Magnetic force enhanced atmospheric plasma polishing ability to improve surface roughness of copper base materials

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Abstract. The global demand for portable miniature products has increased, which has driven the improvement of micro-component technology to meet the precision requirements of miniaturization of product sizes and higher precision of products. As the requirements for the assembly accuracy of precision components and the high quality on the surface treatment of materials, the current precision polishing is also facing a technical bottleneck. Many polishing technologies have been developed, atmospheric plasma polishing is a new polishing technology, which is applied to the precision components of the optoelectronic industry. How to improve the polishing efficiency of atmospheric plasma has become a new research topic. In this study, a non-traditional surface treatment method which low-temperature atmospheric plasma is used to precision polish the copper-based material, and added magnetic force on the surface of the copper-based material, in order to enhanced atmospheric plasma polishing ability to improve surface roughness of copper base materials. The low-temperature atmospheric plasma jet has been used; the power of plasma is 50W and nitrogen (N₂) as reaction gas. The different scanning speed of stages is 2, 5, 10, 15 and 20 mm/s, respectively. The processing time is 10min. A copper foil substrate is as select material. Observe the surface roughness variation of the copper foil substrate treated by atmospheric plasma. The results shown that when the copper foil substrate is treated with low-temperature atmospheric plasma and no magnetic force on the surface, when the scanning speed of the stage is 2 mm/min, the improvement rate of surface roughness is about 17.6%; when the scanning speed of the stage is 20 mm/min, the surface roughness improvement rate is about 5.5%. When the magnetic force on the surface is about 188 mT, the improvement rate of surface roughness is about 30.8% when the scanning speed of the stage is 2 mm/min, and the improvement rate of surface roughness is about 12.5 % when the scanning speed of the stage is 20 mm/min. From the above results, it is known that applying magnetic force on the surface of the work-piece can indeed increase and improve the polishing ability of the low-temperature atmospheric plasma.
1. Introduction

Polishing is one of the commonly used methods of material surface treatment, its purpose is to eliminate the subtle unevenness of the material surface, so that the surface has a smooth. Traditional polishing methods is mainly divided into mechanical polishing, chemical polishing, electrochemical polishing, etc. [1]. Mechanical polishing can achieve high machining accuracy and large production. But direct contact limits the processing size and processing efficiency. In addition fragments from mechanical polishing are easily cause harmful to personnel. Chemical polishing have produce a lot of harmful gases such as N₂ and SO₂. Electrochemical polishing can replace many metal mechanical finishing processes, and not limited by processing size, material composition and part shape, etc. But chemical polishing and electrochemical polishing have waste electrolyte treatment problems that especially seriously affecting the environment [2].

Polishing processes become more important because of the increasing demand for better surface finish. In response to the development of modern optics and electronics industries, the requirements for the surface quality of materials are getting higher and higher. When traditional polishing cannot satisfy the improvement of surface roughness, more precision polishing technology is developed. A high-precision, high-efficiency, and environmentally-friendly surface treatment method is urgently needed [2, 3]. The conditions for reducing environmental impact during in the development of precision polishing technology must also be considered.

Copper-based materials including copper and copper alloys, etc. that are frequently used for electrical and electronic device parts and interconnecting materials because they excel in electrical and thermal conductivity, spreadability, drawability, corrosion resistance, spring characteristics, and so on [5-6]. Cu substrate is an important basic component for electronic parts. Furthermore, Cu is also a potential candidate as the substrate of nanofilm for its excellent conductivity. Precision polishing technology had used for copper and copper base materials such as chemical mechanical polishing [6, 8], hydrodynamic suspension polishing [10, 11]. However, The size of every component for opto-electrical devices has been reduced in recent years which small-size or micro-zone precision polishing are be demand. In order to solve these problems, high-energy beam polishing such as high-pulse-frequency pulsed laser [2, 13], micro-beam plasma polishing [14, 15] and electron beam [16, 17], which provides a contact free, automatable and selective area polishing process. High-energy beam polishing has been investigated by a plenty of researches owing to its capacity of providing a contact free and selective area process to reduce surface roughness [15]. As compare to laser beam, electron beam and plasma beam, which plasma beam has no need for vacuum environment, and lower equipment costs.

Some electronic parts and devices are sensitive to heat and not resistant to high temperatures, and can’t be used wet grinding methods. Low-temperature atmospheric pressure plasma is suitable for polishing such components. The experimental investigation confirms that undertaken to affirm Low-temperature atmospheric plasma could achieve a decent reduction of surface roughness by optimizing parameters. How to improve the polishing efficiency of low-temperature atmospheric pressure plasma has become a new research topic.

Magnetic field assisted plasma reaction has been widely used in magnetron sputtering technology, but it is rarely used in plasma surface treatment and polishing [18]. In this study, an external magnetic field was applied to the surface treatment and polishing of the copper base materials with a low temperature atmospheric-pressure plasma. The influence and effect of the low temperature atmospheric-pressure plasma on the surface treatment and polishing of the copper base materials under different magnetic environments were discussed.

2. Experimental procedure

2.1. Material preparation

The selected material is a commercially available Copper Clad Laminate (CCL) substrate with a size of about 100 x 100 mm obtained from general electronic materials stores, which is then cut into test pieces with a size of about 10 x 10 mm. The surface of the samples were cleaned that the samples soak in an alcohol solution then use an Ultrasonic Cleaner (Ultrasonic Cleaner, Prema, PK-B) for 10 min to remove
the dirt and possible contaminants on the surface. The samples rinse with alcohol in next step, then use Blow dry with high pressure gas.

2.2. Plasma polishing
This study uses low temperature atmospheric-pressure plasma jet, the power is fixed at 50 W, the reaction gas is nitrogen, the gas flow rate is 20 L/min, and the plasma temperature is about 50 °C. The distance between the substrate and the plasma nozzle is about 3 mm. The scanning speed of the stage is 2, 5, 10, 15 and 20 mm/min, respectively, and the processing time is 10 min. Two types of magnets with different magnetic forces are used, namely, a NdFeB magnet with a magnetic field strength of about 188.8 mT; and a ferrite magnet with a magnetic field strength of about 40 mT. Schematic diagram of the experimental equipment as shown in Figure 1.

2.3. Measurement apparatus
The samples magnetic force were measured by magnetic meter (AC/DC magnetic meter, MG-3002, Lutron). The surface morphology of the samples was observed using a laser scanning confocal microscope (VK-X 3D Laser Scanning Microscope, KEYENCE, VK-X1000), and a scanning electron microscope (High Resolution Scanning Electron Microscope (HR-SEM), HITACHI, SU8000) operated at 30 kV. The chemical composition of the samples were confirmed by energy-dispersive X-ray analysis (EDX, Horiba, Japan). The equipment of VK-X1000 is equipped to obtain a three dimensional (3D) topography of polished surfaces. The roughness parameters could be obtained after a 3D-reconstruction, established with the matched software.

![Image of schematic diagram of the low temperature atmospheric-pressure plasma jet surface polishing.](image)

**Figure 1.** Schematic diagram of the low temperature atmospheric-pressure plasma jet surface polishing.

3. Results and discussion
In this study is to evaluate whether the magnetic force will affect the low-temperature atmospheric pressure plasma applied to the precision polishing. The evaluation method uses the surface roughness of the Copper Clad Laminate (CCL) substrate change value which before and after the low-temperature atmospheric pressure plasma treatment as the evaluation reference value. The measured surface roughness values are the Average Roughness ($S_a$), which are evaluated over the complete 3D surface. The change rate of the surface roughness value before and after the treatment, which is called the “Improvement Rate”, which is defined as follows:

$$IR = \frac{S_{ab} - S_{ad}}{S_{ab}} \times 100\%$$

where
IR: Improvement Rate (%)

$S_{aB}$: Surface roughness value before treatment

$S_{aA}$: Surface roughness value after treatment

3.1. No external magnetic field used

The Copper Clad Laminate (CCL) substrate is processed by low temperature atmospheric-pressure without applying an external magnetic field, and the scanning speed of the stage is 2 mm/min. The surface roughness change value, which the surface roughness before treatment $S_{a}$ 0.381 μm and after treatment $S_{a}$ 0.314 μm, respectively. The Improvement Rate (IR) is about 17.6%, as shown in Figure 2. When the scanning speed of the stage increases to 5, 10, 15 and 20 mm/min, the improvement rate of the surface roughness value of the samples after treatment is 13.6%, 9.4%, 5.5% and 5.5%, respectively. The results show that the scanning speed of the stage increases and the surface improvement rate decreases, as shown in Table 1. Figure 3 shows the change of the surface roughness of the test piece before and after treatment when the scanning speed of the stage is 20 mm/min.

Table 1. The surface roughness change of the Copper Clad Laminate (CCL) substrate before and after the surface treatment of the low temperature atmospheric-pressure plasma without applying a magnetic field.

| Surface Roughness (Sa, μm) | Stage scanning speed (mm/min) | 2  | 5  | 10 | 15 | 20 |
|-----------------------------|--------------------------------|----|----|----|----|----|
| Before Treatment            | 0.381                         | 0.411 | 0.393 | 0.365 | 0.385 |
| After Treatment             | 0.314                         | 0.355 | 0.356 | 0.345 | 0.364 |
| Improvement Rate (%)        | 17.6                          | 13.6 | 9.4 | 5.5 | 5.5 |

Figure 2. The surface morphology of Copper Clad Laminate (CCL) substrate is treated with low temperature atmospheric-plasma without applying a magnetic field, and the scanning speed of the stage is 2 mm/min, (a) before treatment $S_{a}$ 0.381 μm, (b) after treatment $S_{a}$ 0.314 μm.

Figure 3. The surface morphology of Copper Clad Laminate (CCL) substrate is treated with low temperature atmospheric-plasma without applying a magnetic field, and the scanning speed of the stage is 20 mm/min, (a) before treatment $S_{a}$ 0.385 μm, (b) after treatment $S_{a}$ 0.364 μm.
3.2. External magnetic field assist

3.2.1. Magnitude 40 mT. The substrate is treated with low temperature atmospheric-pressure plasma assisted in a magnetic force of 40 mT, when the scanning speed of the stage is 2 mm/min. The surface roughness of the substrate before treatment Sa is 0.430 μm, and after treatment Sa is 0.327 μm, and the improvement rate is about 23.9%, as shown in Figure 4. When the scanning speed of the stage increases to 5, 10, 15 and 20 mm/min, the improvement rate of the surface roughness value of the samples after treatment is 17.8 %, 13.8 %, 10.4 % and 7.7 %, respectively. The results shown that the scanning speed of the stage increases and the surface improvement rate decreases, as shown in Table 2. Figure 5 shows the change of the surface roughness of the test piece before and after treatment when the scanning speed of the stage is 20 mm/min.

Table 2. The surface roughness change of the Copper Clad Laminate (CCL) substrate before and after the surface treatment of the low temperature atmospheric-pressure plasma assisted in a magnetic force of 40 mT.

| Surface Roughness (Sa, μm) | Stage scanning speed (mm/min) | 2     | 5     | 10    | 15    | 20    |
|----------------------------|-------------------------------|-------|-------|-------|-------|-------|
| Before Treatment           |                               | 0.430 | 0.408 | 0.376 | 0.393 | 0.375 |
| After Treatment            |                               | 0.327 | 0.335 | 0.324 | 0.352 | 0.346 |
| Improvement Rate (%)       |                               | 23.9  | 17.8  | 13.8  | 10.4  | 7.7   |

Figure 4. The surface morphology of Copper Clad Laminate (CCL) substrate is treated with low temperature atmospheric-plasma assisted in a magnetic force of 40 mT, and the scanning speed of the stage is 2 mm/min, (a) before treatment Sa 0.430 μm, (b) after treatment Sa 0.327 μm.

Figure 5. The surface morphology of Copper Clad Laminate (CCL) substrate is treated with low temperature atmospheric-plasma assisted in a magnetic force of 40 mT, and the scanning speed of the stage is 20 mm/min, (a) before treatment Sa 0.75 μm, (b) after treatment Sa 0.346 μm.

3.2.2. Magnitude 188.8 mT. The substrate is treated with low temperature atmospheric-pressure plasma assisted in a magnetic force of 188.8 mT, when the scanning speed of the stage is 2 mm/min. The surface roughness of the substrate before treatment Sa is 0.454 μm, and after treatment Sa is 0.314 μm, and the
improvement rate is about 30.8%, as shown in Figure 6. When the scanning speed of the stage increases to 5, 10, 15 and 20 mm/min, the improvement rate of the surface roughness value of the samples after treatment is 20.3 %, 18.1 %, 11.8 % and 12.5 %, respectively. The results shown that the scanning speed of the stage increases and the surface improvement rate decreases, as shown in Table 3. Figure 7 shows the change of the surface roughness of the test piece before and after treatment when the scanning speed of the stage is 20 mm/min.

**Table 3.** The surface roughness change of the Copper Clad Laminate (CCL) substrate before and after the surface treatment of the low temperature atmospheric-pressure plasma assisted in a magnetic force of 188.8 mT.

| Surface Roughness (Sa, μm) | Stage scanning speed (mm/min) |
|---------------------------|-------------------------------|
| Before Treatment          | 2                             |
|                           | 5                             |
|                           | 10                            |
|                           | 15                            |
|                           | 20                            |
| After Treatment           | 0.454                         |
|                           | 0.414                         |
|                           | 0.408                         |
|                           | 0.382                         |
|                           | 0.382                         |
| Improvement Rate (%)      | 30.8                          |
|                           | 20.3                          |
|                           | 18.1                          |
|                           | 11.8                          |
|                           | 12.5                          |

**Figure 6.** The surface morphology of Copper Clad Laminate (CCL) substrate is treated with low temperature atmospheric-pressure plasma assisted in a magnetic force of 188.8 mT, and the scanning speed of the stage is 2 mm/min, (a) before treatment Sa 0.454 μm, (b) after treatment Sa 0.314 μm.

**Figure 7.** The surface morphology of Copper Clad Laminate (CCL) substrate is treated with low temperature atmospheric-pressure plasma assisted in a magnetic force of 188.8 mT, and the scanning speed of the stage is 20 mm/min, (a) before treatment Sa 0.75 μm, (b) after treatment Sa 0.346 μm.

3.2.3. Discussion. From the above results, when the surface of Copper Clad Laminate (CCL) were treated with a low temperature atmospheric-pressure plasma, the surface roughness improvement rate decreases with the increase of the scanning speed of the stage without any external magnetic field. The main reason is that plasma is an ionized gas with equal amounts of positive and negative charges. It is composed of ions, electrons, and neutral atoms or molecules [18]. When the scanning speed of the stage increases, the reaction time between the plasma and the substrate surface is short, and the time for ions,
electrons and neutral atoms or molecules in the plasma to bombard the substrate surface is also short, resulting in a decrease in the improvement rate of surface roughness. When an auxiliary magnetic field is applied, a comparison with the same scanning speed of stage 2 mm/min, the results shown that the surface roughness improvement rate increases from 17.6% without any magnetic field to 23.9% when a magnetic field strength of 40 mT is applied; the magnetic field strength increases to 188.8 mT, which improves rate increased to 30.8%. The external magnetic field increases the bombardment on the surface of the substrate between the particles generated in the plasma. This phenomenon has been widely doped by magnetron sputtering technology and related low-pressure plasma [18, 19]. The stronger the magnetic force of the applied magnetic field, the better the improvement of surface roughness. However, under any processing conditions, as the scanning speed of the stage increases, the improvement rate of surface roughness tends to decrease, as shown in Figure 8. From the experimental results, the magnetic field assistance can be applied to the atmospheric-pressure plasma to increase the effect of the plasma to improve the surface treatment effect.

![Graph](image)

**Figure 8.** The improvement rate variation of the surface roughness were treated with the low temperature atmospheric-pressure plasma.

### 4. Conclusion

The surface of the Copper Clad Laminate (CCL) substrate were treated with low temperature atmospheric-pressure plasma assisted in a magnetic force of 40 mT and 188.8 mT, respectively. Observing the changes in the surface roughness of the substrate, the results obtained make the conclusions as following:

1. The improvement rate of the surface roughness is the best when the stage scanning speed is 2 mm/min, the improvement rate reaches 17.6%, in the condition of not applying any magnetic field. The improvement rate gradually decreases with the increase of the stage scanning speed. When the stage scanning speed is 20 mm/min, the improvement rate is 5.5%, the roughness is only slightly improved.

2. When an auxiliary magnetic field is applied, with the same stage scanning speed of 2 mm/min. The improvement rate of surface roughness increases from 17.6% without any magnetic field to 23.9% with a magnetic field strength of 40 mT. The magnetic field strength is increased to 188.8
mT, and the improvement rate is increased to 30.8%. The particles generated in the plasma, which in external magnetic field increases the bombardment force on the surface of the substrate.

(3) The applied magnetic field increasing in plasma treatment, which can get the better the improvement effect of surface roughness. However, under any processing conditions, as the scanning speed of the stage increases, the improvement rate of surface roughness has a downward trend.

(4) The stronger the magnetic force of the applied magnetic field, the better the improvement effect of surface roughness

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