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LASER CONSOLIDATION OF NET-SHAPE SHELLS FOR FLEXTENSIONAL SONAR PROJECTORS

Paper #1206

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Abstract

Laser consolidation (LC) is a computer-aided manufacturing process that builds a functional net-shape part directly from a CAD model, without the use of moulds or dies. The folded shell projector (FSP) is a compact flextensional underwater sound projector developed by DRDC-Atlantic for low frequency sonar applications. The radiating surface of the FSP is a thin-walled shell of complex shape that challenges conventional manufacturing technologies.

In this study, several versions of the FSP were designed using DRDC-Atlantic's MAVART finite element code. NRC-IMTI refined the laser consolidation process and successfully manufactured the complex shells from IN-625 and Ti-6Al-4V alloys. The laser consolidated net-shape shells are metallurgically sound and exhibit excellent surface finish, dimensional accuracy and mechanical properties. Field tests of FSP prototypes demonstrated that the shells met their design goals of resonant frequency and source level. Other manufacturing methods for building the shells (electroforming, hydro-forming and Ni vapor deposition) were also explored. However, at the moment, the laser consolidation process is the only manufacturing technology capable of making the FSP shell to the required tolerances.

Introduction

The Integrated Manufacturing Technologies Institute of the National Research Council of Canada (NRC-IMTI) is developing a novel process called "Laser Consolidation" (LC) for rapid manufacturing of net-shape functional components directly from metallic powder in one step [1-6]. The laser consolidation is a computer-aided manufacturing process that does not require any moulds or dies, and therefore provides the flexibility to quickly change the design of the

components. Thus, the lead-time to produce final parts could be reduced significantly.

Compared to other similar laser powder deposition processes [7-11] that produce near-net-shape parts, the laser consolidation process produces net-shape functional components without need of machining beyond removal of the part from its substrate. This computer-aided manufacturing process provides a unique opportunity for manufacturing complex thin-walled parts in challenging materials that are difficult to make by conventional manufacturing processes. As opposed to the conventional machining process, this technology builds complete parts or features on an existing component by adding rather than removing material. The parts built by the laser consolidation process are metallurgically sound, and free of porosity or cracks. Due to the rapid solidification inherent to the process, excellent material properties are obtained.

DRDC-Atlantic is the Canadian Navy's center of expertise in sonar R&D. One of its special interests is flextensional sonar projectors. These are compact low frequency wide band sound sources, which are key components of military sonar systems. Sound travels further underwater (with reduced attenuation) at low frequency which can be very desirable for both detection and communication. The flextensional design addresses the challenge of generating low frequency sound from a small source, by incorporating a mechanical transformer in its radiating surfaces. This increases the surface velocity, at the expense of the applied force, and improves the impedance match between the relatively stiff motor and the water. The word flextensional refers to the use of structural elements that deform by flexure under tensile loads.

DRDC-Atlantic's patented flextensional folded shell projector (FSP) [12], shown in Figure 1, features a one piece corrugated metal shell as the radiating surface. The shell encloses the piezoelectric motor, which is a stack of piezoceramic rings glued together. The shell

has an overall curvature which controls the mechanical transformer ratio. The corrugations give the shell a high stiffness to mass ratio, which results in wide bandwidth. The fact that the shell is one piece implies the design is inherently waterproof, without the necessity of a polymer cladding (called the "boot") which many projector designs require. While a boot can provide effective corrosion protection from seawater, it also can introduce acoustic losses, and makes a projector susceptible to failure from flooding, if the boot receives even minor damage during use.

Figure 1: Folded shell projector prior to assembly, showing LC IN-625 shell, piezoelectric motor, end caps, stress bolts and clamping screws.

The folded shell is a complex part made of thin wall, high strength and corrosion resistant metals (eg. pure Nickel, Ni-alloys or Ti-alloys). Machining such thin wall parts is extremely difficult by conventional means, because without support, the thin wall will deflect under the load of the cutter, causing poor surface finish and loss of precision.

The first prototype of the FSP was made by electroforming, where an inner expendable mandrel of aluminum was CNC milled to the inside contour of the shell, then a thick coating of nickel was electroformed onto the mandrel, and this coating (which was very rough) was milled to the outside contour. The Al mandrel was removed by dissolution in a NaOH bath. This process was very complex and time consuming, requiring accurate registration of the mandrel that tied up the mill for a long period of time. Electroforming can only be done in a limited choice of materials, with Ni the only suitable one for transducers. After considerable evaluation of alternative manufacturing technologies, laser consolidation was selected as the most promising method for making functional prototype shells for the folded shell projector.

This paper will summarize our work for making the shells in a variety of shapes and sizes by laser consolidation of IN-625 and Ti-6Al-4V alloys, and exploring the opportunities for rapid design evolution that the laser consolidation provides. We will also describe the acoustic performance of sonar projectors built from laser consolidated shells.

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, into which metallic powder is continuously injected. A computer numerically controlled (CNC) motion system 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 along a pre-designed path, creating a bead of molten material on the substrate, which solidifies rapidly to form the first layer. The second layer 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, a complex shaped part can be built directly from CAD model without any mould or die.

A 500W Lasag Nd:YAG laser coupled to a fiber-optic processing head was used for all laser consolidation experiments. The laser was operated in a pulse mode with an average power ranging from 20 to 300 W. A Sulzer Metco 9MP powder feeder was used to deliver metallic powder into the melt pool through a nozzle with the powder feed rate ranging from 1 to 30 g/min. During the laser consolidation, the laser beam and the powder delivery nozzle were kept stationary, while the sample was moved using a 3-axis CNC motion system. All laser consolidation work was conducted in a glove box and at room temperature, in which the oxygen content was maintained below 50 ppm during the process.

Chemical compositions of two alloy powders investigated in this paper, Ni-base IN-625 and Ti-base Ti-6Al-4V alloys are listed in Table 1. Both powders are spherical in shape with the size less than 45 μm . Annealed A36 mild steel plates (0.29% C, 1.0% Mn, 0.2% Cu and Fe) were used as the base material for laser consolidation of IN-625 shells, while wrought Ti-6Al-4V alloy plates were used for laser consolidation of Ti-6Al-4V shells. The substrate plates were machined and ground to a consistent surface finish for the laser consolidation of respective alloy powders.

Table 1: Chemical composition of powder materials
(wt. %)

Element	IN-625	Ti-6Al-4V
C	0.03	0.07
Ni	Bal.	0.02
Ti	-	Bal.
Al	-	6.18
Cr	22.0	0.02
Mo	9.0	-
Ta+Nb	3.7	-
V	-	3.94

A 100 kN Instron Mechanical Testing System was used to evaluate the tensile properties of the LC IN-625 and LC Ti-6Al-4V samples.

Results and Discussion

LC IN-625 Shells for Folded Shell Projector

LC IN-625 Alloy Laser consolidation of IN-625 alloy was initially used for manufacturing the FSP shells since IN-625 alloy has excellent corrosion resistance against seawater. The LC IN-625 material exhibits very good mechanical properties. Along the horizontal direction (perpendicular to the build direction), the yield strength ($\sigma_{0.2}$) and tensile strength (σ_{UTS}) of the LC IN-625 material are 518 MPa and 797 MPa respectively, while the elongation is about 31%. When testing along the vertical direction (parallel to the build direction), both the yield and the tensile strengths are slightly lower to 477 MPa and 744 MPa, respectively, while the percentage elongation increases significantly to 48%. The anisotropic behaviour of the tensile properties of the LC IN-625 alloy may be attributed to its directionally solidified microstructure. The yield strength and the tensile strength of the LC IN-625 along both directions are significantly higher than the cast IN-625 and comparable to the wrought material, although the elongation along the horizontal direction is slightly lower.

Manufacturing LC IN-625 FSP Shells The first design of the LC FSP shell (Design #1) was developed with DRDC's Mavart finite element software and its CAD drawing was sent to NRC-IMTI via Internet. NRC-IMTI created a laser path based on the CAD model and successfully built two IN-625 shells using the laser consolidation process. The shells are about 130 mm in height and around 80 mm in diameter. Visual inspection and acoustic testing revealed that both shells are metallurgically sound, without any cracks or visible defects. Figure 2a shows the as-consolidated FSP shell after removing the loose powder. It is evident that the as-consolidated shell shows very good

Figure 2: LC IN-625 FSP shells (Design #1), (a) full shell, (b) magnified cross-sectional view of crests.

surface finish. The cross-section of one shell reveals that the laser consolidation process successfully created the complex thin wall structure with excellent uniformity. A magnified cross-sectional view (Figure 2b) 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.

In order to ensure the quality of the LC IN-625 shells, DRDC 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.

The laser consolidation process provides an excellent manufacturing method to accommodate rapid design evolution since it does not require any change of hard tooling. To explore this unique opportunity, DRDC modified the design of the FSP shell to further reduce its frequency. NRC-IMTI further refined the laser consolidation processing

Figure 3: LC IN-625 FSP shell (Design #2).

parameters, generated a new laser path from the revised CAD model for the new FSP design and manufactured two LC IN-625 shells. Figure 3 shows the as-consolidated IN-625 FSP shell from Design #2 without any post machining. The key difference from Design #1 is a reduction in the radius of curvature of the circular generator of the shell. The excellent quality of the laser consolidated shells successfully proved that rapid design evolutions can be readily accommodated by the novel laser consolidation process without requiring changes of expensive hard tooling.

Dimensional Inspection Dimensional inspection was performed on the LC IN-625 FSP shells for the purpose of refining the laser consolidation process as well as providing detailed dimensional comparison to the CAD model. The external dimensional accuracy of the FSP shells (Design #1) was inspected using a Mitutoyo PH350 Profile Projector to measure four exterior fold crests, 90 degrees apart, at 9 elevations, along the vertical direction. The measurements were compared with nominal values obtained from the CAD model of the shell and the deviation was calculated for each measurement. 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 (Figure 4) 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.

Two LC IN-625 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.

The wall thickness of the LC IN-625 shells manufactured from Design #2 was 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.

The dimensional measurement results proved that the laser consolidation process has built the complex shell with excellent dimensional accuracy and wall uniformity.

FSP Assembly and Testing Results DRDC assembled two FSPs using LC IN-625 shells (Design #1) for evaluation and functional testing (Figure 4). The transmitting voltage response of the LC IN-625 FSP was measured and compared with the electroformed Ni FSP (Figure 5). The design goal for the FSP was to achieve a resonance frequency of 1000 Hz. The measurements show that the LC IN-625 FSP has a resonance frequency of 1400 Hz, which is substantially closer to the goal than the electroformed Ni prototype (2100 Hz). The Design #2 refined the outer profile of

Figure 4: Assembled FSP using LC IN-625 shell (Design #1) and the half shell showing the cross-sectional view.

Figure 5: Transmitting voltage response (dB re 1 uPa/Volt @ 1 meter) LC IN-625 FSPs & electroformed Ni FSP.

the FSP further and yielded a resonance frequency of 1100 Hz as can be seen in Figure 5.

Figure 5 shows how rapidly (in just a few design and build iterations) we are approaching the design goal of 1000 Hz. As we do so, we are of course compromising source level, and bandwidth. The loss of bandwidth that occurs in Figure 5 as the resonance frequency is reduced is a text-book illustration of what happens when you reduce the frequency, but hold the radiating surface area essentially constant.

LC Ti-6Al-4V Shells for Folded Shell Projector

A Ti-6Al-4V version of the FSP was designed by DRDC-Atlantic using its MAVART finite element code for use in low frequency active towed arrays. The new design reduced the projector diameter over previous versions to reduce the array storage volume, and hydrodynamic drag.

LC Ti-6Al-4V Alloy The LC Ti-6Al-4V material is metallurgically sound and exhibits excellent mechanical properties (Table 2). Along the build-up direction, the yield and tensile strength of the as-consolidated Ti-6Al-4V is about 1062±6 MPa and 1157±11 MPa, respectively, while the elongation is 6.2±0.9 % and the Young's Modulus 116±8 GPa. It should be noted that the tensile properties of the LC Ti-6Al-4V are very consistent and all standard deviations are quite small. It should be further noted that the as-consolidated Ti-6Al-4V is substantially stronger than the as-cast or annealed wrought Ti-6Al-4V, and comparable to the heat-treated wrought Ti-6Al-4V material.

Table 2: Tensile properties of LC Ti-6Al-4V alloy

Materials	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	E (GPa)	δ (%)
LC Ti-6Al-4V	1062 ±6	1157 ±11	116 ±8	6.2 ±0.9
Cast Ti-6Al-4V (As-cast or annealed)	890	1035	-	10
Wrought Ti-6Al-4V (annealed)	825	895	110	10
Wrought Ti-6Al-4V (solution treated + aged)	1103	1172	-	10

Manufacturing LC Ti-6Al-4V FSP Shells The manufacturing of the Ti-6Al-4V FSP shells was performed at NRC/IMTI. An array of data points describing one fold of the new Ti-6Al-4V shell was delivered to IMTI by DRDC through the Internet. IMTI constructed a CAD model using UniGraphics (UG) CAD/CAM software based on the array of points. IMTI successfully manufactured five Ti-6Al-4V FSP shells as per DRDC's design. The shell is about 130 mm in height and around 55 mm in diameter. The surface uniformity of the LC Ti-6Al-4V shell was further improved and the line in the middle of the original LC IN-625 shell was eliminated (Figure 6). Visual inspection and acoustic testing reveals that all shells are metallurgically sound, without any cracks or visible defects.

Figure 6: LC Ti-6Al-4V FSP shell.

Dimensional Inspection The dimensions of external fold profiles of Ti-6Al-4V FSP shells were inspected using a Brown & Sharpe Coordinate Measuring Machine (CMM) at 7 elevations. The CMM probing path was created using Unigraphics to guide the measurement. The measurement results (Table 3) reveal that the LC Ti-6Al-4V FSP shell has an average deviation of 0.098 mm as compared with the CAD model with a minimum deviation of -0.282 mm and a maximum deviation of 0.177 mm.

Table 3: Exterior fold profile measure by CMM

Elevation	Average abs. Deviation (mm)	Minimum Deviation (mm)	Maximum Deviation (mm)
DD	0.093	-0.279	0.028
CC	0.078	-0.282	0.108
BB	0.104	-0.246	0.138
AA	0.121	-0.272	0.172
B	0.120	-0.236	0.177
C	0.116	-0.218	0.173
D	0.071	-0.190	0.131
Overall	0.098	-0.282	0.177

The diameter and wall thickness of the upper and lower flanges were measured using a micrometer with a ball end. The diameters of upper and bottom flanges are 54.501 mm and 54.606 mm respectively, while CAD model requires 54.60 mm. The roundness is about 0.030 mm and 0.044 mm for upper and bottom flanges respectively. The CAD model specified a wall thickness of 0.80 mm, while the measurement shows that the upper and bottom flanges have the same wall thickness of 0.864 mm. It is evident that the LC Ti-6Al-4V shell demonstrates excellent dimensional accuracy.

FSP Assembly and Field Testing To improve the reliability and depth capability of the projector, a new assembly procedure was developed at DRDC-Atlantic to weld Ti end caps directly to the LC Ti-6Al-4V shell (Figure 7). The all-welded Ti construction eliminates glue joints and reduces the number of parts. It pre-stresses the motor with the hydrostatic load rather than bolts. The improved assembly substantially increases the operating depth of the FSP to 200m.

Calibrations of the prototypes were performed at DRDC's Acoustic Calibration Barge, in Bedford Basin, Nova Scotia, and proved that the welded LC Ti-6Al-4V FSP met its design goals of resonant frequency, source level and insensitivity to depth (Figure 8). The LC Ti-6Al-4V FSP was calibrated at depths of 15 m, 25 m and 35 m, showing identical resonant frequency of 1500 Hz. Note that the depth

Figure 7: Assembled LC Ti-6Al-4V FSP with welded Ti end caps

Figure 8: Field testing results of LC Ti-6Al-4V FSP with welded Ti end caps.

dependence of the first null in the response, at around 3500 Hz, has little practical significance, since the projector will be operated near its 1500 Hz resonance, where there is practically no depth dependence.

LC Ti-6Al-4V Shells for Shear Mode Projector

Shear Mode Projector The newest variant of the folded shell is the Shear Mode Projector (SMP) [13], shown in Figure 9. It looks superficially like the FSP, but with a twist applied to the shell. Upon closer examination of the figure, you will see the shell has straight line generators (i.e., it is a right circular cylinder) with sinusoidal corrugations and a twist superimposed, whereas the FSP has circular generators with parabolic corrugations.

The SMP use a new shear mode piezoelectric motor [14] that has 1/2 the resonant frequency of a conventional length expander motor of the same size. The conventional d33 motor in the FSP changes length when the AC drive voltage is applied. The shear mode motor in the SMP deforms in pure torsion. The spiral

Figure 9: Shear Mode Projector, with LC Ti-6Al-4V shell.

corrugations in the shear mode shell convert the torque generated by the motor into radial expansion (and contraction) of the shell through the end caps. A pure torsion drive motor immersed in a fluid by itself would produce essentially zero radiated sound, because it is a zero volume deformation. So the main purpose of the shear mode shell is to transform this zero volume displacement motion into a useful radial volume displacement. The number of corrugations, the angle of the twist in the shell, and the wall thickness were chosen by finite element modelling of the shell, such that the lowest combined torsion/radial breathing mode resonance frequency would be about half that of the lowest torsional mode of the shear mode motor.

Many piezoelectric materials demonstrated substantially high (often almost double) piezoelectric coefficients in shear mode than in tension mode. There are established applications for the shear mode in sensors, but few realizations in projectors. The SMP was developed as a test bed to explore shear mode projectors intended for wide band sonar and underwater communications. The SMP design requires precision, strength, corrosion resistance and light weight. The most challenging component of the SMP is the thin-wall spiral corrugated titanium shell, which could not readily be made using conventional manufacturing techniques. The laser consolidation process was selected as the only proven rapid manufacturing method capable of building functional net-shape Ti-6Al-4V shells for the SMP.

Manufacturing LC Ti-6Al-4V SMP Shells NRC-IMTI received the CAD model of the SMP shell from DRDC via Internet and generated a laser path for the laser consolidation accordingly. Two Ti-6Al-4V SMP shells were successfully built on Ti-6Al-4V substrate using laser consolidation process. The shell is about 130 mm in height, around 82 mm in external diameter and 0.84

Figure 10: LC Ti-6Al-4V SMP shells.

mm in wall thickness. The surface finish of the LC Ti-6Al-4V shell was further improved (Figure 10). Visual inspection and acoustic testing reveals that these two shells are metallurgically sound, without any cracks or visible defects.

Our ability to quickly and smoothly move the SMP from conceptual design to working prototype highlights the value that laser consolidation brings to product development and rapid manufacturing. For a conventional manufacturing technology, even if it could overcome the technical challenges to manufacture functional corrugated shells for FSPs, the change of design to the spiral shape needed for the SMP would introduce substantial technical challenges and cost for re-developing manufacturing processes and tooling. Laser consolidation process readily adapted the significant design change for the SMP without any hard tooling requirements and no loss in precision or metallurgical soundness.

SMP Assembly and Preliminary Testing Results

DRDC assembled the SMP using the LC Ti-6Al-4V shell, shear mode piezoelectric motor and welded Ti end caps (Figure 9). The transmitting voltage response curve of the prototype SMP was measured at a depth of 15 meters (Figure 11).

Figure 11: Transmitting response of LC Ti-6Al-4V SMP.

A remarkable feature of the torsion mode of shear mode piezoelectric stack is that its frequency of resonance is about half that of the lowest mode of a conventional piezoelectric stack's length extension mode. This implies low frequency of operation for the same size of motor, which is very desirable. It also raises the possibility of tuning the motor and shell close enough that the response curve for the complete assembly will be flat between these 2 key resonances, which are visible as the peaks at 1800 and 4000 Hz in Figure 11.

Although the 1st prototype SMP was very successful, we did not obtain the desired flat top response curve from the prototype, as can be seen by the sag between the 2 peaks, which may be attributed to the modelling shortcuts we took. This SMP design was based on eigen analysis of the separate parts of the device in vacuum, and we relied on our experience and rules of thumb to estimate the shift of the frequencies, when the projector is immersed in water. We underestimated how low the shell breathing mode would shift upon immersion. Recently, we have built a fully water loaded Mavart finite element model which can predict the performance of the complete projector in water. The model requires substantial computer resources to run, and we are now installing this model on a Beowulf cluster. We intend to use this improved model to evaluate how to adjust the motor and shell dimensions to further flatten the transmitting voltage response curve in our next design.

Evaluation of Conventional Manufacturing Technologies for Making FSP Shells

Nickel Vapor Deposition In addition to the electroforming, DRDC also evaluated another method to deposit Ni to manufacture FSP using chemical nickel vapor deposition (termed CVD or NVD). In this method, a split inner mandrel of aluminum is placed in a sealed chamber to which nickel carbonyl gas is admitted. The mandrel is electrically heated to over 160°C and pure Ni is deposited from the vapor. The mandrel can be removed from the Ni shell by using differential thermal expansion of the Al and Ni, and with care, can be reused. The NVD process produced usable shells, but they were not of uniform wall thickness. In some cases the wall thickness varied by over 50 % along the vertical axis. This was traced to the vertical gravity-driven density gradient in the gas in the deposition chamber causing higher deposition rates at the bottom of the parts. The solution to this would be to have a slowly rotating mandrel inside the deposition chamber. The consequence of the nonuniform wall thickness in the final projector was

reduced sound output, and distorted transmitting response curves.

Hydroforming An evaluation of low temperature hydroforming of the folded shell was also conducted, using both Al and steel alloys selected for formability. From a number of attempts, using expensive custom dies, no usable parts were produced, the major difficulty being the introduction of work hardening, or cracking and outright failure at the points on the shell of maximum curvature. This experience indicated that high temperature forming processes would be needed to make this part, which would require an even larger investment in tooling.

Although DRDC evaluated various conventional manufacturing technologies, such as electroforming, nickel vapor deposition and hydroforming, at this moment, laser consolidation is the only proven rapid manufacturing method capable of building functional net-shape IN-625 and Ti-6Al-4V shells for the FSP and SMP.

Conclusions

- (1) The laser consolidation process successfully built functional net-shape IN-625 and Ti-6Al-4V FSP and SMP shells that are metallurgically sound, free of cracks and porosity. As-consolidated shells show good surface finish and dimensional accuracy.
- (2) This work demonstrated that the laser consolidation process provides a unique capability for rapid design evolution.
- (3) The sonar projectors built from laser consolidated shells demonstrated excellent acoustic performance.
- (4) The laser consolidation process has been successfully utilized to manufacture seven Ti-6Al-4V and ten IN-625 complex FSP and SMP shells of four different designs and, at this moment, it is the only proven manufacturing technology to make functional net-shape FSP and SMP shells.

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Meet the Authors

Dr. Lijue Xue is a Senior Research Officer with NRC-IMTI and has more than 25 years experience in the areas of materials engineering and laser materials processing. He is currently leading a group conducting R&D in the areas of laser consolidation, laser surface modification, sensing, monitoring and characterization.

Dr. Chris Purcell is a Defence Scientist with DRDC – Atlantic. He is a physicist with 16 years experience in sonar transduction, and his interests include development of finite element modeling tools, design of new transducers, and active materials.