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Femtosecond laser cleaning for aerospace manufacturing and remanufacturing

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***Abstract*—Microsecond and nanosecond lasers have been studied in the past for laser cleaning applications, but femtosecond laser is rarely used for cleaning due to the greater possibility of ablation from the extremely high peak power (in gigawatt range) of ultrashort pulses. This paper reports the investigation into the feasibility of using femtosecond laser as a tool for surface cleaning of aerospace components. Surface contaminants, oxides and surface coatings were shown to be removed effectively and damage to the substrate was avoided by using a defocused laser beam and careful control of laser fluence.**

***Keywords*— laser surface cleaning; femtosecond laser; ablation; aerospace manufacturing; remanufacturing**

I. Introduction

Proper surface cleaning is essential for ensuring quality of aerospace manufacturing and remanufacturing. Aerospace components such as turbine blades and compressor rotor drums require cleaning during manufacture, in-service operation and remanufacture. Processes commonly used in industry such as mechanical abrasive cleaning, thermal cleaning and chemical cleaning can remove dirt and contaminants but may induce damage to the substrate and result in environmental hazards [1]. In contrast, laser cleaning enables much more environmentally friendly removal of surface contaminants or oxides since it does not require using chemicals or other additives. Laser cleaning employs moving short laser pulses to produce micro-plasma bursts and shockwaves leading to direct sublimation and ejection of the target material [2]. The substrate material and surface contaminants have different ablation thresholds; thus by proper choice of laser parameters, the short pulses remove only the target layers of oil, paint, residue or oxides without damaging the substrate.

Different types of lasers have been employed for cleaning of aerospace components. The primary requirement of a laser cleaning system is that it should effectively remove the surface contaminants avoiding undesirable side effects such as surface melting, stress induction, phase transformation and surface oxidation. Tam et al. [3] demonstrated the removal of micron and sub-micron particles from solid surface using a short pulsed UV laser with 16 ns pulse duration and concluded that highest cleaning efficiency is achieved by choosing laser wavelength that is strongly absorbed by the surface. Guan et al. [4] used a pulsed Nd:YAG laser (wavelength 1064 nm, 43 ns pulse width, 6 kHz repetition rate) to remove carbonaceous deposits in diesel engine piston. They could completely remove Fe_3C from the surface; however, they could not prevent surface melting. Similarly, Moskal et al. [5] utilized picosecond laser (wavelength 532 nm) at various parameters to obtain optimum condition for cleaning of AM1 superalloy.

Extensive studies were performed for surface cleaning of titanium alloys used in aerospace application by Turner et al. [6]–[8] using CO_2, Nd: YAG and excimer lasers to remove surface contaminants prior to electron beam welding. They concluded that excimer laser removed surface contaminants by photo-chemical (for organic contaminants) and photo-thermal (for oxide particles) ablation without any damage to the substrate and hence, considered it as the most effective laser for surface cleaning. However, to the best of our knowledge, femtosecond (fs) lasers have rarely been used for cleaning of aerospace components. One of the major reasons could be a greater likelihood of surface ablation damage from the extremely high peak power (in gigawatt range) of the ultrashort pulses.

This paper investigates the use of fs laser to clean surfaces of aerospace alloys. The main aim is to study the feasibility of using fs laser for surface cleaning applications and understand the effects of laser parameters on cleaning. Although an elaborate analysis still ongoing, the results suggest that fs laser have potential to be used for surface cleaning applications.

II. Methodology

A. *Materials*

A used gas turbine blade made of Nickel superalloy and a commercially available titanium alloy plate AMS 4911, Grade 5 with a plate thickness of 1.5 mm were used for experiments. The samples were cut into appropriate sizes for laser surface treatment.

B. *Laser processing*

An ultrashort pulsed Ti:Sapphire diode laser (Quantronix Integra C with average power 1.5 W, wavelength 790 nm,

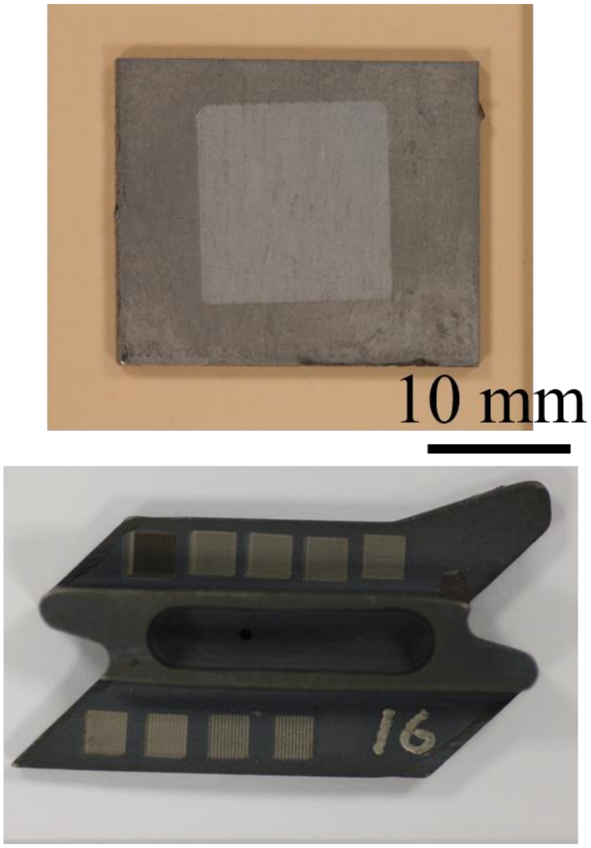

Fig. 1. Femtosecond laser cleaning at different laser conditions in air (top: titanium alloy; bottom: nickel superalloy based turbine blade).

pulse duration 130 fs, repetition rate 1000 Hz) was used. The minimum beam spot diameter achievable was 30 μm. However, a defocused beam at the sample surface was used under normal incidence to reduce the chances of laser induced damage to the substrate. For titanium alloy, a surface area of 15 mm by 15 mm was irradiated at 50 mm/s speed using hatched scanning mode with 38.5% overlapping between scan lines in the program. Due to limited space in turbine blade, smaller areas of 3 mm by 3 mm were scanned at different laser powers using energy filters. A single pass scan was performed for each sample by linearly polarized laser in air.

C. *Characterization*

After laser irradiation, surface morphology was observed using an optical microscope (Olympus OM stereomicroscope), scanning electron microscope (JOEL 5600 LV) and a stylus profiler (Taylor Hobson Precision Talyscan 150). Both non-irradiated and irradiated surfaces were characterized using energy Dispersive X-ray Spectrometer (EDS, Oxford Instruments) and X-Ray Diffractometer (Panalytical Model Empyrean). X-ray diffraction patterns were obtained using copper target as a source of X-ray with wavelength λ=1.5404 Å (Cu Kα1). The scanning angle was in the range of 10°–90° with step size of 0.05° and scan speed of 0.02 °/s.

III. Results and Discussion

Fig. 1 shows the overview of laser cleaned samples. The alloy samples were irradiated at different laser parameters to optimize the surface contaminants removal. While some faint ablation lines in scan direction were observed for high power scans, an effective cleaning was obtained for lower fluences and a fast scanning speeds at defocused beam condition. Surface topography measurements were also carried out using TalyScan 150 surface profilometer. The average surface roughness did not alter much after laser cleaning as can be seen from the data in Table I.

TABLE I. Surface roughness values as measured using TALYSCAN 150 surface profiler

Sample	**Average surface roughness, S_a (μm)**	
	As-received surface	***Laser cleaned surface***
AMS 4911	1.53	1.39
Tubine blade	1.72	1.82

A typical morphology of laser cleaned samples are shown in Fig. 2 and Fig. 3. The surface contaminants were effectively removed from the laser irradiated surface. The surface contaminants adhere to the surface due to either Van der Waals, capillary or electrostatic forces. During laser cleaning, the energy from the laser beam is absorbed by the contaminants and the surface. When the beam energy is sufficient to overcome the adhering forces, the contaminants are removed by direct ablation. The actual removal mechanism can be due to direct coupling of beam energy with the contaminant resulting in its decomposition or with the substrate with energy transferred to the contaminant by conduction or a combination of both. The energy absorbed, ΔE, by the contaminants can be calculated from

$$\Delta E = \frac{P(1-R)}{\delta}\int_0^d e^{-z/\delta}\,dz \qquad (1)$$

where δ is the depth of absorption and d is the thickness of contaminant, P is the incident power and R is reflectivity.

In order to minimize the peak pulse energy from damaging the substrate, a defocused beam condition was utilized. The defocused beam would spread the pulse energy over a larger

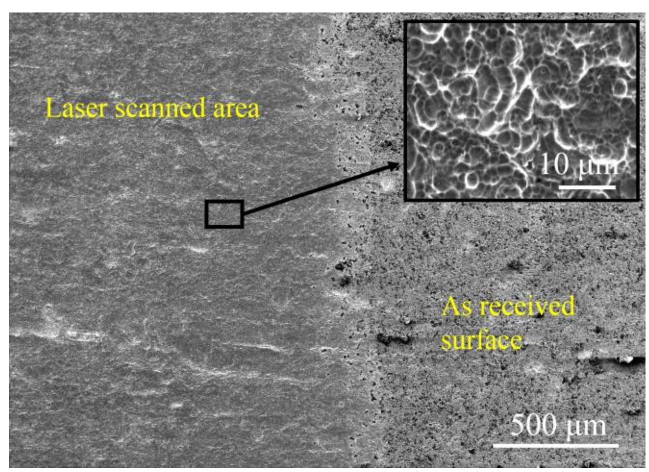

Fig. 2. SEM image showing the AMS 4911 surface before and after laser cleaning (the inset shows blow up image of the laser cleaned surface). Laser fluence of 0.068 J/cm^2 at the surface was used for cleaning.

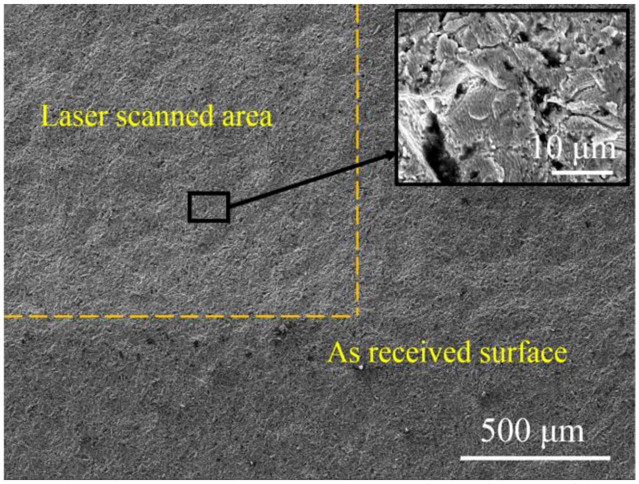

Fig. 3. SEM image showing the turbine blade surface before and after laser cleaning (the inset shows blow up image of the laser cleaned surface). Laser fluence of 0.367 J/cm^2 was used.

area and is calculated as

$$D(z) = D_0\sqrt{1+\left(\frac{4\lambda z}{\pi D_0^2}\right)^2} \quad (2)$$

where D_0 is waist diameter of the beam, λ is the wavelength and z is the axial distance between waist diameter and the plane at which the laser has diameter of D(z).

Table II presents the elemental composition of alloys before and after laser cleaning as measured by EDS. The oxygen was almost completely removed in case of titanium alloy while it was reduced to a lower value for nickel superalloy suggesting the removal of surface oxides. The carbonaceous deposits in the samples were also cleaned as evidenced by reduction in carbon content.

TABLE II. ELEMENTAL COMPOSITION MEASURED USING EDS SYSTEM

Elements (wt%)	**AMS 4911 alloy**		**Ni superalloy**	
	As-received surface	***Cleaned region***	***As-received surface***	***Cleaned region***
Ni	-	-	50.6	58.9
Al	3.8	4.3	8.8	6.4
Co	-	-	8.8	10.7
Cr	-	-	7.4	8.5
C	3.9	2.7	7.5	3.4
O	7.1	0.0	9.1	5.3
W	-	-	5.3	5.0
Ti	81.5	89.1	0.7	0.5
V	3.7	3.9	-	-
Rb	-	-	1.4	0.7
Mo	-	-	0.4	0.4

In order to analyze if there is any phase change due to laser irradiation, X-ray analysis was performed. Fig. 4 shows X-ray diffraction pattern of as-received and laser irradiated surfaces. While the peak position of as-received and laser-irradiated area did not change, a different values of peak intensities were obtained. For titanium alloy, the peak intensities increased slightly compared to as-received surface peak intensities. This is probably because the laser pulses remove the amorphous surface contaminants during cleaning thus revealing a crystalline surface. This cleaned crystalline surface produces a clear peaks and hence, we get an increased peak intensity.

However, the case is reversed for nickel superalloy whereby X-ray peak signals are drastically reduced compared to the as-received surface. This can be attributed to the partial amorphization of the surface during fast femtosecond laser irradiation [9]. The high power laser energy is absorbed by the surface contaminants and results in direct ablation and cleaning. The residual laser energy that did not contribute to the ablation process is absorbed by the substrate which leads to formation of a thin layer of melt phase. The abrupt cooling of this melt layer forms a thin amorphous metal layer on the surface. Since XRD detects the signal up to certain penetration depth (depending on the wavelength and material properties), the weak peak signal should have originated from the crystalline part under the amorphous layer.

IV. CONCLUSION

The feasibility study of laser surface cleaning using femtosecond laser for aerospace applications was performed. Laser parameters were chosen such that a lower fluence value was obtained and used for all experiments. The laser cleaned surfaces before and after laser processing were carefully examined. It was found that the surface contaminants were effectively removed and oxygen content decreased significantly after laser treatment. Moreover, X-ray analysis showed that the peak signals may increase or decrease depending on the material and laser intensity. The increase in peak signal is due to effective removal of surface contaminants revealing crystalline substrate beneath while a dramatic reduction in peak signals can be attributed to the partial amorphous metal formation on the surface after laser treatment. It is concluded that femtosecond laser can be used for cleaning applications using a proper choice of laser parameters.

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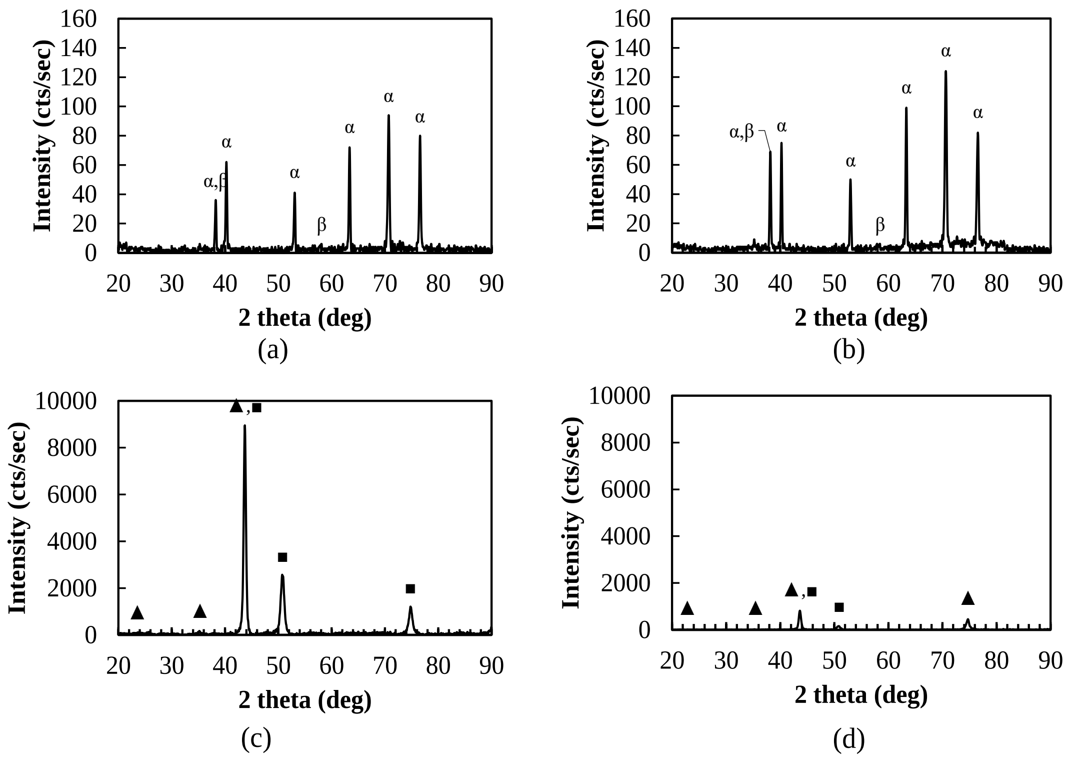

Fig. 4. XRD results. (a) and (b) are the X-ray diffractograms of AMS 4911 alloy before and after laser cleaning respectively. α represents alpha-phase and β represents beta-phase in the alloy. Similarly, (c) and (d) are the X-ray diffractograms of turbine blade before and after laser cleaning respectively. ▲ represents AlNi3 phase while ■ represents Al0.5CNi3Ti0.5 phase.

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