Laser Forming of Simple and Complex Tube Bends

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Abstract: Experimental investigations for bending tubes into complex and simple shapes by using lasers were conducted. The tests were performed on AISI 304L stainless steel tubes with outer diameters of 25 and 60 mm and wall thicknesses of 1.5 and 4.0 respectively. The stainless steel tubes were irradiated by a CO₂ laser beam. The laser beam intensity profile was the TEM_{01*} multiple laser irradiations on the circumference of the tube necessary for achieving large bending radius. Long waiting periods between the scans were required in order to allow the tube to cool sufficiently before the next scan could be applied. Active water cooling eliminated the need for the cool down time between the scans. The bending radius and the wall thickness increased with increasing number of multiple laser scans. However, it was found that when more than 10 laser scans were used the tube wall began to buckle. The tube surface wrinkled on the intrados as the bend angle was made sharper. The microstructure in the heated region showed grain growth near top side of the tube wall and grain refinement near the bottom side of the wall.

Key words: Laser tube bending, active water cooling, multiple pass scanning.

1. Introduction

Early studies on laser forming of thin metal plates were reported by Namba [1] and Scully [2]. Following these early experiments, laser forming has become a viable process for the shaping of metallic components, as a means of rapid prototyping. A number of forming studies have been done for applications such as, micro-manipulation of electronic components; straightening of car body shells without spring back; bending thick section plates for ship building industry [3].

In the laser forming technique, the part to be formed is irradiated with a laser beam heat source without using a mould or a press. The heating process induces thermal stresses in the metal. The internal stresses induce plastic strains which result in elastic deformation of the work piece. It is only when the strains reach elastic yield strength of the material that permanent change in the shaped can be achieved.

Different component geometries can be generated by using the same beam applied differently on the component [4]. Since laser forming is a non-contact process, it offers a wide range of unique application possibilities.

The mechanism of laser bending has been described and summarised by many researchers [5-7]. There are four basic mechanisms for laser forming of sheets, tubes and extrusions proposed. These are the temperature gradient (TGM); the point source (PSM); the bucking (BM); and the upsetting (UM) mechanism. The active mechanism is dependent upon the processing parameters and the material response. The TGM and PSM are dominant when the beam diameter and the wall thickness are nearly the same size. The difference between the two is the irradiation method and the dwell time of the beam on the work-piece. In the BM the laser beam diameter is much larger than the thickness of the work-piece. The UM uses a beam diameter much smaller than the material thickness, the effect of this is to increase material thickness and shortening of its length.

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In the application of laser beam for bending tube, the bending can be made by irradiating the tube around its circumference or along its axis. In the former case, the tube rotates typically between 180° and 300° whilst its outer circumference is being heated by the laser. The beam diameter is chosen such that it is greater than the tube wall thickness. The rotation speed of the tube is normally kept low so that a near homogeneous temperature distribution through the wall thickness can be maintained [8-10]. In axial method, beam path length along the tube is pre-selected this is then used to scan lines on the tube, after such scans the tube is rotated for a new line to be created. It has been found that cooling of the heated tube by external means reduces the time it takes to bend the material. Typically water has been found to be quite suitable for this purpose.

A limited number of computational and experimental studies have been done on the mechanism of laser pipe bending. The influence of laser parameters was experimentally studied by Hao et al. [11]. Based on their experiments they proposed a closed form solution for predicting bending angles and wall thickness as a function of laser power and scanning speeds. They found that there was a minimum energy required before any bending could be induced; the maximum would result in surface melting. The bending angle increased with the laser power. At a given laser power, the bending angle increased with the number of scans across the tube. The increase in the bending was not linear with the laser power increase.

Li et al. [12] conducted detailed experimental and numerical studies on the relationship between laser parameters and geometry of the bending material. The geometric features included circularity, wall thickness and the bending angle. The principal laser parameters were spot size, scanning speed, number of scans and scanning angles. Finite element methods (FEM) was used for numerical studies, it was shown that the bending mechanism was a combination of pipe

shortening in the axial direction and the thickening of wall thickness in circumferential direction. Hao et al. [11] also studies these effects using numerical simulation, their conclusions were similar to the ones already mention. The outward bulge on the inner side of the laser treated area was attributed to axial and tangential thermal strains, as a result of the induced temperature gradients along the tube wall.

The present paper reports experimental investigations of laser bending of stainless steel pipes and tubes. Simple and complex shapes were generated by heating the tubes with a CW CO₂ laser beam. The steel material used was the 304 L type stainless steel. In order to generate large bending angles it is necessary to heat the tube with multiple laser scans. Between the scans, the material must be allowed to cool down so that the temperature gradient can be re-established before the next scan. In these experiments different methods were investigated for cooling the heated tubes. The buckling of the wall as the number of laser scans is also reported. A detailed investigation of the effect the laser heating has on the microstructure is reported.

2. Experiment

A 5 kW continuous wave CO₂ laser was used for tube bending. The beam profile of the laser is a donut (TEM_{01*}). The laser power was varied from 1 to 3 kW, and the beam diameter varied from 5 to 10 mm. During the experiments the laser beam was focused on the external surface of the tube. One end of the tube was clapped to a rotating chuck. The rotation angle of the tube was varied from 180° to 300° and the speed varied from 50°/sec to 75°/sec. The circumference of the tube was irradiated with multiple laser scans at the same location. The laser beam was then moved an adjacent location overlapped by 20% of the beam diameter. The number of consecutive scans delivered to the same location was varied from 2 to 20. After each scan the tube was left to cool in air, this reduced the surface melting. The time for cooling was between

30 sec to 3 min. In another set of experiments the tube was cooled by flowing water continuously through the tube as shown in Fig. 1. The water flow rate was maintained at 0.5 L/min.

The dimensions of the 304L stainless steel tube was 25 mm in outer diameter and 1.5 mm wall thick. The tube was cut to 100, 150, 200 and 300 mm long sections. Before the tubes were laser treated, the surfaces were coated with graphite and “Reflexnix” to increase laser absorption. After the laser tube bending, optical microscopy was used to investigate the microstructure. Cross section of the pipes were cut, mounted and polished for metallurgical examination.

3. Results and Discussion

3.1 Tube Bending Geometries

A 60 mm diameter stainless tube with a 4 mm wall thickness and 1,000 mm in length was laser formed. An optical image of the tube is shown in Fig. 1. A laser power of 3 kW and a rotational speed of 30°/sec were used. Five sections of the tube were irradiated with 10 laser scans. The separation of the laser scanned sections was done in order to increase the bending radius. The continuous water cooling proved beneficial during the experimentation. The bending angle achieved using the above mentioned parameter was 10°. There was a 5% decrease in length suggestion that wall thickening took place.

Stainless steel tubes of 150, 250 and 300 mm in length were laser formed. In the experimental runs the scanning angle of the tube was set at 270° and the rotational speed at 75°/sec. The beam diameter was either 5 or 10 mm and the laser power 2 kW. The result of the 150 mm tube bending is shown in Fig. 2, no water cooling used in this process. The laser scanning of the tube was commenced from the free-edge progressing to the clamped edge. A total of 5 consecutive passes delayed by 3 min were made at each position covering nearly 3/4 of the tube length. The adjacent scans were overlapped by 30%. A bend angle of 20° was achieved on this relatively short tube.

The tube shrank by 10 mm in length after the irradiation. The surface finish of the tube was not completely smooth it consisted of ridge like appearance. This appearance is caused by restriction in thermal expansion forcing the surface to bulge. The overlap between the adjacent tracks was set at 30%, consequently it was insufficient to generate a completely smooth surface.

The laser tube bending process starts from the uniform heating in the direction of the wall thickness. As the material is heated, thermal compressive stresses develop in the material. The thermal stresses are induced in both the axial and circumferential directions. The Young’s Modulus and the Elastic limit of the heated zone both decrease with the increase in temperature. As the tube rotates and the laser beam moves on; the material is cooled off by water, the adjacent cold material inhibits the heated surface from axial expansion, thus resisting the thermally induced stresses. The constrained heated surface swells beyond its elastic limit into the plastic zone. The restriction in the axial expansion is counter-acted by the increase in the wall thickness in the radial direction and consequently the shortening of the tube. The shortening in the axial direction and thickening in the radial direction lead to the tube bending towards the laser beam.

Fig. 3 shows the result of a 200 mm long tube, irradiated by a laser with 2 kW, at 75°/sec rotational speed. In this case the tube was cooled with flowing

Fig. 1 An experimental set showing closed loop water cooling and the laser system.

Fig. 2 Laser tube bending.

Fig. 3 A 35° degree laser formed tube.

water. There was no delay period between the laser scans. The time duration of a single scan was typically 3.6 sec. A much larger bend angle of 35° over a longer radius was obtained. The shortening of the tube in the axial directions was about 10%. The scanned tracks were overlapped by 70% this resulted in a much smoother surface compared to Fig. 2. The wall of the tube was also thickened in the irradiated region.

Fig. 4 shows a nearly 90 degree and a contiguous bends created by laser forming. Fig. 4a shows a bend

angle of ~85° over a long radius, while Fig. 4b shows contiguous angles of 55° and 85°, respectively. In Fig. 4a the tube length was 250 mm, a total length of 100 mm was irradiated with the laser. In this set-up the laser power was decreased to 1.5 kW and the numbers of consecutive laser passes was increased to 10. The increase in the number of passes lead to an increase in the bending angle. The surface quality of the tubes was not very high. The tube wall was characterised by outward buckling. The variation of adjacent track overlap, 10% to 80% did not have any effect on the buckling phenomena. Fig. 4b shows compound bends in a tube of 300 mm length. Twenty laser scan passes were used in order create the sharp bend. Despite the water cooling surface melting took place on the tube. The buckling of the surface almost resembles surface wrinkling.

(a)

(b)

Fig. 4 Complex laser tube bending: (a) 85° degree bend on a tube of 250 mm long, (b) 55° and 85° contiguous bends on a 300 mm long tube.

3.2 Deformations

The thermally induced buckling of the tube wall was further studied by irradiating the tube with multiple scans ranging from 2 to 20. The laser power used was 1.5 kW and beam diameter was 5 mm. In these experiments the irradiation was limited to single tracks, i.e., no large area scanning was carried out. Fig. 5 shows a half section of a tube depicting the treated areas. Fig. 6 shows detailed optical photo-macrograph of the irradiated zones. The cross-section presented in Fig. 6a was irradiated with 5 consecutive passes and continuously cooled with water. It can be seen from this figure that the tube wall has thickened where it was laser treated. There is a clear bulge on the out wall, which is accompanied a slight depression on the inside. When the number of laser scans was increased to 10 (Fig. 6b) the bulge of the wall also increased leading to overall wall thickness. The inside depression of the tube wall remain more or less the same as when the 5 passes were applied. As the number of laser scans was increased further to 15 scans, the tube began to buckle (Fig. 6c). The overall thickness of the wall did not increase any more. In Fig. 7d, 20 laser scans were applied; the buckling of the tube is most pronounced.

The outward bulge of the tube wall which is observed when heating with 5 and 10 laser scans can be described best by the upsetting mechanism. The bulge is caused by the restriction in thermal expansion of the heated material in the axial direction. The only degree of freedom for the material to expand is in the radial direction. As the number of laser scans is increased, the wall bulge also increases in addition the wall begins to show a buckling deformation. The outward bulge in the tube wall and the shortening of the tube length give rises to a combined laser bending mechanism. These mechanisms are the buckling and the upsetting mechanism. This combined effect was identified by Li et al. [13] in laser forming thin wall aluminium tubes. In this case the wall thickness

reached a maximum as it cannot accumulate an unlimited amount of material. The axial plastic compression of the heated material give rise to the outward buckle of the tube, with its thickness retained.

3.3 Microstructure

Fig. 7 shows the optical micrograph of the as received AISI 304 stainless steel before laser treatment. Fig. 8 shows microstructures of the actively laser formed tubes. The tube was irradiated with 5 un-interrupted laser scans, with water cooling. Fig. 8a shows microstructure near the outer surface of the wall. The microstructure in the laser treated region consists of large austenitic grains, similar to those of the untreated AISI 304L as shown in Fig. 6. Fig. 8b shows microstructure near inner surface of the tube wall. The grains in the microstructure are refined. The grain refinement is due to the higher cooling rate aided by the water. During the transient heating to peak temperature, the material is heated to austenite temperature. The temperature gradient increases considerably in the surface vicinity and drops rapidly as the distance from the surface increases. The outer surface of the tube formed a bulge because of the large thermal gradients associated with laser irradiation. The rapid cooling by water from inside up gives rise to finer microstructure in the part of the wall directly in contact. This is because the nucleation rate of new grains under cooling is higher than when there is no cooling.

Fig. 5 Photograph of a wall cross section showing thickening and buckling.

Fig. 6 Optical photomicrographs of wall thickening and deformations: (a) wall thickening after 5 laser scans; (b) gradual wall thickening after 10 scans; (c) thickening and buckling of wall after 15 laser scans; (d) thickening and severe buckling after 20 laser scans.

Fig. 7 Optical micrograph of the as received AISI 304 stainless steel.

Fig. 8 Microstructure of steel irradiated with 5 consecutive laser scans with water cooling: (a) grain growth near the surface wall, (b) grain refinement near the bottom of the wall.

Fig. 9 shows microstructural changes induced when 10 consecutive laser scans were used. Fig. 9a shows the microstructure near the outer side of the wall. Again it can be seen that the microstructure consists mainly of austenitic grains. In addition the grains contain slip lines. The primary grains are

much larger than the original untreated material, and the ones irradiated with 5 laser scan (Fig. 8). It appears that as the laser beam continues to irradiate the material the grain growth continues as long as the temperature is increased in the material. This phenomenon was also observed on the thickening of

Fig. 9 Microstructure of the tube irradiated with 10 consecutive laser scans with water cooling: (a) near the top surface of the wall; (b) near the bottom surface of the wall.

the tube wall.

In Fig. 9b, the resultant grain microstructures are fine structure austenitic grains. The mechanism of the grain refinement is the same as that discussed above. The microstructures shown here indicate when the laser irradiation of the tube is not carefully controlled leads to melting and solidification in the laser treated region. The consequence is that dendritic and fine grain structures are formed. When the irradiation is rapidly quenched with water, grain refinement and growth take place. It is apparent that the laser irradiation affects the net resulting grains.

4. Conclusions

The work presented here shows that simple and complex tube bending can be realised using lasers. The following conclusions can be drawn:

(1) The bending angle and bend radius can be increased when multiple laser scans are applied on the surface. However, it is necessary to allow the material being bent to cool down before any subsequent laser scan is applied. This cool down time makes the

process very slow. The present study shows that, when water cooling is used, it reduces the time it takes to produce a complex or simple bend.

(2) There is a limit on the number of laser scans that be used before the tube wall buckles. The wall thickness increases with the number of laser scans, until the tube wall buckles. The wall buckling in bending radius leads to wrinkled bend in the intrados.

(3) When the tube is heated to near melting point the microstructure is transformed from the single austenitic structure to columnar dendrites and ferrites. The microstructure remains unaltered in the matrix.

(4) When the tube is continuously cooled with water, a grain growth in the microstructure is observed in inner wall of the laser formed tube surface, while grain refinement occurs on the outer wall of the tube.

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