Precision Laser Peen Forming of Challenging Shapes for Aerospace and Marine Applications

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Abstract: Precision forming of components, including panels and structures, are of interest for aerospace and marine applications. Panels that do not match required shapes are often pulled down on to the structure thereby developing undesired tensile stress that can lead to fatigue and corrosion failure. An area of interest to shipyards is the fabrication in metal structure of complex shapes associated with modern ship design such as bulbous bows and skegs. Panels used to construct these and other structures can significantly benefit from precision forming of relatively thick steel or aluminum plate to complex shapes. This work is currently done at shipyards in a time consuming activity with limited precision thereby requiring significant hand fitting and flame shaping. However, laser peening as an advanced approach, can form these thick metal sections with high precision and repeatability saving time and expense in the shipyard. In this work we demonstrate the forming of a skeg panel of dimensions 2 meters by 2 meters by 15 mm thickness in Aluminum 5083

Laser Peening Technology,: The ability of high energy lasers to generate shock waves was first demonstrated in 1963 [1] and developed into laser peening from 1968 through 1981 [2,3] in the USA followed by extensive work in France since 1986 [4,5]. Laser peen forming was first proposed and demonstrated in 2000 [6] and followed by the concept of controlled forming using pretress [7]. In 2008 commercial forming began of the thick sections of wing skins for the Boeing 747-8 aircraft.

Laser peening is a highly controlled process that creates plastic deformation to depths multi-millimeters deep into a metal surface. The process is used to generate desired compressive stress and controlled component strain. Deterministic control, shot-by-shot for each laser pulse enables very specific stress or strain to be generated. Figure 1 shows the basic concept for the laser peening. A high energy laser beam, typically of 20 Joule energy, enables irradiances in the range of 2 GW/cm^2 to 10 GW/cm^2 over large spot sizes of 3 mm squares to 1 cm square[4]. The laser light passes through the water and forms a plasma in nanosecond time on a thin layer of aluminum tape adhered to the metal. Absorbing additional laser light and trapped by the inertia of the water, the plasma pressure builds to 10 to 30 kbars pressure in nanosecond time. By adjusting the footprint size of the laser beam, done as needed robotically in real time, the irradiance of the beam is set to create a plasma pressure wave that is one to two times the dynamic yield strength of the material being treated. The large centimeter scale of the laser beam footprint results in a planer pressure wave that propagates multi-millimeters deep into a metal surface before rarefying and losing it ability to plastically react with the material. A key benefit of high energy laser peening is the generation of this deepest level of plastic strain and thus the resulting deep compressive residual stress.

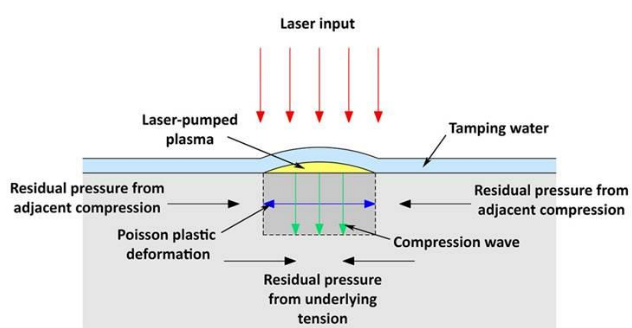

Figure 1. Laser peening concept and response of material compressing normal to the surface and generating transverse stress and strain response

As the material is compressed normal to the surface, it attempts to conserve its volume and expands in the transverse directions. Depending on the geometric stiffness (moments of inertia) of the component and the area being peened, a combination of stress and strain results associated with the peened area. Stiff components (larger moment of inertia) will mostly hold stress and will strain by only small amounts whereas thin components will show significant strain which can result in much less residual stress.

Forming of Large, Thick Panels; Skegs and Bulbous Bows: Laser peening is especially capable of precision forming large, thick section panels and performing exacting corrections to panel and component shapes. Several examples include skegs and bulbous bows. Skegs are an aft hull configuration especially used on combat ships. They surround the shaft just ahead of its screw. They deflect blasts downward providing protection for shafts on the other side of the ship. A twin-skeg arrangement enables the area between the skegs to be left open reducing drag enabling water to flow smoothly under the hull and to the propellers. Figure 2, left, illustrates a design of a twin-skeg configuration

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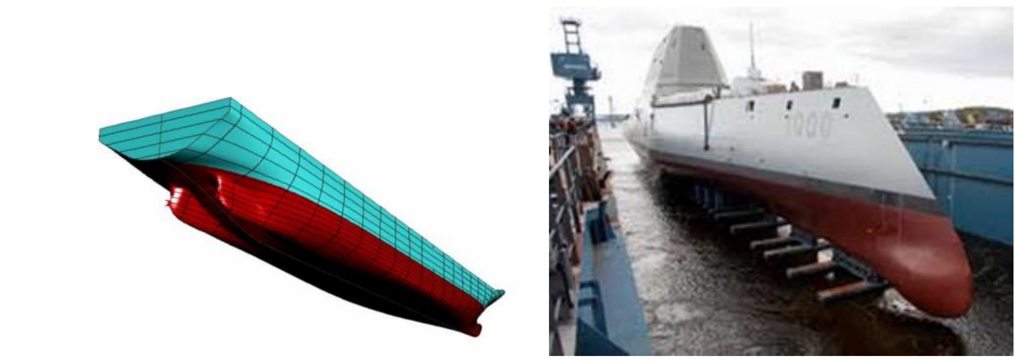

Figure 2. Open source drawing of a dual skeg ship design and photo of a ship with bulbous bow. Both structures designed to aid cruising efficiency.

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As another example of the need for forming of complex shapes, the bows of ships intended for long steady cruising are designed with a protruding bulb at the front at the waterline. These structures modify the water flow around the hull, reducing drag and thus increasing speed, range, fuel efficiency, and stability. Figure 2, right, shows an open source drawing of this structure termed a bulbous bow.

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We chose the forming of a skeg panel as a demonstration of the capability of laser forming for marine applications. A close look at Figure 2 shows the skeg assemblies composed of a number of small highly contoured panel sections of thickness in the range of 15 mm (5/8 inch) and approximately 2 m x 2 m (6 feet by 6 feet). Laser peening can precision form a 5083H116 aluminum skeg panel of this large dimension as a single integral unit larger than normally formed. We evaluated the required panel shape using a finite element analysis tool, defined laser peening parameters including pattern and irradiance..

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Hardware was designed and procured to assemble a pre-stress fixture. We defined the peening method and parameters to be used to shape the panel. This panel needed to be formed into an airfoil shape, that is, essentially formed into a modified cylindrical shape with tightest curvature at the fore end and transitioning to flatter curvature aft. To aid in achieving cylindrical curvature a uniaxial prestress fixture was assembled to apply a bending load in the fore to aft direction enabling the laser induced peening stress to sum with the applied prestress and thus predominantly develop strain in this preferred direction.

To begin forming, the panel was loaded into the pre-stress fixture where tensioning was initiated by bending in the desired direction of curvature or elongation. A simple prestress arrangement shown in Figure 3 was used to develop elastic bending of the panel. The load was set to generate a tensile stress of close to 80% of yield stress at the outer surface. Two aluminum panels of equal shape to the skeg panel were used as the base stiffener. Matching holes were drilled in the stiffener panels and in the panel to be formed. A 150 mm (6inch) diameter aluminum thick-walled tube was the fulcrum. The skeg panel to be formed became the top panel. Steel bolts of 5/8 inch diameter (16 mm) fitted with washers and nuts were inserted through the drilled holes on the panel ends. Strain gauges were glued to the panel surface and connected to an electronic half-wave bridge for strain readout. Bolts were uniformly tightened so as to bring the surface stress of the panel up to 2600 microstrain which equated to approximately 80% of the handbook value of 33 ksi (231 MPa) yield stress for 5083H116 aluminum. A 3-point curvature gauge and FARO arm were used to track and compare curvature to that predicted for 80% prestress by our FEA.

Peening was performed on the panel and shape measured post peening with the Leica interferometer tracking shape changes vs. model prediction. Figure 3, right, shows the skeg and prestress fixture assembly positioned in the peening cell with the laser beam delivery took in the foreground. This laser delivery tool is translated by the robot (also foreground) to position each laser spot to 0.1 mm (0.004 inch) accuracy. In a production environment much faster processing is done using a restoring mirror to position large groups of spots between each motion of the laser beam delivery tool.

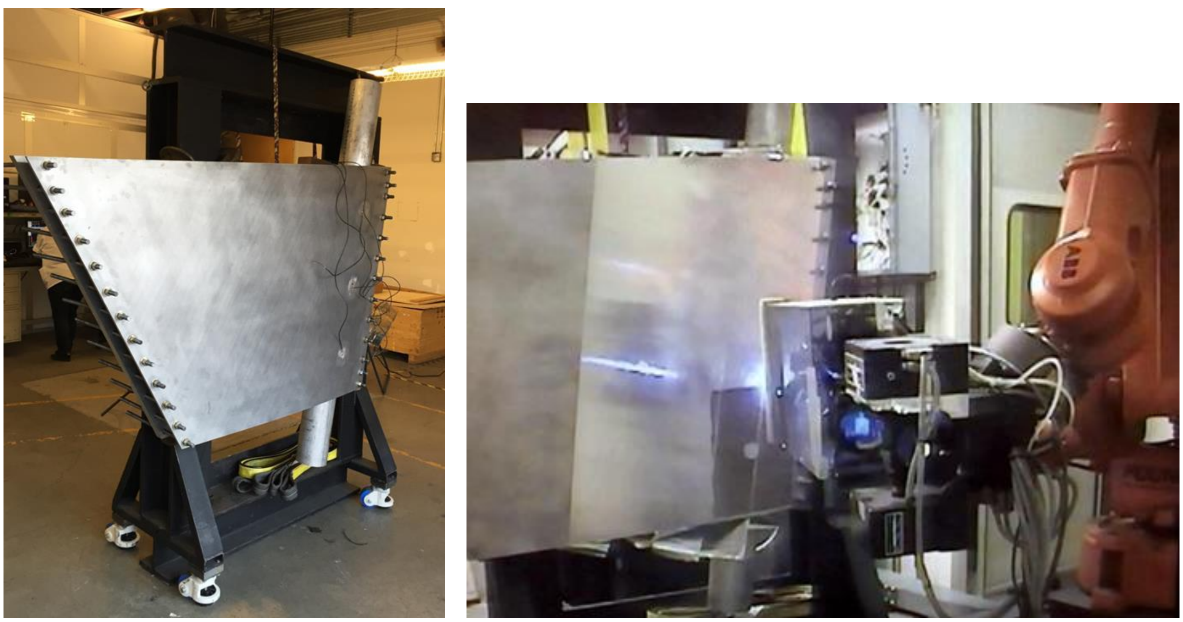

Figure 3. Skeg panel of Al 5083 H116 assembled in prestress fixture as used to bring the top surface under the tube fulcrum to 80% of the 33 ksi (231 MPa) yield strength. The three (3) strain gauges measure stress applied over the tube fulcrum as loading is applied. Right photo shows panel in peening cell.

Shaping of the panel involved processing four (4) separate areas each configured with peening parameters and coverage tailored to attain the local curvature required. Figure 4 shows the panel area peened during each of the four (4) area- applications (visits). Visits 1 and 2 covered the leading-edge of the panel, the end with the highest required curvature. In this area the peening was applied with heavier processing of 2 GW/cm^2 irradiance. At this irradiance square laser peening spots of 6.7 mm were used.

The full peening pattern applied in Visit 1 contained 8317 total peening shots and omitted coverage around the three strain gauges so that post-processing strain measurements could be used to verify the strain attained in the most critical areas. A second equivalent peening was applied to this Visit 1 region requiring the greatest curvature. Then a third and fourth application using a second and third pattern were applied to the mid and aft end of the panel using a reduced 1.5 GW/cm^2 processing irradiance and therefore a larger 6.7 mm spot size because of the lower degree of induced curvature required. The 2nd pattern used 6949 total shots and was completed as a single layer. The 3rd pattern used 7865 shots and was applied in a single layer. A total of 31,448 laser spots were applied to achieve the skeg panel shape.

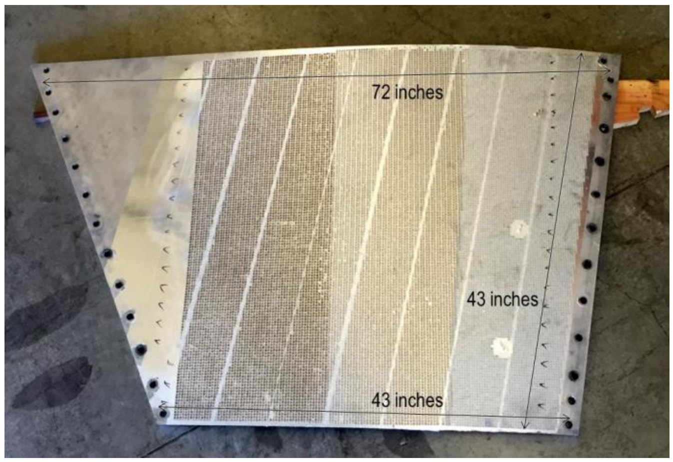

Figure 4. Skeg panel is shown post laser processing with ablative layer tape still intact and peening spots clearly visible. Three separate areas of the panel were formed to attain the desired panel shape. The fore (right hand) end requiring the highest curvature received two layers of peening. The tilted vertical stripes are an artifact of where the individual strips of ablative layer tape overlap.

Figure 4 shows the skeg panel post laser processing with ablative layer tape still intact and peening spots clearly visible. The tilted vertical stripes are an artifact of where the individual strips of ablative layer tape overlap. There was no reduced peening due to this overlap. Figure 5 shows an edge view from aft to fore of the panel clearly displaying the significant curvature achieved by the laser peen forming.
Post laser peening forming the panel was scanned with a Leica interferometer to generate a point cloud of 3-D data that was reduced to generate the actual panel shape and put it in a format to compare to the desired shape. Figure 6 shows the target panel shape and the result of the peen forming and data acquisition and analysis. As can be seen pictorially the formed panel (labeled Post Visit 4 shape) has an impressive leading edge curvature and matches very well in shape and absolute arc-height to the target shape. Additionally the exposed surface of the panel retains a compressive residual stress which is highly important in resisting stress corrosion cracking.

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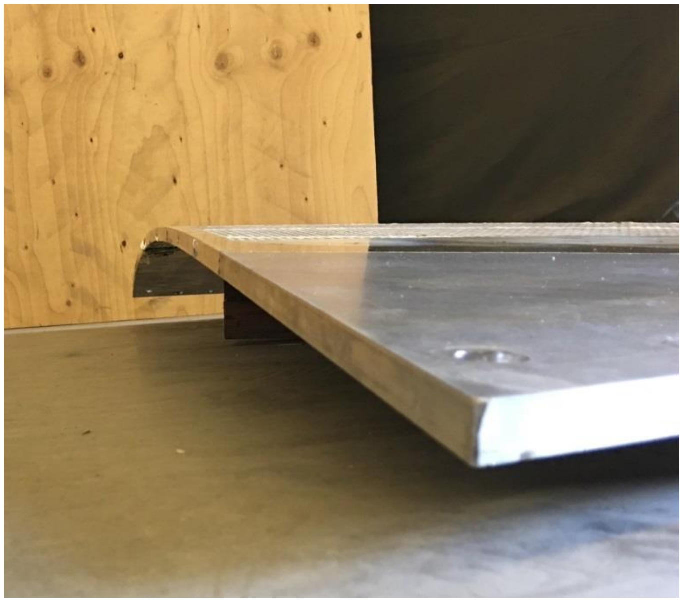

Figure 5. Edge-on view of 5/8 inch (15.8 mm) thick skeg panel showing curvature form aft to fore clearly showing 4 inch (100 mm) arc height generated by the laser forming.

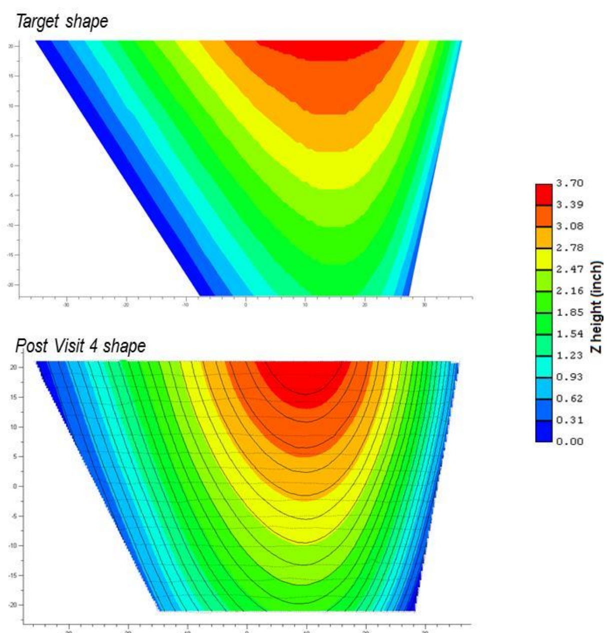

Figure 6. Analysis of the surface shape of the laser peen formed panel shows an arc height and general shape very close to the target shape.

The laser formed panel was packaged and shipped to the customer for evaluation. Initial response was very favorable especially considering that this single panel of about 36 square feet (4 square meters) area would replace approximately 16 panels of 154 square inch (0.25 square meter) area and eliminate approximately 400 inches (10 meters) of welding and associated potential for stress corrosion cracking.

Figure 7. Prestress hardware and beam delivery system used in production laser forming since 2008.

In production application, a panel to be formed, such as a skeg, would be made slightly oversized for processing and then trimmed to required shape. In this demonstration we simply drilled holes in the oversized area, inserted a thick-walled tube as a fulcrum and applied prestress loading by inserting bolts and attaching and tightening nuts to apply the necessary loading. In a production application a dedicated prestress fixture with hydraulic actuators would be built to achieve the loading in a streamlined and time efficient manner. Figure 7 shows a fixture designed and built for forming 1 inch (25 mm) thick sections of 105 foot (32 meter) long wing panels for Boeing's 747-8 aircraft. This equipment has been in operation in a Boeing Wing and Spar plant since 2008. In processing a panel is brought to the forming fixture suspended vertically from an overhead crane. Hydraulic pressure bars are maneuvered to the correct position and pressed against the panel creating the prestress. The top pressure bar (loads the fore area of the panel) and lower bar (loads the aft area of the panel) provide the bending load over the extended area of the skeg pamel. The laser system is located approximately 150 feet away and the process beam is delivered via beam tubes and mirrors placed in a trench within the floor. The laser beam is then directed vertically to a robotic deliver system and output via a rastering mirror over the area of the panel needing forming. In the automated forming process a skeg panel insertion and prestressing is done in 10 minutes and at 5 Hz laser pulse rate the processing is done in 2 hours.

References:

[1] R.M. White, *J. Appl Phys.*, 34 (1963) 2123.

[2] N.C. Anderholm, Bull. Am. Phys. Coc., 13 (1968) 388.

[3] A.H. Clauer, B.F. Fairand and J. Holbrook, in L. Murr (ed.) *Shock Wave and High Strain Phenomena in Metals – Concepts and Applications, Plenum, New Your, 1981, pp 38, 675.*

[4] R. Fabbro, J. Fournier, P. Ballard, D. Devaux and J. Virmont, *J. Appl. Physs.*, 68 (1990) 775.

[5] J. Fournier, *Thesis,* Ecole Polytechnique, France 1989.

[6] L.A. Hackel and F.B. Harris, *Contour Forming of Metals by Laser Peening*, US Patent 6,410,884

[7] L.A. Hackel, J.M. Halpin and F.B. Harris, *Pre-loading of components during laser peenforming,* US Patent 6,670,578.