FACTORS INFLUENCING THE BEND PER PASS IN MULTI-PASS LASER FORMING

S. P. Edwardson, E. Abed, C. Carey, K. R. Edwards, G. Dearden, K. G. Watkins

Laser Group, Department of Engineering, The University of Liverpool, UK

Abstract

Laser forming offers the industrial promise of controlled shaping of metallic and non-metallic components for prototyping, the correction of design shape or distortion and precision adjustment applications. The potential process advantages include precise incremental adjustment, flexibility of application and no mechanical 'spring-back' effect. To date there has been a considerable amount of work carried out on two-dimensional laser forming, using multi-pass straight line scan strategies to produce a reasonably controlled bend angle in a number of materials, including aerospace alloys. A key area, however, where there is a limited understanding, is the variation in bend angle per pass during multi-pass laser forming along a single irradiation track, in particular the decrease in bend angle per pass after many irradiations for a given set of process parameters. Understanding of this is essential if the process is to be fully controlled for a manufacturing environment. The research presented in this paper through empirical data offers a coherent picture of the key influencing factors and at which point in the bend evolution each is active.

Keywords: Laser Forming, Temperature Gradient Mechanism, Multiple Pass.

1 Introduction

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

The process employs a defocused laser beam to induce thermal stresses without melting in the surface of a workpiece in order to produce controlled distortion. These internal stresses induce plastic strains, bending or shortening the material, or result in a local elastic plastic buckling of the work piece depending on the mechanism active [2].

The mechanism employed in this work is the Temperature Gradient Mechanism (TGM). This mechanism is the most widely reported, and can be used to bend sheet material out of plane towards the laser. The conditions for the temperature gradient mechanism are energy parameters that lead to a steep temperature gradient across the sheet thickness. This results in a differential thermal expansion through the thickness. The beam diameter is typically of the same order as the sheet thickness. The path feed rate has to be chosen to be large enough that a steep temperature gradient can be maintained. The feed rate and hence the temperature gradient has to be increased if materials are used which have a high thermal conductivity. The laser path on the sheet surface is typically a straight line across the whole sheet. This straight line coincides with the bending edge. Initially the sheet bends in the direction away from the laser. This is called counter bending. With continued heating the bending moment of the sheet opposes the counter bending and the mechanical properties of the material are reduced. Once the thermal stress reaches the temperature dependent yield stress any further thermal expansion is converted into plastic compression. During cooling the material contracts again in the upper layers, and because it has been compressed, there is a local shortening of the upper layers of the sheet and the sheet bends towards the laser beam. The yield stress and Young's modulus return to a much higher level during this cooling phase and little plastic re-straining occurs. Bends of approximately one degree per pass are achieved with this mechanism [2].

LF can be used for 2D and 3D forming. 2D laser forming encompasses laser forming operations that utilise two dimensional out-of-plane bends to produce three dimensional results e.g. a fold. 3D laser forming encompasses laser forming operations that can utilise combinations of multi-axis two dimensional out-of plane bends and in-plane localised shortening to produce three dimensional spatially formed parts e.g. a dome.

To date there has been a considerable amount of work carried out on two-dimensional laser forming, using multi-pass straight line scan strategies to produce a reasonably controlled bend angle in a number of materials, including aerospace alloys. A key area, however, where there is a limited understanding, is the variation in bend angle achieved per pass (or bend angle rate) during multi-pass laser forming along a single irradiation track (producing a positive bend), in particular the decrease in bend angle per pass after many irradiations for a given set of process parameters consistent with the TGM [2]. An example of this can be seen in **Fig. 1** were data from the multi-pass 2D laser forming of a 1.5mm mild steel CR4 coupon is presented (CW CO_2 laser).

It can be seen in **Fig. 1** that as the number of passes increases over the same irradiation line the bend angle achieved per pass varies. The overall bend angle is shown on the left hand primary Y axis and the bend angle per pass is shown on the right hand secondary Y axis. It can be seen that after the first five passes the bend angle per pass falls consistently for subsequent passes.

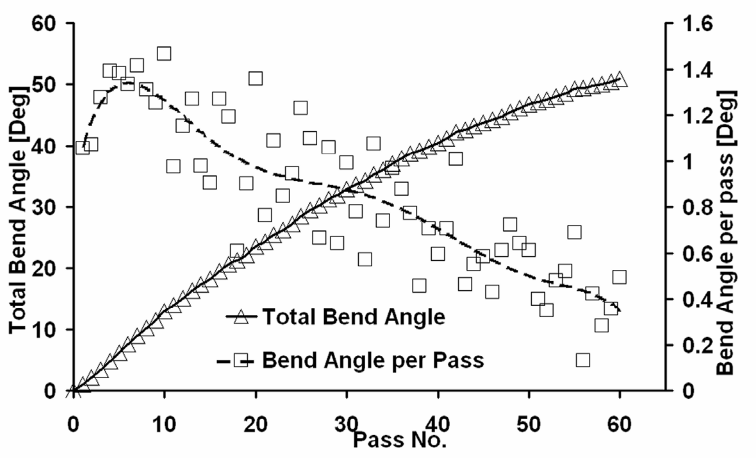

Fig. 1: *Example of the fall off in bend angle per pass during multi-pass TGM, laser forming over the same scan line using the same process parameters per pass. 1.5mm mild steel, 760W CW CO_2, 5.5mm beam diameter, 30mm/s, graphite coated.*

Understanding of this variation in bend angle per pass is essential if the LF process is to be fully controlled for a manufacturing environment. The research presented in this paper brings together the current theories as to why this occurs and offers a coherent picture of the degree of influence of each factor and at which point in the process each is active based on the presented empirical data.

2 Known factors influencing the bend per pass

There are a number of theories identified in the literature to explain the variation in bend angle per pass during multi-pass LF using the TGM, these are:

- Strain hardening.
- Section thickening.
- Variation in absorption.
- Thermal effects.
- Geometrical effect

2.1 Strain hardening

Strain hardening has been cited by a number of researchers [3-5] as a significant factor in the fall off of the bend angle per pass with increasing numbers of passes. The strain hardening phenomenon is attributed to the entanglement of dislocations. Plastic deformation in metals proceeds atomic step by atomic step by the generation and movement (by external force) of dislocations within the crystal lattice. During plastic deformation multiple dislocations created within the lattice interact during movement, as deformation continues the dislocation density increases and entanglement occurs. Further deformation is rendered more difficult by this entanglement and this manifests itself as an increase in hardness.

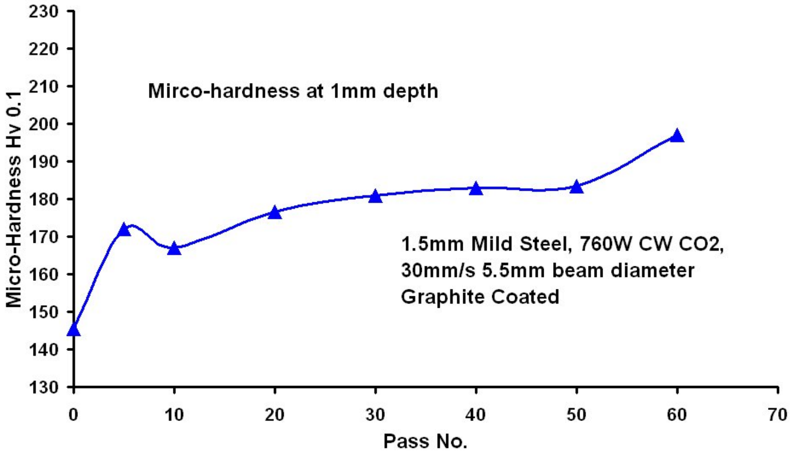

Fig. 2: *Microhardness at 1mm depth for 1.5mm mild steel, 760W CW CO_2, 5.5mm beam diameter, 30mm/s, graphite coated.*

Significant increases in hardness with increasing numbers of passes have been observed within the laser scanned region in a number of materials [3-7]. A typical example of the micro-hardness variation with pass number is shown in **Fig. 2**.

Although hardness does not give a direct measurement of the strain hardening phenomenon an indication of its value can be determined. If significant strain hardening occurs through the cross-section of the heated region over increasing number of passes, the bending strength of the section would increase, and hence the bend angle per pass would decrease. This effect is appears to increase gradually with increasing scans (**Fig. 2**) and likely to therefore influence higher scan numbers.

2.2 Section Thickening

An increase in the section thickness of the heated scan line after laser forming has been reported in a number of studies [2,4,6-11]. An example of this thickening effect can be seen in **Fig. 3**.

This thickening effect has been observed to increase pass by pass when irradiating over the same scan line in multi-pass 2D LF (**Fig. 4**). The effect is attributed to a conservation of volume, in that the lateral plastic compression in the upper surface consistent with the TGM during LF forces material upwards to some degree in order to conserve the volume. It is akin to pinching the upper surface along a line in order to create the bend. If the section is thicker then the material will be harder to bend due to the increase in the section modulus, or alternatively the moment generated about the section for a given set of energy parameters is less effective. This phenomenon has been shown to be confined to approximately the first 20 passes (dependent on process parameters) [12] (**Fig. 4**).

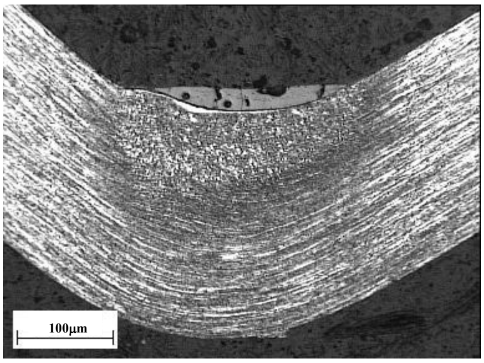

Fig. 3: *Example of section thickness increase during LF on 0.2mm mild steel, 20W CW Nd:YAG, 0.2mm beam diameter,* 30mm/s.

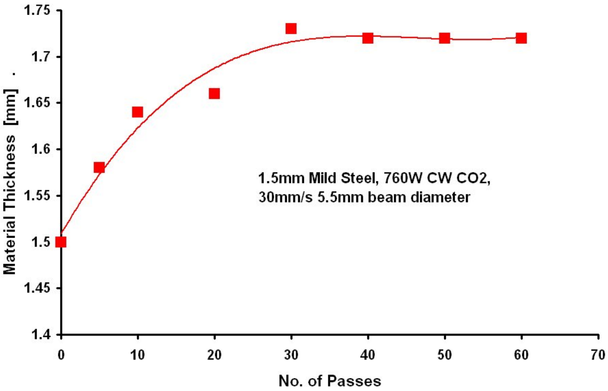

Fig. 4: *Section thickness increase during LF on 1.5mm mild steel, 760W CW CO2, 5.5mm beam diameter, 30mm/s, Graphite coating. Measured perpendicular to top surfac.*

It may be the case that as the geometry of the component changes during forming, i.e. increasing bend angle, the section thickness increase orientation may shift with the change in angle of attack of the beam. This can be observed in **Fig. 3** where a distortion of the HAZ is evident. It may therefore indicate that the fall off in this effect observed in **Fig. 4** after 30 passes could be attributed to the fact that the measurements are not now being taken in the correct place at the hi. Further study in this area is required to ascertain this. This geometrical effect has additional impact on the bend per pass achieved, this will be discussed in a later section.

2.3 Variation in Absorption

Key to the laser forming process is the coupling of a defocused low intensity (invariably infra red) laser beam into a (usually metallic) surface. A considerable amount of the research to date on LF has employed the use of CO_2 (10.6µm) and Nd:YAG (1.06µm) lasers with some high power diode laser work. At these wavelengths, especially 10.6µm, metals are highly reflective (~2% absorptance), for this reason absorptive coatings are usually used. Coatings such as graphite provide an interface for the incident laser radiation to be absorbed and then transferred to the metallic substrate, producing an overall efficiency of 60-80% depending on the substrate. As would be expected, variations in the absortivity of the surface of a workpiece to be formed will affect the bend angle per pass as the coupled energy will vary also.

Coatings such as graphite will be damaged and burnt off by repeated irradiations (**Fig. 5**), thus pass by pass the coupled energy will decrease and hence the bend angle achieved after each pass will also decrease. On some materials the coating burn off is more significant per pass than on others, this is most likely due to the thermal conductivity of the substrate. If the thermal conductivity is low then the thermal input from the laser is not as efficiently transferred into the substrate hence the significant coating degradation. **Fig. 6** shows how reliant the LF process is on the absorption coefficient of the material to the incident laser beam. It can be seen that forming has all but stopped after 20 passes on this material and on re-spraying the surface with graphite the forming rate per pass has approached the levels observed at the start.

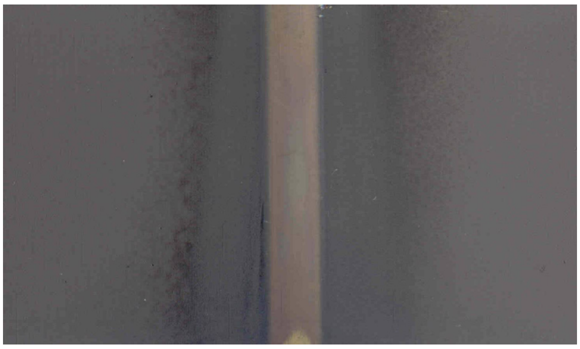

Fig. 5: *Absorptive coating degradation after 20 passes on 1.4mm Ti64, 900W CW CO2, 5.5mm beam diameter, 45mm/s, Graphite coating.*

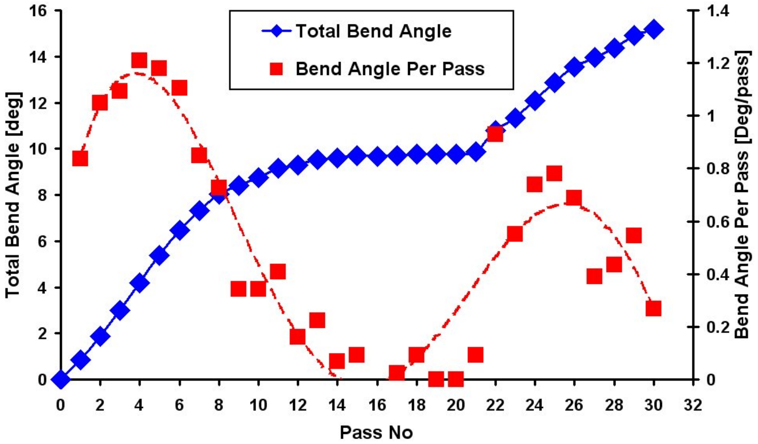

Fig. 6: *Effect of graphite coating re-spray after 20 passes on 1.4mm Ti64, 900W CW CO2, 5.5mm beam diameter, 45mm/s.*

For laser wavelengths and material combinations (e.g. Nd:YAG and mild steel or Ti64) where coatings are not required, variations in absorption can still be present. Surface darkening effects (akin to laser marking) caused by multiple irradiations have been reported [13]. These effects can lead to increased absorption which in turn can lead to excessive heating and surface damage for subsequent passes. For highly reactive surfaces the use of an inert shrouding gas has been shown to eliminate this effect [14].

2.4 Thermal Effects

Thermal effects refer to the heat build up within a component after each pass influencing the subsequent passes. The heat retained in the part can have one of two effects:

1. Aid the process by reducing the temperature dependent properties of the material i.e. flow stress. The analogy being that a hot component is easier to form than a cold one.
2. Increase the bulk material temperature of the component such that the thermal gradient generated by each subsequent pass is reduced (when employing TGM conditions) and hence the bend angle realised is reduced.

These points have been illustrated by thermocouple and numerical analysis of the multi-pass laser forming process (**Fig. 7**) [12,15-17].

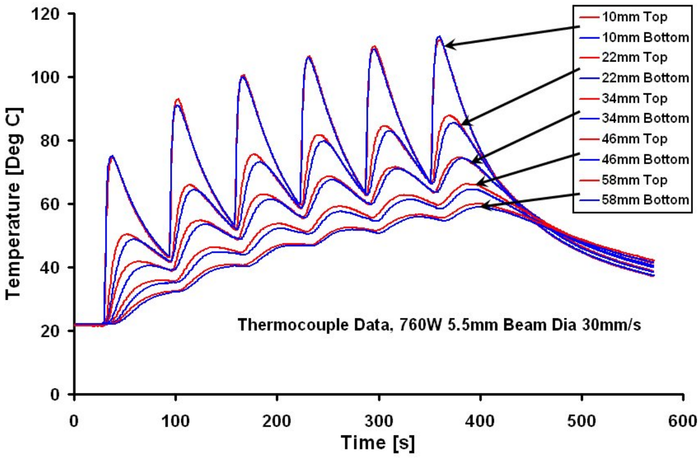

***Fig.** 7: Thermocouple data taken during LF on 1.5mm mild steel, 760W CW CO2, 5.5mm beam diameter, 30mm/s, Graphite coating.*

It can be seen in **Fig. 7** that the peak temperature achieved within the scan line increases pass by pass if there is insufficient dwell time between passes to allow complete re-cooling of the component. This is consistent with the first point that the heat retained in the part is aiding the process. It can also be seen that that the temperature increase for each pass is approximately the same but this is built on the increased bulk material temperature. This additional temperature increase for subsequent passes is akin to forming with higher power and hence more forming should be possible. Reducing the inter-pass delay can enhance this effect and has been proven to be useful for the forming of thick section materials, a so called ‘double pass’ technique [11].

The bulk material temperature increase with increasing number of passes observed in previous work (**Fig. 7**) [11,12,15-17] may potentially have a detrimental effect on the thermal gradient generated which is balanced against the potential benefit outlined above. This would be the case if the bulk material temperature continued to rise indefinitely; however by acquiring thermocouple data for several more passes it was possible to eliminate this effect [12]. It was observed that although the bulk temperature increased for the first few passes, for the subsequent passes up to approximately 10 an equilibrium was reached. This means that the potential beneficial and detrimental thermal effects on the bend angle per pass are confined to the first few passes or so. The beneficial effects may be responsible for the initial increase in bend angle per pass observed in **Fig. 1** over the first few passes, where the steadily increasing peak temperature realised along the scan line produces an increased bend angle.

2.5 Geometrical Effect

A final known factor is based on the geometrical effects of the component deformation influencing the process parameters. It was observed that when laser forming a component using an edge or cantilever clamping arrangement the incident beam geometry is influenced by the existing bend in the sample (**Fig. 8**) [18].

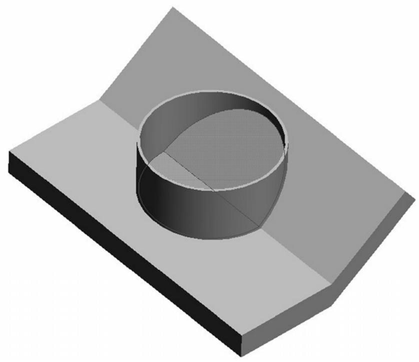

Fig. 8: *Illustration of the intersected beam area for an already bent sample*

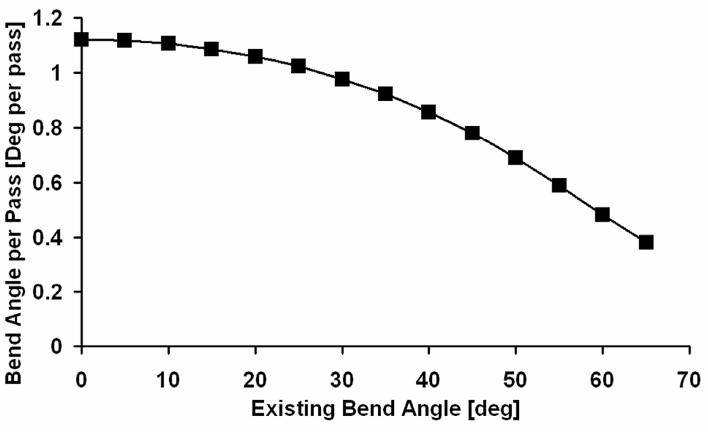

Fig. 9: *The calculated effect of existing bend angle on the bend angle achieved per pass during the LF of 1.5mm mild steel, 760W CW CO2, 5.5mm beam diameter, 30mm/s, Graphite coating. [18]*

More accurately only half of the beam geometry is influenced. A laser beam of circular cross-section (**Fig. 8**) transforms to an elliptical shape when incident on an inclined surface (positively or negatively bent), in which case its area increases and energy fluence decreases compared to normal incidence.

Through empirical and analytical investigations, it was found that this variation in the beam area interacting with a component has a significant effect on the bend angle achieved per pass. The effect of the loss in incident energy density as the component deforms pass by pass was found to increase significantly at higher bend angles (**Fig. 9**).

Experiments employing a V block clamping configuration to limit the geometrical factor showed that the fall off in bend angle per pass at higher passes reduced significantly for the same material and laser parameters [18].

3 Degree of Influence

The degree to which each of the factors discussed in the previous section influences the 2D LF process and at which point each is active is summarised in **Fig. 10**. It can be seen that the effect of the increasing bulk material temperature is likely to be responsible for the initial rise in the bend angle per pass up to a point where thermal equilibrium occurs. The effect of section thickening then influences the initial fall off in bend angle per pass, however this effect is limited to the first 15-20 passes. From 15 passes onwards the condition of the coating (if used) and hence the amount of laser energy absorbed becomes more apparent, if not renewed (re-sprayed) this factor will be increasingly influential for all subsequent scans. At higher number of passes the strain hardening factor will also become influential, experimental data has confirmed that the hardness and hence strain hardening does increase with increasing passes. At higher bend angles the geometrical factor becomes more dominant, experimental work [18] has shown this to be as influential if not more so than the other two factors active at higher passes.

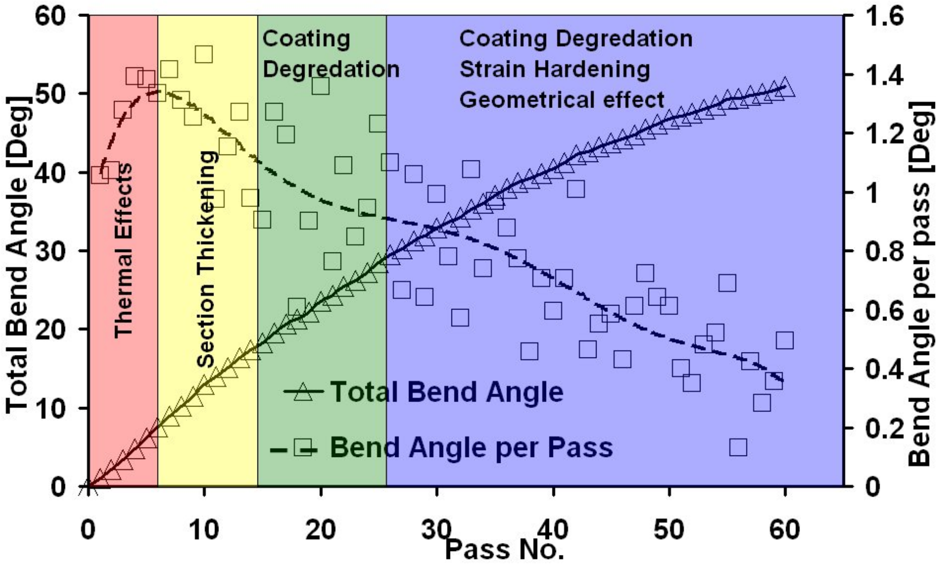

Fig. 10: *Summary of the degree of influence and at which point each of the influencing factors occur during multi-pass 2D laser forming. Example on 1.5mm mild steel 760W CW CO2, 5.5mm beam diameter, 30mm/s, graphite coated.*

4 Conclusions

A key area in the laser forming process where there is a limited understanding, is the variation in bend angle per pass during multi-pass laser forming along a single irradiation track, in particular the decrease in bend angle per pass after many irradiations for a given set of process parameters. Understanding of this is essential if the process is to be fully controlled for a manufacturing environment. The research presented in this paper brought together the current theories as to why this occurs and offered a coherent picture of the degree of influence of each factor and at which point in the process each is active based on the presented empirical data.

Acknowledgment

The authors gratefully acknowledge the support of the EPSRC in the UK, Grant No: GR/S43276/01 for the completion of part of this work.

For more information on the laser group at the University of Liverpool go to: www.lasers.org.uk or www.nwlec.org.uk

References

[1] Magee J; Watkins K G; Steen W M.: Advances in Laser Forming. In: Journal of Laser Applications 10 (1998) 235-236.

[2] Vollertsen F: Forming, sintering and rapid prototyping. In: Handbook of the Eurolaser Academy, edited by Schuöker D (Chapman & Hall, London) (1998) 357-453.

[3] Sprenger A; Vollertsen F; Steen WM; Watkins KG: Influence of strain hardening on laser bending, In: Manuf Syst. 24, (1995) 215-221.

[4] Thomson G; Pridham M: Material property changes associated with laser forming of mild steel components. In: Journal of Materials Processing Technology 118 (2001) 40-44.

[5] Merklein M; Hennige T; Geiger M: Laser Forming of Aluminium and Aluminium Alloys – Microstructural Investigation. In: Journal of Materials Processing Technology 115 (2001) 159-165.

[6] Cheng J; Yao YL: Microstructure integrated modelling of multiscan laser forming Journal of Manufacturing Science and Engineering 124 (2002) 379-388.

[7] Shackel J; Sidhu J; Prangnell PB: The Metallurgical Implications of Laser Forming Ti-6AL-4V Sheet. In: Proc. ICALEO Conf. (Jacksonville, USA) (2001) ISBN 0-912035-73-0.

[8] Marya M; Edwards GR: A study on the laser forming of near-alpha and metastable beta titanium alloy sheets. In: Journal of Materials Processing Technology 108 (2001) 376-383.

[9] Magee J: Laser Forming of Aerospace Alloys. In: PhD Thesis, The University of Liverpool, UK (1999).

[10] Ramos J; Magee J; Watkins K G; Steen W M; Noble F: Microstructure of laser bent aluminium alloy Alclad 2024-T3. In: Proc. International Congress on Applications of Lasers & Electro-Optics (ICALEO) (Orlando, FL, USA) (1998) pp 141–150 ISBN 0-912035-58-7.

[11] Edwardson SP: A Study into the 2D and 3D Laser Forming of Metallic Components. In: PhD Thesis The University of Liverpool UK (2004).

[12] Edwardson SP; Watkins KG; Abed E; Bartkowiak K; Dearden G: Geometrical Influences on the Bend Angle Rate per Pass during Multi-Pass 2D Laser Forming. In: Proc. International Workshop on Thermal Forming (IWOTE'05) (Bremen, Germany) ed F Vollertsen and T Seefeld (2005) pp 29–46 ISBN 3-933762-16-2.

[13] Bartkowiak K; Dearden G; Edwardson SP; Watkins KG: Development of 2D and 3D Laser Forming Strategies for Thin Section Materials using Scanning Optics. In: Proc.International Congress on Applications of Lasers & Electro-Optics (ICALEO) (San Francisco, CA, USA) (2004) ISBN 0-912035-77-3.

[14] Bartkowiak K; Edwardson SP; Dearden G; Watkins KG: 2-D Laser Forming Comparative Study using CW and Pulsed Nd:YAG lasers on titanium alloy Ti-6Al-4V in air and argon atmospheres. In: International Congress on Applications of Lasers & Electro-Optics (ICALEO) (San Francisco, CA, USA) (2004) ISBN 0-912035-77-3.

[15] Edwardson SP; Watkins KG; Dearden G; French P; Magee J: Strain Gauge Analysis of Laser. In: Forming Journal of Laser Applications 15 (2003) 225-232.

[16] Cheng J; Yao YL: Cooling effects in multi-scan laser forming. In: Journal of Manufacturing Processes 3 (2001) 60-72.

[17] Hu Z Labudovic M Wang H Kovacevic R: Computer simulation and experimental investigation of sheet metal bending using laser beam scanning. In: International Journal of Machine Tools & Manufacture 41 (2001) 589-607.

[18] Edwardson SP; Abed E; Bartkowiak K; Dearden G; Watkins K: Geometrical influences on multi-pass laser forming. In: Journal of Physics D: Applied Physics vol 39 issue 2 (2006) pp 382-389.