LARGE DIAMETER AND THIN WALL LASER TUBE BENDING

Paper #107

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Abstract

Large diameter and thin wall tube bending is challenging for mechanical methods. Although laser tube bending has been used for <2" diameter tubes, larger diameter laser tube bending is not thoroughly studied yet. This paper reports the challenges and our progress in large diameter laser tube bending. Special issues such as cooling, surface non-uniformity, beam shape and cross section deformation were investigated in comparison with small diameter tube bending.

Introduction

Tubes are widely used in industry, and mechanical tube bending is a mature technology. A typical mechanical tube bending system is shown in Fig. 1. It has a bend die, clamp die, pressure die, and more advanced systems have wiper die and mandrel to control wrinkle and section distortion. Mechanical tube bending systems can bend tubes with high speed. For example, for tubes with 1 1/4" (27 mm) OD x .065" wall, a mechanical tube bending system can bend tubes to 90 degrees in less than 2 seconds, program up to 10 bends [1]. Readers can find a wide range of CNC tube bending systems in [2], and Ref. [3] gives a short discussion on principles of mechanical tube bending. Normally two dimensional and bending radius 2 times the tube OD can be achieved.

Mechanical tube bending needs expensive tools, and each setup can only produce a single bending radius. Straight segments are needed for clamping, thus compound bending is difficult. Another drawback of mechanical tube bending is that the exterior side stretches and has lower strength than the inside wall. For thin wall tubes, wrinkling and cross section distortion are also difficult to control.

Laser tube bending shows special advantages over mechanical tube bending [4-5]. It is inherently a non-contact process, the tube wall thickness won't thin much even at large bending angles. Many groups are studying laser tube bending, but the tubes studied are mainly tubes with OD < 2 inch, and the wall factor, which is defined as tube OD divided by wall thickness, is less than 30.

Business cares about cost, speed and process robustness. Thus, despite the flexibility of laser tube bending, to use laser tube bending in industry, one must demonstrate more winning factors. To compete with mechanical tube bending in mass production of small OD tubes, laser tube bending doesn't look promising because the speed of laser tube bending is 2 orders slower than mechanical methods, while mechanical methods can bend tubes with both high speed and high quality.

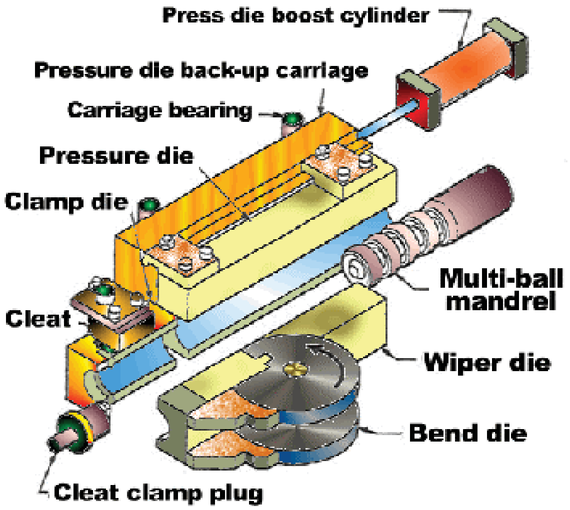

Fig. 1 Illustration of a mechanical tube bending system. (Courtesy from Summo Manufacturing)

A niche for laser tube bending likely resides in small batch production and tasks difficult to achieve mechanically, such as compound bending, fine tubning of bent tubes, etc. This paper discusses large and thin wall diameter tube bending, which is another potential niche for laser tube bending.

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(b)

(c)

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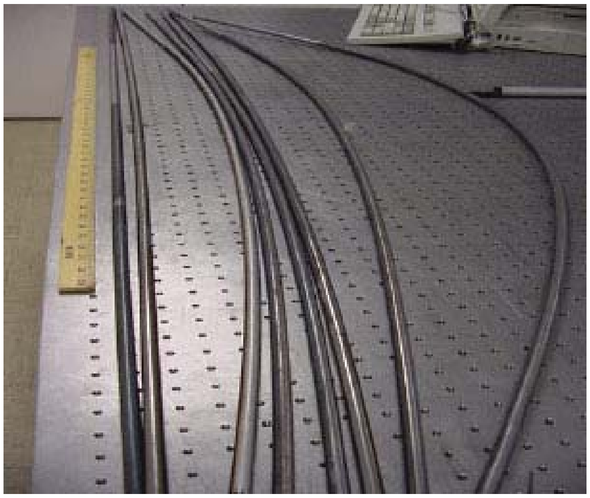

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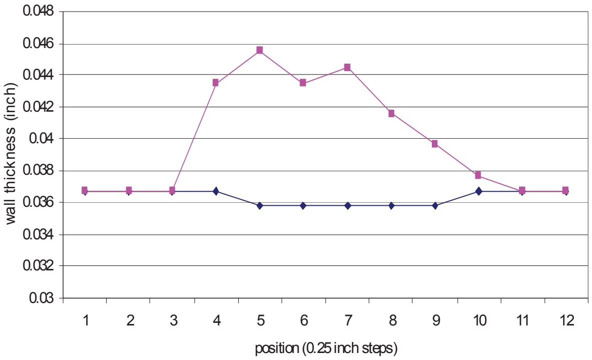


(f)

Fig. 2 SS304 tubes with 0.5” OD bent by Nd:YAG laser. (a) 4D bending achievable easily; (b) 3D transitional bending; (c) the tube with brazed fittings; (d) the tube bent with pre-existing brazed structure; (e) axial long tube bending; (f) Wall thickness variation.

Achievements in Small Diameter Tube Bending

In earlier stage of the laser forming project, we studied laser bending of ½” OD and 0.035” thick SS304 tubes. Using a 2KW Nd:YAG laser, we tried both circumferential and axial scanning tube bending. As shown in Fig. 2(a), the tubes can be easily bent to 4D (bending radius = 4 times tube OD) with high quality. The process is very flexible—it is totally digitally driven. Angles in the achievable range can be controlled by simply changing lasing conditions and overlapping step size and location. However, the 90 degree bend shown in Fig. 2(a) took more than 15 minutes to finish. Thus, for small diameter tube bending, laser tube bending is only applicable for precision prototyping or small batch production.

Fig. 2(b) showed the 3D capability of laser tube bending. The 3D transitional bending can be made without any straight edges between them. This provides new possibilities for tube design, especially when space is limited and the straight segments can be eliminated. Because this is a non-contact process, real 3D tube deformation can be conveniently programmed. Again, since the geometry change is final—there is no spring-back as in mechanical tube bending, and the bending happens in many steps, the geometry can be precisely controlled.

Fig. 2 (c) and (d) showed the special advantage of laser tube bending in contrast with mechanical tube bending. The tube has a brazed fitting and we created bending on both sides of the fitting. This represented a generally useful case. Tubes with add-on structures usually have alignment requirements. With non-contact laser tube bending, one can align the add-on structures when the tube is in a desired geometry and structure, and directly bend the tube assembly.

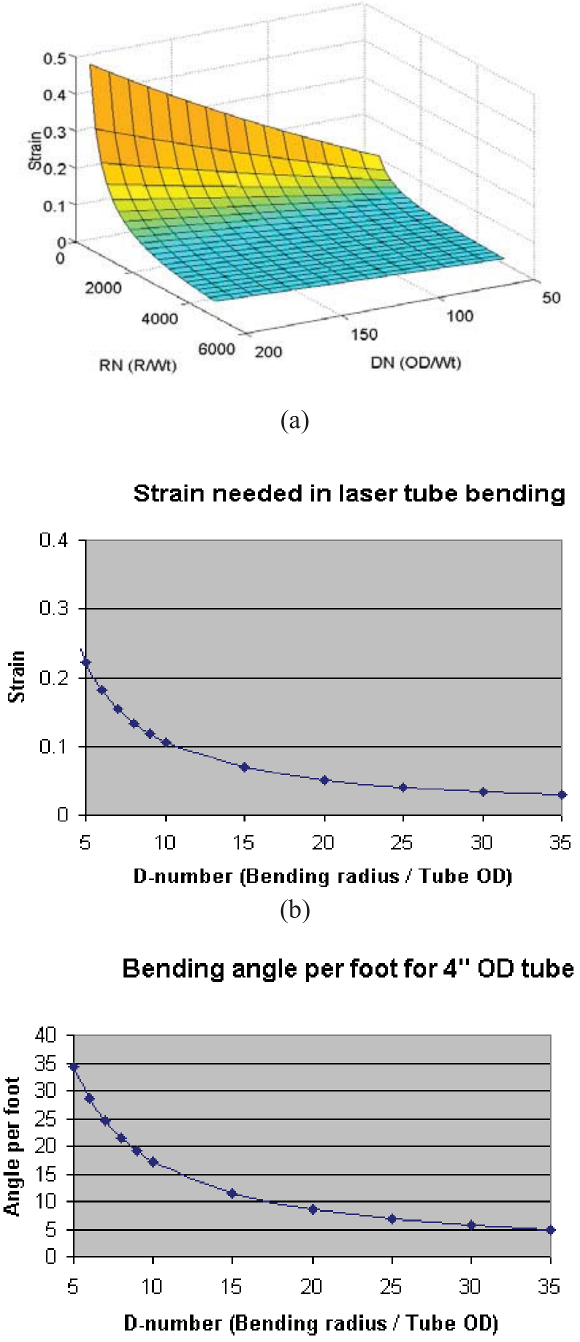
It was found that axial-scanning tube bending was good for long and large bending radius tube bending. As shown in Fig. 2(e), tubes 3 meters long were axially lased at feeding rate around 10-20mm/s, thus in less than 3-6 minutes, the long tubes can be bent into radius around 1 meters without investing in tooling, and the radius is variable, again, savings in tooling cost.

Fig. 2(f) showed the cross section variation of the ½” OD tube. The inner wall thickens ~30% and the exterior wall thins < 3%. The worst case cross section distortion is less than 0.8% [9]. This implies strong advantage over mechanical tube bending, which mainly stretches (thins) the exterior wall to bend the tube. On the contrary, laser tube bending can increase the strength in the bent zone while maintaining high cross section circularity.

In summary, good progress in small diameter laser tube bending had been made and many advantages had been demonstrated. It is realised that special niches should be found before the business really like to adopt it. Precise, small batch, weight critical and complex structure tasks are specifically suitable for laser tube bending.

Challenges of Large Diameter Thin Wall Tube Bending

Thin wall tubes are useful in reducing the weight in aircraft engines. “Thin wall” is a relative concept. There is no clear cut between thin wall and thick wall tubes. In this paper, we refer to wall factors > 80 as thin wall tubes, where wall factor is defined as the ratio between tube OD and wall thickness.



(a)

(b)

(c)

Fig. 3 Analysis of wall geometry on bending

Bending thin wall and large diameter tubes remains a challenging task for mechanical systems. Current NC mechanical systems can bend 6” OD tubes, but when the wall factor goes beyond 60, the process is extremely difficult to control even when the mandrel and wiper dies are used. Long segments of straight edges are wasted in clamping. Wrinkling and cross section distortion are so serious that post-bending cross-section correction steps are needed. Spring back and mechanical scratches on thin wall tubes are also bigger issues than in thick wall tube bending. Due to all these issues, mechanical methods for bending thin wall large diameter tubes are not considered to be inexpensive, fast, or reliable. We are considering laser tube bending as a potential replacement for expensive mechanical bending systems.

Defining D-number as the ratio between the tube centreline bending radius *R* and the tube OD, and assuming that only the interior wall thickens while the exterior wall remains its original thickness, form a pure geometry change point of view, the corresponding wall thickening strain ε to induce the necessary D-number bending is:

$$\varepsilon = 1/(\text{D-number} - 0.5) = 1/(R/OD-0.5) \qquad (1)$$

Introducing the normalized bending radius against wall thickness: *RN = R/Wt*, and the normalized tube OD against wall thickness or the wall factor: *DN = OD/Wt*, where *Wt* is tube wall thickness, then the strain is:

$$\varepsilon = 1/(RN/DN-0.5) \qquad (2)$$

As shown in Fig. 3 (a), given a fixed bending radius number, the thinner the tube, the larger the DN value, the higher the strain, and the more difficult to bend.

For a cylinder under pressure, the stress, both hoop stress σ_h and axial stress σ_a are proportional to wall factor,

$$\sigma \propto OD/Wt=DN \qquad (3)$$

Thus, the larger the wall factor, the higher the stress in the tube, and the higher risk the tube will become unstable. Further analysis of stress/strain may give more guidance on thin wall tube bending.

In GE Global Research, our task is to bend OD 4” x 0.028” wall thickness SS321 tubes into 5 degrees per 12 inch. The wall factor is 143. In our experiments, a 2 KW Nd:YAG laser system with fibre beam delivery (Lumonics Multiwave 2000) was used, the tube was handled by a Staubli robot.

Fig. 3 (b) showed the strain needed to bend any tube to the desired D-number, and Fig. 3(c) showed the bending angle per foot for the 4” OD tube. We can simply measure the deflection along the edge of the tube to determine the bending angle. It is clear that laser tube bending will have difficulty achieving aggressive bending such as D-number less than 4, since the tube wall must thicken > 25% to achieve it. For thin walls this is even more difficult.

It turns out that laser bending of large diameter and thin wall tubes faces the same challenges as mechanical tube bending.

In our earlier stage, we needed to prove that lasers can bend large diameter and thin tubes. Fig. 4 showed the tubes processed in our early stage experiments. The tubes were clamped from one end externally by a 3-claw fixture, it was lased for ~225 degrees for multiple scans using a spot size around 11 mm and laser power around 1.25 KW.

Fig. 4 showed the following quality issues:

1) Serious cross sectional distortion. Due to the large wall factor, the tube collapsed under thermal stress in the lased region, the lased region bends while the opposite side of the lased region flattens. Another observation is that the cross section distortion propagates a large distance from the lased region, the two ends 100 mm away from the lased region are distorted to an oval shape. The strength of the tube at high wall factor couldn’t support itself, thus lasing at some distance from the end doesn’t solve the problem.

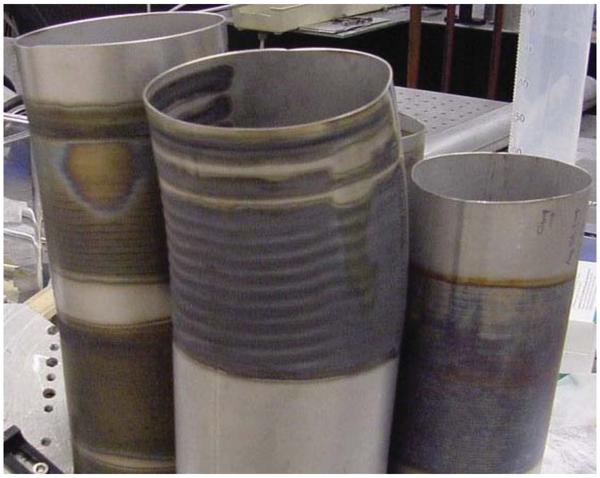


Fig. 4 Early stage results showed quality issues.

2) The absorption of the tube surface is non-uniform, leaving non-uniform surface discoloration and geometry changes. This maybe due to the non-uniform surface finish of the tubes before lasing. The production of

large diameter thin wall tubes normally produces shiny patches on the tube, the change in surface finish results in differences of laser energy absorption.

3) Wrinkling happened when the steps of multiple scans were too small. Laser tube bending relies on thermal plastic deformation to bend the tube, but for thin wall tubes, wrinkling is more likely to happen. This can be avoided by using less aggressive processing conditions.

A positive message, though, is that we proved that lasers could bend such large diameter and thin tubes to our range of desired bending angles. We don't need to worry about tube wall thinning in laser tube bending. The remainder of this paper discusses how we solved each of these obstacles and demonstrated that laser tube bending is a reasonable choice for large diameter and thin wall tube bending, and finally point out some future directions for research in this area.

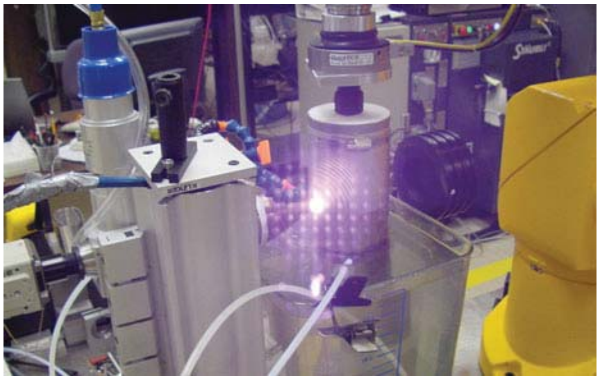
Distortion Control and Cycle Time Reduction

Learning from mechanical tube bending, the collapse of thin wall tubes during bending can be mitigated by mechanical constraint. Mechanical systems use a mandrel and a wiper die to prevent tube collapse and wrinkling. We found that by a much simpler fixture—the two-end plugs, the cross section distortion in laser tube bending can be controlled within our specification.

As shown in Fig. 5 (b), two plugs made of ABS polymer by a rapid tooling system are inserted into the two ends of the 4" OD tube. The plug has a small taper to allow it move in and constrain the tube deformation. The height of the plug is 4 inches, because we found that the lasing should be at least one OD of the tube to avoid end distortion. The plugs have vapour escaping channels and holes to allow the mechanical constraint work compatibly with the alternative cooling process.

Fig. 5(a) showed the experimental setup. The inside wall of the tube is constrained by plugs, the top plug connects to the robot arm. A program controls the motion of the robot and the laser firing time. The robot first rotates the tube in front of the laser, then dunk the tube with the plug into a water tub to actively cool down the tube to room temperature in less than one second, then lift up the tube, move onto next scan. The laser head has a nozzle to apply argon on the tube surface during heating. Fig. 5 (b) showed that the tube bent smoothly, and the circularity of the tube is maintained.

To this point, we proved that laser tube bending can bend the tube 5 degrees over 12 inches, and the straight edge needed is only 4 inches on both sides, far less than the 18 inches in mechanical tube bending. This means a huge material saving is possible in laser tube bending.



(a)

(b)

Fig. 5 (a) Laser bending experiments with two-end plugs and active alternative cooling; (b) Tubes remaining circular after plugs were removed.

To transition laser tube bending to production, speed and cost are always important factors. The fixture cost of laser tube bending is much less than that of mechanical tube bending, but the processing time should be acceptable to the business. To reduce the cycle time, we used the alternative active cooling as described above. The tube is heated, then very quickly quench cooled to room temperature, then moved onto the next heating cycle. 200 scans were finished in 20 minutes producing 5 degree bending in 200 mm length. Such a processing speed is acceptable to the business who has to consider multiple steps to bend the tube.

This strategy served two purposes. First, we don't have to wait a long time for the tube to air-cool, the water immersion cooling is effective, the tube always recovers to a same temperature scan after scan, thus the process is better controlled and processing time is strikingly reduced; second, the risk of material degradation is reduced due to the short time at high temperature.

Solve the Absorption Non-uniformity Issue

The surface non-uniformity issue remains in the experiment of Fig. 5, despite the use of argon protection and active cooling. Thus, although Nd:YAG laser is commonly used to do laser forming without the necessity of coatings, to solve the absorption non-uniformity issue in large tubes, we applied coating on the tube exterior. It was intended to improve the surface absorption uniformity and possibly to protect the surface from serious discoloration.

Fig. 6 Coated laser tube forming using circular beam

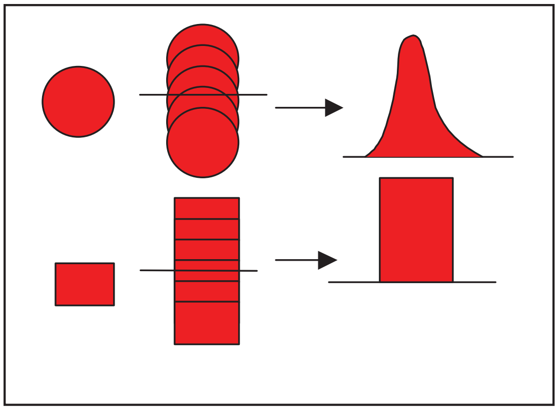


Fig. 7 comparison between circular and rectangular laser energy accumulation during laser scanning.

Dry graphite was coated on the SS321 tube, and Fig. 6 showed the resulting surface feature. It was quite a surprise in several ways. We used a laser beam of 6.5 mm, but the marks of laser heating were < 2 mm. This indicates that the thermal profile is not flat. The laser removed the coated graphite line by line, surprisingly, the scanned region turned into a shining line. With the coating, we see much more uniform absorption along the scanned line. So the coating revealed a question we had normally ignored—a smooth overlap of thermal profile in multiple scans.

Using the Rectangular Beam

Initial thought for the much narrower scanning marks shown in Fig. 6 is that the beam is not top-hat. But even if a totally top-flat circular beam was used, after scanning, the energy at each location would change into sharp-headed as shown in Fig. 7. The top-hat rectangular beam will maintain the uniform energy deposition in laser scanning, thus have a better chance of producing a uniform thermal profile.

Along this thought, we desired to change the circular Gaussian laser beam into a rectangular top hat beam. To do this, one normally uses diffractive optics. Diffractive optics is expensive and hasn't been well tested against high laser intensity at 1064 nm wavelength. Another worry is that even if we can get uniform rectangular beam profile at the focus, it may change to non-uniform energy distribution at defocus. While in laser forming, we desire changing the spot size in certain ranges. There is a general need to convert circular beam into rectangular beams, thus we invented the tapered crystal laser material processing unit to address this issue in general. The design is aimed at developing a general cost effective method to convert beam into any desired shapes.

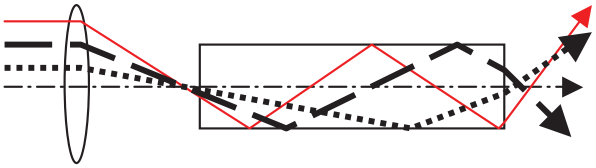
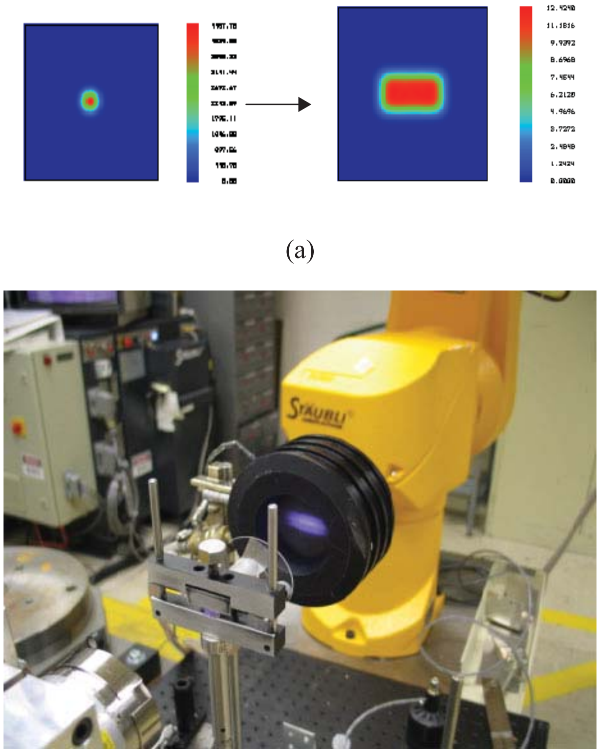


Fig. 8 Principle of beam spreading in waveguide.

Fig. 8 illustrated the principle of beam spreading in a waveguide. A divergent laser beam entering the waveguide will become top-hat after multiple reflections. The waveguide can be made in different geometries to meet different needs.



(a)

(b)

Fig. 9 (a) Simulation results of the beam intensity after tapered crystal; (b) Beam test of the tapered crystal

As a first step, we designed a tapered rectangular crystal. Fig. 9 (a) showed the simulation results. The fused silica tapered crystal converted the beam from circular to rectangular, the intensity is very uniform in a distance from 0 to 15 mm. Using taper helps control the divergence of the beam exiting the crystal, so that we can get sufficient working distance in experiments. Fig. 9 (b) showed the crystal in power and beam profile test. The crystal is carefully clamped between two pieces of aluminium at the injection side, while a protective cover glass is attached on the exit side. As the photo and burn paper test showed, the laser beam was changed into rectangular beam successfully. The measured energy transmission efficiency is above 85%.

Siding with an un-treated tube, Fig. 10 showed the first tube bent with the rectangular beam generated by the tapered crystal from the circular beam. With the much uniform laser intensity and the rectangular beam shape, the thermal scanning marks looks smoother. The graphite coating was removed line by line with a relatively clear cut from the unheated region. The angle achieved is around 4 degrees in 200 mm lased zone. With the system ready, process optimization will be carried out.

Fig. 10 The first SS321 tube bent with the rectangular beam, graphite coating, plug, and fast active cooling

Simulation

Working with Columbia University, extensive simulations have been carried out to understand the physics of laser tube bending. Effects of scanning schemes in laser tube bending were studied in [9]. The following assumptions have been made in the numerical simulation of large diameter and thin wall tube bending. The tube material is isotropic and has constant density. Material properties such as the modulus of elasticity, heat transfer properties, thermal conductivity, specific heat and flow stress are temperature dependent and the flow stress is also strain and strain rate dependent. Heat generated by plastic deformation is negligible compared with intensive heat input from the laser beam. No melting and no external forces are involved in laser bending.

Laser tube bending is numerically simulated as a sequentially-coupled thermal-mechanical process with finite element analysis (FEA). A commercial FEA software *ABAQUS* is used. The same mesh is created for both heat transfer and structural analysis. In structural analysis, using elements of C3D20 without shear locking and hourglass effect is suitable for a bending-deformation-dominated process such as laser forming. To remain compatible with the structural analysis, three–dimensional heat transfer elements of DC3D8 are used for the heat transfer analysis. A userdefined subroutine is developed in FORTRAN to describe the heat flux from the laser beam. All the points in the plane at z=0, which is the scanning plane (plane of symmetry) are fixed in the axial direction. In this plane, two adjacent points at the bottom of the tube are also fixed in the radial and tangent directions to eliminate the rigid body motion. Kinetic coupling constraint is applied in the part of tube inner surface to simulate the plug.

Simulation of large diameter laser tube bending, however, faces new difficulties. Due to the increased diameter, the simulation domain is orders higher. For example, a meaningful tube bending simulation should compute the thermal-mechanical process to a length at least 4*OD. Then, for the 4" OD tube vs. the ½" OD tube, the area ratio is 64. Simulation time can be 20 times longer than ½" tube bending even some measures were taken to shorten the simulation time. Ways to quickly predict the laser bending result are highly desired in the simulation of large diameter tube bending, especially for the purpose of guiding multiple scanning laser tube bending.

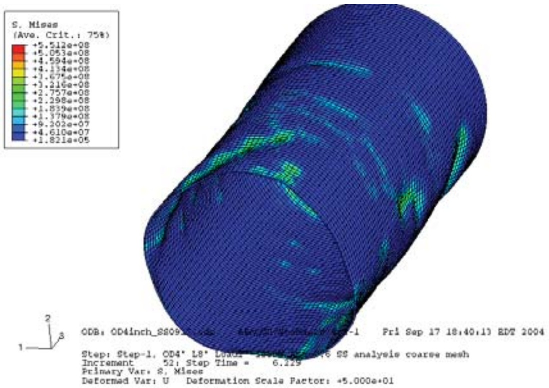
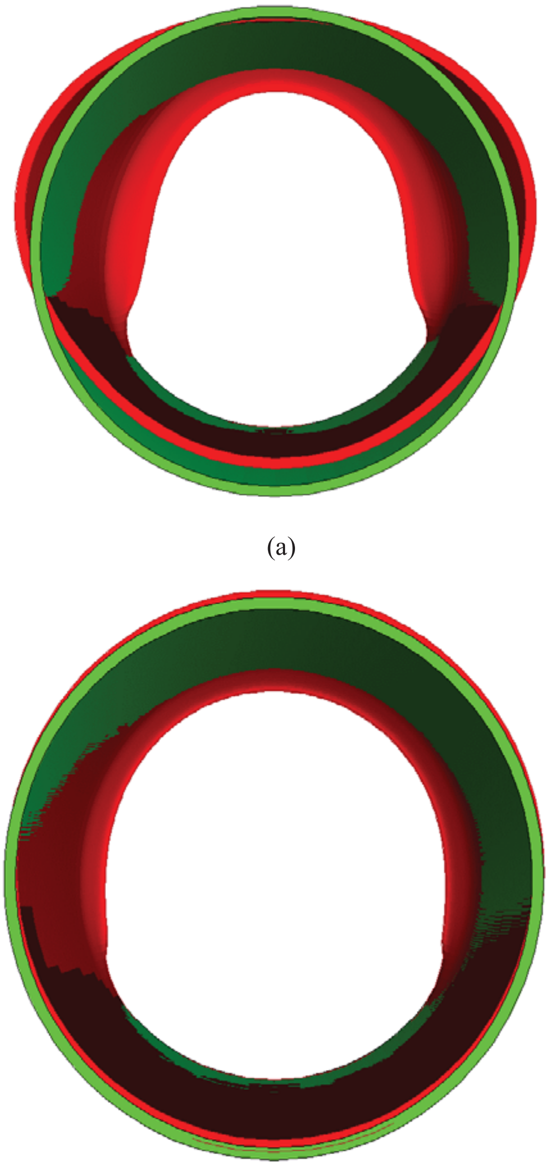


Fig. 11 Simulation predicts strong deformation in thin wall tube bending.

Fig. 11 shows the strong geometry distortion when a thin wall tube is laser heated circumferentially and air cooled without any mechanical assistance, which is consistent with our experimental observation (see Fig. 4).

Fig. 12 compared the cross section distortion with and without plug constraint. The fast quench cooling was considered in both cases. The simulation only calculated one laser scan, and the deformation is scaled up 50 times. Clearly, the cross section circularity is much improved with plug assistance, and the bending is more effective when the cross section is constraint to distort.



(a)

(b)

Fig. 12 Cross section comparison of the unscanned region in laser tube bending, (a) without plug and (b) with plug.

From top to bottom, Fig. 13 shows the thermal profile in laser scanning using a circular beam, a rectangular beam with the narrow side scanning around the tube, and the rectangular beam with the wide side scanning around the tube. Circular beam has a high temperature centre at the laser irradiation point; The rectangular beam scanning the narrow side around the tube shows a similar thermal profile as a circular beam; while the rectangular beam scanning along the wide side shows a flat thermal profile at the lasing location. The condition for rectangular beam scanning along the wide side is desired, because it helps achieve a smooth overlapping of multiple scans. Further study shows that the wide-side circumferential scanning can achieve 25% higher bending angle than narrow-side circumferential scanning, while distortion is also reduced.

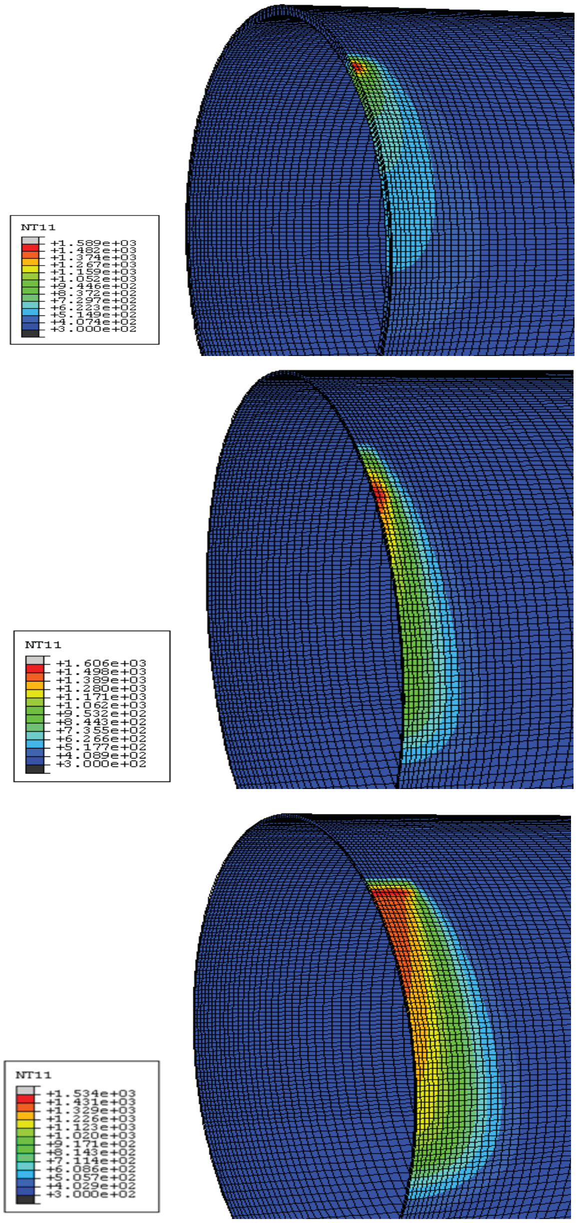


Fig. 13 Thermal profile comparison of circular and rectangular beams.

Fig. 14 shows the thermal history in large diameter tube bending with fast active cooling. The three groups of peaks are the starting, middle and ending points of the scanning path, and the two curves in each peak group are the exterior surface and interior surface, temperature unit in K. Fig. 15 shows the experimentally measured temperature at the laser heating centre, units in degree C. The conditions in Figs. 15 and 14 are not the same, but this shows the possibility of calibrating simulation with experimental results. With fast quenching, the whole tube is recovered to room temperature in less than 1 second, as shown by the abrupt ending of the temperature curves. This eliminates the idle time of lasing and shortens the cycle time.

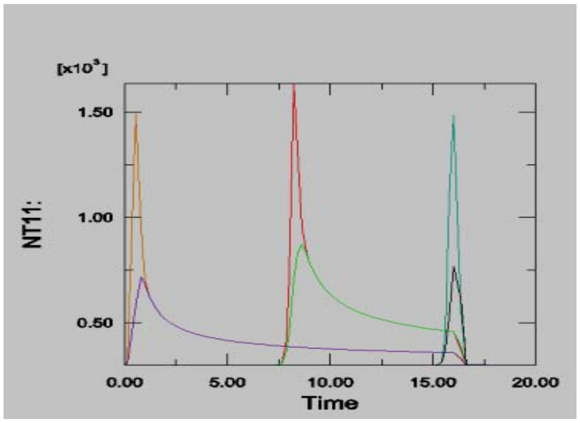


Fig. 14 Thermal history of tube bending with fast quenching.

Fig. 15 Experimentally measured temperature at laser heating centre.

Future Works

Our experiments to this stage have showed the feasibility and industrial value of using lasers to bend large diameter and thin wall tubes. There are still many challenges, but it looks promising for further research to transition this process to production. A tube bending DOE considering laser power, scanning velocity, spot size, step size, and number of scans will be carried out; the peak temperature will be monitored and the bending angle per unit length will be measured. The transfer function relating bending angle and processing parameters will be derived. With this transfer function, a digital driven integrated system for 3D laser tube bending will be developed.

Another future task is to study the physics through simulation. A faster simulation strategy will be developed to predict the final geometry given a processing condition, or provide the processing conditions given the desired geometry.

Conclusions

Large diameter and thin wall laser tube bending is of interest to industry; we have shown that it could be competitive against conventional methods. Laser tube bending faces similar challenges as mechanical tube bending, but the difficulties were solved by applying mechanical constraint, coating, active cooling, and by using the rectangular beam. Faster simulation strategies are needed to guide the process.

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