Influence of laser spot scanning speed on micro polishing using UV nano-second pulse laser

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Abstract

During laser micro polishing of the metallic surface, it is very important to choose the optimal laser energy density and laser spot scanning speed.

In this paper, during micro-polishing on the metallic surface by using UV nanosecond pulse laser, the influence of laser spot scanning speed on the polishing effect was investigated in terms of the relationship with the laser energy density.

The experimental and analytical considerations were shown that there is the optimal scanning speed of laser spot for the best laser polishing effect when the laser energy density on the workpiece surface was rated, and the influence of the overlap ratio of the scanning lines was also considered.

In addition, the optimal process parameters for the laser micro polishing of Ti and Ni metallic surfaces were obtained and the laser micro polishing experiments on theose metallic surfaces were conducted. For Ti and Ni metallic surfaces, the surface roughness improvements of up to 51.6% and 52 % were respectively obtained.

Keywords: laser micro polishing, scanning speed, energy density, surface roughness, laser spot

1. introduction

As a new technology in material surface processing, the laser micro polishing has played one important role in the precision machining of the material surface. As the development of the precision machine manufacturing technology, nanotechnology and MEMS manufacturing technology, the need for the degree of surface roughness of metal products and elements has been increasing all the time. Therefore, precision and super precision polishing technology for the metallic surface has become very important issue.

According to the interaction mechanism between material surface and laser, laser polishing could be divided into the laser cold polishing and laser thermal polishing. Laser thermal polishing generally uses the continuous laser or the pulsed laser, and through the thermal effects produced by the interaction between the material and the laser the surface layer of material is melted to obtain the polishing effect [1]. Especially the UV nano-second laser have been used for the precision and super-precision polishing of non-ferrous metal surfaces [2].

The factors such as the energy and wavelength of the laser beam, the pulse duration, the scanning speed and scanning method of the laser spot, and the characters of the material surface significantly affect the features of laser thermal polishing process [3-7].

The laser energy density directly affects the laser polishing effectiveness and efficiency in the laser micro-polishing process. In general, assuming the incident laser energy on the workpiece surface is constant, the laser energy density can be characterized by the laser spot size. Therefore, the focal offset which is the distance from the objective lens to the material surface is the fundamental factor for determination of the laser spot size [8].

In the Ref [9], using the laser energy density control by the control of the focal offset, the laser energy density to obtain the optimal polishing effect was investigated, and conducted the micro polishing experiments on the surface of stainless steel 316L and determined its optimum parameters.

In this paper, during laser micro polishing processing, the relationship between the scanning speed of the laser spot and the optimum energy density at the given optimal focal offset has been theoretically investigated. The experimental and analytical considerations about the scanning speed of laser spot were investigated. And the optimal parameters of the laser micro polishining for the surfaces of Ti and Ni were determined. Using the optimal parameters, the laser micro-polishing experiments on the surface of Ti and Ni were conducted, and the analysis of the results were discussed.

2. Laser energy density and scanning speed

During laser micro polishing processing, the appropriate selection of the laser energy density has become the most important factor affecting the quality of polishing, it is related to the incident laser energy, focal offset, and scanning speed on the workpiece surface.

When the mode of pulse laser is TEM_{00}, its energy density distribution on the workpiece surface is written as the following equation [9]:

$$\phi(r, \delta) = \frac{8f_0E_0}{\pi\omega_0^2\delta^2}\exp\left(-\frac{8f_0^2r}{\omega_0^2\delta^2}\right) \qquad (1)$$

where ω_0 is diameter of pulse laser beam before focused, δ is focal offset, r is distance from the laser spot center, f_0 is focal distance and E_0 is maximum energy of the laser beam which is irradiated on the workpiece surface.

From the analysis of the Eq. (1), the energy density on the workpiece surface is related to the distance from the laser spot center and the focal offset.

From the Eq. (1), when the foacl offset is constant, the energy density can be rewritten as follows:

$$\phi(r) = \phi_0\exp\left(-\frac{8r^2}{D^2}\right) \qquad (2)$$

where ϕ_0 is maximum energy density of the laser beam which is irradiated on the surface, D is diameter of the laser spot on the workpiece surface.

During laser micro polishing, especially in case of metallic surface, surface shallow melting (SSM) mechanism has particular deployment [9,10], and the threshold of laser energy density, which merely dissolves the surface without evaporation during micro polishing, is as follows:

$$\phi_{th} = \frac{8E_{th}}{\pi D^2} \qquad (3)$$

where E_{th} is pulse laser energy threshold in the laser micro polishing, is a constant for the material in the laser micro-polishing.

From Eq. (2) and Eq. (3), when the diameter of the fusion zone is d, it is expressed as

$$d^2 = 0.5D^2(\ln E_0 - \ln E_{th}). \qquad (4)$$

As can be known in Eq. (4), when a single laser pulse is irradiated on the workpiece surface and the laser spot size is constant, the relationship between the square of the diameter of fusion zone (d^2) and the logarithmic value of the irradiated energy ($\ln E_0$) is a linear proportion. From this relationship, we can obtain the diameter of the laser spot and the pulse energy theshold of laser micro polishing experimentally.

If the several laser pulses are irradiated in the same spot, the incubation effect [11] could be occured, and thus the laser energy density threshold is expressed as follows:

$$\phi_{th}(N) = \phi_{th}(1) \times N^{s-1} \qquad (5)$$

where $\phi_{th}(N)$ is the laser energy density threshold when N laser pulses are irradiated in the same spot, s is a constant related to the material, is called as incubation factor.

On the other hand, during the laser spot scanning on the workpiece surface, the optimal laser energy density depends on the scanning speed and overlap rate of the laser spot.

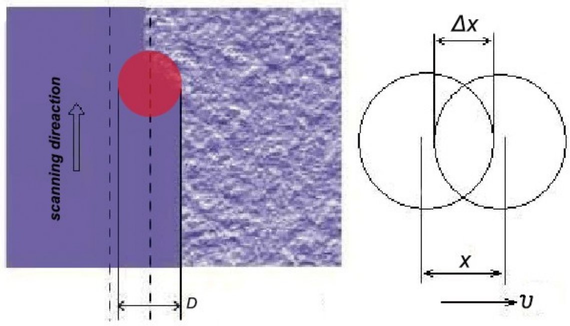

Fig.1 Schematic of laser spot scanning on the workpiece surface

Figure 1 shows the schematic of laser spot scanning on the workpiece surface during laser micro polishing processing, where D is diameter of laser spot on the workpiece surface, Δx is the length of the overlap portion of the adjacent two pulses in the scanning direction.

The overlap rate of the laser spot (Q_D) is written as follows:

$$Q_D = \frac{\Delta x}{D} = \frac{D - x}{D} \quad . \quad (6)$$

Therefore, when the repetition frequency of the laser pulse is F and the scanning speed of the laser spot is υ, Eq. (6) is rewritten as follows:

$$Q_D = \left(1 - \frac{\upsilon}{D \times F}\right) \quad . \quad (7)$$

From Eq. (7), The number N of laser pulses which are irradiated on the same point of workpiece surface can be expressed as follows:

$$N = \frac{d}{\upsilon/f} = \frac{1}{1 - Q_D} \quad . (8)$$

From Eq. (5) and Eq. (8), we can rewrite the laser energy density threshold of which the optimum polishing effect could be obtained as follows:

$$\phi_{opm} = \phi_{th}(1)\left(\frac{1}{1 - Q_D}\right)^{s-1} \quad . \quad (9)$$

3. Experiment and result

The used UV nano-second pulse laser is the high-power Q-Switched Ultraviolet Laser(AVI A355-3000) which has a wavelength of 355 nm, an average power of 3.0W, a pulse width of 40 ns, a beam diameter of 3.0 mm, and a TEM_{00}. The laser micro-polishing system used in the experiments had been introduced in the Ref. [9].

The workpieces are the planar surface shapes of pure Titanium(Ti) and pure Nickel(Ni), which has thickness of

1 mm and size of 1cm×1cm. These were polished by sandpaper in water, coarsely polished by flatting varnish and dried after washing with ethanol.

3.1 Laser energy density threshold for a single pulse laser

Based on Eq. (4), we can experimentally determine the threshold value of laser energy density when a single pulse laser is irradiated on a single spot for the given material.

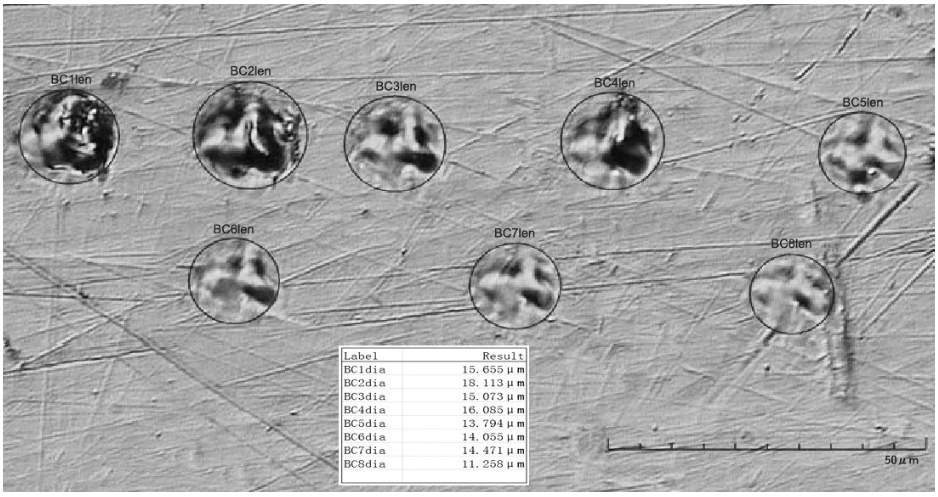

Fig. 2 The change of the fusion zone with laser pulse energy (Ti surface)

The change of the diameter of fusion zone with the varying single pulse laser energy was shown in Fig. 2 the size of the fusion zone is measured with 3D digital microscopy (KH-7700, 7000 times). In the experiment, the workpiece is Ti surface, the focal offset is 180 μm, and the diameter of the laser beam is 3 mm.

Based on the diameters of the fusion zone with different laser energy densities obtained in Fig.2, curve fitting is performed between the square of the diameter of the fusion zone and the logarithm of the pulse laser energy, and the relationship curve is obtained as shown in Fig.3.

The least squares fitting shows that these two parameters approximately satisfy the following linear relationship:

$$y = 582.6 \times x - 2908. \quad (10)$$

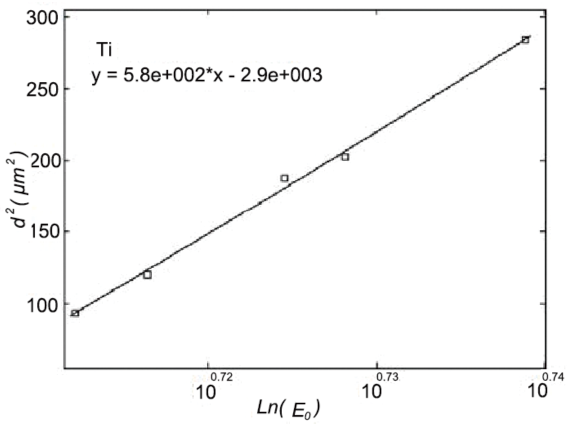

Fig.3 The relationship between the square of the diameter of the fusion zone and the logarithm of the pulse laser energy on the Ti surface

In the same way, we can obtain the change of the fusion zone according to the varying laser energy for Ni surface, the results were shown in Fig.4 and Eq.11.

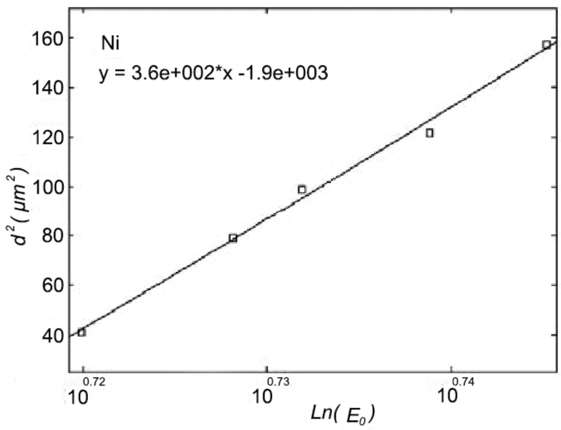

Fig.3 The relationship between the square of the diameter of the fusion zone and the logarithm of the pulse laser energy on the Ni surface

$$y = 362 \times x - 1856 \quad (11)$$

Therefore, when a single pulse laser is irradiated on the surface of Ti and Ni, the laser energy threshold and the diameter of the laser spot are obtained from the Eq. (4) and the empirical Eqs. (10) and (11) were obtained by the experiments, and the laser energy density threshold can be obtained as Table 1.

Table 1 the threshold value of single pulse laser energy density and incubation factor for Ti and Ni

Metallic material	Incubation factor	Laser energy density threshod (J/cm^2)
Ti	0.83[11]	0.36
Ni	0.72[11]	0.74

3.1 Optimum scanning speed of laser spot and overlap of laser scanning lines

It is possible to obtain the pulse laser energy density which can obtain the optimum micro polishing effect under the condition that the threshod value of the single pulse laser energy density is rated for the metal material. Although there is a direct correlation between the laser energy density and the spot size on the workpiece surface, but these two parameters can not be arbitrarily changed in the actual laser micro polishing. Because the laser energy distribution is Gaussian, the higher the laser energy, the higher the energy density gradient in the laser spot. Therefore, when the laser spot size on the workpiece surface becomes larger, the laser energy density distribution in the spot becomes more inhomogeneous, and the laser micro polishing quality also becomes decreased.

And the laser energy density for obtaining the optimum micro polishing effect is also related to the scanning speed of the laser spot.

The laser micro polishing experiments had been carried out for the Ti and Ni metal surfaces.

In Fig. 5 and Fig.6, the surface roughness is plotted for the scanning speed of the laser spot. In the experiments, the UV nano-second pulse laser (AVIA355-3000) mentioned above was used and the surface roughness was measured by the white interference microscope (WYKO NT9300: Veeco).

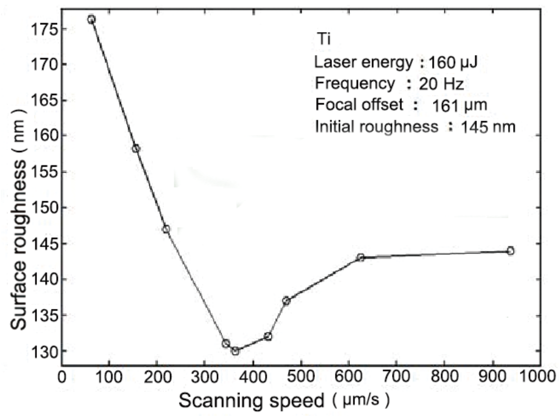

Fig.5 The change in surface roughness with thecchange in scanning speed for the Ti metal surface

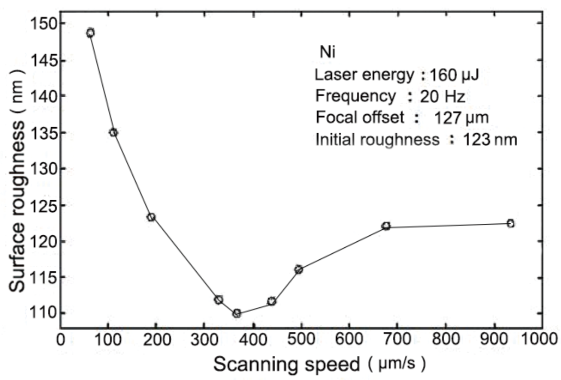

Fig.6 The change in surface roughness with thecchange in scanning speed for the Ni metal surface

As shown in Fig. 5 and Fig. 6, during the laser micro polishing for the Ti and Ni surfaces, the surface roughness changes with the change in scanning speed of laser spot, there is the scanning speed of which the best micro polishing result is obtained.

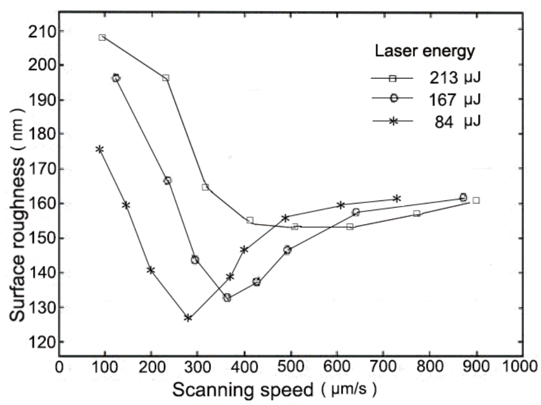

Fig.7 The change in surface roughness with the change in scanning speed and its ccoresponding pulse laser energy

Fig.7 shows the relationship between scanning speed and roughness for different laser energies (213μJ, 167μJ, 84μJ) on the Ti surface.

As shown in Fig. 7, if the laser energy is too large (213μJ), no matter how the scanning speed changes, satisfactory polishing results cannot be achieved. When the scanning speed is too small, although the surface roughness is further reduced, but the total polishing time would be increased and the mechanical properties of the material surface could be changed.

In general, the scanning speed of laser spot influences the micro-polishing effect by the overlap ratio of laser spot and the laser irradiation time. From the point of view of the laser micro polishing mechanism, during the laser micro polishing process, due to the effects of dynamic viscosity, surface tension, and gravity, the mass flow occurs in the fusion region within a short time, and then its mass flow is solidified to eliminate the surface asperities. When the pulse laser energy does not change, the mass flow characteristics of the fusion are related to the viscosity of the liquid phase, the liquid surface tension, the size of the fusion zone, the melting time, and the geometry of the surface. Therefore, if the repetition frequency of the pulse laser is not changed, the size of the fusion zone and the melting time are related to the laser pulse width and the scanning speed. The longer the irradiation time, the higher the temperature in the fusion zone, the viscosity of the fluid becomes smaller, and the flow velocity of the fluid becomes larger. During the laser micro polishing, especially for metal materials, the solidification rate in the fusion zone is very fast. When the pulse laser of which width is several tens of nanoseconds or less is used, the interaction time between the surface material and the laser is very short. If the scanning speed is too high, the solidification phenomenon occurs before the mass flow in the fusion zone is completely balanced, this will reduce the micro-polishing effect. And when the melting time is too long (the scanning speed is too low), the number of laser pulses irradiating the same fusion zone would be increased; the evaporation of the surface material may occur because the temperature rapidly increased; sequentially the surface roughness be increased. Therefore, during laser micro polishing, there is the laser spot scanning speed which can obtain the best polishing effect when laser energy and the surface material are rated.

In the experiments, the laser energy is 160 μJ, the repetition frequency of pulse laser is 20 Hz. And the focal offset is 161 μm, and the initial surface roughness (Ra) is 145 nm for the Ti surface; the focal offset is 127 μm, and the initial surface roughness (Ra) is 123 nm for the Ni surface.

The scanning speed which can obtain the best polishing effect is 355 μm / s for Ti and 363 μm / s for Ni in this experiment.

On the other hand, the overlap ratio of the scanning lines also has a certain influence on the micro polishing effect when the laser beam is scanned.

After conducting laser micro polishing on Ti surface at different overlap ratios of the scanning lines, the surfaces were measured using the white interference microscope, the results were shwon in Fig.8. In Fig. 8, a), b), c), and d) show the shape change and roughness of the surface when the overlap rates of the scanning lines are 0.4, 0.5, 0.6 and 0.7, and the surface roughness(Ra) is 132.52 nm, 117.23 nm, 98.25 nm, and 81.35 nm, respectively.

As shown in Fig. 8, when the overlap ratio is 0.7, the surface roughness (Ra) is the smallest as 81.35 nm. The initial roughness of the Ti surface used in the experiment is 145 nm.

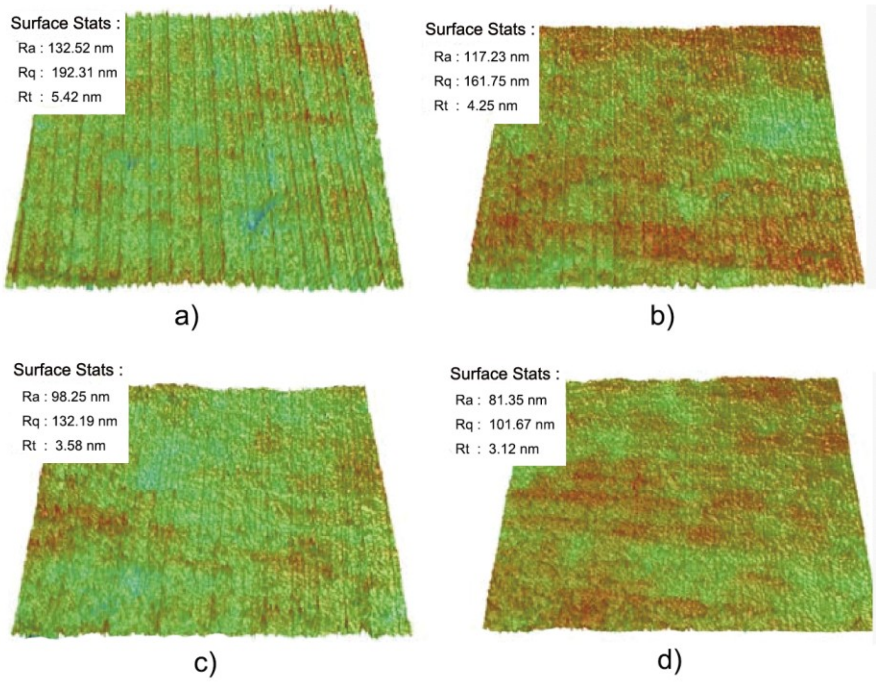

Fig.8 Influence of scanning lines overlap ratio

Comprehensive analysis of the experimental results shows that the process parameters for obtaining the best micro-polishing effect when the Ti and Ni surfaces are polished with the UV nano-second pulse laser (wavelength: 355 nm, pulse width: 40 ns) are shown in Table 2.

Table 2. The optimal process parameters for the laser micro polishing of Ti and Ni surface

Metallic material	Laser energy density threshod (J/cm^2)	Optimum laser energy density (J/cm^2)	Scanning speed (μm/s)	Focal offset (μm)	Pulse rate (Hz)	Overlap rate of scanning lines
Ti	0.36	0.28	355	161	20	0.7
Ni	0.74	0.59	363	127	20	0.7

3.3 Laser micro polishing for the Ti and Ni metal surface

The experiments of laser micro polishing for the Ti and Ni metal surface were carried out based on Table 2. No gas was used in the experiments.

After carrying out the laser micro polishing, the results were measured and analysied by using the scanning electron microscope XL-30 and the white interference microscope.

Figure 9 shows the SEM image before (a) and after (b) the laser micro-polishing of the Ni surface.

From measurement and analysis with the white interference microscope, the surface roughness (Ra) of Ni surface decreased from the initial 123.71 nm to 64.52 nm, thus the reduction rate was 52%.

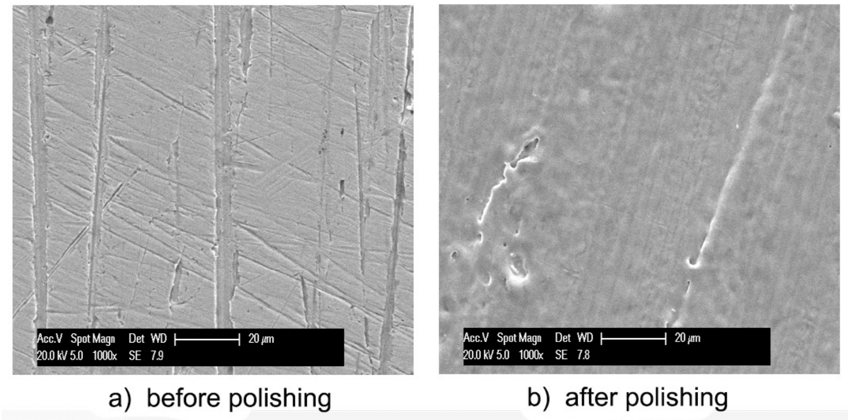

Fig.9 The SEM image before (a) and after (b) the laser micro-polishing of the Ni surface

Figure 10 shows the result of measurement with white interference microscope after the laser micro-polishing of the Ti surface.

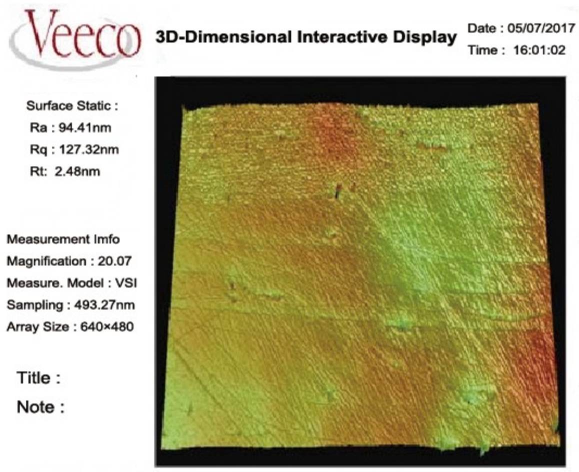

Fig. 10 The result of measurement with white interference microscope
after the laser micro-polishing of the Ti surface

As shown in Fig. 10, the difference of micro asperity in the top and bottom of the image is remarkable. Here, the top portion is not polished, and the bottom is polished.

From measurement and analysis with the white interference microscope, the surface roughness (Ra) of Ti surface decreased from the initial 145.18 nm to 81.25 nm, thus the reduction rate was 56%.

4. Conclusions

In this paper, the influence of laser spot scanning speed on the micro polishing effect is investigated in terms of the relationship with the laser energy density during micro-polishing on the metallic surface by using UV nanosecond pulse laser.

The Experiments had been conducted to reveal the relationship between the scanning speed of laser spot and the surface roughness. The experimental and analytical considerations were shown that there is the optimal scanning speed for the best polishing effect when the laser energy density on the workpiece surface was rated, and the influence of the overlap ratio of scanning lines was also considered.

The optimal process parameters for the laser micro polishing were obtained for Ti and Ni metallic surfaces.

The laser micro-polishing experiments on the surface of Ti and Ni were conducted. The roughness measurements show the roughness reduction of 55.6 % for the Ti and of 52 % for the Ni.

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