

Research on the technology of femtosecond laser micromachining based on image edge tracing

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Received November 7, 2008; accepted June 9, 2009

Aiming at fabrication of complex microstructures and micro-patterns, a kind of femtosecond laser micromachining technology based on the BMP image edge tracing was proposed. We introduced the general principle of this technology and discussed the implementation of the machining paths extraction, optimization, tracing and the feedback of the machining procession in detail. On the basis of this technology, control software for femtosecond laser micromachining was developed. Furthermore, we have accomplished the fabrication of complicated two-dimensional (2D) micro-patterns on a copper thin film. The results indicate that this technology can be used for digital control micromachining of complex patterns or microstructures at micron and submicron scales by femtosecond laser.

femtosecond laser, image edge detection, micromachining, micro-pattern

Citation: Zhang D S, Chen F, Liu H W, et al. Research on the technology of femtosecond laser micromachining based on image edge tracing. Chinese Sci Bull, 2010, 55: 877–881, doi: 10.1007/s11434-009-0550-3

Femtosecond laser micromachining is a new type of micro-manufacturing technology with many incomparable unique advantages. Firstly, femtosecond laser pulse duration is so short (10^{-15} s) that it enables us to obtain extremely high peak power at relative low pulse energy and thereby greatly reduces the energy required for fabrication. For example, when a 10 fs laser pulse at 0.3 mJ pulse energy focuses on a micro-region with diameter of 2 μm , the peak power in the focal spot would reach 10^{18} W/cm^2 . Secondly, the energy of femtosecond laser is concentrated in the range of the skin depth, resulting in minimal heat affected zone. And there will be no trace of melting and re-solidification left after the ablation process, accordingly reducing or even eliminating many negative influences caused by the thermal effect in traditional processing. Thirdly, the nonlinear absorption of femtosecond laser can make laser focus into any position inside transparent bulk materials, thus three-dimensional (3D) microfabrication can be realized. In addition,

because of the accurate laser ablation threshold for each material, laser energy can be controlled to equal to or slightly higher than the ablation threshold so as to carry on sub-micron fabrication beyond the diffraction limit.

With enough short pulse duration and enough high peak power, the femtosecond laser can carry on 2D and 3D fine processing, repair and modification of various materials, especially for high hardness, high melting point, corrosion resistant and brittle materials (such as metals, glasses, ceramics etc.). At present, domestic and foreign scholars have already carried out extensive researches on femtosecond laser micro-machining in the fields of fabrication of micro-optics, microelectronics, micro-mechanical devices and biochemical analysis system, and the fabricated micro-devices including waveguides [1–3], gratings [4,5], micro-electrode [6], Mach-Zehnder interferometer (MZI) [7], and other simple micro-patterns. Moreover, the fabrications of optical switch [8], 3D optical circuit [9,10], multi-layered grating [11] and other complex micro-structures have been reported. Femtosecond laser micromachining plays an in-

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creasingly important role in the field of micromanufacturing. So it has practical significance for the development of femtosecond laser computer numerical control (CNC) software which can automatically produce the manufacturing paths, and implement the fabrication of complex patterns and microdevices in two and three dimensions.

In this paper, we investigate the technology of extraction, optimization, tracing and feedback of the BMP image edge contour and presented the femtosecond laser CNC micromachining program. The microfabrication of complex designed 2D micro-devices can be achieved in combination with the optimization of laser processing technique. A hierarchy slicing approach is employed to transform a 3D CAD model into lots of 2D patterns. The scanning paths of the 2D patterns are produced and optimized subsequently. And then, the focused femtosecond laser pulses are utilized to remove or modify the materials following the paths, and the pattern of each slice can be fabricated on the surface of material or inside a bulk transparent material. By fabricating an accumulation of the 2D patterns in a certain order, a 3D microstructure can be obtained by the multilayer removal process. Our work provides an effective method for the CNC micromachining of complicated 3D structures in micron to sub-micron feature size.

1 Overall construction of femtosecond laser micromachining technology based on image edge tracing

BMP format is currently the most widely used image format, and BMP image processing technology has been extensively applied to micromachining [12,13]. Because the image-based miniature CNC machining technology can easily transfer complex graphics and complex structures onto the processing materials, it will provide an efficient method to fabricate complex microstructures with good quality and high processing efficiency.

The image processing technology enables us to extract the manufacturing paths, optimize them and do scaling according to design specifications. Meanwhile, by optimizing the laser micromachining parameters, complex structures can be fabricated ultimately on particular materials.

Femtosecond laser micromachining technology based on image edge tracing mainly includes the following parts: image processing of complex patterns and structures (including image edge contour extraction and optimization), machining process control (containing manufacturing paths tracing and feedback), CNC program development, femtosecond laser micromachining technique optimization and so on. Figure 1 shows the flow chart of the image processing and process control parts.

Image edge contour extraction can be accomplished by the following procedures: BMP image loading, gray processing, binary processing, and treatment of 8-connectivity

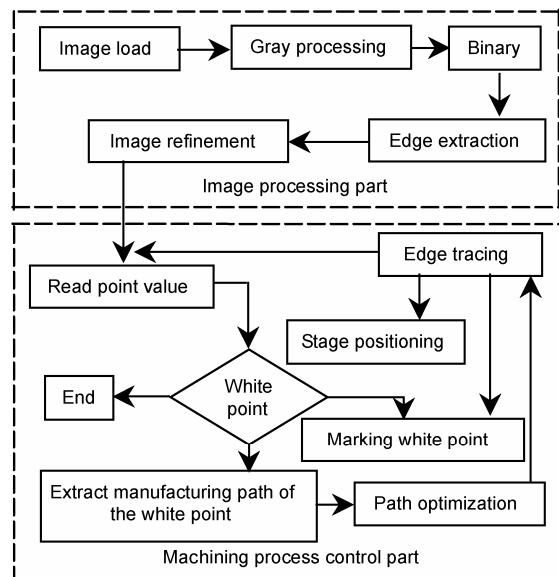


Figure 1 The flow chart of the image processing part and process control part.

Laplace operator [14]. The optimization of image edge contour is to refine the image for better closed contour by removing some isolated and non-connected points, and connecting the breakpoints. By employing Bezier function refinement and edge contour tracing algorithm, we could realize the fabrication of BMP image with smooth edge contour. Furthermore, by marking the processed points on image, the implementation of real-time process monitoring could be done. The control procedure can carry out the BMP image loading and edge contour treatment, as well as processing parameters setup and real-time process monitoring.

2 System design

2.1 Edge contour extraction

In VC environment, the Windows API functions are employed to load BMP image files. The RGB color components of each point in the image are stored in an array. Afterward, through calculating every element's grey value and binary processing, the continuous gray-scale image is transformed into a black-white image. Finally, image edge contour is extracted by the 8-connectivity Laplace operator. In this case, the white points are the manufacturing points with black background color.

2.2 Edge contour optimization

After the operator processing, many discontinuous points and unclosed line segments appear in the edge contour. If this kind of edge contour is directly used for fabrication, the processing pattern will have lots of local defects, resulting in the fabrication failure. At this moment, there needs to deal with three kinds of points to make edge contour

smoother. The first are the isolated white points with the colors nearby all black. The second are the non-connected white points leaving untreated after the tag of every manufacturing path. The third are the endpoints of curves, the so called breakpoints. Therefore, it is essential to take the following measures:

(a) Dealing with the isolated points: Extract colors in the eight locations adjacent to a white point. In case of all black, turn the white point to black.

(b) Dealing with non-connected points: Use the edge contour tracing algorithm to set a manufacturing path to red. After the label, search for the residual isolated white points and change them into black. Repeat the above steps until all paths are completed. Finally, the red points are converted into white.

(c) Connecting the breakpoints: Firstly, mark all discontinuous points. Secondly, set a discontinuous point as the center to seek for other discontinuous point in a 5×5 matrix scope. If there are any, use the DDA algorithm [15] to supplement data points between two discontinuous points.

2.3 Micromachining process control

(1) Edge contour tracing algorithm. Because the microfabrication of image edge contour is implemented by tracing the white pixels, it is necessary to set the traced white points to background color or other colors to avoid repetitive tracing. To distinguish the traced points from the background and to monitor processing progress, the tracing points are set to red. Edge contour tracing of the whole BMP image is achieved by processing the open curve and closed curve successively.

(2) Manufacturing path optimization. Because the values of x -coordinate and y -coordinate are integers, the step-shaped contour will inevitably emerge in the processing path, which necessitates curve fitting programs to smooth the processing paths. By means of three-order Bezier curve fitting, eight fitting points have been inserted evenly into seven adjacent white points in manufacturing paths.

(3) CNC translation stage position control. PC-execution time is much shorter than the motor movement time. If the translation stages have not yet arrived at the designated location before the next instruction, it is easy to cause the so-called “lost step” phenomenon and microfabrication failure. So in the control system, accurate positioning of translation stages is very important.

The precision translation XYZ-stages (PI, M-505.6 DG), with design accuracy of 17 nm, smallest step of 50 nm, and working distance of 50 mm, were utilized. The stages are connected to C-843 control card ports assembled in a computer. The motion control and positioning control can be realized by calling the dynamic link library function of the C-843 control card through software.

The stage instruction pC843_IsMoving (ID, axes, mov) is used to detect the translational state of the stages, the re-

turn value will be deposited in BOOL mov [3] with 1 for moving and 0 for stop. When all three values are zero, the three stages will implement the next processing.

2.4 Control program

The femtosecond laser micromachining control program is developed by calling the library functions of PI stages in VC environment. The control interface of program is shown in Figure 2. The control software can easily realize the bitmap processing, stages initialization, setup and optimization of processing parameters, process coordinate scaling, coordinate transformation, accurate positioning, shutter control, real-time process monitoring and other common functions used in micromachining. Various fundamental graphics such as circle, line, polygon, grooves, gears, via holes and so on, can also be fabricated by this system. Furthermore, precise microfabrication of some complex functional micro-devices is realizable. Figure 3 shows the monitoring window for machining process (the processed points are black, the unprocessed points are white).

3 Experiment results

The laser source was a Ti: sapphire oscillator-amplifier system



Figure 2 The control interface of femtosecond laser micromachining software.



Figure 3 The monitoring window of femtosecond laser micromachining processing.

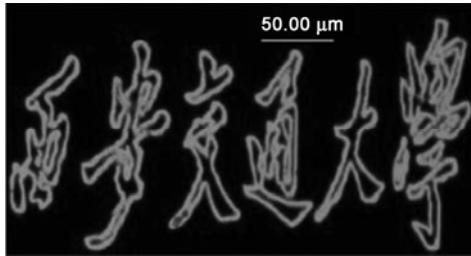


Figure 4 The pattern of "Xi'an Jiaotong University" fabricated on a copper thin film.

(FEMTOPOWER Compact Pro, Austria), which delivered 800 nm, 30 fs Gaussian laser pulses at repetition rate of 1 kHz. Femtosecond laser was focused vertically onto the sample surface by an objective lens. The sample was processed by means of the movement of the stages cooperated with electronic shutter, which was automatically controlled by the software shown in Figure 2. The objective lenses were 50× (Nikon, NA = 0.5) and 100× (Nikon, NA = 0.9). The sample used in the experiment was a copper thin film (25 mm × 25 mm) made by vacuum evaporation. The thickness of thin film was about 100 nm and the thickness of quartz substrate was about 1.2 mm. The processing results were observed and recorded by an optical microscope. Figures 4 and 5 show the micro-patterns processed on the copper film sample.

The size of micro-pattern in Figure 4 was about 300 $\mu\text{m} \times 150 \mu\text{m}$. The pattern was fabricated using the 50× objective lens (NA=0.5), with the scanning speed of 30 $\mu\text{m}/\text{s}$ and processing step of 1 μm . The ablated line width was measured as about 2 μm when the laser average power was 100 μW .

Figure 5 shows a micro-pattern of Xi'an Jiaotong University's motto, with the width of 200 μm , and the height of 150 μm . It was fabricated by 100× (NA=0.9) objective lens, with laser average power of 10 μW scanning speed of 8 $\mu\text{m}/\text{s}$ and processing step of 0.3 μm .

From the figures, we can see that the micro-patterns were fabricated with smooth edges, accurate line lengths, good uniformity and consistency of line widths, and without losing steps or breakpoints. By choosing appropriate pulse energy, the pollution caused by ablated debris was effectively avoided and the sample surface was kept clean during the fabrication process.

It is inevitably required in micro-device production to meet the demands of fabrication according to different size and precision. Therefore it is necessary to implement accurate control of femtosecond laser processing parameters. The ablation width and machining precision are sensitive to femtosecond pulse energy. The materials would not be ablated if the pulse energy is under the laser induced ablation threshold. But on the contrary, when it is well above the laser induced ablation threshold energy influence, the thermal effects will lead unexpected damages to the sample



Figure 5 The pattern of Xi'an Jiaotong University motto fabricated on a copper thin film.

materials. Above the ablation threshold, the lower the pulse energy, the smaller the ablated line width. Meanwhile, the effects of the laser system stability, station stages accuracy and focused spot size have to be taken into account as well. Furthermore, higher processing accuracy can be achieved by the use of lower scanning speed in processing. The focused spot can be minimized to submicron size through high NA objective lens. Nano-scaled microstructures and array holes fabricated by femtosecond laser have been reported [16,17] with ablation width tens of nanometers and depth of several nanometers. The typical speed of femtosecond laser micromachining is tens of microns per second, thus causing low efficiency in processing large-sized micro-patterns or microstructures. By using high-repetition-rate femtosecond laser pulses, the processing efficiency can be raised significantly.

4 Conclusions

The femtosecond laser micro-machining CNC technology based on BMP edge tracing can be used for miniature fabrication of complex image with different scales. Moreover, the continuity of adjacent processing points and Bezier curve fitting can smooth the profile of the fabricated microstructures and promote the micromachining efficiency. By femtosecond laser parameters optimization and processing parameters regulation, we can easily achieve the precise fabrication of complex micro-graphics, microstructures in millimeter, micron and even sub-micron size.

The results show that femtosecond laser CNC micro-machining technology based on the BMP image edge tracing can implement the transformation of complex structures and graphics onto different materials. Therefore it is possible to make use of femtosecond laser to fabricate 2D complex micro-structure or micro-graphics with micron and sub-micron feature size in many kinds of materials. This technology provides a new way for the fabrication of micro-devices with 2D and 3D complex structures.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 60678011 and 10674107).

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