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Development of a Curved Layer LOM Process for Monolithic Ceramics and Ceramic Matrix Composites

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ABSTRACT

A novel rapid prototyping technology incorporating a curved layer building style was developed. The new process, based on Laminated Object Manufacturing (LOM), was designed for efficient fabrication of curved layer structures made from ceramics and fiber reinforced composites. A new LOM machine was created, referred to as Curved Layer LOM. This new machine uses ceramic tapes and fiber prepregs as feedstocks and fabricates curved structures on a curved-layer by curved-layer basis. The output of the process is a three dimensional "green" ceramic that is capable of being processed to a seamless, fully dense ceramic using traditional techniques. A detailed description is made of the necessary software and hardware for this new process. Also reviewed is the development of ceramic preforms and accompanying process technology for net shape ceramic fabrication. Monolithic ceramic (SiC) and ceramic matrix composite (SiC/SiC) articles were fabricated using both the flat layer and curved layer LOM processes. For making curved layer objects, the curved process afforded the advantages of eliminated stair step effect, increased build speed, reduced waste, reduced need for decubing, and maintenance of continuous fibers in the direction of curvature.

Key Words: Laminated Object Manufacturing, Curved Layer, Ceramics, Composites, Software

INTRODUCTION

The major commercially available rapid prototyping systems in the United States are: stereolithography (SLA), laminated object manufacturing (LOM), fused deposition modeling (FDM), selective laser sintering (SLS), and ink-jet printing or droplet deposition. Formal efforts have demonstrated the feasibility of these processes for the direct fabrication of functional ceramics, metals, and/or engineering plastics (Brady and Halloran, 1997; Klosterman *et al.*, 1997; Griffin, C. *et al.*, 1994; Agarwala *et al.*, 1996; Anonymous, 1996b; Yoo *et al.*, 1995). In addition, the following new techniques, currently under development, are specifically targeted for direct fabrication of plastics, ceramics, or metals: CAM-LEM, shape deposition manufacturing (SDM), multiphase jet solidification (MJS), selective area laser deposition (SALD), laser engineered net shaping (LENS), and extrusion freeform fabrication (Cawley *et al.*, 1996; Keitzman *et al.*, 1997; Greulich *et al.*, 1995; Jakubenas *et al.*, 1997; Griffith *et al.*, 1997; Anonymous, 1996a). None of these techniques has deviated from the underlying principle of building parts in a layer-by-layer sequence using *flat* layers. With the exception of LOM and CAM-LEM, these techniques are poorly suited for construction of continuous fiber reinforced parts because they are not capable of accommodating the basic fiber preforms such as woven mats and unidirectional prepregs. LOM and CAM-LEM, on the other hand, are inherently sheet processing operations which are applicable to these types of fiber preforms.

Based on LOM, a novel RP technology has been developed to provide users an enhanced capability for fabricating structural ceramic articles including ceramic matrix composites (CMCs). A comprehensive research program was recently completed that involved materials and process research, machine design, and system software adaptation (Klosterman, 1997, 1998). The envelope of available RP materials was expanded to include structural composites. In addition, an entirely new building paradigm was implemented: the *curved* layer building style. Instead of being limited to building with flat layers, the LOM machine is now capable of building in a curved-layer-by-curved-layer manner. The new curved layer LOM process allows continuous fiber composites to

maintain their fiber continuity in the plane of curvature in order to achieve optimum mechanical performance.

FLAT LAYER LOM MONOLITHIC CERAMICS

The first step in the overall program was to develop the ability to fabricate monolithic ceramic parts with the traditional flat layer LOM process (Figure 1). The process steps are as follows. First, a full layer of material is delivered to the platform via roll or single sheet and laminated to the existing stack. Then a CO₂ laser cuts the perimeter of the cross sectional area, one layer deep. The laser also dices or "cubes" the excess material to help with removal of the finished component. The waste material is left in place during the build to serve as a support. The sequence of laminating and cutting continues, one layer at a time, until the part is complete. The "block" then is removed from the platform and the waste material is manually removed (the part is "decubed") to reveal the three dimensional part.

Several research groups have previously demonstrated that LOM and related techniques can be used to fabricate a wide variety of structural ceramic and metallic parts. These groups include Hydronetics (now Helisys, Inc., with alumina (Anonymous, 1991b), GenCorp, Aerojet Propulsion Division (with Si₃N₄ (Anonymous, 1991a)), Lone Peak Engineering, Inc. (with Al₂O₃, AlN, BaTi, Si₃N₄, ZrO₂, HA, stainless steel (Griffin, A. *et al.*, 1997; Griffin, C., 1997; Griffin C., *et al.*, 1994, 1997; Griffin, E.A., 1996) and Case Western Reserve University (with Al₂O₃, Si₃N₄, stainless steel (Cawley *et al.*, 1996; Liu *et al.*, 1997). None of these programs involved net shape processing.

Most recently, the fabrication of *near net shape* monolithic SiC components was demonstrated as a portion of the overall effort described below (Klosterman, 1997, 1998). The goal of developing a complete process for fabricating net shape or near net shape, nonoxide ceramic components using LOM was achieved. The overall methodology involved fabricating a "green" form using the rapid prototyping machine, followed by conventional binder burnout and ceramic densification. In keeping with the goal of net shape fabrication, it was necessary to avoid the high shrinkage associated with

densification processes such as sintering. Instead, the reaction bonding process was selected.

Reaction bonding is a ceramic densification process whereby molten silicon infiltrates a porous SiC preform and reacts with *in-situ* free carbon to fill up pores. Little or no shrinkage is associated with this process. A raw material for the LOM process was formulated containing bimodal SiC powder (60 μm and 2-3 μm diameter), carbon, and graphite. This powder mixture was formed into 250 μm -thick ceramic tapes using a standard doctor blade tape casting process. The binder system contained a thermoplastic polymer and organic plasticizer to the extent of about 20 wt% of the total composition.

A standard LOM2030 unit was used to produce a wide variety of green SiC parts (see Figure 2 and Klosterman, 1997, 1998). Squares of ceramic tapes were placed on the LOM platform. The lamination was performed automatically using the standard LOM roller set to a temperature of 80°C and a compression of 625 μm . The maximum roller pressure developed from this compression value was measured to be 0.34-0.68 MPa (50-100 psi). It was necessary to apply a solvent in between the layers to enhance both lamination efficiency (adhesion) and repeatability. This was done by spraying n-butanol on one side of the ceramic tape immediately before lamination. The laser cutting of ceramic layers was executed automatically using the LOM machine's 50 W CO₂ laser. Special software and techniques were developed to enable the green parts to be decubed cleanly (Klosterman *et al.*, 1997).

Post processing of green LOM parts involved quasi-isotropic pressing of the part in a bed of powder in order to complete the layer fusion. Binder burnout was also performed partially in the bed of powder (heated up to 200°C) and partially in an oven (up to 600°C). Reaction bonding was then performed using a high temperature vacuum furnace. The microstructure of reaction bonded SiC parts made by LOM shows that almost all evidence of a layered structure has been removed, there is very little porosity, and silicon infiltration is quite good (Figure 3).

An intensive characterization of the mechanical behavior of LOM SiC parts was made. Modulus of Rupture (MOR) bars (4 mm x 3 mm x 50 mm) were fabricated using the ceramic LOM process and densified via reaction bonding. Over 50 bars were made in each of 6 different LOM runs. The results of the 4-point flexure tests are given in Figure 4. It is important to note here that these specimens were tested as received without any polishing. The variability (one standard deviation) in each of the 4 runs ranged from 10 to 34 MPa, a relatively “tight” variation.

It is important to make some comparison of LOM-produced SiC to that fabricated by traditional methods. In general, monolithic SiC is characterized by sample-to-sample consistency in behavior. This hallmark is observed in the LOM data, with little variation of bend strength from run to run. The fact that the bend strength does not change with strain rate indicates that this material does not exhibit slow crack growth, another favorable characteristic of SiC in general. The magnitude of the bend strength is difficult to compare to commercial material because the LOM specimens were not polished. With proper preparation, the bend strength of LOM SiC is expected to significantly increase from 150 MPa, quite possibly by a factor of two. The 4-point bend strength of reaction bonded SiC cited in the literature (Leatherman and Katz, 1989; Lee and Rainforth, 1994) ranges from 210 MPa to 350-540 MPa as the specimen specific gravity ranges from 2.45 to 3.18 respectively. The specific gravity of specimens in this study is approximately 2.90 to 3.0.

CURVED LAYER LOM

The curved layer LOM process originated from the need to fabricate fiber-reinforced structures containing sloping, curved surfaces, especially thin curved-shell components. With these structures, it is critically important to maintain fiber continuity in the curved surfaces. All RP processes are capable of fabricating complex, curved geometries using flat layers, albeit *thin* flat layers, in combination with post machining of the final part. However, flat layer RP processes are incapable of addressing the larger geometrical issues involved with fiber composite fabrication, namely fiber orientation and continuity. In addition to the technical incentives for implementing a curved layer build style there is

an economic incentive. Such a process will have a favorable cost benefit payoff because of the reduced raw material costs compared to flat layer processes.

The curved layer LOM process is illustrated in Figure 5. It begins with production of a matched tool or mandrel for the intended part. The temperature and pressure requirements for this mandrel are not demanding, so it can be made with the standard LOM process using LOM paper. The finished mandrel is mounted to the flat building platform in the curved layer LOM machine. Sheets of the desired build material (e.g., CMC prepreg, 0.5 mm thickness) are loaded onto a rotatable feed table, picked up with a vacuum chuck, and transported to the mandrel. A flexible thermoforming mechanism laminates each new layer to the curved mandrel with steady, uniform pressure. A laser cuts each layer, accounting for the sloped surface and fiber orientation. The fiber orientation can be varied from layer to layer by programming the rotatable feed table. The process proceeds one layer at a time until the part is finished. The part is then removed from the mandrel and the excess material is manually stripped away ("decubed").

Software Development

Development of several new software algorithms was required for the curved layer LOM process (Kalmanovich *et al.*, 1997). The initial task was to produce a matched tool to support a curved layer part. A software routine was needed to generate a numerical description of the support tool geometry from the computer's 3D file (.STL) of the desired curved layer part. This task proved to be an intricate geometrical problem. The goal was to create a smooth tool surface that conformed to the general curvature of the bottom of any curved layer part, thus ensuring effective support during the curved layer building process. The task was similar to that of creating a negative from a master pattern. However, the presence of such features as holes in the curved layer object led to inverted holes on the support tool (i.e. columns extruding from the top of the tool surface). This, in turn, prevented the smoothness of the curved layers and led to difficulty in building the curved layer part. Thus, the software required intelligence to identify and address such features. Heuristic algorithms were formulated to remove

undesired features on the support tool surface. These heuristics are not foolproof, however, they address the common difficulties that arise in creating an effective support tool.

The bulk of the software effort involved the development of a computational framework in order to numerically represent curved layer parts, to slice through such parts with curved cross-sections, and to accommodate the changes in the shape of the curved cross-sections due to the build-up of layers. Because there were no existing methodologies directly applicable to LOM, a novel approach was created and implemented.

In traditional (flat layer) LOM, the .STL file of a 3D object is sliced into a series of flat, 2D cross-sections. In mathematical terms, the 3D object is intersected by a series of parallel planes evenly spaced in the Z direction. Thus, the path of the laser beam as defined by the intersection of a horizontal plane with the object's periphery is two-dimensional.

With curved layer LOM, a 3D object must be sliced with a curved cross-section (infinitely thin), illustrated in Figure 6. The first fundamental issue was to determine an appropriate mathematical/computational framework for representing curved layers that would be capable of performing the necessary geometrical operations. After considering a number of candidates, a "height grid", see Figure 7, system appeared to be the most suitable. In this system, a curved layer is superimposed onto an XY plane. The XY plane is divided into an evenly spaced grid. The curved layer is represented by the height values (Z) at each point on this grid (2D array). Thus, the initial curved layer height values are obtained by projecting the grid elements vertically upward until their intersection with the object. Then, "foreign", non-smooth, values for the heights are filtered out with the same heuristics previously used to obtain the matched support tool. This procedure insures the top of the support tool and the initial curved layer are exactly the same.

Unlike the conventional flat layer LOM, it is impossible to predetermine all the shapes for the necessary curved cross-sections due to the unique geometrical complications arising from the growth of curved layer parts (see Figure 8). When a new curved layer is added to the stack, it does not perfectly replicate the previous layer. Each new layer is ordinarily a smoothed version of the previous layer. Currently, the LOM machine is not equipped with a sensor capable of physically measuring the actual shape of the new layer. Therefore, an open loop method was developed to approximate the new, updated grid heights for each new layer (see Figure 9). The approach involves taking a point from the previous grid along with the four adjacent points on that grid; constructing four triangles originating from the central point; lifting each of the triangles in the direction of their respective normal vectors by a distance equal to the material thickness; fitting a curved surface tangent in desired places to the four offset triangles using a third degree polynomial; and finally, taking the z-height value of the fitted polynomial at the original location in the XY plane. This procedure is repeated for all points on the grid. The resultant curved surface almost exactly approximates the actual top surface of the curved layer part for each step, i.e., successive layer, of the manufacturing process.

Among the models we considered to represent the curved layer, the height grid approach has the advantage of being the least complex. This method accurately predicts the smoothing that occurs as a result of successive addition of layers. It is also superior to a 3D triangle-based format of curved layers since this method does not grow in complexity. The fineness of the grid remains exactly the same with each successive layer. Thus, the computational complexity is not increased with each new layer.

Many of the existing algorithms originally developed for the conventional, flat layer, LOM process were modified to work within the new "curved structure." Algorithms for handling collections of segments in two dimensions, e.g. sorting, laser path generation, crosshatching, etc., were generalized to provide for arrangement of segments into curved continuous loops, curved path generation, and curved crosshatching. Finally, to account for the thickness of the cutting laser beam, the beam offset algorithm, originally

developed for flat layers, was also generalized and incorporated into the curved layer methodology.

Hardware Development

Substantial new hardware development was necessary since most of the process hardware requirements departed significantly from the flat layer LOM process machinery. New machine components included the material sheet feeding and rotating mechanism, curved layer bonding apparatus, and curved surface laser cutting. An automatic sheet feeding system (as opposed to the standard roll feed) was desired for two main reasons. First, many commercially available advanced materials, such as prepregs and ceramic tapes, are stiff at room temperature and/or available only in sheet form. Second, there is more material waste associated with the automatic roll feed system. Although this waste may be affordable when building LOM-paper parts, cost efficient material use is critical when working with fibrous composites and ceramics.

The curved layer bonding mechanism is a flexible, resistively heated pad backed with a silicone rubber frame (Figure 10). The frame consists of a top and bottom horizontal surface connected by narrow (~1 cm) vertical walls. The placement of the internal walls was custom designed to provide even pressure to the curved layer parts under consideration in this study. Vacuum cups protrude vertically through the rubber frame in order to pick-up a new material layer. A single layer is held just underneath the heating surface as the entire assembly is positioned over the mandrel via a rail system. The new layer is laminated by elevating the build platform up into the thermoformer and holding it in contact for about a minute. The bonding pressure developed is approximately 2 to 5 psi (0.014 - 0.036 MPa).

Cutting curved layer parts required new computer algorithms for coordinating simultaneous control of the laser beam in the X, Y, and Z directions. In a conventional LOM machine (Figure 1), laser cutting is performed using a plotter system that transports a mirror and focusing lens over the X-Y envelope. The distance between the focusing lens and the top of the part is adjusted only once (immediately after placing each new

layer) to ensure that the laser focus is maintained on the horizontal part surface. With the curved layer LOM machine, the build platform must be translated up and down dynamically in order to maintain the laser focus on the curved surface. It was necessary to install an eight-axis motion control card to enable this operation.

A major challenge facing the program from the onset was achieving high quality laser cutting of ceramic fibers. All CO₂ lasers were deemed unsuitable due to their cutting mechanism: selective burning through the target material. This mechanism is unacceptable for cutting continuous ceramic fibers because the high power needed causes excessive heat damage in the cut zone. Furthermore, fibers such as SiC are thermally conductive, so the damage zone extends axially. Both fibers and especially polymer resin are susceptible to heat damage. To overcome this problem, a copper vapor laser was used. This laser cuts material via photoablation, operating with high pulsed repetition frequency (8000 pulses/sec), medium-power (1.5 mJ/pulse), and visible wavelengths (511 nm). The laser cuts were excellent, with no fiber end damage, narrow cut channels, and a minimal burn-back zone (Figure 11). Details of cutting studies of ceramics and fibers using this laser are found in the literature (Lightman and Han, 1996).

Several monolithic SiC parts were manufactured to demonstrate the curved layer LOM process. Acceptable process parameters (e.g., temperature, pressure, time) were determined through initial experimentation with a manual operation, mock-up system at the University of Dayton, and finally through operation of the prototype curved layer LOM machine at Helisys, Inc. A miniaturized, concept body armor panel is illustrated in Figure 12. The advantages of the curved layer process are eliminated stair step effect, increased build speed, reduced waste, and easier decubing. Although the monolithic ceramic parts illustrate the advantages of the curved layer LOM process, the larger payoff is for CMCs. A large portion of the overall project/program involved development of appropriate CMC materials and processes compatible with LOM, described next.

CMC PROCESSING

SiC/SiC was used as a focus material system for demonstrating net shape CMC fabrication. From the onset, the most critical issue was fabricating preforms that incorporated a high volume fraction of continuous SiC fibers and would be suitable for flat *and* curved layer LOM. In response to this, a novel approach was used to fabricate CMCs that involved layup of separate, alternating layers of ceramic tape and fiber prepreg (preimpregnated fiber preform). Green parts containing this alternating layer architecture were made using LOM, subsequently pyrolyzed, and densified through reaction bonding.

Preform Development

Fiber prepregs were fabricated with unidirectional SiC fiber tows (Nicalon™, Dow Corning, carbon coated grade) and a furfural-phenolic thermosetting resin (FurCarb® UP440, QO Chemicals, Inc). The furfural resin served a dual role: as a binder and adhesive during the part fabrication and as a carbon source during the subsequent reaction bonding process. Alternating layers of this fiber prepreg and ceramic tape were delivered to the LOM machine as one single sheet, referred to as a "tape-preg." Tape-prepregs, made by pre-adhering a prepreg layer to a tape layer, were stiff, nontacky, and board like at room temperature, becoming soft and pliable at higher temperatures (130°C). The total layer thickness was 0.5 mm. The tape-preg contained approximately 25% fibers by weight, and overall it proved to be a robust sheet material suitable for the LOM process.

The advantages of the alternating layer technique are the relative ease of preparation of the preforms, elimination of fiber abrasion from the ceramic particles, moderately high fiber volume fraction in the final CMC, and low cost resin binder. The tape-preg embodies several important characteristics of other commercially available CMC preforms. Key among these characteristics is the use of a fiber prepreg that contains a thermosetting, ceramic precursor resin. Based on this similarity, it is anticipated that

LOM will accommodate other commercially available CMC preforms as easily as the "tape-preg".

Post-LOM Processing

It was not feasible to execute all of the necessary ceramic processing steps within the LOM machine. The LOM machine was used only to produce the green form. Thus, post processing steps were needed. Far from being a disadvantage, this methodology afforded certain benefits such as independent control of critical high temperature processes using appropriate equipment. The overall process is illustrated in Figure 13.

The first post-processing step combined binder burnout, pyrolysis, and pressing into a single operation. Although green LOM parts were sufficiently laminated to survive LOM processing, decubing, and handling, they require additional layer consolidation prior to the final densification step. Pressure was applied during binder burnout and pyrolysis to counteract delamination and bloating resulting from relaxation of residual stresses imparted during the lamination step. In order to maintain the complex geometry of green parts during pressure application, a technique involving quasi-isostatic powder pressing was developed.

Green parts from the LOM process were placed in a cylindrical chamber which was subsequently back filled with powder and fitted with a ram. Monolithic SiC was used as the powder medium in the chamber. For LOM parts that could be fitted with a porous Teflon bag, silica was used as the powder medium (i.e., sand pressing). A heated, programmable, uniaxial press was used to apply a heated pressure cycle to the enclosed chamber. The powder medium enabled pressure to be evenly distributed while allowing volatile degradation products to escape through a permeable bed. Monolithic SiC and SiC/SiC parts were pressed at 30 psi and 60 psi, respectively, and at temperatures up to 325°C. Shrinkage of SiC/SiC and monolithic SiC parts during this step was $7\% \pm 2\%$ and $5\% \pm 2\%$, respectively, in the z direction (parallel to press movement), and zero in other directions. Appropriate scaling of the computer graphic file for part building in the

z direction by 7% or 5% will compensate for this dimensional change due to compression.

An additional, freestanding binder burnout and pyrolysis step (700°C, argon) was required due to the upper temperature limit of the pressing apparatus. Because most of the binder burnout and resin pyrolysis occurred during the powder pressing step, no part damage or shrinkage accrued during freestanding burnout. The resulting porous structures were densified through reaction bonding. An aircraft engine flame holder demonstrates the capabilities of the curved layer LOM process (Figure 14).

The microstructure of flat LOM SiC/SiC panels prior to pyrolysis illustrates the alternating tape/fiber layer arrangement, excellent compaction, and minimal porosity (Figure 15). The photomicrograph of a specimen that has undergone reaction bonding indicates there is some porosity, although much of this may be attributable to particle and fiber pull-out that occurred when the specimen was polished. It is clear, however, that the flatness, continuity, and integrity of the layers have been well maintained. This microstructure is comparable to those of commercially available CMC systems.

Upon closer examination of the LOM SiC/SiC microstructure, it is evident that although the fibers are intact, there is fiber damage particularly at the fiber interface (Figure 16). This damage occurs as a result of the instability of Nicalon fibers at 1600°C. There are several potential solutions to this problem, such as developing superior fiber coatings and using silicon alloys that will infiltrate the composite at lower temperatures. However, the physical mating of the layers is intimate and the overall infiltration efficiency is quite good relative to commercial CMC systems.

The major result to report here is that the entire process, starting with fiber preforms and ending with a near net shape, densified part, has been fully demonstrated. Densified samples such as the flame holder and body armor are handleable, and photomicrographs illustrate that the microstructure compares quite favorably to commercial CMC systems.

Further work with other material systems is being carried out to fully characterize and assess the overall process reproducibility and accuracy.

SUMMARY AND CONCLUSIONS

A novel rapid prototyping technology has been developed for efficient production of curved layer parts. The new process, based on LOM, incorporated a curved layer building style and ability to accommodate ceramic and fiber reinforced building materials. The curved layer LOM process was a significant departure from the existing process and required significant developments in software, hardware, and materials and process engineering. Monolithic ceramic (SiC) and CMC (SiC/SiC) articles were fabricated using both the flat layer and curved layer LOM processes. For making curved layer objects, the curved process afforded the advantages of eliminated stair step effect, increased build speed, reduced waste, easier decubing, and maintenance of continuous fibers in the direction of curvature.

The limitations on the current process are sheet feeding size requirements (35 cm, x 35 cm minimum size needed), limited bonding pressure available (2-5 psi), limited bonding area (30 cm x 30 cm), limited bonding curvature (height to span ratio of 1:4 or less, simple curvature), ability to handle only dry preforms because there is no backing-ply removal apparatus, and lack of computer-based composite design aids which can be interfaced with the equipment. Fortunately, all of these issues are being addressed through a current development effort. The curved LOM process is inherently suited to work with any flat sheet material that is flexible enough to conform to the desired curvature and which will bond through the application of heat and/or pressure. Example materials are fiber prepreps (unidirectional, mats, and woven), ceramic or metal powder tapes, and plastic sheets.

This project demonstrated that an entirely new fabrication capability is now available for designers and manufacturers. The LOM process holds promise for lowering the cost of fabricating advanced material parts by virtue of its automation, which reduces fabrication

time and eliminates the need for tooling. The process can best be applied by industry as a product development tool for fabricating testable prototypes, or for small lot production.

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ILLUSTRATIONS

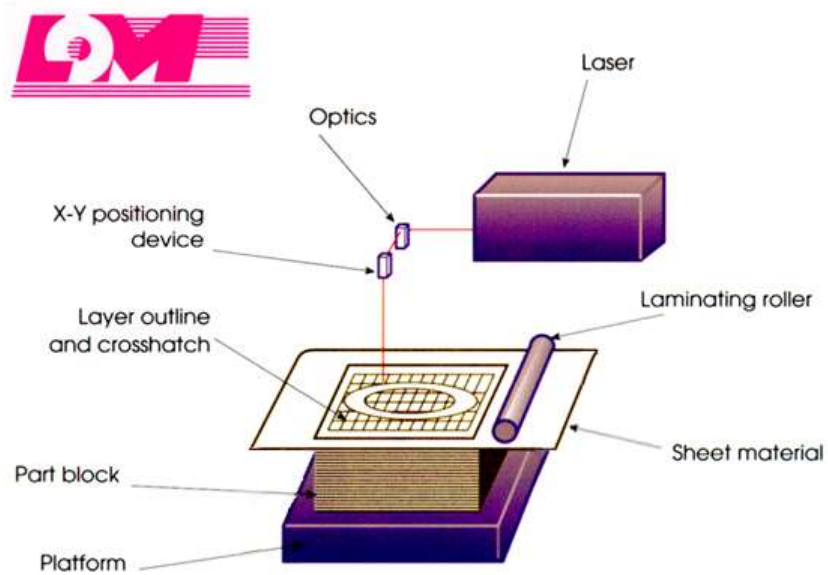


Figure 1: The standard, flat layer LOM process.

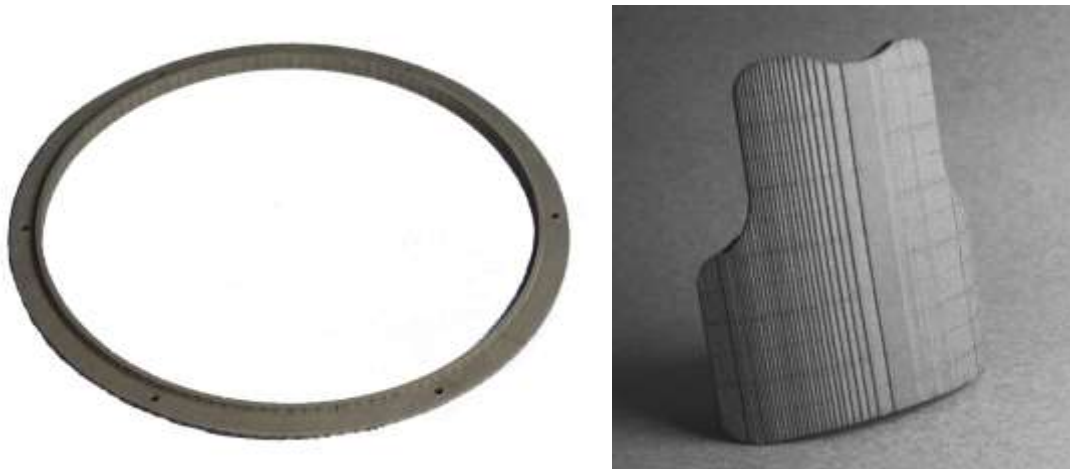


Figure 2: Monolithic SiC parts fabricated with the flat layer LOM process: 11" diameter turbine engine seal and miniaturized, concept body armor panel (3" x 2.75" x 0.6").

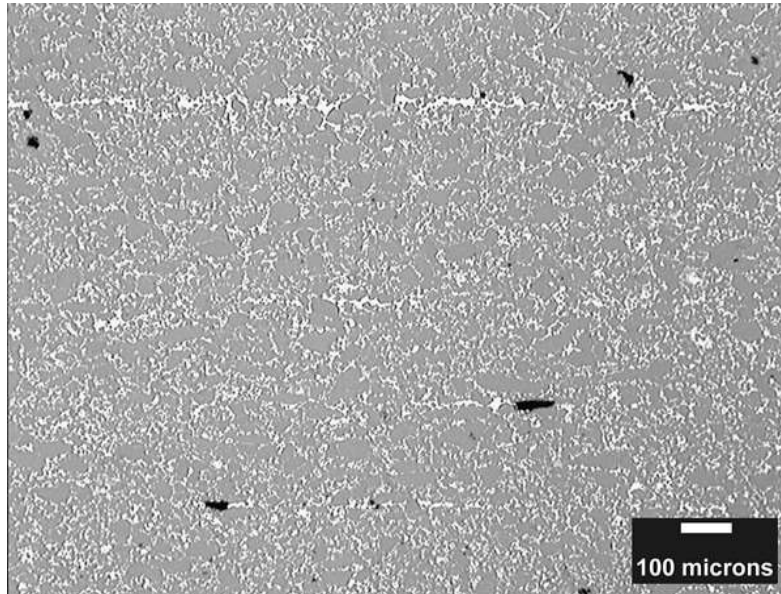


Figure 3: Microstructure of reaction bonded, monolithic SiC part fabricated with LOM showing seamless character.

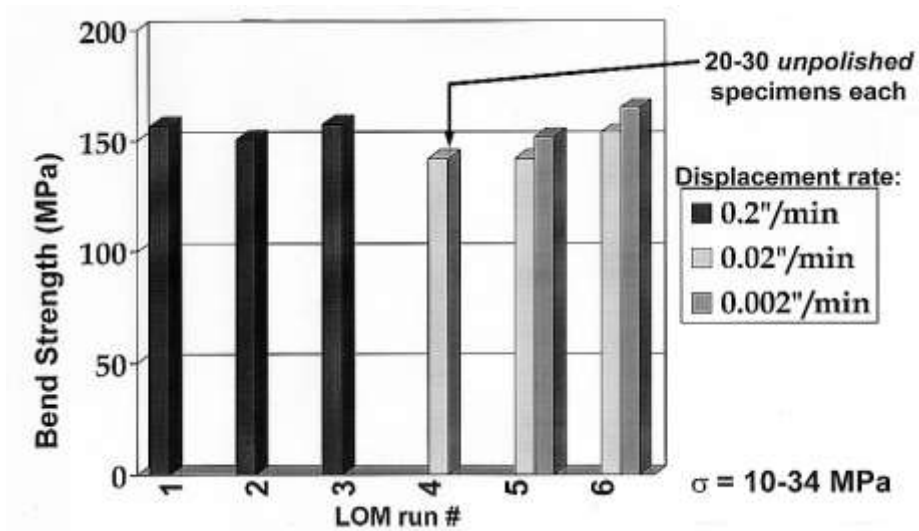


Figure 4: Ambient, 4-point bend strength of reaction bonded LOM SiC.

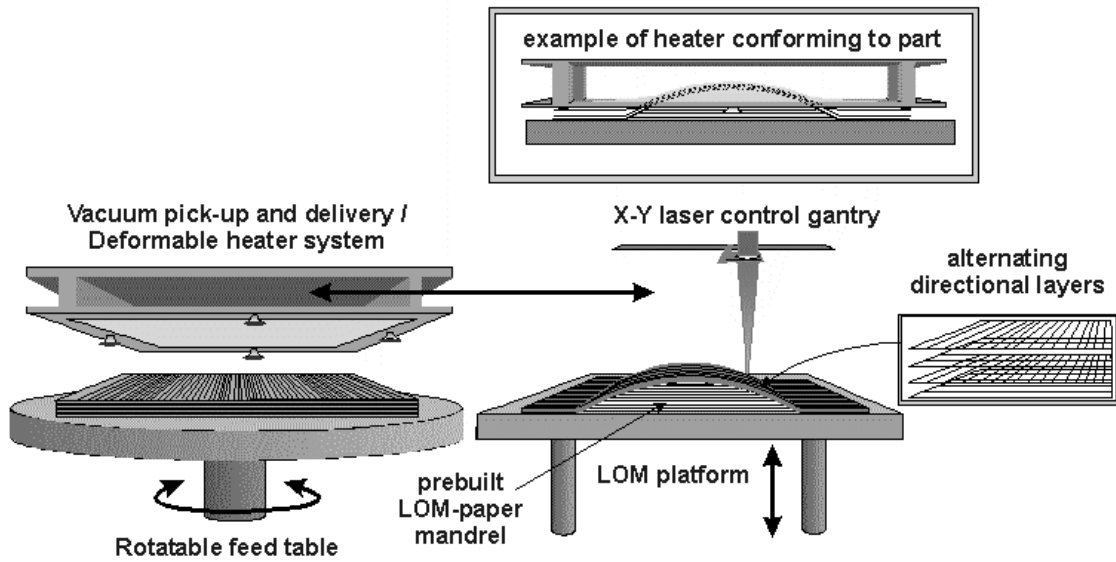


Figure 5: Curved layer LOM process schematic.

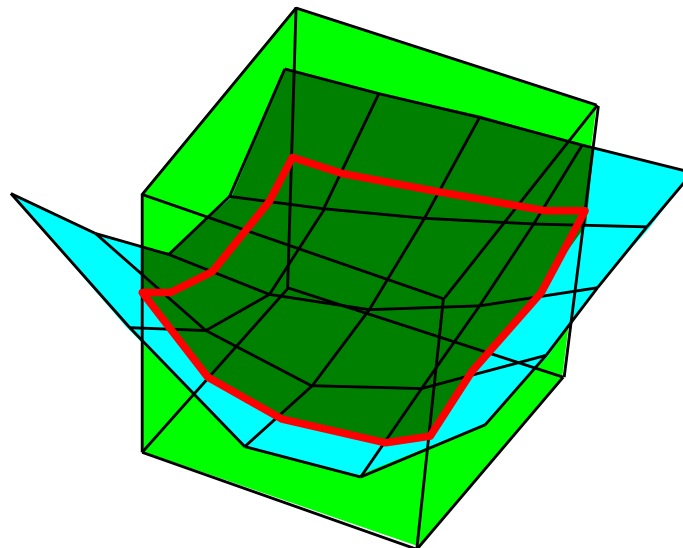


Figure 6: Illustration of a single curved layer intersecting a 3D object, defining the laser cut path for the curved layer LOM process.

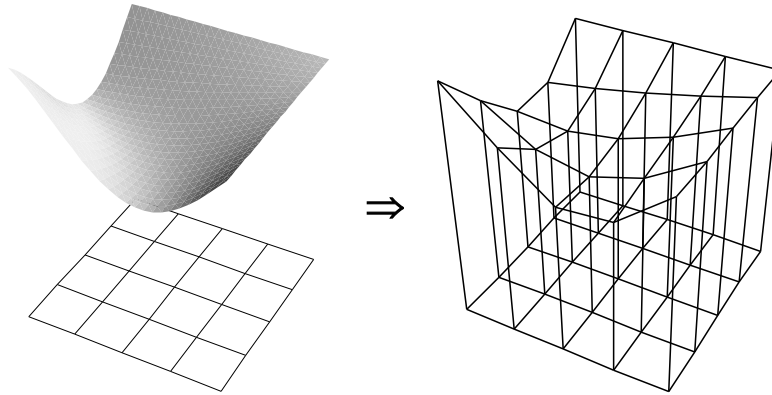


Figure 7: The "height grid" system of representing curved layers.

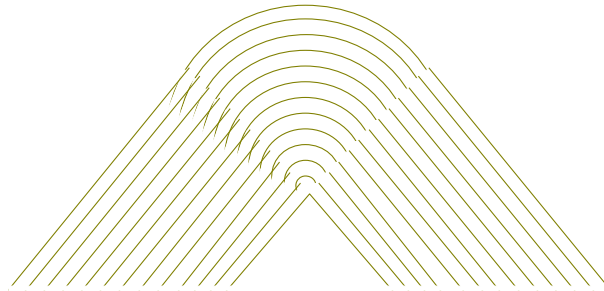


Figure 8: Illustration of part growth in curved layer LOM.

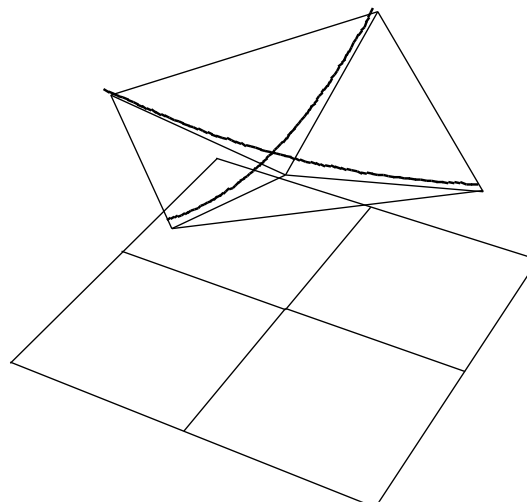


Figure 9: Open-loop method of approximating a new layer based on the previous layer. Shown here is the geometrical construction for estimating the new Z-height of a single data point on the grid

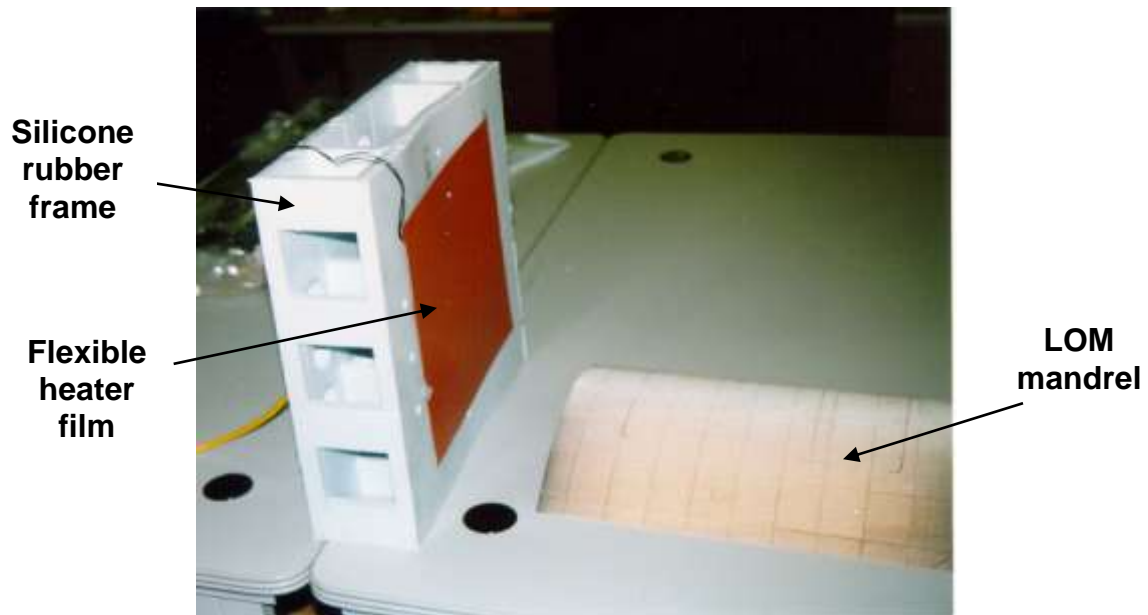


Figure 10: Curved layer bonding apparatus (prior to installation in LOM machine) standing on end. The vacuum cups, which protrude through the structure normal to the heater surface, are not installed in this picture.

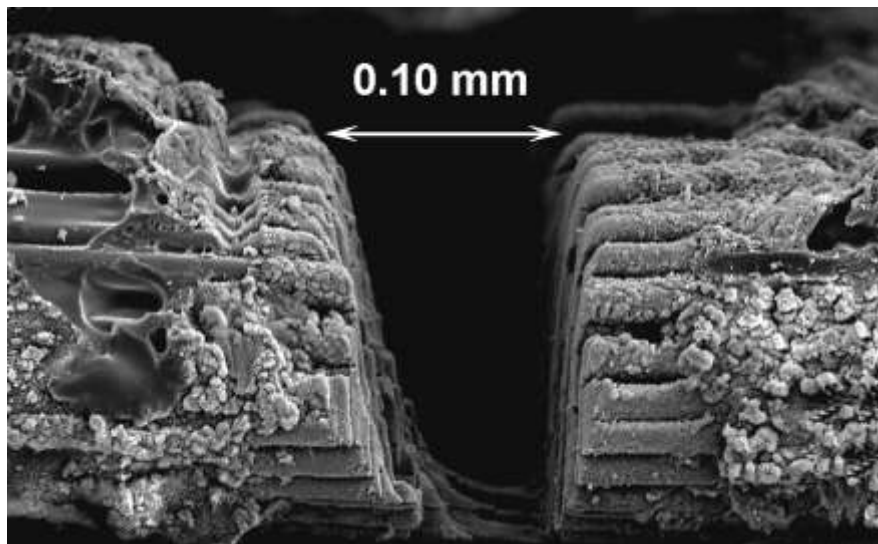


Figure 11: SiC fiber / furfural resin prepreg cut with a copper vapor laser. The fiber diameter is approximately $15\ \mu\text{m}$. High quality laser cutting is characterized by the presence of nearly vertical walls, clean and undamaged fiber ends, and minimal resin burn back.



Figure 12: Curved layer, monolithic SiC body armor panel, immediately after LOM processing. The piece has been fully decubed and placed back on the LOM-paper mandrel for illustration. Notice the smooth surface and lack of stair steps.

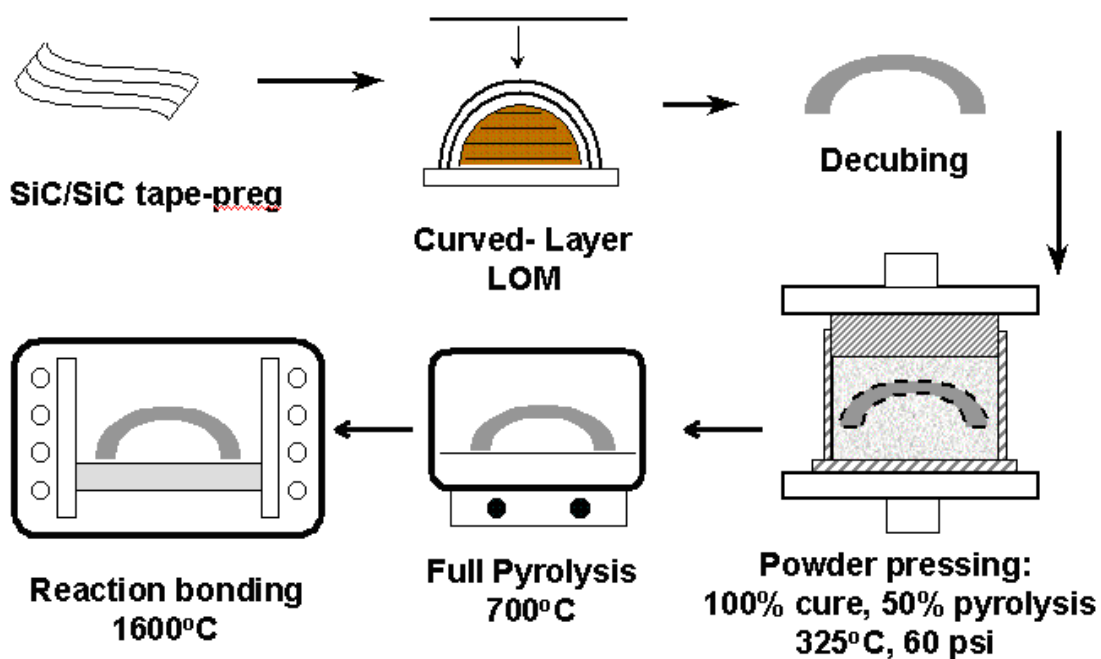


Figure 13: Overall process flow chart for fabricating net shape CMCs with curved layer LOM process

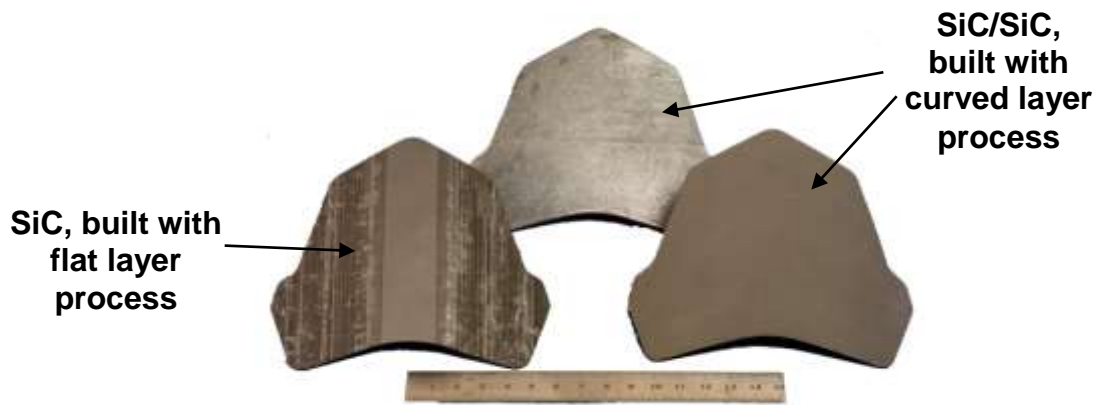


Figure 14: Aircraft engine flame holders. The piece in the center has been reaction bonded. In comparison, the piece on the right, which has not been fully densified, serves to illustrate that there is very little or no shrinkage associated with the reaction bonding process. The piece on the left illustrates the poor surface finish obtained with the flat layer process compared to the curved layer LOM process.

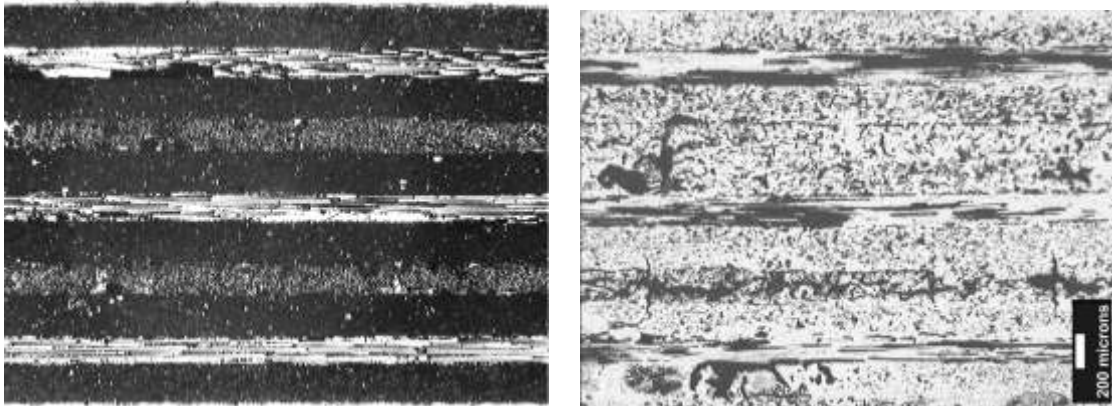


Figure 15: Polished cross section of eleven-layer SiC/SiC LOM composite (left) prior to pyrolysis, and (right) after pyrolysis and reaction bonding. From top to bottom the layers are: ceramic tape, 90° fiber layer, ceramic tape, 0° fiber layer, ceramic tape, etc.

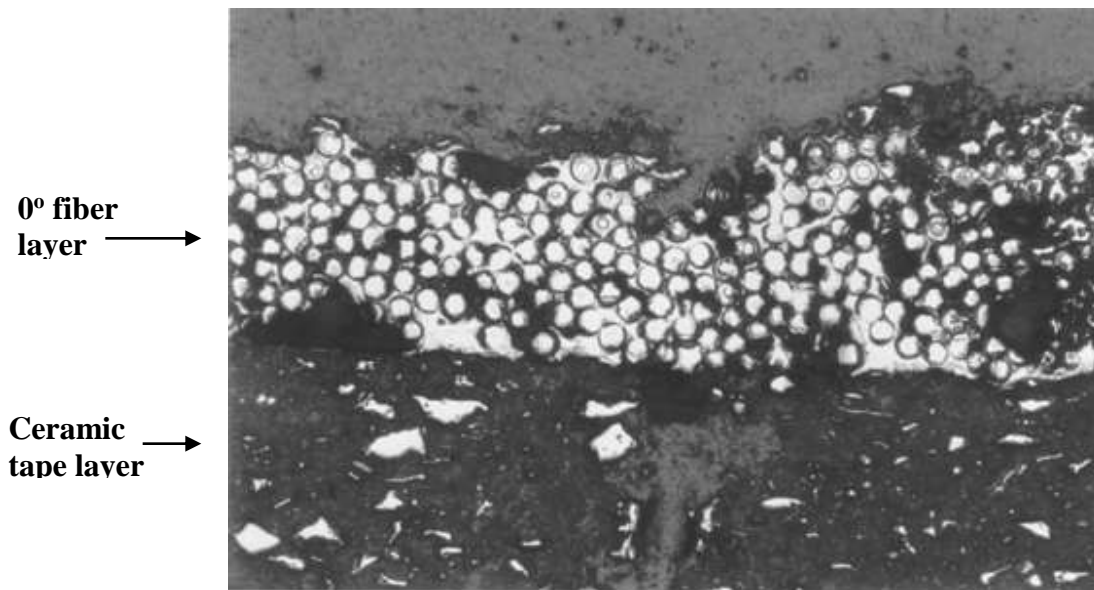


Figure 16: Photomicrograph of reaction bonded SiC/SiC microstructure showing mating of various layers, infiltration efficiency, and fiber condition. Fiber diameter is 15 μm .