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Application of Advanced Laser Consolidation Process for the Manufacturing of Complex FSP Shells

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Abstract

The Integrated Manufacturing Technologies Institute (IMTI) of NRC has developed a novel process called "Free-Form Laser Consolidation" that produces functional net-shape components layer by layer directly from CAD models by using a laser beam to melt and re-solidify the injected powder (or wire). As opposed to conventional machining processes, this computer-aided manufacturing (CAM) technology can build complete parts or features on an existing component by adding instead of removing material. IMTI has investigated laser consolidation of Fe-, Ni- and Co-base alloys, and the work is underway on Ti-alloys. Laser consolidated (LC) IN-625 is metallurgically sound, free of cracks or porosity. The "as-consolidated" IN-625 samples has surface finishes of the order of 1~2 •m (Ra) and dimensional accuracy of around 0.05 mm. The tensile properties of the laser-consolidated IN-625 alloy are comparable to the respective wrought materials. The microstructure of the laser-consolidated samples is similar to the rapidly solidified materials. Laser consolidation is a promising process for manufacturing functional net-shape components.

The folded shell projector (FSP) is a compact flextensional sound source being developed at DREA for low frequency sonar applications including active towed arrays and sonobuoys. The design radiates from a thin walled cylindrical shell with superimposed corrugations. The prototype was built by electroforming, followed by NC machining. This process was expensive and time-consuming, and offered limited choices for the shell material.

An investigation of the laser consolidation process for manufacturing the FSP shell was completed in FY 99/00. Advances in laser consolidation achieved by IMTI permit the free-form production of the FSP shell directly from a CAD file delivered over the Internet. Four shells have been built of IN-625 alloy to validate the process, and assembled into FSPs. The calibration results reveal that the laser consolidated FSPs show substantial improvements over the electroformed prototype. The investigation included changing the design of the shell during the program, proving that rapid design evolutions are readily accommodated since no hard tooling is required. The LC IN-625 shells have wall thickness typically 0.8 mm. The process parameters have been optimized for high accuracy and surface finish, with wall thickness tolerances in most sections of less than 0 02 mm.

Laser consolidation offers designers the possibility that soon they will be able to "print" functional prototypes directly from their computers. Being able to form complex components whose composition is changed as the part is being built up, represents a significant future opportunity for transducer designers. A key implication for defence manufacturing is that small production runs of thin wall superalloy parts will no longer have tooling as the main cost driver.

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Advanced Laser Consolidation Process for Manufacturing Complex FSP Shells

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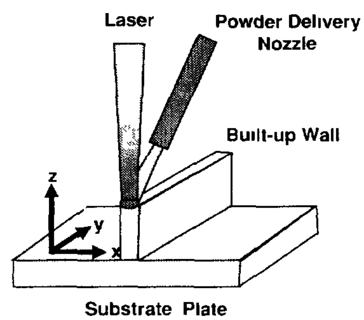
Outline:

- Introduction
  - process description, advantages, current state of the technology
- Functional Properties of LC Materials
  - accuracy, finish, strength, microstructure, etc.
- Manufacturing of FSP shells by Laser Consolidation
  - shell designs, data transfer, dimensional inspection, sensor assembling & testing
- Other Potential Applications of the Technology
- Implications for Defence
- Conclusions

Laser Consolidation:

- A novel process that can produce a net-shape functional part layer by layer directly from a CAD model by using a laser beam to melt the injected powder (or wire) and re-solidifying it on the previous pass
- As an alternative to the conventional machining process, this computer-aided manufacturing (CAM) process can build complete parts or features on an existing part by adding instead of removing material.



Laser Consolidation Process

Advantages of Laser Consolidation Process:

- The laser consolidation (LC) process produces metallurgically sound parts without porosity or cracks.
- Due to the rapid solidification inherent to the process, excellent material properties are obtained.
- Laser consolidation does not require moulds or dies, and has the flexibility to quickly change (if required) the shape and dimension of the part just before manufacturing. As a result, the lead time to produce parts could be reduced significantly.

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IMTI's Laser Consolidation - Dimensional Accuracy

Hollow Square Tube:

Wall Thickness - 0 775 ± 0 025 mm
Wall Height - 20 785 ± 0 038 mm
Parallelness - 0 048 mm (opposite walls)
Squareness - 90 00° ± 0 02°
Perpendicularity - 89 92° ± 0 15°

Cylinder:

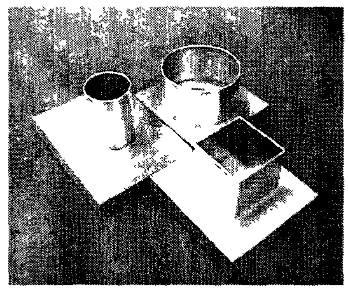
Cylinder ID - 37.041 ± 0.048 mm
Cylinder OD - 38 631 ± 0 033 mm
Height - 20 790 ± 0 069 mm
Circularity - ± 0 043 mm (ID & OD)

Conical Sample with 10° angle:

Angle - 9 93° ± 0 07°
Circularity - ± 0 043 mm (ID & OD)

Note: Samples were made from IN-625 alloy powder All values are averages of at least 6 measurements.

- **LC IN-625 samples showed excellent dimensional accuracy and surface finish.**



Surface Finish - 1-2 μm Ra

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Laser Consolidation - Mechanical Properties

- **The LC IN-625 material is stronger than the respective cast materials and comparable to wrought materials.**

Materials		$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	δ (%)
LC IN-625	Horizontal	518±9	797±8	31±2
	Vertical	477±10	744±20	48±1
Cast IN-625		350	710	48
Wrought IN-625		490	855	50

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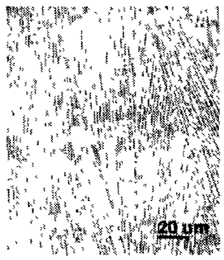
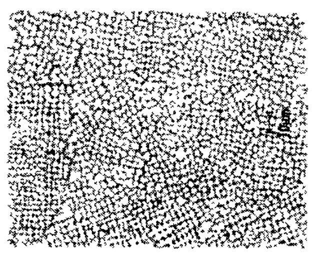
Laser Consolidation - Microstructure of IN-625 Alloy

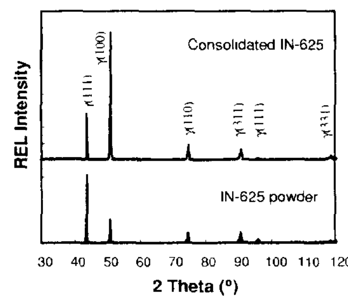
- LC IN-625 alloy shows a directionally solidified microstructure: very fine γ phase columnar dendrites growing almost parallel to the direction of build



Parallel to the build direction



Perpendicular to the build direction



Comparison of XRD pattern of laser consolidated IN625 with the powder

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Laser Consolidation - Stellite 6 Alloy

- **The LC Stellite 6 is harder, stronger and even more ductile than the respective cast or powder metallurgy material.**

Process	Condition	σ_{UTS} (MPa)	σ_y (MPa)	δ (%)	HRc
Laser Consolidation	As-consolidated (Vertical)	1245	751	3.1	58
	As-consolidated (Horizontal)	1362	1023	3.2	59
Sand Casting	Stress-relieved	834	541	1 - 2	46
Investment Casting	As-cast	793	662	3	37
Powder Metallurgy	-	896	-	<1	40

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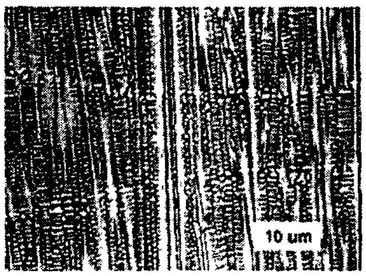
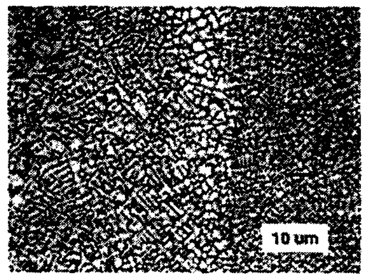
Laser Consolidation - Stellite 6 Alloy

- The exceptional mechanical properties of the LC Stellite 6 can be attributed to its much finer dendrite arm spacing (DAS) (1 - 4 μm) compared to the conventional cast Stellite 6 material (50 - 500 μm).



Vertical direction



Horizontal direction

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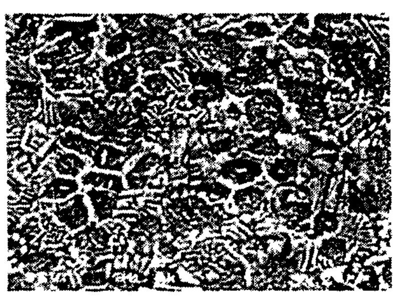
Laser Consolidation - CPM-9V Tool Steel



Microstructure, x 6,500

LC CPM-9V Tool Steel:

- Composition: 1.80%C, 5.35%Cr, 9.26% V, 1.24%Mo, 0.50%Mn
- Hardness (as-consolidated condition): ~ Rc.50.
- Average yield strength: 820 MPa.
- Average tensile strength: 1320 MPa.

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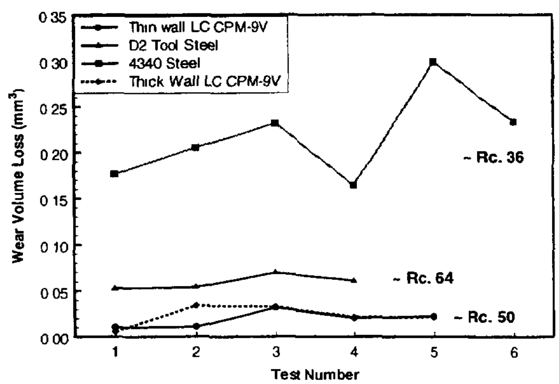
Laser Consolidation - CPM-9V Tool Steel



- **Under test conditions, the wear resistance of LC CPM-9V is almost triple compared to heat treated D2 and almost one order of magnitude better compared to 4340 steel.**

Pin-on-disk wear test against 1/4" WC ball under 500g load at 0.28m/s for 8000m.

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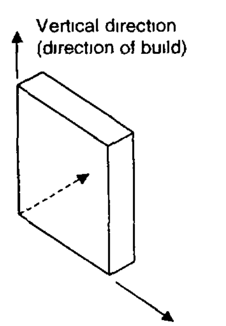
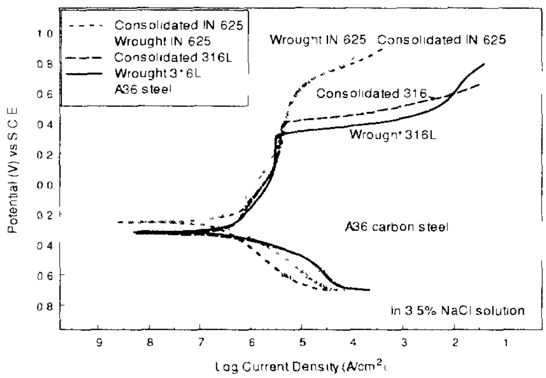
Laser Consolidation - Residual Stresses

- The LC IN-625 material exhibits significant magnitude of residual compressive stresses along the horizontal direction, while the residual compressive stresses along the vertical direction is relatively low.

Method	Residual Stress (MPa)	
	Horizontal Direction	Vertical Direction
X-Ray Diffraction	-412	-147
Hole-Drilling	-349	-42



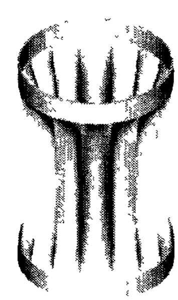
Laser Consolidation - Corrosion Resistance



- LC IN-625 and 316L show corrosion resistance similar to the respective wrought materials in 3.5 % NaCl solution

Folded Shell Projector (FSP)

- The folded shell projector is a compact flextensional sound source being developed at DREA for low frequency sonar applications, including active towed arrays and sonobuoys.
- The FSP radiates sound from a thin walled cylindrical shell with superimposed corrugations
- The initial prototype of the shell was built by electroforming followed by NC machining - expensive, time-consuming, and limited material selection.
- The laser consolidation was identified as the most promising method to manufacture functional prototype shells for refining design & testing



US Patent 5,805,529

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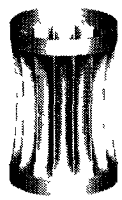
Manufacturing of FSP Shells



Design #1

LC IN-625 Shell

- The manufacturing of the FSP shells was performed at NRC/IMTI (London, Ontario) based on the CAD design from DREA (Dartmouth, Nova Scotia) delivered over the Internet.
- Two shells of design #1 were built by using laser consolidation of IN-625 powder.
- NDT inspection reveals that both shells are metallurgically sound, no porosity or cracks.

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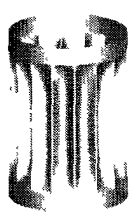
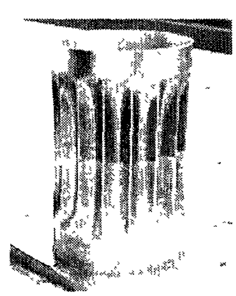
Change of Design through Internet



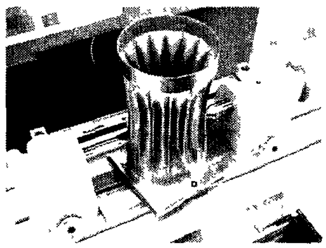
Design #2



LC IN-625 Shell

- Change of shell design through Internet - the rapid design evolutions are readily accommodated by the laser consolidation process since no hard tooling is required
- Two LC IN-625 shells from design #2 are also metallurgically sound, no porosity or cracks.

Dimensional Inspection - Shell Design #1

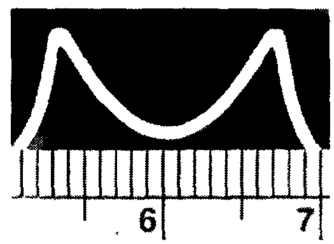


Wall Thickness - Micrometer

Position	0°	45°	90°	135°	Average
Thickness (mm)	0 826	0 82	0 823	0 818	0 822±0 003
Position	**180°**	**225°**	**270°**	**315°**	
Thickness (mm)	0 826	0 818	0 823	0 818	

Exterior Fold Crest - Profile Projector

- Four exterior fold crests, 90 degrees apart, was measure at 9 elevations
- The average deviations of exterior fold crest to the CAD design were 0.458, 0 409, 0 485 and 0.467 mm along 0°, 90°, 180° and 270° respectively



Dimensional Inspection - Design #2

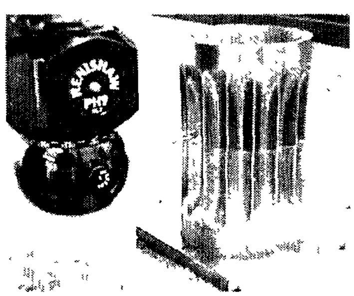


Table 5 Summary of fold profile deviation (shell # 00062

Elevation	Average abs. Deviation (mm)	Minimum Deviation (mm)	Maximum Deviation (mm)
EE	0 208	0 12[illegible]	0 303
DD	0 266	0 044	0 443
CC	0 198	0 065	0 339
BB	0 224	0 070	0 388
AA	0 25[illegible]	0 067	0 441
B	0 178	0 134	0 325
C	0 153	0 099	0 259
D	0 071	0 144	0 10[illegible]
E	0 197	0 288	0 052
Overall	**0 194**	**-0 288**	**0 443**

Exterior Fold Crest - Profile Projector:

- The average deviations of exterior fold crest to the CAD design were 0 077, 0 066, 0.162 and 0 087 mm along 0°, 90°, 180° and 270° respectively

Exterior Fold Profile - CMM

- More detailed comparison of the exterior fold profile with the CAD model - average deviations 0 194 mm with minimum deviation of -0 288 mm and maximum deviation of 0 443 mm

Wall Thickness - CMM

- Measured 4 folds, 90° apart, at 3 elevations 0 761±0 014 mm

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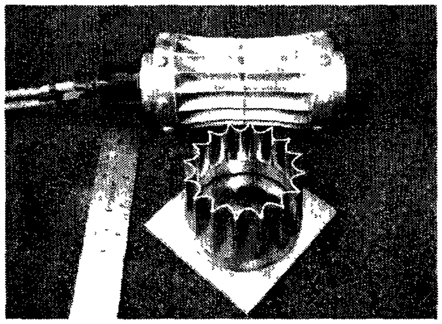
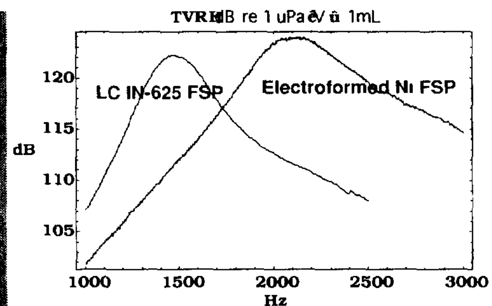
Assembled FSP Transducer with LC Shell





Transmitting Response of LC IN-625 FSP & Electroformed Ni FSP

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Implications for Business

- Functional prototyping, parts on demand, affordable customization.
- Structures and components with continuously variable composition, light weight, high stiffness.
- No joints, fasteners, stress risers - great fatigue properties.
- Reduced waste, energy savings.
- E-commerce.

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Potential Applications in Defence Area

Laser consolidation/cladding and other laser based technologies may have many potential applications in the defence areas to improve equipment performance, shorten prototyping cycle, and reduce maintenance cost and time:

- Navy - functional prototyping, build spare parts and repair expensive parts
- Air force - repair turbine blades, build parts, etc.
- Army - functional prototyping, build spare parts and repair expensive parts

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Summary:

- NRC/IMTI has developed a unique laser consolidation process and is currently leading the technology development for producing high quality net shape components (2 patents obtained and 1 pending).
- By using laser consolidation process, fully functional complex FSP shells were produced and design changes were incorporated quickly – this proves that laser consolidation can have many potential applications in the defence areas .
- NRC/IMTI will like to work collaboratively with DND/DRDC to further explore its applications in defence related areas and to transfer this exciting new manufacturing technology to Canadian industry suppliers for DND.