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FREE FORM FABRICATION OF METALLIC COMPONENTS USING THE DIRECTED LIGHT FABRICATION PROCESS

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Free-Form Fabrication of Metallic Components Using the Directed Light Fabrication Process

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Abstract

The Directed Light Fabrication (DLF) process uses a laser beam and metal powder, fed into the laser focal zone, to produce free-standing metal components that are fully dense and have structural properties equivalent to conventional metal forming processes. The motion of the laser focal zone is precisely controlled by a motion path produced from a 3-dimensional solid model of a desired component. The motion path commands move the focal zone of the laser such that all solid areas of the part are deposited and the part can be built (deposited) in its entirety to near net shape, typically within +/-0.13mm. The process is applicable to any metal or intermetallic. Full density and mechanical properties equivalent to conventionally processed material are achieved.

SOLID FREEFORM FABRICATION (SFF) refers to the technology of forming components without molds or dies, typically from a three dimensional solid model design of the desired component, which is used to define the part as a series of layers [1,2]. These processes typically deposit material a planar layer at a time, and stack successive layers until the entire part is built to a high level of accuracy. Hence the name "additive" processing is also applied and contrasted to "subtractive" machining processes. Layer deposition processes involving liquid polymers photocured by laser or ultraviolet light, thermoplastic powders sintered by a laser beam, precision cutting, stacking and bonding of thin paper and metal sheets, extrusion of liquid waxes, extrusion of epoxy with metal or ceramic powder, ink jet printing of materials, laser deposition of powder and wire feed, and other similar processes continue to be developed since the early 1980's.

The rapid prototyping processes offer the potential advantage of single step processing, eliminating multiple conventional processing steps, and place the manufacturing process at the control of the designer. Material is placed where desired with little waste and processing environments are contained and thus controlled with minimal human handling and intervention, and minimal risk of contamination from lubricants, solvents, or handling. Relatively small space is required, compared to many conventional processes and the equipment runs unattended with only maintenance operations being required.

However, these same processes were primarily developed initially for plastics, waxes, paper and not direct deposition of metals. Usage was limited primarily to fabrication of patterns and models providing form and fit but not the functionality with full structural properties required for the desired product. From the early '90s on, development has been extended to metals by fabricating non-metal patterns used to make ceramic molds for investment casting of metals. This practice has added the fabrication steps of applying ceramic to the pattern, removing the pattern by burning, melting or dissolving, casting the metal into the remaining mold, and removing the part from the mold and finishing the part. These added processes have diverged from the essence of solid freeform fabrication in a single step without molds or dies, but have proven economical in both time and value for specific cases.

Other powder metal fabrication technologies [3] such as thermal spraying, low pressure plasma spraying, and powder injection molding continue to be developed and offer relatively high rate metal forming. But the high volumetric forming rates are traded in time and cost because of the multiple step processing required to produce a finished part, the need for design and fabrication of molds, patterns and mandrels, and the lack of precision in depositing metal.

Solid freeform fabrication of metals has developed more slowly than for plastics and is now merging into the rapid prototyping and rapid manufacturing technologies. Metal coating, cladding, vapor deposition and welding technologies have also been developing since the late 70's and early 80's. However, the precision has been poor because of lack of control of relative motion between part and heat source, lack of control over feed material input to the hot zone of the heat source, and lack of directionality and precision in placing the deposited material. With application of precision motion control, use of a highly directional heat source such as the laser, and control of feed material, parts are now being built additively, to better precision than ever before, directly with metals.

Directed Light Fabrication Process

Directed Light Fabrication (DLF) is a solid metal free-form fabrication process in development since 1991 [4-13]. This process uses a laser beam to fuse gas delivered metal powder particles that form a molten pool and solidify to a fully dense deposit. The position of the laser focal zone and molten pool is controlled by a motion system, programmed from a solid three dimensional model of the desired part using CAD-CAM software. The motion path moves the laser focal zone that creates a molten pool and re-solidified line or bead of deposited metal along the path. Beads are laid side by side and overlapped until all the solid area of a cross-section of the desired part is filled. The thickness of the cross-section is determined by the distance the laser focal zone is moved away from the previously deposited layer of material and is typically equal to the depth of metal deposition for that layer. Successive layers are deposited and stacked to form the entire part.

A system with three axes of motion and a system with five axes of motion have been designed and built. The three axis system provides motion in the horizontal plane with a vertical z-axis that provides the stacking of planar layers to build a part in 2.5 dimensions, defining a vertically extruded cross section. The 5-axis machine adds a rotary axis in the horizontal plane and a tilt axis to the laser beam. The added axes increase the system capability to deposit metal in any plane, instead of only the horizontal plane of the three axis system. Over-hangs, attached features, and non-planar deposition have been achieved.

Figure 1 schematically shows a plate of single layer thickness being built and Figure 2 shows a thicker plate made by laying single beads of metal side by side. Re-melt into the previous layer for the single bead width plate and re-melt into the previous layer and previous bead for the thick plate assures that full density is achieved in the deposit. Laser power, speed and powder feed rate are also controlled to achieve desired bead width and layer depth.

Heat flow away from the deposition zone also determines the resultant bead width and depth for constant process parameters. Higher cooling rates might be expected for the thick plate than the thin plate in Figure 1 because of the larger conductive area surrounding the molten pool on two sides compared to one side for the thin plate. Edge and corner heat flow variations would also influence deposit characteristics, such that tailoring, or refinement of process parameters may be required.

3-Axis Fabrication

A hexagonal cross-section, 7 hole array, structure was built as shown in Figure 3. The structure was built to a height of 356mm from Inconel 690, a difficult to process high temperature

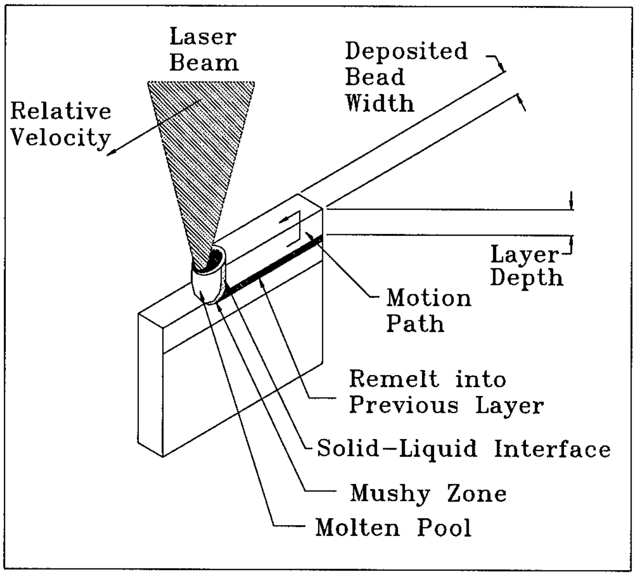

Figure 1. Schematic representation of a single-bead width plate. Melt-back into previous layer occurs with each layer added.

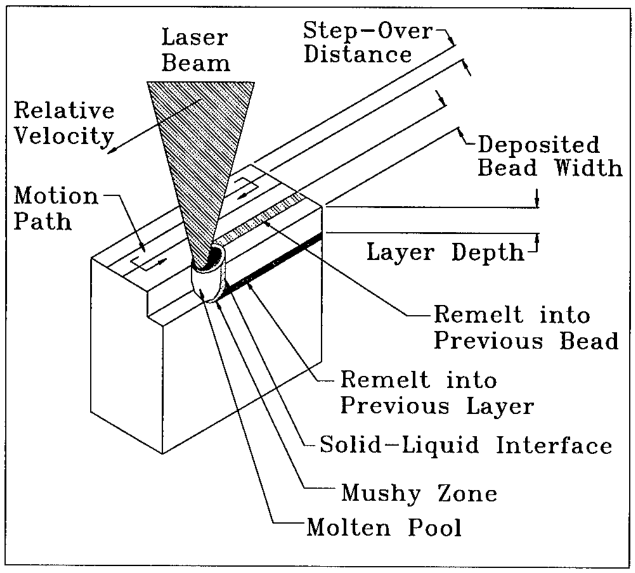

Figure 2. Schematic representation of a multiple bead plate made by laying beads side by side. Melt-back into underlying layers and adjacent layers occurs to assure full density.

nickel base alloy. Figure 4 shows the motion path, superimposed on the part cross section, that was used to produce the cross-sectional geometry. Once the motion path was established it was repeated for the next layer until the entire part was deposited. The part was deposited with the vertical axis along the length.

The part was deposited at a laser power of 160w, speed of 12.7mm/s, vertical layer increment of 0.25mm, bead overlap of 0.27mm, and the powder feed rate was approximately 9g/min. Oxygen was controlled to less than 10ppm in an argon atmosphere.

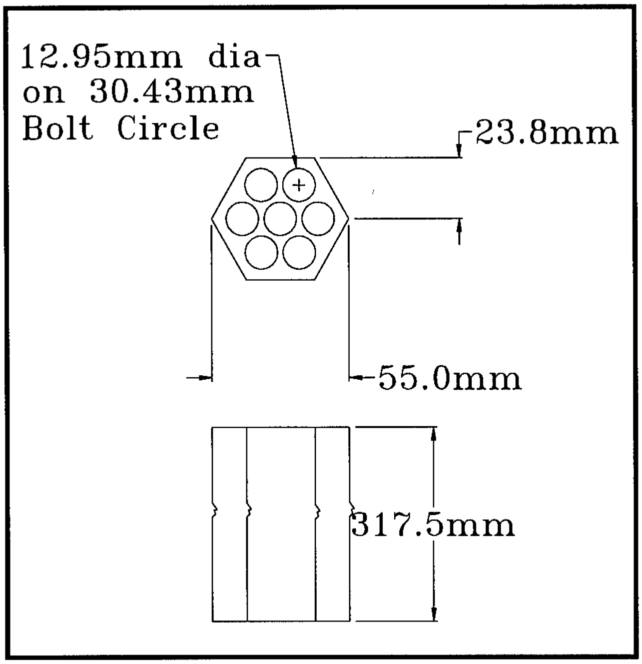

Figure 3. Design of Solid Hexagon with hole array.

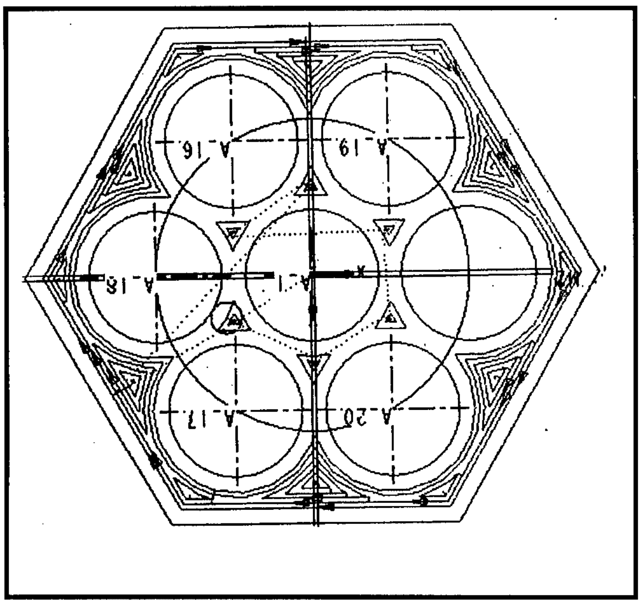

Figure 4. Motion path superimposed on part cross section to produce fully dense deposited part.

Figure 5 shows the deposited part after separation from the steel base plate that the part was started on. A fully dense deposit was produced with high dimensional accuracy. The microstructure of an area showing two of the hole contours and an adjacent hexagonal face is shown in the photograph in Figure 6. The overlapping layers resulting from the motion path are shown.

Dimensional inspection of the part features indicated hole diameters were produced within +/-0.05 mm of the specified diameter for 6 out of the 7 holes and were centered within +/-0.13mm of the specified location. Radial distance from the center of the cross section to the center of the hexagonal faces was within +/-0.076mm. Surface roughness was 12μm, arithmetic average, which is similar to investment cast surfaces. However, one hole was smaller because of an extra deposition pass inserted into the inside radius of the hole motion path, making it 12.62mm dia, and two extra passes were inserted for motion outside the desired hexagon boundary making it 24.33mm instead of the specified 23.8mm. These extra passes could easily be removed but a second part was not made.

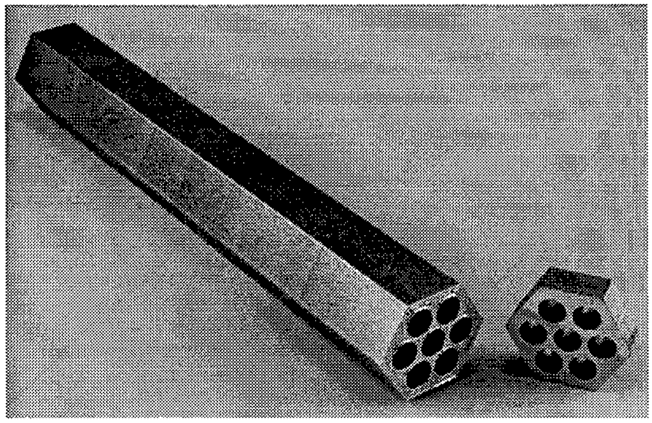

Figure 5..Finished part with bottom section removed for analysis.

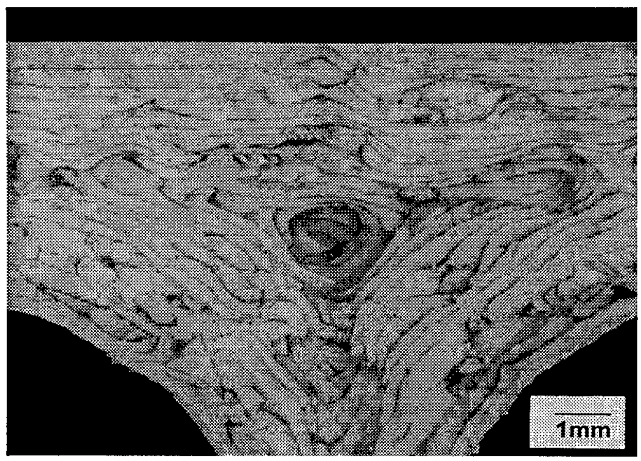

Figure 6. Microstructure of cross sectional area near holes and face (top of photo) showing fully dense, overlapped, layered structure produced from the motion path in Figure 4.

Tensile properties were measured from deposits of 19mm dia. solid Inconel 690 cylinders. Cylinders were tested before and after heat treatment. Table 1 shows the results and comparison to strengths reported by the manufacturer for conventionally processed 16mm dia. hot rolled rod. Yield strengths for the DLF material exceeded conventional wrought material in all cases. Ultimate strengths were lower by about 10% and elongation's were similar. This strength comparison shows that in a single process, wrought properties can be achieved by the DLF process. Conventional processing requires casting and hot working to develop and refine the cast microstructure for improved strength in the wrought condition.

Table 1
Tensile Properties of As-Deposited and Heat Treated Inconel 690 Bar Produced From Powder by DLF Compared to Conventionally Processed

Condition	0.2% YS Mpa (ksi)	UTS Mpa (ksi)	%El
DLF—As deposited	449.5 (65.2)	666.0 (96.6)	48.8
DLF—1700F/1 hr.	487.5 (70.7)	687.4 (99.7)	46.0
DLF—2000F/1 hr.	383.3 (55.6)	650.9 (94.4)	52.0
Conventionally Processed 16mm hot rolled rod [14]	372.3 (54)	737.7 (107)	50.0

Five Axis Deposition

Deposition of a hemisphere using the five axis DLF system is shown schematically in Figure 7. Beads of material are added side by side with each revolution of the part to build the desired wall thickness. The laser beam axis is maintained perpendicular to the deposited bead and tangent to the hemisphere contour along a longitudinal line. The hemisphere is started by tilting the head at 90 degrees to a support stalk and then changing the head position with each layer along with rotational velocity to maintain constant surface velocity as the radius of the hemisphere is formed.

Figure 8 shows the actual fabrication of a type 316 stainless steel hemisphere. Hemispheres ranging in diameter from 50mm to 280mm are fabricated within the working volume of the 5-axis system. Wall thicknesses from 0.7mm, which is the width of a single deposition pass, up to any maximum thickness desired can be fabricated within a 4% wall thickness tolerance. Parts are supported by a deposited post that is removed after deposition is complete.

A three dimensional solid model is first made of the required part. From the model a motion path is created and defined using a Computer Numerical Control (CNC) program which is then post processed into the actual processing commands driving the 5-axis equipment.. Process parameters are then established to produce full density. Laser power is 200w and surface speed is held constant at 13mm/s. Overlap distance is approximately 0.3mm, layer depth is 0.2mm, surface velocity is 18mm/s and powder size is 44-105μm dia.

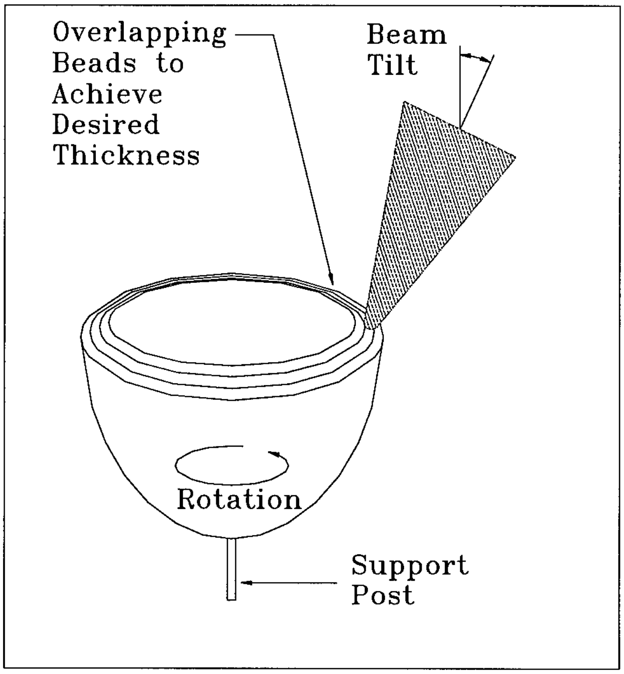

Figure 7. Schematic of 5-axis DLF Hemisphere deposition.

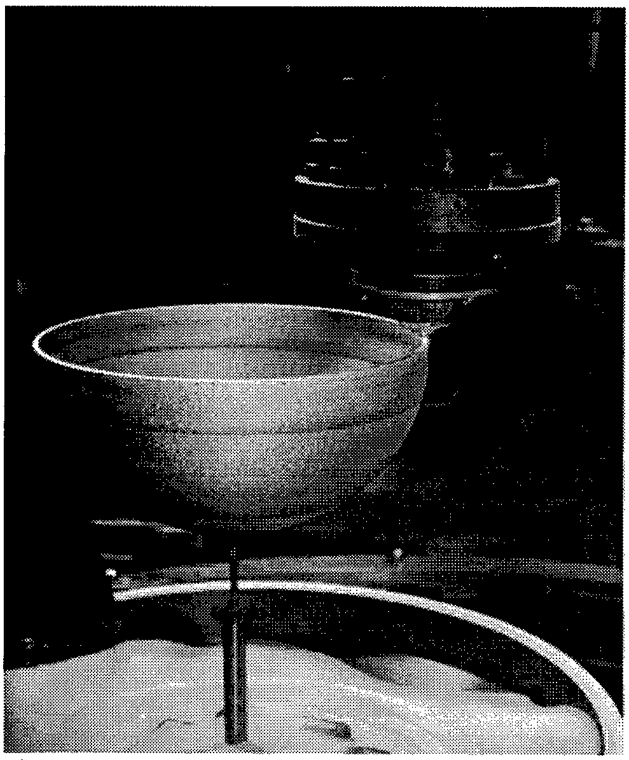

Figure 8. Deposition of hemisphere using 5-axis DLF system.

The as-deposited microstructure is shown in Figures 9 and 10. Seven beads were overlapped side by side to produce the wall thickness. The semi-elliptical profile of the deposited beads are shown with overlapping profiles forming layers across the wall thickness. Epitaxial growth across layer boundaries demonstrates metallurgical continuity for a fully dense deposit. A cellular solidification structure similar to

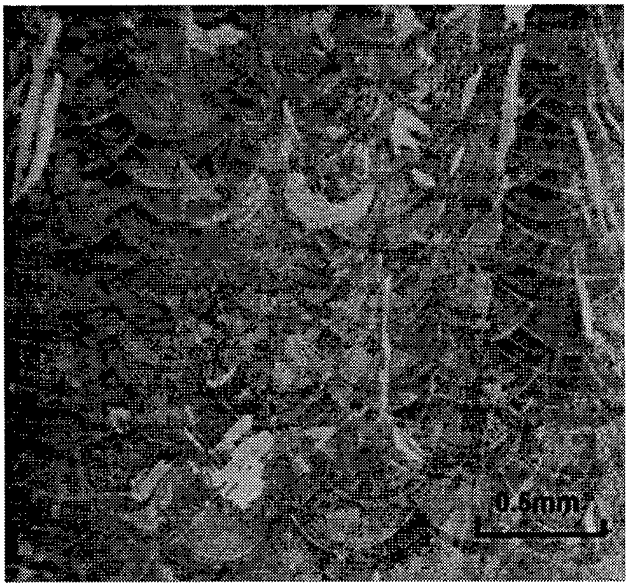

Figure 9. Microstructure of deposited beads laid side by side across wall of hemisphere.

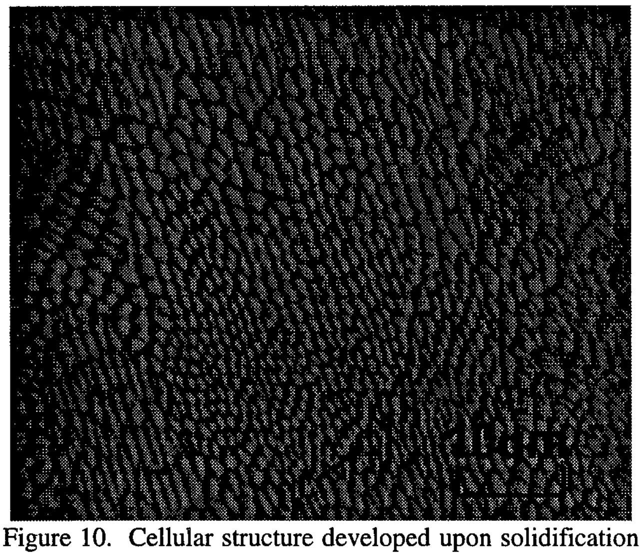

Figure 10. Cellular structure developed upon solidification of 316 stainless steel deposit.

that of a laser welded microstructure is shown in Figure 10.

Tensile properties were measured for deposited 316 stainless steel bars, 4.06mm x 4.22mm x 114.3mm long, processed at a laser power of 175w and traverse speed of 15mm/s. Overlap distance for laying beads of material side by side was 0.3mm and vertical layer thickness was 0.25mm. No porosity was observed and the deposits were fused to full density and had a re-solidified cellular microstructure similar to the hemisphere.

The tensile test results for 316 stainless steel in the as-deposited and annealed condition are compared to conventionally processed wrought material and investment cast 316 stainless steel in Table 2. Yield strength is 11% higher for the DLF material but elongation is 47% compared to 63% for wrought material, however the DLF material exceeds investment cast 316ss in strength and ductility. Similarly to the Inconel 690, wrought properties have been achieved in a single processing step eliminating the multiple themomechanical processing required to first condition cast material and then refine the chemistry and microstructure to achieve high strength.

Table 2
Tensile Properties of As-Deposited and Annealed 316 Bar Produced From Powder by DLF Compared to Conventionally Processed

Heat Treatment/Condition	0.2% YS Mpa (ksi)	UTS Mpa (ksi)	% El
DLF—As deposited Average of 3 tests	296.5 (43)	579.2 (84)	41
DLF-- Annealed 1050C/0.5 hr/water quench	296.5 (43)	524.0 (76)	47
Wrought annealed 316 [Ref. 15]	262.0 (38)	572.3 (83)	63
Type 316 (CF8M) Investment Cast (Nominal 316 cast composition) [Ref. 16]	268.9 (39)	517.1 (75)	39

Conclusions

Fully dense metal parts with a mechanical strength equal to or greater than conventionally processed wrought material have been produced by the Directed Light Fabrication process. High dimensional accuracy within an envelope of 0.1mm or better with surface finish of about 12 µm, arithmetic average was achieved. Parts have been successfully fabricated up to 355mm in height and 200mm in length and width. Microstructures are finer than conventional cast and welded structures, producing enhanced properties that are closer to wrought properties of conventionally processed material.

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