Properties of Near-Net Shape Metallic Components Made by the Directed Light Fabrication Process

Gary K. Lewis
John O. Milewski
Dan B. Thoma

Materials Science and Technology Division
Los Alamos National Laboratory
Los Alamos, New Mexico

Ron B. Nemec
SyntheMet Corporation
Los Alamos, New Mexico

The DLF Process

Directed Light Fabrication (DLF) [1-8] is a process invented at Los Alamos National Laboratory that can be used to fuse any metal powder directly to a fully dense, near-net shape component with full structural integrity. A solid model design of a desired component is first developed on a computer work station. A motion path, produced from the solid model definition, is translated to actual machine commands through a post-processor, specific to the deposition equipment. Shown schematically in Figure 1, the DLF process uses a multi-axis positioning system, (3 and 5 axes are used) to move the laser focal zone over the part cross-

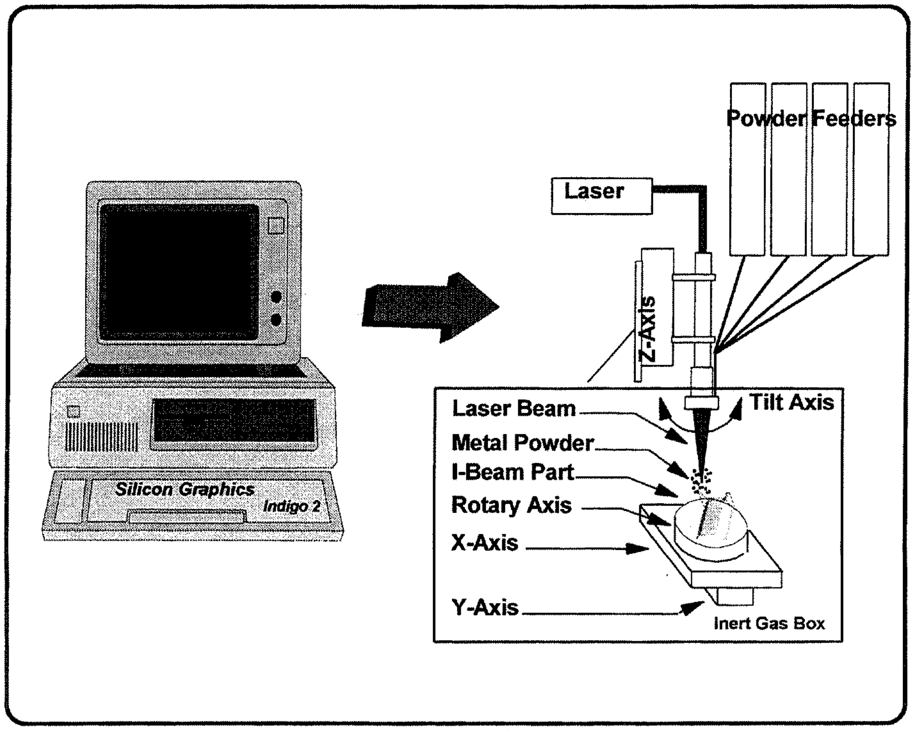

Figure 1. Schematic Diagram of the 5-Axis DLF System

section defined by the part boundaries and desired layer thickness. Metal powders, delivered in an argon stream, enter the focal zone where they melt and continuously form a molten pool of material that moves with the laser focal spot. Position and movement of the spot is commanded through the post-processor. Successive cross-sectional layers are added by advancing the spot one layer thickness beyond the previous layer until the entire part is deposited. The system has 4 powder feeders attached for co-deposition of multiple materials to create alloys at the focal zone or form dissimilar metal joint combinations by changing powder composition from one material to another.

Parts produced by the DLF process vary in complexity from simple bulk solid forms to detailed components fabricated from difficult to process metals and alloys. Deposition of complex 3D parts such as the hemisphere in Figure 2 require more degrees of freedom in the motion path and additional axes of motion (4) than 2.5D bulk solids or hollow parts that are simple "extrusions" of part cross section in a single direction. Figure 3 shows representative parts produced by the DLF process. Assemblies of components can be built as one DLF deposited component, such as the multi-tube assembly and housing, which would have to be welded or brazed if processed conventionally. Components 355mm tall and 200mm x 200mm in the horizontal plane requiring build times of over 120 hours continuous operation have been

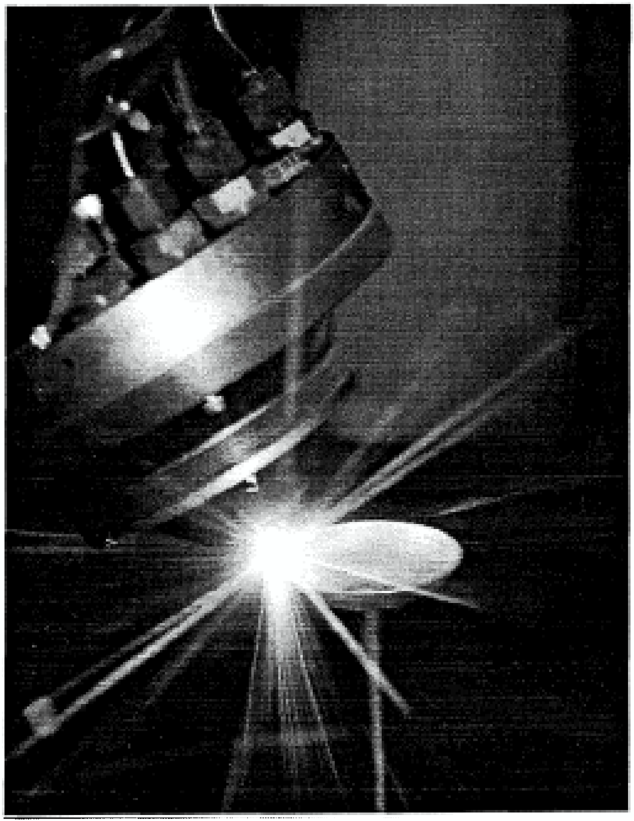

Figure 2. DLF deposition of a hemisphere on a tubular stem demonstrates 4-axes of motion to produce an over-hanging part.

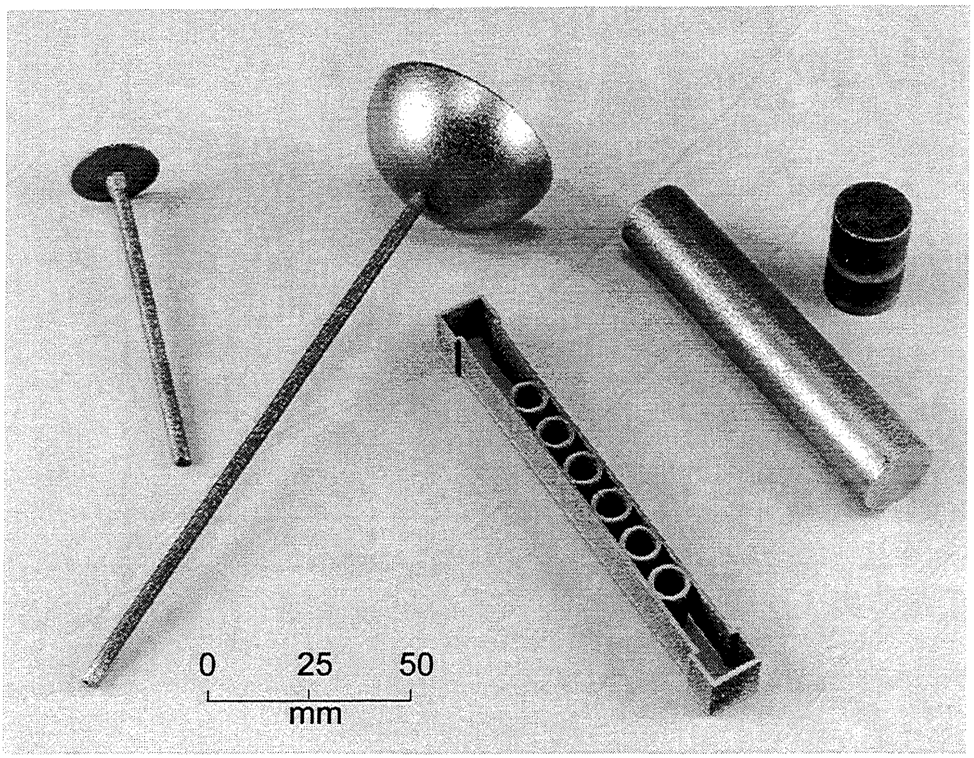

Figure 3. Representative DLF parts and assemblies. From left to right, tantalum stem and disc, 316 stainless steel stem and hemisphere, 316 stainless steel tube assembly and housing, and Inconel 690 solid cylinders.

fabricated with capability to build larger with the present system. Parts have been deposited at rates up to 33 cm^3/hr with 12 cm^3/hr more typical. Feasibility of processing any metal ranging in melting point from aluminum to tungsten has been demonstrated.

Control over process parameters provides optimization of deposit density and deposition rate. Laser power, velocity, powder feed, layer thickness (step-up), and overlap (step-over) are controlled. All but powder feed rate can be controlled within the post-processor code in the DLF process. Parameter optimization depends on the thermal balance for any specified component and material.

DLF Deposit Properties and Characteristics

Metallurgical characterization of DLF metal deposits reported in previous DLF studies has shown that fully dense deposits can be formed at high solidification rates and velocities. Cooling rates of 10,000 k/s [2] have been observed by measurement of secondary dendrite arm spacing [9] on plate structures. Solidification velocities [2] have been measured by eutectic spacing measurements [9] and are shown to be scaleable to the beam velocity during processing. Knowledge of the microstructural development during the DLF process is necessary both to understand the resultant mechanical properties and to improve the characteristics of the deposits.

Mechanical properties of bulk deposits in this study were measured for three alloy powders using DLF. Ti-6Al-4V and 316 stainless steel powders were fabricated into rectangular bar, and Inconel 690 powder was fabricated into a solid cylinder. Flat tensile bars were machined from the Ti-6Al-4V and 316ss material and round tensile bars were machined from the solid Inconel 690 cylinders. All tests reported were run in the longitudinal direction, which is parallel to the laser beam axis.

DLF Process Parameters

Powder: Ti-6Al-4V
Powder Screen Size:
-80+140 Mesh
Powder Size Range:
105μm-177μm
Power: 175-180w
Traverse Speed: .02m/s
Step-Up: 0.25mm
Step-Over: 0.3mm
Dimensions: 15.47mm x
49.40mm x 112.9mm

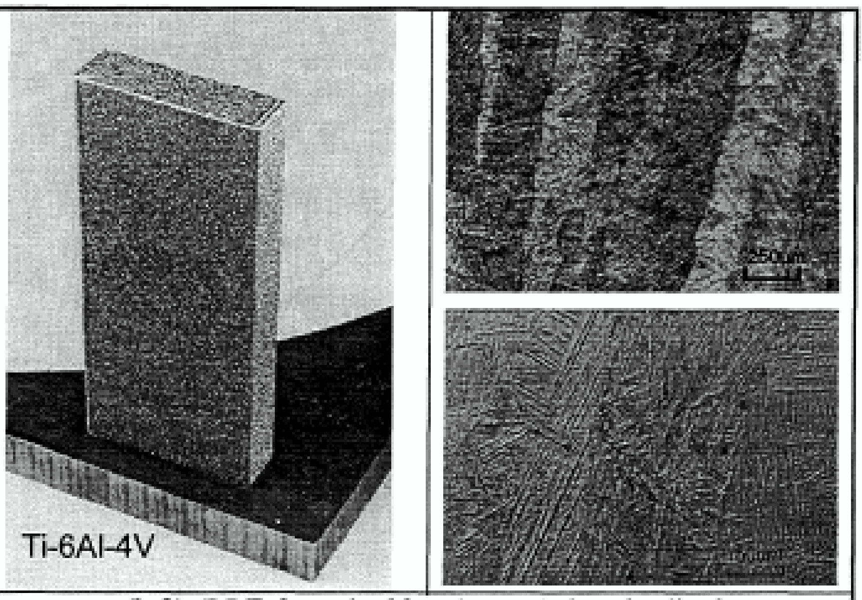

Figure 4. DLF processing parameters (left), DLF deposited bar (center), longitudinal microstructures--annealed (right-top) and as-deposited (right-bottom). Columnar growth during solidification (vertical direction) eliminated deposition layer boundaries.

Figure 4 shows the DLF processing parameters for the bar (center) and the as-deposited and annealed microstructures (right). The deposited microstructure is comparable to Ti-6Al-4V weld microstructures [16] showing acicular alpha with some beta phase. No voids due to lack of powder fusion or cracks were observed on the surface or interior of the bar, however some small pores due to gas evolution during solidification were observed in the Ti-6Al-4V microstructure. Columnar growth in the longitudinal direction of the plate, which is perpendicular to the deposited layers, is in the as-deposited structure and the boundaries remained after the annealing cycle.

DLF material, in the mill annealed condition (730C/4 hr/furnace cool), was tested in the longitudinal direction. Tensile test results are shown in Table 1 with comparison to wrought, cast and powder met forged Ti-6Al-4V bar in the annealed condition. Yield and tensile strength properties of the DLF deposited Ti-6Al-4V exceeds or is equivalent to wrought bar, cast and powder metallurgy forging material in the annealed condition. However, elongation was 6.2% compared to AMS specified 10%. Gas analysis of powder and deposit, additional heat treating and testing are being conducted to explain the low ductility or how to improve it.

Bars of 316 stainless steel were deposited and milled into flat tensile bars. Processing conditions and the deposit microstructure are shown in Figure 5. No porosity was observed and

Table 1
Tensile Properties of Annealed Ti-6Al-4V Bar Produced From Powder by DLF Compared to Conventionally Processed

Heat Treatment	0.2% YS (ksi)	UTS (ksi)	%El
DLF--Mill Anneal -- 730C/4 hrs/furnace cool Average of 4 Tests	139	149	6.2
Conventional Processed Wrought Bar –Annealed (Spread for 36 tests) [11]	120-145	135-155	15-20
Cast + Anneal [12]	129	147	10
Powder Met Annealed and Forged	134	122	12

a fully fused and resolidified cellular microstructure is shown. The deposition layers are defined because of the melt back depth into each previous layer. Tensile test results in Table 2 for 316 stainless steel in the as-deposited and annealed condition are compared to conventionally processed wrought material and investment cast 316 stainless steel. 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.

Inconel 690 round bars were deposited and shown with the deposition process parameters used in Figure 6. Deposited bars were fully dense and crack free. Microstructures for the as deposited bars and material heat treated at 1700F and 2000F are shown in Figure 7 and resultant tensile properties in Table 3.

DLF Process Parameters
Powder: 316 stainless steel
Powder Screen Size: 140+325 Mesh
Powder Size Range: 44μm-105μm
Power: 175-180w
Traverse Speed: .015m/s
Step-Up: 0.25mm
Step-Over: 0.3mm
Dimensions: 4.06mm x 14.22mm x 114.3mm

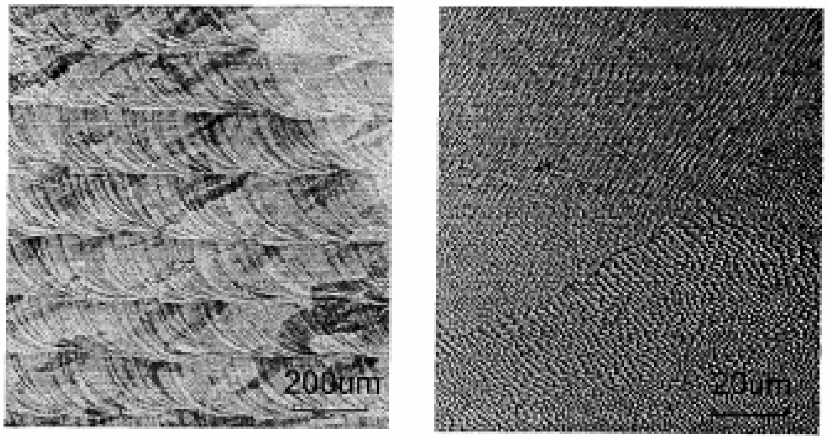

Figure 5. Process parameters for deposition of 316 stainless steel bars (left), microstructure showing the deposited layer structure (center) and cellular microstructure within the layers (right).

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 (ksi)	UTS (ksi)	%El
DLF—As deposited Average of 3 tests	43	84	41
DLF-- Annealed 1050C/0.5 hr/water quench Average of 2 Tests	43	76	47
Wrought annealed 316 [Ref. 13]	38	83	63
Type 316 (CF8M) Investment Cast (Nominal 316 cast composition) [Ref. 14]	39	75	39

DLF Process Parameters

Powder: Inconel 690
Powder Screen Size:
100+325 Mesh
Powder Size Range:
44µm-149µm
Power: 330w
Traverse Speed: .025m/s
Step-Up: 0.381mm
Step-Over: 0.305mm
Dimensions: 21.0mm dia. x 356mm

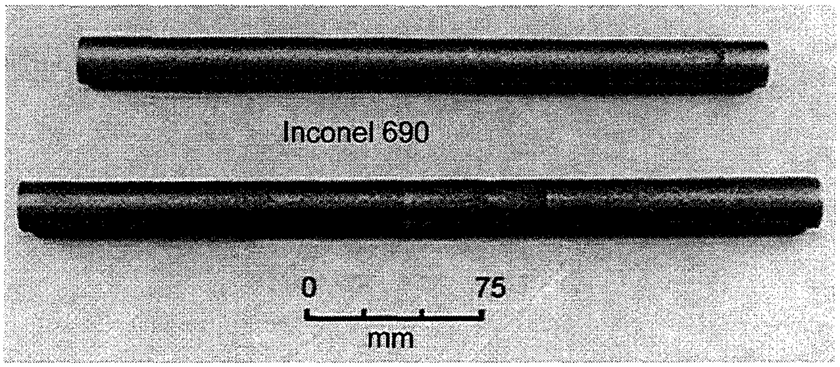

Figure 6. Inconel 690 process parameters (left) and bars (right).

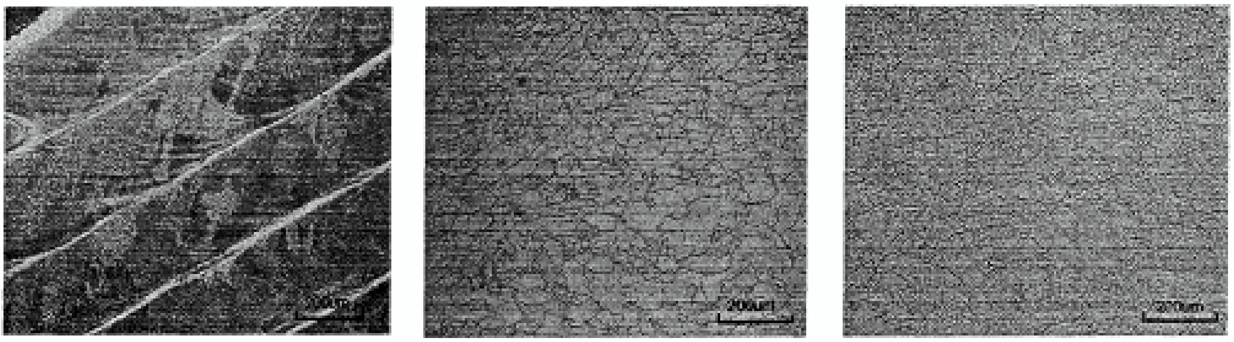

Figure 7. Inconel 690 microstructures are shown as deposited (left), 1700F/1 hr (center) and 2000F/1hr (right). The layered cellular microstructure in the deposit was transformed to equiaxed grains with 26.5µm grain size at 1700F and 37µm grain size at 2000F.

Inconel 690 tensile properties are shown in Table 3 for the as-deposited and heat treated conditions. Properties for conventionally processed hot rolled rod of similar diameter are shown for comparison. Yield strengths for the DLF material exceeded conventional in all cases. Ultimate strengths were lower by about 10% and elongation's were similar.

Table 3
Tensile Properties of As-Deposited and Heat Treated Inconel 690 Bar Produced From Powder by DLF Compared to Conventionally Processed

Heat Treatment/Condition	0.2% YS (ksi)	UTS (ksi)	%El
DLF—As deposited	65.2	96.6	48.8
DLF—1700F/1 hr.	70.7	99.7	46.0
DLF—1800F/1 hr.	69.0	99.3	46.0
DLF—1900F/1 hr.	65.0	97.0	47.0
DLF—2000F/1 hr.	55.6	94.4	52.0
Conventionally Processed 16mm hot rolled rod [15]	54	107	50

Conclusions

Yield strength for the DLF processed Ti-6AL-4V, 316ss and Inconel exceed wrought, cast and powder metallurgy yield strengths for conventionally processed material. Elongation's are less than wrought, powder and cast Ti-6AL-4V and 316ss material, but equivalent for wrought Inconel 690. The importance of the data is that it shows that strengths equivalent or higher than conventionally processed material can be achieved in a single step with the DLF process. Conventional wrought and powder metallurgy processing require mold or die design and manufacture followed by many thermomechanical processing steps in series to refine grain structure, achieve chemical homogeneity, and desired properties. DLF requires no molds or dies and offers potential for controlling solidification microstructures, which determine resultant mechanical properties so that desired properties may be achieved in a single step.

Acknowledgments

Work by Los Alamos National Laboratory was performed under contract W-7405-ENG-36. Inconel 690 investigations were performed under DOE contract DE-AC12-76SN00052 and Ti-6Al-4V deposition tests were performed by SyntheMet Corporation. The authors wish to thank Patrick Dickerson, Ann Kelley, and Joe Fonseca for the deposition processing and metallography performed on the test samples.

References

1. G.K. Lewis, R.B. Nemec, J.O. Milewski, D.J. Thoma, M.R. Barbe, and D.A. Cremers, "Directed Light Fabrication", *Proc. ICALEO '94*, Laser Institute of America, Orlando, Florida, 1994, p. 17.
2. D.J. Thoma, G.K. Lewis, R.B. Nemec, "Solidification Behavior During Directed Light Fabrication", To appear in *Beam Processing of Advanced Materials",* J.Singh, ed., ASM, Cleveland, OH, 1995.
3. D.J. Thoma, C. Charbon, G.K. Lewis, and R.B. Nemec, "Directed Light Fabrication of Iron-Based Materials", To appear in *Advanced Laser Processing of Materials-Fundamentals and Applications,* MRS, Pittsburgh, 1996.
4. G.K. Lewis and D.J. Thoma, "Free Form Metal Deposition to Near-Net Shape", ASM-TMS, Cincinatti, Ohio, October 6-10, 1996.
5. G.K. Lewis, and D.J. Thoma, J.O. Milewski, J.O., and R.B. Nemec, "Directed Light Fabrication of Near-Net Shape Metal Components", World Congress on Powder Metallurgy and Particulate Materials, Washington, D.C., June 16-21, 1996.
6. D.J. Thoma, G.K. Lewis, E.M. Schwartz, and R.B. Nemec, "Near Net Shape Processing of Metal Powders Using Directed Light Fabrication", Advanced Materials and Technology for the 21st Century, Journal of the Institute of Metals, 1995 Fall Annual Meeting (117th) Hawaii, Dec. 13-15, 1995.
7. G.K. Lewis, and D.J. Thoma, J.O. Milewski, J.O., and R.B. Nemec, "Directed Light Fabrication of Refractory Metals", 1997 International Conference on Powder Metallurgy and Particulate Materials, Chicago, Illinois, June 29-July 2, 1997.
8. D.J. Thoma, G.K. Lewis, J.O. Milewski, R.B. Nemec "Rapid Processing of Materials Using Directed Light Fabrication, Thermec '97, University of Wollongong, Australia.
9. W. Kurz and D.J. Fisher, "*Fundamentals of Solidification*", 3rd. ed., Trans Tech Publications, VT, (1989).
10. American Society for Metals, *Metals Handbook, Ninth Edition, Vol. 7, Powder Metallurgy*, Metals Park, Ohio, 44073, 1980, p. 295-492.
11. *Aerospace Structural Metals Handbook, Vol. 4, 1995 Edition*, Code 3707 Pg. 15, Fig. 3.0312, Purdue University, West Lafayette, IN 47907-1293.
12. American Society for Metals, *Metals Handbook, Ninth Edition, Vol. 3, Properties and Selection: Stainless Steels, Tool Materials and Special Purpose Metals*, Metals Park, Ohio, 44073, 1980,p. 370.
13. *Aerospace Structural Metals Handbook, Vol. 2, 1995 Edition*, Code 13307 Pg. 32, Fig. 3.03113, Purdue University, West Lafayette, IN 47907-1293.
14. *Aerospace Structural Metals Handbook, Vol. 2, 1995 Edition*, Code 1307 Pg. 35, Fig. 3.03120, Purdue University, West Lafayette, IN 47907-1293.
15. Huntington Alloys, Inc., "Inconel 690", Product Literature, Huntington Alloys, Inc., Huntington, WV.
16. American Society for Metals, *Metals Handbook, Eighth Edition, Vol. 7, Atlas of Microstructures of Industrial Alloys*, Metals Park, Ohio, 44073, 1972, p. 330.