Absorptance of nonferrous alloys to Nd:YLF and Nd:YAG laser light at room temperature

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The measurement of absorptance is important for the analysis and modeling of laser–material interactions. Unfortunately, most of the absorptance data currently available consider only polished pure metals rather than the commercially available (unpolished, oxidized) alloys that are actually being processed in manufacturing. We present the results of absorptance measurements carried out at room temperature on as-received engineering grade nonferrous metals (Al, Cu, and Zn alloys). The measurements were made using an integrating sphere with a Nd:YLF laser at two wavelengths (1053 and 527 nm, which means that the results are also valid for Nd:YAG radiation at 1064 and 532 nm). The absorptance results obtained differ considerably from the existing data for polished, pure metals and should help improve the accuracy of laser–material interaction models. Some clear trends were identified. For all 22 cases studied the absorptance was higher than for ideal pure, polished metals. For all Al and Cu samples the absorptance was higher for the green than it was for the infrared wavelength, while for all Zn coatings this trend was reversed. No clear correlation between absorptance and surface roughness was found at low roughness values (S_a 0.15–0.60), but one rougher set of samples (S_a 2.34) indicated a roughness–absorptance correlation at higher roughness levels. © 2007 Optical Society of America

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1. Introduction

In laser materials processing of metals, an understanding of the laser absorption mechanisms plays a vital role in determining the optimum processing parameters. The absorptance, which is the fraction of the incident laser light that is absorbed, depends on a number of different parameters, the most important of which are listed in Table 1.¹ (Absorptivity is a term restricted to flat, pure surfaces, absorptance is a more general term).

When modeling laser processing applications, such as cutting, welding, drilling, cladding, and hardening, it is important to model the absorption correctly. In very sophisticated models it may be necessary to have an analytical function for the different absorption mechanisms. In other, simpler, cases it may be suffi-

cient to have an accurate average absorptance value to plug in. In any case, published data for the absorptance and reflectance of metals are usually presented only for perfectly pure, clean, and flat surfaces that are free from oxide layers (measurements are commonly done in vacuum). This is quite different from the normal situation found in real-life material processing applications. Most metal surfaces are rough to some extent, and oxide layers are more of a rule than an exception. Also, the concentration on pure metals has meant that there is very little information available for the absorptance of alloys (stainless steel and brass, for example), polished or otherwise. In real processing environments alloys are far more commonly used than pure metals. It is therefore generally inappropriate to use the published values of absorptance for pure polished surfaces in mathematical models of laser processing.

Figure 1 demonstrates some of the complexities of photon absorption by an engineering grade metal surface. Such a surface has a characteristic roughness and is always covered by an oxide layer. The surface roughness can result in multiple reflections that involve multiple absorption events [Fig. 1(b)]. Surface roughness can also involve the incoming radiation in absorption events at high angles of incidence, close to the Brewster angle. This can result in very high local absorptance levels. The oxide layer

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Table 1. Laser and Metal Properties of Importance to Absorption^a

Laser Properties	Metal Properties
Wavelength	Chemical composition
Polarization	Temperature
Angle of Incidence	Roughness/topography
Intensity	Oxide layers
	Contamination (dust, dirt, surface defects)

^aSee Ref. 1.

may be absorbing in its own right or may be responsible for multiple reflections or waveguiding [Fig. 1(c)]. In addition to these effects the surface may be contaminated with material that has a higher absorptance than the underlying metal.

All of the above phenomena increase the absorptance of the surface in question, and the use of alloying elements will also tend to complicate the situation. For this reason the best way to establish the absorptance of an engineering metal surface is by direct measurement.

It would, of course, be extremely difficult to measure the absorptance of the molten, turbulent surfaces typical of laser welding or cutting. However, it is possible to accurately measure the absorptance of the solid material at room temperature, and the values obtained can provide an insight into how the materials behave at elevated temperatures. This can be argued from the fact that for metals, at wavelengths at approximately 1 μm , the temperature dependence of absorptance is small. It is well established that metals usually have a

so-called *X point*, a wavelength point or band where the temperature coefficient of absorptance changes sign.² The reason for this kind of behavior lies in the different temperature coefficients for intraband (free-electron) and interband (bound-electron) absorption, the two intrinsic absorption mechanisms prevalent in metals. Intraband absorption increases with temperature simply because the free electrons gain kinetic energy while the phonon population grows, which increases the electron-phonon collision frequency (i.e., the energy conversion efficiency between the light, the free electrons, and the lattice). Interband absorption, on the other hand, is much more complicated and depends on the particular band structure of the metal. The general principle is that as the temperature is elevated, the electron Fermi energy distribution function is smoothed out, and the absorption bands are broadened. The competition between these two effects leads to the *X point*, which for most metals lies at a wavelength near 1 μm .³

In any case, the absorptance of the solid material as opposed to the molten state is in itself very important for two reasons:

1. During the initiation of any weld or cut the laser is interacting with the solid surface.
2. During welding or cutting the leading edge of the laser beam in many cases interacts with the solid surface of the material.

A comprehensive literature survey with 46 references on experimental absorption measurement meth-

Fig. 1. Some of the mechanisms that increase the absorptivity of real engineering surfaces. (a) Typical cross section of an engineering surface, (b) high (Brewster) angle absorptance and multiple reflections due to surface roughness, (c) multiple reflections within an oxide layer.

Fig. 2. Experimental setup for measuring reflectance.

ods has been prepared by the present authors.⁴ In addition the authors have provided a comprehensive literature survey on the theory and modeling of the absorption mechanisms in metals,¹ with reference to 47 publications.

This paper presents the results of an experimental survey of the room-temperature absorptance of a wide range of as-received commercially available alloys. There are a number of different experimental methods available for measuring laser absorptance in opaque solids. Some of the more commonly used are laser calorimetry, gonireflectometry, integrating sphere or integrating mirror reflectometry, and emittance spectroscopy.⁴

In this paper reflectometry using an integrating sphere was selected, mainly because integrating spheres are commercially available, relatively inexpensive,

Fig. 3. Optical diffusivity can be measured by excluding the specular fraction of the reflected light through an empty port or by fitting a light trap.

Table 2. List of the Alloys Examined in This Survey and Their Chemical Composition

No.	Alloy	Al	Fe	Cu	Zn	Mn	Si	Mg	P
Al1 Al2, Al3 Al4	Aluminum Alloys								
	AA1050, Al, cp aluminum	99%	0.4%	*	*	*	0.25%	*	—
	AA 5251, AlMg, NS4	95.5%	0.50%	0.15%	0.8%	0.8%	0.4%	2.0%	—
	AA6082, AlMgSi, T6	96%	0.5%	*	0.2%	0.7%	1.0%	0.9%	—
Cu1 Cu2, Cu3	Copper Alloys								
	Pure copper, C106-Cu7n37	—	—	99.8%	—	—	—	—	*
	Brass, CZ108 or Cu DHP	—	—	63%	37%	—	—	—	—
Zn1 Zn2 Zn3, Zn4	Zinc Coatings								
	Zintec, electroplated				>99% [†]				
	Galvatite, electroplated				>99% [†]				
	Hot-dipped liquid coated				>99% [†]				

*Trace (<0.1%).

[†]Surface composition.

Table 3. Surface Conditions of the 11 Samples Studied

No.	Alloy	Surface	Percent	Isotropic	S_a [μm]	S_q [μm]
Aluminum Alloys			Al%			
Al1	AA1050	Cold rolled	99%	N	0.25	0.32
Al2	AA5251	Cold rolled, 3 mm thick	95.5%	N	0.28	0.35
Al3	AA5251	Cold rolled, 6 mm thick	95.5%	N	0.23	0.29
Al4	AA6082	Cold rolled	96%	N	0.30	0.36
Copper Alloys			Cu%			
Cu1	Pure Cu	Cold rolled	99.8%	N	0.16	0.20
Cu2	Brass	Cold rolled, nonpolished	63%	N	0.50	0.62
Cu3	Brass	Cold rolled, polished	63%	N	0.54	0.66
Zinc Coatings			Zn%			
Zn1	Zintec	Galvanized-electroplated	>99%	Y	2.34	2.77
Zn2	Galvatite	Galvanized-electroplated	>99%	Y	0.52	0.68
Zn3	Hot-dip Galv.	Hot-dipped-liquid coated	>99%	Y	0.33	0.43
Zn4	Hot-dip Galv.	Hot-dipped-liquid coated	>99%	Y	0.58	0.78

and easy to use while at the same time being very accurate and versatile. By measuring the reflectance R of a sample, we get immediate information regarding the absorptance A , since $A = 1 - R$ for opaque solids.

Although all the following measurements were made using an Nd:YLF laser, the results are also valid for Nd:YAG lasers because the wavelengths of the two types of laser (1053 or 527 nm and 1064 or 532 nm, respectively) differ by less than 1%.

2. Experimental Setup

A. Instrumentation

The reflectance measurements were carried out in the laser laboratory at the Mid Sweden University,

Ostersund. The laser used as the radiation source was a 1 W cw Nd:YLF laser with a fundamental wavelength of 1053 nm, equipped with a SHG (second-harmonic generation) crystal to also allow production of green light at 527 nm.

The reflectance of the various metals was measured by using an integrating sphere in a double beam setup, as shown in Fig. 2. The 150 mm diameter six-port integrating sphere has a barium sulphate-based coating called Spectrafect, which has high reflective Lambertian properties for wavelengths between 300 and 2400 nm.

The Nd:YLF laser beam was directed onto a rotatable mirror (M2 in Fig. 2) that was flipped between

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
15.7%	1.3%	32.4%	2.8%

Sa[μm]	0.25	Sq[μm]	0.32
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Fig. 4. (Color online) Al1: AA1050, commercially pure aluminium.

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
20.7%	0.7%	42.6%	1.2%

Sa[μm]	0.28	Sq[μm]	0.35
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(a)

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
26.9%	1.3%	53.9%	1.8%

Sa[μm]	0.23	Sq[μm]	0.29
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(b)

Fig. 5. (Color online) AA5251, AlMg: (a) Al2: AlMg, 3 mm thick, (b) Al3: AlMg, 6 mm thick.

two positions to produce sample and reference beams. The flipping frequency was set to approximately 1 Hz to ensure mirror stability. Mirrors 3 and 4 (M3 and M4 in Fig. 2) then directed the beams onto the sample and reference, respectively, at an angle of incidence of 8° . As reference, a port plug of Spectrafect was used. After spatial integration by the sphere, the reflected light was then detected by a reverse biased 5.7 mm^2 Si photodiode, with a spectral response between 190 and 1100 nm. The voltage signal of the photodiode was finally digitized in an analog-to-digital (A/D) converter and sampled by a personal computer (PC).

The laser beam was partially focused from its original diameter of 10 mm to approximately 3 mm on

the sample surface by using a lens with a diameter of 25 mm and a focal length of 150 mm (see Fig. 2). The port diameters (see Fig. 2) were 25 mm. The samples were cleaned with isopropyl alcohol and dried before measurements were taken. In all cases the samples were checked for differences in reflectance as a function of any directional surface structure. This was done by rotating the sample between measurements. For these samples no correlation between surface structure orientation and reflectance was observed.

B. Error Correction Methods

Several correction methods were applied to the reflectance measurements to improve accuracy and

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
23.9%	1.3%	39.3%	3.0%

Sa[μm]	0.30	Sq[μm]	0.36
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Fig. 6. (Color online) Al4: AA6082, AlMgSi.

minimize errors. Clarke and Compton⁵ have identified the following main sources of error in integrating sphere reflectometers:

- Light losses through ports in the sphere wall.
- Unequal illumination of the sample and standard and changes in throughput when a single beam method is used.
- Directional dependence of light scattering from the sample and standard surfaces.
- Errors attributable to diffraction effects in apertures.
- Errors attributable to imperfect diffusion of reflected light from the sphere walls (non-Lambertian characteristics).

(f) Baffling.

To minimize these errors the following procedures and correction methods were applied to the measurements.

1. Light Losses

With the aim of reducing light losses, all ports not in use were closed with port plugs.

2. Unequal Illumination of Sample and Standard

The double beam configuration used in these experiments avoids the substitution error, which is often a feature of single beam measurements (and can be as large as 4%–5% according to the manufacturers⁶).

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
5.6%	1.0%	57.6%	1.3%

Sa[μm]	0.16	Sq[μm]	0.20
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Fig. 7. (Color online) Cu1: commercially pure copper.

The double beam configuration also has the advantage of reducing the influence of possible laser power fluctuations.

3. *Directional Dependence of Light Scattering*
 Light behaves slightly differently inside the sphere when reflected from a rough surface as compared to a relatively flat one. The light incident on a flat surface is subjected to mirrorlike, specular reflection in contrast to rough surfaces where the reflected light is scattered diffusively in many different directions. This produces differences in the number of reflections needed inside the sphere before the light is homoge-

neously scattered, which will lead to detector throughput changes. This error can be corrected for by using a combination of diffuse (rough) and specular (flat) reflectance standards.
 By knowing the sample's optical diffusivity, D_s , which is the fraction of reflected light that is scattered diffusively, the reflectance of the sample, R_s , can be obtained by

$$R_s = S_s \left[(1 - D_s) \frac{R_{s,r}}{S_{s,r}} + D_s \frac{R_{d,r}}{S_{d,r}} \right], \tag{1}$$

λ=1053nm		λ=532nm	
A	σ	A	σ
10.2%	1.0%	34.1%	2.0%

Sa[μm]	0.50	Sq[μm]	0.62
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(a)

λ=1053nm		λ=532nm	
A	σ	A	σ
13.3%	1.7%	37.5%	2.1%

Sa[μm]	0.54	Sq[μm]	0.66
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(b)

Fig. 8. (Color online) Brass: (a) Cu2: nonpolished brass, (b) Cu3: polished brass.

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
77.6%	0.2%	60.5%	0.3%

Sa[μm]	2.34	Sq[μm]	2.77
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Fig. 9. (Color online) Zn1: Zintec.

where S_s is the signal measured with the sample, $R_{s,r}$ is the reflectance of the specular standard (mirror), $S_{s,r}$ is the signal measured with the specular standard, $R_{d,r}$ is the reflectance of the diffuse standard, and $S_{d,r}$ is the signal measured with the diffuse standard.⁷

The optical diffusivity can be measured by opening the specular exclusion port (or attaching a light trap) and comparing the signal from the sample to a signal from the diffuse standard (see Fig. 3). The optical diffusivity is then given by

$$D_s = 1 - \frac{S_{s,spex}/S_s}{S_{d,spex}/S_{d,r}}, \quad (2)$$

where $S_{s,spex}$ is the signal measured with the sample and with the specular exclusion port opened, and $S_{d,spex}$ is the signal measured with the diffuse standard and the specular exclusion port opened. Using this method, a diffusivity of 100% was assigned to the diffuse standards and 0% to the specular mirror standard. This error was empirically seen to be almost

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
53.8%	1.9%	33.4%	1.4%

Sa[μm]	0.52	Sq[μm]	0.68
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Fig. 10. (Color online) Zn2: Galvatite.

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
63.1%	3.7%	48.7%	3.9%

Sa[μm]	0.33	Sq[μm]	0.43
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(a)

$\lambda=1053\text{nm}$		$\lambda=532\text{nm}$	
A	σ	A	σ
63.0%	3.5%	45.1%	6.6%

Sa[μm]	0.58	Sq[μm]	0.78
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(b)

Fig. 11. (Color online) Hot-dipped galvanized (spangled). (a) Zn3: sample I, (b) Zn4: sample II.

negligible for $\lambda = 527 \text{ nm}$, but could amount to more than 1% in absolute reflectance for $\lambda = 1053 \text{ nm}$.

4. Diffraction Effects in Apertures

To get a suitable laser spot size on the sample, a lens was put in front of the sample beam entrance port. Owing to diffraction, this produces a characteristic halo around the sample and sample port, which causes a slight error to the measurements. Empirically this was shown to be approximately 0.2% in absolute reflectance. This error was easily corrected

for by measuring the signal with the sample port empty and subtracting this from the signal with the sample in place.

Errors (e) and (f) are due to the specific sphere designs and are not easily corrected for.

Another error was identified in the case of structured samples with contoured surfaces (termed lay in the literature on surface properties). According to Roos⁸ this error can be substantial if care is not taken in positioning the samples correctly in the sample ports. A contoured surface produces a reflected band

of light (termed specular-diffuse radiation by Roos⁸), which will produce errors if the band crosses the detector (giving too high a reflectance value) or passes through any open beam ports (giving too low a reflectance value). No corrections other than correct positioning was applied in this case.

In experiments such as this it is always important to eliminate the possibility of error as a result of polarization effects. In this work polarization of the laser beam was identified as having a trivial effect upon the results because the angle of incidence of the beam was very close to normal (between 8° and 9°). At these low angles of incidence, polarization effects are minimal.

The measurements were performed in a dark room to minimize the influence of external light sources, such as lamps. Corrections were also made to the current flowing through the photodiode in the absence of light. These dark current measurements were performed before each measurement, which were then subtracted from the measured signals.

Using the correction methods outlined above, the reflectance values of all the diffuse and specular standards were seen to be reproducible to at least within 0.3% in absolute reflectance. The same reliability can be attributed to the following results for the samples investigated.

C. Samples and Measurements

Table 2 lists the different nonferrous samples examined in the survey in terms of their standard identification numbers and their chemical composition. Three types of material groups were studied: Al alloys, Cu alloys, and Zn coatings on mild steel (the substrate having no importance because the light interacts only with the zinc surface). Note that a similar study on mild and stainless steel was also performed and is under preparation as a separate paper.

The corresponding technical surfaces for the 11 samples studied are described in Table 3. The roughness values given in this table are supported by scanning electron microscopy (SEM) and optical microscopy together with profilometry imaging in Section 3 of this paper. In the case of the Cu and the Al alloys investigated here, the final cold rolling process gives a directional grain to the surface roughness of these materials. The two electroplated Zn coatings have a fine isotropic grain structure, and the hot-dipped Zn coating has a distinctive spangled appearance. All the metal surfaces were measured in the as-received condition.

The samples were laser or mechanically cut from sheets into 30 mm squares with thicknesses varying between 2 and 6 mm. For each sample, the absorbance measurements were taken at five separate locations; they were then averaged, and a standard deviation was calculated. Each measurement for every location is in turn an average of over 300 data points.

All integrating sphere measurements were carried out relative to a standard of known reflectance. In these experiments a combination of diffuse and specular reflectance standards was utilized. The diffuse

Fig. 12. Absorbance as a function of the surface roughness for the four aluminium alloy samples studied (reference values in Figs. 4–6).

standards had reflectances between 2% and 99%. The specular standard consisted of an Al-coated mirror, which was calibrated at the Angström Laboratory in Uppsala, Sweden. It had a reflectance of 97.7% at 1053 nm and 98.9% at 527 nm.

The reliability of the measurement method was regarded as satisfactory. The variance σ of the measured A values was low. In 15 of 22 cases (11 material samples, 2 wavelengths) the variance of the five measurements taken for each sample was less than 2.0%; only in one case (Zn3, green) was the variance higher than 4% (namely, 6.6%).

3. Results and Discussion

A. General

Figures 4–6 for the Al alloys, Figs. 7 and 8 for the Cu alloys, and Figs. 9–11 for the Zn coatings present the optical microscopy (OM), SEM, profilometry, and absorbance results obtained in this survey. In each figure the magnification used is 100 times for the OM pictures, 2000 times for the SEM photos, and 5 times for the 3D optical profilometry scans. The surface was measured with a Wykon NT1100 optical profiler, achieving a horizontal resolution of 6.8 μm and a vertical resolution in the nanometer range. In the tables below the photos the average absorbance A and standard deviation σ are given for both wave-

Fig. 13. Absorbance as a function of the surface roughness for the three copper alloy samples studied (reference values in Figs. 7, 8).

Fig. 14. Absorbance as a function of the surface roughness for the four Zn coating samples studied (reference values in Figs. 9–11).

lengths as well as the results of the optical profilometry measurements. S_a and S_q are the average roughness and rms roughness evaluated over the complete 3D surface, respectively. If the surface elevation is given by $Z(x, y)$, S_a and S_q are evaluated mathematically as follows (with surface area A):

$$S_a = \iint_A |Z(x, y)| dx dy,$$

$$S_q = \left(\iint_A (Z(x, y))^2 dx dy \right)^{1/2}. \quad (3)$$

Figures 12, 13, and 14 show the measured absorbance plotted as a function of the surface roughness for Al, Cu, and Zn alloys, respectively.

B. Aluminium Alloys

The measured absorbance as a function of the roughness is plotted in Fig. 12 for the four Al samples and for the two wavelengths used. It is clear from this figure that there is no clear correlation between surface roughness and absorbance.

Previously published figures put the absorbances of Al as 4.8% at 1053 nm and 7.6% at 527 nm.⁹ The figure we measured for our commercially pure (99% Al, sample Al1) aluminium sheet for 1053 nm was ~16%, and this threefold increase is clearly attributable to the oxidized and unpolished nature of our sample. The average figure of ~32% we obtained for

527 nm is surprisingly higher than the previously published value, but the accuracy of this new value is supported by the fact that all the results for 527 nm were considerably higher than for 1053 nm over the whole range of Al samples studied.

The increased absorption for the AA5XXX (samples Al2, Al3) and AA6XXX (sample Al4) grades compared with the pure aluminium sample Al1 is probably related to the increase in alloying elements in these grades.

It is interesting to note that there is an absorbance peak for Al at a wavelength of 800 nm owing to the atomic band structure of the material. This may, in the future, have positive consequences for Al processing with high power diode lasers in this wavelength region.

C. Copper Alloys

The measured absorbance as a function of the roughness is plotted in Fig. 13 for the three Cu-based samples and for the two wavelengths applied. Once more there is no clear correlation between roughness and absorbance.

Once again the pure Cu has a higher absorbance (6% at 1053 nm and 58% at 527 nm) than the previously published values [e.g., 2.4% at 1053 nm and 38.2% at 527 nm (Ref. 9)]. The explanation for the quite large difference in absorbance between the two wavelengths lies in the details of the band structure of Cu, showing a typical interband absorption edge at $\lambda \sim 550$ nm. The addition of 37% of Zn to the Cu (to produce brass) increases the absorbance at 1053 nm but decreases it at 527 nm for reasons that will be discussed below for the Zn coatings.

D. Zinc Coatings

The measured absorbance as a function of the roughness is plotted in Fig. 14 for the four Zn-coated samples and for the two wavelengths applied. Once again there is no clear correlation between roughness and absorbance at the lower roughness values. There is, however, a noticeable increase in absorbance for the samples with roughness values above 2 μm .

Zn coatings come in a wide range of finishes, and three of the most commonly available have been tested here. Of course, we are no longer dealing with a mild steel surface in this case, and the laser is interacting only with the Zn. It can be observed from Fig. 14 that in every case except where Zn is involved,

Table 4. Summary of the Absorbance and Reflectance Measurements

Material	$\lambda = 1053$ nm		$\lambda = 527$ nm	
	Absorbance	Reflectance	Absorbance	Reflectance
Al1: Commercially pure Al	16%	84%	32%	68%
Al2,3: AA5251, AlMg (average)	24%	76%	48%	52%
Al4: AA6082, AlMgSi	24%	76%	39%	61%
Cu1: Commercially pure Cu	6%	94%	58%	42%
Cu2,3: Brass, CuZn37 (average)	12%	88%	38%	62%
Zn1–4: Zinc coatings (average)	64%	36%	47%	53%

Fig. 15. Absorbance as a function of the surface roughness (below an S_a value of $0.6 \mu\text{m}$) for all Al alloys, Cu alloys, and Zn coatings studied for both wavelengths.

the absorbance of the metals at 527 nm is higher than it is at 1053 nm. In the case of brass (37% Zn) and the Zn-coated mild steel this trend is reversed. The reason for this lies in the band structure and the absorbance spectra of Zn, the latter of which has a sharp peak at $\lambda \sim 1080 \text{ nm}$.¹⁰

The absorbance of the Zintec sample is considerably higher than that of the Galvalite or galvanized (spangled) samples. The SEM photographs and surface roughness measurements indicate that the reason behind this higher absorbance is the considerably rougher surface texture of the Zintec (the Zintec sample gave roughness values that were more than three times greater than any other sample in this whole series of tests).

E. Summary of the Absorbance Measurements

Table 4 provides a summary of the absorbance and reflectance values obtained for all the various alloys investigated. All these measurements demonstrated that engineering grade metal surfaces have absorbances that are considerably higher than those published for pure, polished surfaces. In the case of Cu and Al alloys the absorbance is higher for a wavelength of 527 nm than for one of 1053 nm. For Zn this trend was reversed. All the absorbance values are shown in Fig. 15 as a function of the surface roughness with the exception of the Zintec sample.

It is clear from Fig. 15 that, if the surface roughness of the sample is lower than $S_a = 0.6$, then there is no clear correlation between roughness and absorbance. On the other hand, it appears that absorbance does increase if the surface roughness measurement S_a has a value above 2.3 (Zintec; S_a : 2.34; A: 77.6 for 1053 nm, 60.5 for 532 nm) this phenomenon is the subject of an ongoing investigation by the present authors.

4. Conclusions

Reliable absorbance results have been measured for a range of nonferrous alloys for Nd:YAG and Nd:YLF lasers at their IR and green wavelengths. These results have, as expected, been found to differ substantially from existing published data for pure, polished metals.

The increases in absorbance for engineering grade surfaces can be broadly attributed to surface oxides, roughness, and alloying ingredients, but further study is necessary to isolate the contribution of each factor.

Over the range of surface roughness from approximately $S_a = 0.15$ – 0.60 there was no clear correlation between surface roughness and absorbance. However, one much rougher sample ($S_a = 2.34$) indicated that outside this range there could be a roughness–absorbance correlation.

For the Al and Cu alloys studied here the absorbance was higher for the green wavelength than for the IR. This trend was reversed for the Zn surfaces as a result of the band structure and absorption spectra of Zn.

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