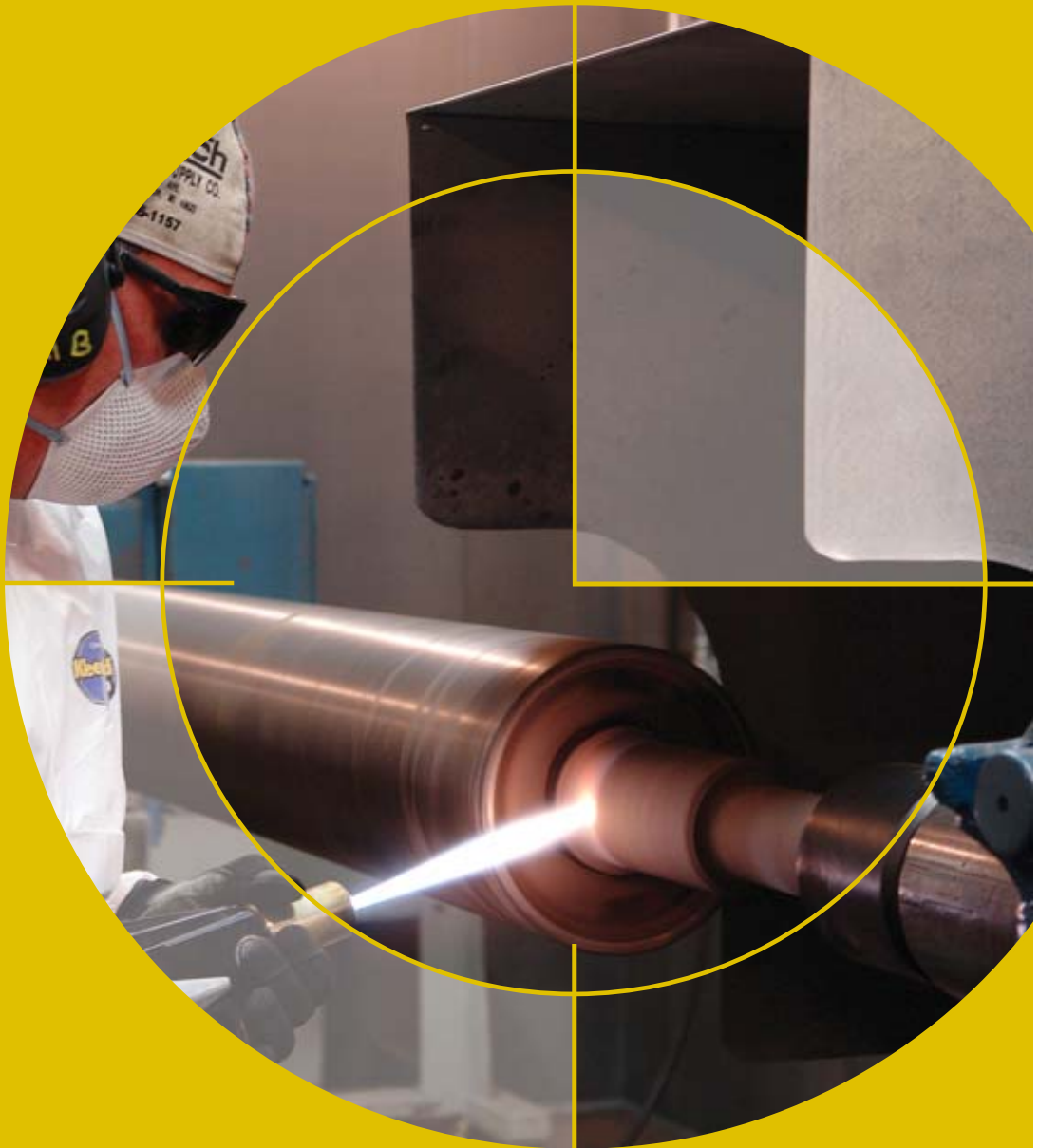


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Surface Engineering – Scope and Utility

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Surface engineering involves tailoring the surface composition and/or microstructure of the near surface region of a component without affecting the bulk. The main purpose of surface engineering is to improve surface dependent physical (reflectivity, colour, emissivity), chemical (corrosion, catalysis, oxidation) and/or mechanical (wear, friction, erosion) properties of engineering components and extend their service life. Improved functionality, enhanced performance, reduction in cost, innovating new products and conservation of scarce material resources are the notable advantages associated with surface engineering of metals and alloys.

Conventionally, surface engineering of the components like gears, cutter, pins, shafts made of steel is achieved either by surface hardening without change in composition (flame/induction hardening) or by incorporating carbon or nitrogen to the surface (carburising/nitriding) followed by a specific heating/quenching cycle. Many of these conventional techniques suffer from lack in precision, kinetic and thermodynamic constraints, toxicity of ingredients used and inadequate degree of improvement possible. To circumvent these limitations, high energy sources like laser, plasma, electron or ion beams are used to modify the surface microstructure and/or composition which offer unique combinations of flexibility, precision, time-economy, automation worthiness and vastly improved properties. However, large installation cost, high operational skill needed and inertia against changing established practices often prove enough deterrents for the industry to adopt surface engineering practices based on laser, plasma, electron or ion beams.

Deposition of coating may be achieved by physical, chemical, electro-chemical and thermal routes. Physical routes (different physical vapour deposition based techniques) are predominantly applied for deposition of thin film (both metallic and ceramic) for structural (wear and corrosion resistance) or functional (optical, magnetic and electrical property improvement) applications. Chemical (sol-gel, electro-less deposition) and electro-chemical (electro-plating, electro-phoretic deposition) routes may be applied for deposition of thin film/thick coating of metallic or ceramic species. Among thermal routes, hot dipping is usually applied to coat low melting metal on substrate, while thermal spraying may be applied for the deposition of metallic/ceramic materials on any substrate. The selection of suitable technique and coating depends on property requirement on the surface, economic consideration and ultimate application of the component.

Iron is prone to galvanic attack in moist environment and oxidation at elevated temperature, because iron oxide, like any other metallic oxide, is thermodynamically more stable than the native metal itself in aggressive environment. Thus, iron and steel components need protection through painting, galvanising, diffusion coating or any such surface protection strategy against corrosion or oxidation. Similar measures are also necessary to prevent chipping, wear, erosion and identical modes of degradation/failure by carburising, nitriding, laser hardening, etc. Thus, surface engineering is as important an activity as the primary manufacturing of steel or cast iron components. It is for these reasons the current issue of STEEL TECH has been dedicated to **Surface Engineering of Steel** to showcase some of the recent developments and promote awareness about the importance of this field. These articles address a wide variety of topics like plasma assisted surface modification (Alphonsa et al.), hydrogen embrittlement (Chattoraj), coating of nanometric rare-earth oxides (Suresh Babu et al.), diode laser assisted surface modification (Lin Li), application of sol-gel coating (Singh et al.) and laser forming for naval applications (Edwardson et al.). Since the subject and its scope are too vast and concerned issues are too many, the next volume of STEEL TECH will also contain a similar set of distinguished articles on the same subject.

Laser Forming for Ship Building Applications

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Abstract

Laser forming has become a viable process for the shaping of metallic components, as a means of rapid prototyping and of adjusting and aligning. The process is similar to the well established torch flame bending used on large sheet material in the ship building industry but a great deal more control of the final product can be achieved. This paper outlines the process and mechanisms of laser forming and reviews the potential of the process for the shipbuilding industry. Also outlined are experimental results of high powered 2D laser forming of thick section material, the results demonstrating the potential of the process for shipbuilding in terms of accurate net shape manufacture and the secondary distortion correction process.

INTRODUCTION

The laser forming process (LF) has become viable for the shaping of metallic components, and as a means of rapid prototyping and of adjusting and aligning. Laser forming is of significant value to industries that previously relied on expensive stamping dies and presses for prototype evaluations. Relevant industry sectors include aerospace, automotive, shipbuilding and micro-electronics. In contrast with conventional forming techniques, this method requires no mechanical contact and thus promotes the idea of "virtual tooling." It also offers many of the advantages of process flexibility associated with other laser manufacturing techniques, such as laser cutting and marking^(1,2).

Laser forming can produce metallic, pre-determined shapes with minimal distortion. The process has its origins in flame bending for ship construction, with the earliest work on LF beginning in the mid-1980s^(3,4). The process has similarities to this well established torch flame bending used on large sheet material in the shipbuilding industry^(5,6) but a great deal more control of the final product can be achieved. The process employs a defocused laser beam to induce thermal stresses in the surface of a work piece in order to produce controlled shaping.

It can be argued that the use of a defocused laser to form could be replicated by cheaper more cost effective means, e.g. a plasma torch⁽⁷⁾. However, it could also be

argued that laser forming could be a secondary process when considering the cost effectiveness of a laser system, in that a system would be purchased for primarily a cutting or welding operation, proven to be cost effective and competitive, and used for laser forming as a bonus additional process.

The laser forming process is realised by introducing thermal stresses (without melting) into the surface of a work piece with a high-power laser beam. These internal stresses induce plastic strains that bend the material or result in local elastic/plastic buckling⁽⁸⁾.

The laser forming process is principally used at the macro level to form metallic sheet material. Current research at the University of Liverpool (UK) and other research groups has shown that it can produce both parts with 2-D bends or 3-D spatially formed parts in a controlled fashion⁽⁹⁻¹³⁾. Research is also ongoing on the use of the process to remove unwanted distortion in conventionally formed parts, as well as the distortion due to welding operations, and in the use of lower-powered lasers to align micro-electronic components and actuators⁽¹⁴⁾.

The current picture of shipbuilding technology and projections for the near future suggest a continuing demand for metal forming processes. Currently, various types of sheet metal forming processes are employed in shipyards, these mainly being mechanical (such as roll bending). Using typical figures on the approximate levels of cost and time of forming in naval shipbuilding today, some projections for the demand for forming over the coming decade can be made. On the percentage cost of steel plate and section forming, considering that (i) steelwork fabrication is around 15% of the total labour spend on a vessel; (ii) steel preparation is approximately 15% of the steelwork fabrication labour spend; and (iii) steel plate and section forming is approximately 8% of the total steel preparation time, then (multiplying these factors together) it can be seen that forming constitutes approximately 0.2% of the total labour spend on a vessel. While this may appear to be a small fraction, it is projected that the cost of steel forming over the next decade would be significant (in the order of several hundred thousand dollars per shipyard for labour alone – not accounting for any re-

work which has been reported to be considerable).

Some projections for potential applications of laser forming in shipbuilding can be made by considering it either as a substitution process for existing forming methods (for reasons of enhanced flexibility, increased control, etc.), but also for wholly novel techniques that perhaps could not have been considered with other forming processes and which may even provide unique advantages. With this in mind, the potential applications under consideration in work at Liverpool are in the following areas:

- Hull section fabrication (and alignment in future assembly operations).
- Correction of distortion (due to welding and other processes).
- Shaft / propeller alignment.

In the fabrication of hull sections, the main area of interest is to use 2-D and 3-D laser forming to replace mechanical methods of steel plate bending, for a material thickness range of up to 20-25 mm (1 inch). The most straightforward case is the 2-D laser forming of part-cylinder shapes for hull skin panels to be subsequently welded together. However, as the capabilities of 3-D laser forming begin to evolve, it will be possible to consider using the process to produce primitive 3-D shapes involving various double-curvatures (“saddles” and “pillows”), which would then be patched together as elements of a larger, more complex structure. A key example of this concept is the “bulbous bow”, which has been quoted by a number of yards as being one of the most difficult and time consuming parts of a ship to construct.

The correction of distortion (chiefly that due to welding operations) in shipbuilding remains a significant issue, even though the last few years have seen the introduction of a number of advanced reduced distortion welding techniques (including laser-based or laser hybrids⁽¹⁵⁾). For many larger projects, the manual re-working of weld distortion can effectively use up 30% of the total ship production labour costs and the new techniques referred to above can often only be applied to ship deck flat panel construction, where component geometry allows. Therefore, there must be significant potential for using an advanced 3-D laser forming system to address at least some of this need, for example to correct plate distortion in light hull structures required to specified sea speeds. Since laser cutting is already being used and laser welding is currently under investigation, there is now growing interest in laser forming for thin plate if it can deliver productivity, throughput or cost savings.

For shaft alignment, there is potential for using laser forming for the straightening of rod and cylindrical tubes at smaller scales, where a glancing incidence of the laser beam allows an almost self-straightening effect to be established as the component is rotated and the

laser beam moved along the component length. It would be of interest to see if this could be scaled up to marine shaft parts.

Ships propellers are large components cast from special alloys and their performance characteristics depend strongly on the curvature variations along their surfaces. Once cast, if modifications are required either during production or at a later maintenance / repair phase, this requires large-scale and expensive machining capability. This is a further area for investigation of laser forming.

EXPERIMENTAL

To be relevant to the ship building industry, particularly for the fabrication of hull components, the laser forming process must be capable of thick section large scale processing. A number of studies have been made to this end in both 2D and 3D laser forming of various materials⁽⁹⁻¹⁴⁾. These studies and others have demonstrated the potential of the LF process to produce accurately repeatable geometries in a controlled fashion.

Presented here is a study on thick section 2D laser forming of mild steel. Investigated are the factors influencing a scaling of known scan strategies for thinner section materials. The study was conducted on 5 mm thick mild steel using three different laser systems. An initial study was conducted on an ElectroX 1.5 kW CO₂ laser system, wavelength 10.6 μm, run in continuous wave mode, described earlier (Fig. 1a). A second study was conducted on an 8 kW Ferranti CO₂ laser and a 0.9x1.5m Wadkin CNC table (Fig. 1b). A third study was conducted at the Lairdside Laser Engineering Centre (LLEC) on a large 5 Axis Laserdyne 890 beam delivery system, employing a 3 kW PRC CO₂ laser (Fig. 1c).

The sample dimensions used for the initial study were 360x190x5 mm, the samples were sprayed with graphite in order to increase the absorption of the 10.6 μm radiation, not as necessary for shorter wavelengths. For the other studies the sample dimensions were 800x400x5 mm. An attempt was made to reproduce the work on part-cylinders using thinner section material. For a part-cylinder the scan strategy is relatively simple, a series of straight line multi-pass bends across the longer axis will produce the desired geometry. For previous studies using 1 to 1.5 mm mild steel, titanium alloy and

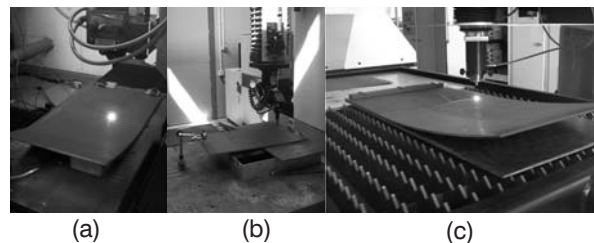


Fig. 1: a) Initial study set-up b) Ferranti 8 kW CO₂ laser, 0.9x1.5 m table, 800x400 mm sample c) 5 Axis beam delivery system

aluminium alloy sheet, a single pass strategy was used per line, i.e. after each single direction pass the bend angle was measured and the plate was allowed to cool before the next pass in the opposite direction was made. However, as the section thickness and hence material strength increases, more energy input is required to achieve the same forming result and if power availability is limited then thick section forming can be difficult. In order to address this issue a 'double pass' technique was developed initially for the laser forming of thick section high strength titanium alloy. However, it was found to be very effective for thick section steels. The technique involves a scan strategy of a pass in one direction followed immediately by a return pass in the opposite direction; the plate is allowed to cool after each double pass (forced cooled by air jet to decrease process time). The concept behind this strategy is that, providing the material surface is not damaged on the second pass, the additional energy input per pass is essentially akin to processing with a much higher laser power (factor increase dependent on overlapping interaction times); this was confirmed by thermocouple data. Another factor in this technique is that on the second pass the heat retained in the irradiated area from the first pass could serve to produce additional forming by reducing the temperature dependent flow or yield stress of the material, in that a hot plate is easier to form than a cold one. This implies that the technique could be used even where the available laser power is not a concern in order to improve the available amount of forming and reduce the processing time. To produce the part-cylinder one end of the plate was fixed to the work bed by a bar (Fig.1), the laser scans were started at the free end and worked towards the clamped end. This ensured that the plate would be flat and at the same height for the next line. The plates were forced cooled by a compressed air jet on the bottom surface.

For the smaller samples it was possible to confirm the geometry formed using a laser range finder based CMM system installed on the laser forming rig (Fig.1a). For the larger samples on the larger workstations (Fig.1b and c), a CMM system was not available so the formed geometries were confirmed by manually taking Z height measurements at 10 and 20 mm steps along the edges of the plates and inferring the geometry in the centre.

Studies were conducted into the 2D LF of part-cylinders along the shorter axis and the longer axis of the larger plates using a number of laser powers, pass numbers and step distances. Bends along the longer axis, 800 mm long, would demonstrate the potential of LF for larger scale applications. Bends of this length have not been reported in the literature. A thermocouple study was also conducted on one of the plates to confirm the double pass strategy and to ascertain the effect of laser line heating on the rest of the plate.

RESULTS AND DISCUSSION

The results of the initial study on 360x190x5 mm mild steel sheet using the 1.5 kW ElectroX workstation (Fig. 1a) are shown in Fig. 2. The processing parameters used were; 900 W, 6.5 mm beam diameter, 20 mm/s traverse speed, 30 lines, 10mm step and 6 double pass per line. As the sheet was small enough to be processed on this workstation the formed sheet geometry could be verified using the in-built CMM (co-ordinate measuring machine) system.

It can be seen in the Fig. 2 that it has been possible to produce a considerable bend in this thick section material with relatively low laser power using the 'double pass' technique. It can also be seen that a reasonably uniform part-cylinder has been produced in this size of plate, showing that the additional weight of the thicker section sample appears to have little effect on the outcome. For the next investigation this successful scan strategy was scaled up for the use on an 800x400x5 mm plate using a higher power laser (8 kW CO₂) and larger translation stages (0.9x1.5 m). As more power was available the processing parameters were effectively doubled (except beam diameter) for the doubled sheet size. These were; 1.8 kW, 6mm beam diameter, 40 mm/s traverse speed (doubled traverse speed means that the overlap time is the same as the smaller sample for the double pass), 35 lines, 20 mm step, 6 double pass per line at 60 second intervals.

The results of the larger scale forming strategy can be seen in Fig. 3. As the plates were too large to be measured by the CMM system the formed geometries were confirmed by manually taking Z height measurements at 10 and 20 mm steps along the two longer X and two shorter Y edges of the plates (as the plate sits unclamped on the work bed) and inferring the geometry in the centre (backed up by observations).

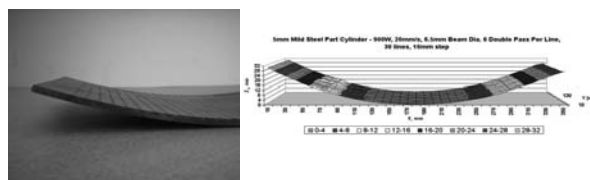


Fig. 2: Part-cylinder formed from 390x180x5 mm mild steel plate and CMM 3D contour plot of part-cylinder geometry

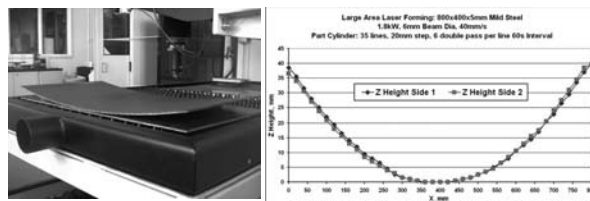


Fig. 3: 800x400x5 mm mild steel sheet formed into a part-cylinder and height measurements along the two longer axis edges

It can be seen in the above figure that a considerable amount of forming has been possible in the 800x400 mm sheet (~40 mm max). It was also observed that there was very little evidence of edge effects or unwanted distortion along the bend line on the shorter edges. This may indicate that as the bending line increases in length the factors that cause the edge effect phenomenon are somehow reduced. Further study will be required to fully understand this. For the sample size and when considering the larger tolerances used in the shipbuilding industry the observed non-uniformity (~3 mm) in the plate above after forming is extremely promising.

A third study was conducted using the 800x400x5 mm mild steel plates forming longitudinally along the X or longer 800 mm axis. This was to ascertain whether forming was possible over such a long scan track and if any significant distortion would occur. A third CO₂ laser system with limited power capability had to be employed here due to a temporary failure in the previous system during the investigation. Due to the system change the forming parameters were re-tuned, the following were used; 1.8 kW, 6 mm beam diameter, 83.3 mm/s speed, 35 lines, 10 mm step, 3 double pass per line at 60 second intervals. The higher traverse speed does allow for a better overlap of the passes along the 800 mm track. The results using this scan strategy are shown in Fig. 4.

It can be seen in the above figure that it has been possible to laser form along the 800 mm axis to produce a reasonably uniform part-cylinder shape. The amount of forming has only been limited by the power level used, ideally because of the increased scan path length an increase in power coupled with the increased traverse speed would allow for the same energy fluence whilst maintaining the same overlap time for the double pass. It was observed that over the 800 mm length the plate remains relatively straight with only a deviation near the edges of only ~2 mm. On the shorter edges (Fig. 4) it can be seen that, whilst the same curvature is present at either end, there is an offset between the two of approximately 2 mm which may indicate a slight longitudinal bowing of the plate. However, the distortion levels recorded in this sample when compared to shipbuilding tolerances are promising.

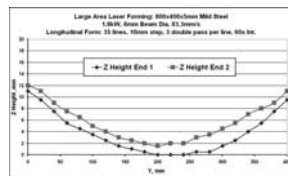


Fig. 4: Laser forming a part-cylinder along the longitudinal X axis from 800x400x5 mm mild steel sheet (height measurements along the two shorter Y axis edges)

The results here demonstrate that bends of this length and may be longer are possible using LF, which shows promise for large scale component manufacture. Providing a sufficiently high power level can be maintained and a high traverse speed can be realised (to avoid any temporal or asymmetric factors that may occur when forming a large component at slow traverse speeds) thicker section plates can be laser formed.

A fourth study was undertaken using a thermocouple technique to confirm the double pass strategy used on the larger plates (800x400x5 mm) and to ascertain the effect of laser line heating on the rest of the plate. The thermocouples were placed on the top surface apart from location 1 (on the scan line), where a hole was drilled in the bottom surface (to a depth of ~2.5 mm) and the thermocouple tip inserted and held in place with adhesive. The results of this study are shown in Fig. 5. Given is the temperature response from the three locations during one double pass and three successive double passes at 60 second intervals using; 1.8 kW, 6mm beam diameter, 83.3 mm/s.

It can be seen from the thermocouple data above that the double pass effect has been confirmed. The temperature rise for the second pass per double pass is built on the temperature remaining in the scan line from the first pass. This is therefore, akin to forming with greater power. In addition, the heat remaining in the plate aids the process by reducing the temperature dependent flow stress. The overlap per pass would be greater if the laser power and hence traverse speed were larger. Over the three double passes recorded it can be seen that the peak temperature per pass is increasing. The temperature increase per pass is built on the bulk material temperature which is steadily increasing. This effect may be beneficial to the process as an increase in the bend angle rate per double pass could be occurring over the three passes as the plate is heated up. It can be seen that at the other locations monitored little effect of the laser is experienced. This is possibly due to the size of the component and the relatively low thermal conductivity of the mild steel, emphasising the localised nature of the LF process

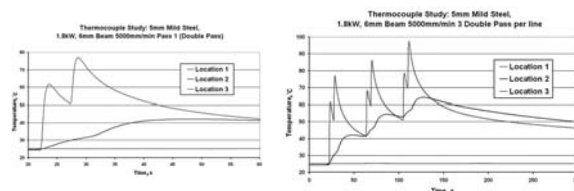


Fig. 5: Thermocouple output, 1 and 3 double passes, 800x400x5 mm mild steel sheet. Location 1 – bottom surface under beam, Location 2 – 20mm away upper surface, Location 3 – bulk temperature

CONCLUSION

The plate dimensions and amount of forming achieved in studies presented in this paper have proven to be a useful demonstration of the laser forming process in terms of ship component manufacture, in particular for the manufacture and or correction of distortion of hull components that require high accuracy such as the bulbous bow. It is unlikely that the whole component could be laser formed in one, more likely is that the shape could be split into manageable sub-components or surfaces and (laser) welded together after laser forming to make the final shape. There may well be an upper limit to the thickness of material that can be laser formed (thicker material than 5 mm is widely used in shipbuilding). The limitation may largely be down to available laser power and usable larger beam diameters (to match the section thickness increase). Whilst future work is planned utilising the full capability of an 8 kW Ferranti laser system, it may be necessary to find alternative heating sources for the process for thicker section materials, such as induction coils and stadium lights. These may provide a cheaper cost effective method of forming thicker materials where the unique capabilities of the laser are not necessarily required. However, a laser system can provide a user with a versatile cutting, welding, marking, surface heat treatment, etc. capability as well as laser forming. If a system was purchased for the other applications it could well be used for laser forming as a bonus application thus making it more cost effective.

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