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Publisher's version / Version de l'éditeur:

Proceedings of ICALEO 2001, 2001

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Laser Consolidation for the Manufacturing of Complex Flextensional Transducer Shells

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Abstract

The folded shell projector (FSP) is a compact flextensional sound source being developed for low frequency sonar applications. 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. However, this was an expensive and time-consuming process providing limited choices for the shell material.

A novel laser consolidation process for the manufacturing of complex FSP shells was investigated in this study. Advances in the laser consolidation process achieved by IMTI permitted the free-form production of the FSP shell directly from a CAD file delivered over the Internet. The investigation included changing the design of the shell during the program, proving that rapid design evolutions are readily accommodated, as no hard tooling is required. Four shells have been built using IN-625 alloy to validate the process, and assembled into projectors. The laser consolidated (LC) IN-625 shells have a wall thickness of typically 0.8 mm. The process parameters have been optimized for high accuracy and surface finish, with wall thickness tolerances of less than 0.02 mm. The calibration results reveal that the LC FSPs show a substantial improvement in performance over the electroformed prototype.

1. Introduction

The Integrated Manufacturing Technologies Institute of the National Research Council Canada (IMTI-NRC) is developing a novel process called "Free-Form Laser Consolidation" to build functional net-shape components directly from metallic powder in one step¹⁻³. The parts built by the laser consolidation process are metallurgically sound and free of porosity or cracks. The laser consolidation is a one-step computer-aided manufacturing process that does not require any moulds or dies, and therefore provides the flexibility of quickly changing the design of the

components. Thus, the lead-time to produce parts could be reduced significantly. In addition, this computer-aided manufacturing process provides an excellent opportunity for manufacturing complex parts that are difficult to make by conventional manufacturing methods.

The folded shell projector (FSP) is a compact flextensional sound source being developed by Transducer Group of the Defense Research Establishment Atlantic (DREA) for low frequency sonar applications, including active towed arrays and sonobuoys^{4,6}. The FSP radiates sound from a thin-walled cylindrical shell driven by a piezoelectric or magnetostrictive motor. The shell has superimposed corrugations (Fig.1), which creates a significant challenge for the existing manufacturing technology.

Fig.1 A CAD drawing of the complex FSP shell.

The initial prototype of the shell was built by Ni electroforming followed by NC machining, which is an expensive and time-consuming process providing limited material selection. In addition, the performance of the Ni-electroformed shell did not fully satisfy the design goals. In order to refine the FSP design for various operating environments, a low-cost functional rapid prototyping method was required to manufacture complex thin-walled corrugated metal shapes. Based on the technical specification and quantity requirements, conventional machining, casting and forming processes were deemed unsuitable for this purpose.

Laser consolidation process was identified as the most promising method to manufacture functional prototype shells for refining the FSP design. In the future, it may also become a cost-effective medium volume manufacturing method for producing components with expensive and hard to machine materials, since it produces finished complex parts with very little wasted material. This paper summarizes the feasibility study on the laser consolidation of IN-625 alloy for building the FSP shells, including metallurgical evaluation of the LC IN-625 material, dimensional inspection of the consolidated shells, FSP assembling and acoustic testing results.

2. Experimental Details

The laser consolidation process requires a solid base onto which a part is built. A focused laser beam is irradiated on the substrate to create a molten pool and metallic powder is injected simultaneously into the pool (Fig.2). A numerically controlled (NC) motion system (3 to 5 axes) is used to control the relative movement between the laser beam and the substrate. The laser beam and the powder feed nozzle are moved following a CAD model through a pre-designed laser path, creating a bead of molten material on the substrate, which solidifies rapidly to form the first layer. The second layer bead is deposited on the top of the first layer. By repeating this process, a solid thin walled structure is built. When the laser path is designed properly to guide the laser beam movement, a complex shaped part can be built directly from a CAD model without any mould or die.

A Nd:YAG laser coupled to a fiber-optic processing head is used for the laser consolidation work presented in this paper. The laser is operated in a pulse mode with an average power ranging from 20 to 300 W. A powder feeder is used to simultaneously deliver metallic powder into the melt pool through a nozzle with the powder feed rate ranging from 1 to 30 g/min. All laser consolidation work is conducted in a glove box and at room temperature, in which the oxygen content is maintained below 50 ppm during the process. Ni-base IN-625 alloy powder was used for the laser consolidation in this study, while annealed A36 mild steel plates with a thickness of 12.7 mm were used as the base material. Chemical compositions of these experimental materials are listed in Table 1. The base plates were machined into coupons and ground flat on a surface grinder prior to consolidation.

Fig.2 Illustration of laser consolidation process.

Table 1 Chemical compositions of experimental materials (wt%)

Materials	C	Ni	Fe	Cr	Mo	Ta+Nb	Mn	Cu
IN-625	0.03	Bal.	0.4	22.0	9.0	3.7	-	-
A36 steel	0.29	-	Bal.	-	-	-	1.0	0.2

The microstructures of the LC IN-625 material was revealed with Marbles reagent (10g CuSO₄, 50ml H₂O and 50ml HCl) and studied using an optical microscope as well as a scanning electron microscope (SEM). A Philips X'Pert X-ray diffraction system was used to identify the phases of the LC samples. Flat tensile specimens with 25 mm gauge length were machined from the consolidated thin walls (approximately 0.8 mm in thickness). A 100 kN Instron Mechanical Testing System was used to evaluate the tensile properties of the LC samples.

Four shells from two designs (#1 and #2) were manufactured by laser consolidation of IN-625 powder. The external dimensional accuracy of the FSP shells was inspected using a Mitutoyo PH350 Profile Projector to measure four exterior fold crests, 90 degrees apart, at 9 elevations, along the vertical direction. One LC IN-625 shell of design #1 was sectioned horizontally to measure the wall thickness using a micrometer. For the design #2, a Brown and Sharpe coordinate measurement machine (CMM) was also used to measure the exterior fold profile to provide a more detailed comparison with the CAD model.

3. Results and Discussion

Characterization of LC IN-625 Alloy

The LC IN-625 alloy shows a unique directionally solidified microstructure (Fig.3): very fine γ phase columnar dendrites growing almost parallel to the direction of build, resulting from the rapid solidification inherent to the laser consolidation process. Optical microscope

observation reveals that the cell size of columnar dendrites is very fine, only around 2-3 μm in diameter (Fig.3b). The X-ray diffraction pattern shows that the LC IN-625 has a face-centered cubic structure (γ) with a lattice parameter of 3.59 $\text{\AA}$, identical to the IN-625 powder used for laser consolidation (Fig.4). Figure 4 also reveals that the directional solidification of LC IN-625 is along the (100) crystallographic plane, which is the typical dendritic growth direction of face-centered cubic structure materials⁷.

Fig.3 Microstructure of LC IN-625 alloy (a) along vertical direction, and (b) along horizontal direction.

Fig.4 XRD patterns of LC and powder IN-625 materials.

The LC IN-625 material exhibits excellent mechanical properties. In general, the LC IN-625 material is stronger than the respective cast material and comparable to wrought material (Table 2). The yield strength of LC IN-625 is around 518 MPa and 477 MPa along the horizontal and vertical directions respectively, which is significantly higher than cast IN-625 (350 MPa) and is comparable to wrought IN-625 (490 MPa). The tensile strength of LC IN-625 material also reveals the same trend.

Table 2. Mechanical properties of LC IN-625 alloy

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

It is interesting to note that the tensile properties of LC IN-625 material show some degree of anisotropy: relatively higher tensile and yield strengths along the horizontal direction and relatively high elongation along the vertical direction. Along the horizontal direction (perpendicular to sample growth direction), the yield strength and ultimate tensile strength of the LC IN-625 material are 518 MPa and 797 MPa respectively, while the elongation is about 31%. In the vertical direction (parallel to sample growth direction), both the yield and the ultimate tensile strengths are slightly lower, 477 MPa and 744 MPa respectively, while the percentage elongation increases significantly to 48%. The anisotropic behavior in the tensile properties of the LC IN-625 material could be attributed to its directionally solidified microstructure. Because the dendrites in LC IN-625 material are growing almost parallel to the growth direction, there are relatively less grain boundaries along the vertical direction to arrest the dislocation movement.

As a result, the elongation along the vertical direction is relatively high but the strength in this direction is relatively low.

The laser consolidation is a rapid solidification process that produces residual stresses in the finished components. The state and magnitude of the residual stresses can significantly affect the performance of the LC parts. The knowledge of the residual stresses in the LC IN-625 samples will be very helpful in assessing their effects in practical applications. The state of residual stresses in the LC IN-625 material was measured using a hole-drilling strain-gauge method as well as the X-ray diffraction (XRD) technique (Table 3). The hole-drilling method measured the average residual stresses through the consolidated wall. The results show that a significant amount of compressive residual stress (about -350 MPa) exists along the horizontal direction, while the vertical direction shows only a small amount of compressive residual stress (about -40 MPa). The XRD technique reveals that the near surface residual stress along the transverse direction was in compression (about -410 MPa), while a relatively low level of surface compressive residual stress was observed along the build direction (about -150 MPa). The XRD results are consistent with the hole-drilling method. It is interesting to note that both methods reveal that the LC IN-625 material shows a high level of compressive residual stress along the horizontal direction, while the vertical direction shows a relatively low magnitude of compressive residual stress. Although the mechanism of the residual stress formation is still under investigation, it is anticipated that compressive residual stress will be beneficial to the performance of the LC FSP shells.

Table 3 Residual stress measurements of LC IN-625 material

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

The corrosion resistance of the shell material is an important consideration for the FSP design, because it will operate in the ocean environment. The corrosion resistance of the LC IN-625 material was electrochemically tested in 3.5% NaCl solution and its potentiodynamic polarization curve is plotted in Fig.5. For comparison, the polarization curves of wrought A36 carbon steel, 316L stainless steel and IN-625 alloy are also displayed in the figure. The wrought A36 carbon steel exhibits very poor corrosion resistance in the solution. Its corrosion potential is only about -600 mV (SCE) and its current density rapidly increases with the potential without forming any passive region. The corrosion potential of 316L stainless steel is more positive, about -368 mV (SCE). With the increase in potential, 316L stainless steel shows a passive region (up to about +280 mV, SCE) and the corrosion current in the region is very low, only about 10^{-5} - 10^{-6} Acm⁻². However, it is a well-known phenomenon that 316L stainless steel shows strong pitting corrosion tendency in the 3.5% NaCl solution. Severe pitting damage was observed on the surfaces of the 316L specimens after the polarization test.

The wrought IN-625 alloy shows corrosion potential and passive current very similar to the 316L stainless steel, but its passive region is much wider (up to about +700 mV, SCE). LC IN-625 material shows the same corrosion potential (about -250 mV, SCE) as well as the same passive region (-250 to +700 mV, SCE) as the wrought IN-625, which indicates that the corrosion resistance of the LC IN-625 alloy is very similar to the respective wrought material in the test solution. In addition, no pitting was formed on both LC IN-625 and wrought IN-625 specimen surfaces after testing, which is significantly better than 316L stainless steel. The excellent corrosion resistance of LC IN-625 material in 3.5% NaCl solution indicates that the LC IN-625 shells will be suitable for operation in the ocean environment.

Fig.5 Polarization curves of laser consolidated and wrought materials (in 3.5% NaCl).

Manufacturing of FSP shells

The first design of the LC FSP shell (Design #1) was generated with DREA's MAVART3D finite element software and its CAD drawing is displayed in Fig.1. The manufacturing of the FSP shells was performed at NRC/IMTI located at London, Ontario, based on the CAD design from DREA delivered over the Internet. Two shells of design #1 were built by using laser consolidation of IN-625 powder. The shell is about 130 mm in height and around 80 mm in diameter. One photo shows an as-consolidated FSP shell after removing the loose powder (Fig.6a). It is evident that the as-consolidated shell shows very good surface finish. A cross-sectional photo of a half shell (Fig.6b) reveals that the laser consolidation process successfully manufactured the very complex thin wall structure with excellent uniformity. A magnified cross-sectional view (Fig.6c) shows that, as per the CAD design requirement, the laser consolidation process managed to generate a sharp corner inside each crest, which is very difficult to form using conventional manufacturing methods.

Fig.6 Laser consolidated Design #1 FSP shells (a) full shell, (b) half shell and (c) magnified cross-sectional view of crests.

Fig.7 Shell Design #2 (a) CAD drawing and (b) LC IN-625 shell.

Based on results from Design #1, DREA generated Shell Design #2 (Fig.7a) and sent it to IMTI through the Internet. IMTI manufactured two LC IN-625 shells based on the CAD file of Design #2 (Fig.7b). This proved that rapid design evolutions are readily accommodated by the laser consolidation process since no hard tooling is required.

In order to ensure the quality of the LC IN-625 shells, DREA performed strict NDT inspection on the LC shells by using ultrasonic, dye penetrant, X-ray and magnetic methods. The NDT inspection results reveal that the LC IN-625 shells are metallurgically sound, without porosity, cracks or other detectable defects.

Dimensional inspection

Dimensional inspection was performed on the LC FSP shells for the purpose of refining the laser consolidation process as well as providing detailed dimensional comparison to the CAD model.

The FSP shell manufactured according to Design # 1 was measured using a profile projector to provide preliminary dimensional verification on the overall exterior shape and size of the LC shell. The measurement was performed along four exterior fold crests, 90 degrees apart, at nine elevations. The measurements were compared with nominal values obtained from the CAD model of the shell and the deviation was calculated for each measurement (Table 4). 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.

The wall thickness of the FSP shell (Design # 1) was measured on the half shell (Fig.6b) which was surface ground to the middle of the shell. The measurements were taken using a micrometer with a ball end. The wall thickness varied from 0.818 to 0.826 mm with an average of 0.822 ± 0.003 mm (Table 5). The measurement results proved that the laser consolidation process has built the complex shell with excellent dimensional accuracy and wall uniformity.

Table 4. Measurements of exterior fold crest to center line of the shell (Design #1)

Elev.	CAD (mm)	Measurement (mm)				Deviation (mm)			
		0 deg	180 deg	90 deg	270 deg	0 deg	180 deg	90 deg	270 deg
EE	40.678	40.450	40.480	40.560	40.450	-0.228	-0.198	-0.118	-0.228
DD	38.743	38.300	38.310	38.400	38.295	-0.443	-0.433	-0.343	-0.448
CC	37.561	37.030	37.020	37.130	37.025	-0.531	-0.541	-0.431	-0.536
BB	36.573	36.115	36.095	36.180	36.115	-0.458	-0.478	-0.393	-0.458
AA	36.303	35.865	35.865	35.890	35.890	-0.438	-0.438	-0.413	-0.413
B	36.573	36.105	36.084	36.185	36.065	-0.468	-0.489	-0.388	-0.508
C	37.561	37.130	37.015	37.140	37.067	-0.431	-0.546	-0.421	-0.494
D	38.743	38.245	38.170	38.225	38.235	-0.498	-0.573	-0.518	-0.508
E	40.678	40.055	40.010	40.020	40.065	-0.623	-0.668	-0.658	-0.613
Average absolute deviation =						0.458	0.485	0.409	0.467

Table 5. Measurements of wall thickness of a half shell (Design #1)

Region	Wall thickness (mm)							
	0 deg	45 deg	90 deg	135 deg	180 deg	225 deg	270 deg	315 deg
Through	0.826	0.820	0.823	0.818	0.826	0.818	0.823	0.818
Average								
0.822±0.003								

Two FSP shells manufactured from Design #2 were also inspected using the profile projector along the exterior fold crests. The average absolute deviations from the CAD design were from 0.066 to 0.162 mm on one shell and from 0.106 to 0.128 mm on another shell. These results show that, due to the refined process control, significant improvement on dimensional accuracy was achieved over the shells built from Design # 1.

In addition to the exterior fold crest dimensional inspection, a Coordinate Measuring Machine (CMM) was also used to measure the individual fold profile along horizontal direction to provide a more detailed comparison to the CAD model. The measurement was performed along four individual folds, 90 degrees apart at nine reference elevations. Graphical comparison drawings were generated for each elevation to show the measured points plotted against the CAD model. Numerical deviation reports were produced for each elevation measured to provide a detailed numerical analysis of the deviation. A summary of fold profile deviations of one shell is listed in Table 6. It shows that the overall average absolute deviations of the fold profile to the CAD model is 0.194 mm with a minimum deviation of -0.288 mm and a maximum deviation of 0.443 mm.

The wall thickness of the shells manufactured from Design #2 was also inspected using the CMM along 4 folds, 90° apart, at 3 elevations. The overall average wall thickness was 0.761±0.014 mm for one shell and 0.779±0.017 mm for the second shell.

Table 6. Summary of fold profile deviations measured by CMM.

Elevation	Average abs. Deviation (mm)	Minimum deviation (mm)	Maximum deviation (mm)
EE	0.208	0.123	0.303
DD	0.266	-0.044	0.443
CC	0.198	-0.065	0.339
BB	0.224	-0.070	0.388
AA	0.251	-0.067	0.441
B	0.178	-0.134	0.325
C	0.153	-0.099	0.259
D	0.071	-0.144	0.100
E	0.197	-0.288	-0.052
Overall	0.194	-0.288	0.443

FSP assembly and performance testing

DREA assembled two FSPs using LC IN-625 shells (Design #1) for evaluation and functional testing (Fig.8). Transmitting response of LC IN-625 FSP was recorded and compared with the electroformed Ni FSP (Fig.9). The optimal target for the FSP design is to generate a resonance frequency of 1000 Hz. However, the electroformed Ni FSP had a resonance frequency of 2100 Hz, which is too far away from the design goal. The Design #1 of the LC FSP was expected to have a resonance frequency of 1400 Hz. The transmitting response measurements show that the LC IN-625 FSP has a resonance frequency of 1400 HZ, which matches excellently with the design prediction from DREA's finite element model. The initial performance results reveal that the LC IN-625 FSPs show substantial improvements over the electroformed Ni prototype. DREA also conducted functional testing of the LC FSPs at sea and the performance of the LC FSPs is excellent. Currently, DREA is working on the assembly of FSPs using the LC IN-625 shells from the Design #2, which is expected to further reduce the resonance frequency to 1200 Hz. A more complete evaluation of LC FSPs will be reported in the near future.

Fig.8 Assembled FSP using LC IN-625 shell.

Fig.9 Transmitting response of LC IN-625 FSP & electroformed Ni FSP.

4. Conclusions

- (1) By using the laser consolidation process, fully functional complex FSP shells were successfully manufactured of IN-625 alloy. NDT inspection results reveal that the LC IN-625 shells are metallurgically sound, no cracks, porosity or other detectable defects.
- (2) The laser consolidation process readily accommodates rapid design changes through the Internet since no hard tooling is required.
- (3) Dimensional inspection reveals that the LC IN-625 shells have excellent dimensional accuracy and wall uniformity.
- (4) The initial performance testing reveals that the LC IN-625 FSPs show substantial improvements over the electroformed Ni prototype.

Acknowledgements

The authors would like to thank A. Gillett for his enormous effort in the process development for building the very complex FSP shells. Thanks are also extended to J. Chen, S. Kowala, M. Meinert, D. Gray, A. Chen and A. Drozdowski for their numerous contributions to the project.

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