The forming of mild steel plates with a 2.5 kW high power diode laser

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Abstract

Bending of 07 M20 mild steel sheets to various degrees using a contemporary 2.5 kW high power diode laser (HPDL) has been successfully demonstrated for the first time. The experimental results revealed that the HPDL induced bending angle increased with an increasing number of irradiations and high laser powers, yet decreased as the traverse speed was increased. It was also apparent from the experimental results that the laser bending angle was only linearly proportional to the number of irradiations when the latter was small. It is believed that the absence of linearity observed when the number of irradiations was high is due to local material thickening along the bend edge. From graphical results and the employment of an analytical model, the laser line energy range in which accurate control of the HPDL bending of the 07 M20 mild steel sheets could be exercised was found to be between 138 J mm^{-1} and 260 J mm^{-1}.

Keywords: High power diode laser (HPDL); Steel; Forming; Bending; Materials processing

1 Introduction

Over recent years the notion of the laser as merely another machine tool available to the contemporary engineer has become a reality. Indeed, laser forming has revealed itself to be a viable process for the production of sheet metal prototypes. Furthermore, the process has been seen to demonstrate potential uses in a great many other engineering applications, some hitherto not possible with other techniques. In particular, many possibilities exist for the deployment of laser forming within production engineering for alignment and adjustment procedures [1], whilst complex geometric forms, which otherwise can only be produced with great difficulty using conventional forming techniques, can be made very simply with laser forming [2]. Although the origins of the laser forming technique can be traced back to the established method of flame bending [3, 4], laser forming is a much more refined and controllable technique that offers numerous unique applications possibilities. This extensive variety of possible applications within engineering results from the reasonably high degree of control over the energy transfer, the high levels of accuracy and reproducibility, the very high degrees of flexibility and the non-contact nature of the technique; attributes directly afforded it by the inherent operating characteristics of lasers. In addition, the laser based nature of the technique means that it could be employed to form parts in locations where it would otherwise be impossible to use conventional forming methods, such as in outer space [5].

Essentially laser forming is a spring-back free, non-contact process in which bending is induced by a localised laser generated temperature gradient between the irradiated surface and the neighbouring material. This temperature distribution forces the material to expand non-uniformly, which in turn leads to non-uniform thermal stresses. Where the thermal stresses exceed the yield point of the material plastic deformation is occasioned. As a consequence the material initially curves inwards and then outwards. The latter occurrence being driven by the compressive nature of the thermal stresses induced by the more rigid interior material layers which are much cooler.

Early work by Namba [5, 6] reported on the potential high degrees of flexibility of the laser forming process. Since then many researchers have studied various aspects of the technique in great detail. In particular, Vollersten [7, 8], Vollersten *et al.* [9, 10] and Geiger *et al.* [11] have investigated thoroughly the mechanisms active in laser forming. In more recent times the technique has been advanced through the development of a number of numerical [12-15], analytical [16] and finite element method (FEM) [17-20] mathematical models for various aspects of the laser forming process. Additionally, Hennige *et al.* [21] and Magee *et al.* [22] have conducted studies to improve the dimensional accuracy of parts produced using laser forming, whilst similarly, both Sprenger *et al.* [23] and Li *et al.* [24] studied the effects of stress and strain on the quality of laser bends. Both Arnet *et al.* [25] and Vollersten *et al.* [26] have successfully demonstrated the techniques ability to form complex shapes.

In all the above studies, however, the sheet metal forming was conducted using the well established CO_2 or Nd:YAG lasers. This present work, on the other hand, investigates for the first time the use of the contemporary 2.5 kW high power diode laser (HPDL) to carry out the laser forming of common engineering mild steel (07 M20). It is believed that a number of process advantages can be realised through the employment of the HPDL as a opposed to the CO_2 or Nd:YAG lasers. These include the on-site deployment potential as a result of the HPDL's inherent portability and robustness and the better material coupling efficiency (beam absorption) of the HPDL.

2 Theoretical principles of laser forming

As mentioned earlier, the laser forming process is realised by introducing thermal stresses into the surface of a workpiece. These internal stresses induce plastic strains which result in the local elastic buckling of the workpiece. Essentially there are three laser forming mechanisms [10, 11]: the temperature gradient mechanisms, the buckling mechanism and the upsetting mechanism.

2.1 The temperature gradient mechanism

The conditions for the temperature gradient mechanism are energy parameters that lead to a steep temperature gradient across the sheet metal thickness. The beam diameter is typically in the order of the sheet metal thickness, whilst the traverse rate has to be large enough so that a steep temperature gradient can be maintained. The path of the laser beam on the surface of the metal is usually a straight line across the whole width, with this straight line being the bending edge.

Initially the surface of the metal is heated, which in turn leads to pure elastic strains. Owing to the thermal expansion of the surface layer of the metal there is a counter-bending of the workpeice away from the laser beam. The amount of counter-bending is very small as only the heated area on the surface, which is approximately the size of the beam spot, has to generate forces which produce the counter-bending of the whole sheet. Further heating leads to a decrease of the flow stress in the heated area and a further increase of the thermal expansion of the surface layer. At a certain temperature, which is dependant upon the material, the geometry and the degree of counter-bending, the thermal strains reach the maximum elastic strain that the metal can endure at the given temperature. A further increase in the temperature results in a conversion of the thermal expansion into plastic compressive strains. These plastic compressive strains accumulate until the laser beam moves on allowing cooling to begin.

Cooling is mainly due to self quenching, with the heat flowing into the surrounding bulk material resulting in cooling of the heated area within 10-20 seconds. During cooling shrinkage of the heated material occurs. This is due to the fact that the surface layer was plastically compressed during heating and is therefore shorter after cooling than the non-heated layers. Owing to the different lengths of the surface layer and the lower layers of the material, a bending angle develops towards the laser beam. Typically angles of between 0.1^0 and 3^0 are achieved after one laser pass.

2.2 The buckling mechanism

The buckling mechanism will occur if the laser beam diameter is large compared to the sheet metal thickness and the processing time is low, resulting in a small temperature gradient across the sheet metal thickness.

Primarily the material is heated, which in turn leads to the thermal expansion of the material and results in compressive stresses in the heated region. If the heated area is large enough, and if there is a small natural deviated from the perfect plane which normally exists in real metal sheets, an instability, or buckle, develops. In the centre of the buckle the temperature is extremely high, therefore the flow stress in this region is relatively low and the bending of the sheet in this region is consequently nearly totally plastic. In contrast, the root of the buckle, which is far away from the centre of the laser beam, is heated to a much lesser extent. Therefore the temperature is low and the flow stress in this region is relatively high, resulting in completely elastic bending of the sheet in this region. By controlling certain parameters, positive (concave bending towards the laser beam) or negative (convex bending away from the laser beam) bending can be achieved with the buckling mechanism [25, 26].

As the beam is traversed along the surface the buckle shifts along the bending edge. The direction of the buckling is predetermined by the existing buckle, and as such the remaining part of the sheet buckles in the same direction. The traversing of the beam across the surface also causes the stiffness of the workpiece to alter. At the start of the buckling process the bending legs are held in the original plane due to the stiff surrounding material. As an increasing amount of the sheet is formed by the buckle, the forces that held the bending legs straight decrease. Therefore the elastic part of the buckle relaxes and only the plastic part remains in the sheet, resulting in an angular bend. Because the buckling mechanism results in more energy being coupled into the workpiece, bending angles are often up to 15^0 after one pass of the beam.

2.3 The upsetting mechanism

The upsetting mechanism will occur if the laser beam diameter is in the order of, or less than the sheet metal thickness and the traverse speed is low compared to the thermal conductivity of the material. Also, the geometry of the workpiece must be such that buckling of the material is prevented. The low processing speed will result in almost homogenous heating across the thickness of the sheet metal. Owing to the temperature increase, the flow stress decreases in the heated area and the thermal strains approach the elastic strains at the yield stress. Additional heating leads to a plastic compression of the heated material as it is hindered in free expansion by the surrounding bulk material. Therefore a large amount of the thermal expansion is converted into plastic compression.

During cooling the material contracts and the plastic compressive strain remains in the sheet for exactly the same reason as in the temperature gradient mechanism. Owing to the constancy of volume there is an increase of the sheet thickness in the compressed area.

3 Experimental procedure

The steel studied in the HPDL forming experiments was a common engineering low carbon mild steel (07 M20). The mild steel was received in the form of rectangular billets (100 x 50 x 0.8 mm) and, save for cleaning of the surfaces with methanol to remove any unwanted grease, the billets were used as-received in the experiments.

The laser used to conduct the forming experiments was the contemporary 2.5 kW HPDL (Rofin-Sinar, DL-025), emitting at 940 nm. The defocused multimode laser beam was fired directly onto the samples with rectangular beams of 4 x 4 mm with powers ranging from 1.5 - 2.3 kW. The laser head assembly and focusing optics are shown schematically in Fig. 1. The beam was traversed across the samples by means of mounting the assembly head onto the z-axis of a 3-axis CNC table. The defocused laser beam was thus fired across the surface of the mild steel by traversing the samples beneath the laser beam using the x- and y-axis of the CNC table at speeds of 360 - 840 mm/min, whilst 20 l/min of Ar gas was blown across the laser optics to act as a shield. No surface melting of the mild steel was observed on any of the samples during or at the end of HPDL forming. In all the experiments, the holding time between each irradiation was fixed at 0 s.

The bending angles obtained as a result of HPDL forming were digitally captured using a CCD camera and measured to an accuracy of $\pm 0.1^0$ using image processing software.

4 Results

Owing to the fact that the size of the HPDL beam employed in this study was large (4 x 4 mm) compared to the sheet metal thickness (0.8 mm), then, based on the work of Arnet *et al.* [25] and Vollersten *et al.* [26], the buckling mechanism can be sited as the laser forming mechanism responsible for the bending induced by the HPDL.

According to Scully [27], the relationship between laser bending angle and the number of irradiations in a multiple-irradiation process is best represented by an α-n curve, where α is the bending angle and n is the number of irradiations. Fig. 2 shows the α-n curves for the 07 M20 mild steel obtained at different laser powers but with a fixed traverse speed of 600 mm min^{-1}. As one can see from Fig. 2, the HPDL induced bending angle increases almost linearly with the increasing number of irradiations, whilst at the same time, the gradients of the curves increase with increasing laser incident power. Fig. 3 illustrates the effect of laser power on the final bending angle (after 40 irradiations) at different traverse speeds. As is evident from Fig. 3, a laser power threshold exists below which no bending will occur. Additionally, it is worthy of note that when the laser power has reached a certain value, further increases in power, regardless of the magnitude, effect only marginal increases in the bending angle.

The effects of varying the traverse speed, whilst fixing the laser power at 2 kW, on the α-n curves for the 07 M20 mild steel are shown in Fig. 4. Here the bending angle was seen to increase almost linearly with the number of irradiations, with the gradients of the curves decreasing with increasing traverse speed. The influence of traverse speed on the final bending angle (after 40 irradiations) is shown in Fig. 5, revealing that the HPDL induced bending decreased in gradual increments as the traverse speed increased.

5 Discussion

The α-n curves given in Fig. 2 and Fig. 4 are in general agreement with the findings of a number of workers [6, 27, 28] who have observed the existence of a linear relationship between laser bending angle and the number of irradiations. Yet such findings are in contrast to those of other researchers [22, 23] who have reported a decaying increase in the bending angle with an increasing number of irradiations. This significant difference between the findings of this study and those of the latter workers is believed to be due to different degrees of local thickening and strain hardening of the 07 M20 mild steel sheet during HPDL bending. From comprehensive studies conducted by Vollersten [7] and Sprenger *et al.* [23], the laser bending angle was said not to increase linearly with the number of irradiations due to: (i) changes in the absorption behaviour of the steel with increasing irradiations; (ii) the increase in the sheet thickness along the bending edge and (iii) the strain hardening effect on the underside of the sheet.

In this present study a HPDL was employed. By virtue of its beam wavelength, the HPDL is a laser that is known to possess relatively high levels of beam absorption with many metallic materials. For mild steel the absorption of HPDL radiation is around 45%, compared with only 10-15% for the CO_2 laser [29]. Furthermore, since the wavelength of the HPDL is very similar to that of the Nd:YAG laser, 940 nm and 1064 nm respectively, then it is reasonable to assume that the minimised changes in absorptivity observed by Scully [27] for the Nd:YAG laser will occur likewise with the HPDL.

It is known that strain hardening only becomes manifest for relatively thick sheets of typically more than 1 mm in thickness [22]. Moreover, if the sheet is relatively thin, as was the case in this study, the influence of strain hardening and material thickening along the bend edge can be considered to be almost insignificant when the number of irradiations is small [28]. Hence a linear relationship between bending angle and the number of irradiations will exist. But, strain hardening and material thickening along the bend edge is unavoidable if the number of irradiations increases. This is principally because local thickening will occur under the temperature gradient mechanism, causing the sheet to increase its thickness locally in the irradiated (and thus heated) zone. In addition, the bending angle enlarges when the number of irradiations increases, therefore more work has to be done on the underside of the sheet, which subsequently leads to strain hardening on the underside of the sheet. Consequently, it is thought that the bending angle will no longer be linearly proportional to the number of irradiations as the effects of strain hardening and material thickening along the bend edge become more pronounced. This postulation is borne out somewhat by Fig. 6. Here the number of irradiations was increased considerably from the experimental normal of 40 to 80 irradiations. It is clearly evident from Fig. 6 that the increase in the bending angle is no longer linearly proportional to the number of irradiations when the latter exceeds around 55 irradiations. It is therefore possible to conclude that for the HPDL bending of the 07 M20 mild steel sheets used in this present study, the bending angle is only linearly proportional to the number of irradiations when the latter is small, less than approximately 55 irradiations. It is also reasonable to assert that for the 07 M20 mild steel sheets investigated, thickening of the material along the bend edge was the predominant factor influencing the absence of linearity when the number of irradiations was large, rather than strain hardening. This is due to the fact that the sheets used were less than 1 mm in thickness, thus, since the process is thermally driven and the material was thin, only a small amount of cold work could be expected as a result of heat conduction effects.

As one can see from Fig. 3, a laser power threshold exists below which no bending could be occasioned. Such a finding is in accord with that of Holt [4], who noted that a critical temperature was required for thermal upsetting or a permanent change in shape to take place. It is also apparent from Fig. 3 that as the laser power was increased beyond a certain value, which differed depending upon the traverse speed used, the induced increases in the bending angle were only marginal. This is believed to be due to the fact that at high laser power, the resultant heat generated will penetrate fully to the underside of the sheet. Consequently the temperature gradient across the sheet thickness will reduce, causing a considerable reduction in the bending efficiency.

To further determine the significance of these observed thresholds, it was necessary to examine the relationship between the laser bending angle and the laser line energy (with laser line energy being defined by the ratio of the laser power and the traverse speed). This relationship is shown in Fig. 7. As with the results shown in Fig. 3, it is evident from Fig. 7 that a threshold energy input of around 138 J mm^{-1} exists, along with an almost linear region when the laser line energy is below 260 J mm^{-1}. Such linearity, coupled with the existence of a minimum laser line energy threshold, implies that the HPDL induced bending angle could be accurately controlled by adjusting the laser operating parameters. Furthermore, the presence of this linearity and the minimum laser line energy threshold conforms with the analytical model developed by Yau *et al.* [30]. According to this model, laser bending angle can be expressed by

$$\alpha = \frac{3\beta AP}{\rho C_p v h^2}\left(\frac{7}{2}\right) - 36\frac{l}{h}\frac{Y}{E} \quad (1)$$

with the critical condition for bending to occur being given by

$$\frac{AP}{vl} \geq \frac{12\left(1+m^2\right)}{7\left(1+m\right)}\frac{Y\rho C_p}{E\beta}h \quad (2)$$

where α is the final laser bending angle, β is the coefficient of thermal expansion, *A* is the absorptivity, ρ is the density, C_p is the heat capacity, *Y* is the yield strength, *E* is Young's Modulus, *h* is the thickness, *m* is the thickness ratio, *P* is the laser power, υ is the traverse speed and *l* is the beam radius. However, since only one type of material is under investigation, Equation (2) can be simplified to

$$\frac{P}{v} \geq C' \quad (3)$$

where C' is a constant relating to both the material and the geometry characteristics of the 07 M20 mild steel sheets. Thus, from Equation (3) it can be deduced that to exercise accurate control of the HPDL bending of the 07 M20 mild steel sheets investigated, it is necessary that the process should be operated in the line energy range of 138 J mm^{-1} < P/v > 260 J mm^{-1}.

6 Conclusions

The hitherto unreported bending of 07 M20 mild steel sheet (100 x 50 x 0.8 mm^3) to various degrees using a contemporary 2.5 kW high power diode laser (HPDL) has been successfully demonstrated. Owing to the fact that the size of the HPDL beam employed in this study was large compared to the sheet metal thickness, the buckling mechanism was sited as the laser forming mechanism responsible for the bending induced by the HPDL. The experimental results revealed that the HPDL induced bending angle increased with an increasing number of irradiations and high laser powers, yet decreased as the traverse speed was increased. It was also apparent from the experimental results that the laser bending angle was only linearly proportional to the number of irradiations when the latter was small, less than approximately 55 irradiations. It is believed that the absence of linearity observed when more than approximately 55 irradiations were used is due to local material thickening along the bend edge. From graphical results and the employment of an analytical model, the laser line energy range in which accurate control of the HPDL bending of the 07 M20 mild steel sheets could be exercised was found to be 138 J mm^{-1} < P/ν > 260 J mm^{-1}.

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List of Figures

Fig. 1

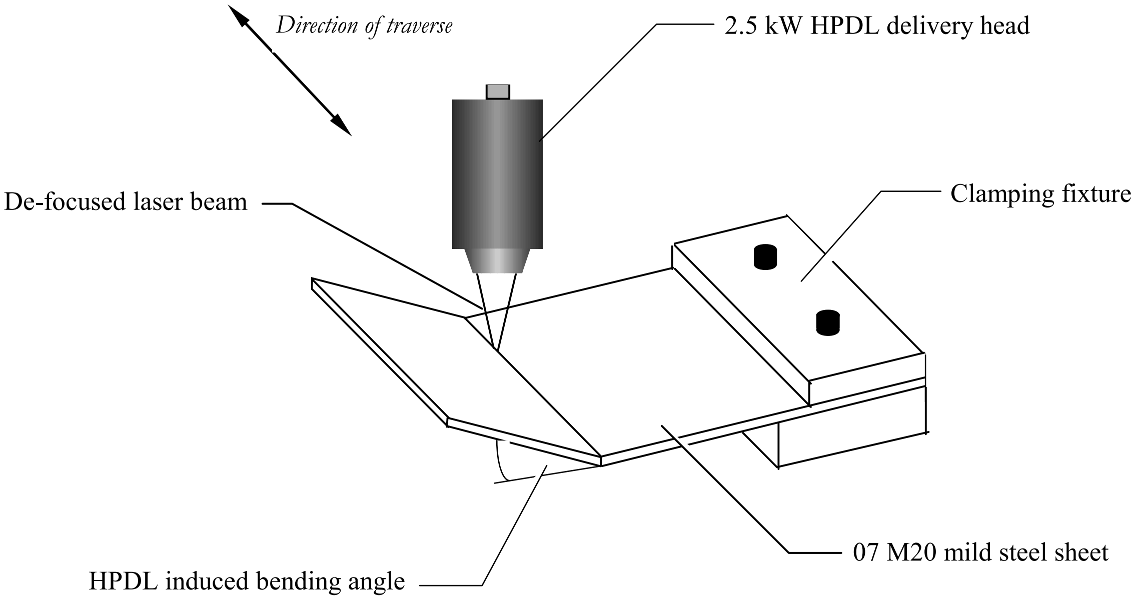

Direction of traverse
2.5 kW HPDL delivery head
De-focused laser beam
Clamping fixture
HPDL induced bending angle
07 M20 mild steel sheet

Fig. 2

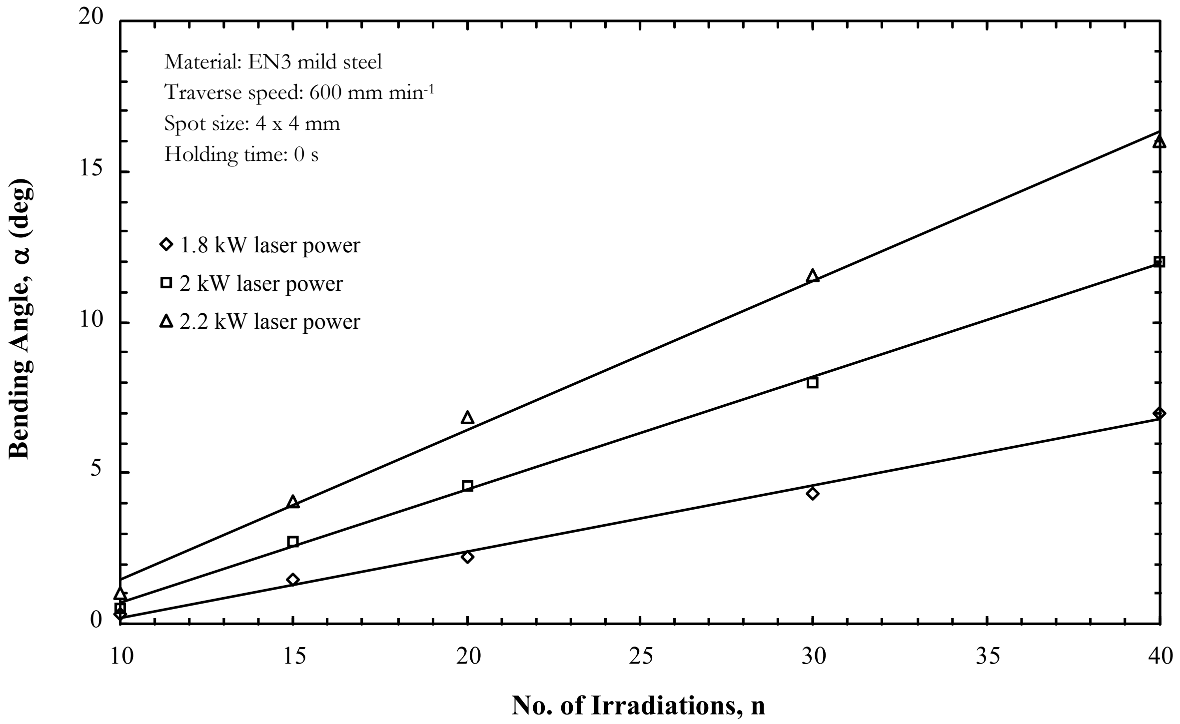

Material: EN3 mild steel
Traverse speed: 600 mm min-1
Spot size: 4 x 4 mm
Holding time: 0 s
1.8 kW laser power
2 kW laser power
2.2 kW laser power
Bending Angle, α (deg)
No. of Irradiations, n
0
5
10
15
20
10
15
20
25
30
35
40

Fig. 3

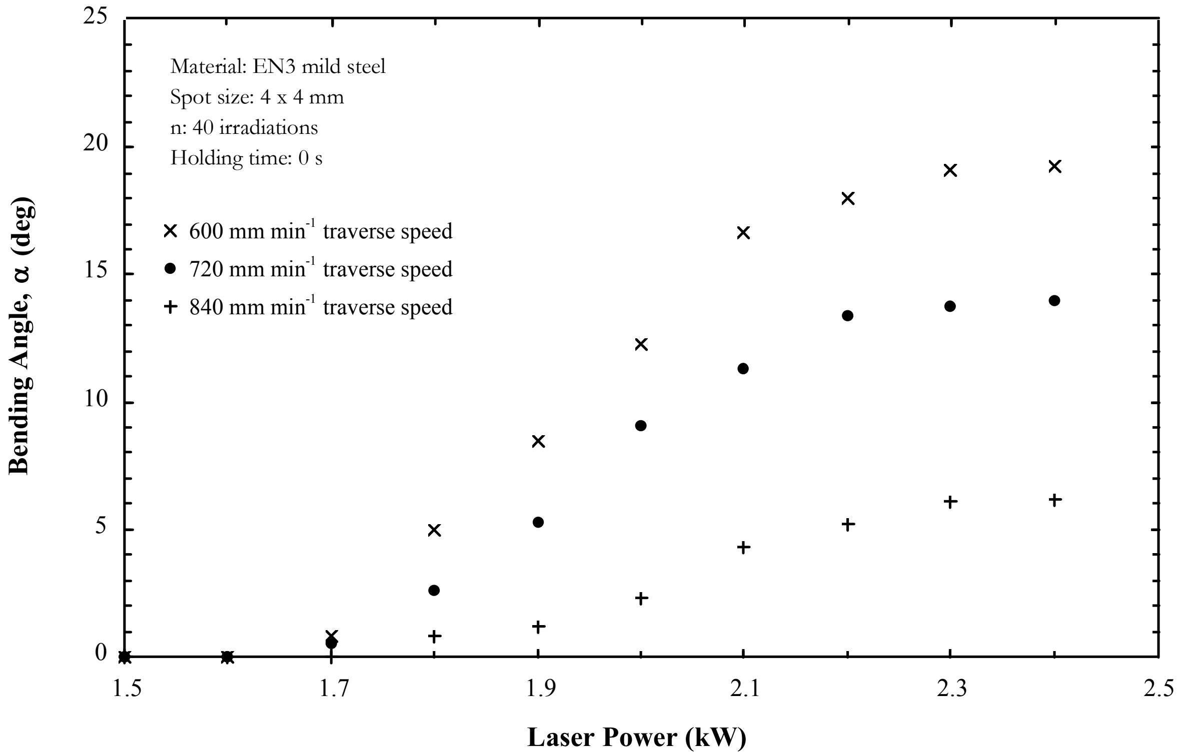
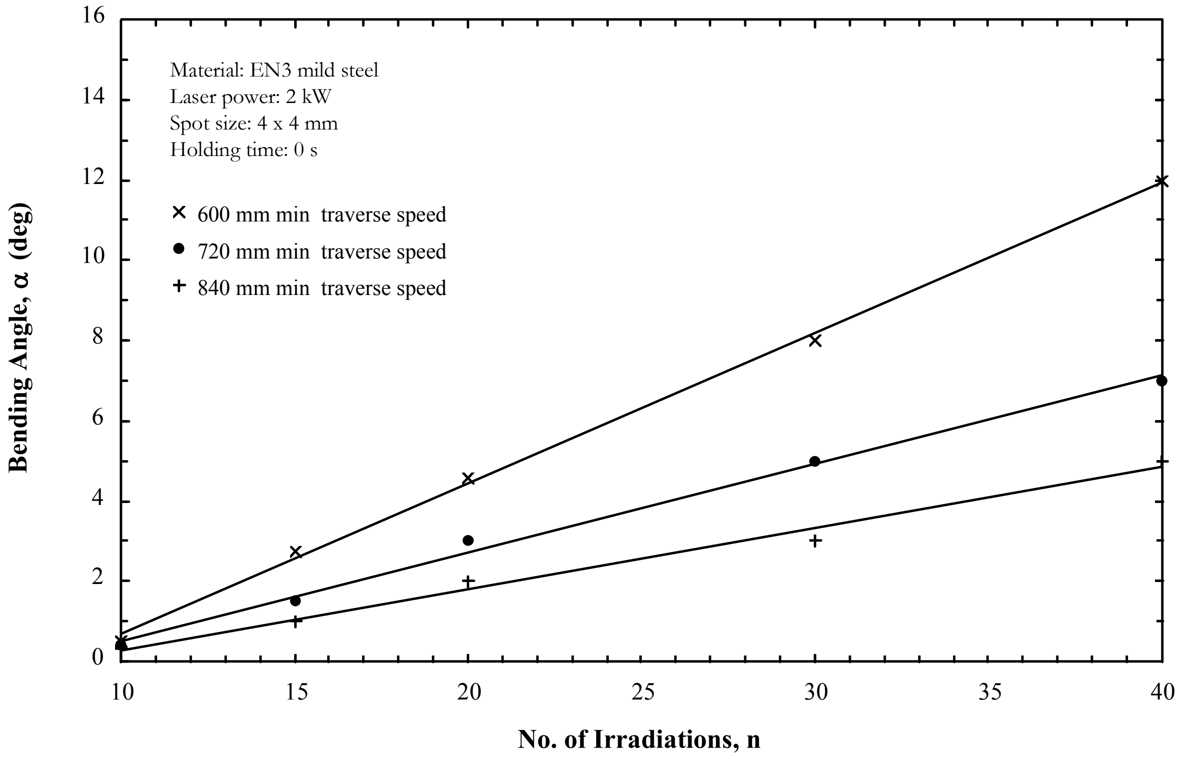

Material: EN3 mild steel
Spot size: 4 x 4 mm
n: 40 irradiations
Holding time: 0 s
600 mm min-1 traverse speed
720 mm min-1 traverse speed
840 mm min-1 traverse speed
Bending Angle, α (deg)
Laser Power (kW)
0
5
10
15
20
25
1.5
1.7
1.9
2.1
2.3
2.5

Fig. 4


Material: EN3 mild steel
Laser power: 2 kW
Spot size: 4 x 4 mm
Holding time: 0 s
600 mm min traverse speed
720 mm min traverse speed
840 mm min traverse speed
Bending Angle, α (deg)
No. of Irradiations, n
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2
4
6
8
10
12
14
16
10
15
20
25
30
35
40

Fig. 5

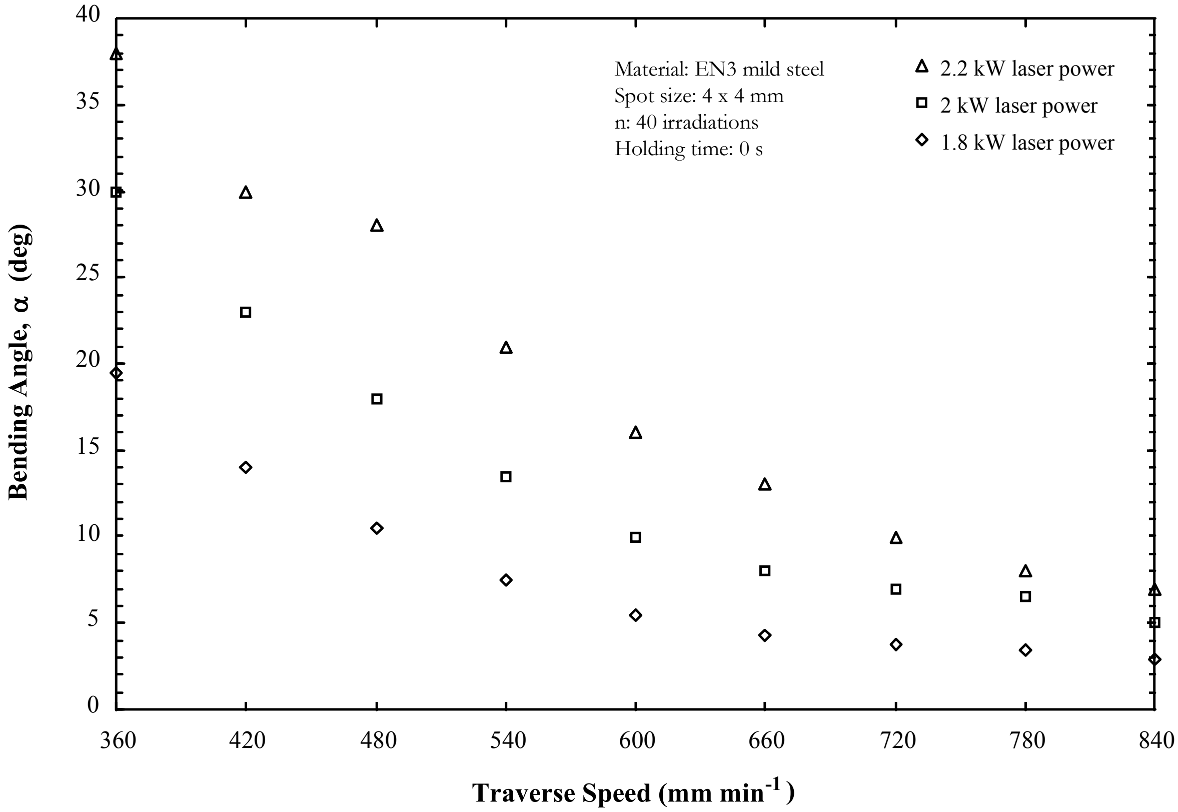

Material: EN3 mild steel
Spot size: 4 x 4 mm
n: 40 irradiations
Holding time: 0 s
2.2 kW laser power
2 kW laser power
1.8 kW laser power
Bending Angle, α (deg)
0
5
10
15
20
25
30
35
40
360
420
480
540
600
660
720
780
840
Traverse Speed (mm min-1)

Fig. 6

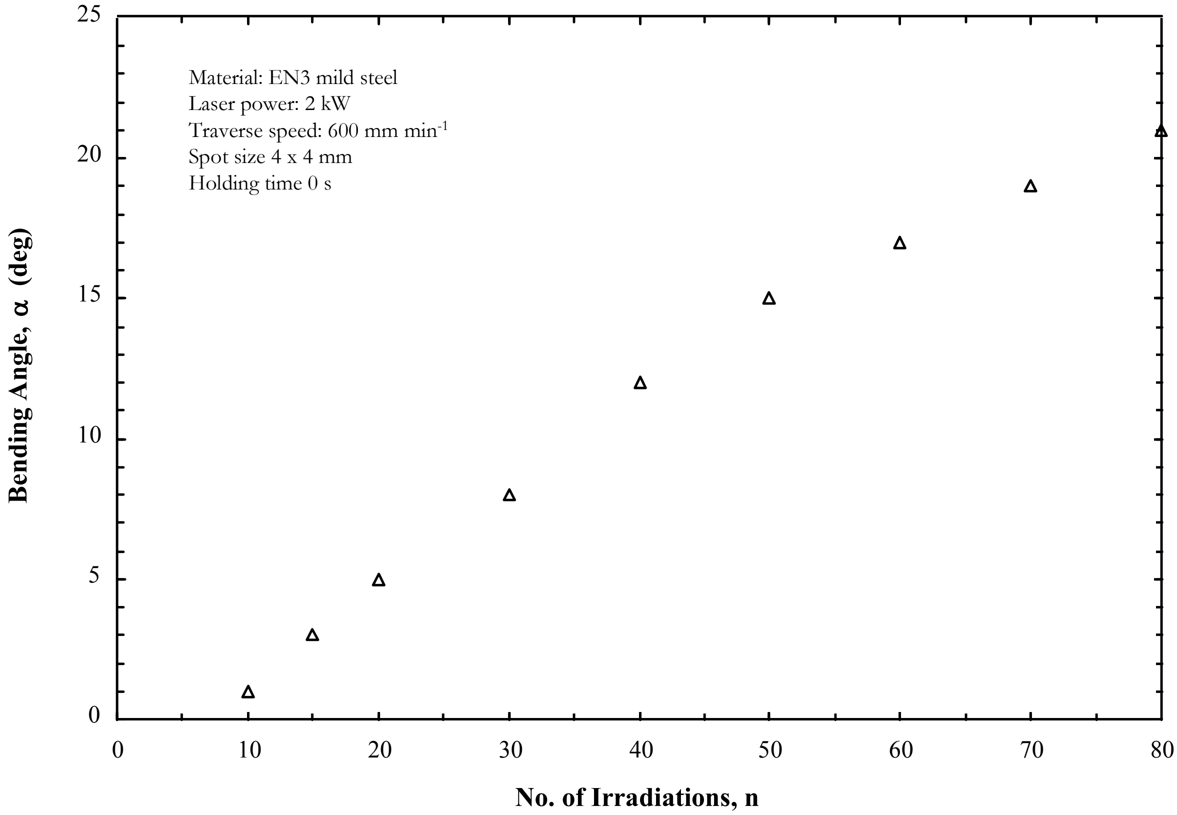
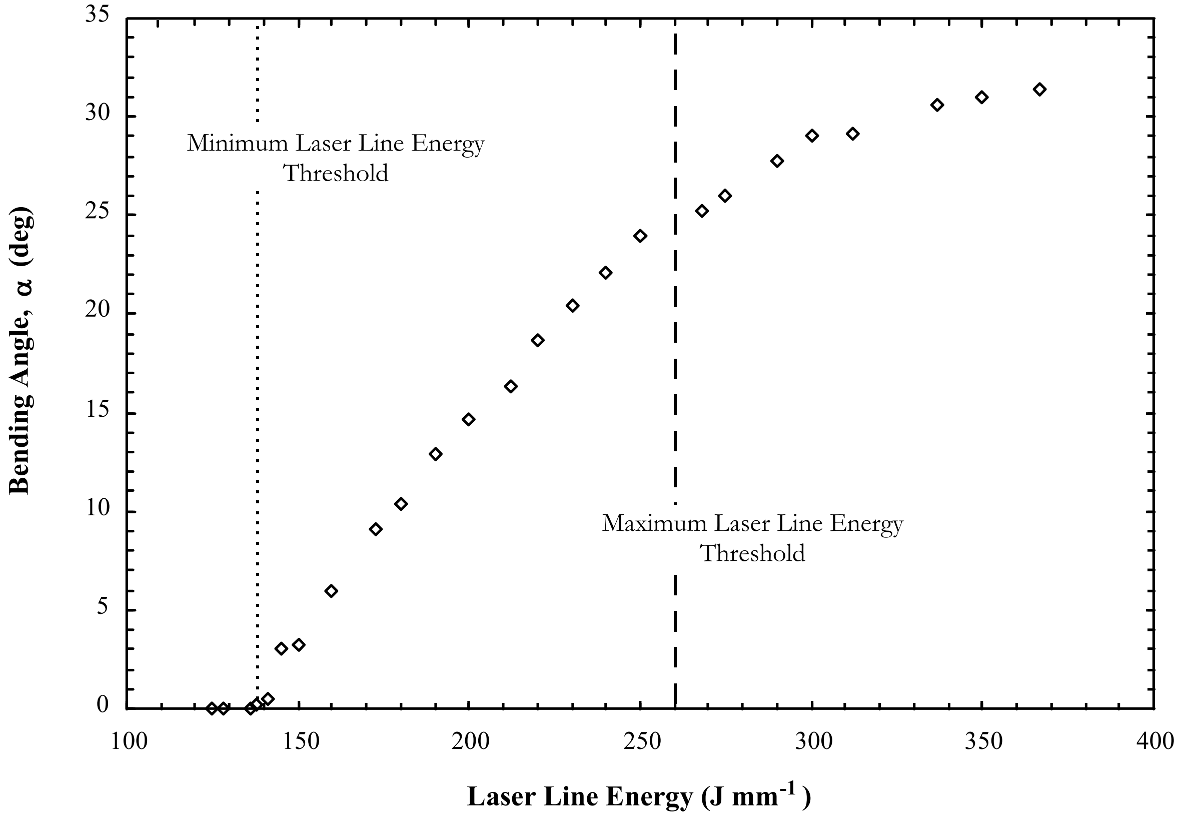

Material: EN3 mild steel
Laser power: 2 kW
Traverse speed: 600 mm min-1
Spot size 4 x 4 mm
Holding time 0 s
Bending Angle, α (deg)
No. of Irradiations, n
0
5
10
15
20
25
0
10
20
30
40
50
60
70
80

Fig. 7



35
30
25
20
15
10
5
0
100
150
200
250
300
350
400
Minimum Laser Line Energy Threshold
Maximum Laser Line Energy Threshold
Bending Angle, α (deg)
Laser Line Energy (J mm-1)