ABSTRACT

A facility for rapid prototyping of MEMS devices is crucial for the development of novel miniaturised components in all sectors of high-tech industry, e.g. telecommunications, information technology, micro-optics and aerospace. To overcome the disadvantages of existing techniques in terms of cost and flexibility, a new approach has been taken to provide a tool for rapid prototyping and small-scale production: Complex CAD/CAM software has been developed that automatically generates the tool paths according to a CAD drawing of the MEMS device. As laser ablation is a much more complicated process than mechanical machining, for which such software has already been in use for many years, the generation of these tool paths relies not only on geometric considerations, but also on a sophisticated simulation module taking into account various material and laser parameters and micro-effects. The following laser machining options have been implemented: cutting, hole drilling, slot cutting, 2D area clearing, pocketing and 2½D surface machining. Once the tool paths are available, a post processor translates this information into CNC commands that control a scanner head. This scanner head then guides the beam of a UV solid-state laser to machine the desired structure by direct laser ablation.

Keywords: Laser micromachining, rapid prototyping, UV solid-state laser, CAD/CAM laser processing software

1. INTRODUCTION

The vision is old: You design your 2½D-device in a CAD-program, you select the material and the laser parameters, and some clever software generates the code for the laser machine to produce your device. This would open up many possibilities for rapid prototyping and small-scale production and give you finally the full flexibility you expect from a laser tool.

The vision is old – and has years ago been realized for other tools such as mills and routers. Even for certain operations of a laser, e.g. welding and cutting, such software has been developed. But if you want to use the laser like a milling tool and machine pockets and 2½D structures, things become more complex; a simulation module is needed to be able to predict the result of a certain machining operation.

We have tackled this problem, using existing CAD/CAM software (alphaCAM by Licom Systems Ltd.) as a basis for our graphical user interface (GUI). Using the application programming interface (API) to communicate with the alphaCAM software, we generate our own tool paths. For the simpler machining operations as hole drilling and slot cutting, we have incorporated our experience with different machining strategies and provide a high degree of flexibility to make it easy to experiment with different parameter sets; our area clearing function is able to process extensive and complex structures; for the most complex machining operations – pocketing and 2½D surface machining – we rely furthermore on our simulation module for feedback on the effect of machining along the envisaged tool paths. Once the tool paths are generated, they are translated into CNC commands.

Our CAD/CAM software LaseCAM has been developed for a purpose-built laser micromachining tool, the Exitech M1000. The main features of this tool are: A small footprint, a UV solid-state laser and a scanner head with a short focal length f-theta lens to achieve spot sizes of a few µm. But the LaseCAM software is not restricted to the use with this particular tool; it has already been widely used on other systems with or without scanner head and with lasers of various wavelengths.
2. LASER ABLATION VERSUS MILLING

Laser ablation as a process has many advantages over mechanical machining, certainly in the area of micromachining. Apart from being a non-contact technique, it allows a wide range of materials to be machined and very small dimensions and high resolution and accuracy to be achieved. Open tool paths are easily achieved by simply switching the laser off while moving to the starting point of the next tool path rather than lifting the tool out of the workpiece. And it is not necessary to drill pilot holes in order to move the tool into position in the first place.

On the other hand, laser ablation is a much more complex process than for example milling. Figure 1 illustrates in a schematic and simplified way the differences between milling and laser ablation. Whereas with milling, the result of a machining operation is completely determined by the geometry and the position of the tool, this is not so with laser ablation. One fundamental issue is the depth control: Given the length of a milling tool you can easily position it so that it will remove material exactly down to a predefined absolute z-level. A laser beam, however, machines down to a certain depth relative to the surface – wherever the surface is. In particular, overlap of tool paths results in extra depth. Similarly, with milling the profile of the cut is entirely determined by the shape of the milling tool. With laser ablation, on the other hand, there are many factors that influence the profile of the cut: The beam profile and shape, laser parameters such as the pulse repetition rate and the shot overlap, physical properties of the material (e.g. optical penetration depth, thermal diffusivity), the curvature of the tool path (the cut will be deeper at the inside of a curve due to higher shot overlap) and the shape of the surface of the substrate.

To sum up: There is no way of determining the result of laser ablation along a given tool path other than simulating shot by shot what happens to the work piece. And if you cannot predict what happens if you machine along a given tool path, there is no way to find the tool paths for producing a predefined shape.

3. SIMULATION MODULE

The role of the simulation module is to predict the shape of the surface remaining after a specified machining operation, given information about the initial surface shape, the material ablation characteristics, the tool path, the laser parameters and the beam delivery optics. As noted above, the only general approach to this problem is to consider the effect of each successive pulse on the evolving surface. An important consideration here is that the volume of material removed by each pulse is very small, so that for structures of any practical use the number of shots required is typically very large (often in excess of $10^6$). Consequently, simulations based on run-time implementation of semi-rigorous physical models of the ablation process can be ruled out on grounds of computation time. Such models have been used extensively in the
past by researchers to explain observations of ablation by plane illuminating beams [1,2]; however, for an industrial prototyping tool where the operator is looking for immediate feedback, much faster calculations are required. Our current approach is to propagate the surface in response to each pulse using an etch function that relates the material removal rate to the local fluence and surface orientation. This etch function may be derived from experimental measurements or from physical modelling. The key steps in the simulation process are outlined below.

The first task is to determine the fluence distribution over the illuminated region of the surface. The normal approach for direct-write machining of a complex structure is to remove material layer by layer. In this case the focus is normally adjusted for each successive layer so that the average surface level of the region to be machined corresponds to the focal plane of the optical system. The fluence in the vicinity of this plane may be determined by classical imaging theory; furthermore, for the important case of a focussed solid-state laser beam, a Gaussian profile may be assumed with good results. Calculation of the fluence over a 3D region around the focal spot allows for local height variations in the surface. This is necessary in regions where there are large height variations (e.g. at steps in the machined surface), because the fluence is reduced and the spot size is increased outside the focal plane. The fluence calculation ignores the presence of the workpiece, and consequently it only needs to be done once for a given optical set-up (i.e. combination laser beam profile, aperture if applicable, and lens).

Once the fluence distribution is known, the local material removal rate is estimated based on the etch function of the material in question. In the simplest case, a classical Beer’s law ablation curve is assumed, i.e.

\[
d = \begin{cases} 
\frac{1}{\alpha} \ln \left( \frac{F}{F_T} \right) & F > F_T \\
0 & \text{otherwise} 
\end{cases}
\]

where \(d\) is the depth to which material is removed, and \(F\) is the fluence at normal incidence. This kind of etch function is specified by just two parameters: an effective absorption length \(\alpha\) and a threshold fluence \(F_T\). Alternatively, more realistic ablation curves - either measured or generated by physical modelling - can be stored as data pairs. Some account has to be taken of the angle of incidence, and in the absence of measured data we simply take the component of fluence in the direction of the local normal to the surface. This assumption has been used previously when modelling excimer laser ablation of microstructures, and has been shown to give reasonable agreement with experiment, at least for some common polymer materials [3,4]. A third option for estimating material removal, which we have not yet implemented, would be to store measured single pulse ablation crater profiles, covering a range of spot sizes and pulse energies. This would clearly require more data storage, but would be expected to yield the most accurate simulation results.

For the purposes of simulation, the surface is described by a rectangular matrix containing the surface height at each point on a rectangular grid. For each incident pulse, the sub-set of points on the surface that is affected by material removal is determined (i.e. points for which the normal component of fluence is above threshold), and only these points are processed. Each point is propagated in the direction of the local normal by a distance corresponding to the local etch depth. For example, in the case of a simulation based on Beer’s law ablation curves, the point with position vector \(\mathbf{S}\) on the surface moves to \(\mathbf{S}'\) where:

\[
\mathbf{S}' = \mathbf{S} + \frac{1}{\alpha} \ln \left( \frac{F}{F_T} \right) \hat{n}
\]

\(\hat{n}\) being the local unit normal into the surface. Interpolation is used to move the propagated points \(\mathbf{S}'\) back onto the original regular grid before arrival of the next pulse.

The simulation approach just described, while fast, clearly contains many simplifying assumptions. Most importantly,
we neglect the possibility that reflections from the directly illuminated region may cause material removal elsewhere on the surface. This is reasonable on parts of the surface that are almost normal to the incident beam, but is likely to break down in steeply sloping regions. Consequently, the simulator predictions are expected to be less accurate in the vicinity of steps in the surface, and in cavities with high aspect ratios (i.e. ratios of depth to width). On the other hand, the simulator should perform well on the bottom surface of an open cavity, making it useful for optimising the tool path to remove unwanted surface height fluctuations arising from the beam profile and pulse overlap.

4. TOOL PATH GENERATION

When going from a CAD drawing of the desired device to the CNC commands that will produce this device, tool paths – curves along which the tool will move – are generated as an intermediate step. As we generate these curves, we have to take into account the width of the cut in order to compensate for it.

4.1 Cutting

In terms of tool path generation, cutting is certainly the easiest machining option. According to the width of the cut and the machining side defined by the user, the cut is offset from the contours defined by the CAD drawing. Applications are widespread; one example is the manufacture of the apertures used on the Exitech M1000.

4.2 Hole drilling

Drilling micro-holes has many applications, such as fuel injector systems, probe cards and vias in silicon and ceramics.

Unlike a mechanical drill, the laser beam has often a smaller diameter than the hole to be drilled and more sophisticated techniques than percussion drilling are used. When using helical trepanning, an incoming and an outgoing arc are added to achieve good edge quality. A spiraling technique is used to remove the material starting at the centre of the hole; this avoids a deep narrow cut along the edge, out of which it is hard to expel further material. These techniques are well known, but our software makes it easy to adjust various parameters (e.g. the number of revolutions of the spiral) and to try the new configuration by translating it directly into scanner commands.
4.3 Slot cutting

In many cases, the most efficient way to machine a slot is not cutting along its edges, but raster scanning the whole slot. This technique is the analogue to the spiraling technique for hole drilling and has the same effect: Material is removed from the whole area of the slot in order to avoid a narrow cut. Again, it is not the technique itself that is innovative, but the ease of use and convenience provided by our software.

As an example of an application for slot cutting we can mention the machining of ink feeding slots for ink jet printer heads.

4.4 2D area clearing

2D area clearing is mainly used for single shot processes where no depth control is required, e.g. for patterning of transparent conductive oxide (TCO) layers on glass or flexible substrates as required for flat panel displays.

Tool paths are generated that allow all the material in the areas defined by the borderlines in the CAD drawing to be removed. In the case of nested borderlines, we build up a tree structure reflecting which borderline is inside which. This allows us to identify the different regions, each of which is delimited by an outer border and possibly contains islands. The user can choose the distance between the cuts according to the size of the beam and select between a rastering (Figure 8) and a contouring option (Figure 11).

Figure 5: Tool path (grey) for rastering a slot (black).
Figure 6: Slot cut in Silicon using the rastering technique.

Figure 7: Back-lit panel display button (black paint on clear plastic).
Figure 8: Tool paths (grey) for machining the logo in Figure 7 (detail). Rastering mode.

Figure 9: Fan-outs machined into TCO on display panel.
Figure 10: Detail of Figure 9.
Figure 11: Borderlines (black) and tool paths (grey) for the fan-outs shown in Figure 10. Contouring mode.
The main difference to similar functions that are commercially available is that the LaseCAM area clearing function can deal with much more extensive and complex structures (e.g. a $\varnothing 80$ mm clock display containing 217 borderlines and requiring about 42 m of tool paths in total).

### 4.5 Pocketing and 2½D surface machining

As with the area clearing operation, the user can choose between a contouring and a rastering mode; in the case of pocketing, there are the options of vertical or sloping sidewalls. The work on these operations is ongoing.

The tool paths are generated layer by layer: The first layer of tool paths is derived from the contours given in the CAD-drawing in the same way as the tool paths for area clearing. Then the machining along these tool paths is simulated and the result compared to the desired device. This comparison is quantified by calculating the differences between the machining depth achieved so far and the machining depth specified by the drawing at each pixel of the simulation grid. The next step is to derive from this “matrix of remaining machining depth” the contours for the second layer of tool paths. These contours are the borders of the areas where the remaining machining depth is above a certain threshold. In order to translate the discrete information from the matrix of remaining machining depth into the continuous curves needed to generate further tool paths, we use edge detection and edge linking algorithms similar to those known from image processing applications. Once the contours have been derived, the second layer tool paths are generated as before. Again, machining along these tool paths is simulated and the result compared to the device in the drawing, etc.

With a circular beam, the machining depth at the centre of the cut is greater than close to the edges due to higher shot overlap; in the case of a Gaussian beam profile, this effect is even more pronounced as the intensity decreases with the distance from the centre of the beam. In order to average out these differences in machining depth, the tool paths of subsequent layers are offset with respect to each other.

To avoid extra machining depth caused by increased shot overlap, the tool paths can be enhanced by trimming them at acute angles and speeding up the scanner movement (to reduce shot overlap) where the tool paths are too close together.

![Figure 12: Fragments of tool paths that cause extra machining depth: Acute angle (left) and two fragments close together (right). The grey scale in the schematic drawing of the corresponding shots reflects the amount of shot overlap.](image)

Applications for the pocketing and 2½D surface machining operations include embossing tools, micro injection molding tools and devices for passive alignment.

### 5. Scanner Post Processor

Once the tool paths are available as geometric information, they have to be translated into CNC commands to control the tool. In our case, these are commands for the scanner head. As the scanner is not able to machine along curved lines, all the arcs in the tool paths have to be approximated by straight lines. The user can specify the maximum chord error that can be accepted.
In case the device to be machined is larger than the scan area, the machining area has to be subdivided into “tiles” of the size of the scan area and the tool paths have to be broken up into pieces that are entirely within one of the “tiles”. This makes it possible to machine the desired device in a step and scan process, stitching the “tiles” together.

If the system on which the LaseCAM software is used does not have a scanner, other post processors are available that translate the tool paths as geometries into other languages, e.g. into commands for the Aerotech UNIDEX 500 motion controller.

6. GRAPHICAL USER INTERFACE

The graphical user interface (GUI) provided by the alphaCAM software has been customised in order to allow the user to access the functionality of LaseCAM by means of menu items and buttons. Many user forms have been created to make it convenient for the user to edit and enter parameters and to choose between different options.

![Figure 13: Screen shot of the GUI of the LaseCAM software showing another example for the area clearing operation (borderlines in black, tool paths in grey).](image)

![Figure 14: Examples of user forms.](image)

7. EXITECH M1000 LASER MICROMACHINING TOOL

The Exitech M1000 laser micromachining tool was specifically designed as a small footprint workstation integrating the LaseCAM software described in this paper.

The Exitech M1000 tool (Figure 15) is a compact, floor mounted unit. It incorporates a Q-switched UV solid-state laser source. The laser beam is delivered to the workpiece via a scanner head for rapid beam displacement. A very short focal length telecentric f-theta lens (f = 30 mm) makes it possible to achieve a spot size of 2 - 3 µm at 266 nm wavelength. The size of the scan field is about 10 x 10 mm. There is a maximum of flexibility for the lay-out of the optical path: One option is to image an aperture with x 100 demagnification using an aperture changer, which allows a variety of different spot sizes and shapes to be generated at the workpiece. To achieve the smallest spots, direct focusing of the Gaussian
beam is used. Figure 16 shows the optical layout for these two versions. Precision X and Y stages are used for step and scan operations. Various system diagnostics such as an alignment camera, height sensor with autofocus and a power meter are integrated.

The machine is built on a rigid platform with a granite gantry. The laser, all critical optical components, the stages and the scanner head are attached to the granite structure for stability and freedom from vibration. An enclosure makes this tool class 1 laser-safe.

It should be noted, though, that the LaseCAM software developed for this workstation can also be used on other systems with or without scan head and with lasers of different wave lengths suited to the respective application.

8. CONCLUSIONS

User-friendly CAD/CAM software for a novel laser micromachining tool concept has been developed on a commercial CAD/CAM platform. The LaseCAM software automatically generates laser beam tool paths for 2D and 2½D structures, relying on a simulator module for the more complex machining operations. These tool paths are then translated into motion control commands for conventional motor-driven stages or for x-y laser scanners, or a combination of both. The use of state-of-the-art scanners with short focal length f-theta (telecentric) lenses and deep-UV diode-pumped solid-state lasers (266 nm) allows high resolution, accurate micromachining of most metals, ceramics, polymers and electronic
compounds. Applications include micro-hole drilling, thin-film patterning, micro rapid prototyping and micro injection molding tool manufacture.

REFERENCES


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