Experimental study on sheet metal bending with medium-power diode laser

M-L Chen[1], **J Jeswiet**[1]*, **P J Bates**[2], and **G Zak**[1]
[1]Mechanical and Materials Engineering, Queen's University, Canada
[2]Chemistry and Chemical Engineering, Royal Military College, Canada

The manuscript was received on 15 July 2007 and was accepted after revision for publication on 8 November 2007.

DOI: 10.1243/09544054JEM951

Abstract: In an experimental study of laser sheet bending, a 160 W diode laser is used for two-dimensional sheet bending of low-carbon steel. The variables investigated include metal sheet thickness, laser scan speed, laser power, laser beam width, and laser scan pass number. Bend surface appearances are also analysed.

The laser sheet bend results demonstrate that a 940 Nm diode laser is an effective tool for laser forming of carbon steel sheets. No additional surface coating was required. The buckling mechanism may be the main source contributing to the large angle of bend found for the laser-beam-width to sheet-thickness aspect ratio close to 4; for a laser-beam-width to sheet-thickness aspect ratio of less than 2, both temperature gradient and buckling mechanisms contributed to the lower bend angles. The laser beam width study showed that, for the given material thickness range and laser beam profile, the maximum bend angle depends mainly on the material thickness, not the power intensity distribution across the bend line. However, a more evenly distributed laser beam gave the same bend angle with less material property and surface appearance changes. For obtaining the same bend angle, less laser line energy was required if a higher laser scan speed was applied, except for the extreme high-line energy level. Also, multi-path bend strategies may be preferred for maximizing the total bend angle as well as reducing bend surface morphology changes.

1 BACKGROUND

Through high-power laser irradiation, sheet metal can be formed by a laser-generated temperature gradient between the laser irradiation heated local area and the neighbouring materials [**1**]. The continuously changing temperature gradient forces the material to expand first and then contract non-uniformly, which creates thermal stresses and results in plastic deformation once the thermal stresses exceed the yield point of the sheet metal. The thermal behaviour of heating up rapidly and locally, but cooling down gradually and more evenly, plays an important role in laser sheet-metal forming. Three individual mechanisms, or a combination of them, may be used to explain the laser forming behaviour [**2**, **3**]. These are:

(a) a temperature gradient mechanism;
(b) a bulking mechanism;
(c) an upsetting mechanism.

**Corresponding author: Department of Mechanical Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada. email: jeswiet@me.queensu.ca*

Analytical, experimental, and finite element (FE) methods have been applied on the laser forming process analysis [**4–11**].

A laser metal-forming process may supply a highly flexible, non-contact, and controllable means for making sheet-metal prototypes, ship planking, as well as for alignment and adjustment procedures in production engineering [**4**]. Laser-assisted metal forming may improve the shaping possibilities of the conventional metal-forming process such as laser-assisted hydroforming and stretching [**4**].

Carbon dioxide (CO_2) and neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers are well-developed technologies and are the most widely used tools in laser metal forming. The laser power used for metal-forming research and application is usually in hundred watt to kilowatt level, depending on the metal sheet thickness and forming process conditions [**12–14**]. Yu [**11**] conducted a finite element method (FEM) study of a 2.6 kW laser forming on 25.4 mm thick, mild-steel plates, the thickness scale in which the ship building industry is interested [**12**]. There also has been work dealing with the laser forming of 0.1 mm and 0.3 mm metal sheets using a 30 W Nd:YAG laser [**15**]. In contrast to CO_2 and Nd:YAG lasers, newly developed compact, highly energy-efficient, cost-effective, diode lasers are being adopted by industry [**16**, **17**]. Very limited information is available about applying diode lasers to sheet-metal forming [2.5 kW diode laser]. No reports have been found in the public domain about the application of medium-power (100 W) diode lasers with sheet-metal forming.

For medium- to high-power diode lasers, the laser beams are created by a group of diode laser bar arrays [**16**, **17**]. Compared with CO_2 or Nd:YAG lasers, these joined laser beams usually have a larger beam size, and may have more evenly distributed beam profile in terms of the laser power intensity [**16**, **18**]. The wavelength of diode lasers is usually around 810 Nm and 940 Nm, close to Nd:YAG laser's 1.06 μm, but very different compared with CO_2 laser's 10.6 μm. Hence, the process characteristics of metal forming using diode lasers are investigated.

2 OBJECTIVE

This experiment investigates the characteristics and applicability of a medium-power (160 W) diode laser to sheet-metal forming. Only the bending of two-dimensional sheet metals was used to demonstrate

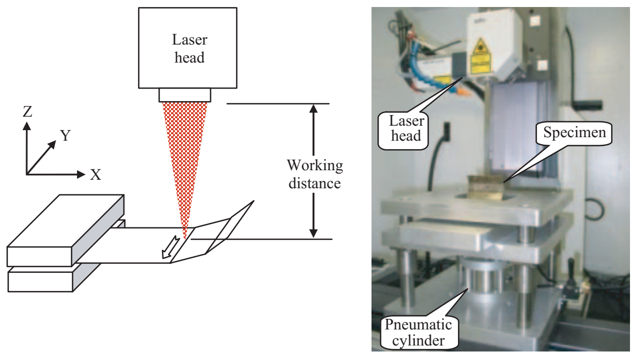

Fig. 1 Laser bending system set-up

the capabilities and advantages of the medium-power diode laser on sheet-metal forming. Cold-rolled, low-carbon steel was used in this experiment. The measured bend angles of metal sheet were used as primary evaluation parameters. Variables tested include metal sheet thickness, laser scan speed, laser power, laser beam width, and laser scan pass number.

3 TEST EQUIPMENT, FIXTURE, AND MATERIAL

3.1 Test equipment and fixture set-up

The laser system used for laser bending is a Rofin-Sinar DLx16 160 W diode laser in a UW200 workstation. The workstation contains 18 in $X \times 18$ in $Y \times 12$ in Z motion-controlled linear stages for translation of the components. Figure 1 shows the fixture set-up for the laser sheet-metal bending research. The Z-axis linear stage in the workstation was used to move the laser head along the Z-axis vertically for focusing the laser beam on the top surface of the metal sheet. The metal sheets were clamped on the fixture with a pneumatic cylinder and moved along the X- and Y-axis driven by the linear stages in the bending process.

3.2 Laser beam profile

The DLx16 diode laser was set to continuous wave mode with a wavelength of 940 nm. The laser beam profile (laser power intensity distribution across the beam path) around the focus point was measured using both a pinhole method and a knife-edge method [**18**]. Figure 2 shows the measured one-dimensional beam profile along the X- and Y-axis respectively at the working distance from the laser head. From Figs 1(a) and (b) it is known that an approximate 0.6 mm beam will be applied if the metal sheet is scanned along the X-axis, and an approximate 1.0 mm width laser beam

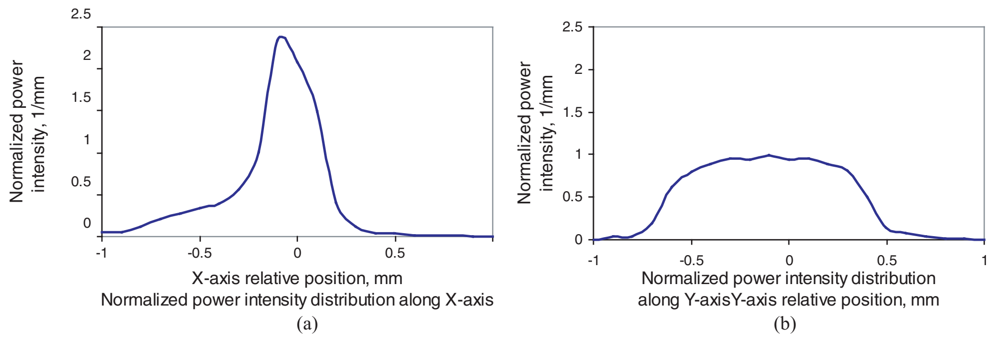

Fig. 2 Measured DLx16 diode laser beam profile at the working distance [**15**]

will scan through the metal sheet if scanning is carried out along the *Y*-axis.

3.3 Materials to bend

The metal sheet used in the test is cold-rolled grade 1008–1012 carbon steel, B90–B100 in hardness, ASTM: A109. The materials comes in 6 in wide by 100 in long rolls. The thicknesses of the sheets are 0.25 mm (0.01 in), 0.51 mm (0.02 in), and 0.79 mm (0.031 in).

The metal sheets were cut into 75 mm (width) × 150 mm (length) specimens using a shear press. The metal sheets were used in the experiment directly with the surface conditions as is – no treatment such as graphite coating was applied on the sheet surface.

4 TEST PARAMETERS AND PROCEDURE

4.1 Test parameters

In addition to laser power, the bend angle related parameters to be tested include those below.

4.1.1 Material thickness

Three levels of material thickness, 0.25 mm, 0.51 mm, and 0.79 mm, were tested for a series of laser power settings. The laser scan speed was fixed at 1000 mm/min for scanning four passes in only one direction. A 10 s dwell time between two scans was used. A wide 1.0 mm laser beam was applied here; see Fig. 1(b). The tests were repeated three times as the test results were quite stable, except for the bending of the 0.25 mm sheet under high-power laser radiation.

4.1.2 Laser beam width

A narrow 0.6 mm laser beam (Fig. 1(a)) and a wide 1.0 mm laser beam (Fig. 1(b)), were applied for bending the three thicknesses of metal sheets. The same values of laser powers, scan speed, pass number, scan direction, and dwell time were used, similar to those used in the material thickness test.

4.1.3 Laser scan speed

Three scan speeds, 500, 750, and 1000 mm/min, were investigated for the same line energy settings as those used in the material-thickness test for the 0.79 mm sheet. The line energy is defined as the laser-delivered, light energy per unit length of the laser scan path, which can be calculated as the laser beam power divided by the laser scan speed. In this test a wide beam scanned the specimens for four passes along one direction having a dwell time of 10 s. From the test parameters selected here it can

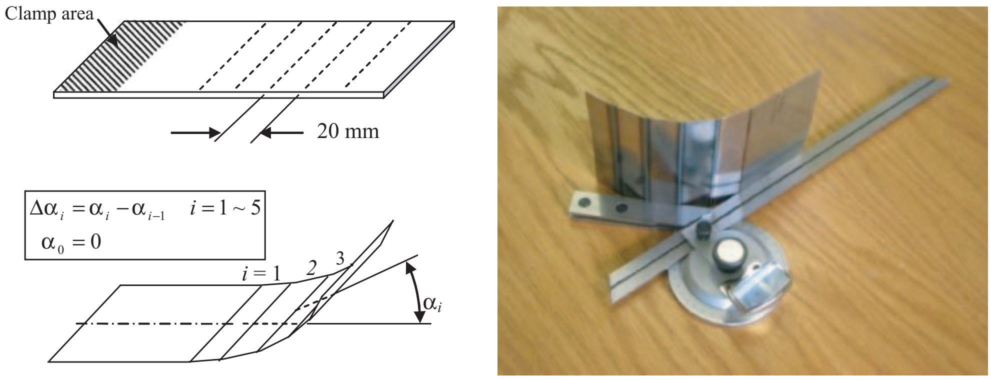

Fig. 3 Bend path arrangement and bend angle, $\Delta\alpha i$ ($i = 1{\sim}5$), measurement

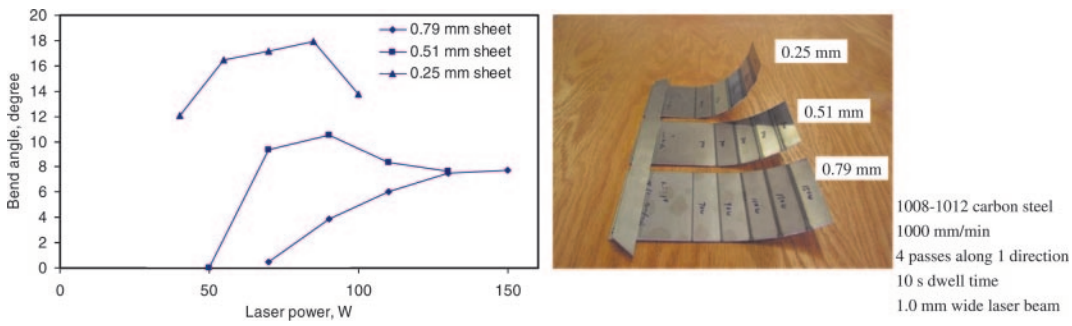

Fig. 4 Bend angle versus laser power for laser bending of low-carbon steel sheets

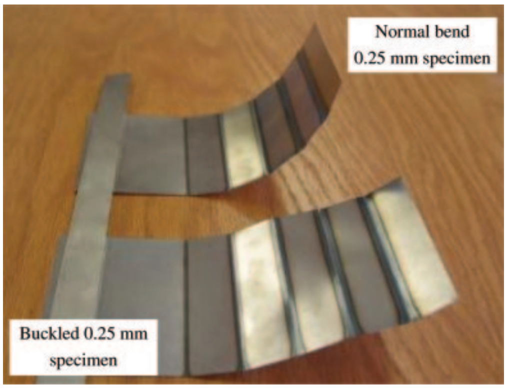

Fig. 5 Pictures of laser bent normal specimen (upper) and buckled specimen (lower) under identical process conditions

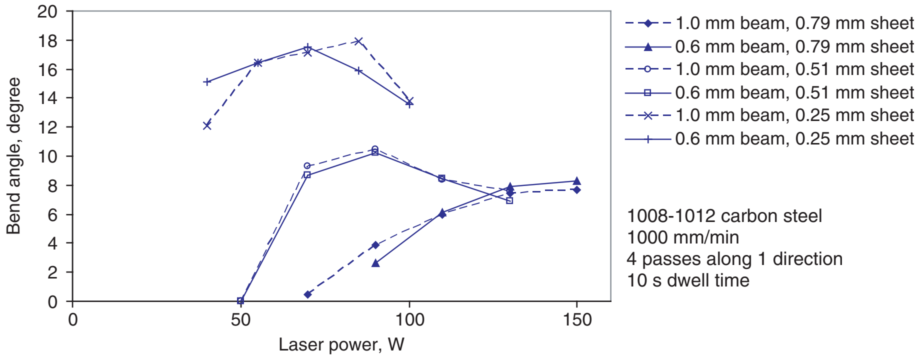

Fig. 6 Laser beam widths effect on bend angle for three thicknesses of specimens

be seen that only scan speeds of 500 and 750 mm/min need to be examined as the bending results of 1000 mm/min are available from the test results for the material thickness test.

4.1.4 *Laser scan passes*

Ten levels of laser scan passes, 1, 2, 3, 4, 6, 8, 10, 15, 20, and 30, were applied along one fixed direction on the sheets. The dwell time was also fixed at 10 s. All other parameters used in this test are: laser power, 130 W; scan speed, 1000 mm/min; beam width, 1.0 mm; and specimen thickness, 0.79 mm.

A laser power of 130 W was chosen according to the test results for the material thickness test. This power value resulted in a high bend angle, but without significant burn to the metal surface even for paths having less than four passes.

4.2 Test procedure

Laser bending tests, for the variables described above, were conducted in the following steps.

Step 1. Clamp the sheet specimen using a pneumatic cylinder on the fixture in the UW200 workstation, the top surface is located at the focus plane of the laser head (Fig. 1).

Step 2. Laser scan over the specimen along the given path (Fig. 3) with the parameters specified in each test set (section 4.1).

Step 3. Measure and calculate the bend angle for every specimen as shown in Fig. 3. The angle is measured along the centre line of the sheet. The angular ruler has a resolution of 1/12°(5').

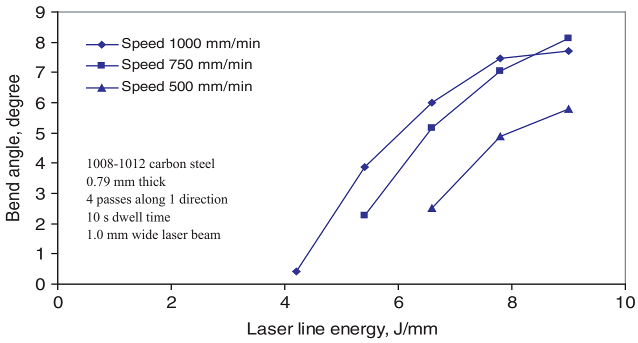

Fig. 7 Bend angle versus laser line energy relationship for three laser scan speeds

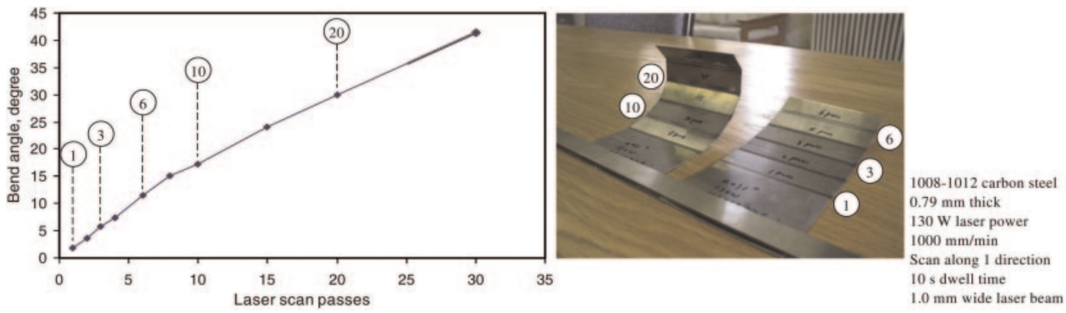

Fig. 8 Bend angle versus laser scan passes relationship

5 TEST RESULTS

5.1 Material thickness

For the laser power and material thickness relationship study, the bending test for 0.79 and 0.51 mm thick metal sheets were repeated three times, and the test results were quite stable. However, the tests for 0.25 mm sheet were repeated six times, as two out of the six specimens buckled irregularly when irradiated with higher power. Figure 4 shows the measured relationship between the average bend angle and the laser power for three thicknesses of specimens. Figure 5 shows a normal bend specimen (upper) and a buckled specimen (lower) for the 0.25 mm metal sheets. Mixed bending up (toward the laser head) and bending down (away from the laser head) were observed in the buckled specimen.

5.2 Laser beam width

The laser beam width influence on the bend angle was investigated for three thicknesses of metal sheets, for a series of laser power irradiation for two laser beam dimensions:

(a) narrow laser beam – 0.6 mm beam;
(b) wide laser beam – 1.0 mm beam.

Figure 6 plots the average bend angle results for the given process conditions. As in the case of the material thickness test described above, the tests for the 0.51 and 0.79 mm specimens were repeated three times, and the test for the 0.25 mm sheet was repeated five times because one out of the five specimens buckled irregularly when the laser irradiated with high power.

5.3 Laser scan speed

The bend angles for three laser scan speeds were compared based on a common parameter – line energy (Fig. 7). The line energy can be calculated as

$$\text{Line energy} = \frac{\text{Laser power}}{\text{Laser scan speed}}$$

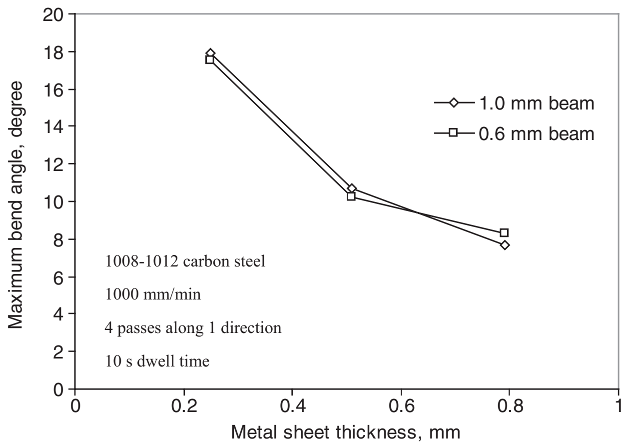

Fig. 9 Maximum bend angle versus metal sheet thickness for laser bending of low-carbon steel sheet

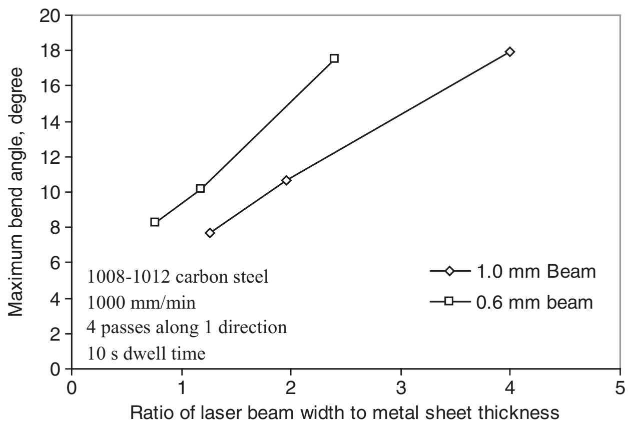

Fig. 10 Maximum bend angle versus aspect ratio of laser beam width to metal sheet thickness for laser bending of low-carbon steel sheet

Three scan speeds, 500, 750, and 1000 mm/min, were investigated for the same line energy settings as those used in the material thickness test for the 0.79 mm sheet; section 5.1. The tests were repeated three times and the average bend angles were used in the drawing of Fig. 7.

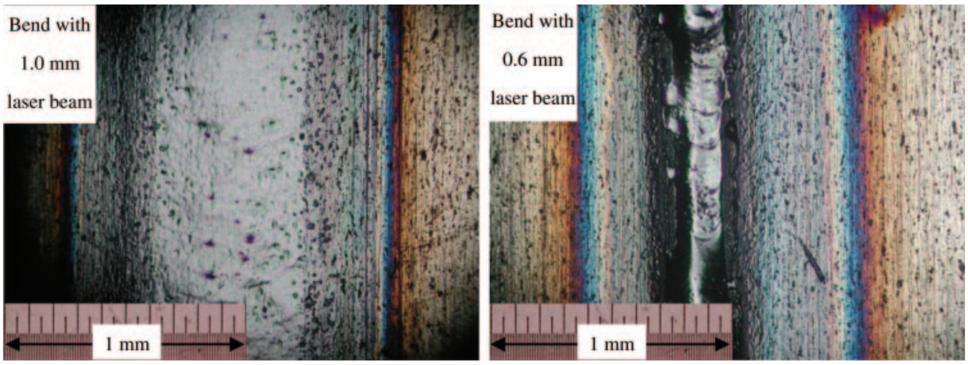

Fig. 11 Surface appearances of the bends for laser bending with a 1.0 mm width laser beam (left) and 0.6 mm one (right) (0.79 mm specimen, 90 W laser power, 4 passes along 1 direction, 10 s dwell time)

5.4 Laser scan passes

Up to 30 laser scan passes were examined in this test set; Fig. 8. A laser power of 130 W was chosen according to the test results in the material thickness test. This power level can result in a high bend angle, and may also change the morphology of the surface metal. The bend angles for passes six and below (Fig. 8) are measured, receiving average values from three specimens. Only one specimen was tested for the pass numbers eight and above.

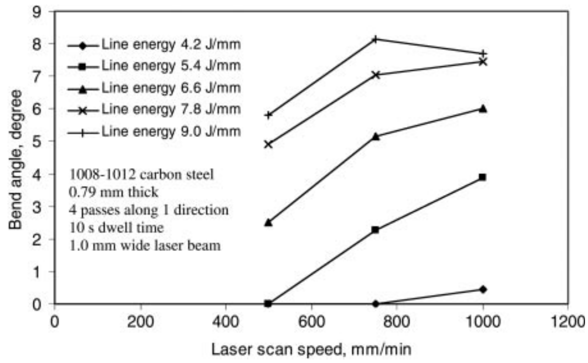

Fig. 12 Bend angle versus laser scan speed relationship for five laser line energies

6 TEST RESULTS ANALYSIS

6.1 Laser power level and material thickness

From Fig. 4 it can be seen that a power level of 200 W is good enough for the bending of low-carbon steel up to a thickness of 0.79 mm. In comparison with a CO_2 laser, no additional surface coating is required in this process [**19–22**]. This is owing to the high laser absorption coefficient of carbon steels for the short wavelength diode laser (940 Nm).

For a given material thickness, shown in Fig. 4 and Fig. 6, the bend angle increases initially with the increased laser power, but decreases once the laser power goes beyond a certain high level. This bend angle drop with high laser power may be caused by the reduced temperature gradient.

6.2 Bending mechanisms and laser beam width

From a bend angle point of view, regardless of the surface quality, a maximum bend angle and material thickness relationship can be drawn, as shown in Fig. 9, for both wide and narrow laser beam conditions. A relationship can also be drawn between the maximum bend angle and the ratio of laser beam width to sheet metal thickness as shown in Fig. 10.

From Fig. 6 and Fig. 9, it can be seen that, for the two given laser beam intensity distributions (see Fig. 2), the maximum bend angles have no significant difference for bending the same thickness metal sheets ranging from 0.25 to 0.79 mm. This result suggests that, for the given laser beam profile and sheet thickness range here, the maximum bend angle mainly depends on the material thickness, not the power intensity distribution across the bend line.

The maximum bend angle decreases from 18° to 8° along with the increase of sheet thickness in the test range from 0.25 to 0.79 mm. This bend angle difference may be explained as:

(a) for the 0.25 mm sheet, the laser beam width to sheet thickness ratio is around 2.4–4.0, the buckling mechanism may be the main source contributing to the large angle of bend [**2**, **3**, **5**, **6**, **8**, **12**];
(b) for the 0.79 and 0.51 mm sheet, the laser beam width to sheet thickness ratio is only about 0.8–2.0, both the temperature gradient and buckling mechanisms contribute to the lower angle bends [**2**, **3**, **12**].

The buckling of 0.25 mm sheet, when bending with both wide and narrow laser beams, is evidence of the work of buckling mechanism [**5**, **6**, **8**], which did not

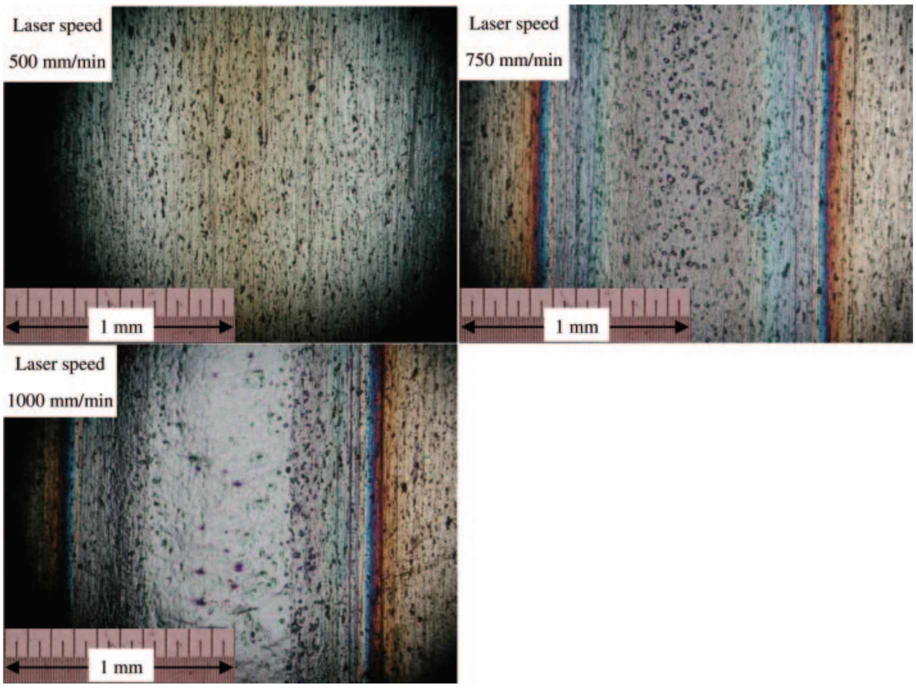

Fig. 13 Surface appearance difference for 3 laser scan speed bends having the same line energy of 5.4 J/mm (0.79 mm specimen, four passes along one direction, 10 s dwell time, 1.0 mm laser beam)

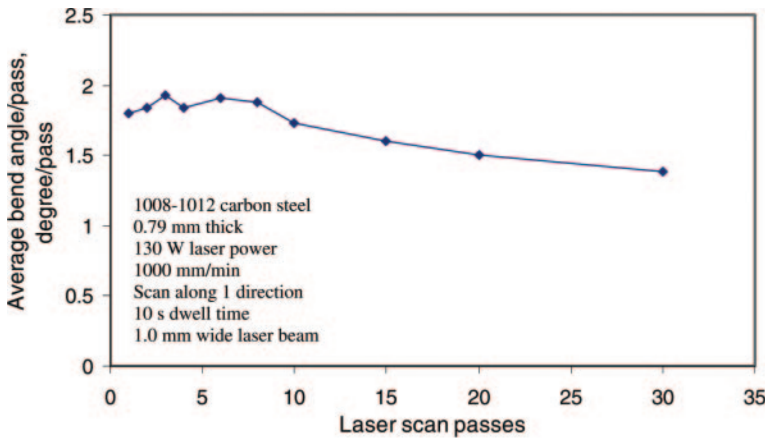

Fig. 14 Average bend angle per pass versus laser scan passes relationship

happen among any one of the 0.51 and 0.79 mm sheets tested here (Fig. 5).

Figure 10 shows that, for both 0.6 and 1.0 mm laser beam, and for the given sheet thickness range, the maximum bend angle increases fairly linearly with the increase of laser beam width to metal sheet thickness ratio. However, for the same ratio of laser beam width to metal sheet thickness, the maximum bend angle was different for these two different laser beam widths.

When looking at the bends under a microscope as shown in Fig. 11, it can be seen that, relative to a wider laser beam, a high-intensity laser power from a narrow laser beam can create greater surface melting under the same welding parameter settings. This suggests that a more evenly distributed laser beam (Fig. 2(b)), is preferred to the sharp one (Fig. 2(a)) for obtaining approximately the same bend angle, but with less material property and surface appearance changes.

6.3 Laser scan speed

In addition to Fig. 7, the bend angle and laser scan speed relation can also be expressed in the form shown in Fig. 12. From these two figures it is known

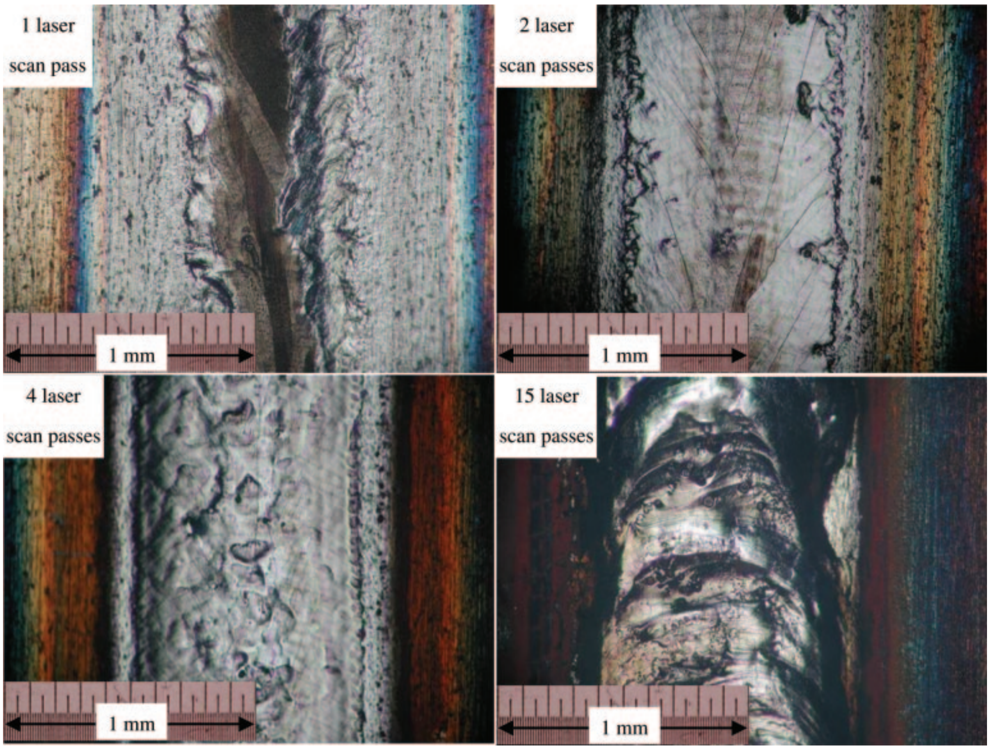

Fig. 15 Surface appearance of laser bending with different passes (0.79 mm specimen, 130 W laser power, 1000 mm/min moving speed along one direction, 10 s dwell time, 1.0 mm laser beam)

that, for obtaining the same bend angle, less laser line energy was required if a higher laser scan speed were applied, except for the extreme, high-line, energy level. This result can be explained as follows. With a high-speed laser movement, light energy is accumulated more locally when the laser passes by, this creates a higher temperature gradient in that area and so results in a higher bend angle. Figure 13 shows the surface appearance difference caused by three different laser scan speeds, even having the same line energy of 5.4 J/mm.

6.4 Laser scan passes

For the given bending parameters and bend results described in the laser scan pass test results, the average sheet bend angle per pass decreased gradually along with the increase of scan pass number (Fig. 14). The average bend angle per pass for each pass number is defined as the total bend angle divided by the respective pass number. This experimental result demonstrates that laser bending is more effective with an initial small number of passes. So, instead of only increasing the pass number, it may be more effective for maximizing the total bend angle to increase both the laser scan paths and the numbers of scan passes. Multi-path bending may also reduce surface morphology change compared with the scan with all the passes on the same line.

Figure 15 shows the appearance of the bend with 1, 2, 4, and 15 passes. For this high-power bending, the surface morphology changes even from the first scan. The pictures listed in Fig. 13 (bottom) and Fig. 15 (bottom left) also show the influence of power on the surface appearance.

7 CONCLUSIONS

For the given test conditions in this experimental study, the two-dimensional laser bending of the low-carbon steel sheet demonstrated that a 940 Nm diode laser is an effective tool for laser forming of carbon steel sheets. No additional surface coating is required. The buckling mechanism may be the main source contributing to the large angle of bend as well as the mixed bending up and bending down for the laser beam width to sheet thickness aspect ratio close to 4; both temperature gradient and buckling mechanisms contributed to the lower bend angles for a laser beam width to sheet thickness aspect ratio less than 2. This laser beam width study showed that the maximum bend angle depends mainly on the material thickness, not the power intensity distribution across the bend line for the given laser beam profile and material thickness range tested here. However, a more evenly distributed laser beam is preferred to a sharp one for obtaining approximately the same bend angle but with less material property and surface appearance changes. For obtaining the same bend angle, less laser line energy is required if a higher laser scan speed is applied, except for the extreme high-line energy level. Laser bending is more effective in the initial number of passes. So, a multi-path bend strategy may be preferred for maximizing the total bend angle as well as reducing the bend surface morphology change.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Canadian Foundation of Innovation (CFI), the Ontario Innovation Trust (OIT), and NSERC discovery grant for their foundations for purchasing Rofin-Sinar DLx16 160 W diode laser and UW200 workstation used in this research.

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