Optics and Lasers in Engineering 63 (2014) 58–69

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

# Nanosecond multi-pulse laser milling for certain area removal of metal coating on plastics surface

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A R T I C L E  I N F O

*Article history:*
Received 19 February 2014
Received in revised form
16 June 2014
Accepted 16 June 2014
Available online 11 July 2014

*Keywords:*
Laser processing
Ablation depth
Nanosecond multi-pulse laser
Machining parameters optimization
Metal coating with functional pattern

A B S T R A C T

Metal coating with functional pattern on engineering plastics surface plays an important role in industry applications; it can be obtained by adding or removing certain area of metal coating on engineering plastics surface. However, the manufacturing requirements are improved continuously and the plastic substrate presents three-dimensional (3D) structure—many of these parts cannot be fabricated by conventional processing methods, and a new manufacturing method is urgently needed. As the laser-processing technology has many advantages like high machining accuracy and constraints free substrate structure, the machining of the parts is studied through removing certain area of metal coating based on the nanosecond multi-pulse laser milling. To improve the edge quality of the functional pattern, generation mechanism and corresponding avoidance strategy of the processing defects are studied. Additionally, a prediction model for the laser ablation depth is proposed, which can effectively avoid the existence of residual metal coating and reduces the damage of substrate. With the optimal machining parameters, an equiangular spiral pattern on copper-clad polyimide (CCPI) is machined based on the laser milling at last. The experimental results indicate that the edge of the pattern is smooth and consistent, the substrate is flat and without damage. The achievements in this study could be applied in industrial production.



## 1. Introduction

In the fields of aerospace, energy, biomedical and MEMS, the precision parts that are obtained by manufacturing of metal coating with functional pattern on engineering plastics surface have gained increasing attention recently; the typical precision parts include microstrip antenna [1,2], micro-power sources [3], miniature sensor [4], etc. With ever-escalating expectation of the performance for engineering applications, this kind of precision part needs higher geometric accuracy and edge quality of the functional patterns. Moreover, the engineering plastics substrate presents three-dimensional (3D) structure, so as to meet the performance requirements or the limitation of installation space. Through various studies by many scholars, this kind of precision parts can be fabricated through adding or removing certain area of metal coating on engineering plastics surface.

When using the method that adds metal patterns onto the engineering plastics substrate, such as 3D printing or laser Direct-Write [5,6], the manufacturing of parts with a 3D structure can be realized. However, after printing or deposition, the whole parts need to be annealed at 150–550 °C to make the metal layer cured, as annealed temperature is higher than the thermal deformation temperature for most kinds of engineering plastics—the applications of this method are limited. Another method makes the surface of plastic substrate coated with a metal coating first, and then removes a certain area of metal coating and leaving functional pattern on the substrate surface. The common machining method for certain area removal of metal coating on the engineering plastics surface is photolithography [7,8]. Through this method, the functional pattern of metal coating on planar substrate can be manufactured precisely. However, due to a series of steps like mask alignment, exposure and development, it is difficult for photolithography to complete the manufacturing of metal coating with functional pattern on the 3D substrate.

Because of the above processing method, it is not suitable to fabricate metal coating with a functional pattern on the engineering plastic surface when the substrate has a low thermal deformation temperature or a 3D structure—an advanced manufacturing technology is urgently needed. At present, the laser-processing technology shows desirable superiority compared with the conventional machining method, such as high flexibility, speed, resolution and precision—especially capable of 3D parts processing

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http://dx.doi.org/10.1016/j.optlaseng.2014.06.009
0143-8166/

and manufacturing [9,10]. Therefore, precision fabrication of metal coating with functional pattern on the surface of the 3D substrate could be promisingly achieved by the laser-processing technology.

In this study, the machining method for certain area removal of metal coating on the engineering plastics surface is studied based on the nanosecond multi-pulse laser milling. The manufacturing steps of the metal coating with functional pattern are as follows: First, thin metal coating is uniformly plated on the surface of the engineering plastics substrate; then the metal coating outside the functional pattern is completely removed by the laser-processing technology, and the damage of the engineering plastics substrate should be avoided as far as possible; finally, the functional pattern of metal coating with a high accuracy could be obtained and there are no burrs and warps of the pattern edge.

In order to remove certain area of metal coating on an engineering plastics surface via laser machining technology, the choice of an appropriate laser source and the corresponding machining parameters are directly relevant to the machining quality of functional pattern, machining cost and operation efficiency. Nowadays, the nanosecond multi-pulse laser technology is more widely used in industrial application with its sophisticated development—for instance, fabrication of the fiber grating to realize optical switching [11,12], hard disk texturing, silicon wafer marking, IC repair, cutting of thin Al-alloy sheet and lubricant groove processing [13–17]. For the existence of narrow strip-line in the functional pattern and the short pulse laser, this technology exhibits the advantage of a high accuracy in micro-machining. The nanosecond multi-pulse laser can be chosen for laser machining of metal coating with functional pattern based on the optimal processing parameters.

To meet the requirements of industrial production, nanosecond multi-pulse laser processing technology for various materials and the optimization of processing parameters are also studied by numerous academics and research institutions [18–20]. Most studies have been done mainly on homogenous target materials such as metals, ceramics and polymers [21–24]. However, there are few reports about the study of nanosecond multi-pulse laser technology aiming at thin metal coating on engineering plastics with low melting point like metal cladding engineering plastics. Meanwhile, many researches about laser processing technology focus on the effect of single pulse laser [25,26] or laser drilling and punching that laser spot does not move continuously [27,28]. Although these researches are very significant, they cannot be used for the functional pattern of metal coating machining directly by nanosecond multi-pulse laser milling.

As the metal coating with functional pattern on the engineering plastics surface can be applied under various extreme conditions, the edge quality of the functional pattern should be superior, the residual copper layer and damage of substrate should be avoided, so as to guarantee better electrical and mechanical performances of the parts. In this paper, the machining method for certain area removal of metal coating on the engineering plastics surface is studied based on the nanosecond multi-pulse laser milling. In order to improve the edge quality of the functional pattern, the generation mechanism and the corresponding avoidance strategy of the processing defects are studied. Additionally, a prediction model for the laser ablation depth is proposed, which can effectively avoid the existence of a residual metal layer and reduces the damage of the substrate. The machining parameters of nanosecond multi-pulse laser milling mainly include laser fluence $F_0$, pulse repetition frequency $f$ and feeding speed of laser spot $v$. Subsequently, the optimizing selection for machining parameters is carried out. As the laser spot is very small compared to the parts, the machining results on the 3D structure are basically as same as the planar one; therefore, a planar copper-clad polyimide (CCPI) is chosen as the raw material to carry out the experiments. At last, with the optimal machining parameters, a typical functional pattern sample on CCPI is machined based on the laser milling.

## 2. Mathematical modeling for the processing defects and laser ablation depth

Metal coatings with equiangular spiral pattern with two arms on the 3D structure are widely used for a signal receiver or a sensor. The manufacturing process of the parts is shown in Fig. 1. It can be seen from the picture that the curvatures of the pattern change continuously; therefore, the machining parameters should be chosen appropriately, so as to guarantee the machining accuracy meeting the requirement for different curvatures. To meet the requirements of industrial applications, the edge quality of the strip-line should be neat and consistent, the metal layer should be ablated completely and the damage of substrate should be in a minimal degree.

In this section, the generation mechanism of the processing defects for certain area removal of metal coating is analyzed to improve the edge quality of the functional pattern, and the prediction model for the laser ablation depth is proposed, which can be used for the optimization of machining parameters.

### 2.1. Modeling for the processing of functional pattern

When using the laser processing technology to remove certain area of metal coating on an engineering plastics surface, it is hard to fill the processing area completely by the laser spot with a fixed shape. Therefore, the processing defects are formed by the residual area. When the edge of functional pattern is curved, the processing defects for the inner edge of functional pattern are significantly greater than the value of the straight-line processing, while the defects are less than the straight-line processing for the outer edge. Thus, in order to ensure the maximum processing defects are taken into account, the condition that laser spot locates inside the curve pattern is considered to analyze the generation mechanism and variation characteristics of the processing defects. The path of the laser processing for the inner edge of the functional pattern and the generation mechanism of processing defects $E$ (the shaded area) is presented in Fig. 2.

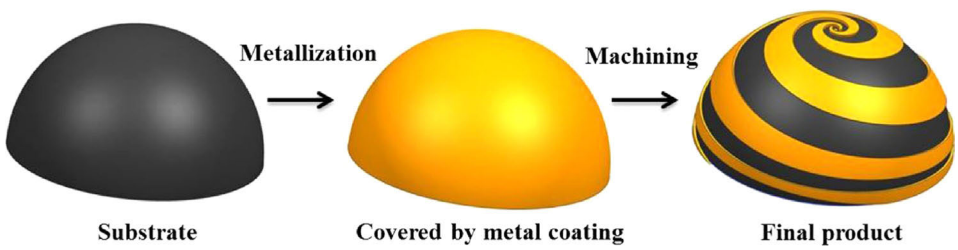


**Fig. 1.** Manufacturing process of the parts by laser milling.