Measuring laser power as a force: A new paradigm to accurately monitor optical power during laser-based machining operations

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ABSTRACT

In laser manufacturing operations, accurate measurement of laser power is important for product quality, operational repeatability, and process validation. Accurate real-time measurement of high-power lasers, however, is difficult. Typical thermal power meters must absorb all the laser power in order to measure it. This constrains power meters to be large, slow and exclusive (that is, the laser cannot be used for its intended purpose during the measurement). To address these limitations, we have developed a different paradigm in laser power measurement where the power is not measured according to its thermal equivalent but rather by measuring the laser beam's momentum (radiation pressure). Very simply, light reflecting from a mirror imparts a small force perpendicular to the mirror which is proportional to the optical power. By mounting a high-reflectivity mirror on a high-sensitivity force transducer (scale), we are able to measure laser power in the range of tens of watts up to ~ 100 kW. The critical parameters for such a device are mirror reflectivity, angle of incidence, and scale sensitivity and accuracy.

We will describe our experimental characterization of a radiation-pressure-based optical power meter. We have tested it for modulated and CW laser powers up to 92 kW in the laboratory and up to 20 kW in an experimental laser welding booth. We will describe present accuracy, temporal response, sources of measurement uncertainty, and hurdles which must be overcome to have an accurate power meter capable of routine operation as a turning mirror within a laser delivery head.

Keywords: Radiation pressure, high power laser, metrology, radiometry, laser welding

1. INTRODUCTION

High power lasers capable of continuous output powers ranging from hundreds to tens-of-thousands of watts present exciting opportunities for rapid, directed delivery of energy – particularly in the area of materials processing and laser machining. Laser-based techniques for cutting and welding have been around for many years and offer advantages of operation at a distance, rapid and localized heat delivery, cost reduction, and reduced material waste. The result of a laser welding or cutting operation depends on many factors including intrinsic material properties, geometry of the workpiece, feed rate, shield gas type, flow parameters, and of course the delivered laser power. In this paper, we will examine a novel technique of using radiation pressure to measure the output power from the high-power lasers used in laser machining operations. We focus on laser welding but the principles are extendable to other laser processing operations.

The laser power, or more specifically power density, determines the energy delivery rate into the material. To characterize the weld operation for qualification purposes, or to fully specify the desired setup, or for use in failure analysis, it is important to accurately quantify the delivered laser power.

Here we describe the measurement of optical power from its radiation pressure, which allows accurate measurement of a laser's power without absorbing it. This unique measurement property enables a new paradigm in high-power laser calibration, and in this paper, we demonstrate two specific opportunities afforded by this technique. First, the laser power can be accurately measured simultaneous to the laser welding operation. Second, the unique operation of the radiation pressure power meter and its portability enable it to easily be used for on-site calibration of existing high power laser power meters.

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High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications V,
edited by Friedhelm Dorsch, Stefan Kaierle, Proc. of SPIE Vol. 9741, 97410L
© 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2213300

1.1 Traditional approaches for high power laser radiometry

Not surprisingly, it is difficult to accurately measure the optical power emitted by a high power laser. The current approach is a power meter which fully absorbs as much as possible of the incident laser light and reports a temperature increase which can then be related to the optical power injected by the laser[1]. This presents the requirement that the sensor size (total heat capacity) must increase proportionally with the maximum laser power to be measured, and more thermal mass translates to a slower measurement response time. For multi-kilowatt power levels full power measurements can be carried out by either a thermopile or a "flowing water" style power meter, which have claimed uncertainties of 1 % - 5 %. In the case of laser welding such power meters can be installed in the welding workstation and periodic laser power calibration is accomplished by directing the weld head to inject laser light onto the power meter. Since these power measurement techniques require the full laser power to be incident on the power meter, they require exclusive operation. That is, laser power cannot be measured during a weld operation, but only before or after the weld takes place.

A less complicated measurement with a much faster response time can be achieved by using a non-thermal technique (a photodiode for example) where the light from the high power laser is measured by sampling only a small fraction of the power, this puts stringent requirements on how accurately the fractional splitting ratio of the beam needs to be known. The photodiode and the splitting ratio of a beam pickoff can exhibit temperature sensitivity due to heating by the laser light, and spatially sampling the beam would require a well-characterized and stable power profile across the beam face. Fractional beam sampling can be very useful for fast, relative measurements of laser power fluctuations, but is less attractive when high-accuracy absolute (traceable) measurements of total power are required.

1.2 Optical radiation pressure as a measure of optical power

Optical radiation pressure allows for the measurement of a laser beam's power without absorbing it. This completely changes concerns about thermal management and response time scaling with laser power as well as opening the possibility of measuring the laser's optical power while simultaneously using it for materials processing (e.g. welding).

The idea of radiation pressure or photon momentum has been understood for centuries[2,3], and was experimentally demonstrated over 100 years ago[4,5]. Since light carries momentum, a force is required to change its direction (wavevector). If the momentum carried by a light beam is $\boldsymbol{p}$, then the force it imparts depends on the time rate of change of that momentum $\boldsymbol{F}=\mathrm{d}\boldsymbol{p}/\mathrm{d}t$. The magnitude of the momentum of a quantity of light carrying energy E is given as $|p|=E/c$, where c is the speed of light. So, for a beam with optical power $P=\mathrm{d}E/\mathrm{d}t$, a perfectly reflecting mirror will reverse the momentum of the incident light, generating a force $F=2P/c$. So, light incident on a non-scattering mirror with non-ideal reflection and absorption will push on the mirror with a force

$$F = \left({}^{2P}\!/_{c}\right) r \cos(\theta), \tag{1}$$

where $r = R + (1 - R)\alpha/2$ describes the reflectivity and absorption, accounting for the fact that an absorbed photon imparts all its momentum, and a reflected photon imparts twice its momentum. R is the mirror reflectivity, α is the fraction of non-reflected light absorbed by the mirror, and θ is the angle of incidence. Equation (1) describes a maximum power-to-force conversion factor of $2/c = 6.67\times10^{-9}$ N/W for normal incidence on a perfectly reflecting mirror.

The first experimental demonstrations of radiation pressure came in the early 20th century[4,5]. Heroic efforts were made using torsion balances to detect deflections due to tiny forces from incident light with powers on the order of 100 mW. These and later works[6–11] have used these highly sensitive torsion balances almost exclusively to achieve the required sensitivities and have thoroughly demonstrated the validity of radiation pressure. However, a torsion balance is not readily portable and would not lend itself to operation in a non-laboratory environment.

With the recent advances in high power lasers and the commercial availability of sensitive force transducers ("scales" or "balances"), practical measurement of laser power by measuring the photon force of the light has become practical. The 2/c power-to-force conversion factor shows that a kilowatt of laser power normally incident on a perfectly-reflecting mirror will generate a force of 6.67 μN, which, for reference, is the force of gravity acting on a mass of 0.68 mg. Fairly robust, off-the-shelf commercial balances are available with readabilities (sensitivities) in the range of 1 μg - 10 μg, so the measurement of kilowatt-level forces are easily achievable.

With this in mind, consider the alternative laser power meter depicted in Figure 1. A scale has its balance pan replaced with a highly reflecting mirror (reflectivity optimized for the angle of incidence θ). Laser light incident on the mirror will be measurable as a force on the scale. An advantage of this technique is that such a radiation pressure power meter can be calibrated with a precision mass, relating the optical watt to the kilogram.

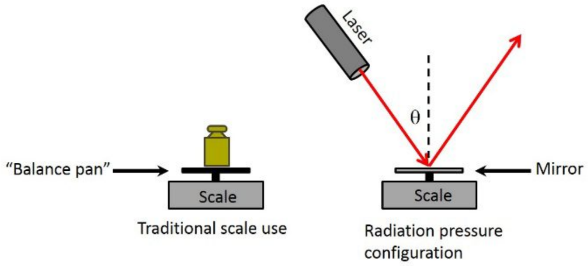

Figure 1. Traditional use of a scale (left) and a scale configured to measure radiation pressure (right). The "balance pan" for weighing materials is replaced with a highly reflective mirror.

1.3 *In situ* power monitoring of a laser weld

As seen in Figure 1, radiation pressure permits the measurement of the power in a laser beam without attenuation, leaving the beam available for other uses (e.g., laser welding). This presents the possibility of a radiation-pressure-based laser power meter that could be miniaturized and placed in a laser weld head as a simple turning mirror. Light reflecting from this turning mirror could have its power accurately measured without perturbing the beam, enabling real-time power measurement during laser welding operations. We will describe our use of a prototype radiation pressure power meter to demonstrate the feasibility of such an approach in a laser welding workstation at NIST using optical powers up to 5 kW.

1.4 Portable power meter calibration

The ability to measure laser power without absorbing the light also opens the possibility for a new approach in calibrating conventional laser power meters at the manufacturing site without the need to send the power meter to a calibration laboratory. By directing a laser beam onto the sensing mirror of a radiation pressure power meter and then placing the conventional power meter in the path of the reflected light will allow simultaneous measurement of the same laser power with both power meters. This represents a greatly simplified calibration geometry and could reasonably be performed in a welding environment allowing for efficient (and frequent) calibration of conventional power meters in the manufacturing environment. In order to test this possibility, we have used our prototype radiation pressure power meter to perform a calibrating measurement of a conventional "flowing water" power meter located in a welding workstation at the Federal Institute for Materials Research and Testing (BAM) in Berlin. Measurements of laser powers from 500 W to 20000 W were carried out illustrating the measurement possibilities with this approach.

2. EXPERIMENTAL SETUP

2.1 Radiation pressure power meter design

Very simply, a radiation pressure power meter (RPM) consists of a highly reflective sensing mirror attached to a sensitive scale to measure the force, and a protective shroud to shield against air currents. Our prototype RPM uses a commercial style scale with a readability (sensitivity) of 10 μg and a 2.5 g capacity. The scale was selected for its ability to measure either vertically or horizontally-directed forces[12]. The scale has a response time of ~ 2 s and as operated yielded a sampling rate of 4 Hz. In practice, we found for the force levels measured in these demonstrations, a significant perturbation required a period of 5 s for the scale reading to settle to its final value (to within the scale readability). This is typical of commercial scale technology, but a dedicated RPM could be expected to have a more rapid response. For high laser powers, the sensing mirror must be of the highest reflectivity possible since residual un-reflected light can heat the scale, at best affecting its reported force and at worst, damaging the scale. We used a molecular beam epitaxy process at NIST to create alternating GaAs and AlGaAs layers forming a distributed Bragg reflector (DBR) mirror. This mirror has a reflectivity better than 0.999 at a 45° incidence angle at a wavelength of 1071 nm. As with any sensitive scale, air currents and acoustic noise can generate drift or noise on the measured force, so an isolating chamber is necessary. We surrounded the scale with a protective aluminum housing and anti-reflection-coated windows.

Force as a function of applied laser power has been previously tested[13] for this RPM for powers from 50 W to 92000 W applied in a horizontal direction (Figure 2). Results agreed with theory to within our ability to measure at the time. Since then, more carefully controlled measurement comparisons between laser power and measured force at 5 kW have shown agreement with theory to approximately 1 %[14].

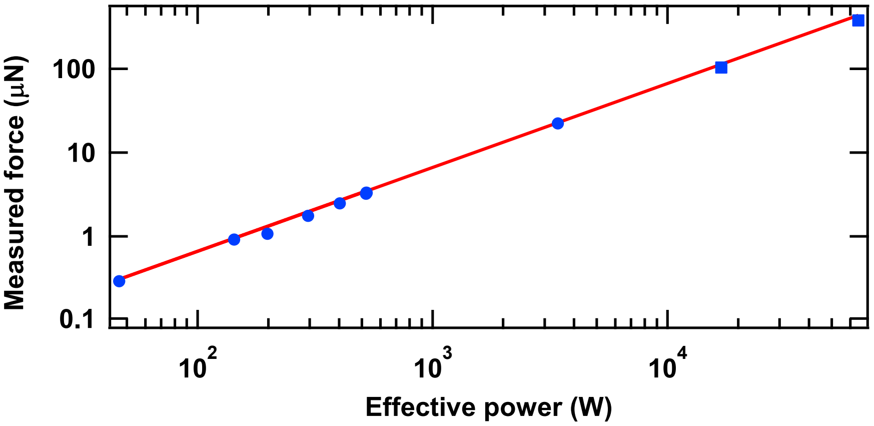

Figure 2. Measured radiation force for various laser powers. “Effective power” normalizes the cosine scaling to remove the dependence on the angle of incidence. The red line is the predicted conversion curve with slope $2/c$.

Preliminary estimates of measurement uncertainty for the current RPM design are dominated by the uncertainty in scale calibration. For the lowest mass range (300 µg to 500 µg), which corresponds to about 600 W to 1000 W of laser power, the uncertainty in scale calibration is estimated to be approximately 1.5 % (includes a coverage factor of 2 giving an approximate 95 % confidence interval). We use this as our preliminary uncertainty estimate.

2.2 *In situ* power monitoring of a laser weld - Design

In order to use our prototype radiation pressure power meter for in-situ weld monitoring, we had to make some accommodations. Our welding workstation uses a 10 kW capacity Yb-doped fiber laser (operating wavelength 1071 nm) fed to a weld head producing a vertically downward-travelling focused beam. However, our prototype RPM expects a horizontally-travelling beam. Therefore, for the quick test of laser weld power monitoring, we modified our weld head to produce a horizontally-travelling beam. Figure 3 shows an overhead view of the setup of the RPM in the welding workstation. The process fiber (300 µm core diameter) from the laser was terminated in a 140 mm focal length collimator, with the output of the collimator acting as the input window to the RPM. The collimated light reflected off the DBR sensing mirror (76.2 mm diameter) at an angle of 45˚ (±0.25˚) and exited into a lens tube where it encountered a BK7 focusing lens (50.8 mm diameter, 300 mm focal length, anti-reflection coated, reflectance $R<0.002$ per side). The lens was followed by a protective window (BK7, $R<0.002$ per side) to guard the lens from degradation in the welding environment.

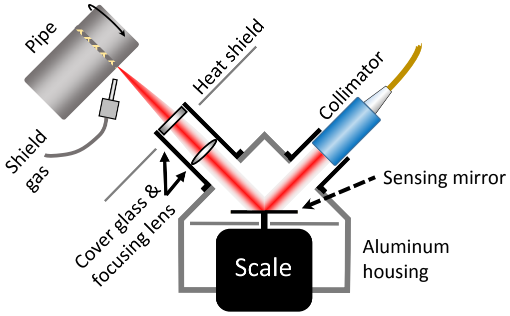

Figure 3. Design of prototype radiation pressure power meter (RPM) in laser welding booth (overhead view). The RPM consists of the scale with attached mirror. The process fiber leads to the collimator which launches collimated light at a 45˚ angle of incidence onto the mirror. The reflected light encounters the focusing lens and the protective cover glass, passes through the foil heat shield and is focused onto the stainless steel pipe on a rotation stage. Note the diagram is an overhead view, the welding laser beam is travelling horizontally and the scale is configured to measure horizontal force.

The light was focused onto the work-piece, which was a stainless steel pipe (type 304L, 89.5 mm outer diameter, 5.6 mm wall thickness) on a rotary stage. The spot size was not measured but from the core diameter of the multi-mode process fiber, the collimator focal length, and the focal length of the focusing lens, we expect the spot to be approximately 640 μm diameter. A nozzle emitting nitrogen shielding gas (flow rate 56 liters/minute) was positioned approximately 2 cm from the work surface. In order to partially shield the RPM from the heat of the welding process, a foil heat shield was placed between the work-piece and the RPM (with a nominally 75 mm diameter hole to allow the light to pass).

Although the response time of the prototype RPM is as fast or faster than traditional thermal power meters, a faster response is desirable for monitoring rapid changes in the laser power. We combined the accurate RPM measurement with the voltage output of an uncalibrated photodiode power monitor that is included in the Yb-fiber laser source. Simple photodiode power monitors can easily achieve millisecond or even microsecond response times. They are not generally suited for accurate measurement of the delivered laser power because they could have a nonlinear response and measure an uncalibrated fraction of the laser power. That fraction could change with time, delivered power, fiber coupling fraction, etc. However, a hybrid measurement that combined the real-time accuracy of the radiation pressure power measurement with the rapid response of a monitor photodiode signal would overcome these limitations. We therefore recorded both the RPM signal and the monitor photodiode signal during the laser welding process and have combined them to produce a fast and accurate measurement of *in situ* welding laser power.

2.3 Portable power meter calibration - Design

Figure 4 shows how the RPM was implemented for on-site calibration of the flowing water power meter at the BAM welding workstation. The weld head was controlled by a multi-axis robot which positioned it for a horizontal laser launch into the RPM. Light emerged from the laser weld-head with a diameter of 27 mm and a working distance (focal length) of 450 mm. The RPM sensing mirror was placed 120 mm from the weld-head exit. The entrance and exit windows from the aluminum housing around the sensing mirror were anti-reflection coated with reflectance $R\sim 0.001$ per surface. Downstream of the RPM, the light made an intermediate focus approximately 330 mm from the RPM sensing mirror. After the focus, the light was incident (at 45˚) on a turning mirror ($R = 0.99$) and directed vertically downward into the entrance aperture of the flowing water power meter to be calibrated ("test power meter").

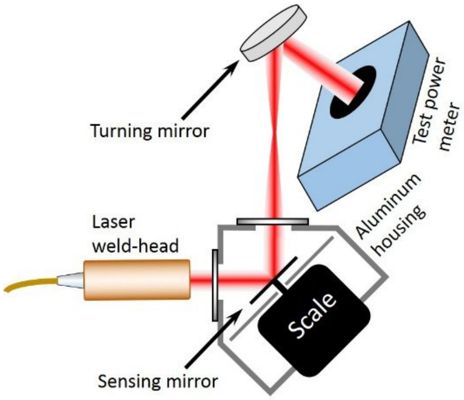

Figure 4. Layout of RPM setup for calibration of the test power meter (flowing water design) at BAM. From the weld-head, the light propagated horizontally to the sensing mirror and horizontally to the turning mirror and then vertically downward to the test power meter.

3. RESULTS

3.1 *In situ* power monitoring of a laser weld - Results

Regarding the *in situ* power monitoring setup at NIST, as expected, the precision scale in the RPM saw effects of mechanical vibration from the welding workstation. The mechanical noise from the exhaust fan, the resulting air currents within the work station, and vibration from the mechanical motion of translation/rotation stages were found to cause varying degrees of noise and drift on the scale reading. However, we found the exhaust fan caused a bias to the measured force and therefore we ran the fan even when the laser was not operating to allow us to establish a baseline from which the radiation pressure could be extracted. This illustrates a key aspect of radiation-pressure-based measurement of laser power - with such small forces, the best measurement must be differential, comparing the force measured with and without the applied laser power. This is similar to the approach in precision scale measurements as well as many thermal power meters. The noise effects from the rotating stage were negligible.

With the RPM in place, we measured laser power during “bead-on-plate” welds on the stainless steel pipe for optical powers ranging nominally from 500 W to 5000 W and feed rates between 5 mm/s and 20 mm/s. After welding, the pipe was cross-sectioned, polished and etched with mixed acid (equal parts HCl, HNO_3, and acetic acid) to reveal the macrostructure using optical microscopy. Cross sections of the resulting welds are shown in Figure 5.

This represents the first time to our knowledge that the total incident beam power from a welding laser has been measured simultaneous to the weld operation. The RPM measured the force of the laser light on its sensing mirror as a function of time during the laser weld, and the uncalibrated photodiode voltage was also recorded. The scale reading (in grams) was converted to force using the gravitational force relationship $F=mg$ where $g=9.8\ \mathrm{m/s^2}$ is the gravitational constant; the laser power was then determined from Equation (1) with correction made for the power loss due to reflections from the lens and protective cover glass downstream of the sensing mirror. The linear heat input, HI was calculated for each weld using the input power P and the pipe rotational speed ω (in units of mm/s) to give $HI=P/\omega$.

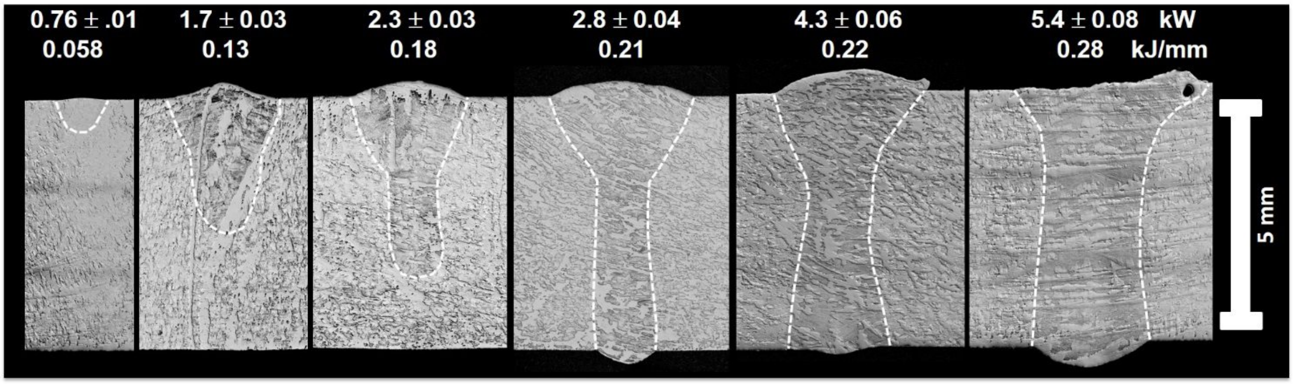

Figure 5. Cross sections of welds in the 304L stainless steel pipe at several laser powers measured simultaneously using the radiation pressure power meter. Numbers at top indicate the RPM-measured laser power (kW) with 1.5 % uncertainty. Below that, is the linear energy density (kJ/mm) deposited along the weld (calculated from the combination of laser power and material feed rate).

Figure 6 shows the optical power measured by the RPM as well as the uncalibrated photodiode voltage measured during a laser weld of nominally 5 kW optical power and 19.5 mm/s feed rate.

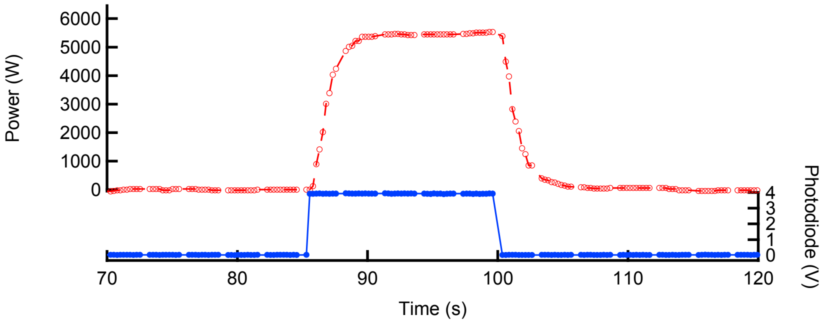

Figure 6. Laser power (red, dashed line, open circles) measured with radiation pressure power meter, and unscaled voltage (blue, solid line, closed circles) from the monitor photodiode. Lines connecting data points are only to guide the eye.

We then used the RPM-reported power to calibrate the photodiode monitor signal. This was done by forcing it to agree at two key points – one before the injection occurs and the other during the injection but after the scale’s 5-second settling time. For example, for the injection shown in Figure 6, the pre-injection power measurement was taken from *t*=80 s – 85 s, and the injected power measurement was taken from *t*=90 s – 95 s. The averaged photodiode voltage over these same time intervals was forced to agree with the corresponding RPM powers using an offset and a scale factor. This provided a "volts per watt" calibration factor for the photodiode voltage, which safely assumes a linear photodiode response over the narrow range of power variation.

Figure 7 shows the results. The laser power as measured with the simultaneously-RPM-calibrated photodiode is compared with the power measured by the RPM. Here we see the benefit of this hybrid approach. The absolute accuracy afforded by the radiation pressure measurement is combined with the rapid response of the photodiode, giving a calibrated measure of the welding laser power (blue curve) during the weld that is not limited by the scale's rise time.

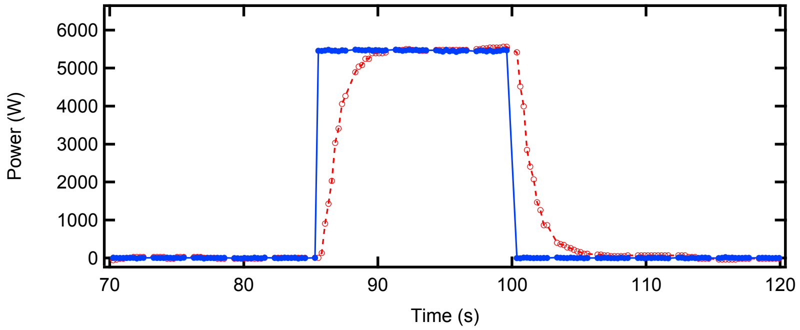

Figure 7. Laser power from the RPM-calibrated laser diode signal (blue, solid line, closed circles) and the supporting radiation pressure result (red, dashed line, open circles). Lines connecting data points are only to guide the eye.

Finally, we empirically tested the linearity of the photodiode response by performing a weld that included a step in the delivered power (Figure 8). Recall that the weld is performed on a rotating pipe, so the length of the weld is the pipe circumference. We set the initial weld power for nominally 2300 W over the first 180 degree rotation of the pipe and it was stepped to ~ 2700 W over the last 180 degrees (feed rate 13 mm/s). Following the same procedure as above, we shifted and scaled the photodiode voltage to agree with the power measured by the RPM over the ranges *t*=82 s – 87 s (dark condition) and *t*=92 s – 97 s (during injection). We find the result shown in Figure 8. Interestingly, the level of the power reported by the hybrid radiation-pressure-calibrated photodiode (blue) does not completely agree with the pure radiation pressure result at the end of the second step, showing up to 3 % disagreement. We attribute this to either a nonlinearity of the photodiode voltage or a thermal drift in the radiation pressure result. We are in the process of characterizing the linearity of the photodiode response and if it can be shown to be stable, we can incorporate the photodiode linearity in the calibration for a more accurate result. Thermal drift is also suspect in Figure 7 where at the end of the injection, the RPM power rises slightly but with no corresponding increase in the photodiode power. Our future studies will include efforts to understand the source of these thermal drifts.

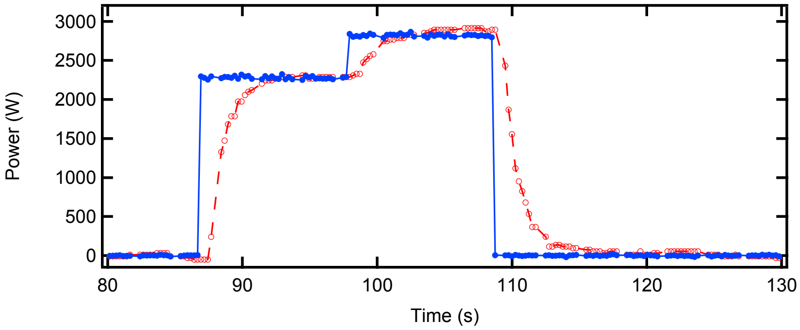

Figure 8. Hybrid laser power measured during injection (blue, solid line, closed circles), which is the photodiode voltage calibrated by the radiation pressure power measurement (red, dashed line, open circles). Lines connecting data points are only to guide the eye.

3.2 Portable power meter calibration - Results

The on-site calibration of the flowing water power meter using the RPM was carried out at BAM facilities by performing a series of power injections from 500 W to 20000 W with injection times ranging from 30 s to 110 s. We found that the RPM was able to make stable, repeatable low-noise calibrating measurements up to a powers just below 10 kW. However, we found that for higher powers, dust on the turning mirror seemed to negatively affect the measurement. Periodically, during injection at these higher power levels, the scale reading would begin to change with time in a manner that did not seem to be caused by actual power fluctuations of the laser. The mirror was by no means isolated from contamination as the aluminum housing and windows on the RPM were removed several times during the setup and between measurements. We believe laser heating of dust settling on the mirror caused a thermal effect that resulted in an anomalous force on the mirror (due to scale heating or convective airflow). Under the operating conditions, the power density on the mirrors for the susceptible 10 kW – 20 kW power levels was approximately 1.5 kW/cm^2 to 3 kW/cm^2. Cleaning the mirror usually made this effect stop, but future implementations will need to be sealed against contamination.

From the measurements, a calibration factor of the flowing water power meter can be deduced and the meter has been sent from BAM to NIST to perform a conventional calibration to cross-check the validity of the RPM calibration. Results will be forthcoming.

4. CONCLUSIONS

We have demonstrated a radiation pressure power meter which provides improved accuracy and speed in the measurement of delivered laser power during a laser weld. The hybrid approach of using the RPM for real-time calibration of a monitor photodiode combines the accuracy of the radiation pressure approach with the speed of the photodiode. The prototype power meter we used was large and only intended as a proof of the concept. To fully implement such a mechanism in a non-research environment, the size of the radiation pressure power meter will need to be reduced for inclusion in the laser weld head itself. In that design, the sensing mirror would just act like a turning mirror but simultaneously would measure the delivered laser power. Such a design will also require a design modification to reject false signals from scale vibration, motion of the weld head, and the force of gravity. We also showed that on-site calibration of conventional power meters for laser welding can be carried out in a relatively simple manner, but that the mirror environment must be more protected against contamination during the measurement.

ACKNOWLEDGEMENTS

The authors thank A. Feldman for his work in producing the DBR mirrors.

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