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. 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 Temperature Gradient Mechanism (TGM) based 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. The research presented in this paper through empirical data and numerical simulation using Comsol Multi-Physics of the multi-pass laser forming of sheet mild steel, Ti6Al4V and AA5251 by CO\textsubscript{2} laser offers a novel coherent picture of the key influencing factors and at which point in the bend evolution each is dominant.

Keywords: Laser Forming; Bending; TGM; Temperature Gradient Mechanism

1. Introduction

The laser forming (LF) process has become viable for the direct shaping of metallic components, in particular high value low volume components, as a means of rapid prototyping and of adjusting or distortion removal, perhaps after a conventional forming procedure. 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]. Laser forming as a manufacturing tool would likely be considered a secondary process when considering the cost-effectiveness of a laser system, in that a system could be purchased for primarily a cutting or welding operation, proven to be cost effective and competitive, and used for laser forming as a bonus additional process.

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]. Among the as-known forming mechanisms such as the Temperature Gradient Mechanism (TGM), the buckling mechanism (BM), the upsetting mechanism (UM) and the elastic expansion mechanism (EEM), the TGM is one of the dominating mechanisms in laser forming.

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], hence multi-pass irradiation is needed for higher bend angles, but it offers the potential for good control in an incremental process.

To date a number of studies on the control of both 2D and 3D laser forming have shown the potential of the process for direct forming operations, for the correction of unwanted distortion and the precise alignment of macro and micro scale components [3-5]. 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). Of particular importance is 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 figure 1 (a), were typical TGM LF data from the multi-pass 2D laser forming of a number of materials at optimised processing condition is shown. It can be seen that the bend angle produced per pass shows a far from linear relationship, falling off at higher number of passes for each of the materials investigated.

This is further illustrated in figure 1(b) by analysing the pass by pass data for 1.5mm mild steel from figure 1(b). It can be seen 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.

Understanding of this variation in bend angle per pass is essential if the LF process is to be fully controlled for a manufacturing environment. There are a number of theories that have been identified both individually in the literature and new to this research 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.

The mechanisms by which these factors influence the LF process and at which point they are active are demonstrated in this paper through empirical data and numerical simulation of the laser forming of sheet mild steel, Ti6Al4V and AA5251 by CO2 laser. This offers a novel coherent picture of these key influencing factors and at which point in the bend evolution each can be active and dominant which has not been presented before.

2. Experimental

The experimental study was conducted on graphite-coated 1.5mm thick Mild Steel AISI 1010, 1.4mm thick Ti6Al4V, and 2mm thick AA5251 using a 1.5kW Electrox CW (Continuous Wave) TEM00 CO2 laser with a 3-axis Galil CNC beam delivery system with custom written control software. The samples were laser cut into 80x80mm coupons and these were edge clamped in a cantilever arrangement for processing (Figure 2a). For a study on the effect of beam shape distortion due to geometry, a V block or flat clamping arrangement was used (Figure 2b).

For an experimental study of the thermal aspects of LF K type thermocouples attached by high temperature adhesive pads to the coupons were used in conjunction with a high speed data logger.

To assess strain hardening behaviour Micro-hardness HV0.1 values through the thickness of the processed samples with increasing number of passes were obtained using a Vickers Micro-hardness tester. The load force was set to 9.806 N and the loading time was 10 seconds.

![Fig. 2. Sample clamping arrangement: (a) cantilever or edge clamp and (b) simply supported V-block or flat clamp](image)

To fully understand the thermal aspects of the LF process a FE model was developed. A 2005 element thermo-mechanical simulation of the laser forming of 80x80x1.5mm AISI 1010 steel, using multiple irradiations, was developed using COMSOL Multi-Physics. Material properties were sourced from the ASM Metals Handbook, COMSOL’s built in materials library and via experimentation. Thermal expansion co-efficient, Young’s modulus, poissons ratio, specific heat capacity, thermal conductivity, density and yield stress were all considered temperature dependant and validated against empirical results. The incident laser beam was approximated by a Gaussian distributed heat source and an absorption coefficient of 0.8.
3. Results and Discussion

Empirical and numerical results and discussion are presented in the following sections specific to each of the influencing factors and are then combined in the final section.

3.1. Strain Hardening

Strain hardening has been cited by a number of researchers [2, 6] 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.

Significant increases in hardness with increasing numbers of passes have been observed within the laser scanned region in a number of materials [6-11]. An example of the micro-hardness variation during the LF of 1.5mm mild steel at selected depths into the irradiated section with pass number is shown in figure 3 (a). It can be seen that after an initial jump there is a steady increase in the average micro-hardness value of the irradiated section with increasing number of passes. To further illustrate this, figure 3 (b) shows the variation of micro-hardness through the irradiated section at various pass numbers. It can be seen that there is complex distribution of micro-hardness values through the section. The micro-hardness can be seen to increase, from the as received (pass 0) value, with an increasing pass number right through the section. A significant increase in the upper middle region can also be seen by pass 60, an indication perhaps of significant work hardening in this area.

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 appears to increase gradually with increasing scans (figure 3(a)) and is therefore more likely to be an influence at higher deformation and hence higher scan numbers. Whilst active from the start, at 20 passes the hardness value has increased by 25% of the as received and for this study strain hardening is therefore considered to be a significant dominant factor past this point.

Strain hardening behaviour during laser forming will be dependent on material type and the influence of this factor will therefore be more significant in materials that strain harden at a greater rate. It is also possible that a metallurgical change (e.g. phase transformation to martensite) due to heating of the section could account for a portion of the micro-hardness change and if so would be difficult to separate out from strain hardening. However,
parameters were selected for this study to specifically avoid excessive heating to mitigate micro-structural change influencing the result, this will be discussed in a later section. Further work analysing materials with different strain hardening characteristics such as heat treated alloys of aluminium may yield further understanding of the influence of this factor.

3.2. 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, 7-11]. An example of this thickening effect on 1.5mm thick mild steel sheet can be seen in figure 4(a), where the material can be seen to bulge at the centre of the bend radius. This thickening effect has been observed to increase pass by pass when irradiating over the same scan line in multi-pass 2D LF. Figure 4(b) shows the pass by pass section thickness of a cantilever clamped (clamped at one edge) laser formed mild steel sample measured directly under the centreline of the laser scan line.

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, 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. The influence of sheet thickness on the TGM is considerable, Vollertsen [2] showed analytically that the sheet thickness $s_0$ has an inverse square relationship with the bend angle $\alpha_b$ per pass in his derived two layer model:

$$\alpha_b = 3 \frac{\alpha_{th} p_t A}{\rho C_p v_t s_0^2}$$

(1)

Where $p_t$ is the laser power, $A$ is the absorption coefficient, $v_t$ is the processing velocity, $C_p$ is the specific heat and $\rho$ is the density. It can be noted that this relationship would not account for any fall off in bend angle per pass if all components are taken as constant. Another analytical model by Vollertsen, a residual stress model, suggests that this is even an inverse cube relationship [2], therefore potentially an even more significant factor. It can be seen in figure 8 however, that for the LF of mild steel this thickening phenomenon is confined to approximately the first 15-20 passes (material and process parameter dependent), becoming a constant factor in the process after this point.

Fig. 4. (a) Example of section thickness increase during LF on 1.5mm mild steel CR4, 760WCWCO2, 5.5mm beam diameter, 30mm/s, and 60 passes. (b) Section thickness increase during LF on 1.5mm mild steel, 760W CW CO2, 5.5mm beam diameter, 30mm/s, and graphite-coated. Measured perpendicular to the top surface. Cantilever edge clamped and V-block flat clamped samples.

An additional complication to this factor is that as the geometry of the component changes during forming, i.e. on increasing bend angle, the section thickness increase orientation may shift with the change in angle of attack of the
beam or distortion of the intersected beam area by the bending leg of the sample. This can be observed in figure 4(a) where a distortion in the symmetry of the HAZ (Heat Affected Zone) around the centreline is evident on the clamped left hand side of the micrograph. It may therefore indicate that the fall off in this effect observed in figure 6 after 30 passes could be partially attributed to the fact that the measurements are not being taken in the same orientation as the continuing section thickness increase past this point. By repeating this study using a V-block or flat clamping arrangement (figure 2b) to reduce the beam area distortion with increasing bend angle, it can be seen that the section thickness does continue to increase. However, this is at a much reduced rate at higher pass numbers. A similar result would likely be found if the section thickness in the cantilever case was measured taking into account the change in angle of attack. The dominance of this factor for a given clamping condition therefore appears to be limited to the first 20-30 passes with a reduced impact after this point. A further numerical sensitivity analysis on various materials could yield a better understanding of this, however. This geometrical beam distortion effect has been found to have an additional impact on the bend per pass achieved and this will be discussed in a later section.

3.3. Variation in Absorption

Key to the laser forming process is the coupling of a defocused low intensity (usually 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 absorptivity of the surface of a workpiece to be formed will affect the bend angle per pass as the coupled energy will vary also. This can be clearly seen in equation 1.

Coatings such as graphite will be damaged and burnt off by repeated irradiations [12]. This can be seen in figure 5(a), where the coating condition after a number of irradiations can be seen to have degraded. 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. Figure 5(b) 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 of the 1.4mm thick Ti6Al4V sample (data taken from figure 1(a)) has all but stopped after 20 passes (graphite surface condition as in figure 5(a)) and on re-spraying the surface with graphite the forming rate per pass has approached the levels observed at the start.

![Graph showing Total Bend Angle and Bend Angle per Pass](image)

(a)

(b)

Fig. 5. (a) Example of absorptive coating degradation after 20 passes on 1.4mm Ti6Al4V, 900W CW CO$_2$, 5.5mm beam diameter, 45mm/s, and graphite-coated. (b) Effect of graphite coating re-spray after 20 passes on 1.4mm Ti6Al4V, 900W CW CO$_2$, 5.5mm beam diameter, and 45mm/s

For laser wavelengths and material combinations (e.g. Nd:YAG and mild steel or Ti6Al4V) where coatings are not as required (sufficient coupling possible), 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 and improved process efficiency. However, for the same process parameters, an improving absorption coefficient 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 but with a reduced process efficiency due to low inherent surface absorption characteristics [13].

As discussed this factor is significant in the multi-pass TGM laser forming process in particular when graphite coating is used. The burn off rates for the graphite are dependent on substrate type and processing conditions. For mild steel for example the burn off rates are not as significant as for Ti6Al4V for similar process conditions [12] and the effect on bend angle achieved per pass is less pronounced but is still present (figure 1(a)). Therefore this factor must be considered to influence the higher number of passes on the majority of materials from 15 to 20 passes onwards.

3.4. 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 [14].

These points have been illustrated by thermocouple and numerical analysis of the multi-pass laser forming process on sheet mild steel. It can be seen in figure 6(a) that for the LF of mild steel, the peak temperature at 10mm from the scan line, and hence within the scan line, increases pass by pass if there is insufficient dwell time between passes to allow complete re-cooling of the component to room temperature [15]. 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 with the available laser power. Reducing the inter-pass delay can enhance this effect and has been proven to be useful for the forming of thick section materials - the so called ‘double pass’ technique [16] - providing melting and adverse metallurgical change does not occur.

The bulk material temperature increase with increasing number of passes observed in figure 6(a) 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 is possible to eliminate this effect. It can be seen in figure 6(a) that although the bulk temperature increased for the first few passes, for subsequent passes equilibrium is 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 figure 1(b) over the first few passes, where the steadily increasing peak temperature realised along the scan line produces an increased bend angle.

Another potential factor in the decrease in bend angle per pass in the TGM related to thermal effects is any change in microstructure due to the thermal cycle. Whilst parameters were selected for this study to specifically avoid excessive heating to mitigate microstructural change influencing the result, if the peak temperature, time at temperature and cooling rate exceeds a critical value for a phase transformation, dynamic re-crystallisation or precipitation coarsening in a given material, then this could have an effect on the ductility of the material and hence the bend angle achieved per pass. As it was found to be difficult to obtain experimentally the temperature cycle directly under the laser beam, a FE model was developed and verified against the experimental data to estimate this. Figure 6(b) shows the Comsol Multi-Physics model at the mid pass point for the LF of mild steel using the same conditions as the experimental data for temperature. Also given in figure 6(b) is the temperature profile in degrees C for a point at the centre of the plate directly in the beam path, the calculated peak temperature is 971°C. It can be seen that the heating and cooling rates are very high and so either unique microstructures may form or little effect may be observed due to the lack of time at elevated temperatures. Although austenitic temperatures may be rapidly reached (> 723°C) these are equally rapidly quenched (into the bulk material) and may either prevent a phase transformation or lock a non-equilibrium phase transformation in place. The time the material is above the austenitic temperature (0.06s at the top surface), for these non-equilibrium process conditions, is unlikely to be sufficient for the microstructure to react but a repeated thermal cycle over multiple passes may induce a retained change. Further analysis would be needed to confirm this and this will form the basis of future work. Another possibility for the mild steel due to the high quench rates involved in the process (~1000°C/s calculated in the upper surface) is the formation of martensite (dependent upon the austenite formation). Both these phase transformations would adversely affect the ductility of the material in the irradiated zone and hence reduce the bend angle per pass with increasing volume fraction of each. Further study is required to assess LF induced microstructural change and its effect on the multiple pass laser forming process. Recent published work [17] on the metallurgical implications of laser forming of mild steel has shown that for certain processing conditions, at a higher energy density than that used in this study, martensite and grain refinement was found to occur during processing and hence this would affect subsequent passes.

3.5. Geometrical Effect

A final known factor is based on the geometrical effects of the component deformation influencing the process parameters. Similar to that observed in the section thickening phenomenon, it was observed that when laser forming a component using an edge or cantilever clamping arrangement (figure 2a) the incident beam geometry is influenced by the existing bend in the sample.

More accurately only half of the beam geometry is influenced. A laser beam of circular cross-section 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. The beam area A was found to vary with bend angle \( \alpha _{b} \) for a given beam radius \( R_{1} \) with the following relationship:

\[
A = \frac{\pi R_{1}^{2}}{2} \left( 1 + \frac{1}{\cos \alpha _{b}} \right)
\]  

(2)

The variation of this function can be seen in figure 7(a), where the increasing bend angle has a significant impact on the beam area, in particular at higher angles, 40 degrees and over. In preliminary work to the present study [18], the effect of a beam area increase was linked to the effect on bend angle per pass by studying the influence of
increased beam diameters and hence incident beam area at constant line energy on the LF of the same material, 1.5mm thick mild steel. The averaged relationship over many passes between bend angle and beam diameter (and hence beam area) at a constant line energy was found experimentally and used to predict the bend angle per pass for a given incident beam area. Figure 7(a) (primary axis) shows the calculated bend angle per pass against the existing bend angle for the 1.5mm mild steel sample. Whilst not a direct comparison, as only half the beam area is affected in the edge clamped case, this still showed that the reduction in energy density due to changing geometry has a significant effect on the process, in particular at higher bend angles. This was further confirmed by experiments employing a V block or flat clamping configuration (figure 2b) to limit the geometrical factor, where a sheet component can sink into the clamp as it is formed (whilst maintaining the focus control) with each of the bending surfaces free to move upwards. Although in this arrangement the incident beam would be distorted on both sides of the centreline, there is only a dependence on half the bend angle on the incident beam area and therefore the effect at higher bend angles is reduced. A comparison of the two clamping arrangements can be seen in figure 7(b), where at higher bend angles (30-40 degrees and above) the fall off in bend angle achieved per pass for the V block condition is significantly less than for the edge clamped condition. Although not the only active factor, this would suggest that the clamping arrangement has a large influence on the multi-pass TGM laser forming process at higher bend angles. In addition, this factor is certainly linked to the section thickening effect discussed earlier, with the distorted beam changing how the sheet is thickening.

![Fig. 7. (a) Increase in the incident beam area with increasing bend angles (second axis) and the calculated effect of this on the bend angle achieved per pass during the LF of 1.5mm mild steel, 760W CW CO2, 5.5mm beam diameter, 30mm/s, and graphite-coated (b) Comparison of edge and V-block or flat clamping arrangements for LF of 1.5mm mild steel, 760W CW CO2, 5.5mm beam diameter, 30mm/s, and graphite-coated](image)

3.6. Overall Degree of Influence of Each Factor

The factors found to be influencing the bend angle per pass in multi-pass TGM laser forming have been presented and discussed in the previous sections. For the laser forming of a given material, the degree of influence and exactly at which point each of these factors would be active and dominant is dependent on the specific processing conditions such as: material properties, process parameters (speed, power, pass dwell time etc.), clamping condition, absorptive coating, laser type etc. However, in order to give a more generalised overview of these factors in terms of the order and approximate point at which they would be active, the experimental data for edge clamped 1.5mm mild steel has been used to summarise the factors.

Figure 8 shows the data from figure 1(b) for mild steel overlaid with the regions where each of the presented influencing factors would be active and dominant. The position of and reasons for selecting the regions of influence are summarised in table 1. As discussed earlier, 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, from the presented experimental data this effect appears to be limited to the first 15-20 passes as an active or increasing dominant factor. The effect of the increased sheet thickness would be still present past this point but would remain constant with each subsequent pass. 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. The presented 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 for an edge clamped sample; presented experimental work has shown this to be as influential if not more so as the other two factors active at higher passes (figure 7(a)).

Fig. 8. Summary of the degree of influence and at which point each of the influencing factors can occur during multi-pass two-dimensional LF. Example on 1.5mm mild steel, 760W CW CO2, 5.5mm beam diameter, 30mm/s, and graphite-coated

Table 1. Summary of influencing factors, at which point each is active and dominant plus the reasons for selection, for the LF of 80 × 80 × 1.5mm mild steel AISI 1010, 760W, 5.5mm beam diameter, 30mm/s, graphite-coated, edge-clamped, 60 passes

| Factor               | Pass No Active from | Pass No Dominant From | Pass No Dominant To | Reason                                                                                                                                 |
|----------------------|---------------------|-----------------------|---------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| Strain Hardening     | 1                   | 20                    | 60                  | By pass 20 the average micro-hardness value has increased by 25% and was considered dominant past this point.                          |
| Section Thickening   | 1                   | 5                     | 15                  | Only a small percentage section increase over the first 5 passes and the section increase has fallen off significantly by pass 15.    |
| Variation in Absorption| 1               | 15                    | 60                  | Coating degradation observed around pass 15 onwards, re-spray of graphite on Ti6Al4V sample at this point yielded increased forming. |
| Thermal Effects      | 1                   | 1                     | 5                   | Initial increase in bend angle achieved per pass corresponded to a measured steady increase in bulk material temperature aiding the process before equilibrium has been achieved by pass 5. |
| Geometrical Effect   | 1                   | 40                    | 60                  | By pass 40 the calculated bend angle achievable per pass has fallen by 25 % and so this effect is considered dominant.              |
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 TGM 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 and the factors that influence this. Understanding of this is essential if the process is to be fully controlled for a manufacturing environment. The factors presented were: strain hardening, section thickening, thermal effects, variation in absorption and a geometrical effect.

The research presented in this paper through empirical data and numerical simulation of the laser forming of sheet mild steel, Ti6Al4V and AA5251 by CO2 laser offers a novel coherent picture of the key influencing factors and at which point in the bend evolution each is dominant which has not been presented before. A summary of the influencing factors for the LF of mild steel based on the presented empirical and numerical data was also given.

Further work is required however to assess LF induced microstructural change and its effect if at all on the multiple pass laser forming process.

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