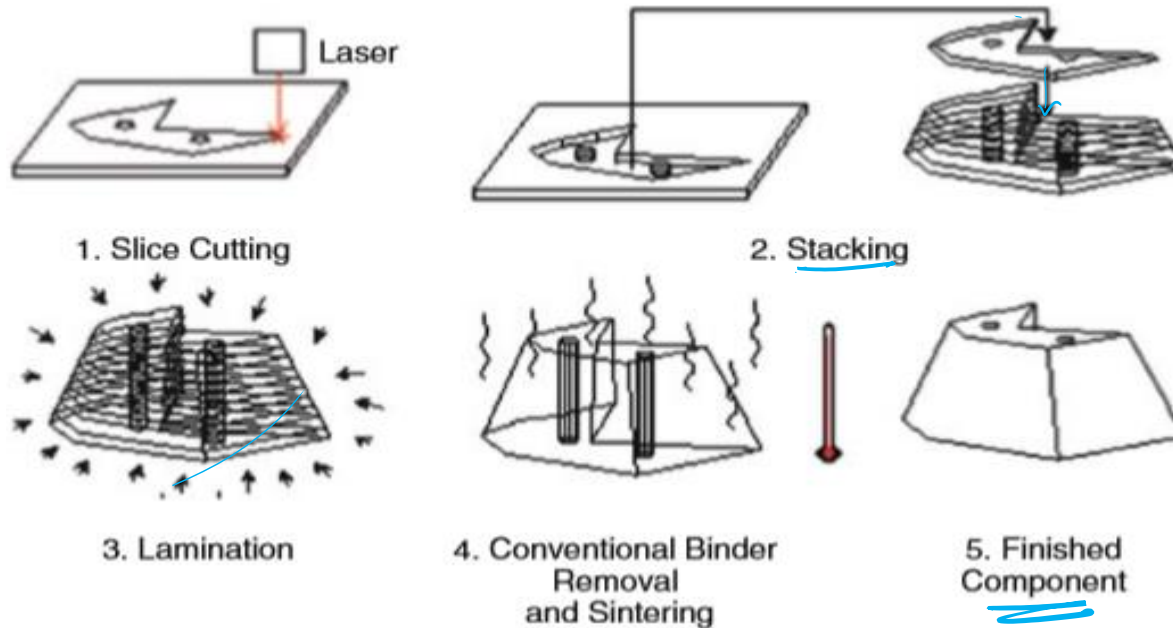


Gluing or Adhesive Bonding

Form-then-Bond Processes

Computer-Aided Manufacturing of Laminated Engineering Materials process

(Courtesy CAM-LEM, Inc.)



Source: Gibson et al. Additive manufacturing Technologies, 2010

Gluing or Adhesive Bonding

CAD → slice → geometric features

Form-then-Bond Processes

Computer-Aided Manufacturing of Laminated Engineering Materials process

- 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.

Gluing or Adhesive Bonding

Form-then-Bond Processes



- The green part is then furnace processed in a manner identical to indirect processing of metal or ceramic green parts.
- The CL-100 machine produces parts within its 150 mm (600) cube work envelope.
- Up to five types of materials, including materials of differing thickness, can be automatically incorporated into a build.
→ *varying material & varying thickness is possible.*
- One or more of these materials may act as secondary support materials to enable internal voids or channels and overhangs.
→ *Functional graded Product (FGP)*

Gluing or Adhesive Bonding

Form-then-Bond Processes

- These support materials are later removed using thermal or chemical means.
- A wide layer thickness range is possible, from 30 mm 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).



Gluing or Adhesive Bonding

Form-then-Bond Processes

A ceramic microfluidic distillation device cutaway view (left) and
Finished part (right)

(Courtesy CAM-LEM, Inc.)



Gluing or Adhesive Bonding

Form-then-Bond Processes:

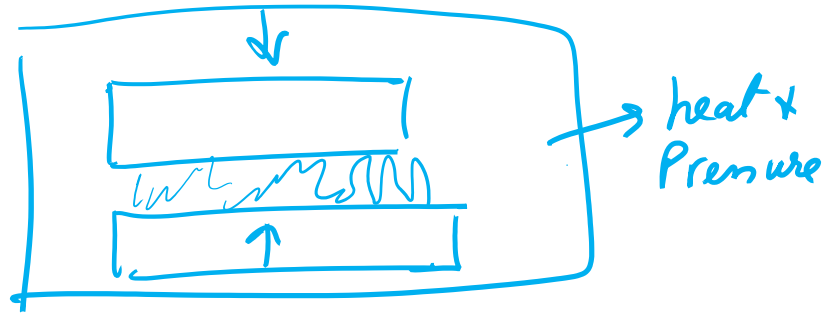
Stratoconception approach $\Rightarrow$ thickness is layer

- In Stratoconception approach, 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.
- 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.

Thermal Bonding

- 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.

Thermal Bonding



- Yi et al. 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. 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.

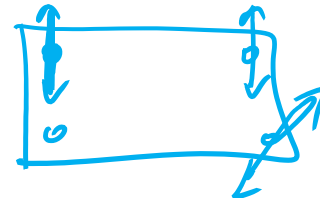
Thermal Bonding

- 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.

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.



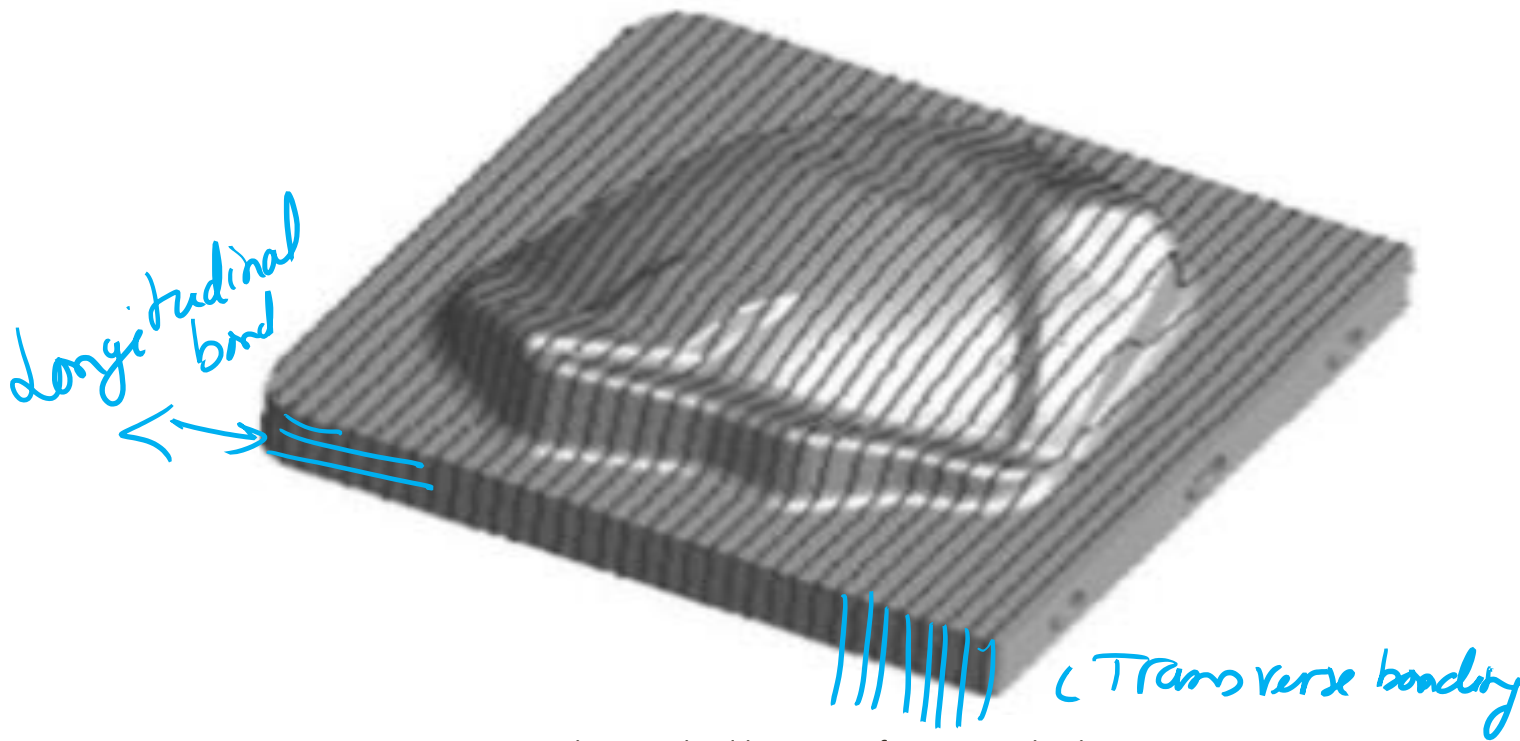
Processes based on Sheet Metal Clamping

- 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 Figure below. Of course, this type of profiled edge can also be utilized with adhesive and thermally bonded layers as well.

Processes based on Sheet Metal Clamping

Profiled edge laminate tool

(courtesy Fraunhofer CCL)

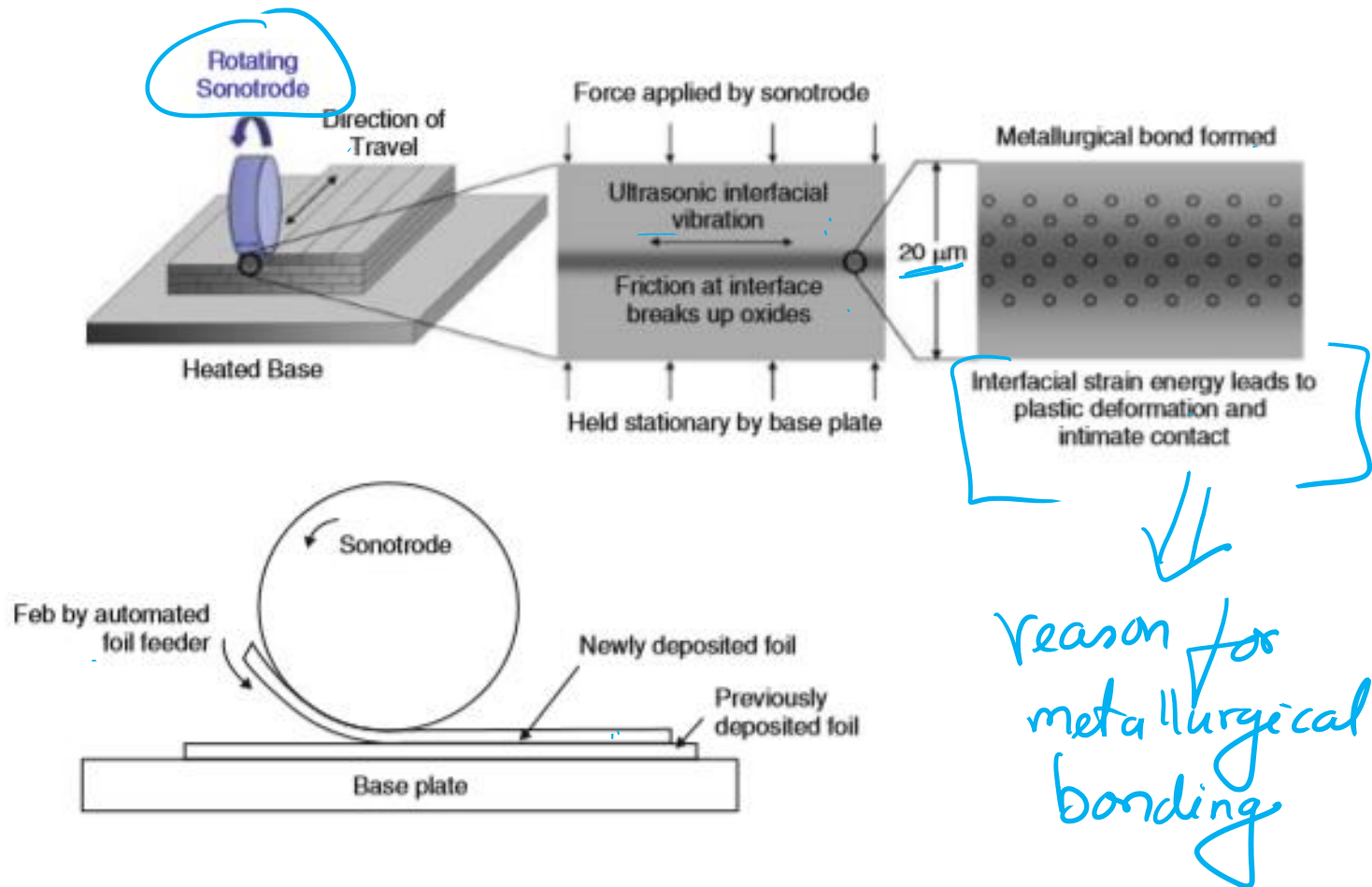


Source: Gibson et al. Additive manufacturing Technologies, 2010

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 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 mm thick).
- The foil is held closely in contact with the base plate or previous layer by applying a normal force via the rotating sonotrode.

Ultrasonic Consolidation



Ultrasonic Consolidation

- The sonotrode oscillates transversely to the direction of motion, at a constant 20 kHz frequency and user-set oscillation amplitude. $(1 - 10 \mu m)$
- 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.

Ultrasonic Consolidation

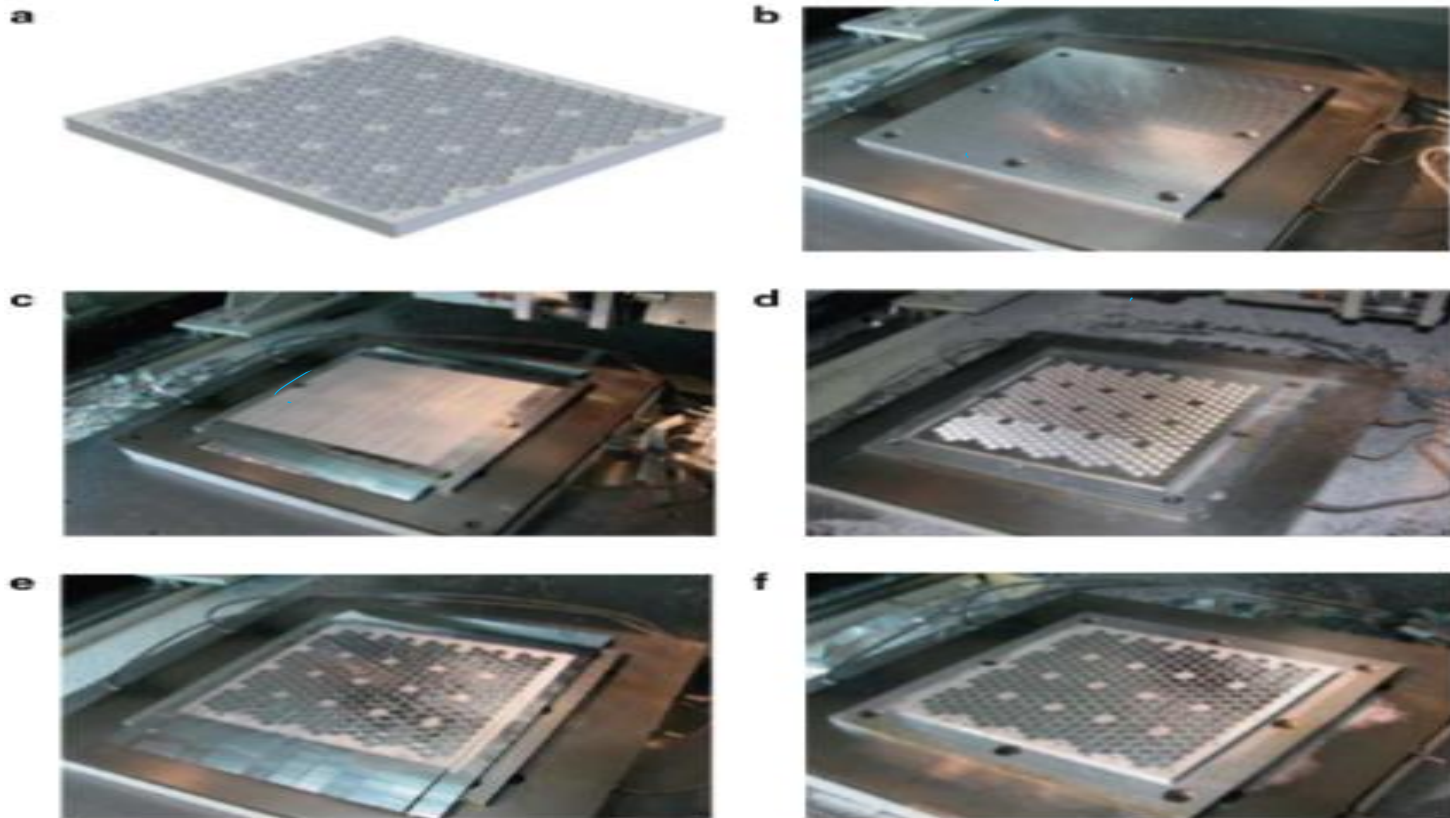
- Thus, UC is a bond-then-form process, where the forming can occur after each layer or after a number of layers, depending on the settings chosen by the user.
- Additionally, each layer is typically deposited as a combination of foils laid side-by-side rather than a single large sheet, as is typically 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.

Ultrasonic Consolidation

- 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.

Ultrasonic Consolidation

Fabrication procedure for a honeycomb structure using UC



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.

UC Process Parameters and Process Optimization

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.

UC Process Parameters and Process Optimization

Oscillation Amplitude

- 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.

UC Process Parameters and Process Optimization

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.

UC Process Parameters and Process Optimization

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.

UC Process Parameters and Process Optimization

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 150⁰ C.
- Heating directly benefits bond formation by reducing the flow stress of metals.

UC Process Parameters and Process Optimization

Preheat Temperature

- 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.

Properties of UC Parts

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.
 - a) Type-1 defects are the voids along layer/layer interfaces due to foil surface roughness and/ or insufficient input energy.
 - b) 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.
 - c) Type-3 defects are found between adjacent foils within a layer.

Properties of UC Parts

Defects

- 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 Figure below).
- 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.

Properties of UC Parts

Defects

- 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.

Properties of UC Parts

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.

Properties of UC Parts

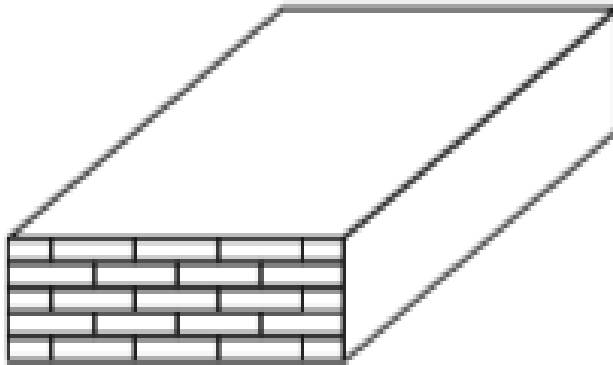
Defects

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

Properties of UC Parts

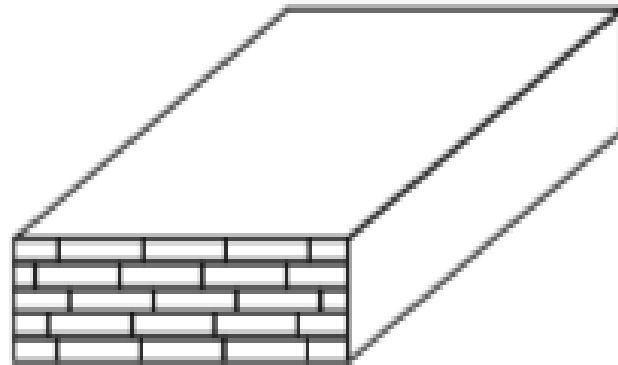
Foil overlap:

a



50% overlap

b



Random overlap

Source: Gibson et al. Additive manufacturing Technologies, 2010

Properties of UC Parts

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.

To recapitulate:

- **What are UC Process Parameters and Process Optimization.**
- **What is Ultrasonic Consolidation?**
- **Describe Gluing or Adhesive Bonding**
- **Advantages and limitations of the processes?**
- **Define briefly Thermal Bonding.**

Thank you