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Title: DIRECTED LIGHT FABRICATION

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Directed Light Fabrication

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Abstract

Directed Light Fabrication (DLF) is a rapid prototyping process being developed at Los Alamos National Laboratory to fabricate metal components. This is done by fusing gas delivered metal powder particles in the focal zone of a laser beam that is programmed to move along or across the part cross section. Fully dense metal is built up a layer at a time to form the desired part represented by a 3 dimensional solid model from CAD software. Machine "tool paths" are created from the solid model that command the movement and processing parameters specific to the DLF process so that the part can be built one layer at a time. The result is a fully dense, near net shape metal part that solidifies under rapid solidification conditions.

Introduction

Processing of metals into desired shapes and assemblies historically has involved the conventional thermomechanical processes of casting and metal forming (rolling, stamping, forging, extrusion) followed by machining and joining operations. Characteristics of these processes are heavy equipment requiring large capital investment and long lead times required for design and fabrication of precision molds, dies and tools specific to the desired shape. Multiple steps are usually required to achieve desired metallurgical properties and mechanical strength in the finished part, and as a result of the metal processing requirements, large production volumes of parts are typical to justify the cost of equipment, die design and manpower. Additionally, design iterations to improve the quality of components may be cost prohibitive, and design is limited to the formability of the chosen material.

Development of the the plastics rapid prototyping processes since the early 1980's demonstrates the feasibility of producing parts from three dimensional solid model designs by a single process and single piece of equipment (1). In this processing the parts are made by additive deposition of planar layers of plastic material until the complete part is formed. Additive deposition offers the capability to form assemblies and complex features that would otherwise have to be joined together, or may be impossible if conventional processing were used. However this processing has mostly been applied to plastics fabrication and has not been fully extended to make fully dense metal parts.

Other potential rapid prototyping processes for metal fabrication include liquid metal spraying, plasma spraying, electron beam vapor deposition, and investment casting processes. However, these processes are non-directional deposition techniques that require molds patterns or masks to gain the detail for complex parts and assemblies. The molds and patterns typically require additional processing steps both to fabricate the mold or pattern prior to deposition and to extract the mold or pattern after deposition, adding cost to the overall process. Other characteristics such as shadowing of one feature by another occurs, promoting uneven deposition and only partial density in the finished deposit.

The Directed Light Fabrication (DLF) uses the directionality of a laser beam guided by CNC machine commands to directly deposit metal to form an accurate, fully dense metal part. No molds, patterns or masks are required, only the digital representaion of the desired part in a 3 dimensional computer model. The part model is composed of 3D features which are split into planar layers equal to the deposition thickness for the process and a tool path is generated to guide the laser focal zone over the part cross section to deposit fully dense metal one layer at a time, feature by feature. The ability to directly form metal parts by a process such as DLF offers the advantage of structural integrity gained by achieving full mechanical strength in the metal deposit.

Experimental Procedure

The DLF process is designed to utilize standard commercially available CAD-CAM software to produce 3-dimensional solid models from which tool paths are generated. The tool paths move the focal zone of the laser systematically along all areas of the part to fuse metal powder particles that are delivered to the focal zone into solid metal and form the part a planar layer at a time.

The process is shown schematically in **Figure 1.** The Nd-YAG laser beam is delivered via fiber optic to a sealed boom that holds the laser focusing head and is attached to the "z" (vertical) axis. The focused laser beam enters the chamber through a quartz window in a nozzle that also delivers the metal powder to the focal zone. The entire process takes place in an inert gas box connected to a dry train that reduces the oxygen content to 5ppm or less. In the upper right of the schematic is a chamber that can be evacuated and backfilled with inert gas that contains the powder feeder. The powder feeder entrains the powder in an argon stream that delivers the powder to the laser focus nozzle and then to the focal zone. An Anorad positioning controller drives the "x", "y", and "z" tables, switches the laser shutter and powder feeder on and off, and controls various gas flows.

The deposition process is started on a metal plate that is cut off after deposition is complete. Typically a few passes of the laser beam are made without the powder feed turned on to preheat the plate and promote better adhesion of the first fused powder layers. Powders are then fed into the focal zone and the part is deposited a layer at a time until complete. The powders melt and resolidify as heat is removed by conduction through the base and by radiation from the hot zone. Excess powder that did not reach the focal zone of the laser beam accumulates at the base of the part and can be reused. Part sizes are limited in this equipment to slightly less than a 3-in. cube with motion in 3 orthogonal directions. Future equipment designs will recycle the powder directly back to the powder hopper in a continuous loop.

Three dimensional CAD/CAM models have been constructed using both Pro/ENGINEER and ICEM software. Pro/ENGINEER software provides a highly integrated 3D solid modeling environment which is finding strong recent interest within the DOE and industry, paticularly in the field of rapid protoyping. ICEM has been used for many years at Los Alamos to support 3D CAD/CAM design needs and provides extensive CAM programming capabilities. Manufacturing models (tool paths) have been constructed for a number of different 3D shapes and translated into motion system program code using a custom post processor specifically configured for the 3 axis DLF system as shown in **Figure 2**. A post processor has also been constructed to translate manufacturing models into 3 and 5 axis machine tool motion programs for the second generation 5 axis system. The 5 axis motion will allow the following of complex surfaces (**Figure 3**) and orientation of the laser to deposit material to create finishing passes to achieve final dimensions and features deposited along a horizontal plane such as over hangs. Process simulation has been performed to determine processing times for various processing conditions. **Figure 3** shows a portion of one such simulation report. These simulations are being used to determine the effect of process variables such as deposition speed, focal zone size and successive pass overlap. These simulations also provide a means to analyze computational requirements such as computer processing times, file sizes and data transfer rates. Manufacturing models are being created , based on a methodology akin to a reversed machining process. Non-standard use of the CAM software utilizes a feature based additive method in which parent features are produced and additional features are added to successively realize the final shape of the part. Simulation is also being used to investigate and develop the CAM procedures necessary to realize parts of increasing complexity. This evolving fabrication methodology is being verified and tested with the fabrication of 3D parts. Integration of commands and routines, specific to the DLF process, into the tool path for additional control are being performed. Customization of the CAD/CAM interface and post-processing capability is being performed to define and develop a software system specific to the DLF process .

Results and Discussion

A representative sampling of the parts made by the DLF process are shown in **Figure 4.** Fully dense metal tubes, channels, plates, a hollow I-beam and rods have been made of 316ss. These parts are uniform in surface texture, straightness and wall thickness. All parts were deposited in the vertical (z) direction parallel to the axis of the laser beam.

Microstructures of the 316ss deposits are fully dense as shown in **Figure 5** for a cross section of a vertical plate deposit. The deposited layers show up in the structure and are delineated by changes in the angle of the structure at the layer boundaries.

The angle is the reverse of the previous layer corresponding with the direction of travel of the laser beam relative to the deposit. Continuous epitaxial growth is often found across many layers. Vickers hardness measurements across the deposit and 316ss composition analysis at the top and bottom of the vertical plate deposit are shown in **Figure 6** indicating uniformity throughout. No significant elemental depletion has been observed in the deposits from layer to layer or from top to bottom of a 2 inch high vertical plate.

The microstructural development in the DLF processed samples typically displays continuous morphologies as well as refined segregation features, indicating a constant solid/liquid interface and rapid solidification kinetics. The continuous microstructural features are illustrated for a 316 stainless steel rod in **Figure 8**. A schematic diagram of the solid/liquid interface is illustrated in **Figure 7**. Apparently, a thin molten layer of the alloy resides at the top of the rod, and the solid dendrites continuously grow (in the mushy zone) during the process. Of course, if the molten zone is too large or too small, the stability and integrity of the process decreases. Therefore, the processing variables are critical in producing uniform components. Similarly, a continuous solid/liquid interface is present in wall samples produced by multiple beam passes. The continuous microstructural features of a wall are shown in **Figure 5** and schematically demonstrated in **Fig. 7**. Strong evidence of epitaxial growth off of the prior solid interface can be observed with each beam pass, supporting the existence of the solid/liquid interface. The continuous solid/liquid interface region produced in the DLF process yields fully dense components. This contrasts to other near net shape liquid powder techniques (e.g., thermal spraying) in that a molten droplet does not impact onto a solid substrate, and as a result, structural integrity degradations attributed to splat gaps and other pore defects are absent.

The refined dendritic microstructures observed in the rods and plates indicate that the cooling rates during solidification are rather high. Therefore, dendrite arm spacings (DAS) of ferrous samples produced with the DLF process were evaluated to estimate the attainable cooling rates. Relationships between the DAS and the cooling rate (ε) have been developed for a variety of alloy systems and show a linear relationship between log DAS and log ε (2). Two alloys were evaluated in both plate and rod form: Fe-25wt.%Ni and 316 stainless steel. Both primary DAS (λ_1) and secondary DAS (λ_2) were examined, and for Fe-25wt.%Ni, the equations are $\lambda_1 = 190\varepsilon^{-0.5}$ (3) and $\lambda_2 = 60\varepsilon^{-0.32}$ (4). For type 310 stainless steels, the experimentally determined relationships (5) which have been used in another rapid solidification study on stainless steels (6) are $\lambda_1 = 80\varepsilon^{-0.33}$ and $\lambda_2 = 25\varepsilon^{-0.28}$. In both sets of equations, the dendrite spacings are expressed in microns and the cooling rates have the units of K/s.

The Fe-25%Ni wire samples were examined under a variety of processing conditions, and the primary DAS varied between 5 μm to 30 μm while the secondary DAS varied between 5 μm and 12.5 μm. Therefore, stable rods could be grown with cooling rates varying between ~50 K/s to 10^3 K/s. Most rods cooled in the 10^2 K/s regime. Assuming that the interface growth scaled identically with the vertical speed of the laser (V_b), growth velocities from 1 mm/s to 1 cm/s are possible during DLF rod processing. For the Fe-25%Ni plate samples, the cooling rates varied between 10^3-10^4 K/s, with most plates experiencing cooling rates on the order of 10^4 K/s. The higher cooling rates in the plate samples can be attributed to the cooler bulk solid below the solid/liquid interface when the beam makes a deposition pass across the sample. As the laser beam passes across the substrate, the bulk away from the laser beam has sufficient time to cool before the next beam pass cycle. The larger temperature gradient (as compared to the rod growth process) provides a larger driving force for conductive cooling. The melt-back zone during the horizontal beam pass was typically less than two microns.

For the 316 stainless steel samples, similar results to the Fe-25%Ni were obtained with cooling rates for the rods at ~10^2 K/s and cooling rates for the plates at ~10^4 K/s. The two complimentary and independent alloy results provide a reasonable estimate of the rapid solidification conditions possible during DLF processing. Fully dense microstructures with reduced segregation can be produced, and refined microstructures produced during rapid solidification yield enhanced mechanical properties in ferrous alloys (7). However, in contrast to most rapid solidification processes such as melt-spinning, splat-quenching, or powder atomization, bulk product can be produced. Moreover, in comparison with other potential rapid prototype techniques such as thermal spraying, fully dense and uniform microstructural development can be achieved.

Several different types of materials were used to demonstrate that the DLF process could be applied to the processing of other materials than stainless steel. Rods were deposited from pure tungsten, and two intermetallic compounds: nickel aluminide (NiAl) and molybdenum disilicide ($MoSi_2$). **Figure 8** shows photographs of the starting powders, the rods including those made from 316ss, microstructures, and fracture surfaces for each of the four different rods. All of the rods fabricated were fully dense. Both of the intermetallics were very brittle and would break if bent at room temperature which is characteristic of those materials when processed conventionally. Both microstructures showed large columar grains along the rod axis. Some intergranular cracking was observed in the NiAl deposit. The tungsten rod could be bent once after depositing by the DLF process and when fractured the surface was typical of a very brittle fracture. The tungsten microstructure was very fine compared to conventional processed rods of similar diameter (8). The 316ss rod had a fine cast microstructure with a very ductile fracture surface.

Processing of these other materials demonstrates the DLF process can produce properties that are different than conventional processing. Tungsten wire for example is typically made by compacting tungsten powder and sintering to a porous structure. The porosity is eliminated by multiple metalworking (drawing, swaging) and annealing cycles (9). The DLF process produced a fully dense tungsten rod in a single process. Similar comparisons can be made for the NiAl and $MoSi_2$. These materials are processed by sintering or reactive sintering and hot isostatic pressing techniques (10, 11) where the DLF process can form the materials (at least for rods) in a single step.

Conclusions

The DLF process can produce near net shape metal components that are fully dense in a single processing step. Tool paths generated from solid models are used to accurately trace the part cross section with a laser beam that melts metal powder particles entering the focal zone and upon solidification forms a deposit representing a planar cross-section of the part. Multiple cross-sectional layers are formed until the part is complete. Conventional processing is bypassed by this single step technique.

Microstructural features indicate that cooling rates for rods are 10^2 °K/s and for plates 10^4 °K/s for both the 316ss and the Fe-25Ni alloys tested. The growth mechanism involves a continuous solid-liquid interface resulting in a full density component, with growth velocities ranging from 1 to 10mm/s.

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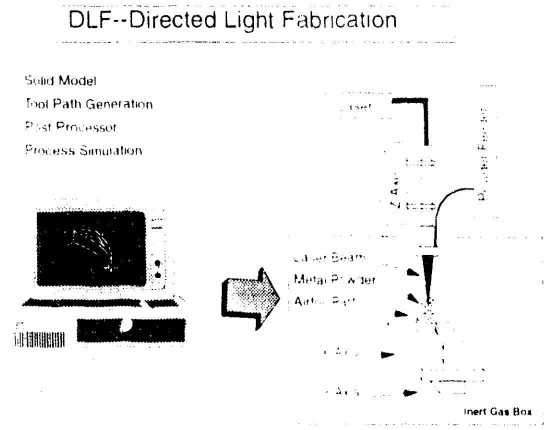


Figure 1: Schematic of the DLF process. A 3D digital design is transformed into machine commands that reproduce the solid model to near net shape by fusing metal powder with a laser beam.

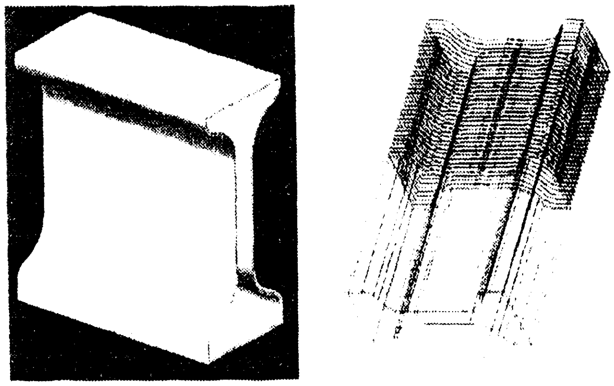
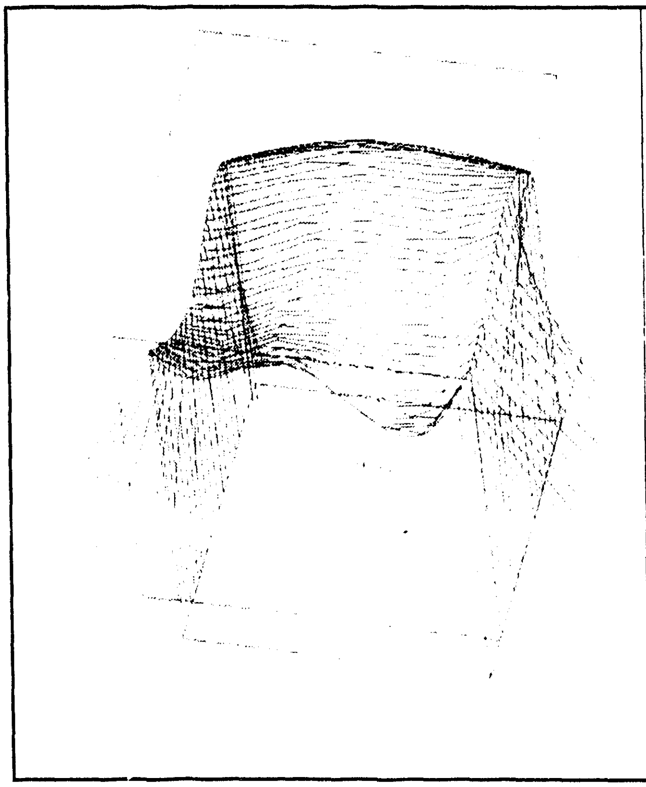


Figure 2: Solid model (left) and tool path (right) for the DLF process. The hollow I-Beam was fabricated in the orientation shown in the tool path representation.



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*********************************************
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Figure 3: (Left) Five axis tool path following a complex surface. (Right) A portion of a process simulation report.

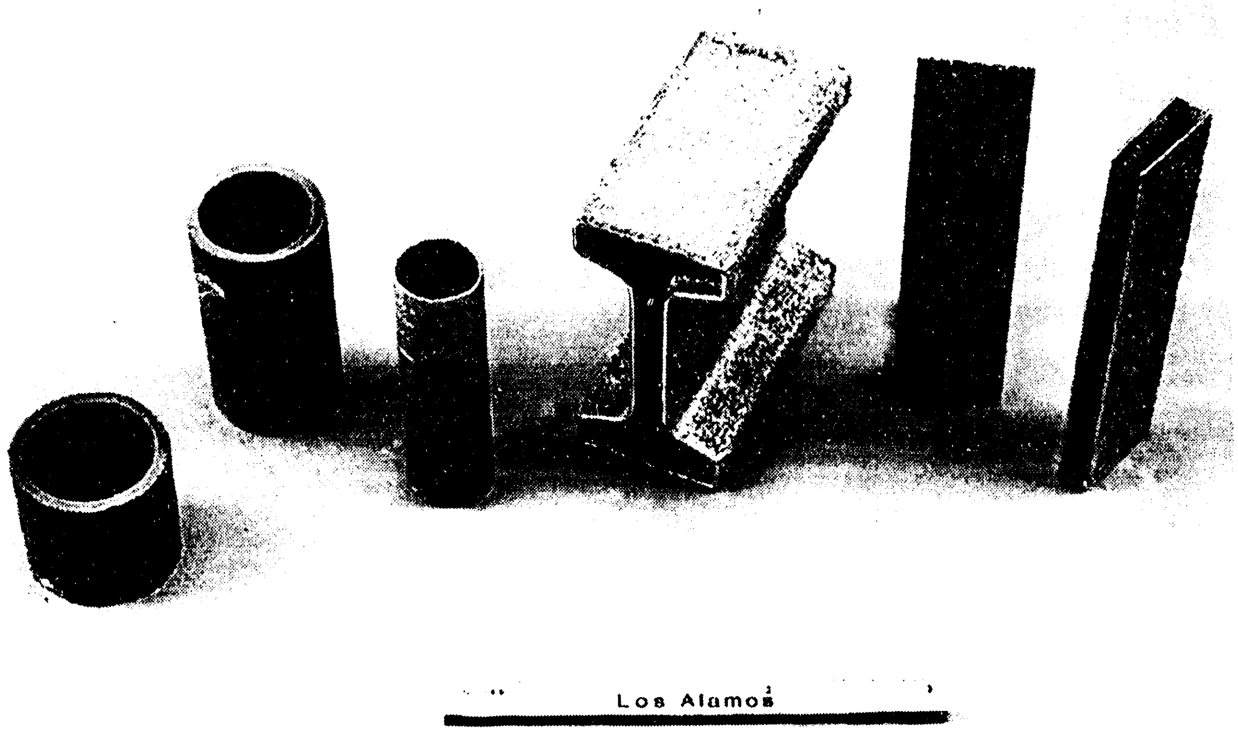


Figure 4: Typical DLF parts made from 316ss are uniform in surface roughness, straight sided and fully dense.

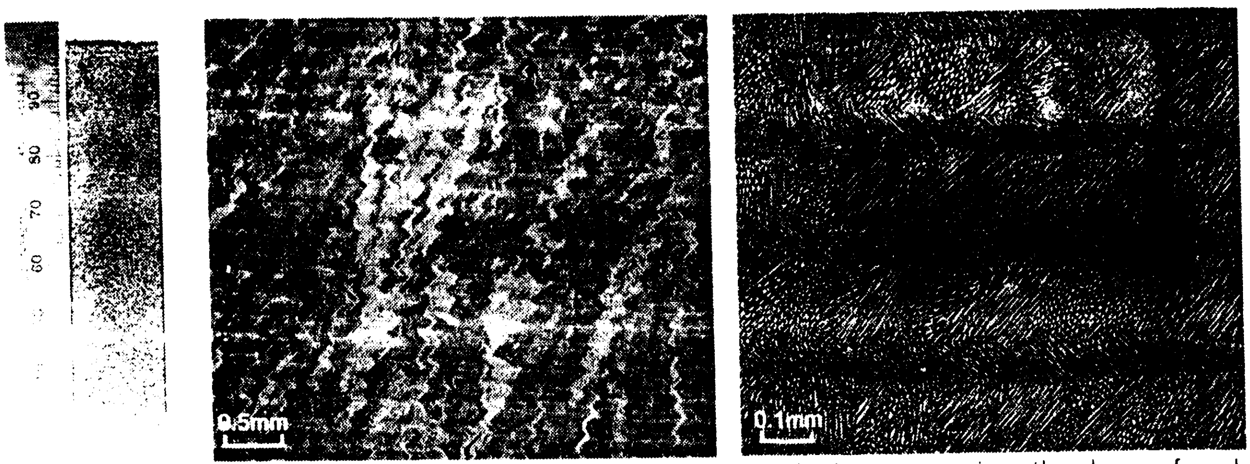
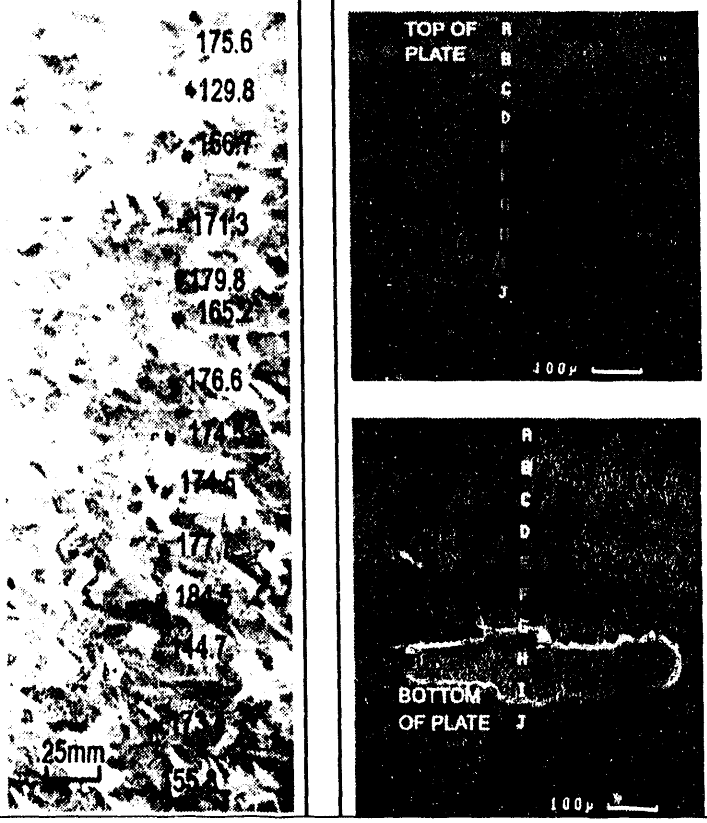


Figure 5: Metallography of a vertical wall deposit made by traversing the laser focal zone back and forth along its width shows a fully dense austenitic structure. Layers correspond with each laser pass and are delineated by the change in angle of the solidification structure at the layer boundary. Epitaxial growth of crystals from one deposited layer to the next often occurs producing the reverse angle in the next pass leaving a pattern across many layers of the deposit.



	Cr	Fe	Ni	Mo
A	21	68	9.8	1.4
B	21	68	9.5	1.5
C	21	69	9.3	1.5
D	21	68	9.7	1.2
E	21	69	8.9	1.2
F	21	69	9.5	1.2
G	21	68	9.6	1.3
H	21	69	8.9	1.2
I	21	68	9.4	1.4
J	21	68	9.1	1.4
A	21	68	9.3	1.4
B	21	68	9.0	1.4
C	21	68	9.4	1.3
D	21	69	9.1	1.1
E	21	69	9.4	1.4
F	21	68	9.6	1.0
G	21	69	8.9	1.6
H	21	68	9.2	1.4
I	21	68	9.5	1.2
J	21	68	9.5	1.5

Figure 6: Vickers Hardness and elemental analysis of a vertical wall deposit show little variation across layers in the microstructure and in the top and bottom of the deposit for 316ss.

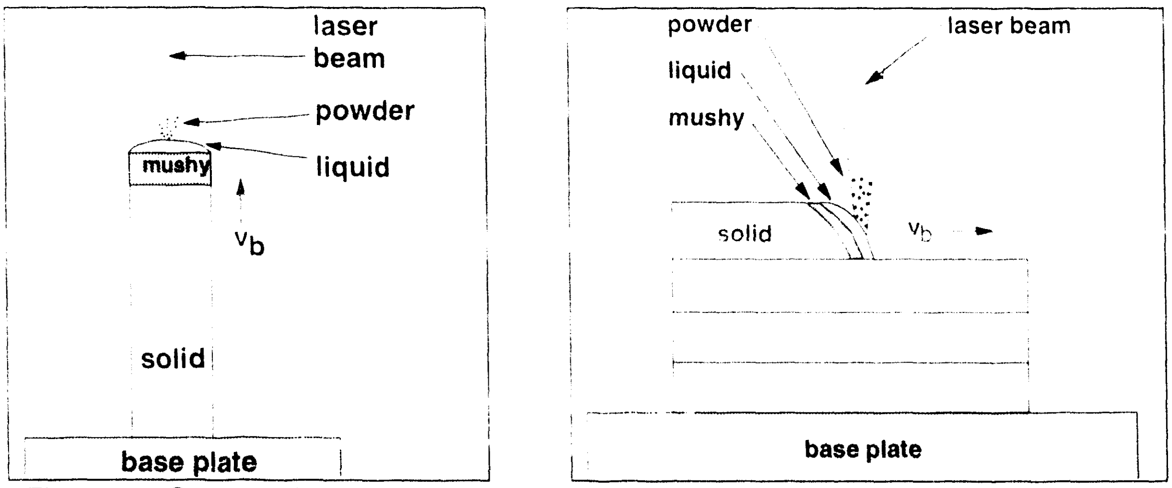


Figure 7: Schematic of rod and plate formation. Rod moves vertically and plate is formed a layer at a time horizontally at speed (V_b).

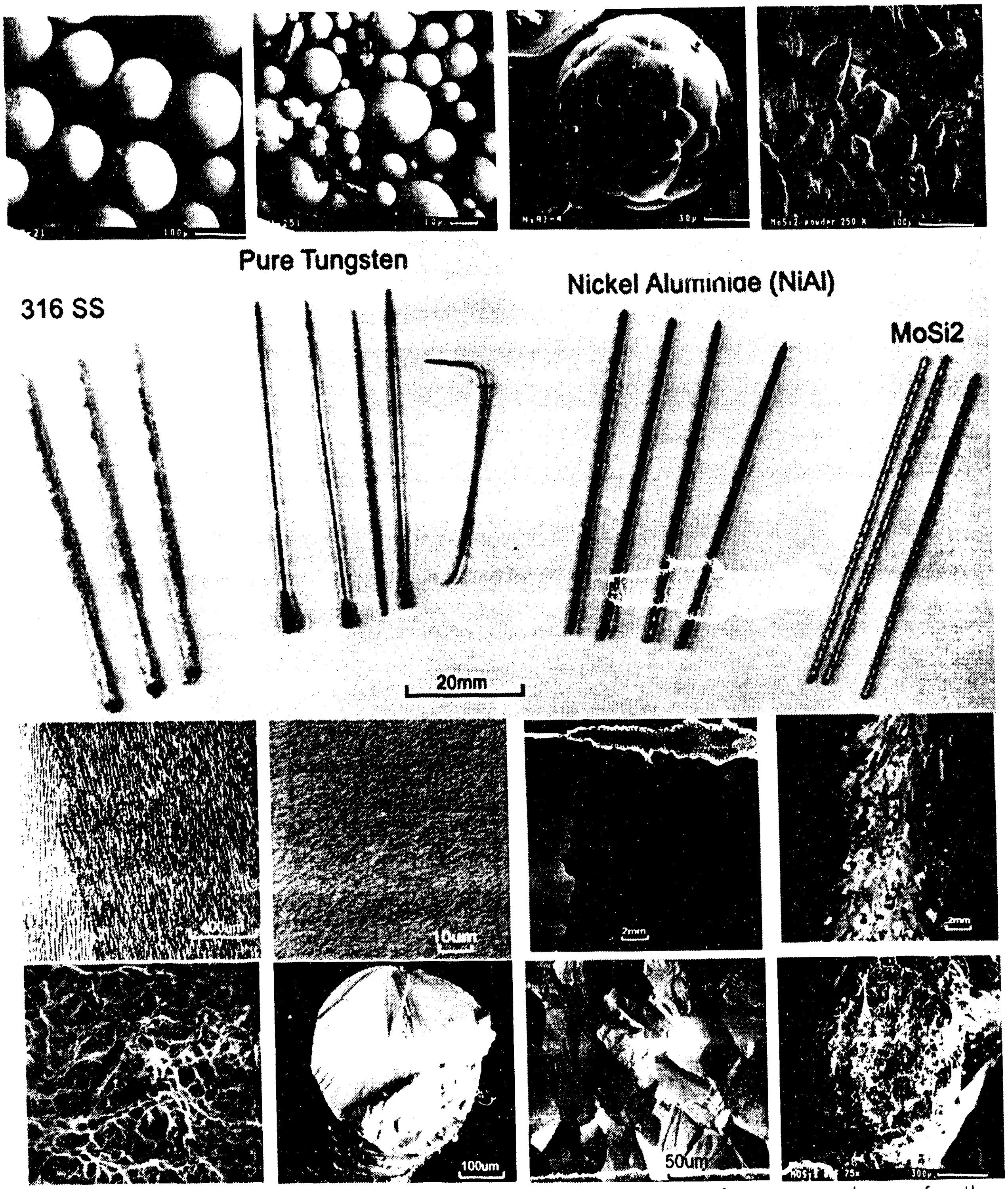


Figure 8: Starting powders, microstructure and fracture surfaces are shown for the rods deposited by the DLF process in Figure 9. From left to right--316ss, tungsten, NiAl, and $MoSi_2$.

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