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14. ABSTRACT

This project enabled the integration of ultrasonic consolidation, direct write dispensing, and material deposition technologies into a manufacturing workcell capable of fabricating advanced, integrated Naval-relevant structures. The workcell was shown to be capable of spatial composition control and complex internal geometries – including embedded electronics, thermal management, reinforcement fibers and other features – along with the resolution, scalability, repeatability, dimensional accuracy and surface finish of milling, all within an integrated Direct Digital Manufacturing (DDM) workcell. A one-year extension led to the development of a computational modeling infrastructure for ultrasonic consolidation that has revolutionized the prediction of the effects of process parameter variations on bonding, microstructure and mechanical properties of parts made using ultrasonic consolidation.

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Final Report
Direct Digital Manufacturing of Integrated Naval Systems using Ultrasonic Consolidation, Support Material Deposition and Direct Write Technologies

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Dr. Ryan Wicker, University of Texas at El Paso, Co-PI

Project Overview

The objective of this project was to integrate ultrasonic consolidation, direct write dispensing, and material deposition technologies into a seamless manufacturing workcell capable of fabricating advanced, integrated Naval-relevant structures. The combination of UC, DW and MD enables spatial composition control and complex internal geometries – including embedded electronics, thermal management, reinforcement fibers and other features – along with the resolution, scalability, repeatability, dimensional accuracy and surface finish of milling, all within an integrated Direct Digital Manufacturing (DDM) workcell.

In addition to the original scope of work, a one-year extension led to the development of a computational modeling infrastructure for ultrasonic consolidation that has revolutionized our ability to predict the effects of process parameter variations on bonding, microstructure and mechanical properties of parts made using the integrated DDM workcell. This model is being further developed in subsequently funded projects, and is being applied beyond UC to selective laser melting, electron beam melting, and other DDM processes.

In order to meet the objectives of this project, the following five research tasks were developed and completed.

Research Task 1 – Experimental Investigation of Multi-Material UC-produced Parts:
We have broadly explored the types of multi-material structures which can be produced using UC. We have demonstrated bonding of numerous types of dissimilar materials which are useful for Naval-relevant structures, including material combinations which would otherwise form brittle intermetallics if bonded using fusion or thermal bonding techniques. In addition, we have investigated, identified, and discussed bond defects and bond formation at a greater level than any previous research group. This research task led to ten different publications that form the foundation of our group's and others' understanding of ultrasonic consolidation, UC's general capabilities, and the materials which can be used [1,2,3,4,5,6,7,12,13,17].

To illustrate some of these results, we have included figures at the end of this report. A complete set of all of the publications (listed below) are also being delivered to ONR for further information.

Our studies showed that Ni can be bonded very well to itself and to Al 3003 (Fig.1). After careful process parameter optimization, Cu proved to be an excellent material to work with (Fig.2). Ti presented some problems. Use of acid pickling for removing the surface oxide layers (just prior to deposition) and surface machining for removing the sonotrode-induced roughness on the previously deposited foil surface were found to be helpful. We have achieved excellent bonding between Ti and Al 3003 (Fig.3). Detailed microstructural studies at weld interfaces were carried out to gain insight into the fundamental mechanisms of ultrasonic bonding. Our studies show:

1. Some amount of plastic deformation occurs at weld interfaces during UC, but the lower power UC system used in this work (as opposed to the more recent high-powered systems developed by Edison Welding Institute) does not significantly affect the overall foil microstructure. This opens up unique opportunities for optimizing part microstructures. The micrographs shown in Fig.4 (Ni 201) and Fig.5 (Cu 10100) support these conclusions.
2. No evidence of localized melting was observed in any of the UC samples.
3. No significant diffusion occurred across the weld interface (Fig.6) or intermetallic formation (Fig.7) was observed.
4. There is little evidence of mechanical interlocking in UC. Bond lines appeared flat in most cases without any waviness typical of mechanical interlocking (Fig.2 and Fig.3)
5. Oxide layers still persist at defect surfaces (Fig.8 and Fig.9).

In UC, a layer is generated by depositing foils side-by-side. Examination of Al 3003 UC samples showed that large physical discontinuities occur at many of the foil junctions within a layer (Fig.10). As the amount of foil overlap increased, tensile strength increased. Excessive foil overlap resulted in a drop in tensile strength. Sample microstructures provided insight into these findings. Fig.11 shows the microstructure of a UC sample made using an optimized setting. This sample was found to be free from large physical discontinuities, and illustrates the importance of using proper foil overlap settings. These issues can be avoided altogether, however, if sheets of material large enough to form an entire layer are used. We anticipate investigating the use of sheets instead of foils as a build material for future research projects.

In order to test the effect of post-fabrication thermal treatments, Al 3003 deposits were subjected to annealing treatments. Fig.12 shows an Al 3003 microstructure with a few unbonded regions between layers as well as at foil junctions within a layer. Annealing treatments resulted in elimination of most of the defects along layer interfaces (Fig.13), thus showing that the quality of UC parts can be significantly improved by appropriate post-fabrication heat treatment.

<u>Research Task 2 – Experimental Determination of Optimum Parameter Settings for Stainless Steel 316L:</u>

We developed UC process parameter sets for using SS316L metal foils to create dense 3-dimensional structures. These alloys are much more robust than the Al 3003 alloys typically used in UC and are particularly relevant for naval applications due to their corrosion resistance and mechanical properties. Optimum process parameters were developed experimentally using an extensive design of experiments-based methodology. Examples of SS316L deposits are shown in Fig. 14.

The measured response variable for these experiments was linear weld density (LWD). %LWD is simply the bonded length divided by the total length of an interface, as observed under an optical microscope. %LWD is a commonly used parameter in journal articles, however there has been no standard approach to its measurement. We developed an approach and MatLab script to automate the measurement of %LWD (Fig. 15). This approach was validated and used for SS316L process parameter optimization.

One key conclusion from Research Tasks 1&2 was that the time and cost it takes to optimize the UC process for a new material is prohibitive. A new modeling infrastructure would significantly aid in the identification of materials suitable for UC processing and for the development of optimum process parameters, thus minimizing the need for extensive designed experiments. This recognized need formed the basis for the work described below in Research Task 5.

Research Task 2 resulted in three publications [11, 21, 24].

Research Task 3 – Integration of a Fused Deposition Modeling extrusion system onto an Ultrasonic Consolidation Apparatus and Deposition of Support Materials for Ultrasonic Consolidation:

A dual-material FDM deposition head was integrated with our UC machine for support material deposition and insulative material deposition (to keep deposited electronics from "shorting" electrically to the surrounding metal structure). Numerous experiments with candidate polymer and metal materials were undertaken to ascertain their suitability for use in an FDM extrusion head and as a UC support material.

Rib-in-channel plates with different rib height-to-width ratios were made (Fig. 16). Various prospective materials were deposited using a commercial FDM system to fill the channels and support the freestanding ribs (Fig. 17). A series of UC foil depositions were performed, followed by peeling of the tapes from ribs to observe bond quality (Fig. 18 & 19). It was observed that certain water-soluble materials were effective support materials, thus opening up the possibility of geometrically complex part generation using water-soluble supports in UC. We were thus able to create more complex geometries than was previously possible using UC (Figs. 20, 21, 22). A collaborative agreement with Solidica (the maker of UC technology) was in place to support this aspect of our work.

One aspect of our work which shows promise for future investigation is the deposition of metal alloys using an FDM head (Fig. 23). A self-funded study is now in progress to see if this may lead to new intellectual property and an opportunity for a new type of metal-FDM machine to be introduced into the marketplace.

Research task 3 resulted in four publications [8, 9, 18, 23].

Research Task 4 – Integration of an nScrypt Direct Write dispensing head onto an Ultrasonic Consolidation Apparatus, and Demonstration Prototypes of Integrated Electronics using the Integrated DDM Workcell:

Prior to integrating direct write into UC, we investigated more thoroughly the concept of DW deposition in an additive manufacturing machine using a combination stereolithography/direct write system (Fig. 24). This system was shown to be capable of producing highly integrated embedded electronics structures. An example of a functional 3D embedded circuit, a LM555 temperature sensor circuit with embedded passive electrical components and DW interconnections between components was fabricated. Fig. 25 illustrates the evolution in circuit design and size that is possible using embedded 3D circuitry, where the final design represented an ~25% decrease in total cross-sectional area and volume as compared to the initial layout. As a result of the need for improved ink/conductive media performance, we began discussing collaborative opportunities with nScrypt, Inc, a leading manufacturer of DW equipment. They sell a head with 100 picoliter or less volume control, valving action with suck back control at the pen tip, viscosity range from 1 centipoise to 1,000,000 centipoise, and optimal tip design to reduce pressure of more viscous materials. In addition, nScrypt uses a conductive epoxy for conductive traces that exhibits minimal shrinkage and is a superior candidate for vertical interconnections. We purchased and integrated an nScrypt direct write dispensing system (Fig. 26) onto our UC machine for the purposes of further investigation.

The combined UC/DW/MD machine is shown schematically in Fig. 27. Upon the completion of this workcell, we created several proof-of-concept parts which integrated direct write dispensing into a UC part to create a functional electronic device. An example part shown half-way through a build (before being covered by subsequent aluminum layers) is included as Fig. 28.

One key conclusion from Research Task 4 was the recognition that the UC apparatus used for this work was not a sufficiently robust platform to form the basis for a commercially-viable UC/DW/MD workcell. As a result, we worked with Edison Welding Institute (EWI) to identify a better machine architecture for a next-generation ultrasonic consolidation machine. EWI and Solidica formed a joint venture, called Fabrisonics, which is designing and marketing next-generation ultrasonic additive manufacturing machines. Our recommendation to them, which they have included in numerous proposals and future planning documents, is to develop a robust machine tool with an integrated "tool changer" capable of interchangeably using a "direct write tool" for electronic material deposition, a "material extrusion head" for support materials, a "pick and place tool" to insert pre-fabricated devices, and a sonotrode for material bonding. This integrated machine tool should be combined with a user-friendly Windows-based software interface that utilizes the best practices for process planning developed by us and others who have experimented with automating the production of embedded electronics during additive manufacturing. Research task 4 resulted in four publications [10, 15, 16, 22].

Research Task 5 – A New Computational Model for Ultrasonic Consolidation:

A one-year extension of our research was granted to investigate the development of a dislocation density based crystal plasticity finite element modeling (DDCP-FEM) method for predicting microstructural evolution and bonding in ultrasonic consolidation. This modeling effort was highly successful and led to the development of a completely new modeling infrastructure for ultrasonic consolidation, which has been implemented in the following manner:

1. Large Deformation Quasi-Static Crystal Plasticity Description

The deformation map in space and time is described by the total deformation gradient tensor **F** (Fig. 29). Applying the Kroner-Lee assumption, **F** is decomposed into elastic **Fe** and plastic gradient **Fp** tensors using multiplicative operator theory:

$$\mathbf{F}=\mathbf{F}_e\mathbf{F}_p \qquad \mathbf{(1)}$$

The rotation and stretching of the lattice are taken into account through the elastic deformation gradient **Fe.** The Plastic deformation gradient **Fp** includes constant volume plastic deformation without disturbance of the crystal lattice. Elastic distortion and rigid rotation of the lattice are described by a unique intermediate configuration free of local stresses.

2. Incorporation of non-local dislocation density motivated material models at integration points

The flow response for a given slip system 'α' is given by Equation 2. The slip system 'α' could be a conventional slip system as well as an unconventional slip system, such as for slip in Nickel based superalloys

$$\dot{\gamma}^{\alpha} = \begin{cases} \dot{\gamma}_0^{\alpha} \exp\left[\frac{-Q_{slip}}{K_B T}\left(1 - \frac{|\tau^{\alpha}| - \tau_{pass}^{\alpha}}{\tau_{cut}^{\alpha}}\right)\right] \mathrm{sign}(\tau^{\alpha}) & if|\tau^{\alpha}| \geq \tau_{pass}^{\alpha} \\ 0 & if|\tau^{\alpha}| \leq \tau_{pass}^{\alpha} \end{cases} \tag{2}$$

with the pre-exponential variable $\dot{\gamma}_0^{\alpha}$, which is the upper limit of the shear rate for the case where the Boltzmann factor is equal to 1 in Equation 2.

The pre-exponential variable $\dot{\gamma}_0^{\alpha}$ is defined as

$$\dot{\gamma}_0^{\alpha} = \frac{K_B T}{c_1 c_3 G b^2}\sqrt{\rho_P^{\alpha}} \tag{3}$$

and the passing stress, τ_{pass}^{α} , caused by parallel dislocations is given by

$$\tau_{pass}^{\alpha} = c_1 G b \sqrt{\rho_P^{\alpha}} \tag{4}$$

and the cutting stress, τ_{cut}^{α}, at 0K caused by forest dislocations is formulated as

$$\tau_{cut}^{\alpha} = \frac{Q_{slip}}{c_2 c_3 b^2}\sqrt{\rho_F^{\alpha}} \tag{5}$$

where Q_{slip} is the effective activation energy for dislocation slip.

The incompatibility in plastic deformation gradient and non-local geometrical non-linearity is introduced using ρ_{GND}^{α} which computes the geometrically necessary dislocations required to maintain continuity throughout the material. The evolution law for ρ_{GND}^{α} is

$$\dot{\rho}_{GND}^{\alpha} = \frac{1}{b}\|\nabla_X \times (\dot{\gamma}^{\alpha} F_P^T)\tilde{n}^{\alpha}\| \tag{6}$$

The material hardening at an integration point is both a function of ρ_{GND}^{α} (geometrically necessary dislocation density) and ρ_{SSD}^{α} (statistically stored dislocation density). The evolution laws for ρ_{SSD}^{α} are generally linear in shear rate, as in

$$\dot{\rho}_{SSD}^{\alpha} = c_4\sqrt{\rho_F^{\alpha}}\dot{\gamma}^{\alpha} - c_5\rho_{SSD}^{\alpha}\dot{\gamma}^{\alpha} + c_6 d_{dipole}^{\alpha}\rho_{mobile}^{\alpha}\dot{\gamma}^{\alpha} - c_7\exp\left(-\frac{Q_{bulk}}{K_B T}\right)\frac{|\tau^{\alpha}|}{K_B T}(\rho_{SSD}^{\alpha})^2(\dot{\gamma}^{\alpha})^{c_8} \tag{7}$$

3. Applied Boundary Conditions

The applied boundary conditions in UC are applied normal pressure, vibration frequency & amplitude, sonotrode rotational speed, surface finish of the foils, temperature, and foil material properties.

4. Local and global evolution of volume and surface hardening/softening effects

Friction Effects. Friction and wear play an important role during the sliding of two surfaces under cyclic loading. Friction effects are captured as follows:

$$T_t = \begin{cases} 0 & \text{if } T_t < \mu T_N \\ T_t - \mu T_N & \text{if } T_t \geq \mu T_N \end{cases} \tag{8}$$

where T_t and T_N are shear and normal tractions respectively, and μ is the coefficient of friction at the interface. Also, friction causes a local increase in the stored dislocation content and is incorporated as a linear evolution of ρ^{α}_{SSD} in terms of local normal pressure, p and shear strain rate, $\dot{\gamma}^{\alpha}$ as follows:

$$\dot{\rho}^{\alpha}_{SSD,interface} = F(\dot{\gamma}^{\alpha}, \dot{p}) \tag{9}$$

Thermal Softening Effect. Thermal softening during UC occurs because of frictional heating or due to a heated platen. Frictional heating is a local phenomenon and occurs as a surface effect at the material interface. The temperature increment can be obtained by solving the non-homogenous heat equation, with friction work at the interface being the source heat generation term,

$$T(x,t) = S(t)\emptyset(x) + \int_0^t S(t-s) f(x,s) ds \tag{10}$$

where $S(t)\emptyset(x)$ is the solution to the homogenous heat equation. The homogenous solution at room temperature is 293K, S(t)=1 and $\emptyset(x) = 293K$. For obtaining the temperature increment as a function of space and time, f(x,t) has to be incorporated.

The mathematical description for f(x,t) is

$$f(x,t) = \frac{q_{gen}}{\rho c} \tag{11}$$

where q_{gen} is the modified friction work, which is converted to heat. The quantities ρ and c are density and specific heat per unit volume for the material being consolidated.

5. Global and local solution strategies

The global and local solution strategy for solving the DDCP-FEM mesoscopic-level crystal plasticity constitutive equations are shown in **Table 1**.

Table 1: Solution strategy for DDCP-FEM

Algorithmic Sequence (Newton-Raphson Implicit)
(A) Load steps k=0,1,...,k_{max}
Set $u_0 = u_k, F_{p,0} = F_{p,k}, \rho^{\alpha}_{SSD,0} = \rho^{\alpha}_{SSD,k}, \rho^{\alpha}_{GND,0} = \rho^{\alpha}_{GND,k}$
(B) Iteration from i=0,1,..., i_{max}
(I) Determine $\dot{\gamma}^{\alpha}_i$, $F^i_{p,k}$ and $\rho^{\alpha,i}_{SSD,k}$ with $\rho^{\alpha,i}_{GND,k} = \rho^{\alpha}_{GND,k}$ via local iteration at integration points (B-bar integration scheme)
(II) Determine $Q(u^i_k, \lambda_k), K_T(u^i_k)$ and solve $K_T(u^i_k)\Delta u = -Q(u^i_k, \lambda_k)$
(III) Displacement increment: $u^{i+1}_k = u_0 + \Delta u^{i+1}_k$
(IV) Determine curl on all nodes calculate $\rho^{\alpha,i+1}_{GND,k} = \rho^{\alpha}_{GND,0} + \Delta\rho^{\alpha,i+1}_{GND,k}$ on all integration points
(V) Check (B) Local convergence: GND, SSD, and shear strain rate on each slip system (A) Global convergence for $\lVert Q(u^i_k, \lambda_k) \rVert$
(VI) If (V) is true then: $u_{k+1} = u^{i+1}_k, F_{p,k+1} = F^{i+1}_{p,k}, \rho^{\alpha}_{SSD,k+1} = \rho^{\alpha,i+1}_{SSD,k}, \rho^{\alpha}_{GND,k+1} = \rho^{\alpha,i+1}_{GND,k}$ else *goto* (I)

This approach to modeling of UC has been highly successful and accurately predicts the experimentally observed responses of UC to changes in vibration amplitude, applied normal force, surface roughness changes, material changes, fiber embedment, and other phenomena. This research has resulted in four publications [14, 19, 20, 25] and a follow-on proposal to ONR's Cyber-enabled Manufacturing Systems program; which resulted in the funding of its continued development and application to closed-loop control of UC.

Potential for Future Naval Impact:

Through the successful completion of this project, we have illustrated that the combination of UC, DW and MD enables spatial composition control and complex internal geometries – including embedded electronics, thermal management devices, reinforcement fibers and other features – along with the resolution, scalability, repeatability, dimensional accuracy and surface finish of milling, all within an integrated DDM workcell. It is our belief that future ultrasonic consolidation machines will be built to incorporate the best practices developed through this project, resulting in the commercial availability of machines for the Navy and others. These machines will enable lighter, more functional and more capable products to be designed and fabricated for Naval use and in Naval system.

Engineering Implications & Broader Impacts

Many engineered products include a combination of computational, electrical, structural and thermal needs within miniaturized and ruggedized products. In order to meet the needs of increasingly complex systems within constrained environments, it becomes necessary to be able to spatially control the placement of electronics, wiring, thermal management features, and materials within geometrically complex structures that exhibit specific macroscopic and microscopic properties. By combining UC, DW and MD, we have illustrated the ability to fabricate complex systems directly from digital data in a more optimized manner.

As a result of the involvement of 2 faculty, 4 post-doctoral scholars, 3 Ph.D. students, 3 M.S. students, 6 undergraduate students and additional staff in this project, this project was well-integrated with both the research and educational missions of the two universities involved. Additionally, 2 corporations (Solidica and nScrypt) were involved in this work and are seeking to commercialize and make available to the Navy and to industry successfully developed technology improvements.

This work resulted in 25 publications (attached to this report).

The researchers involved in this work received numerous honors and awards during its duration (due in part or in total to the success of the funded efforts). These honors included:

- 2011 Participant in the National Academy of Engineering's Frontiers of Engineering Symposium; a select group of emerging engineering leaders (ages 30-45) from industry, academe, and government labs which discuss pioneering technical work and leading edge research
- 2011 Outstanding Paper Award, *VRAP 2011*, for paper "Some Studies on Dislocation Density based Finite Element Modeling of Ultrasonic Consolidation."
- 2010 Robert J. Painter Memorial Award from the Standards Engineering Society and ASTM International, in recognition of outstanding service to additive manufacturing standards development (w.r.t. ASTM F42).
- SFF Symposium Outstanding Paper 2009 for our portfolio of contributions to that year's conference.
- 2009 Outstanding Service Award, Emerald LiteratiNetwork, recognizing my work as Regional Editor for the Americas for the *Rapid Prototyping Journal* from 2004-2009.

In addition, the notoriety gained in part by the success of this program enabled Dr. Stucker to act in the following international service roles:

- Chairman, ASTM F-42 Committee on Additive Manufacturing Technologies, 2009-present

- Information Science and Technology (ISAT) advisory committee member for the Defense Advanced Research Projects Agency (DARPA), 2011-present
- National Advisory Board, Technician Education in Additive Manufacturing program, 2011-2014
- Editorial Board, *Rapid Prototyping Journal*, 2004-present.
- Co-Chairman, DARPA/ISAT "Future Manufacturing" Study Group, 2010-2011.
- Rapid Technologies & Additive Manufacturing Steering Committee, Society of Manufacturing Engineers, 2007-2011.
- "Direct Digital Manufacturing" Technical Group, Society of Manufacturing Engineers, 2004-2011.
- Co-Editor, Solid Freeform Fabrication Special Issue of the *Rapid Prototyping Journal*, 2010.
- Editor for North & South America, *Rapid Prototyping Journal*, 2004-2009
- Co-author of the *Additive Manufacturing Roadmap* co-funded by NSF and ONR, 2009.

This work involved the following international collaborations:

- Loughborough University, UK
    - focusing on ultrasonic consolidation
- Andong National University, South Korea
    - focusing on multiple material process planning, and metal processing using fused deposition modeling technology
- VTT Technical Research Center, Finland
    - focusing on direct write technologies and applications of direct digital manufacturing

We would like to express our gratitude to the Office of Naval Research for funding this grant and giving us the opportunity to achieve these results.

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22. "Integration of Ultrasonic Consolidation and Direct-Write to Fabricate an Embedded Electrical System within a Metallic Enclosure," Ludwing A. Hernandez, M.S. thesis, 2009.
23. "Support Materials Development and Integration for Ultrasonic Consolidation," Matthew L. Swank, M.S. thesis, 2009.
24. "A Study on Stainless Steel 316L Annealed Ultrasonic Consolidation and Linear Welding Density Estimation," Raelvim Gonzalez, M.S. these, 2010.
25. "Dislocation Density-based Finite Element Modeling of Ultrasonic Consolidation," Deepankar Pal, Ph.D. thesis, 2011.

List Current/Ongoing U.S. & International Collaborations/Partnerships:

- Loughborough University, UK: focusing on ultrasonic consolidation
- Andong National University, South Korea: focusing on multiple material process planning, and metal processing using fused deposition modeling technology
- VTT Technical Research Center, Finland: focusing on direct write technologies and applications of direct digital manufacturing

Research Outcomes:

Major accomplishments (FY07-FY09) (limit to 3)

- Integrated FDM and DW technology with UC technology.
- Developed new support materials and support material strategy for UC technology.
- Developed a more fundamental understanding of bond formation in ultrasonic consolidation.

Transition information, commercialization, or industrial interest

- Technology Funding and Sharing Agreement, Solidica Inc., 2008: between Utah State University and Solidica, Inc.

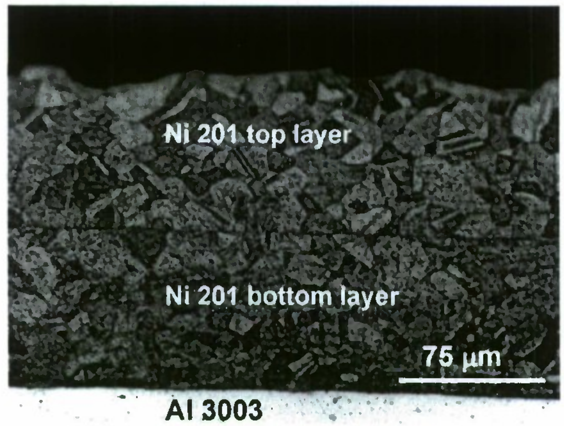


Fig.1. Optical microstructure of an Al 3003-Ni 201 multi-material deposit. Ni 201 bonded well to itself and to the Al 3003 substrate.

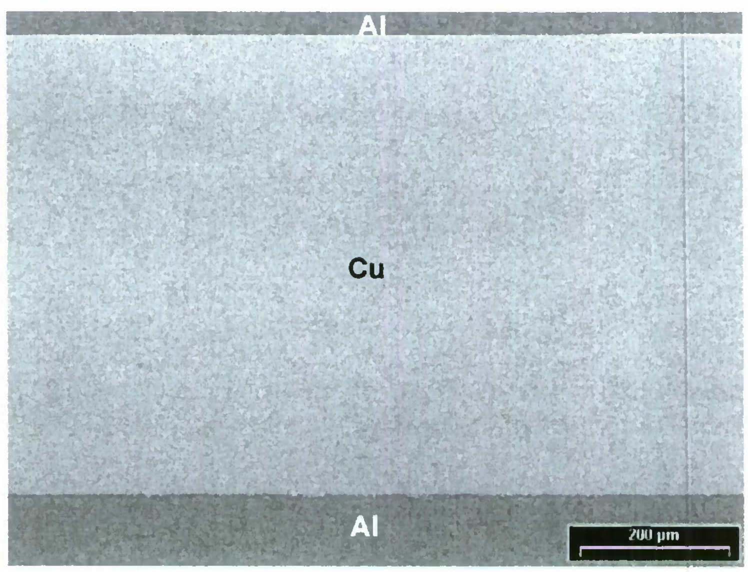


Fig.2. SEM microstructure of an Al-Cu multi-material deposit with six layers of Cu. Cu bonded very well to itself and to the Al 3003.

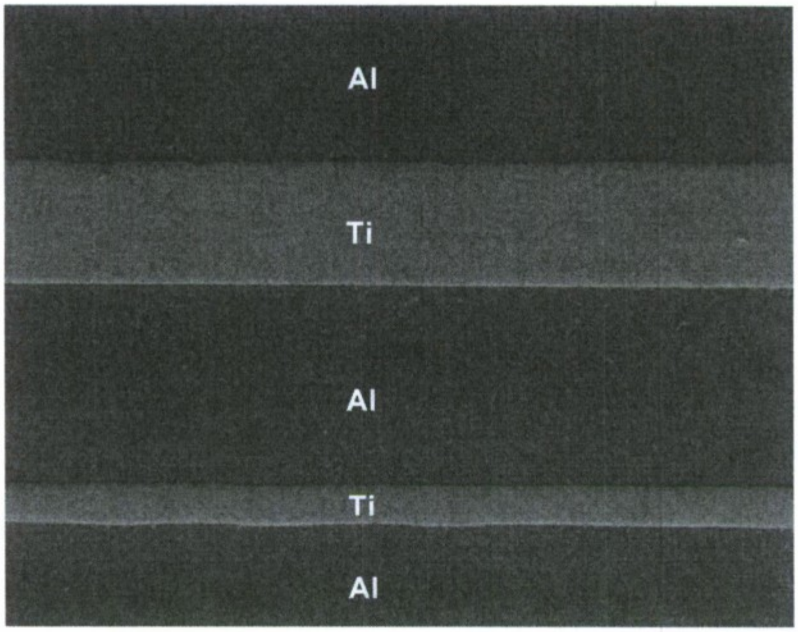


Fig.3. SEM microstructure of an Al-Ti multi-material deposit.

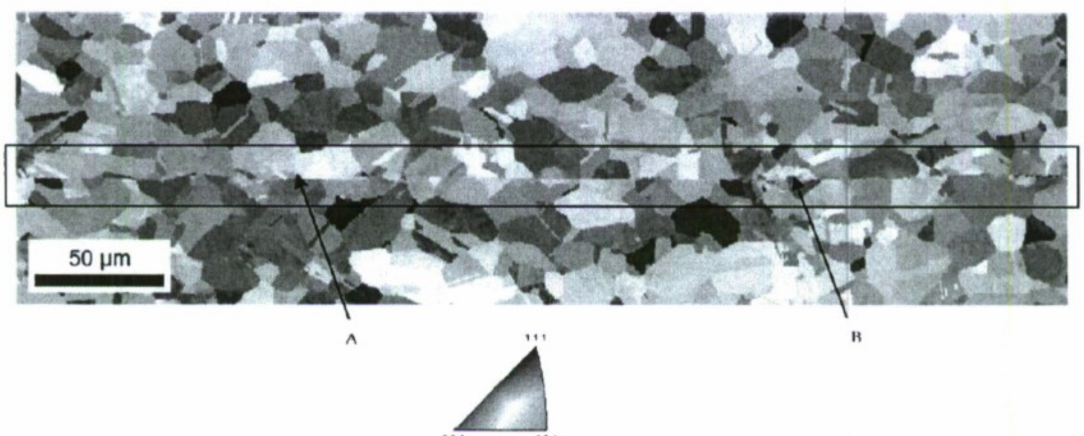


Fig.4. An orientation imaging microscopy image of several inverse pole figures of contiguous areas of a Ni 201 UC weld zone stitched together. The grains in the image are color coded to reflect their orientation. The line across the center of the image (located inside the rectangular box) defines the location of the UC weld boundary.

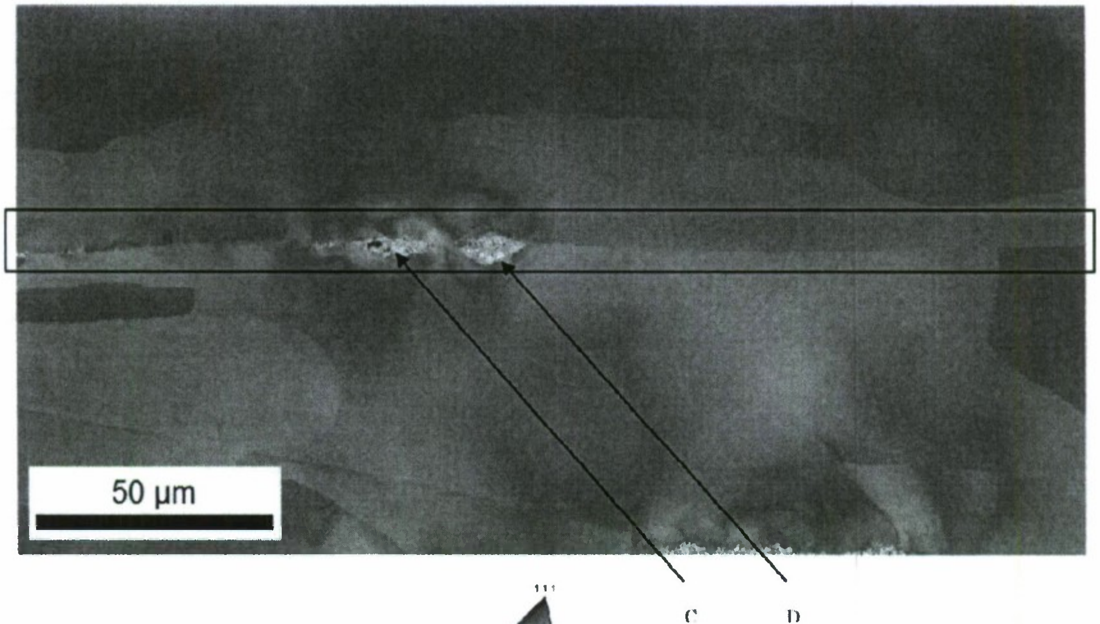
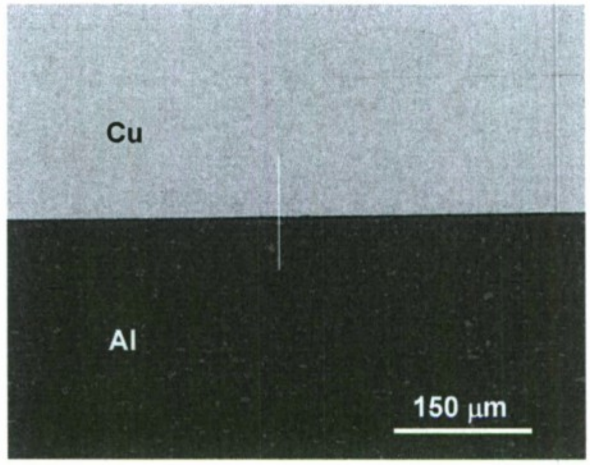
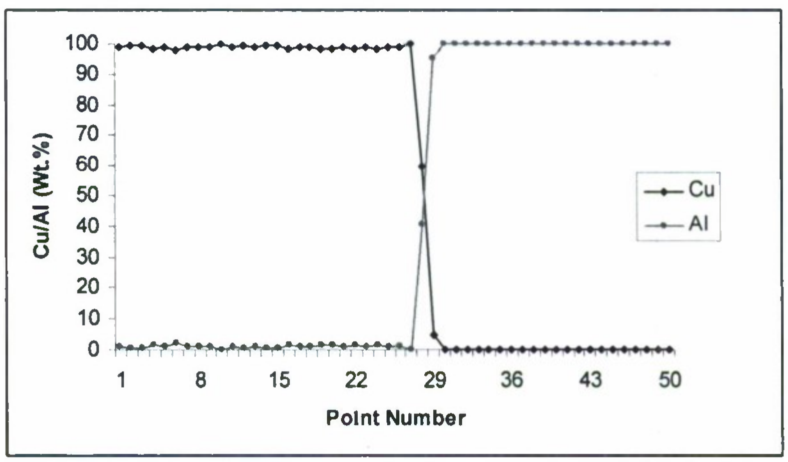


Fig.5. An image of several inverse pole figures of contiguous areas of a Cu 10100 UC weld zone stitched together. The grains in the image are color coded to reflect their orientation. (Note their strong {100} orientation.) The line across the center of the image (located inside the rectangular box) defines the location of the UC weld boundary. The multicolored regions on the weld boundary indicate locations where the oxide surface layer has not been fully eliminated.

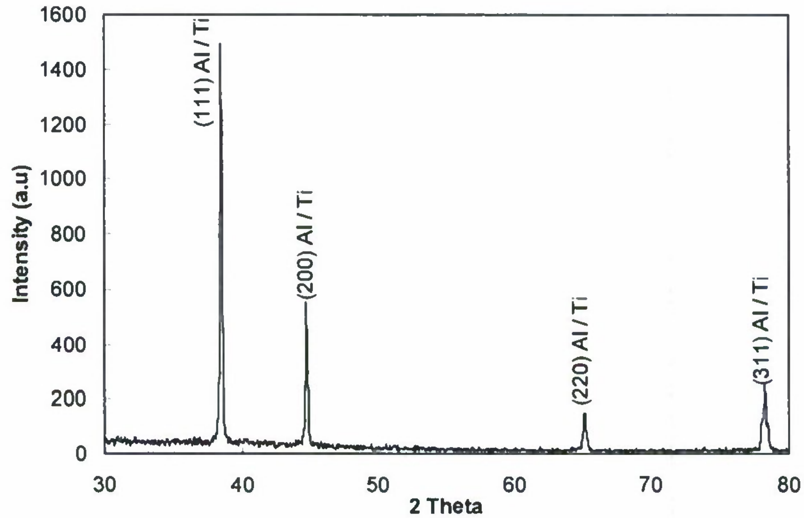


(a)

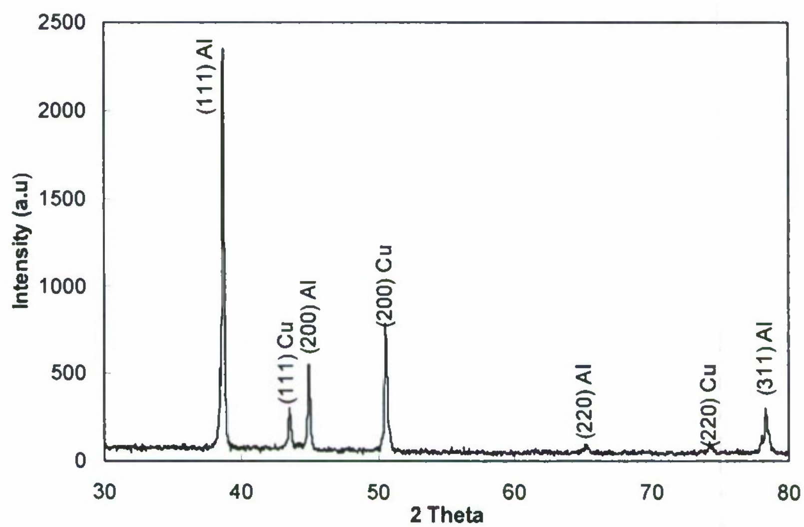


(b)

Fig.6. (a) BSE image, Al-Cu interface (EDS scan line superimposed). (b) EDS data (50 points, 1.5 μm spot spacing, from Cu side to Al side).



(a)



(b)

Fig.7. X-ray diffraction patterns showing absence of intermetallic formation when bonding dissimilar materials using UC. (a) Al-Ti, (b) Al-Cu.

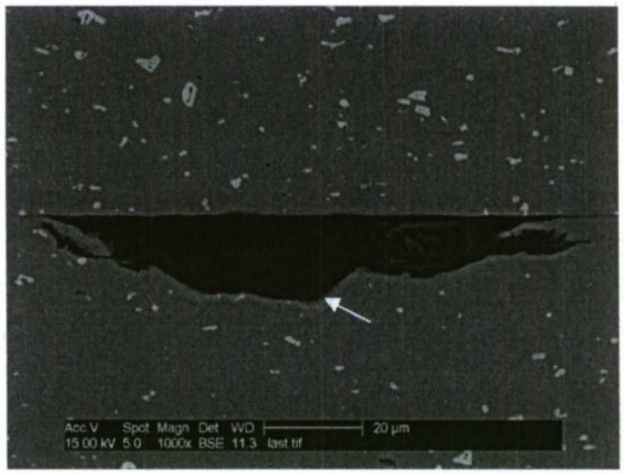
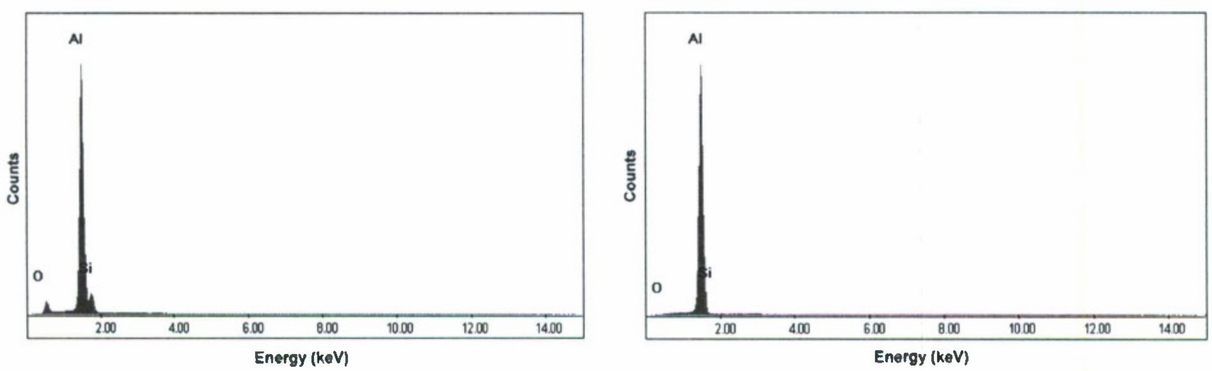


Fig.8. BSE image of a defect/unbonded region in ultrasonically consolidated Al 3003. Note the thin layer with a different contrast along the defect surfaces (arrow).



(a) (b)

Fig.9. (a) EDS spectra showing a distinct oxygen peak in the thin layer with a different contrast. (b) The oxygen peak is absent in the regions adjacent to, but outside the thin layer.

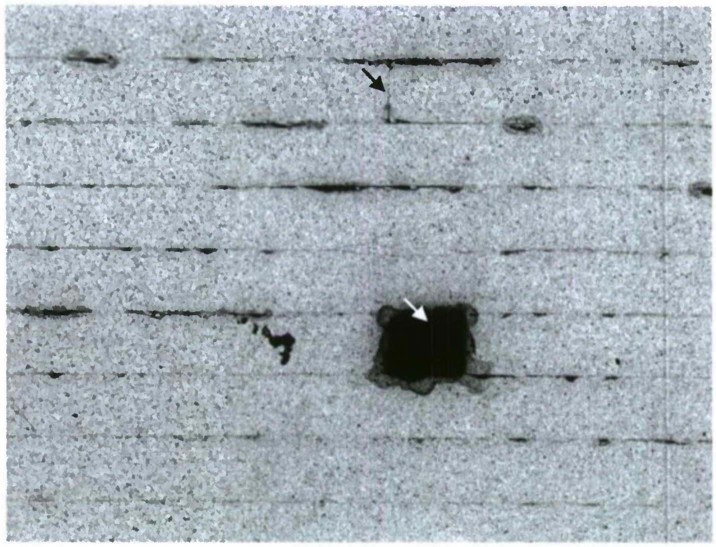


Fig.10. Microstructure of an Al 3003 UC sample made using the machine default overlap setting (0.9411 inch). A few foil junctions were tight (black arrow), but many of them showed large physical discontinuities (white arrow).

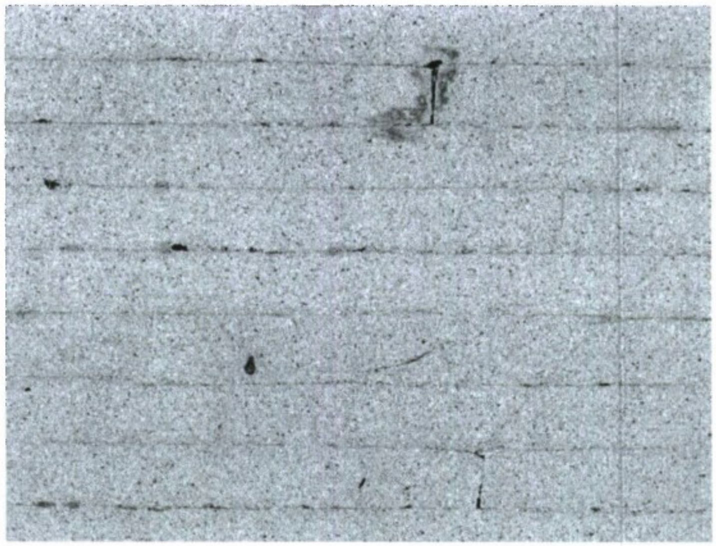


Fig.11. Microstructure of an Al 3003 UC sample made using a foil width setting of 0.9375 inch. The sample is free from large physical discontinuities at foil junctions.

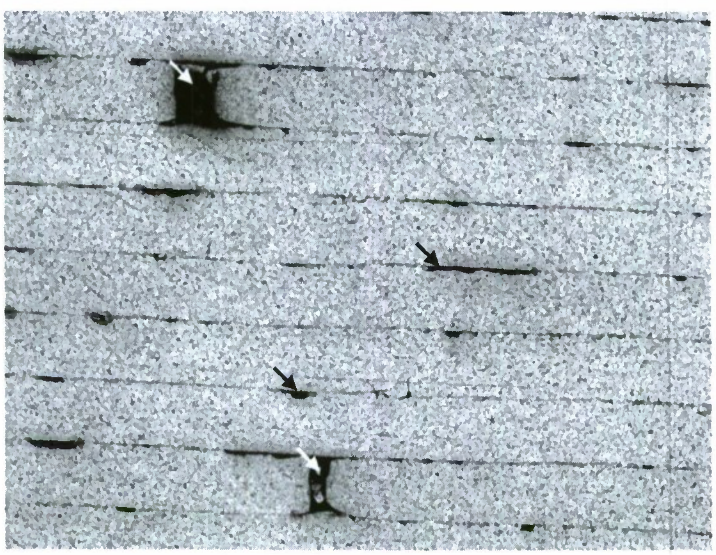


Fig.12. Microstructure of an Al 3003 UC sample made using the default foil width setting of 0.9411 inch. White arrows show defects at foil junctions. Black arrows show unbonded regions along layer interfaces.

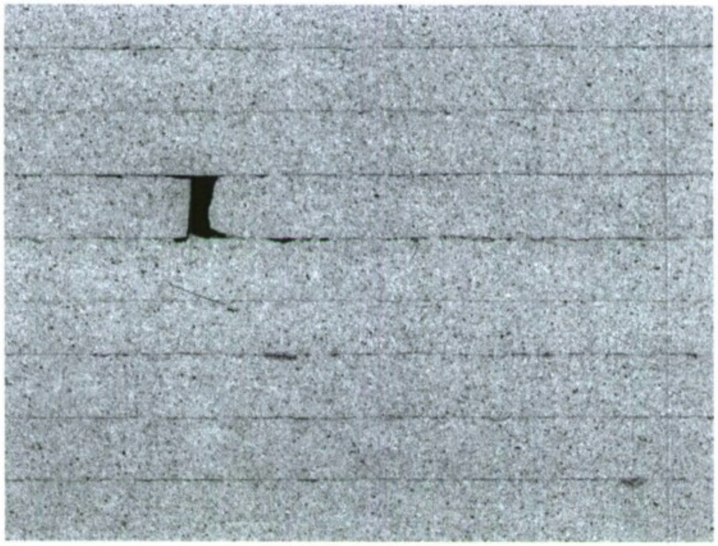


Fig.13. Microstructure of an Al 3003 UC sample made using the default foil width setting after heat treatment (400°C, 90 minutes). Most of the unbonded regions originally present along layer interfaces were eliminated (compare with Fig. 13). Only large defects that were originally present at foil junctions persisted after heat treatment.

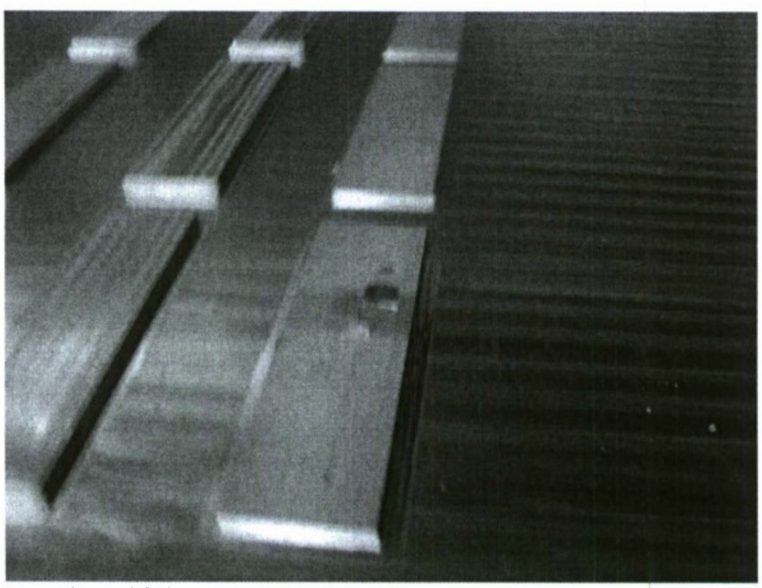


Fig. 14. SS316L deposits which were subsequently cut, polished and scanned to determine linear weld density.

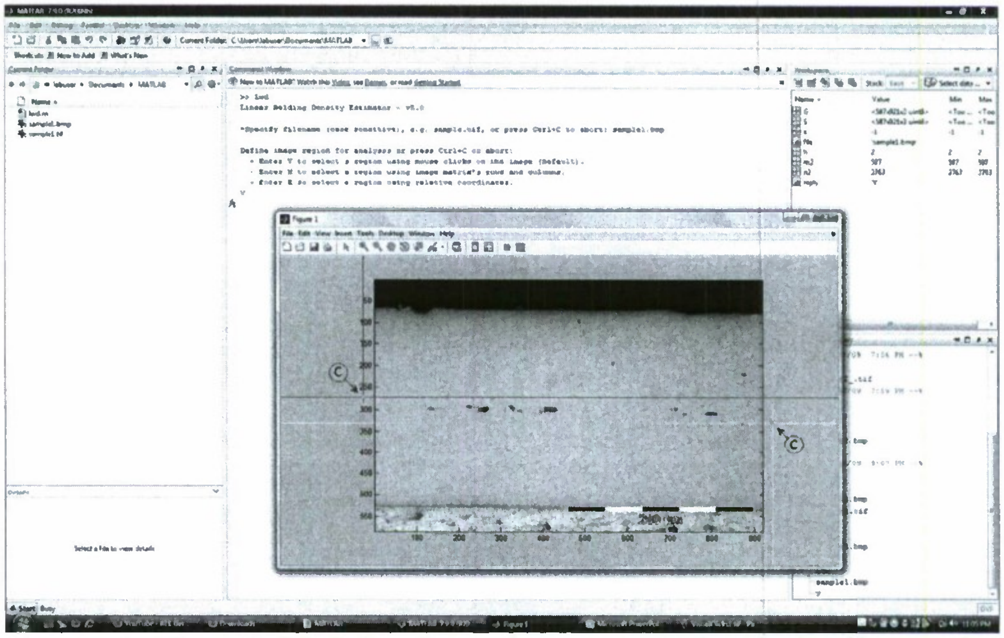


Fig 15. Screen shot from the MatLab script used to automatically calculate linear weld density.

Fig. 16. Aluminum rib in channel plate before being filled with support materials.

Fig. 17. Plate with candidate support materials.

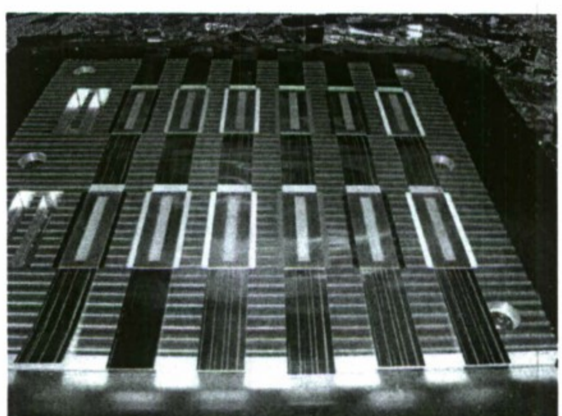


Fig. 18. Welded tapes across the supported channels and ribs.

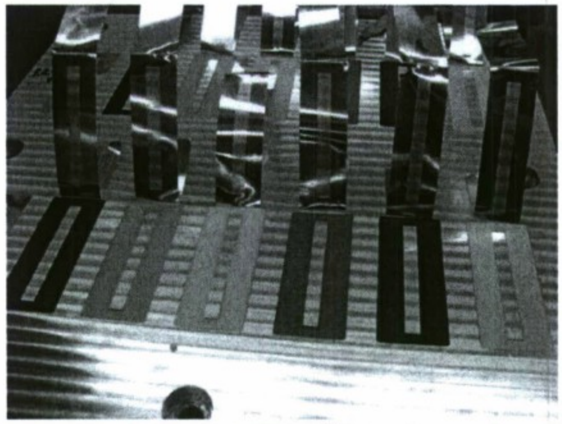


Fig. 19. Tapes after being "peeled off" to observe bonding quality.

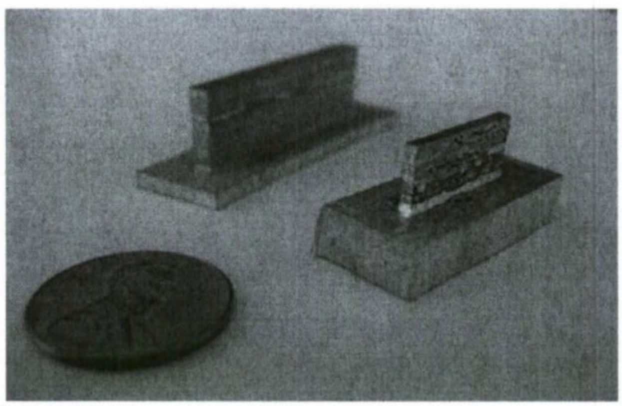


Fig. 20. Freestanding ribs taller than possible without support materials

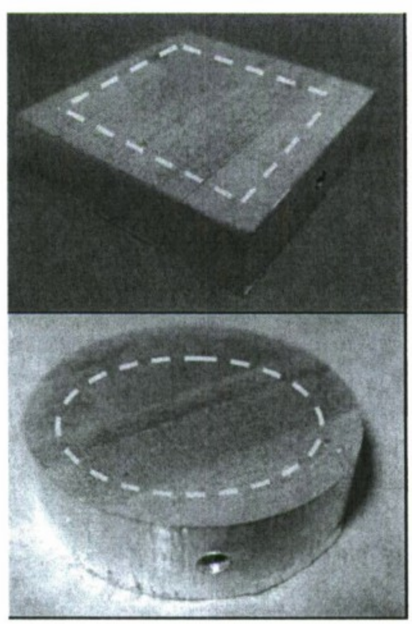


Fig. 21. Entrapped enclosed cavities (marked by dotted yellow lines) covered by additional layers of material

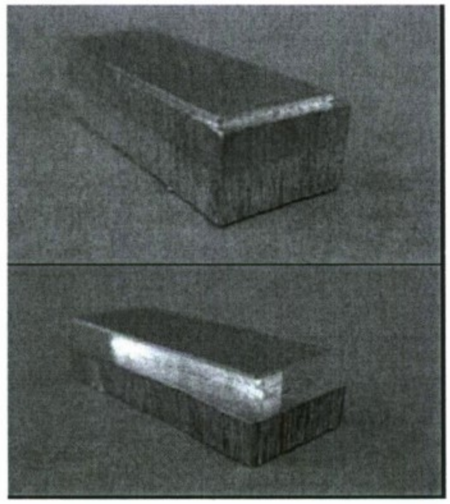


Fig. 22. Overhanging Cu on Al rib structure made possible using a support material (top) that was subsequently removed (bottom)

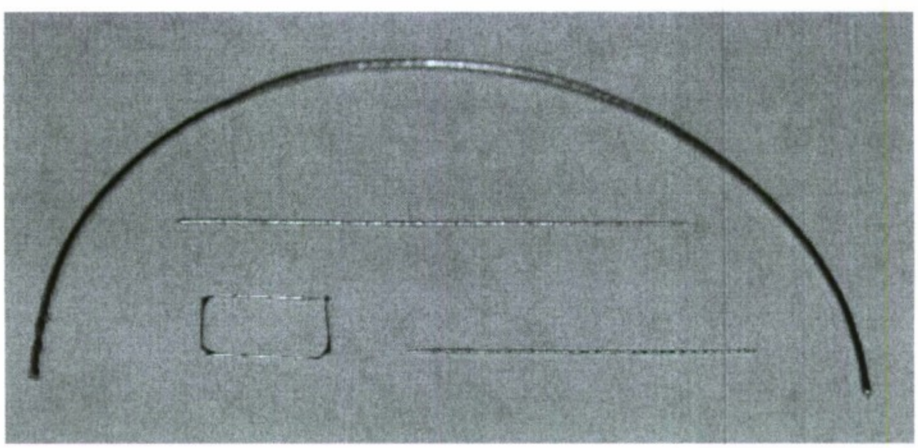


Fig. 23. Simple multi-layer structures made extruded from metal filaments fed into an FDM head.

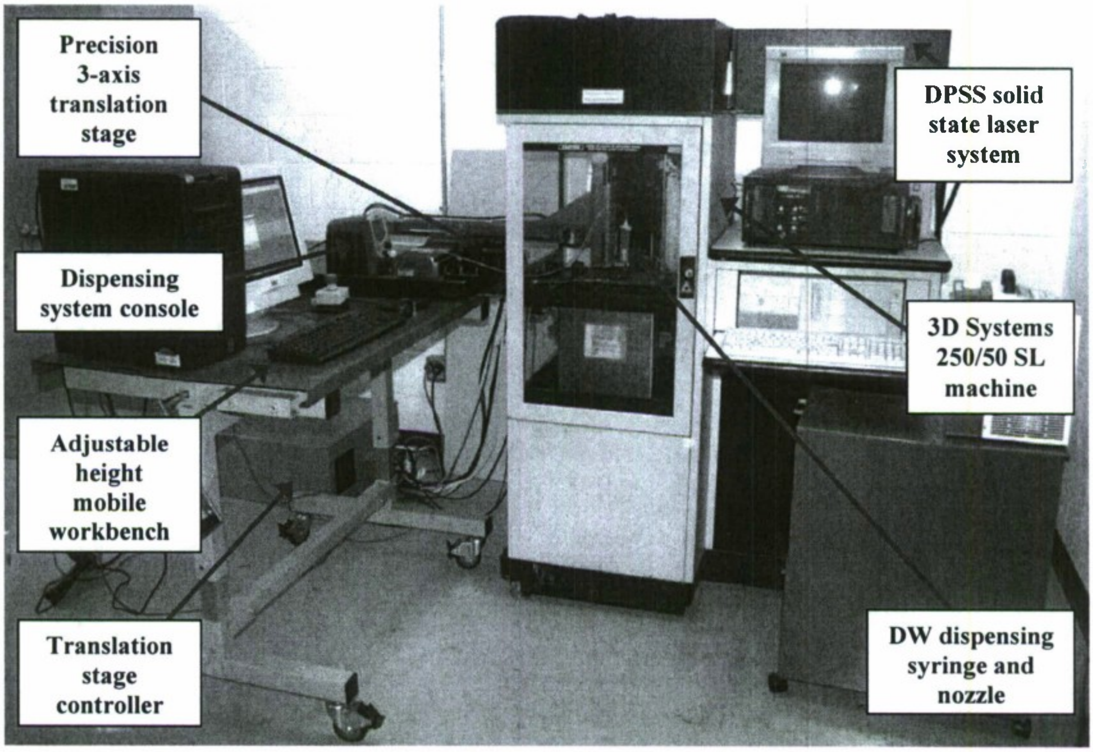
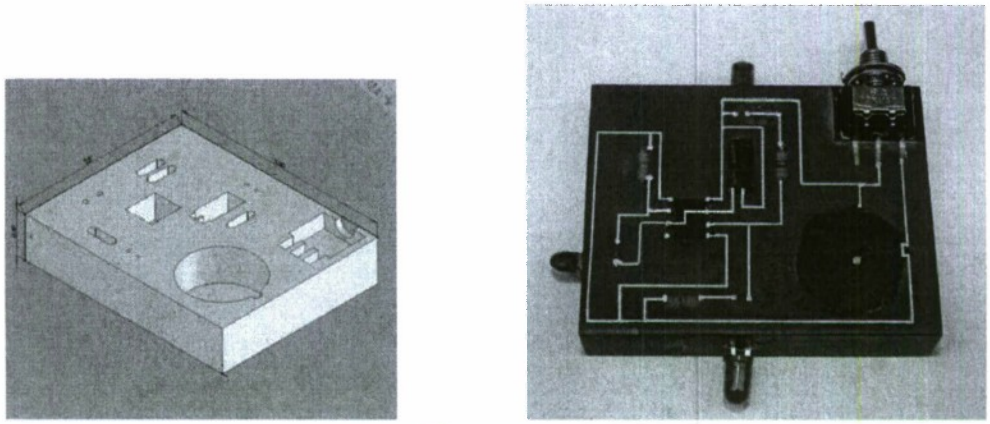
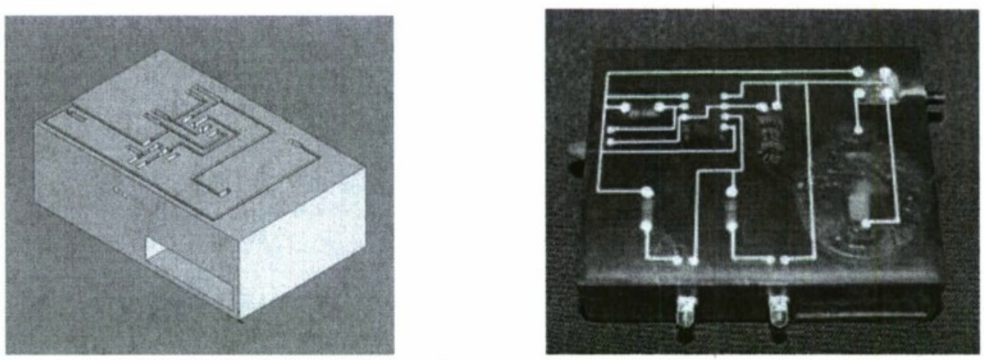


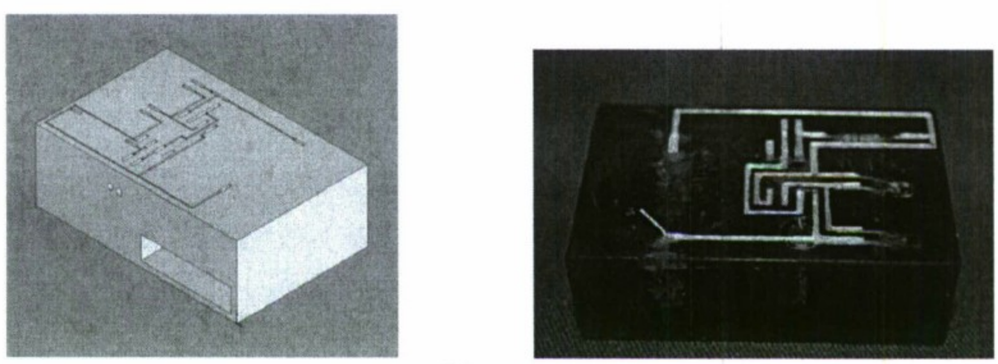
Fig. 24. The integrated SL/DW machine setup.



(a)

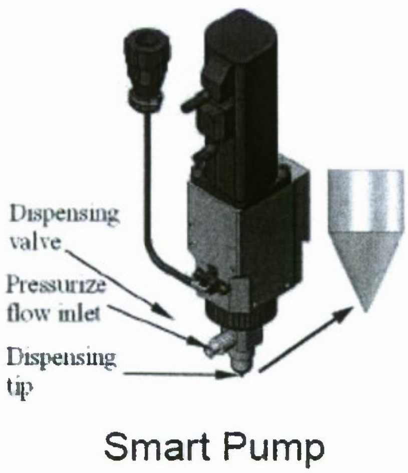


(b)



(c)

Fig. 25. Evolution (three generations) of LM555 temperature circuit with increasing use of vertical placement of components using the integrated SL/DW setup



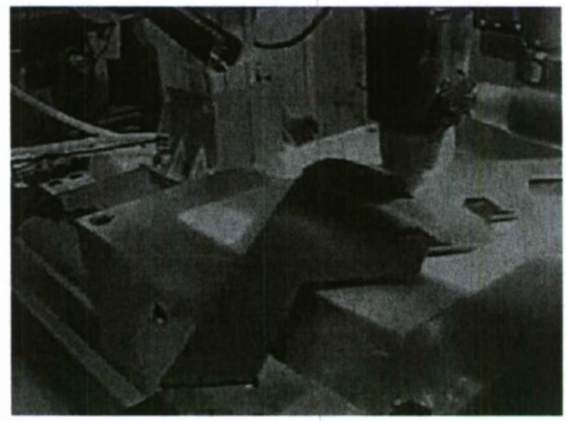


Fig. 26. The nScrypt direct write "Smart Pump" system (www.nscryptinc.com)

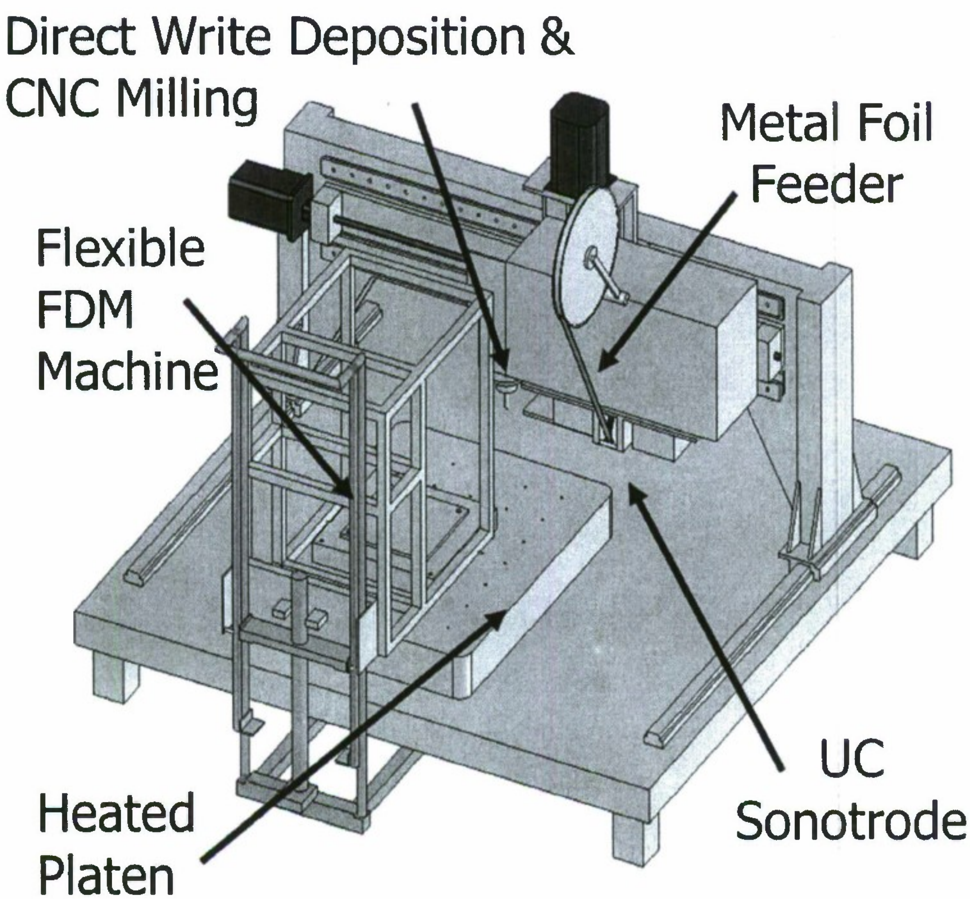


Fig. 27. Schematic of the Integrated DDM workcell

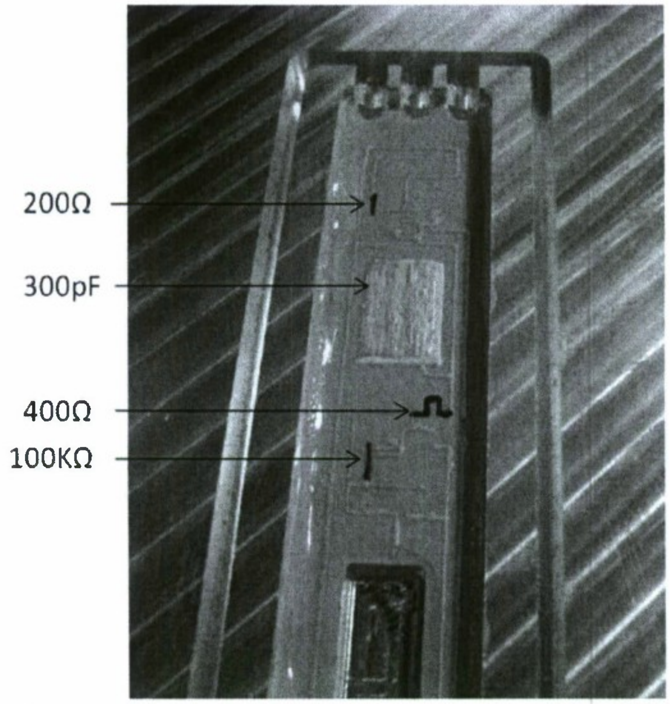


Fig. 28. Embedded circuitry created using the combined UC/DW/MD workcell

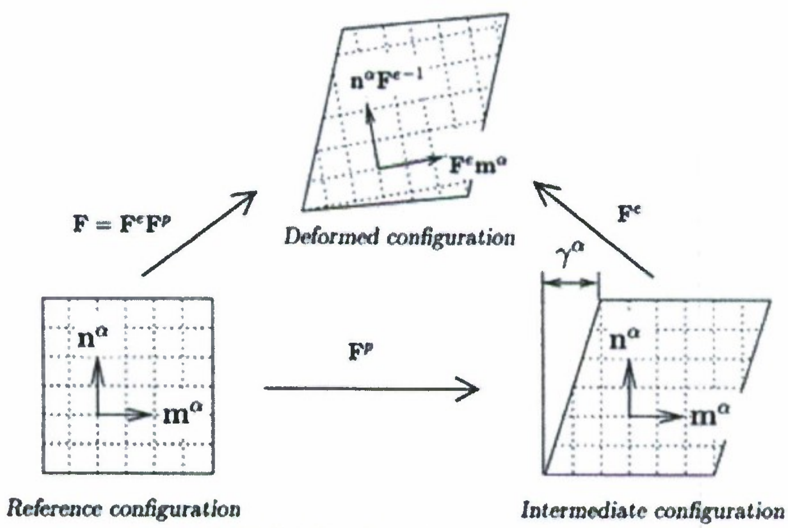


Fig. 29 Multiplicative decomposition of the total deformation gradient, **F=FeFp**.

UtahState University
OFFICE OF RESEARCH AND GRADUATE STUDIES

Sponsored Programs

February 28, 2012
Refer to: scb/070185

Defense Technical Information Center
8725 John J. Kingman Road, Ste 0944
Fort Belvoir, VA 22060-6218

Subject: N00014-07-1-0633 Final Report, w/ SF 298

Defense Technical Information Center:

Utah State University (USU) is pleased to return one signed copy of the referenced documents.

We appreciate your interest in using the resources of USU and appreciate the opportunity to work together on this effort. Please feel free to direct questions of a technical nature or regarding the Statement of Work to Dr. Brent Stucker at brent.stucker@louisville.edu. Questions of a contractual or administrative nature should be directed to the undersigned at 435-797-1661 or Corey.Burger@usu.edu.

Sincerely,

S. Corey Burger
Contract Administrator