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Dynamic and absolute measurements of laser coupling efficiency during laser spot welds

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Abstract

Laser absorptance (coupling efficiency) changes rapidly during laser metal processing due to temperature and multiple phase changes. We find that there is limited literature data available, but that this property is vital for accurate process simulations, as well as the fundamental understanding of the dynamics of high-power laser-matter interaction. We measure the dynamic, absolute absorbed power with sub-microsecond resolution during a 10 ms laser spot weld in 316L stainless steel from conduction to keyhole welding conditions using an integrating sphere. Our data show several important features including the points of melting and keyhole formation. Conclusions from the optical data are supported by weld cross-section analysis.

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1. Introduction

Lasers are being increasingly deployed in manufacturing, particularly for use in metal joining for welding and in additive manufacturing. When lasers are used for this purpose, an intense beam of light melts a target area such that when it solidifies a mechanical bond remains. The process by which this occurs involves complex light-matter interaction with a material system that is rapidly changing from a solid to a liquid and can include interactions with vapor and particle ejections as well. As a result, a basic property like optical absorptance is difficult to measure or predict. The absolute value of the absorption of incident energy is the foundation of any model that hopes to give predictive information about a joining process, and is therefore of vital importance.

Previous measures of optical absorptance have either been calorimetry based [1-4], and thus gave average values over the weld process, or dynamic approaches based on scattered light [5-8]. Here, we build of these earlier studies of dynamic absorptance by measuring the time-resolved, absolute absorptance during a single laser spot weld using a custom made integrating sphere. The spot-welded material was a National Institute of Standards and Technology (NIST) standard reference material (SRM) for 316L stainless steel [9]. Our laser weld conditions covered low to high input energy spot welds resulting in conduction through keyhole weld conditions. These determinations were made by observing the weld nugget cross-sections. The data we obtained with this technique will be useful for weld model validation as well as for a better general understanding of laser interaction with the weld pool.

2. Methods

Sample material was cut from NIST SRM 1155a [9] feedstock into discs that were 11 mm in diameter and 2 mm thick and had an average mass of 1.464 ± 0.020 g. A consistent surface finish was obtained by consecutive

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polishing of the surface, first with 240 grit sandpaper followed by 2400 and 4000 grit for 30 seconds each. This process achieved a near mirror-like finish. Before laser spot welding, the samples were cleaned with acetone and blown dry with clean, dry compressed air.

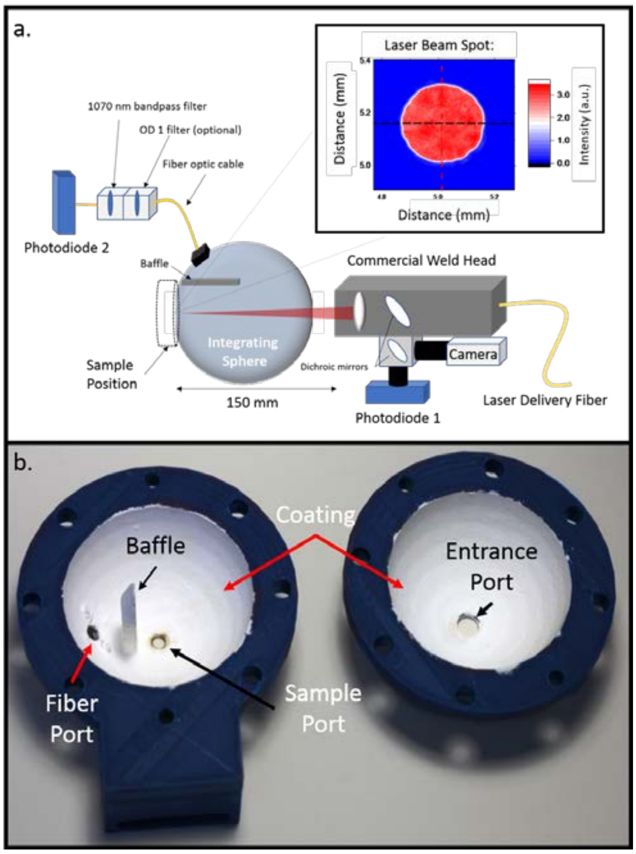

Fig. 1 a. An experimental diagram of the apparatus used to measure dynamic absorptance. The inset shows the measured beam profile at the focus. b. This shows the interior of the two halves of our custom made integrating sphere.

A diagram of the experimental arrangement is shown in Fig. 1a. The laser used was a fiber laser capable of 1.5 kW output power operating at 1070 nm. The laser spot welds in this study were 10 ms in duration.

An integrating sphere was used to collect the scattered light during the laser spot weld. The SRM sample was placed at the focus of the weld laser at one end of the sphere with a laser light input aperture directly opposite. The laser light was delivered through a commercial weld head with 150 mm focal length optics that produced a top-hat profiled beam 303 µm in diameter (see inset Fig. 1a.). Two photodiodes were used to collect the scattered light: one attached to the laser weld head, and one connected to the surface of the integrating sphere. The former was necessary to collect the light returning to the weld head normal to the original material surface. It was calibrated using a specular sample of known reflectance. The second photodiode was calibrated using a sample of known diffuse reflectance. Both photodiodes had bandpass filters to transmit only 1070 nm light.

The integrating sphere was made by 3D-printing two sphere halves, which are shown in Fig. 1b. The interiors of these spheres were coated with a $BaSO_4$ paint [10], which created an even, diffuse surface after the application of several (~20) thin layers. A baffle was incorporated on the interior of the sphere to shield the detection port from directly scattered light and the weld plume.

The absolute value of the absorbed laser energy was calculated from calibration parameters, C, from the photodiodes. The weld head photodiode was calibrated with a specularly reflective sample (uncoated fused quartz window) of measured reflectance and a constant C_{head} (units of W/mV) relates the photodiode voltage to the total power reentering the weld head. The absorptance of this sample is negligible at 1070 nm and therefore effects of heating should not exist. This was confirmed by measuring the temporal profiles of the directly back scattered light which did not show any time dependence during the calibration procedure. If S_{head} is the weld-head photodiode signal (in mV), the absolute laser power scattered back into the weld head, P_{head}, is given as

$$P_{head} = C_{head} \times S_{head} \,. \tag{1}$$

The photodiode mounted on the integrating sphere is similarly calibrated except with a sample with a known diffuse reflectance distribution. Details on this calibration standard can be found in reference [11]. The absolute power for the sphere is given by

$$P_{sphere} = C_{sphere} \times \left(\frac{S_{sphere}}{T} \right). \tag{2}$$

The additional term, T, is the transmission of a 1070 nm attenuation filter that was used during the laser spot weld (but not during calibration so that the signal ranges in both calibration and experimentation were comparable).

The total absorbed power, $P_{abs}(t)$, was then found by subtracting the total light lost during the weld from the input power, $P_0(t)$, as

$$P_{abs}(t) = P_0(t) - \left(P_{head}(t) + P_{sphere}(t)\right). \tag{3}$$

The functional form of P_0 was determined from a measurement of the backscattered light from the quartz sample during the weld head photodiode calibration. Its actual value was found by forcing the integrated value of this functional form to equal the measured input pulse energy, E_0. Normalizing $P_{abs}(t)$ by $P_0(t)$ gives the dynamic absorptance, $A(t)$, during the spot weld:

$$A(t) = \frac{P_{abs}(t)}{P_0(t)} \,. \qquad (4$$

The total energy absorbed during the spot weld, E_{abs}, is determined from the time integral of the absorbed power:

$$E_{abs} = \int P_{abs}(t)\, dt \,. \tag{5}$$

The average absorptance, or coupling efficiency, during the 10 ms spot weld can be calculated according to

$$\eta_{coupling} = \frac{E_{abs}}{E_0}. \quad (6)$$

3. Results and Discussion

Figure 2 shows the dynamic absorptance results found through equation (4) for 3 different input energy values over the 10 ms injection. They can be considered low, medium, and high energy values of 1.2 J, 3.3 J, and 4.6 J.

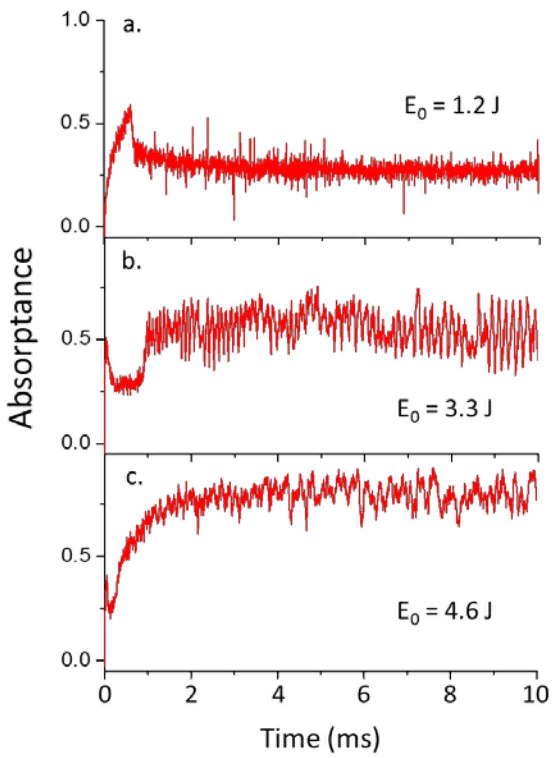

Fig. 2. Dynamic absorptance data for low (a.), medium (b.) and high (c.) input energy laser spot welds.

These data correspond to the cross-section images presented in Fig. 3 for the same values. These images clearly show that at low energy (1.2 J) a low aspect ratio weld nugget was produced that is indicative of a conduction weld. At high energy (4.6 J) a fluted, high aspect ratio weld bead was formed, which indicates that keyhole formation was achieved. The cross-section taken at medium energy (3.3 J) shows signs between these two extremes.

Several features of the weld pool dynamics can be identified from the time-dependent absorptance seen in Fig. 2. At short times, less than 1 ms, all data show a steep rise in the absorptance. This behavior is due to solid state heating from a combination of effects including Drude absorption [12,13], oxide formation [14], and semisolid phase-induced surface roughness [15]. This peak was quickly followed by a sudden drop in absorptance.

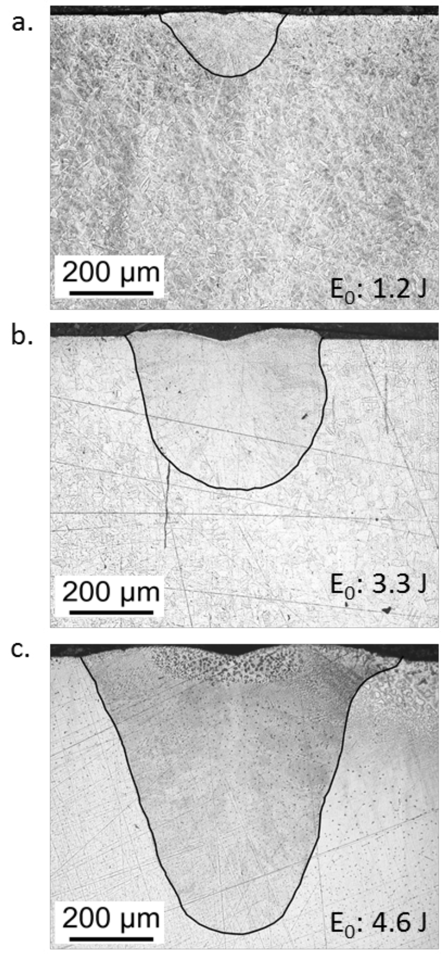

Fig. 3. These are cross-sections for the low (a.), medium (b.), and high (c.) energy spot welds corresponding to the same dynamic data given in Fig. 2. The black lines are given as an aid in defining the outline of weld nugget cross-section.

This can be explained by a sudden loss of surface roughness due to melting when surface tension creates a highly reflective, specular surface. This explanation is consistent with experimental works that have studied the absorption of metals as a function of temperature and surface finish [15-17].

At medium and high input energies, this absorptance was followed by an additional rise, most dramatically seen (nearing 90% absorption) in the high energy case. As the weld nugget cross-section of the high energy case clearly indicates, a keyhole regime has been achieved, and since a keyhole results in a significant increase in absorption due to multiple reflections, it is reasonable to conclude that this second increase is a mark of keyhole formation. The above interpretation is supported by the average coupling efficiency computed through equation (6). These values over a range of input energies, E_0, are shown in Fig. 4. One clearly sees a step function behavior from low coupling efficiency around 0.3 to a steep transition eventually approaching nearly 0.9. Such behavior has been seen by other groups [1,4,5,18] and is viewed as a transition from conduction to keyhole welding regimes as E_0 increases. This is consistent with the weld cross sections given in Fig. 3.

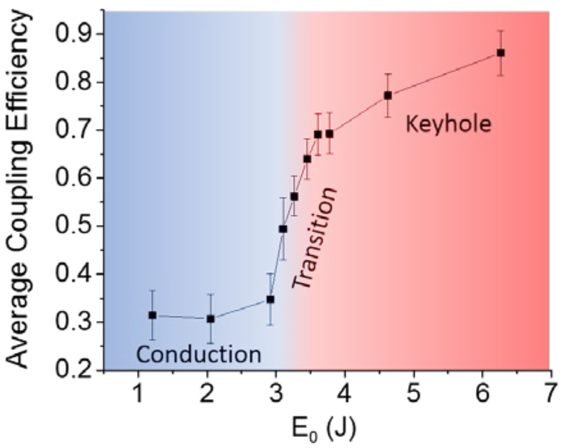

Fig. 4. Average coupling efficiency as a function of input energy during a 10 ms laser pulse.

4. Conclusions

We have demonstrated a method for accurately measuring the dynamic absorptance of laser light during a 10 ms laser spot weld using an integrating sphere. These data reveal phase change information as the target melts and, at sufficiently large input energies, a keyhole is formed. Weld nugget cross-sections are used to validate conclusions about the dynamic absorptance. The average coupling efficiency over a wide range of input energies shows a sharp transition from low coupling efficiency (around 30%) to very high coupling efficiency approaching 90%. This is consistent with the formation of a keyhole cavity that enables increased absorption through multiple reflections of the incoming laser light.

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