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SURFACE ABLATION OF 52100 BEARING STEEL USING FEMTOSECOND LASER IRRADIATION

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Laser ablation is a rapid material removal technique with potential application in remanufacturing of bearings to clean damaged surface. This study reports the ablation morphology and change in surface composition of 52100 bearing steel irradiated with a femtosecond laser. A smooth ablated surface was achieved by operating the laser at fluence just above the ablation threshold, but higher fluences resulted in roughened surfaces with recast formation. Such coarse morphology is believed to result from higher energy deposition and surface melting. Minimal oxidation occurred at lower fluences. Periodic ripple patterns formed in the ablated area at low fluence; their morphology and possible formation mechanism is discussed.

Keywords: ablation; laser cleaning; bearing steel; femtosecond laser; ripples.

1. Introduction

Remanufacturing of large size bearings used in milling, wind turbines, mining and aerospace industries is increasingly being pursued in prolonging the service life of bearings to reduce cost, lead time and environmental impact.¹ Old worn bearing requires initial cleaning and damage layer removal to prepare it for eligibility testing and subsequent operations. Laser can be used for this purpose since it is a non-contact and precise tool. By coupling rapid

short pulse laser energy to the surface, the contaminants and damaged surface layer can be effectively removed by direct ablation without inducing thermal damage to the bulk material.

The surface ablation by pulse laser irradiation is a widely studied topic with its application in various fields such as improving wear and corrosion resistance,^{2,3} controlling wettability,⁴ and modulating surface properties for other tribological applications.⁵⁻⁷ The phenomenon can be exploited

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for surface cleaning and damage layer removal of machine components as well. Tam et al.⁸ used a nanosecond pulsed UV laser to remove surface particulates of sizes as small as 0.1 μm . Zheng et al.⁹ used a second harmonic pulsed Nd:YAG laser to ablate the epoxy flashes from a multilayered heatsink surface. Guan et al.¹⁰ used a pulsed Nd:YAG laser to remove carbonaceous deposits in diesel engine piston. Extensive studies were done by Turner et al.^{11–13} on surface cleaning of aerospace components using CO₂, Nd:YAG and excimer lasers. They found that excimer laser produced superior cleaning due to removal by photo chemical and photo-thermal ablation process.

Although ultrashort pulse lasers are ideal for ablating the surface, they are rarely used for cleaning of engineering components. This is possibly due to low material removal rate and high peak power. Previous studies have shown that the contaminants can be removed by operating the ultrashort pulses in near ablation threshold region.¹⁴ Thus, there is an opportunity to employ short-pulse based ablation for remanufacturing applications. However, changes occurring on the cleaned surface after ablation is often ignored. An elaborative study on the surface morphology after ablating with ultrashort laser pulses is still lacking.

In this work, we explore the feasibility of using femtosecond laser as ablation tool for remanufacturing of bearing steel by systematically studying the ablated surface. The ablation threshold of bearing steel is determined first and the surface modifications during near ablation threshold fluence and high fluence operation are carefully investigated. The incubation effect on ablation threshold is also presented. Special attention is paid to understand the effect of laser fluence on morphological evolution and surface oxidation induced by laser treatment.

2. Methodology

2.1. Material

The material studied was AISI 52100 bearing steel with following chemical composition (in wt%): C 0.98, Si 0.25, Mn 0.35, P 0.02, S 0.02, Cr 1.42 and Fe balance. Specimens in dimensions of 25 mm by 25 mm by 3 mm were extracted from a single piece of steel using electric discharge machining. Surfaces of the specimens were ground with progressively finer

SiC papers (P120, P180, P320, P400, P800, P1200) and polished with 9 μ and 3 μ diamond suspensions followed by a final oxide polishing. The specimens were finally cleaned with alcohol and dried with an air gun.

2.2. Laser processing parameters

The Quantronix Integra C-1.0 femtosecond laser (with a center wavelength of 790 ± 10 nm and pulse duration of 130 fs) was used for laser irradiation. The laser was operated at 1000 Hz repetition rate with pulse energy varying in the range of 0.100 J/cm² to 9.000 J/cm². The laser beam approximates a Gaussian shaped intensity distribution at the center. An objective lens of 100 mm focal length was used which created a beam spot radius of about 26.48 ± 1.39 μm at the $1/e^2$ intensity. The sample was placed in the focal plane and irradiated under normal incidence by linearly polarized laser in air.

Ablation craters were created on the sample surface at different peak fluences and number of shots. The number of laser shots striking the surface was controlled by means of computer controlled fast optical shutter. The average power of the laser beam was measured just above the sample surface using PM3 5500 E16R power-meter from Coherent Inc. and pulse energy was calculated as the ratio of average power to repetition rate.

2.3. Surface Characterization

After laser irradiation, the ablation morphology of irradiated areas were investigated using Carl Zeiss AxioCAM optical microscope (OM) and JEOL 5600 LV SEM equipped with Energy Dispersive X-ray Spectrometer (EDS). The surface measurements were carried out in OM and SEM images using freely available image processing software ImageJ.

3. Results and Discussion

3.1. Ablation threshold

Material ablation during short pulse laser irradiation involves multiple mechanisms such as heating, melting, evaporation, sublimation and splashing. Determination of the critical fluence value for surface damage to occur, i.e. ablation threshold, is significant to understand this interaction between powerful laser pulses and material surface. The start of damage to

Fig. 1. Graph of squared diameter, D^2 , of ablation craters in steel as a function of peak fluence, ϕ_0 . The lines represent the least-squares fit according to equation (1).

the surface may be assessed by appearance of plasma during irradiation or formation of permanent crater on the surface due to some material removal. Since there is a lot of variation in ablation threshold value reported in the literature, it was considered necessary to calculate it for the steel sample used in our experiment.

The ablation threshold for given steel was determined based on surface diameter measurement method¹⁵ which is a widely accepted technique. Considering a Gaussian spatial distribution of laser intensity, the relation between peak fluence, ϕ_0 and surface crater diameter, D , is given by

$$D^2 = 2\omega_0^2 \ln \frac{\phi_0}{\phi_{th}} \quad (1)$$

where, ω_0 is the beam spot radius at $1/e^2$ intensity and ϕ_{th} is the threshold fluence. We used peak fluence for ablation threshold determination since it determines the extent of damage to the surface and gives a more realistic value for ablation than average fluence. The peak fluence can be derived from pulse energy, E_p and beam spot radius using following equation:

$$\phi_0 = \frac{2E_p}{\pi\omega_0^2} \quad (2)$$

The ablation threshold can then be determined by plotting the square of crater diameters, D^2 ,

against the logarithm of peak fluence, ϕ_0 . Extrapolating D^2 to zero gives the value of ablation threshold fluence.

Fig. 2. Graph showing the reduction in ablation threshold with increase in number of laser shots.

Fig. 3. Graph of accumulation fluence against number of laser shots. The line represents the least square fit according to equation (3).

Ablation thresholds for different number of laser shots were determined applying this method. The ablation threshold of steel for 100 laser pulses was calculated to be 0.164 J/cm² which is comparable to the values mentioned in literature.^{16,17}

A reduction in ablation threshold fluence was observed with increasing number of laser shots as shown in Fig. 1 and Fig. 2. The reduction can be

attributed to incubation effect or damage accumulation effect.¹⁶ Based on the power law, the ablation threshold fluence, $\phi_{th}(N)$, for N laser shots is related to single shot ablation threshold fluence, $\phi_{th}(1)$, by

$$\phi_{th}(N) = \phi_{th}(1)N^{S-1} \quad (3)$$

where S is the incubation coefficient. The incubation coefficient is calculated by plotting graph of $N \cdot \phi_{th}(N)$ against N as shown in Fig. 3. It was calculated to be 0.955 and the single shot ablation threshold was found to be 0.208 J/cm².

Different theories are available on mechanisms responsible for incubation.^{18–20} One explanation is the sudden reduction in surface reflectance after first few laser shots which results in a higher percentage of incident energy being absorbed by the material. On the other hand, the excitation of surface plasmons could also aid in energy coupling mechanism. The overall outcome is the reduction in ablation threshold value. It is however, noteworthy to point out that the ablation threshold does not keep on decreasing and stabilizes after about 50 shots (see Fig. 2). This is because of the reduction in beneficial effect of reflectance drop after few pulses and decoupling of plasma from the surface.

3.2. Surface morphology

After determining the ablation threshold fluence, experiments were performed at different fluence values ranging from near ablation threshold to higher fluences. The aim was to remove the surface contaminants with minimal damage to the substrate. No visible damage occurred to the surface at fluences lower than ablation threshold. As can be seen in Fig. 4(a), a smooth crater was obtained at a low fluence value just above the ablation threshold. The surface crater did not show any sign of melting. At very high fluences however, a rough surface recast layer was observed (Fig. 4(b)). The ablated crater had a deep hole (in the range of tens of micron) at the center with lots of re-solidified metal droplets ejected from the ablation center.

When the femtosecond laser pulse is irradiated on the surface, the incident energy is absorbed by surface electrons via inverse Bremsstrahlung process which results in rapid increase of surface temperature. The heat is then transferred to ions or lattice

Fig. 4. Ablated surface of AISI 52100 steel at 100 pulses and different peak fluences: (a) 0.317 J/cm^2 ; and (b) 8.522 J/cm^2 .

through electron-phonon coupling.²¹ Since the pulse duration for femtosecond laser is shorter than thermal relaxation time and laser is a very intense, the focal area of the interacting surface where fluence value exceeds ablation threshold is directly ablated by spallation and vaporization.^{22–24} Therefore, a fine smooth ablated surface is achieved at laser fluences just above the ablation threshold value for the irradiated material. At higher laser fluence, more energy is deposited on the surface which results in larger plasma formation²⁵ and greater volumetric heating. This causes rapid phase explosion and melting to occur. The melting starts as a thin molten layer first followed by a coarse regime with recast layer formation.²⁴ The result is a coarse morphology on the ablated surface where a dominant feature is widespread melt formation.

Fig. 5. Illustration showing influence of fluence on ablation diameter.

The laser fluence and the number of laser shots are the primary factors determining the ablation crater on the surface and hence, affect the removal efficiency. Therefore, the laser fluence and the number of shots were varied and crater diameters were measured. The results are shown in Fig. 6. It was

Fig. 6. Graphs showing variation of ablation diameter with (a) peak fluence; and (b) number of laser shots.

found that the surface crater increased rapidly as the peak fluence is increased from near threshold value to about 2 J/cm² (see Fig. 6(a)). After that, the increment in diameter was gradual. Peak fluence increases with increase in pulse energy as seen from equation 2. Thus, at high peak fluence, more area of Gaussian intensity profile will lie above ablation threshold. This obviously increases crater diameter as illustrated in Fig. 5.

The number of laser shots also had similar effect with diameter increasing rapidly up to 50 shots and then stabilizing after that (see Fig. 6(b)). It must be noted that only the area covered by the Gaussian beam with intensity above ablation threshold will undergo ablation. As discussed in Section 3.1, the ablation threshold value reduces with increase in number of laser shots. Thus, the crater diameter increases with increase in number of laser shots. However, the maximum crater diameter attainable is limited by the size of the Gaussian beam and therefore, no further change in crater diameter is observed after 100 laser shots.

3.3. Oxidation

The elemental composition of ablated area was analyzed by EDS to check surface oxidation. At low fluences (< 1 J/cm²), a maximum of 1-2 wt% oxygen was detected in the ablated area. At fluences higher than 1 J/cm², a thin scaly layer formed around the ablated area as shown in Fig. 4(b). With increase in fluence, the scales became more prominent with oxygen content increasing from 10 wt% to 40 wt%. Table 1 compares the results of EDS observation on as-received and typical ablated surfaces. At 0.317 J/cm², the oxygen was not present on the surface while about 22.80 wt% oxygen was detected at 8.522 J/cm².

Table 1. Typical elemental surface composition obtained before and after laser irradiation

Element	Weight percentage(%)		
	Untreated	0.317 J/cm ²	8.522 J/cm ²
C	4.15	4.74	2.5
O	-	-	22.80
Si	0.25	0.24	0.24
Cr	1.35	1.41	1.17
Mn	0.36	-	-
Fe	93.89	93.61	73.28
Total	100.00	100.00	100.00

When the steel is in contact with air, increase in temperature will generally increase the rate of oxidation. During ablation at low fluence, the heating is insignificant to bring about any increase in surface oxidation. At very high fluence, however, the interaction between air and surface plasma generates a larger hot plume around the ablated surface which enhances the rate of surface oxidation. This results in formation of a thick oxide scales and increases oxygen content on the metal surface.

3.4. Laser Induced Periodic Surface Structures (LIPSS)

Careful examination of the ablated areas revealed a periodic ripple patterns on ablated surface as shown in Fig. 4(a) and Fig. 7. These ripples had periodicity in the range of 590-630 nm which is close to the wavelength of laser beam. The evolution of the ripples is shown in Fig. 7. With increase in pulse energy, rough bumps appeared at the center (at fluences more than 1 J/cm²). A rough periodic pattern with periodicity of about 2 μ m appeared at the center with direction normal to the original ripples. These micro-ripples soon disappeared with formation a rough ablation regime at the center due to surface melting. The ripples were visible only at the periphery after irradiation at high fluence.

Although a clear explanation for formation of these periodic ripples is still lacking, most studies suggest that they are formed due to interaction between surface plasmons and incident laser energy.²⁶⁻³⁷ The femtosecond laser irradiation excites surface plasmons which changes the refractive index of air-metal interface.²⁶ This causes a slight deviation of spatial period from laser wavelength as observed in the experiment.

Similarly, increasing pulse number resulted in formation of two types of surface ripples one with periodicity around 600 nm at the ablation center and the other with periodicity around 350 nm at the edges. These are often termed as LSFL (Low Spatial Frequency LIPSS) and HFSL (High Spatial Frequency LIPSS) respectively in the literature (see Fig. 4(a)). The formation mechanism of HFSL is not clearly understood yet although it is believed to have occurred from increase in dielectric constant of air due to plume ejection from laser spot.³⁷ The detailed investigation of LIPSS formation is beyond the scope of this paper and can be found elsewhere.

4. Conclusions

The ablation morphology of a bearing steel surface during femtosecond laser irradiation is studied. The ablation threshold of bearing steel during femtosecond laser irradiation is calculated for different number of laser shots. It is calculated to be 0.164 J/cm² for 100 laser shots. Based on the incubation effect, the single shot ablation threshold is found to be 0.208 J/cm².

Laser fluences just above the ablation threshold are found to produce smooth surface with negligible oxidation and are therefore recommended for use in damaged surface removal for bearing remanufacturing. At higher fluences, surface melting occurs with a deep hole at the center. A thin oxide layer and lot of melt redeposition occurs in the periphery of the hole. This is attributed to the larger plasma formation and reflow of melt region due to higher energy deposition. The characteristic laser induced ripples, with periodicity in the order of wavelength, are observed in the ablated area at low fluences.

Acknowledgments

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Fig. 7. SEM images showing morphological evolution of steel surface after irradiation with increasing peak fluences at 10 (a,b,c,d) and 100 (e,f,g,h) laser shots : (a,e) 0.317 J/cm^2 ; (b,f) 0.843 J/cm^2 ; (c,g) 1.223 J/cm^2 ; and (d,h) 1.994 J/cm^2 .

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