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Xie, Lijue

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LASER CONSOLIDATION - A RAPID MANUFACTURING PROCESS FOR MAKING NET-SHAPE FUNCTIONAL COMPONENTS

Lijue Xue

National Research Council of Canada
Integrated Manufacturing Technologies Institute
800 Collip Circle, London, Ontario, Canada N6G 4X8
Tel: (519) 430-7059; Fax: (519) 430-7064;
E-mail: lijue.xue@nrc.ca

ABSTRACT

Laser consolidation is a novel rapid manufacturing process that produces a net-shape functional complex part layer by layer directly from a CAD model without any moulds or dies. This process uses a laser beam to melt a controlled amount of injected powder on a base plate to deposit the first layer and on previous passes for the subsequent layers. As opposed to conventional machining processes, this computer-aided manufacturing (CAM) technology builds complete net-shape functional parts or features on an existing component by adding instead of removing material. The LC samples also show very good surface finish and dimensional accuracy. Surface finish of the order of 1~2 μm (Ra) is obtained on as-consolidated IN-625. In this paper, laser consolidation process will be introduced, the functional properties of the laser-consolidated IN-625 and Ti-6Al-4V alloys will be described, and two applications of the process will be discussed.

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1. 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 '(Xue, 2000)'. The laser consolidation is a one-step computer-aided rapid 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. In addition, this computer-aided manufacturing process provides an excellent opportunity for manufacturing complex parts that are difficult to make by conventional manufacturing processes. As opposed to the conventional machining process, this new 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, free of porosity or cracks. Due to the rapid solidification inherent to the process, excellent material properties are obtained.

Research work has been reported by various institutions '(Keicher, 1998; Mazumder, 1997; Arcella, 2000)' using a similar process on various alloys and steels, such as Ni-base superalloys, Ti-alloys and stainless steels. Although the technology has a great potential for many industrial applications, concerns about the surface finish and dimensional accuracy have been raised.

In this paper, laser consolidation process is introduced, the functional properties of the laser-consolidated materials are described, and the applications of the process for manufacturing net-shape functional PSF shells and structural components for ARMS are discussed.

2. EXPERIMENTAL DETAILS

The laser consolidation process requires a solid base onto which a part is built (Figure 1). A focused laser beam is irradiated on the substrate to create a molten pool, while metallic powder is injected simultaneously into the pool. 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 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 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 based a CAD model without any mould or die.

A 500W Lasag Nd:YAG laser coupled to a fiber-optic processing head was used for all the 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 or 5-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. 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, while wrought Ti-6Al-4V alloy plates were used for laser consolidation of Ti-6Al-4V. The substrate plates were machined and ground to a consistent surface finish for the laser consolidation of respective alloy powders.

The microstructures of the LC samples were examined using an Olympus optical microscope as well as a Hitachi S-3500 scanning electron microscope (SEM). A Philips X'Pert X-ray diffraction system with Mo tube was used to identify the phases of the LC samples. A 100 kN Instron Mechanical Testing System was used to evaluate the tensile properties of the LC samples.

3. RAPID MANUFACTURING OF FUNCTIONAL COMPONENTS

3.1 Net-shape functional FSP shells

The folded shell projector (FSP) is a compact flextensional sound source being developed by researchers at the Defense Research & Development Canada (DRDC) for low frequency sonar applications, including active towed arrays and sonobuoys. The FSP radiates sound from a thin-walled cylindrical shell driven by a piezoelectric or magneto-strictive motor. The shell has superimposed corrugations (Figure 2), which creates a significant challenge for the existing manufacturing technology. Laser consolidation process was identified as the most promising method for rapid manufacturing of functional prototype shells for refining the FSP design as well as field testing, since, compared to similar process, the process produces net-shape instead of near-net-shape functional complex parts directly from CAD design without needs of moulds of dies '(Xue, 2001)'. Laser consolidation of IN-625 alloy was used for manufacturing FSP shells in this study.

3.1.1 LC IN-625 alloy

Optical and SEM microscope observations reveal that the LC IN-625 alloy shows a unique directionally solidified microstructure: very fine columnar dendrites growing almost parallel to the direction of build, resulting from the rapid solidification inherent to the laser consolidation process. The X-ray diffraction pattern shows that the LC IN-625 has a face-centered cubic structure (γ), identical to the IN-625 powder used for laser consolidation.

The LC IN-625 material exhibits very good mechanical properties (Table 2). 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.

3.1.2 Manufacturing FSP shells using LC process

Two FSP designs (#1 and #2) were investigated in the study. The manufacturing of the Design #1 of the FSP shell was performed at NRC-IMTI, based on the CAD design (Figure 2) generated by DRDC and 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. Figure 3a shows an as-consolidated FSP shell after removing the loose powder. It is evident that the as-consolidated shell shows very good surface finish. A cross-sectional photo of a half shell (Figure 3b) reveals that the laser consolidation process successfully manufactured the very complex thin wall structure with excellent uniformity. A magnified cross-sectional view (Figure 3c) 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.

Based on the initial success, Shell Design #2 (Figure 4a) was generated by DRDC and sent to NRC-IMTI through the Internet. NRC-IMTI generated laser path for the new design and successfully manufactured two LC IN-625 shells from Design #2 (Figure 4b). This proved that rapid design evolutions are readily accommodated by the laser consolidation process since no hard tooling is required.

3.1.3 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 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 (Table 3). 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 3b) 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 4). The measurement results proved that the laser consolidation process has built the complex shell with excellent dimensional accuracy and wall uniformity.

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 Brown and Sharpe coordinate measurement 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. 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.

3.1.4 Testing results

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.

DRDC assembled two FSPs using LC IN-625 shells (Design #1) for evaluation and functional testing (Figure 5). Transmitting response of LC IN-625 FSP was recorded and compared with the electroformed Ni FSP (Figure 6). The optimal target for the FSP design is to generate a resonance frequency of 1000 Hz. The measurements show that the LC IN-625 FSP has a resonance frequency of 1400 HZ, which matches excellently with the design prediction from DRDC's finite element model. The initial performance results reveal that the LC IN-625 FSPs show substantial improvements over the electroformed Ni prototype.

3.2 Structural components for ARMS

In the Advanced Robotic Mechatronics System (ARMS) project in collaboration with MD Robotics and Canadian Space Agency, NRC-IMTI utilized laser consolidation as a rapid functional prototyping method for making Ti-6Al-4V structural components '(Xue, 2003)'.

3.2.1 LC Ti-6Al-4V alloy

The LC Ti-6Al-4V material is metallurgically sound and exhibits excellent mechanical properties. 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 (Table 5), 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 stronger than the as-cast or annealed wrought Ti-6Al-4V, and comparable to the heat-treated wrought Ti-6Al-4V material.

Table 6 shows the bond strength of the LC Ti-6Al-4V to the wrought and laser-clad Ti-6Al-4V substrate. Under tensile testing at room temperature, the as-consolidated Ti-6Al-4V shows excellent bond strength: about 1048 MPa to wrought Ti-6Al-4V substrate and about 1072 MPa to laser-clad Ti-6Al-4V substrate. In both cases, the standard deviations are quite small. It is interesting to note that all bond test specimens failed in the LC Ti-6Al-4V due to the stress concentration effect instead of at the bond area, which indicates that the actual ultimate tensile strength at the bond area is higher than the data listed in Table 6.

3.2.2 Multi-functional structural components

One goal of the ARMS project was to develop a multifunctional structure capable of providing high structural stiffness, with dedicated features to support electronic driver/control cards and the data/power bus while allowing the dissipation of the heat generated by the electronic drivers. The laser consolidation process was successfully used to build functional demonstration pieces for the various designs as well as the final test-pieces of the multifunctional boom. Figure 7 shows a Ti-6Al-4V boom built using laser consolidation process. The boom has four ribs forming a slot to hold electronic card. The LC Ti-6Al-4V boom is used in as-consolidated surface finish, except the contact surfaces that were machined for assembling.

Conventional design of a space robot manipulator generally consists of separate booms and joint housings that are connected to each other through a flanged interface, which substantially increases the weight and complexity. One-piece integrated boom/housing design is preferable to reduce the weight, complexity and increasing interface stiffness of a typical robotic arm. However, it is extremely difficult or even impossible to make the one-piece integrated boom/housing using conventional manufacturing processes.

The LC process is a free-form fabrication process that allows the building of net-shaped functional features on existing components. Therefore, it offers the unique capability to build multi-functional boom on pre-built housing to realize the innovative design for one-piece integrated boom/housing. Figure 8 shows an integrated boom/housing manufactured using laser consolidation of Ti-6Al-4V alloy. The integrated LC Ti-6Al-4V boom/housing shows as-consolidated surface finish, except the contact surfaces that were initially machined for next stage final machining and assembling.

3.2.3 Laser consolidation of Ti-6Al-4V structural components

The Advanced Robotic Mechatronics System (ARMS) consists of four LC Ti-6Al-4V structural components:

- One Ti-6Al-4V multi-functional boom.
- Two Ti-6Al-4V housings #1 with interface.
- One Ti-6Al-4V housing #2 with integrated boom.

Laser consolidation process successfully built all of them from Ti-6Al-4V alloy. The ARMS prototype robotic joint was assembled by MD Robotics using the LC Ti-6Al-4V structural components along with the other mechanical and electronic components. Figure 9a and 9b show a close view of the assembled joint and Figure 9c shows the ARMS with required payload during laboratory testing. The real time testing results demonstrated that the laser-consolidated components performed very well and all design requirements such as low weight and high strength were achieved.

4. CONCLUSIONS

- By using the laser consolidation process, net-shape functional complex FSP shells and structural components for ARMS were successfully manufactured from IN-625 and Ti-6Al-4V alloys, respectively.
- The laser consolidation process readily accommodates rapid design changes since no hard tooling is required.
- Laser consolidation process is particularly suited for manufacturing components with complicated internal features (such as rails locating electronic cards along the booms) or the complex component consisting of multiple parts integrated into one final assembly that are very difficult or even impossible to make using conventional manufacturing methods.

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Dr. Lijue Xue received his Ph.D in Mechanical Engineering from Carleton University (Canada) and M.Eng. in Materials Engineering from Shanghai Jiao Tong University (China), respectively. As a group leader, Dr. Xue is currently leading R&D in the areas of laser consolidation, laser surface modification and gas dynamic spray. He is working extensively with various industrial partners and other research organizations.

TABLES

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

Table 1: Chemical compositions of alloy powders (wt.%)

Conditions		$\sigma_{0.2}$ (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

Table 2: Tensile properties of LC IN-625 alloy

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 3: Measurements of exterior fold crest to center line of the shell (Design #1)

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

Table 4: Measurements of wall thickness of a half shell (Design #1)

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 bar)	825	895	110	10
Wrought Ti-6Al-4V (solution treated aged bar)	965	1035	110	8
Wrought Ti-6Al-4V (solution heat treated + aged)	1103	1172	-	10

Table 5: Tensile properties of LC Ti-6Al-4V alloy

Sample No.	LC Ti-6Al-4V on wrought Ti-6Al-4V plate	LC Ti-6Al-4V on laser-clad Ti-6Al-4V
#1	1055	1095
#2	1074	1093
#3	1023	1030
#4	1040	-
Average	**1048±21**	**1072±37**

Table 6: Bond strength of the LC Ti-6Al-4V to Ti-6Al-4V substrate (MPa)

ILLUSTRATIONS INCLUDING CAPTIONS

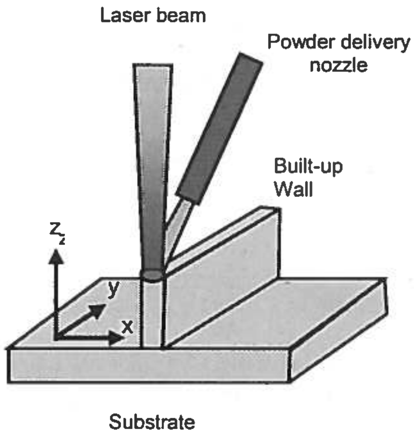
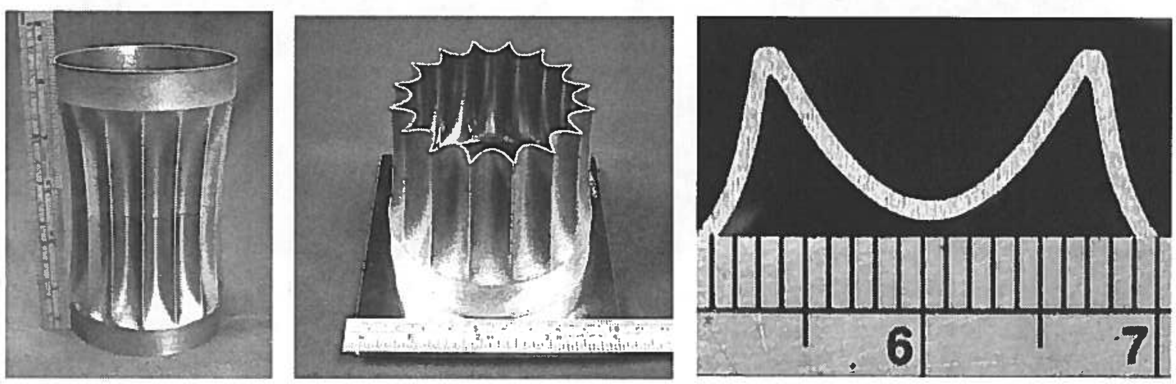


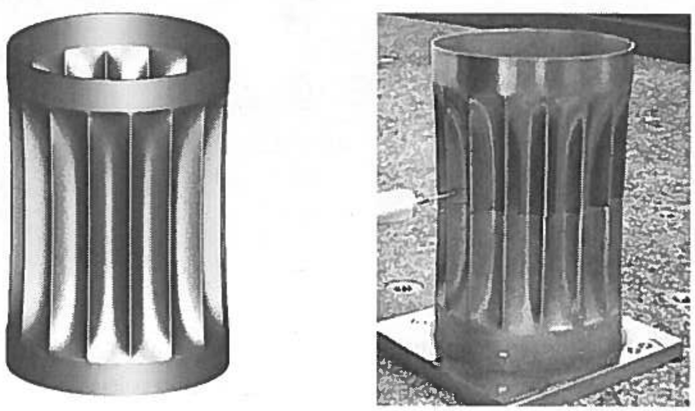
Figure 1: Laser consolidation process.

Figure 2: A CAD drawing of the complex FSP shell.



(a) (b) (c)

Figure 3: LC IN-625 FSP shells (Design #1), (a) full shell, (b) half shell and (c) magnified cross-sectional view of crests.



(a) (b)

Figure 4: FSP Shell Design #2, (a) CAD drawing and (b) LC IN-625 shell.

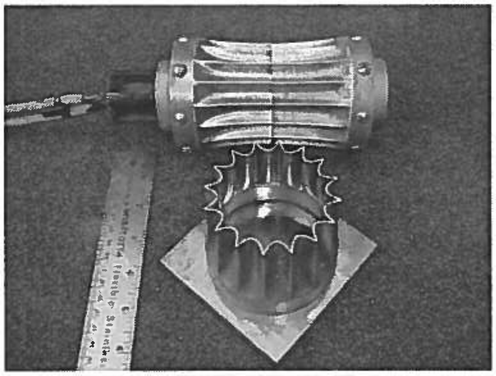


Figure 5: Assembled FSP using LC IN-625 shell.

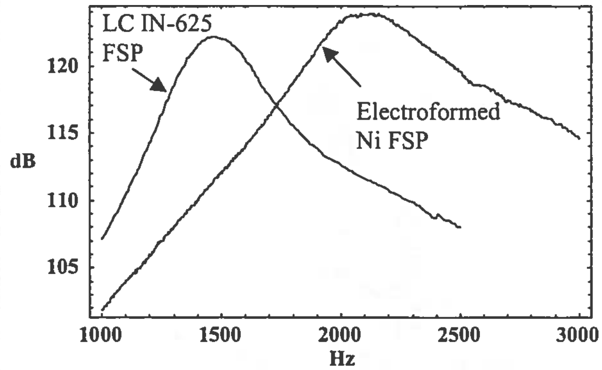


Figure 6: Transmitting response of LC IN-625 FSP & electroformed Ni FSP.

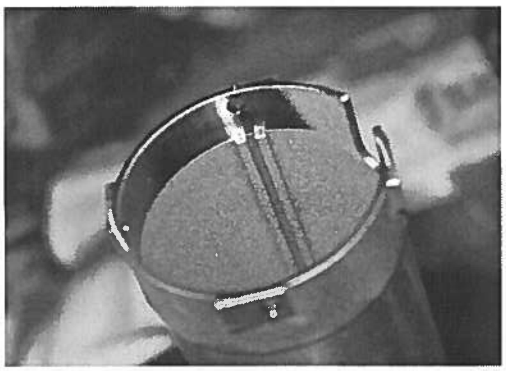


Figure 7: LC Ti-6Al-4V boom with a slot to hold electronic card, after final machining.

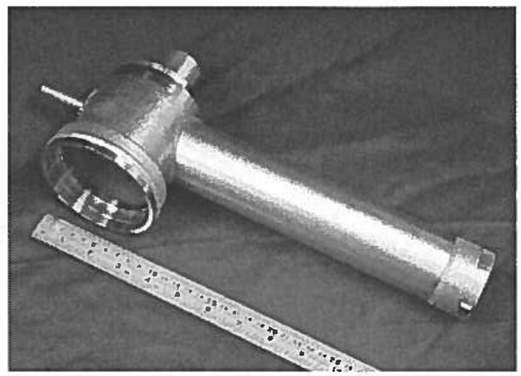
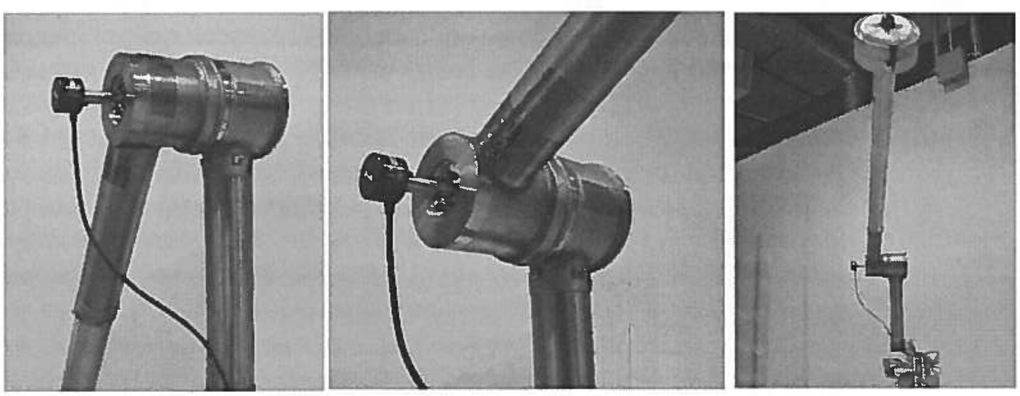


Figure 8: LC Ti-6Al-4V integrated boom/housing, after initial machining.



(a) (b) (c)

Figure 9: Assembled ARMS with LC Ti-6Al-4V structural components, (a) and (b) close views, and (c) testing with payload.