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Surface & Coatings Technology 197 (2005) 77–84
SURFACE & COATINGS TECHNOLOGY
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An approach to modelling of laser polishing of metals

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Received 8 March 2004; accepted in revised form 13 January 2005
Available online 19 February 2005

Abstract

Based on heat transfer analysis and the consideration of the evaporation of surface asperities, a simplified model for laser surface polishing was established. As the dimension of asperities is usually in the scale of sub-micron, the model thus assumed uniform temperature over and in an asperity entity and the heat transfer could thus be treated as a point unit problem. The model aimed at preliminary prediction of the adequate setting of the processing parameters (typically the laser irradiation time) for laser polishing of a metal with known geometric surface consisting of micro-asperities and material properties. Prediction for polishing metallic materials of Fe, Al, Ti, and the 304 stainless steel showed the temperature rise in asperity varying significantly with the original surface topography of the substrates. Results indicate that, for the polishing of most metals with pulsed laser, laser with short pulse duration normally in the range of nano-second or less is required. Laser polishing of steel using a KF excimer laser with the pulse duration of 30 ns was subsequently performed. Characterizing the irradiated surface morphology by scanning electron microscope (SEM) and atomic force microscope (AFM) showed evident improvement in surface finish of the tested specimens.

Keywords: Laser polishing; Metal; Physical model; Surface roughness; Thermal analysis

1. Introduction

Laser can be used to produce desired surface morphology of some materials, typically: laser polishing and laser texturing. The purpose of laser polishing is to decrease the surface roughness, while laser texturing is to produce the desirable surface textured patterns, in which the surface roughness may be increased or decreased. Laser polishing is quite a new technique developed in recent years, and appears as an attractive alternative to supplement the deficiency of those conventional abrasive methods since it is a non-contact process and would facilitate the automation of the polishing process [1]. Up to now, laser polishing was mainly used for the polishing of diamond [2–13], optical articles such as glasses, lens, fibers and etc. [14–18], and was seldomly used for polishing metals. As metals are important engineering and constructural materials for making mechanical and structural systems in the industry, the advantageous manner of laser polishing will surely find its useful applications in engineering the surface of many metallic components. For example, laser polishing may be developed to improve the surface finish of deep and small blind-holes of mould cavities for the mold making industry. Unfortunately, studies on laser polishing of metallic materials are still very much lacking. The report of the polishing phenomenon of titanium implant material by Bereznai et al. [19] is a typical literature currently available. Systematic and logical investigation of laser polishing of metals still awaits to be explored.

Laser polishing is a complex thermodynamic process involving material properties, surface geometry, and interaction between laser and materials and their individual thermal phenomenon, etc. The two kinds of mechanisms dominating the laser polishing process are (i) the evaporation of surface material [20] and (ii) the flowing or flattening of softening and melting material under the effect of surface tension [1]. It is almost impossible to establish an ideal model to take all the complexity in the real operational

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doi:10.1016/j.surfcoat.2005.01.010

conditions into consideration. For example, a correct description of the morphology of three-dimensional surface still remains very difficult [21]. The complication of the variation of material properties such as conductivity, specific heat, as well as latent heat of fusion and of vaporization with respect to temperature in laser treatment process makes their determination difficult and inaccurate. Subsequently, the quantitative analysis of laser polishing process, especially when surface morphology is taken into account, seems either exhaustic or almost impossible. However, establishing a simplified model so as to approximate the real operational conditions is beneficial in reducing a vast number of trial and error in experimental approaches. By doing so, it allows the basic criteria influencing the operating parameters to be evaluated so as to guide the parameters selection of the real laser polishing process. For such purpose, adequate simplifications can be made in establishing the necessary model.

In most other laser processing technologies, surfaces are considered absolutely smooth when studying the interaction between laser and materials since their surface roughness is usually in micro-scale that is normally insignificant to affect the quality of an operation. As laser surface polishing mainly concerns the change of material surface, it is always in the scale of surface roughness and is usually in the regime of sub-micron. It is therefore important to study the interaction between laser and surface micro-asperities as well as their relevant thermal processes between a surface and its conjoint substrate.

This paper simplifies surface asperities on substrate as the constituent of three common types of asperity models that is commonly used in available literature of tribology investigations. It then establishes a simple mathematical model, based on the heat balance theory, for predicting the laser fluence to improve the surface finishing of metallic substrate. Parameters predicted from the model have been used to polishing steel using a KF excimer laser with a pulse duration of 30 ns that was subsequently performed. Characterizing the irradiated surface morphology by scanning electron microscope (SEM) and atomic force microscope (AFM) showed an evident improvement in surface finish, supporting the applicability of the model for guiding the operation of laser polishing of metals.

2. Modeling

2.1. Assumptions

Considering a rough surface distributed with asperities irradiated by a laser beam as shown in Fig. 1, the maximum height between peak and valley of its surface asperities is R_{max}. To facilitate the analysis, the following simplifications and assumptions are made:

a. The distribution of the input laser energy is uniform within the spot area.

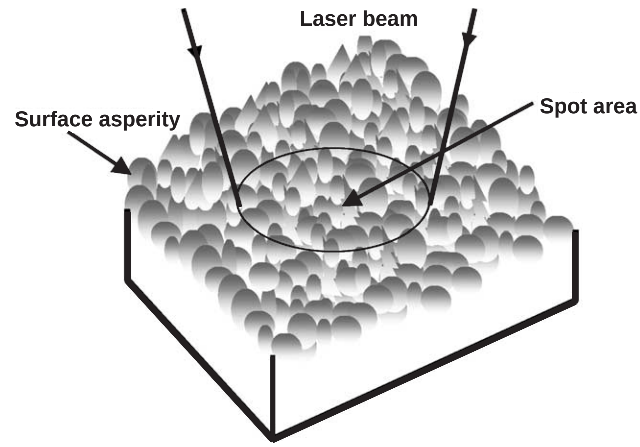

Fig. 1. Laser irradiation of a rough surface distributed with asperities being irradiated by laser.

b. The absorption of the materials to laser remains unchanged and uniform throughout the processing conditions.
c. Radiation and convective heat transfer from the spot to its vicinity during laser processing is negligible.
d. The chemical process effect, such as oxidation, during laser-material interaction can be neglected.
e. The thermal parameters of material always remain constant in the process.
f. The defocusing effect resulting from the surface roughness is negligible and can be ignored.

2.2. Single asperity model

A material surface is usually composed of a large number of surface asperities. In the analysis of laser surface polishing, an incident laser beam is assumed to irradiate onto all the asperities simultaneously within the spot area. Practically, the surface morphology of metals as produced by most of the rough machining processes like turning, milling and planning, etc., changes approximately in a periodical mode with largely similar asperities. In such a case, the surface can be approximately treated as an ideal one, in which all the asperities are regularly distributed in the laser spot area and have the identical shape and height. Supposing there is no interaction between asperities during laser irradiation, the input laser energy density is the same as the individual one. Naturally, assumptions in Section 2.1 allow one to firstly focus on studying the behavior of a single asperity under the irradiation process of a laser.

Consider the case of a typical single asperity and its conjoint substrate area as shown in Fig. 2, in which the associated parameters are defined as:

h Height of asperity
A_0 Area of asperity in the cross section at the bottom z=0
V_0 Volume of the integrity asperity corresponding to A_0

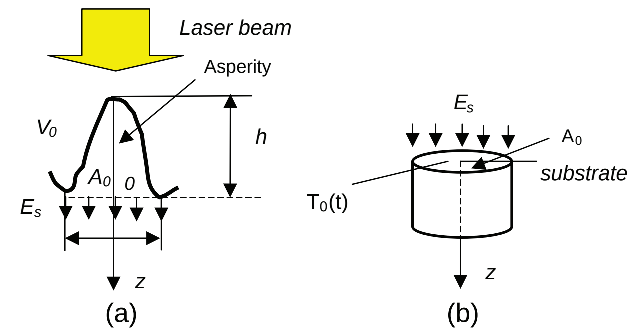

Fig. 2. A typical asperity irradiated by laser beam.

E_s Energy transmitted to the underlying substrate by conduction

$T_0(t)$ Temperature at z=0.

The laser energy absorbed Q_i by the asperity surface is supposed to be completely coupled with the material and transformed into heat which (i) partly raises the temperature of the asperity, and (ii) is partly transferred to the underlying substrate by conduction. As the dimension of asperity is usually in the scale of sub-micron, the temperature rise T=$T_0(t)$, i.e. beyond its initial ambient temperature $T_a(t)$, e.g. $T_o(t)$=$T(t)-T_a(t)$, is reasonably assumed uniform and identical over and in the whole asperity. The heat transfer problem could therefore be treated as a point unit and as one-dimensional. The temperature rise in the asperity under the laser fluence E_i can subsequently be formulated as:

$$T_0(t) = \frac{Ak_1E_iA_0}{\rho cV_0} - \frac{E_s}{\rho cV_0} - \frac{L_f + L_v}{c} \tag{1}$$

$L_f = 0$ and $L_v = 0$ for $T_0(t) < T_{mp}$

$L_v = 0$ for $T_{mp} \leq T < T_{vp}$

where: A is laser absorbtivity of the irradiated material; K_1 is laser reflective factor between asperities on material surface topography $k_1 \geq 1$; E_i is energy density in the irradiated spot area; T is laser irradiation time (pulse duration for pulsed laser irradiation); ρ is specific density of the material; c is specific heat of the material; L_f is latent heat of fusion; L_v is latent heat of vaporization; T_{mp} is temperature of melting point; T_{vp} is temperature of evaporating point.

Let the depth of heat conduction from the root of an asperity to the underlying substrate be z (Fig. 2b), the energy E_s transmitted to the substrate is thus a function of temperature $T_0(t)$ and time t. This energy E_s, by Carslaw and Jaeger [22], can be described by one-dimensional heat transfer equation as:

$$T_0(t) = \frac{E_s}{A_0\lambda t}\frac{\sqrt{4\alpha t}}{\sqrt{\pi}} \tag{2}$$

Alternatively as:

$$E_s = A_0\lambda\sqrt{\frac{\pi t}{4\alpha}}T_0(t) \tag{3}$$

where: α is the thermal diffusivity, and λ is the thermal conductivity of the material. Substituting Eq. (3) into Eq. (1) thus gives:

$$T_0(t) = \frac{Ak_1E_iA_0}{\rho cV_0} - \frac{A_0\lambda\sqrt{\frac{\pi t}{4\alpha}}T_0(t)}{\rho cV_0} - \frac{L_f + L_v}{c} \tag{4}$$

Eq. (4) can be rewritten as:

$$\begin{aligned} T_0(t) &= \left(\frac{Ak_1E_i}{\rho c}\frac{A_0}{V_0} - \frac{L_f + L_v}{c}\right) \Big/ \left(1 + \frac{\lambda}{\rho c}\sqrt{\frac{\pi t}{4\alpha}}\frac{A_0}{V_0}\right) \\ &= \left(\frac{Ak_1E_i}{\rho c}\frac{A_0}{V_0} - \frac{L_f + L_v}{c}\right) \Big/ \left(1 + \sqrt{\frac{\pi\alpha t}{4}}\frac{A_0}{V_0}\right) \end{aligned} \tag{5}$$

Following the assumptions in Section 2.1, the keeping of the parameters A, ρ, c, L_f and L_v for the irradiated material constant means that the rise in temperature varies mainly with: (i) the energy density E_i, (ii) the irradiation time t, and (iii) the ratio of A_0/V_0 that is the geometrical character and represents the shape of the asperity. The values of A_0/V_0 for the several typical asperity models that are commonly used in tribological investigations are tabulated in Fig. 3.

The main concern for laser polishing a surface of metals is the minimum energy density required to evaporate or melt

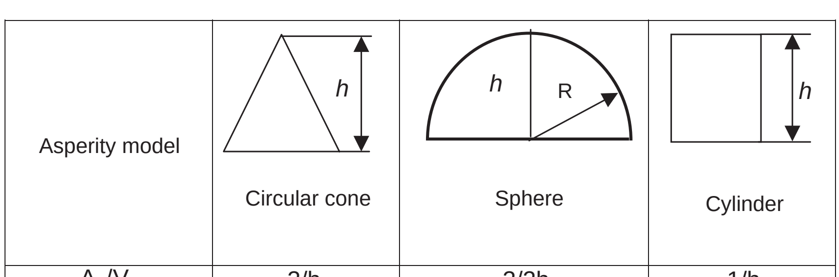

Fig. 3. A_0/V_0 of the typical asperity models commonly used in tribological investigations.

the individual asperity. Consequently, Eq. (5) can be re-expressed as:

$$E_{\mathrm{i}} = \frac{T_0(t)\left(1+\sqrt{\frac{\pi\alpha t}{4}}\frac{A_0}{V_0}\right)+\frac{L_{\mathrm{f}}+L_{\mathrm{v}}}{c}}{\frac{Ak_1}{\rho c}\frac{A_0}{V_0}}$$

$$= \frac{T_0(t)\rho c}{\frac{A_0}{V_0}Ak_1} + \frac{T_0(t)\rho c}{Ak_1}\sqrt{\frac{\pi\alpha t}{4}} + \frac{(L_{\mathrm{f}}+L_{\mathrm{v}})\rho}{Ak_1\frac{A_0}{V_0}} \tag{6}$$

As shown in Eq. (6), the minimum energy density E_{i} is composed of three constituents: (i) the energy supply to raise the asperity to the temperature $T_0(t)$, (ii) the energy transmitted to the underlying substrate; and (iii) the energy absorbed as the latent heat during evaporation or/and fusion of the material. Eq. (6) also illustrates that the E_{i} varies with the asperity shape factor of material surface and is a parabolic function of the laser irradiation time.

2.3. Criterion of laser polishing

For a given surface topology, its finish can be improved when the peak of its asperities is suitably removed. The essence of laser polishing is thus to utilize laser heating in removing or reducing the height of the surface asperities by melting or evaporation. Under the irradiation of a laser, the asperity temperature changes continuously from its surface to its underlying substrate. Evaporation or melting of the surface asperities generally causes the temperature rise of underlying substrate material, which leads to change in material properties and/or recursively affects the surface roughness. When the depth of evaporation/melting is large enough and the temperature rise is sufficiently high, such change and effect will become very complex that may lead to the surface roughness becoming uncontrollable. The disappearing of asperities and the truncation of asperity height, as a result of evaporation and/or melting in the process of laser polishing, are likely to decrease the surface roughness, whilst the phase transformation or fusion of underlying substrate materials due to temperature rise may roughen the surface instead. These two major phenomena are likely to occur simultaneously in the course of laser irradiation. Subsequently, the roughening or smoothening of an irradiated surface is determined by whichever the phenomenon is predominant.

When a metal, under the irradiation of a laser beam, reaches either temperature regimes of (a) $T<T_{\mathrm{mp}}$, (b) $T_{\mathrm{mp}} \le T < T_{\mathrm{vp}}$ and (c) $T_{\mathrm{vp}}<T$ (where T_{mp} is the melting point and T_{vp} is the evaporating point of the material), a corresponding phase-change for that regime is expected. Since the temperature of asperity in the first regime [i.e. case (a)] is less than the melting point of the material, the possible alteration of surface roughness may be mainly owing to the surface tension that is likely caused by interior thermal stress and the allotropic phase transformation of the asperities. The influence of such change on the surface roughness is usually insignificant [23].

The temperature in the second regime [i.e. case (b)] is between the melting point and the evaporating point of the material. Melting of asperities thus occurs, and surface roughness changes as a result of the flow and re-solidification of the material [24]. When the melting is just confined within the asperities, surface polishing is likely to take place. When temperature exceeds the evaporation point as the third regime of case (c), asperity is evaporated and the temperature of its underlying substrate likely exceeds the melting point, causing flow or/and re-solidification. Under case (c), surface roughness mainly changes with the melting depth of the underlying substrate. Theoretically, decreasing surface roughness occurs when such a melting depth is less than that of the height of the original asperity, which can be set to satisfy the following temperature condition:

$$T(z_0,t)<T_{\mathrm{ml}}$$

that can be rewritten as:

$$\frac{T(z_0,t)}{T_0(t)}<\frac{T_{\mathrm{ml}}}{T_{\mathrm{vp}}} \tag{7}$$

in which z_0 is the melting depth into the substrate material from the surface of asperity root.

The above analysis suggests that there exist two kinds of laser polishing mechanisms: (a) evaporating and/or (b) melting of surface asperity. When no heat loss occurs, the input laser energy for either mechanism should be completely absorbed by the surface asperities and has magnitude just equal to that for vaporizing or melting the asperity. Practically, energy loss due to heat conduction means the energy input always beyond the range required for polishing the surface roughness. For obtaining a satisfactory polishing quality, the minimal energy should be allowed transmitting to the substrate and the temperature gradient between asperities and substrate should be as large as possible. For a material with given asperity shape, Eq. (6) indicates that the dominant parameter governing the energy being transmitted to the substrate is mainly the irradiation time (or the pulse duration) of the pulse laser used. Generally, shorter the irradiation time means less the energy transmitted to the substrate.

According to Carslaw and Jaeger [22], the ratio of the instantaneous temperature of substrate at the depth z from asperity root to the surface temperature $T_0(t)$ can be calculated by:

$$\frac{T(z,t)}{T_0(t)} = e^{-\left(\frac{z}{\sqrt{4\alpha t}}\right)^2} - \sqrt{\pi}\frac{z}{\sqrt{4\alpha t}}erfc\left[\frac{z}{\sqrt{4\alpha t}}\right] \tag{8}$$

As can be seen from the above equation, the ratio $T(z,t)/T_0(t)$ that is assumed independent of the intensity of the energy input, is essentially a function of the following: (i) the depth z from the asperity root, (ii) the irradiation time t

Table 1
Thermal parameters of some commonly used metallic materials [20]

Material	Absorptivity A	Density ρ (g/cm^3)	Thermal conductivity λ (W cm^{-1}K^{-1})	Specific heat c (J g^{-1}K^{-1})	Thermal diffusivity $\alpha=\lambda/\rho c$ (cm^2 s^{-1})	Latent heat		Melting point T_{mp} (K)	Evaporation point T_{vp} (K)	T_{mp}/T_{vp}
						L_f (J g^{-1})	L_v (J g^{-1})			
Al	0.1	2.7	2.26	0.9	0.93	397	9492	933	2723	0.34
Ti	0.4	4.5	0.19	0.52	0.08	437	9000	1941	3533	0.55
Fe	0.4	7.8	0.5	0.46	0.14	275	6362	1809	3273	0.55
304 Stainless steel	0.4	8.0	0.2	0.5	0.05	300	6500	1728	3273	0.53

of the laser, and (iii) the thermal diffusivity of the material. For a given material, Eqs. (6) and (8) can be used for plotting various operational curves to facilitate the setting of processing parameters for generating relatively good quality polishing using a pulse laser.

3. Prediction for some commonly used metallic materials

Using those thermal parameters as tabulated in Table 1 for Fe, Ti, Al and 304 steel, behaviour of any one of the processing parameters with others being kept constant was plotted in Figs. 4–9. The prediction assumes that there is not any laser reflection between asperities, i.e. k_1=1 in Eq. (6).

Figs. 4 and 5 were the prediction results for polishing Fe material. Fig. 4 showed the minimum energy density E_i required to evaporate the asperities of the three individual shapes shown in Fig. 3, whilst Fig. 5 showed the corresponding E_i value for evaporating cylindrical asperities of different heights. Fig. 6 was the predicted minimum energy density E_i required for evaporating a cylindrical asperity of the four different materials of 0.1 μm in height. Results showed that, for a given asperity shape, the energy required to achieve the polishing effect varies with the materials, and the E_i value generally decreases with the irradiation time t. Their level (Fig. 6) differs with the thermal parameters of the materials. Prediction (Figs. 4–6) also clearly affirms that, for a given material, the parameters determining the required energy are the laser irradiation time and the original geometric charaters of the asperity. But, the influence of t on E_i is negligible at small value of t (see the slope of the curves in the range of 10^{-13} s$\leq t \leq 10^{-8}$ s; Figs. 4–6). The sharply increasing slope of the curves (Figs. 4–6) for $t>10^{-8}$ s implies that the E_i is very sensitive to the irradiated time t (pulse duration of pulse laser), which makes the control of the process relatively difficult. The curve for Al material with relatively smallest E_i values for $t<10^{-10}$ s and its very sharp slope steeper than the rest of the metals (Fig. 6) for $t>10^{-9}$ s indicate that it is more difficult to select and control laser in irradiating Al than Ti, 304 steel, and Fe when being polished with pulse duration or irradiation time above 10^{-9} s. Prediction results (Figs. 4–6) suggest that pulse laser with short pulse durations, normally in the range of nano-second or less, are more suitable for use in polishing most of metallic materials.

Fig. 7 shows the variation of the temperature gradient, which is the ratio $T(z,t)/T_0(t)$ of the temperature at different depths to the surface temperature, from the surface to its substrate. It illustrates that the ratio, for a given depth,

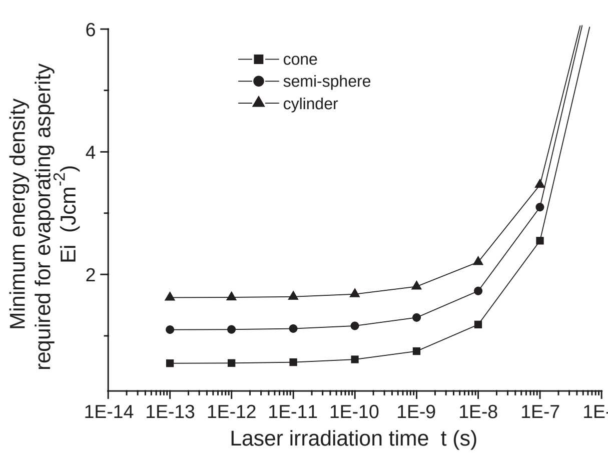

Fig. 4. Correlation between laser irradiation time and the energy density required for evaporating asperities with different shapes (asperity height 0.1 μm).

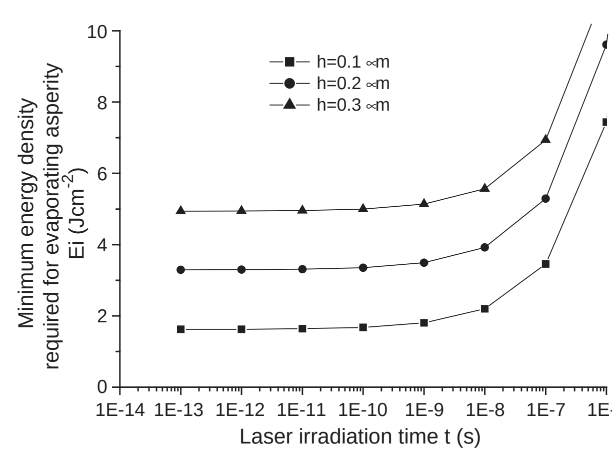

Fig. 5. Correlation between the energy density required for evaporating cylindrical asperities with different heights.

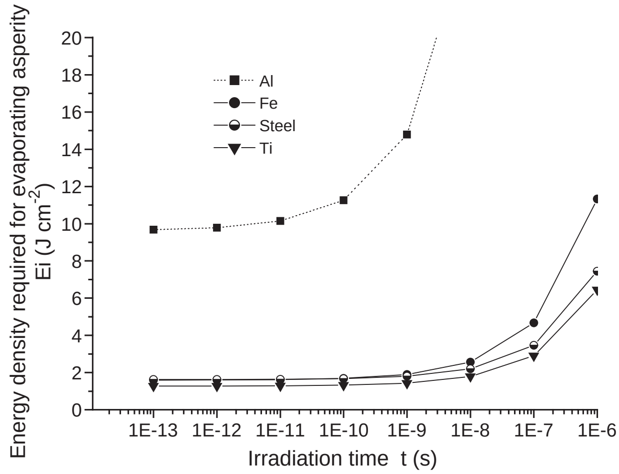

Fig. 6. Correlation between the energy density required for evaporating cylindrical asperities of different materials (asperity height 0.1 μm).

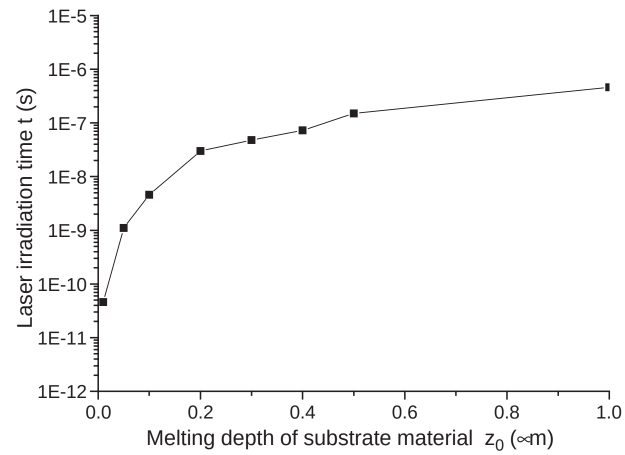

Fig. 8. Variation of the melting depth with irradiation time corresponding to $T(z_0,t)/T_0\ (t)$=0.55.

increases with increase of the irradiation time. Theoretically, to obtain a polished surface by means of evaporizing the surface asperity, the melting depth of the underlying substrate material must be kept in the range of the asperity height (Section 2.3) so as to satisfy the condition stipulated in Eq. (7). The relationship between the maximum melting depth z_0 and the irradiation time t for accomplishing $T(z_0,t)/T_0(t)$=0.55 in irradiating Fe material was shown in Fig. 8. Using the data from the figure, the maximum irradiation time in a laser polishing process for achieving the corresponding maximum melting depth can be evaluated. For example, the laser irradiation time t has to be shorter than 2 ns so as to ensure the melting depth being less than the original asperity height of 0.1 μm to be evaporized. While t is shorter than 35 ns for adequately polishing the original asperity height equal to 0.3 μm. The correlation of the temperature gradient to irradiation time for the different metallic materials of 305 steel, Ti, Fe and Al was shown in Fig. 9. It is observed that the minimum laser irradiation time is proportional to the thermal diffusivity of the materials as can be seen in Table 1.

4. Discussion

4.1. On the modeling

Physically, mechanisms involved in laser irradiation are very complicated. The evaporation of asperity material is likely to bring the laser beam closer to the underlying substrate that is then directly irradiated and subsequently leads to complex heat transfer and material transformation problems. However, the formation of plasma vapor may deplete the laser energy arriving at the substrate, etc. Modeling the associated phenomena in relation to the original surface morphology of the substrate and its change during and after irradiation is complicated and exhausting, which may not be economical and worthy of pursuing. The simplified model proposed in Section 2 and predictions in

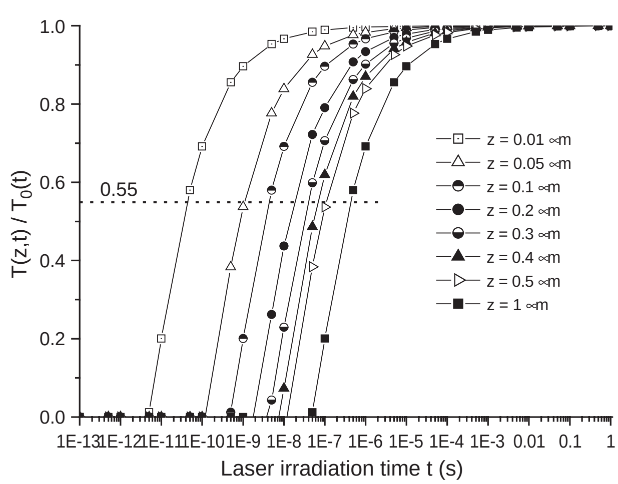

Fig. 7. Ratio $T(z,t)/T_0(t)$ versus irradiation time t for laser polishing Fe material.

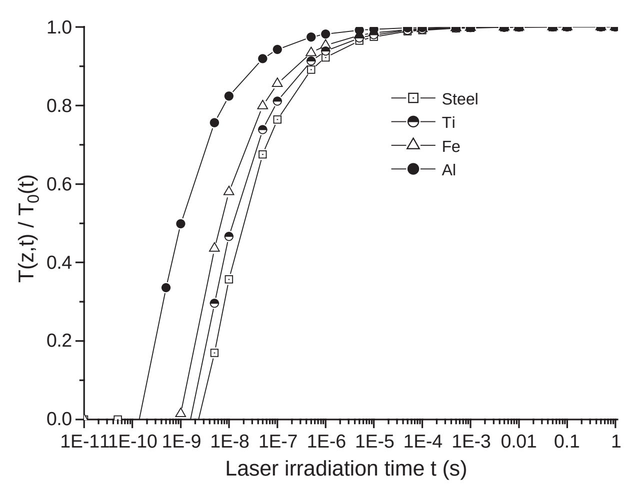

Fig. 9. Ratio $T(z,t)/T_0(t)$ versus irradiation time t for laser polishing different metallic materials with z=0.1 μm.

Section 3 only serve to provide some guidance in selecting laser setting parameters for achieving the polishing effect of a laser irradiated surface. The energy density in Figs. 4–6 represents the lower bound of the required value required for the polishing processing. As (i) asperities on surface are in micro-scale and (ii) laser energy intensity is very high, the assumption of uniform temperature $T_0(t)$ throughout the entire body as under irradiation should be reasonable. Practically, high laser energy intensity is likely to melt/evaporate asperities rapidly so that the time for the heat transfer to the vicinity of the asperities is short. Hence, a one-dimensional heat transfer model would be acceptable. Theoretically, asperities start to evaporate as $T_0(t)$ reaches the evaporation temperature T_{vp} and the underlying substrate melts when its corresponding temperature $T(t)$ is at the melting point T_{mp}, subsequently the control of laser setting for the maximum allowable depth z_0 can be governed by Eq. (7) with the known relevant thermal parameters (Table 1). Then, the irradiation time (pulse duration of laser) can be determined by Eq. (8) and subsequently E_{i} from Eq. (6). To reduce the effect of material transformation, melting and evaporation on the surface roughness, the value of z_0 should be as small as possible. This implies that the irradiation time t (pulse duration) must also be sufficiently small.

4.2. Regular surface

Since most of the available rough machining processes of metals (such as turning, milling and planning) produce surface morphology approximately in a periodical mode and largely similar asperities, the machined surface can thus be approximately treated as regularly distributed ideal-asperities that have the identical shape and height, as any one shown in Fig. 3. Furthermore, the assumption of free interaction between asperities during laser irradiation implies that the uniform and identical input laser energy density over any individual irradiating spot is reasonable.

4.3. Irregular surface

Some surfaces, especially machined by precision machining, in some applications, normally have dissimilar asperities of various shapes and heights. The assumption of a single asperity in the present analysis suggests that the temperature rise of an asperity, under a given laser operational condition, is proportional to its A_0/V_0 ratio (i.e., a high ratio of A_0/V_0 implies a high temperature—see Sections 2.1 and 2.2). As the ratio A_0/V_0 decreases with the height of asperity (Fig. 3), temperature for a "short" asperity is usually higher than that for a "tall" one. Under the improper setting of laser parameter, the "shorter" asperities may be completely evaporated/melted while their "taller" counterparts may just be partially removed (or may still remain intact), which is the undesirable processing condition likely to occur. Hence, ablation of asperities with lowest ratio A_0/V_0 is of prime importance in determining the required laser processing parameters.

4.4. Influence of materials

The ratio $T_{\mathrm{mp}}/T_{\mathrm{vp}}$ and the laser absorbtivity are different from material to material, subsequently differing from the setting condition for laser processing parameters. Moreover, thermal parameters of the materials like the thermal diffusivity are the main factors determining the temperature gradient (Fig. 9 and Table 1). The prediction (Figs. 4–9) shows that it is necessary to keep the laser irradiation time (pulse duration for pulsed laser) below a critical value in order to obtain an anticipated temperature gradient in the underlying substrate material. Since pulse duration is generally related to the type of laser, its magnitude can be treated as the basis for selecting laser equipment.

5. Experimental result

An as-machined DF-2 cold work steel block with measured surface roughness of 0.14 μm was processed by an LPX305iF 248 nm KF excimer laser with the pulse duration set at 30 ns. The other processing parameters were set as repetition rate 5 Hz, scanning velocity 2 mm/min, pulse energy 1015 mJ, laser spot diameter 0.2 mm approximately. SEM micrographs of (a) the as-machined surface and (b) the laser irradiated area are illustrated in Fig. 10. The results showed that those scratches as measured with intervals of approximately 5 μm on the as-machined surface

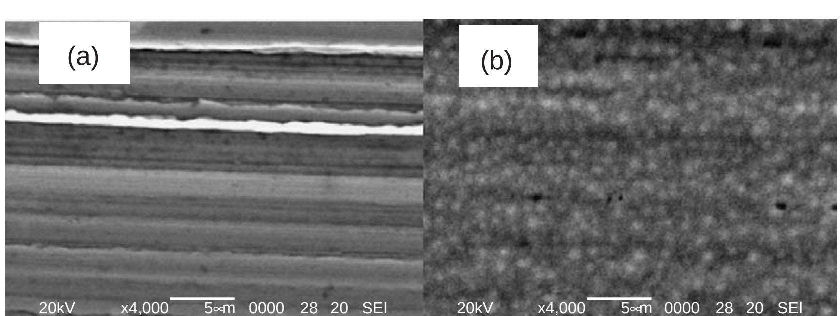

Fig. 10. SEM micrographs of (a) original surface and (b) laser irradiated area.

(Fig. 10a) disappeared on the counterpart surface that was significantly improved after laser irradiation (Fig. 10b). The latter surface (Fig. 10a) was obviously smoother. The surface roughness as measured by AFM gave R_a value for the laser-polished surface as 99.5 nm. The results are quite comparable with the results obtained by Bereznai et al. [19] who used a 193 nm KrF excimer laser with pulse duration of 18 ns to irradiate titanium discs.

6. Method and steps of laser parameter setting

The purpose of the theoretical analysis aims at providing a method to guide parameter setting for practical applications. As the main parameters for laser polishing are the laser energy density E_i and the laser irradiation time t, the selection of these parameters are considered in the proposed model. According to the approaches and assumptions in Section 2, the method and steps for selecting the setting of laser parameters for polishing could be as follows:

a. First, determine the original geometric characters of the surface asperities using surface profile-meter and/or corresponding apparatus.
b. Second, determine the thermal parameters of the surface material.
   – For most metallic materials, their thermal parameters are well known from available materials handbooks. Subsequently, the selection of proper values, according to the status of the surface materials, is crucial.
c. Third, use Eqs. (7) and (8) to determine the maximum laser irradiation time.
d. Fourth, use Eq. (6) to calculate the magnitude of the required energy density of the laser used.
e. Fifth, irradiate the specific metallic material according to the settings determined in (c) and (d) above.
f. Sixth, repeat the measurement in (a) above for the irradiated surface and select the matching geometric character of the surface asperities from Fig. 3. Repeat (b) to (e) until the anticipated surface finish of the material is achieved.

7. Conclusions

1. The original geometrical characters of surface micro-asperity have significant effects on laser surface polishing of metals.
2. For a given material with known surface geometrical characters, the most important parameter determining the polishing process is laser irradiation time. For polishing most metallic materials with pulsed laser, it is necessary to use short pulse laser with pulse duration in the range of or below nano-second scales.
3. A method was introduced for guiding the setting processing parameters in laser polishing of metals. Theoretically, it is easy to set up the laser processing parameters for laser polishing operation once the surface parameters and the material properties of the target material are known.

Acknowledgement

The work described in this paper was supported by grants from the Research Grants Council of Hong Kong Special Administrative Region, China [Project No. CityU 1175/03E (9040809 CityU)].

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