Temperature-dependent absorptance of painted aluminum, stainless steel 304, and titanium for 1.07 μm and 10.6 μm laser beams

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Abstract
We measured the temperature-dependent absorptance of metals (Al, Ti, SS304) for continuous beams from 1.07 μm fiber laser and 10.6 μm CO2 laser using power sensors and infrared (IR) pyrometers. The absorptance measurements were repeated for metals with three different paint coatings. For measurements at elevated temperatures up to the melting point, integrating sphere is not practical since high temperature radiation from a heated target disturbs weak output from the sphere considerably. Our results provide how each metal, whether coated or uncoated, absorbs the infrared beams as temperature is elevated to a melting point. A polynomial approximation to the measured absorptance of each target is provided for modeling of the laser–metal interaction at elevated temperatures.

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1. Introduction

Measuring the light absorptance of metal is a well established area of research for years. However, temperature-dependent absorptances are rarely reported in the literature [1-9]. The beamed material absorptance data is in great demand for various applications that include laser processing of temperature sensitive metals in manufacturing industry as well as in the laser-powered weapon system for military purpose.

Recent studies have considered measuring the absorptance of various steels and nonferrous alloys to neodymium-doped yttrium lithium fluoride (Nd:YLF) lasers and neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers at room temperature with an integrating sphere [1,2], and measuring the absorptance of artificial diamond and cubic boron nitride to solid-state YAG lasers [3]. In studies of temperature-dependent absorptances, the absorptance of Al to CO2 laser [4,5], the measurement on low-carbon steel to Nd:YAG laser [6] and ceramics to both Nd:YAG and CO2 laser [7] have been reported with several theoretical studies of such topics [10-13].

Integrating spheres are used in previous works on absorptance measurements at room temperature. In an elevated temperature environment, metal emits thermal radiation which affects output signal that passes through the integrating sphere. The output signal from the integrating sphere is about 1% of the probing beam, such that the radiation spectrum can affect measurement accuracy. Thus, we devised a measuring scheme for the test at elevated temperatures with combinations of power sensors and IR pyrometers.

The absorptances at elevated temperatures are measured for three common metals: Al, SS304 and Ti. Both 1.07 μm fiber laser and 10.6 μm CO2 laser are used along with IR pyrometers and power sensors for detection. Also, the absorptances of painted metals of three different coats are provided. The polynomial approximation of measurements is made to guide the test-based modeling of beam–matter interaction aimed at high power continuous wave irradiation.

2. Experimental setup for absorptance measurement

For absorptance measurement at room temperature, integrating sphere is commonly used in many studies because of its accurate and versatile nature [1,2,6,7,14,15]. However, for measuring absorptances of metals at elevated temperatures, the output signal passed through the integrating sphere becomes weak, and the high temperature radiation of the metals affects the output data considerably.

In our experiment, we measure the reflectance of metals using power sensors and IR pyrometers. We used single laser for both heating and incident beaming of the sample. Heating of the sample was performed without focusing, and the beam diameter of fiber...
(1.07 μm) beam was 5.85 mm and 8.5 mm for the CO2 (10.6 μm) beam. In order to vary the heating temperature on the sample beyond melting point, the beam power was adjusted from 50 to 200 W for fiber laser and 100 to 300 W for CO2 laser. The power is detected at three locations. The reference power of the laser beam is marked as the incoming laser power, and the reflected power of laser is measured with 45° incidence angle. Since the theoretical angular dependence of absorptance by the Fresnel’s law is negligible at 45°, the results are also applicable when the normal incidence angle is used. The absorptance α is defined as

\[ \alpha = 1 - R, \quad R = \frac{P - P_t}{P_0} \]  

where \( R \) is the reflectance of the sample, \( P \) is the reflected beam power from the sample, \( P_t \) is the power affected by radiation from the heated sample, and \( P_0 \) is the reference beam power [10–13].

Fig. 1 shows the experimental setup for measuring the absorptance.

The performance specification of the laser system and the experimental set up may give rise to measurement errors. The laser beam fluctuation of less than 3%, the beam scattering, and the radiation from the metal surface may lead to detection errors. Smoothed surface of the sample gives rise to the specular reflection; however, small quantity of the diffused reflection is also taken into account [16]. The diffused beam intensity drastically decreases as a function of cosine when the difference between the actual and the specular angle is increased. Also, the distribution of the incoming beam is Gaussian, and thus reflected beam is assumed to follow a Gaussian distribution as shown in Fig. 2(a). The error by the scattering of diffuse reflection from the ideal Gaussian distribution is kept below 1% by adjusting the distance between power sensor and the sample. The radiation from the sample is assumed negligible when the temperature of the sample is low. When the temperature of the metal becomes high; however, radiation from metals is no longer negligible as the radiation power reaches over 1% of the reference power. Thus, to calibrate the absorptance error by the radiation of metal, we monitor \( P_t \) at the back side of the metal as shown in Fig. 2(b).

IR pyrometer, used mainly for high temperature regions, requires a-priori determination of emissivity of a target sample. The necessary calibration of the pyrometer is performed by using a separate thermocouple as illustrated in Fig. 3. Temperature is measured at two points at the same distance from the center by both pyrometer and thermocouple. Thus the emissivity of a test sample can be determined by the simultaneous temperature measurement.

The beam wavelength of fiber laser is 1.07 μm, and the CO2 laser is 10.6 μm. The maximum power of 1.07 μm beam is 1 kW and the maximum power of 10.6 μm beam is 300 W. Also, the beam diameters are 5.85 mm and 8.50 mm for each beam, respectively.

For target samples, we used three metals: Al, SS304, and Ti. We measured the absorptance of each metal from room temperature to the melting point (660 °C for Al, 1450 °C for SS304, and 1660 °C for Ti) [17]. The size of the samples used in the experiments was 40 mm x 40 mm x 0.2 mm. The samples were polished to reflect the similar roughness grade. The average roughness of each metal was described by the arithmetic average \( Ra \) as shown in Table 1. Also, three-dimensional (3-D) surface of each metal was scanned using a scanning tunneling microscope (STM) as shown in Table 1.
**Fig. 3.** Calibration scheme for IR pyrometer using thermocouple.

**Table 1**
Roughness and surface profiles of metals.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Rₐ</th>
<th>2-D Profile</th>
<th>3-D Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>339 nm</td>
<td><img src="image1" alt="2-D Profile" /></td>
<td><img src="image2" alt="3-D Profile" /></td>
</tr>
<tr>
<td>SS304</td>
<td>331 nm</td>
<td><img src="image3" alt="2-D Profile" /></td>
<td><img src="image4" alt="3-D Profile" /></td>
</tr>
<tr>
<td>Ti</td>
<td>469 nm</td>
<td><img src="image5" alt="2-D Profile" /></td>
<td><img src="image6" alt="3-D Profile" /></td>
</tr>
</tbody>
</table>
Three kinds of paint coatings were considered. The first paint-1 has the following characteristics: weatherproof, thermal resistant, moisture tolerant, oil resistant, and anticorrosive. The second paint-2 has thermal resistance and is anticorrosive. The third paint-3 is weatherproof and chemical-proof. We detected the absorptance of coated metals, and compared these to the results of same metals without coating. Table 2 summarizes the properties of paints used in the experiment.

3. Results and discussion

For metals at elevated temperatures, the absorptances for 1.07 μm laser beam were higher than the absorptances for 10.6 μm laser beam as shown in Figs. 4 and 5. At room temperature, the absorptance for 1.07 μm beam was about 20% higher than for 10.6 μm beam for SS304, and absorptance for 1.07 μm beam was about 25% higher than for 10.6 μm beam for Ti. For Al, the absorptance for 1.07 μm beam was about 12% higher than for 10.6 μm beam for all range of temperatures.

The ordering of absorptance for each metal did not vary by the wavelength. For 1.07 μm beam, the absorptance of Ti was highest among three metals, and the absorptance of Al was the lowest. Also, the ordering remained the same with 10.6 μm beam: the absorptance of Ti was the highest, and the absorptance of Al was the lowest.

The absorptance of Al did not vary noticeably to the melting point. However, the absorptances of SS304 and Ti increased, evidently onward from a melting point where the oxidation effect is believed to cause this increase. For 1.07 μm beam, the absorptances of SS304 and Ti remained steady near 700 °C, and then started to increase toward the melting point (over 700 °C). For the 10.6 μm beam, the absorptance of SS304 changed at above 1000 °C, and the absorptance of Ti changed near 600 °C. For SS304, the absorptance increased from 31% to 59% for 1.07 μm beam, and from 11% to 14% for 10.6 μm beam from room temperature to a melting point. For Ti, the absorptance increased from 41% to 69% for 1.07 μm and from 14% to 28% for 10.6 μm case, for temperature ranging from room to a melting point.

In support of these observations, blackened rings on the surfaces of SS304 and Ti were observed due to oxidation, whereas no change on the surface of Al was observed. Also, according to Crane et al. [18], absorptance of oxidized metals is much higher.
than that of non-oxidized. Thus, the surface oxidation effect is believed to be responsible for pronounced absorptance variations in the SS304 and Ti samples. As for the Al sample, the amount of Al surface oxidation was approximately 0.1% [19], and such a surface oxidation effect did not affect the absorptance measurement at the elevated temperatures.

In comparison to other studies in the literature, the present data are confirmed to be consistent. Al for 1.053 μm is 16% at room temperature according to Bergstrom et al. [2], which is in agreement with our measurement for 1.07 μm beam. The absorptance of SS304 for 1.053 μm is 32.4% according to Bergstrom et al. [1], which is about 1% higher than our result. One notes however, the composition of SS304 may vary from sample to sample, and such 1% difference may be tolerable. Our laser-heated aluminum sample showed minor increase from 4% up to the melting point for 10.6 μm beam. Similar curve from [4] rose slightly above 5% and declined before reaching a melting temperature, whereas Ursu et al. [5] showed increase beyond 5% near the melting point. Minor variation in our results is due to limited oxidation seen on the surface of the aluminum sample.

The third-order polynomial fitting of each absorptance is based on the following formula:

\[ \alpha = a + bT + cT^2 + dT^3 \]  (2)

where \( \alpha \) is the absorptance, \( T \) is the temperature, and \( a, b, c \) and \( d \) are constants as summarized in Tables 3 and 4.

As for the painted samples, the absorptances are 50% or above, whereas for most metals without the coating, absorptances are below 50% as shown in Figs. 6–8. For paint-1, the absorptance for 10.6 μm beam was measured lower than for 1.07 μm beam. For paint-2 and paint-3, however, the absorptances for 10.6 μm beam were higher than absorptances for 1.07 μm beam since the resins of these paints are polymers which absorb the longer wavelength beams well.

Fig. 9(a) shows paint-3 case for 1.07 μm beam for varying temperatures, where the values remain unchanged until about 700 °C. Both painted Ti and SS304 decrease beyond this point, whereas Ti alone starts to bounce back at temperature near 1000 °C. Fig. 9(b) shows 10.6 μm beam effect. Nearly 95% of the beam is absorbed initially, and the absorptance starts to decrease until about 750 °C. For Ti and SS304, the value starts to increase until reaching a uniform value of ~80%.

Table 3
Polynomial approximation of absorptance for 1.07 μm laser beam.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Temperature (K)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>373–933</td>
<td>1.54E+01</td>
<td>1.20E–03</td>
<td>1.07E–06</td>
<td>–5.99E–10</td>
</tr>
<tr>
<td>SS304</td>
<td>373–823</td>
<td>2.95E+01</td>
<td>5.79E–03</td>
<td>–1.08E–05</td>
<td>6.53E–09</td>
</tr>
<tr>
<td>Ti</td>
<td>373–963</td>
<td>8.19E+01</td>
<td>–1.41E–01</td>
<td>1.16E–04</td>
<td>–2.41E–08</td>
</tr>
<tr>
<td></td>
<td>963–1473</td>
<td>3.51E+01</td>
<td>2.88E–02</td>
<td>–4.79E–05</td>
<td>2.64E–08</td>
</tr>
</tbody>
</table>

Table 4
Polynomial approximation of absorptance for 10.6 μm laser beam.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Temperature (K)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>373–933</td>
<td>3.67E+00</td>
<td>3.57E–04</td>
<td>–1.42E–14</td>
<td>8.31E–18</td>
</tr>
<tr>
<td>Ti</td>
<td>373–1073</td>
<td>9.21E+00</td>
<td>2.68E–02</td>
<td>–4.09E–05</td>
<td>2.06E–08</td>
</tr>
<tr>
<td></td>
<td>1073–1933</td>
<td>–9.12E+01</td>
<td>1.78E–01</td>
<td>–9.32E–05</td>
<td>1.71E–08</td>
</tr>
</tbody>
</table>

Fig. 6. Absorptance of Al coated with paint-1 (top), paint-2 (middle), and paint-3 (bottom) for 1.07 μm and 10.6 μm laser beams.
From these figures we see that below 700 °C, absorptance of the paint dominates the overall characteristics, suggesting that melting of the pigment in paint-3 (in particular at 660 °C for aluminum) is responsible for uniform rise (in 1.07 μm case) and a decline (in 10.6 μm case) in the measured absorptances of painted samples. Beyond this point, absorptance does not change.

Fig. 7. Absorptance of SS304 coated with paint-1 (top), paint-2 (middle), and paint-3 (bottom) for 1.07 μm and 10.6 μm laser beams.

Fig. 8. Absorptance of Ti coated with paint-1 (top), paint-2 (middle) and paint-3 (bottom) for 1.07 μm and 10.6 μm laser beams.
drastically and stabilizes near 60%. It is believed that charred debris of the melted paint remains on the surface of the metals, causing the surface absorptivity to remain high. In return, the measured values for each sample are still higher than the results of the uncoated samples of Figs. 4 and 5.

Fig. 10 shows absorptance of Ti without and with paint coating for 1.07 \( \mu \text{m} \) beam. The results vary according to the paint types until below 1100 °C, beyond which the absorptance follows that of Ti alone. This suggests that most of the paint coats and coating debris have been removed at this temperature. Since absorptance has strong dependence on surface oxidation [20], painted metals are believed to have undergone similar oxidation process before reaching ~70% of absorptances.

4. Conclusion

We obtained temperature-dependent absorptance measurements of Al, SS304 and Ti for 1.07 \( \mu \text{m} \) and 10.6 \( \mu \text{m} \) continuous wave laser beams. For SS304 and Ti, the absorptance increased with temperature up to a point where oxidation effect became significant. For Al, it maintained a steady value until temperature reaching its melting point. In all cases, 1.07 \( \mu \text{m} \) beam is absorbed better than 10.6 \( \mu \text{m} \) beam for temperature ranging up to the melting. The order of metals with higher absorptance is Ti, SS304, Al for both 1.07 \( \mu \text{m} \) and 10.6 \( \mu \text{m} \) beams. In addition, metals coated with three different paints were characterized by the beam absorptance at elevated temperatures. The paint coats enhanced the beam absorption overall, and temperature-dependent absorptance data for all three paint coats were obtained. After paint coats were removed from the coated target, the measured absorptance remained higher than that of uncoated samples due to the surface remains and surface oxidation that enhanced the beam absorption. The absorptance measurements of this work are being used in the modeling of laser–matter interaction at the range of highly elevated temperatures.

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