LASER FORMING AS A METHOD OF PRODUCING DESIGNED OBJECTS

S. Silve, H. Zhao
Department of Mechanical Engineering
Brunel University
Uxbridge, Middlesex, UK

ABSTRACT

Laser forming can manipulate sheet, tubes and spinnings into sophisticated surfaces appropriate for decorative objects. The process offers non-contact forming in a wide range of metals; the laser induces compressive stresses by precise localised heating which in turn causes the material to bend. Three mechanisms of laser forming have been established; they are characterised by the heating through the materials' thickness and the bending direction. A straight line bend will create a fold and to this end the process can be used to replicate scoring without the need for soldering. Laser forming can, however, be used more extensively as there is a relationship between the heating pattern and the resulting form. Processing considerations and heating strategies will illustrate the complexity of both the technique and the parts that can be created. The future development of the process and the potential advantages for design and practical working will be put forward.

INTRODUCTION

Laser forming is a flexible metal forming technique in which laser induced stresses shape the metal rather than hard tooling and exerted forces. The utilisation of thermal distortion for metal bending is not entirely new; "flame straightening" uses the non-uniform heating with an oxyacetylene torch to create the necessary compression to bend mis-aligned girders.[1]

Laser bending works in much the same way as flame straightening, except the laser CNC workstation offers greater control. A laser beam has more power density for the area of distribution compared to the flame of a torch and this results in a much smaller heat affected zone, while the ability to program movement in a minimum of the x and y axes adds accurate positioning which in turn means repeatable processing and manufacturing potential.

Laser forming has been researched worldwide for about twenty years. Three bending mechanisms have been established and the bending efficiency of various materials has been widely published. Laser bending has a direct application in realigning parts that have "spring back" as a result of conventional folding techniques, and could easily be combined with laser techniques such as cutting and welding for fabricating net objects. In most instances, the laser bends material without modifying its structure or properties and for these reasons, laser forming is being developed by the automotive and aerospace industries for producing body panels. Using sheet metal, tubes and spinnings as starting forms, laser forming can create prototypes without the need for expensive tooling. Working in this way, the laser is capable of producing complex surfaces such as those found in tableware and holloware.

BENDING MECHANISMS AND PROCESSING PARAMETERS

Laser forming typically uses a CO_2 laser with a maximum power in excess of 500W. The process involves material being traversed under the laser beam by means of an x-y table. Raw laser beams are often directed through a lens so that the beam is focused to a spot. Laser forming uses a defocused beam, this means that the work piece lies in the portion of the beam beyond the focus point of the lens. The laser operating power and beam diameter affect the power density of the beam, while the traverse speed affects the amount of heat penetration through the material. There are three main mechanisms of laser bending and each method is characterised by the gradient of compression that is created by the distribution of heat through the thickness of the metal. A heating gradient can lead to bending towards or away from the beam, while homogenous heating through the thickness causes a shortening of the part. The following descriptions of the bending mechanisms assume the model of a straight traverse from one side of a sheet to the other to create a fold.

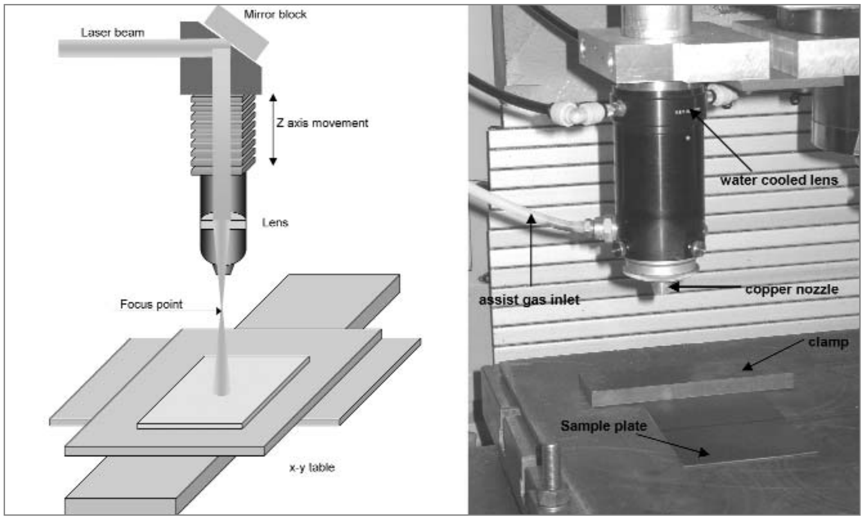

Figure 1 *The CO_2 laser set up for laser bending.*

The Temperature Gradient Mechanism (concave bending)

The laser can bend metal towards the beam when there is a temperature gradient through the thickness of the sheet. This mechanism relies on a small beam diameter with a high path feed rate; essentially the heat is not given time to penetrate fully to the bottom of the sheet. Furthermore, the more thermally conductive the metal, the faster the beam will need to travel across the surface to maintain the temperature gradient. As heating begins, the locally heated area of the sheet expands and there is an initial counter bending (away from the beam) due to the expansion of the heated surface. Sometimes, depending on the material being used, this counter bending is large enough to be seen. The expansion is hindered by the cooler material below the surface which still has a large elastic modulus. Further heating results in the thermal expansion being converted to compressive plastic strains. The heat dissipates forward and through the sheet, any point behind the beam has begun to cool. Cooling proceeds by heat conduction through the part, and the plastically compressed area contracts. The contraction through the sheet thickness is relative to the induced temperature gradient, with more compression occurring in the upper layers. The shortening near the surface causes a bending of the material towards the laser beam. As a result, a ridge develops along the bending edge on the heated side. For most materials, the angle is almost fully developed by the time the laser has left the sheet's surface. The bending angle achieved by this mechanism for one irradiation depends on the coupled energy, the materials thickness and mechanical properties of the material, but is typically between 0.1° and 3°.[2]

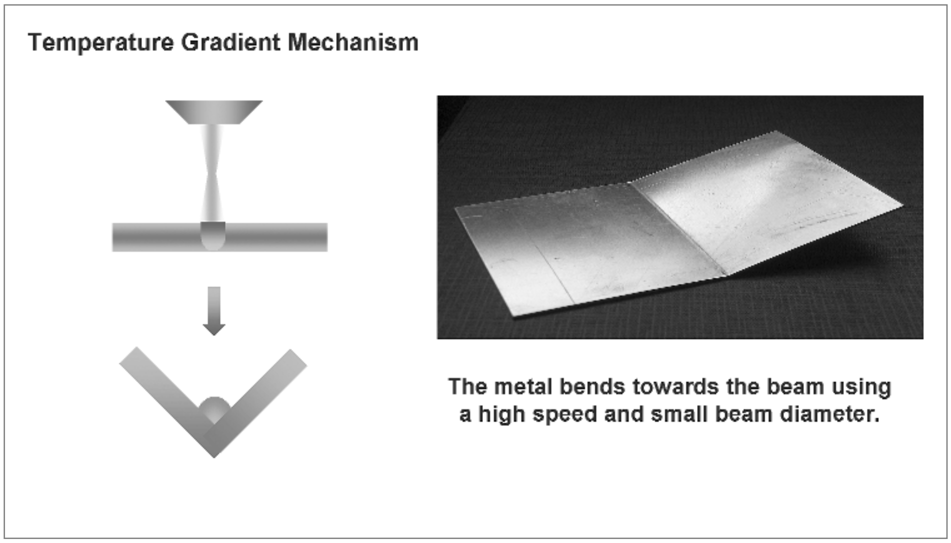

Figure 2 *The Temperature Gradient Mechanism (TGM).*

The Buckling Mechanism (convex bending)

The buckling mechanism can result in either bending towards or away from the beam, and requires almost even heating through the sheet's thickness. This can be achieved using a slow speed with a large beam diameter. As the beam begins to travel across the sheet, the localised area expands, which gives rise to compressive stresses in the heated area. The heated area begins to buckle and this movement can be either towards or away from the beam. Cooler surrounding material restrains the material either side of the fold to the original plane. The hottest part is the centre of the buckle where the flow stress is low, consequently almost all of the bending in this area is plastic. Material outside the beam centre is not as intensely heated and the flow stress is high; as a result, bending in this area is elastic. As heating continues across the sheet, the bending is guided by the direction of the initial buckle. This heating alters the stiffness of the sheet and the elastic bending at the base of the buckle relaxes, so that the profile straightens to what can be recognised as an angle. The buckling mechanism produces angles of up to 15° per scan, which is larger than can be achieved with the temperature gradient mechanism.[2] This is due to being able to use higher power with larger beam sizes without melting the metal, however, the bending edge is rounded as a result of the wider heat affected zone. In the 1990's, H. Arnet and F. Vollertsen carried out research to create convex shapes with good reproducibility.[3] Their work suggested that parameters of instability make it possible for the buckling mechanism to produce both positive and negative angles (see Figure 3).[3] It was also noted that thin sheets are hardly ever totally flat, and this pre-bending was shown to have an influence on the bending direction.[3] For process reliability, it therefore seems sensible to predict the direction of the buckling mechanism by pre-bending.

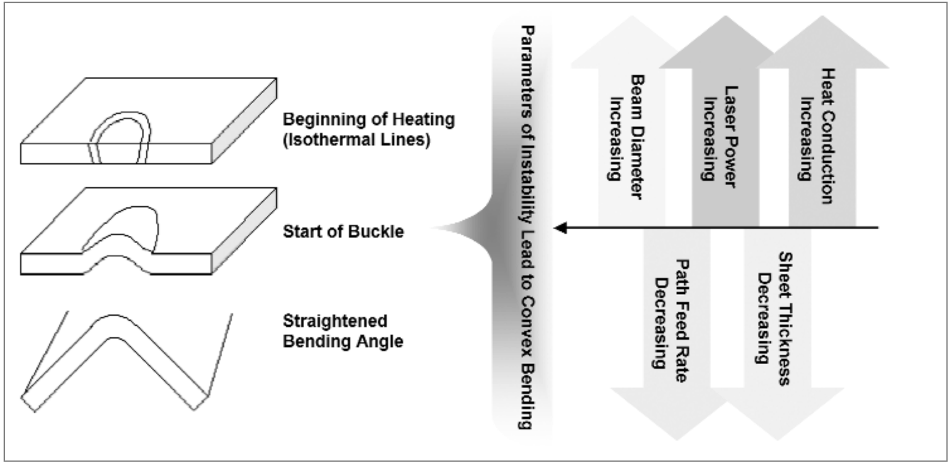

Figure 3 *Convex bending of the buckling mechanism.*

The Upsetting Mechanism

The third mechanism is called upsetting; it occurs when heating is nearly homogenous through the sheet. Upsetting results in the shortening of the material through the sheet thickness in the heat affected zone. The beam diameter is smaller than that used with the buckling mechanism, and the path feed rate is slow. As irradiation begins, the stresses in the heated area relax. Further heating results in plastic compression of the heated area because the surrounding material prevents expansion. On cooling, the metal contracts; the material shortens through the sheet thickness and as a result becomes thicker as no material is lost. This mechanism achieves form by reducing the surface area and is particularly appropriate for making bowl shapes and manipulating tubes. To create a bowl from a metal disc, there needs to be an increasing loss of surface area from the centre of the disc to the edge, so that the perimeter is raised from the table surface; this is possible with the upsetting mechanism. The through compression of the upsetting mechanism is difficult to achieve with thin materials, since the buckling mechanism is likely to be effective resulting in a bending direction. It may be possible to achieve through compression with thin metals by restricting the movement of the surrounding material through clamping. Upsetting is more easily attained with stiffer materials, in terms of increased plate thickness or part geometry in the case of tubes.

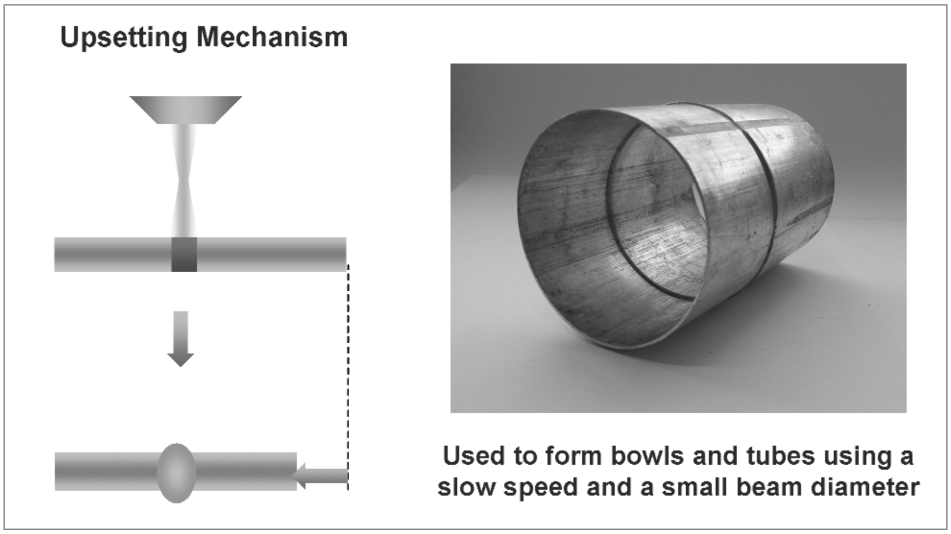

Figure 4 *The upsetting mechanism increases the thickness of the material. Tube with a ring of compressed metal about its circumference.*

The Point Source Mechanism

This fourth lesser known mechanism is effective under the same conditions as the temperature gradient mechanism, except there is no movement of the work piece with respect to the laser beam. The heated zone is therefore the diameter of the laser beam, and the metal is exposed to a pulse of energy. This mechanism has not been intensely investigated, although F. Vollertsen reports that the resulting bending angle is very small, perhaps 0.1° to 0.01°.[2] Such an amount of bending makes it useful for aligning electronic parts.[2,4] To this end, electronics manufacturers have used this laser forming mechanism to alter the angle of the lens in CD and DVD players.[5] Since there is no bending edge defined by the laser path because it is a spot, the sheet dimensions are an important factor in determining the bending edge. If the point source irradiates a rectangular sheet, the bending will occur across the width, since the energy required for the bending momentum is lower.[2]

Forming Parameters

Each laser formed component relies on a particular laser path. Where possible, it is best to extend the laser lines beyond the sample dimensions to allow for the ramping of the table and initiation of the laser. Laser forming is an asymmetrical heating process and each line can be in one of two directions. For a given pattern, there may be several possible heating sequences which can result in different forms. Forms often require a period of development, however once the scanning pattern and sequence are correct, then only the laser parameters should need changing to produce that object in a different material or thickness.

Material Properties

It is usual to change the laser parameters with respect to the material being processed. Young's modulus denotes a material's resistance to change in length strains, such as is caused by stretching. Each material also has a different rate of thermal expansion and conductivity. Sample sheets for bending may be subject to residual stresses in the way they have been rolled or stored; the stock material may be either hard or annealed. When using shiny materials there is a chance that some of the energy could be reflected rather than coupled into the work piece. To prevent reflectivity, the sheet's surface needs to be altered either by roughening the surface e.g. sandblasting, or applying a coating. Surface roughening may be uneconomical to the manufacturing process. Graphite spray is a coating which can also increase absorption and is generally the preferred solution. Essentially it is best to carry out laser forming under consistent conditions.

Multiple Scanning

A single scan produces a small amount of bending and consequently multiple scans of the laser path are usually necessary. The rate of incremental forming is not usually linear; it has been shown that over a period of time the amount of bending per scan is reduced due to work hardening.[2,6] In addition to heating the metal, the amount of time for which the part is allowed to cool is also a factor. Generally it will take about 20 seconds for a part to cool after a reasonable amount of heating.

Angle of Incidence

Laser energy is best absorbed when the beam is perpendicular to the work piece. As the form develops, areas of metal move closer to the focus point and the beam diameter is reduced. Similarly, as the laser scans its path, the angle at which the beam strikes the work piece is continually changing. Changes in the beam's angle of incidence away from the perpendicular, result in a slower rate of bending. A constant beam diameter can be achieved using a height sensing system. The changing angle of incidence is more difficult to overcome. The beam can be kept perpendicular to the work piece by utilising robotic arms and installing additional axes, however, a high level of modeling and experimentation is needed to predict the resulting form and calculate the respective motion of the axes. In most systems, jigs are made to support the part so that the change in the bend rate is evenly distributed.

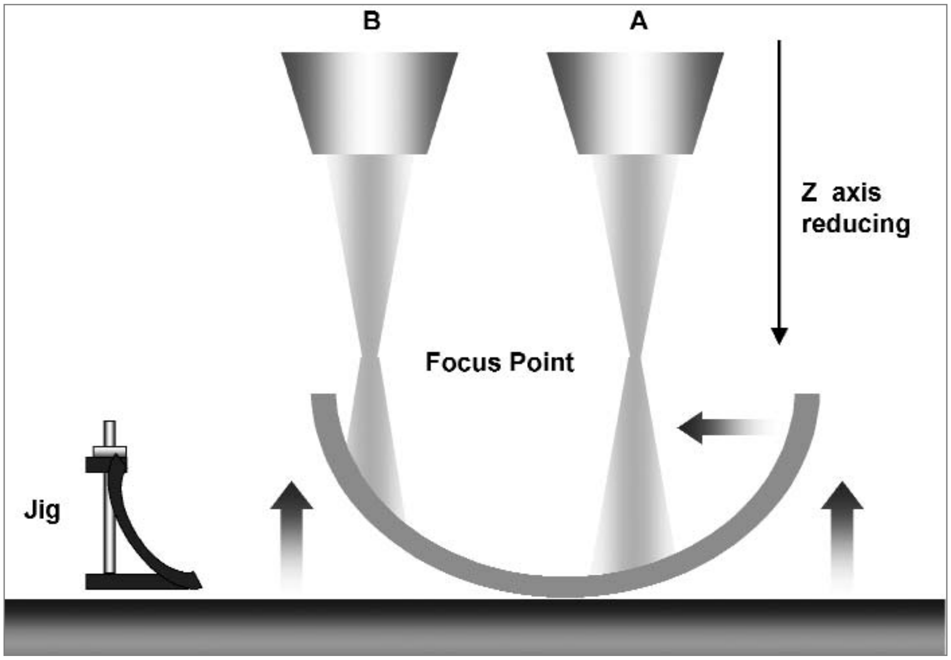

Figure 5 *The angle of incidence.*

PRACTICAL INVESTIGATION

Lines as Vertices

Using the temperature gradient mechanism, it is possible to create folds that are as defined as those made by traditional scoring. Laser forming offers advantages over hand-scoring in that it is less arduous and time consuming; there is no removal of material since the bending occurs as a result of compression and subsequently there is no seam to solder. “Lines as Vertices” is the authors’ term to describe a pattern which effectively replicates the scoring process; the lines of the pattern become the vertices of the new object. Many silversmiths are interested in the effect of folds on the material’s surface, where subtle undulation occurs as a result of folded curves. The ability of the laser to form a single sheet, and the possible curving of planes as a result of the relationship between sheet geometry and pattern, is intriguing. While it is a non-contact process, laser forming is still dependent on the material’s properties and geometrical constraints; i.e., the metal can only be bent so far before it will buckle. Forming an isolated shape within a rectangular sheet may produce rounded folds as the surrounding material can have a restraining effect, such as shown in the right of Figure 6. Similarly, as a part develops, it may move slightly with respect to the projected geometry, in which case more rounded folds can result and the part begins to resemble a pressing. The object shown bottom left in Figure 6 is made from two parts joined together. Each part is made using 4 lines; with these four lines there are 96 possible sequences. This is inconceivable in the experimental development of the object and illustrates the need to observe forming tendencies.

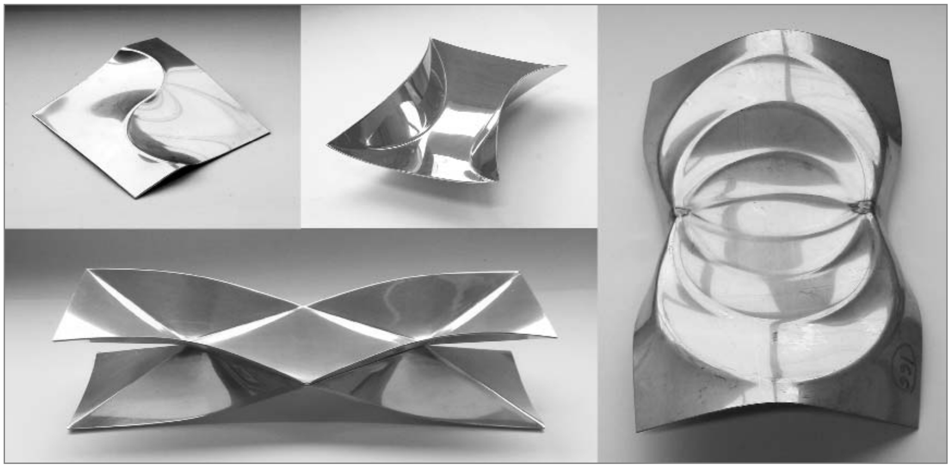

Figure 6 *A selection of forms using folded lines.*

Feed Rates and Pre-Cutting

With laser forming it is possible to use the same path geometry to produce a range of forms. Figure 7 shows two stainless steel samples that were produced using the same pattern, however, the laser parameters were changed so that different bending mechanisms were effective. The complete pattern *C* was broken into component sets *A* and *B*. Each set of lines was scanned in the order shown. The dish on the left of the image used different feed rates for set *A* and set *B*. It was scanned from the underside. The 150 x 150 x 0.9mm sample was irradiated using set *A* at 450W with a 5mm beam and a path feed rate of 15mm/s, giving positive and negative bending of the buckling mechanism. The path feed rate was increased to 30mm/s for the lines in Set *B*, resulting in bending towards the beam. The object received 12 scans and was rotated 90º between scans to maintain symmetry. The dish was produced in a little over an hour. The pyramid surface (sample's underside shown right in Figure 7) illustrates how pre-cutting can be used to enhance forming. Cuts were made in the sample leaving just enough metal where the lines intersect. The cuts reduced the sheet's rigidity allowing it to bend with respect to the laser path, so that it became a sheet of small pyramids joined together. Pattern *C* (*A*+*B*) was used at 400W and 80mm/s with a 3mm beam so that bending was towards the beam under the temperature gradient mechanism. With cutting assisted forming, the laser can also perform the cutting operation.

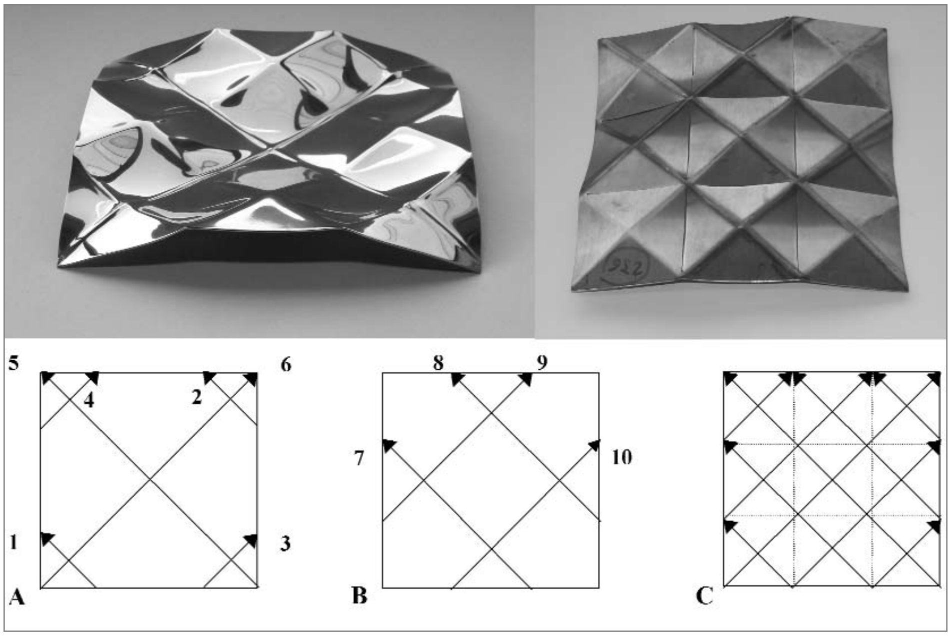

Figure 7 *Patterns can be used to produce more than one form.*

Offsetting Laser Scans

Irradiating a series of parallel lines produces a curved profile due to incremental bending. This technique is known as offsetting. Scans are usually in the same direction to maintain an even rate of heating and cooling for each line, as the time lapse between any adjacent point will be the same between irradiations. Scans in opposite directions, without cooling, may lead to overheating and melting of the sample edges, which may be used for decorative effect. This surface melting can be exaggerated by using lines that do not over-run the edges of the sheet. The principle for offsetting is incremental bending and, for a given set of operating conditions, the smaller the offset between the lines the tighter the curvature of the resulting profile. The relationship between the offset and the radius of the profile has been expressed mathematically using trigonometry by M. Pridham and G. Thomson as $R=s/(2\sin(a/2))$, where R is the radius of the curvature, s is the offset of the passes and a is the amount of bending for a single pass.[7] The size of the offset will also contribute to the visual quality of the form, very small offsets will produce smooth profiles while larger steps will have a more folded appearance.

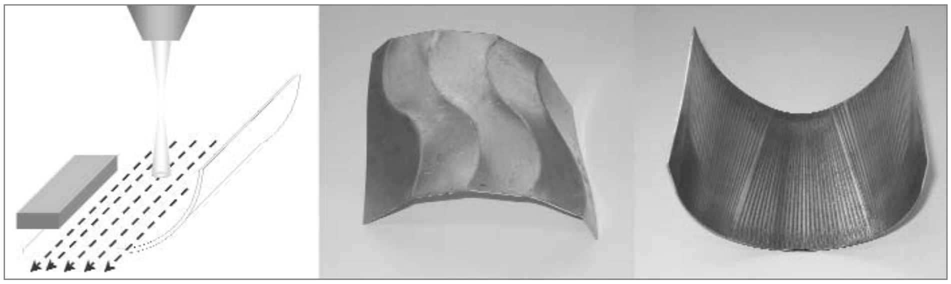

Figure 8 *The size of the offset affects the profile's smoothness.*

Offsetting can also use lines which are not straight or parallel as shown in Figure 8. Lines can be offset by an angle (radial offsetting). This makes use of the relationship between the offset and the resulting profile, as tapering the offset will give a change of radius across the sheet, and we can begin to imagine forms as sections of cones. Lines may be similarly offset using ratios, for example the lines may start 1mm apart, progress to 3mm apart before returning to 1mm apart further along the sheet. Several examples of tapered offsetting are shown in Figure 9, and it is clear that the proportions of the pattern govern the final form. With endless combinations of line ratios and proportions, it becomes evident that the process is capable of directly shaping material into forms that might be traditionally achieved using hammers and stakes. Samples shown in the bottom of Figure 9 demonstrate that shapes are generally repeatable.

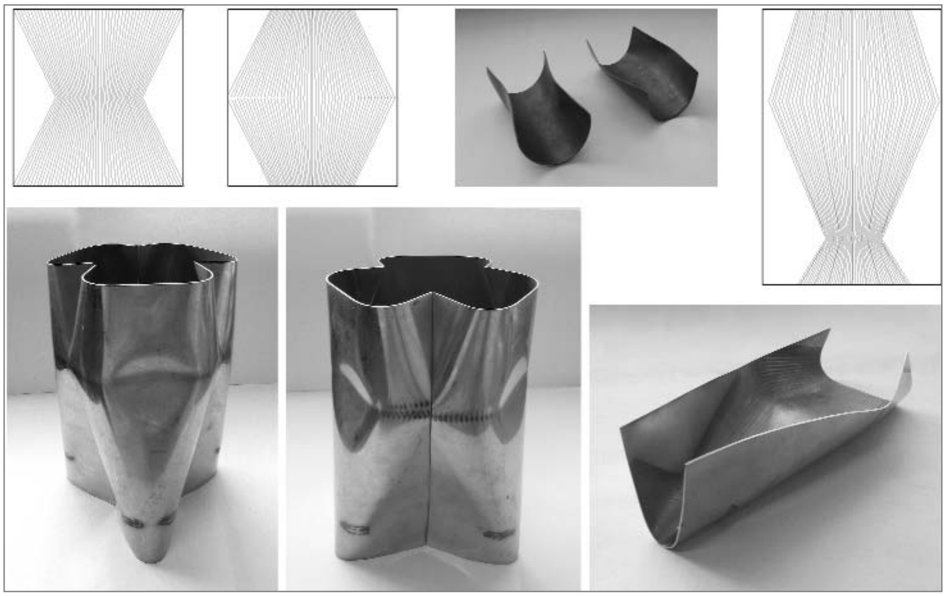

Figure 9 *Tapered offsetting can create fluid forms from conical sections.*

Concentric Offsetting

Patterns of concentric lines can create dished forms when using parameters that would lead to the temperature gradient mechanism under straight line bending conditions. The concentric dishing method is dependent upon focusing a lot of heat to the centre of the sheet, subsequently forming starts from the edge of the sheet and works inwards; trials working from the centre to the edge of the sheet have only curved the sheet about its diagonal. The processing time is usually continuous without any cooling between lines, only cooling between complete scans of the laser path. Figure 10 shows samples irradiated with decreasing concentric polygons. When decreasing octagons 3mm apart, on a sheet 150 x 150 x 1mm, the parameters used were 250W, a 3mm beam and a speed of 100mm/s. Different results were achieved using stainless steel A304 and aluminium. With aluminium, the first scan curved the sheet predominantly in one direction. The varying distance of the work piece from the beam affected subsequent scans as the beam diameter was larger and therefore power density lower, in the areas furthest from the beam. When decreasing polygons, the points where the laser changes direction, receive more heating due to the table ramping, and they become the vertebrae of the form. The stainless steel sample was limiting in containment but it showed depth and vitality. Spiralling the start points of the octagons gave the stainless steel sample more symmetry. With concentric offsetting, the amount of bending is not usually equal across the length and width of the sample. Such uniformity is heavily reliant on an equal amount of surrounding material and evenly distributed compression. A more equal amount of dishing is evident in the square sample shown in Figure 10, which may be a result of equal surrounding material, however, there is still a dominant bending direction overall.

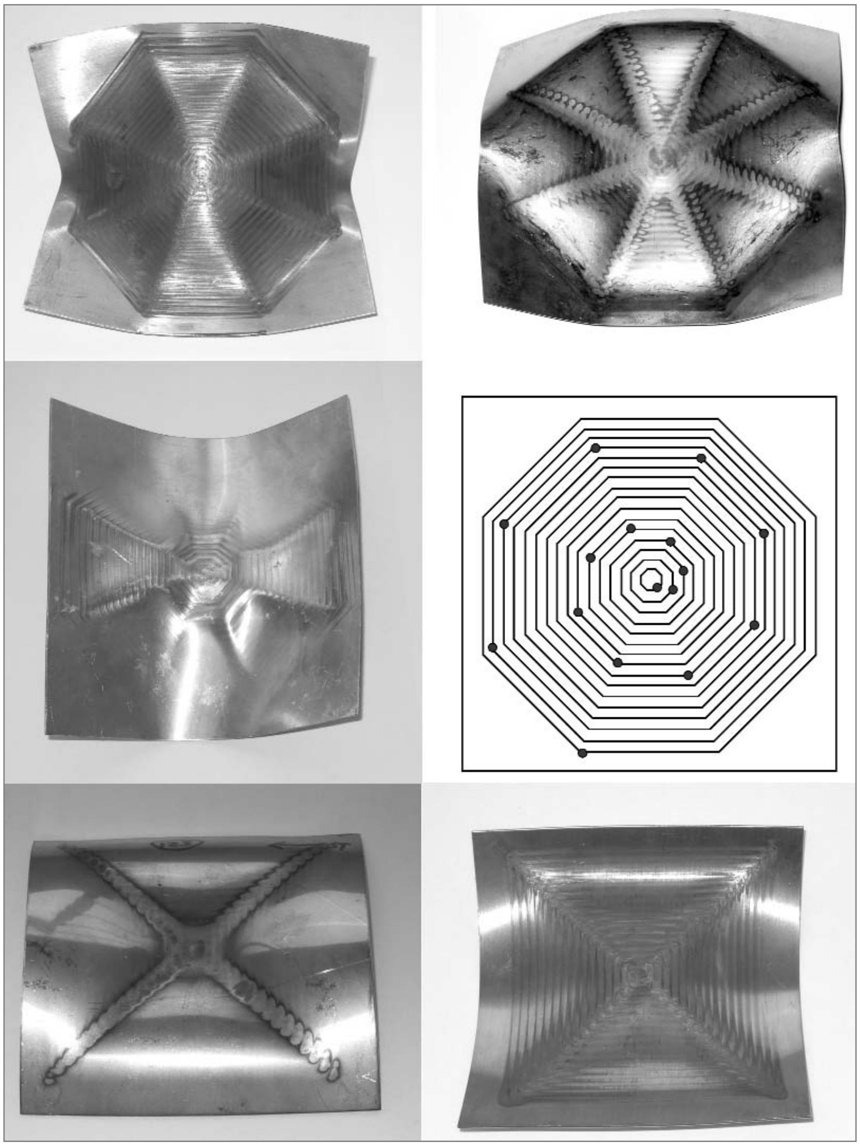

Figure 10 *Concentric offsetting to create dished forms.*

The stainless steel sample shown right in Figure 11, was scanned with concentric rectangles offset by 5mm starting from the outside and working towards the middle of a sheet 133 x 171 x 0.9mm. The parameters used were 440W at 60mm/s with a 3.5mm beam. The first rectangle was scanned starting in the bottom left corner and scanning anticlockwise, after which the starting points were spiralled as they were with the decreased octagons experiments. A central rectangle remains un-scanned but is elastically formed into a dish by the stresses induced from the plastically formed areas. The aluminium sample, shown left in Figure 11, used the same path geometry and sample dimensions but the sheet was 1mm thick. This plate however, was scanned from the innermost rectangle outwards, the beam diameter was increased slightly to 4mm while the speed and power were reduced to 40mm/s and 300W respectively. Each rectangle was scanned twice consecutively before moving on to the next. This creates homogenous heating through the plate, which results in an increased plate thickness at the point of scanning by the upsetting mechanism. The central un-scanned area remains flat. In repeating the experiment, steel weights approximately 6cm in length, were centred on the shortest edges; each covered an estimated 5mm of the sample’s length. The weights restricted movement of the edges in the early stages and helped maintain symmetry. These examples illustrate how a pattern can be used to produce more than one form by changing the mechanism or sequence. It is also becoming apparent that laser forming is capable of imparting surface decoration, and that such embellishment is intrinsic to the form rather than applied which is, of course, an interesting design concept.

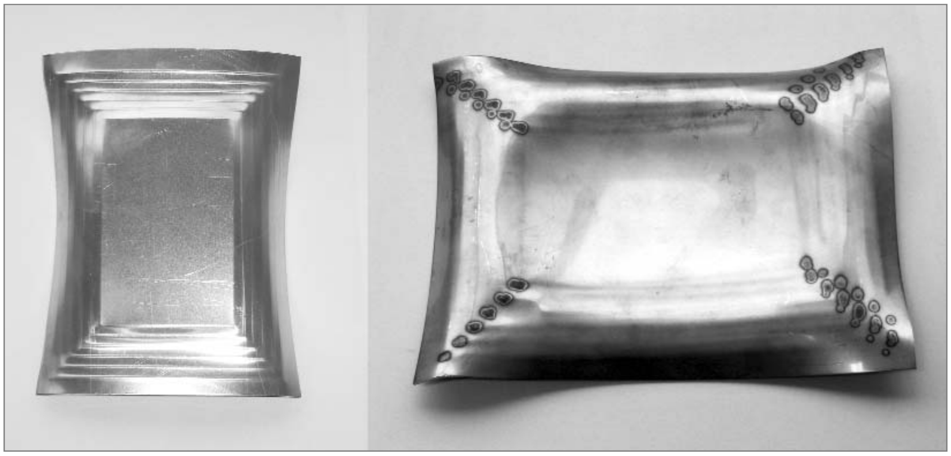

Figure 11 *Concentric rectangles. Different forms can result from the same pattern using a different mechanism or sequence.*

It is worth noting that a circular bowl is not easily produced by the concentric offsetting method, it may be created with offset radial lines of upsetting about the centre of a metal disc. The compression that laser forming creates is more active across the width of the scan, and to form a bowl, the surface area needs to be reduced circumferentially, hence the appropriateness of radial offsetting. Irradiation strategies for forming shallow bowls have been investigated by J. Magee et al,[8] and T. Hennige.[9]

Tapered Compression for Forming Tubes

A mitred joint shows that only 3 sides need irradiating for single axis bending. The removed wedge shape shows a need for tapered compression. This could be achieved by increasing the beam diameter and power along the traverse, which in practice means moving the lens further away from the work piece in the z-axis. A numerical study was undertaken by the author S. Silve during a placement at the University of Liverpool. That work showed that tapered compression could also be obtained using the asymmetry of the laser forming process.[10]

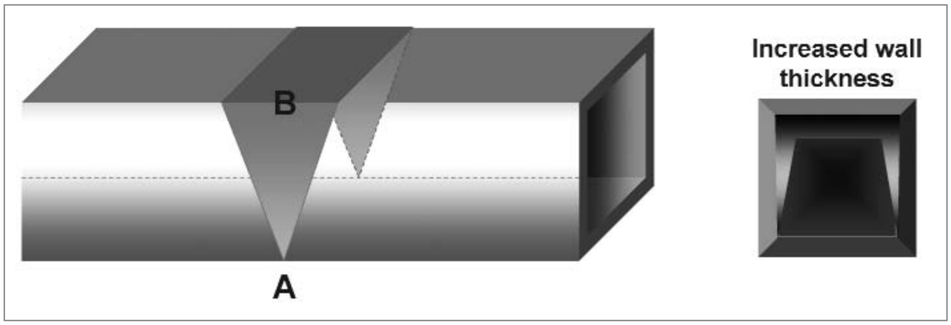

Figure 12 *Bending square tube in a single axis by laser.*

When irradiating the parallel tube sides, we are looking to achieve a plastically compressed area in the form of a cone; this reduces the surface area appropriately by increasing the tube's wall thickness. The laser begins irradiating a tube side from point "A" using a slow processing speed; the tube is cold and the heating progresses from a sharp zone to a wider zone "B" due to the heating of the whole specimen by the process. As heating begins, the compression through the thickness is similar to that of the temperature gradient mechanism but as the line is traversed, the heating becomes more homogeneous, resulting in upsetting. The finite element modelling of irradiated extrusions by J. Kraus similarly showed that a combination of the temperature gradient and upsetting mechanisms is effective during the early stages of the laser scan.[11]

For single axis bending of a square tube, the bending axis (top side) requires uniform compression, which is achieved by the upsetting mechanism and occurs when there is homogenous heating through the thickness; this is best obtained by scanning when the part is already hot. The sequence for single axis bending could be to go up one side, allow cooling, then up the other side, creating tapered compression on the parallel sides, and to then immediately scan along the top in order to maintain upsetting. Scans along the face of the bending axis should alternate in direction to prevent slight deviation from the axis resulting from the asymmetry of the process; this results in a cyclic sequence as shown in Figure 13.

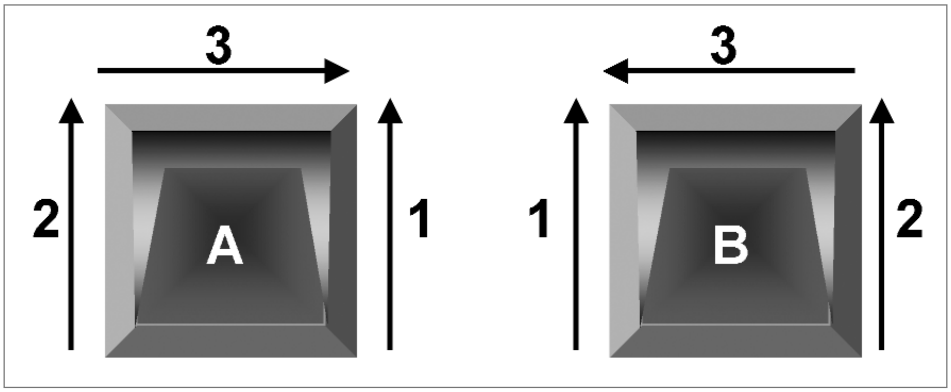

Figure 13 *Cyclic sequence for tapered compression.*

In the numerical study, various sequences for single axis bending were tried using a range of parameters. The resulting angle of each experiment was recorded. Each side was sectioned through the middle of the laser scan, mounted in resin and viewed with a microscope. The increased thickness was measured incrementally along the length of each side. The information for each sequence was plotted to ascertain the degree of tapered compression on the parallel sides and to see whether the upsetting mechanism was maintained along the topside. The sequences were then used with offsetting to curve a tube in one axis. The profile of each side was measured and compared to the geometric ideal. Naturally, there was some difference between the ideal (which might be achievable by machining) and the laser formed parts, which in fact correlated with craft experience; this is not surprising as both use compressive forces. In all of the tests, the cyclic sequence shown in Figure 13 faired well. The numerical aspect of the study concluded that the asymmetry of the process enables the section of compression to be manipulated, and that this could be applied to produce more creative forms from square tube. In light of this, it seems sensible to consider the necessary surface loss for a given form and use it as an indicator of the required distribution of compression, so enabling sequences to be derived using tapered compression, upsetting and compensatory methods. The asymmetry of the process makes the laser a much more sensitive tool for forming tubes than previously thought by upsetting alone.

The following experiments show the potential use of offset tapered compression for manipulating square tubes. Forming this way is time consuming but it can make fluid forms difficult to achieve by other means. The tubes used were 50.8mm seamed square section mild steel, 123mm long, with a wall thickness o 1.5mm. All of the tubes were scanned using 500W at 10mm/s with a 5mm diameter beam. The tube shown in Figure 14 has been scanned on two adjacent sides Each side has been scanned with lines towards the corner in common. The orde of irradiation was alternated as shown, and the tube was worked from the end towards the middle. The tube's front faces have been compressed and are curved with regard to each vertex while the back vertex remained straight. The sides no scanned by laser are elastically formed by tension.

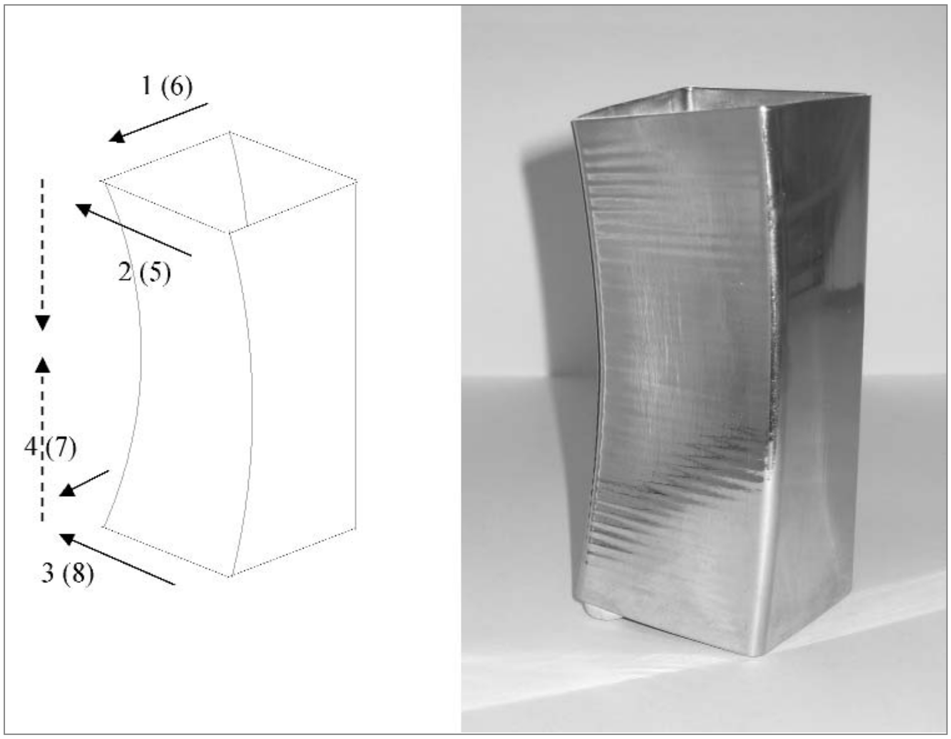

Figure 14 *Tapered compression-two sides scanned towards a corner.*

Figure 15 shows two views of the same tube. All four sides have been irradiated. The sides have been scanned with lines from opposite corners towards the other two opposite corners. The tube was allowed to cool between each line so that tapered compression would result. The order of irradiation was alternated to prevent bending in a preferred axis. The tube was scanned on alternate ends working towards the middle. Each side was subtly formed from the curving of its vertices. Corners with most compression became concave, while those formed by the base of the taper became convex. This effect had been a general tendency with the single axis bending, except when the parallel sides where irradiated from the top side (bending axis) down, in which case a taper was still formed in the correct direction by the loss of mechanical obstruction of the upset side. There was no bending axis with this experiment however, and this led to the tendency being considered as a general rule for bending square tubes using tapered compression.

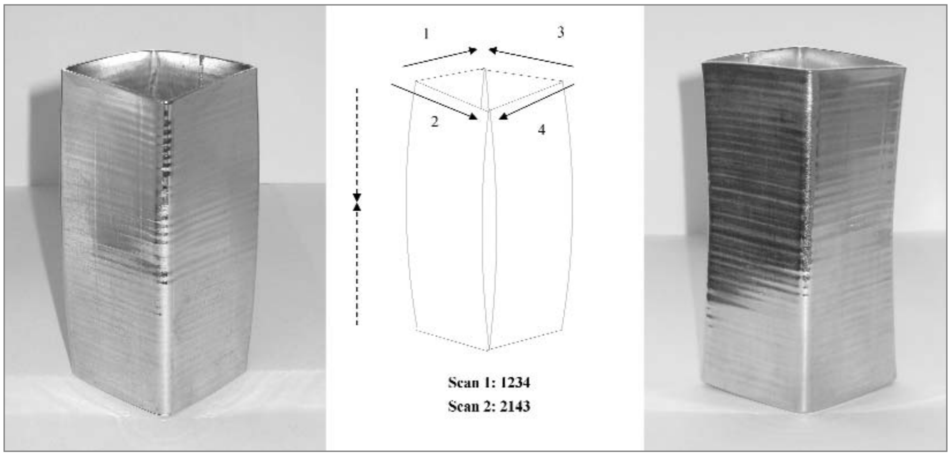

Figure 15 *Convex and concave forming using tapered compression.*

It is difficult to bend a square tube about a vertex without it bending in more than one direction. Laser forming can achieve vertex bending without any tooling. Greater compression is required on the inner two sides. The outer faces were scanned first, from the outermost corner to the middle two corners. This was done to enhance the compression of the inner two sides by reducing the mechanical obstruction. The front faces were then scanned twice to obtain the correct proportion of surface loss. As with the previous tubes, the scanning order was alternated to help prevent deviation from the main bending axis, and the tube was worked alternately from either end towards the middle.

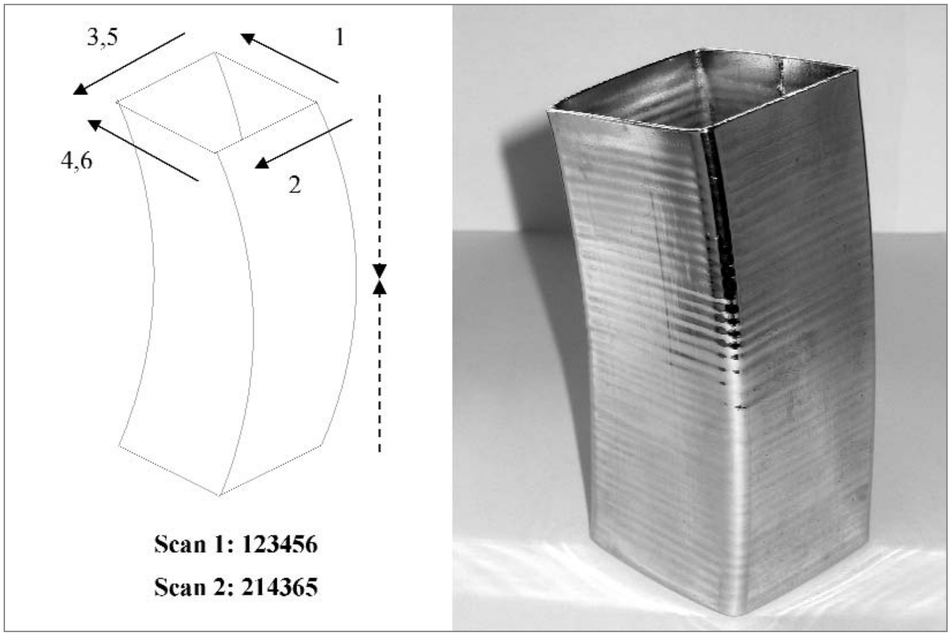

Figure 16 *Vertex bending.*

Rings of Compression

Using a rotary axis, the laser can be set up to manipulate round tubes. The rotary axis typically lies in the longer x-axis. Rotating the tube slowly under the beam will cause homogenous compression under the upsetting mechanism; this will result in an overall shortening and an increased wall thickness about the circumference of the tube at the point of heating as shown in Figure 4. Incorporating movement along the length of the tube in addition to the tube rotation, results in a spiral of upsetting. The metal ridge created on both sides of the tube wall is characteristic of the upsetting mechanism. This quality may offer advantages over existing techniques and offer solutions to particular problems, for instance the ridge may be useful for creating collapsible telescopic parts. Likewise, a ring of half round wire cannot be completely joined to a tube at an angle, there is always some gap; this ring could however be achieved through the compression of the upsetting mechanism, see Figure 17. There is however, increased thickness on the inside of the tube, which may not be required. It may also be considered that this somewhat novel aspect of metal forming should be exploited in designs.

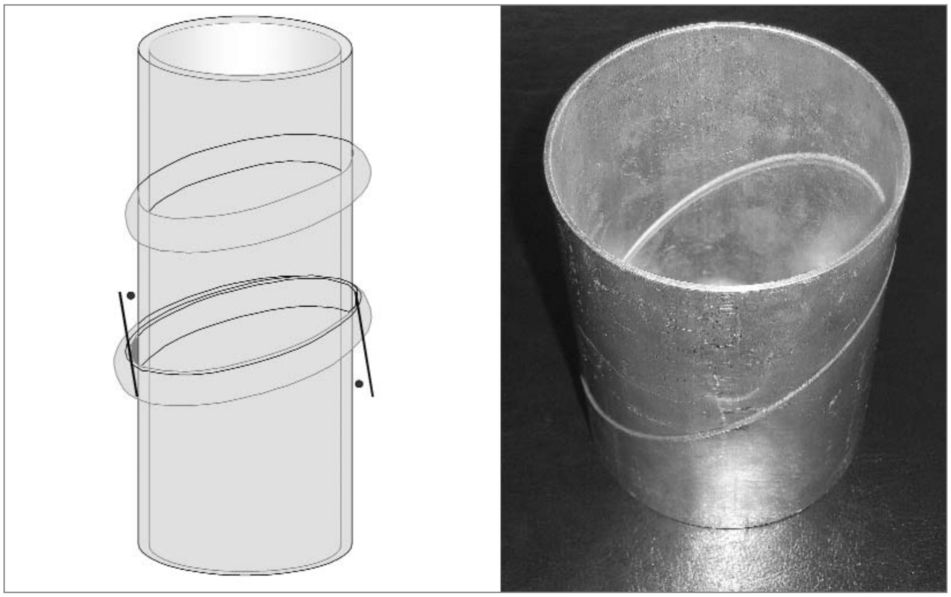

Figure 17 *A ring of half round wire cannot be joined to round tube without a gap; however, laser forming can create a ring of compression.*

Rings of compression can be seen on many levels for the design of objects, in producing finer details such as lips to vessels, for making one object fit tightly inside another, but perhaps most dynamically as texture. When elliptical rings of compression are used as an element of design composition, the whole tube is formed. The path geometry and spacing of the rings can begin to involve principles used in sheet forming such as offsetting. The 3.5" aluminium tube shown in Figure 18 has a wall thickness of 1.8mm, it was scanned using 600W at 20mm/s with a 5mm beam. With this tube, aside from a central ring, three ellipses were used spanning 60, 40 and 20mm about the middle of the tube. Working at origins of 0° and 180° resulted in the ellipses being symmetrically repeated about the horizontal. The middle ring was made first, then the ellipses spanning 60mm, then 40, and finally 20mm. When rings are placed at angles along the length, the shrinkage in the metal across the laser path causes a concave bending that has visual similarity to offsetting with the temperature gradient mechanism. Where the paths of several ellipses cross, there is an accumulation of homogeneous compression. The material is thicker here than at any other point. In the example, the distance between the outer rings has been reduced from 60mm to 55mm due to the compression of the metal and the concave forming.

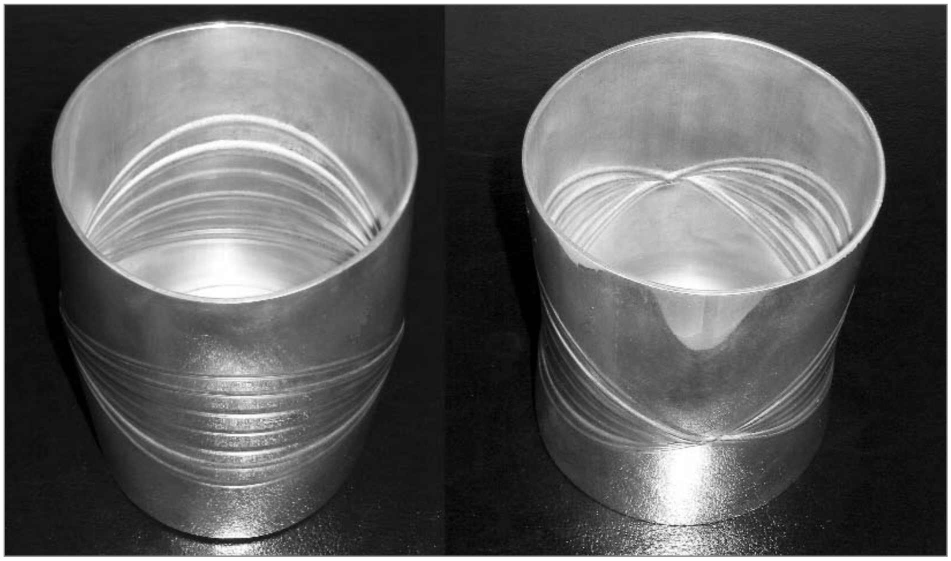

Figure 18 *Using ellipses as the basis for design.*

Decreasing the Heating Zone

Decreasing the heating zone is a strategy that can create forms similar to those made by raising. To create a waist in a round tube, the tube is irradiated with parameters leading to upsetting. The whole surface of the tube is scanned along the length with lines approximately 4° apart. After cooling, it may be seen that the tube is no longer round. To re-establish the tube's circular section, the sequence is repeated at a displaced angle, such that will produce an odd number of arcs over 360° around the circumference; e.g., 72° or 120°. The displacement is repeated as necessary until the tube is round again. The length of the line is then reduced leaving an equal distance to the tube ends and the whole sequence is repeated. The length of the heating zone is reduced again and again until the middle of the tube is reached. Working in this way, the amount of compression varies along the length of the tube, getting thicker towards the middle. The aluminium tubes shown in Figure 19 were scanned in this manner, using 600W, a 5mm beam and a scanning speed of 30mm/s. Each of the samples shown has used a slightly different pattern, however, both achieved the same result since the patterns' structure was the same. Some surface reticulation occurred because the scanning was bi-directional. When using the zone method to form tubes, it is advisable to start with a slightly longer tube than is desired for the final part, to allow for the shortening.

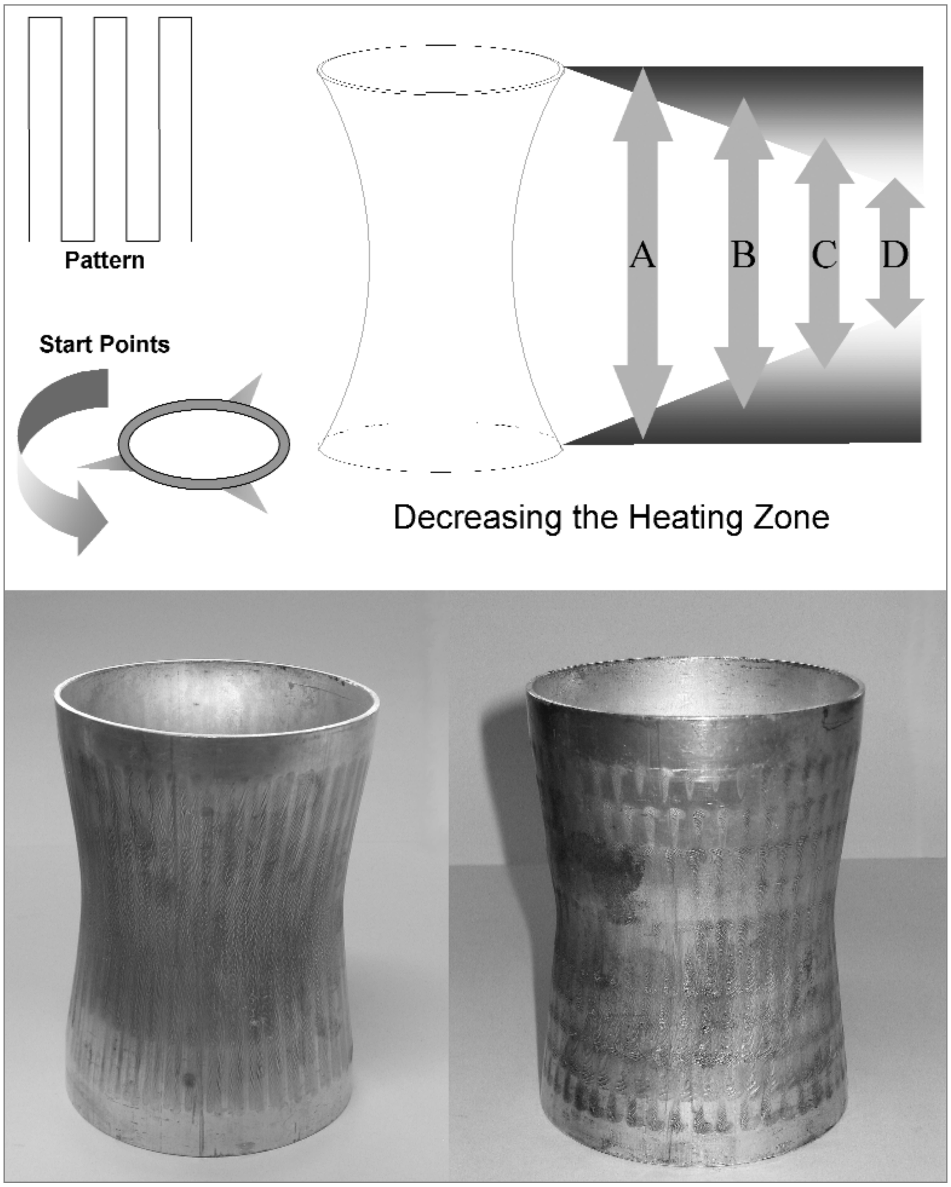

Figure 19 *The principle of decreasing the heating zone and resulting waists in aluminium tubes.*

The amount of decrease to the zone and the number of repeats in each zone will affect the overall profile; the relationship is similar to that between the size of offset and the resulting curvature when offsetting. Decreasing the heating zone can be applied to tubes in different formations, in this way it is as open ended as ratio offsetting (See Figure 20A).

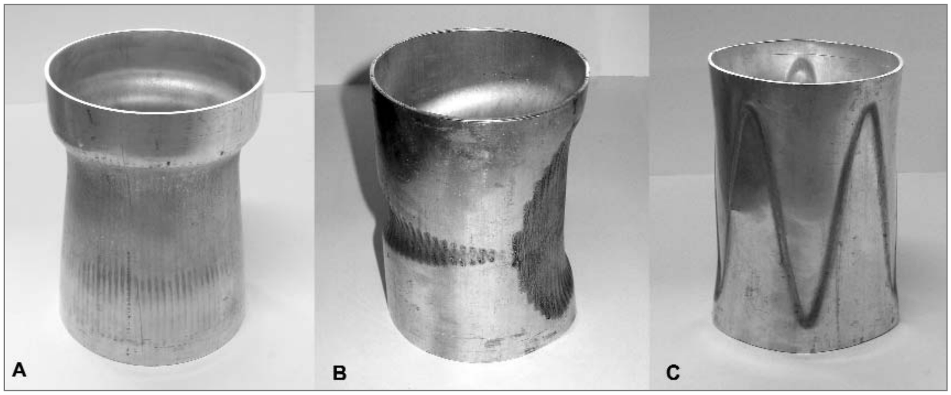

Figure 20 *Inspiration and development of the zone principle.*

Tube A: The focus for decreasing the zone is no longer the middle of the tube but a point about an inch from the tube's end. Scanning is in one direction, towards the focus point.

Tube B: Decreases the zone about the circumference. The lines are close together and irradiation is continuous which leads to surface reticulation. The level of indentation has potential for ergonomic design features.

Tube C: This tube was the inspiration for developing the heating zone principle. Repeated sine waves around the tube with the upsetting mechanism resulted in a flaring of the tube ends.

Laser Forming Spinnings

Silversmiths are content with using spinning as the method of producing bowls. To this end, the application of laser forming for spinning lies in the modification of conventionally spun bowls to make new forms not easily made by hand. Using a rotary axis and a tailstock, the workstation can be set up to manipulate spinnings. In order to maintain a constant beam diameter, the z-axis needs to move the lens in accordance with the spinning's profile. All three mechanisms can be used to alter the section of tubes and spinnings. The buckling mechanism is particularly effective since the round section predetermines the bending direction, resulting in a pulling of the metal into corners. The temperature gradient mechanism has difficulty bending the metal towards the beam because of the rigidity of the part; it will create proportional compression through the thickness which reduces the surface area to some extent, but not as much as can be achieved with the upsetting mechanism. These effects were exemplified by H. Frackiewicz who made a round tube square using a combination of the temperature gradient and buckling mechanisms.[12]

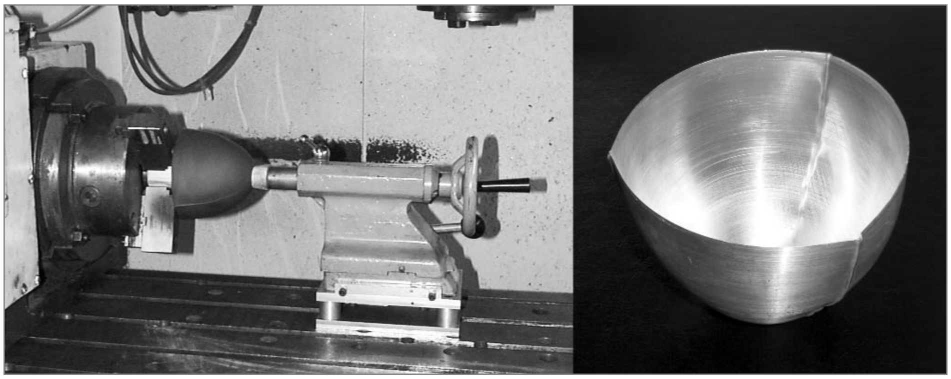

Figure 21 *The laser workstation can be set up to modify spinnings.*

The aluminium tube shown in Figure 22 was produced by the buckling mechanism using 600W, a speed of 45mm/s and a 6mm beam. The round tube's circumference was divided into three using longitudinal lines and the tube was rotated 120° during the traverse of each line. This created a triangular tube with a twist. The technique was then applied to two spinnings, one used the buckling mechanism while the other used the temperature gradient mechanism. After 50 passes, the spinning modified by buckling had formed the most and now had dynamic twisted creases. The spinning formed by the temperature gradient mechanism was vaguely triangular and the scanned lines appeared to have an increased thickness on both sides. The upsetting mechanism was not effective, the rigidity of the part was preventing the formation of a bending angle and the compressed ridge continued to develop on the heated side.

Figure 22 *Rotating the form while traversing creates twisted forms.*

The aluminium spinning shown in Figure 23 has been irradiated about the circumference to produce undercuts. A circular rotation was given six equally spaced reference points. This path was offset by 3mm for a distance of 50mm. The start point of each offset was rotated by 120° to maintain symmetry. The parameters were 500W, a 3.5 mm beam and a speed of 60mm/s. Scanning began near the base of the spinning. There was a wait period of 15 seconds between each radial scan. The parameters should have meant that the temperature gradient mechanism was effective, however, the six reference points about the circumference caused a reduction of speed at those points resulting in some upsetting and a pinching in of the material. The form is very fluid, but is somewhat irregular. With development, laser forming techniques could be applied to spinnings to produce regular undercuts and accurate shaping, this could save costs on the production and use of multi-part mandrels.

Figure 23 *Using laser forming to create forms with undercuts.*

Texture by Laser Forming

Texture created by laser forming is dependant on the heating pattern and the mechanism in use, and is related to the resulting form. Laser forming can texture metal in a number of ways; some examples are shown in Figure 24:

A: Operating the laser in long pulses using the laser as a point source. The material may be thickened at the point of heating; this may be used for ornamentation although some bending may occur. The beam mode is particularly relevant to the shape of the thickening; the ring shown top in image A was produced with a $\text{TEM}_{01}{}^*$ (doughnut mode) beam, while the bottom nodule was made using the round TEM_{00} mode beam.

B: Consecutive scans of offset lines without cooling between the lines can lead to surface reticulation as seen in Figures 19, 20B and 26. The reticulation of sample B is due to bi-directional scanning. The back of the sample is shown on the left, while the scanned surface is shown on the right.

C: With modern computing it is very easy to change the file format of an image. Image C shows a sample where a CAD drawing has been converted to a plotted bitmap file so that the pattern is executed as a series of pulses or dots. In this instance, the laser's interaction with the material has led to vaporisation leaving small pits in the metal. While the texture may be of interest, the execution of the program is very random and subsequently offers little forming control.

D: Close folds of offsetting can create an intricately faceted surface.

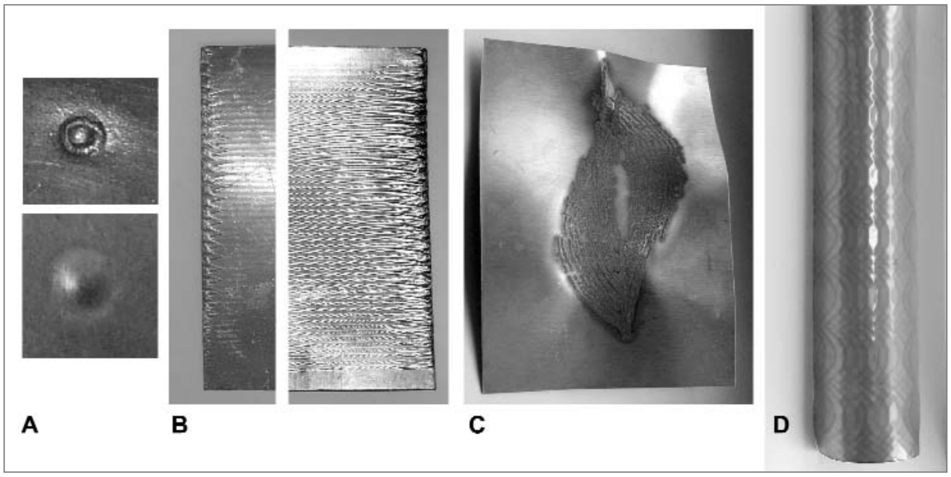

Figure 24 *Laser forming can create various kinds of texture.*

Laser Forming Silver

In order for laser forming to become an accepted method in silversmithing, it is necessary to be able to form silver. Silver is difficult to form by laser due to its high thermal conductivity. Peter Johns has developed a silver alloy with added germanium to prevent fire stain. The alloy is less conductive than standard sterling.[13] Initial tests show that it is easier to laser form than sterling silver. Early results show that silver bends efficiently within a narrow range of parameters. Silver can bend at approximately the same rate as aluminium as shown in Figure 25. The radius of the bending edge will be affected by heat conduction. For a crisp edge, it is essential to maintain a small beam diameter, (approximately 1.25mm diameter for 1mm sheet) as the heat affected zone will be widened by the conduction of the part. Maintaining a constant beam diameter is problematic, as a 3D surface will undulate with respect to the laser focus. A sensing system would maintain a beam diameter by moving the laser focus (z-axis).

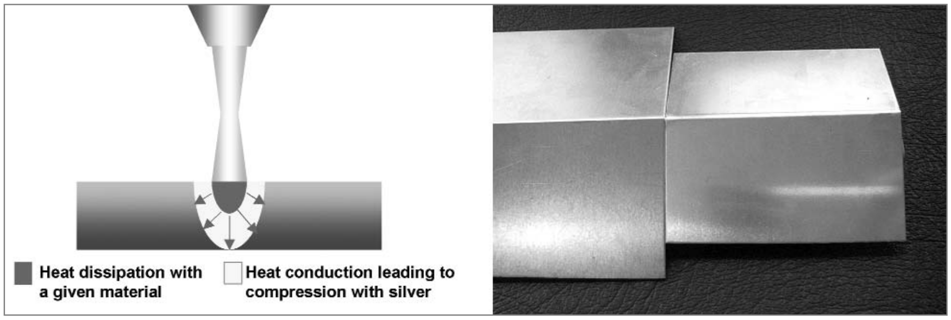

Figure 25 *Left: Silver's conductivity leads to a wider heat affected zone. Right: Silver and aluminium samples achieve the same angle in 30 scans.*

Forms of Impact

The aluminium sample shown in Figure 26 was scanned with the "X" pattern shown on the left. The sheet dimensions were 150 x 210 x 1mm. At the widest span the lines were offset by 3mm, the lines converged through a common point and diverged again to an offset of 2mm at the end of the sheet. The scans of offset lines were alternated left and right working from the edges of the widest span of lines towards the middle of the sheet's width. The sheet was scanned once using a 4mm beam and 300W at 20mm/s. Repeated irradiation of the common point led to an area, which from the underside appears as though it could have been made by a shaped punch. There is a thickening of material towards the focus point suggesting a change of mechanism during the traverse. The heated top surface has become reticulated as a result of a slow scanning speed, a small beam diameter and a lack of cooling between lines.

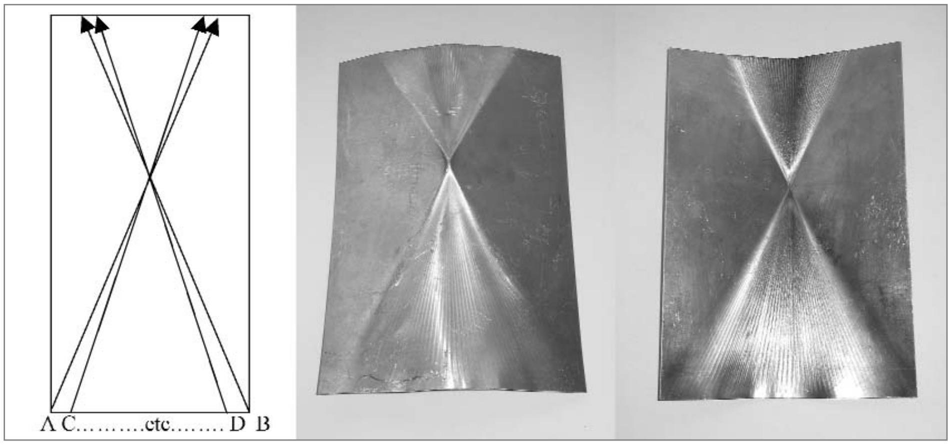

Figure 26 *Repeated irradiation of a common point led to a "punched" area*

Figure 27 shows an experiment in which a 100mm diameter disc of 1mm thick aluminium sheet has been scanned with lines radiating from a centre point. The parameters were 300W, at 75mm/s, with a 2.5mm beam. The path was repeated 15 times, with the centre point receiving a total of 240 irradiations. At the centre point a depression had been formed, such as might be achieved with a small doming punch.

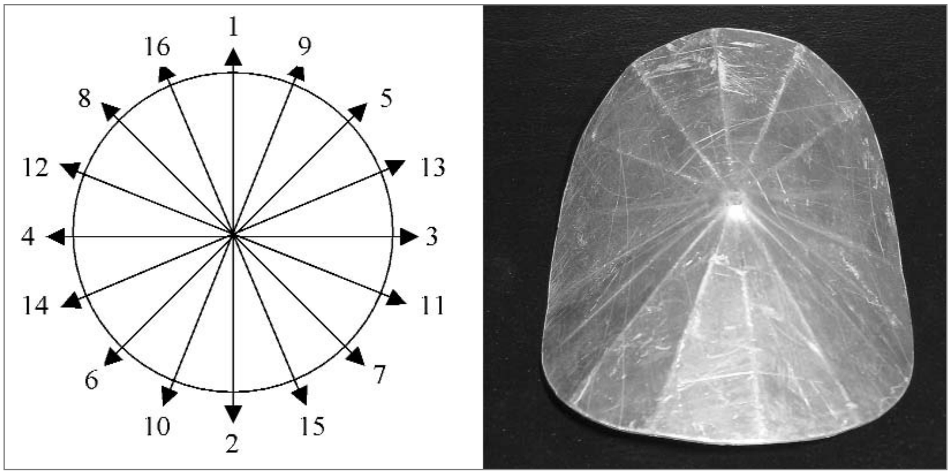

Figure 27 *Domed form of impact.*

This type of forming seems to result from the repeated irradiation of a small area. The laser path, order and speed are all factors. Impact forming offers potential because the shape can be varied. It may be possible to make the area of the "impact" larger. The pattern could similarly be repeated within a sheet to create texture. This type of forming has so far only been achieved using aluminium.

Building blocks

The pattern of lines radiating from a centre point pictured in Figure 27, has been reduced in scale to 30mm in diameter and arranged 12 times within a larger aluminium sheet (150 x 210 x 1mm). This new pattern was executed alphabetically, as shown in Figure 28, so that the heating was evenly distributed and the next phase began where the sample was coldest. The sheet was irradiated 8 times using 400W of power and a 3mm beam at 100mm/s. There was a 10 second wait between each set of radiating lines. The resulting form featured 12 individual domes as pictured in Figure 27, however, the sheet was completely formed and resembled a buttoned cushion, with the spaces between the elements playing an equally important role.

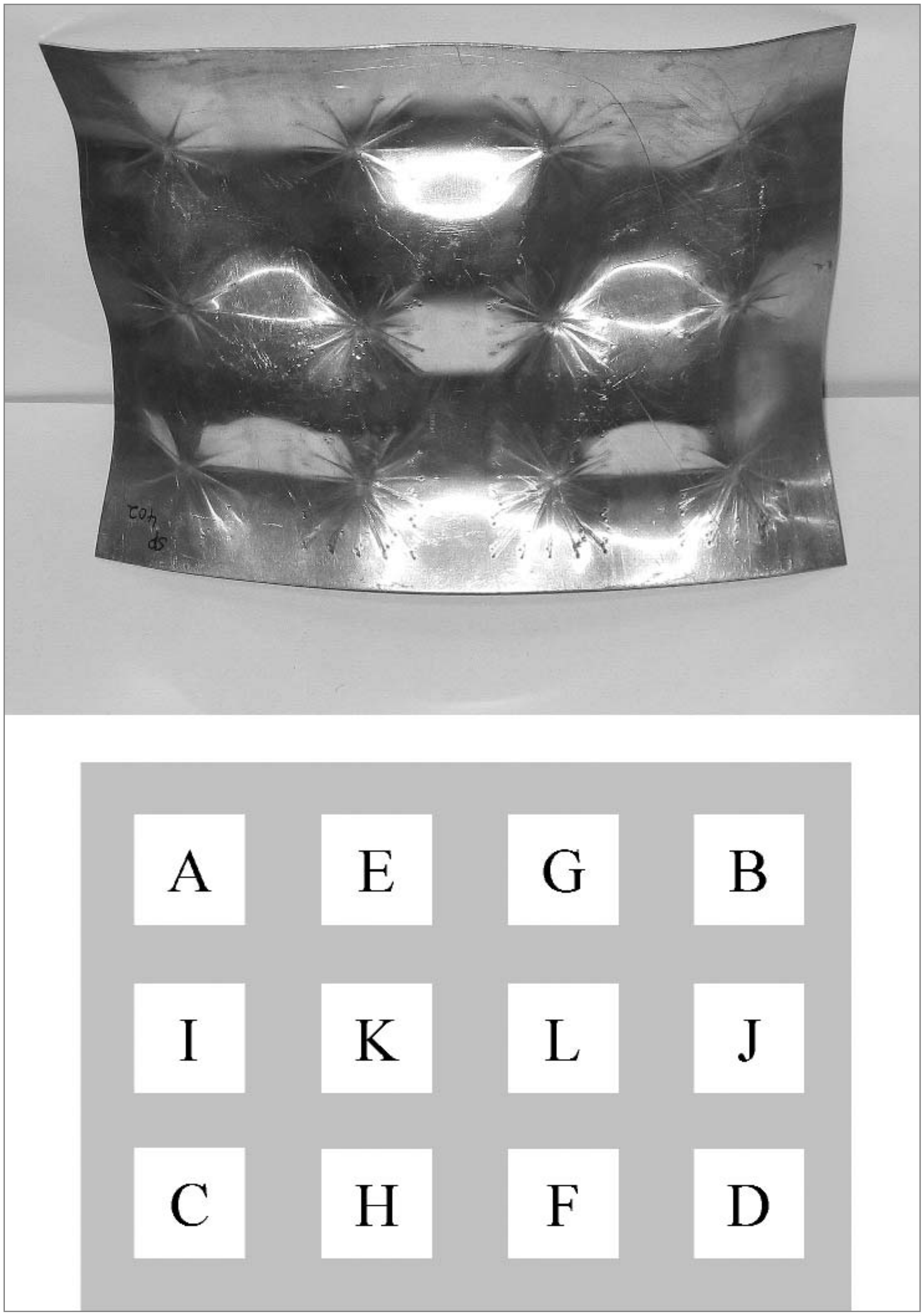

Figure 28 *Repeated elements. The spaces between repeats play an important role. It is necessary to consider the irradiation order.*

The vase shown in Figure 29 was produced by manipulating an aluminium tube which was 2½" square in section, 150mm long with a 1.2mm wall thickness. The tube was irradiated with a pattern similar to that shown in Figure 26 using a power of 450W, a beam 3mm in diameter and a speed of 20mm/s. Scanning was in the order of opposite sides, and the tube was not cooled between scans. The form developed quickly and became difficult to align with the pattern after 2 complete passes. It took approximately half an hour to form the body of the vase; it took much longer to fit a base.

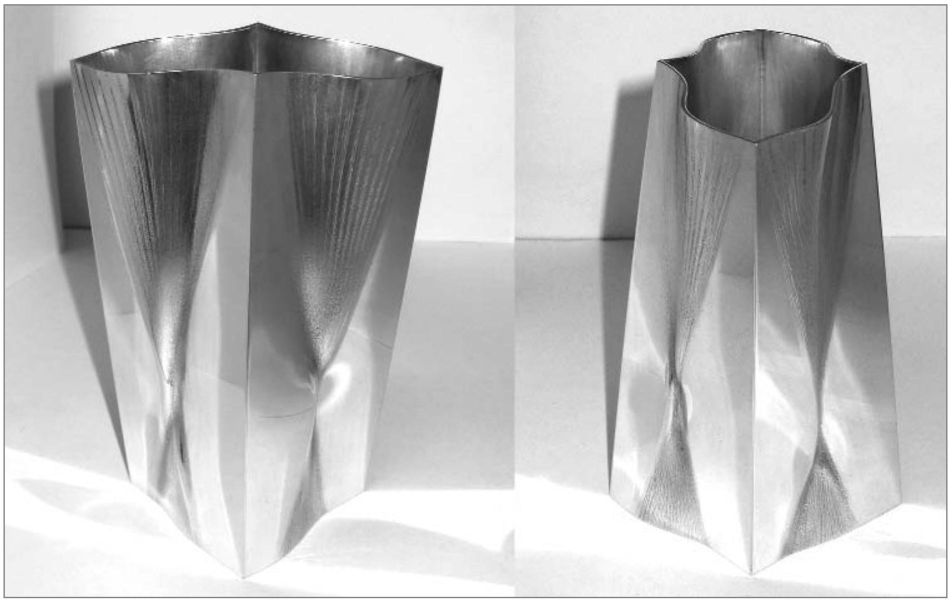

Figure 29 *Vase body produced in half an hour.*

Exploration of the laser forming process has led to a range of heating strategies. Sheet forming strategies can be adapted for tubes as was the case with the vase shown in Figure 29. Techniques can be layered and combined, for instance offsetting is widely utilised in the development of further strategies such as “decreasing the heating zone.” There have been several examples where one pattern has been used to produce more than one form. Figure 28 demonstrates that individual patterns can be treated as elements within a much larger pattern for laser forming and that in these cases much attention must be paid to the structure of the sequence. Compensatory measures for achieving symmetrical components have been put forward; these include alternating sequences, rotational repeating of sequences and the restricting of movement by weights. Laser forming involves elements of design and concepts of direct metalworking. For a process so intrinsically linked with geometry, it can produce organic form.

THE DEVELOPMENT OF LASER FORMING FOR PRODUCING OBJECTS

In this paper, practical examples have demonstrated that laser forming is capable of producing parts suitable for silversmithing and designed metalwork. In recent years, various new technologies have infiltrated the jewellery and silversmithing industry. Lasers have become accepted tools of the trade, finding widespread applications in the marking and welding of precious metals. Their use is stimulating new approaches to making jewellery, and makers are beginning to evolve their own aesthetics in response to the possibilities lasers bring. Laser techniques are also being used to increase the quality or volume of production. CAD/CAM has been the driving force behind several new and revolutionary casting related technologies such as wax printing, stereolithography and selective laser sintering. CAD based programming software similarly offers greater flexibility for laser forming, as sophisticated geometric patterns can be used without heavy programming. In this current climate of change, it would seem advantageous to develop laser forming as a compliment to these new techniques so that objects can be produced in either cast and sheet materials which can then be joined and ornamented.

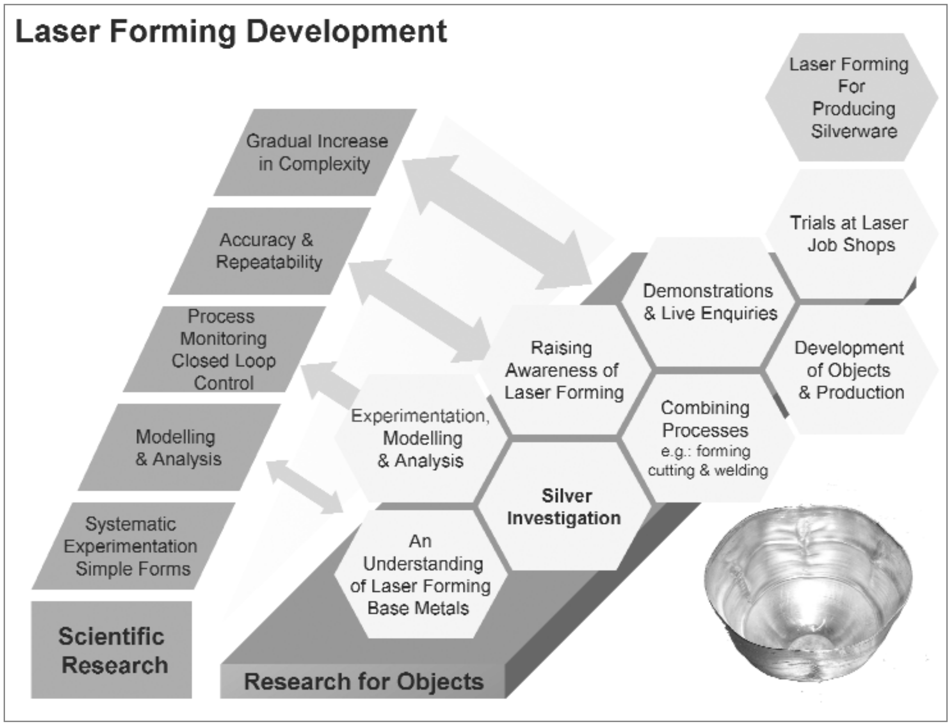

Figure 30 *Laser forming development for producing objects.*

Further research and development of laser forming within the scientific community should bring about greater prediction and accuracy of the resulting part, enabling the process to be reliably used. It will of course be the preference of the end-user to be presented with a CAD/CAM environment in which the correct laser path is determined from the input drawing. Such a platform may be a reality many years into the future. In the meantime, there are several possible strands for the development of laser forming within scientific and design research, these are summarised in Figure 30. Scientific research will continue to underpin and positively influence the development of the process for producing objects. The development of laser forming for producing objects is likely to proceed by taking into consideration the different context and applications of the process. The jewellery and silversmithing industry is made up of various types of practitioners and companies, all of whom may have their own requirements of laser forming. Laser forming equipment, namely a CO_2 laser and CNC workstation, is a considerable piece of kit both in terms of size and financial outlay. It is therefore likely that access to laser forming facilities will be the preferred route for makers and companies. It is possible that commercial facilities already exist for laser forming by way of the laser cutting job shops that have been established worldwide. Job shops use industrial CO_2 lasers for cutting, and their set up could be modified to carry out forming. Laser forming would need to become a recognised process with predictive software to thoroughly establish that relationship. In the near future however, it may become possible for the process to be accessed via smaller facilities and innovation centres.

The use of a CO_2 laser means that several techniques can be used within a single object. As has been shown in Figure 7, laser cutting can be used to enhance forming by altering the rigidity of the sheet. In the sample shown in Figure 31, laser cutting has been used to remove small circles. This has significantly influenced the subsequent bending of an array of ellipses, as the major bending axes are between the ellipses where the bending momentum is lower. Cutting capabilities allow the starting plate for laser forming to be altered with relative ease; this offers flexibility for design. Figure 32 shows three bowls, the starting plates were laser cut, each plate has the same structure, however CAD/CAM software enabled the slight modification of each plate's shape. The bowls were then laser formed. They were completed very quickly, taking approximately 15 minutes, since the removal of material about the circumference had enabled them to be folded. The bowl in the centre of the image has been folded until its facets touch, the laser could be further used to weld the facets of the bowl.

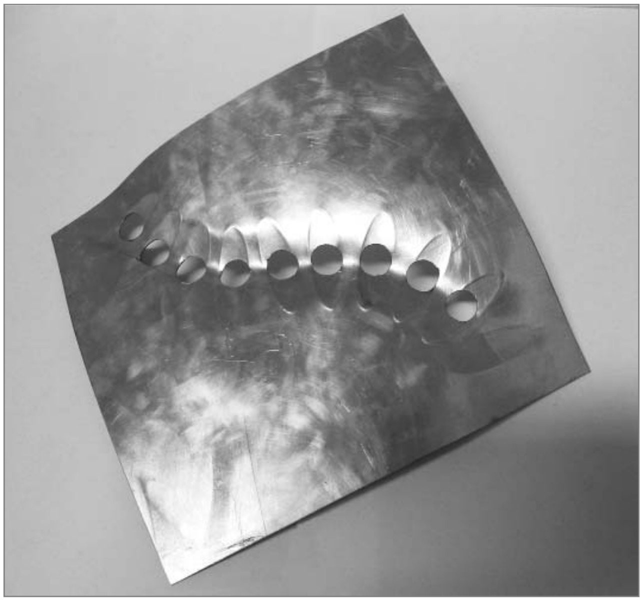

Figure 31 *Cutting and bending are a fruitful combination.*

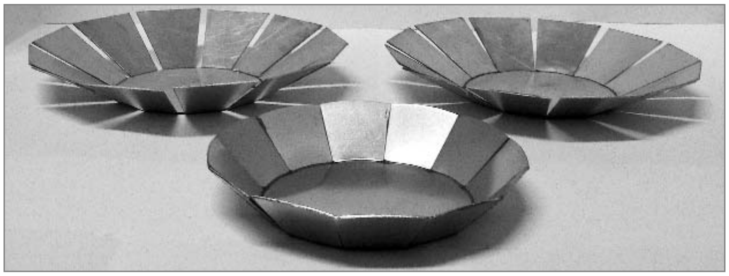

Figure 32 *Starting plates for laser forming can be varied using laser cutting. These aluminium bowls were formed in approximately 15 minutes by folding.*

Viewing the three bowls in Figure 32, it becomes feasible to consider whether laser forming might be used for production. With straightforward heating strategies it is possible to set up the workstation for batch production. The overall time taken to produce each part is reduced as whilst one part is cooling the next can be heated; however it is necessary to keep the transitions constant to allow the correct amount of cooling across all of the parts. Production might be possible with modified round tubes where there is no bending axis; several parts may be formed as one long tube, after which the laser cuts the tube into sections. With very complex parts that require an amount of handling or turning, production is not very feasible without additional automation such a pick and place. The suitability of laser forming for the production of particular parts is an issue to be addressed both technically and economically, since in many cases laser forming is too costly compared to mechanical techniques such as pressing.

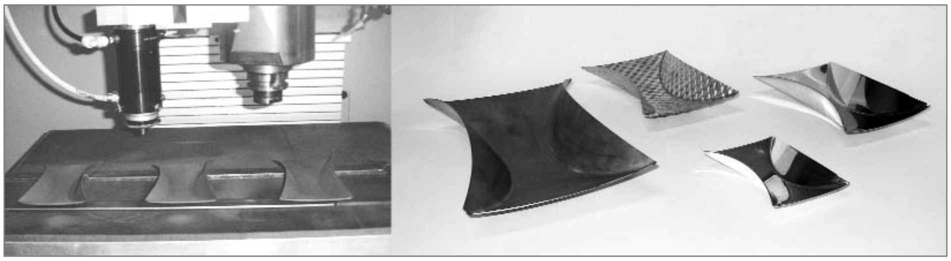

Figure 33 *Left: The workstation has been set up to produce 3 dishes. Right: Path geometry and laser parameters have been scaled to produce a dish in a range of sizes and materials*

SUMMARY

The ability of the laser to bend metal in either direction without any contact makes laser forming a flexible process. The upsetting mechanism is an intriguing method, resulting in ridges of compression which may be exploited visually in designed objects. The most potent use of the process is in making components that cannot be produced by other means, as this can have technical and aesthetic implications. This paper has shown a range of forming abilities and demonstrated that the process can produce components with reasonable repeatability. It is difficult to predict the level of uptake and the precise applications that forming might find within the jewellery and silversmithing industry. Within our diverse discipline there are may possible uses for laser forming; as well as being used for production, it may provide a solution to a problem or be used to create one-off objects and prototypes without the costly manufacture of dies. As with many other new technologies, the use of laser forming is likely to compliment rather than substitute conventional techniques. The costs involved in laser forming make it suited to producing high value products such as those made of silver. To this end, the development of laser forming for objects relies on the development of silver products in conjunction with the progression of the process through scientific research towards being more easily predicted and dimensionally accurate. Laser forming has undergone significant progress in the last twenty years; it will be interesting to see it evolve into a recognised process within manufacture.

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