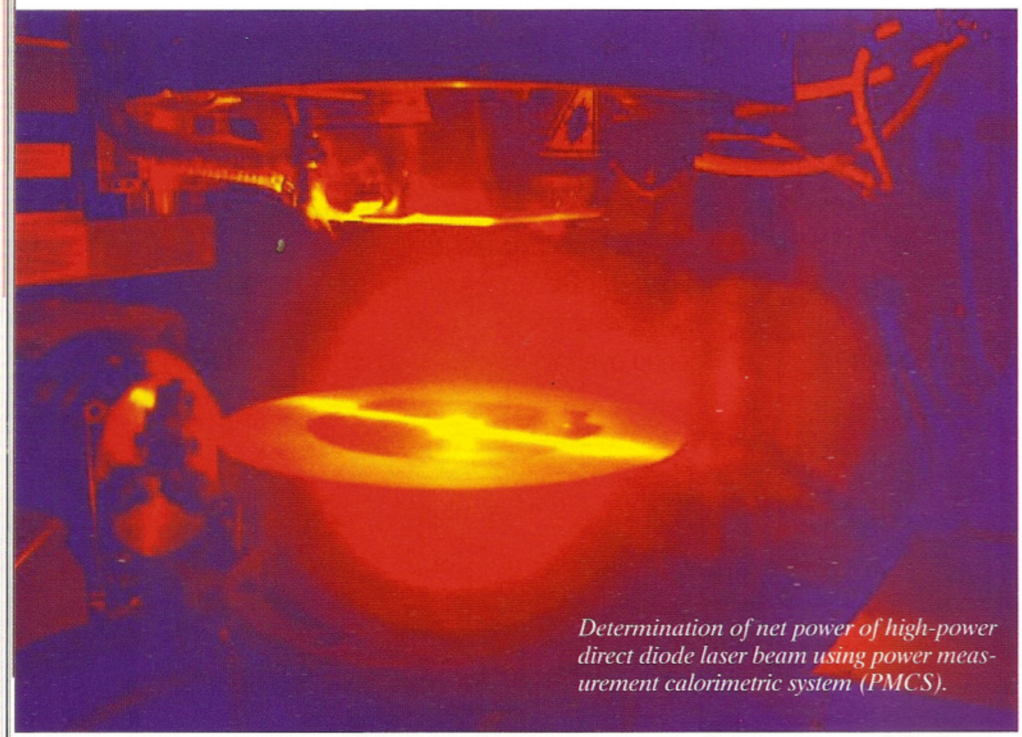
Controlling Heat Input by Measuring Net Power



Determination of net power of high-power direct diode laser beam using power measurement calorimetric system (PMCS).

Industrial calorimeter measures net power of various heat sources to control heat input

BY VALDEMAR MALIN AND FEDERICO SCIAMMARELLA

Control of heat input (H) has always been considered a very important task in many critical applications in arc and laser-beam welding and cladding. Tremendous progress in welding automation and control of welding variables has been made recently, especially over the last two decades. For example, the accuracy of controlling welding current has improved dramatically, from ± 50 to ± 1 A. Similar improvements took place for other variables, including voltage, travel speed, and input power.

VALDEMAR MALIN (vmalin@alionscience.com) *and FEDERICO SCIAMMARELLA* (fsciammarella@alionscience.com) *are with Alion Science and Technology Corp., St. Charles, Ill.*

However, the most influential variable of the welding process that largely determines heat input, net power, remains the only variable that has been passed over by the advances in science and technology for more than 70 years. In fact, industrial technology for accurate, repeatable, and rapid measurement of net power has not been available. It is unfortunate because, at constant travel speed, net power (rather than input power) is directly responsible for all physical and metallurgical changes in metal being welded.

The situation has changed with the introduction by Alion Science & Technology Corp. of an industrial device for direct net power determination[1]. This device can measure net power of various heat sources, including laser beams (high-power direct diode, Nd: YAG or CO_2) and welding arcs (gas tungsten arc, plasma transferred arc, gas metal arc, submerged arc). The net power can be measured also in friction stir welding, oxyfuel welding, heat treatment, and laser surface modification. In-process net power control in rapid 3-D direct metal deposition is also possible.

The problems of net power measurements and solutions are described in this article.

Heat Input

Heat input is an amount of energy that is transferred to the base metal by a source

1. *Winner of the 2005 R&D 100 Award.*

of energy (an arc or laser beam) per unit of weld length (cm or in.). It is calculated as follows (Ref. 1):

$$H = P_{net}/S \text{ (joule/cm or joule/in.)} \quad (1)$$

$$P_{net} = k\, P_{in} \quad (2)$$

where P_{in} = input power generated by a source of energy (Watt)

P_{net} = net power (the power transferred to a substrate, Watt)

k = thermal efficiency that defines a share (or %) of P_{in} transferred to a substrate

S = travel speed of a source of energy.

Input Power

In arc welding applications, input power P_{in} is generated by a power source and can be determined by two variables: welding current (I) passing through the arc (ampere); and V — voltage or potential between an electrode and a workpiece (volts). Both I and V can be accurately measured using ammeters and voltmeters, respectively.

P_{in} can be determined using the following formula:

$$P_{in} = I \times V \quad (3)$$

In laser beam welding applications, P_{in} is determined by special devices. Some of them are reportedly able to determine P_{in} with a very high accuracy of ± 1%, as reported by Kramer, et al. (Ref. 2).

Net Power

Both I and V are always specified in WPS in arc welding not only because they are energy related, but because their effect on weld geometry is different. However, when the weld integrity and properties are of critical importance, heat input is specified as well. But in order to do that, net power (P_{net}) should be known. In laser beam welding applications, there is no other energy-related parameter, but heat input.

The role of P_{net} is difficult to overestimate: it determines weld quality. At constant travel speed, P_{net} (rather than P_{in}) is directly responsible for all physical and metallurgical changes in metal being welded, including weld geometry (penetration, dilution, and weld dimensions), weld integrity (cracks, incomplete fusion, etc.), metallurgical characteristics (microstructure, grain structure, etc.), and mechanical properties (hardness, strength, impact toughness, etc.).

Furthermore, P_{net} is the single most important variable in any modeling of welding processes, including prediction of thermal conditions; weld pool characteristics; weld geometry, integrity, and properties; distortion and other physical and metallurgical reactions caused by welding. To know P_{net} is absolutely imperative in the welding of critical components. It is considered a mandatory variable in numerous welding procedure specifications in the welding industry.

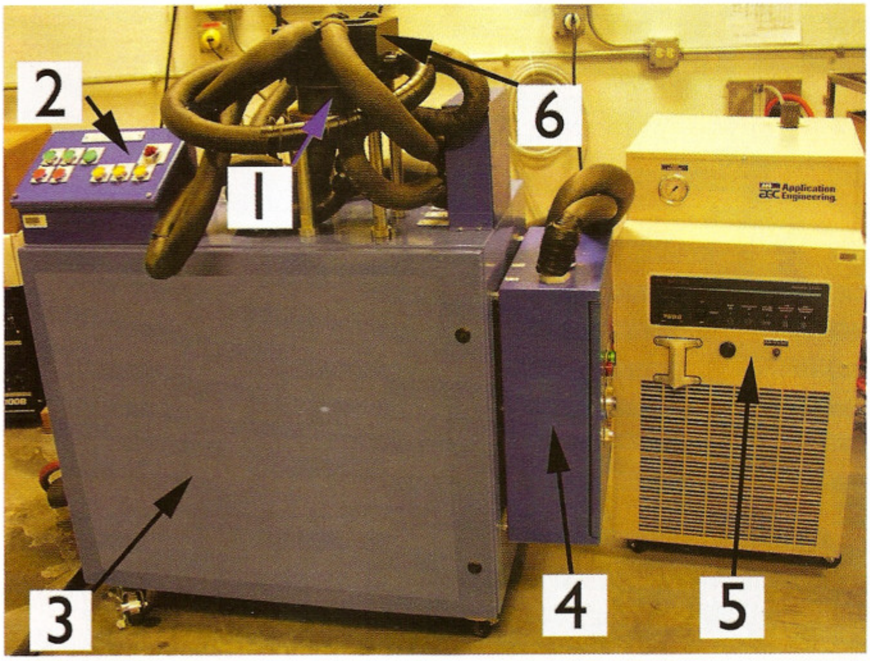


Fig. 1 — Power Measurement Calorimetric System (PMCS). Legend: 1-calorimeter, 2-control system, 3-water supply system, 4-calibration unit, 5-chiller, 6-auxiliary calorimeters.

Strange as it may seem, such an important variable has never been practically used in the welding industry. The reason is that P_{net} determination in arc and laser beam welding is an extremely difficult and complex problem. It requires special complex devices to be made. However, a device that could measure P_{net} directly, accurately, repeatedly, and fast enough does not exist. In the absence of a standardized device, researchers build their own devices for specific research purposes. As a result, the reported data obtained by such devices suffer from lack of accuracy and repeatability. In fact, the reported data for thermal efficiency k of GTA welding obtained over the last five decades vary from 21 to 80% as summarized by Giedt, et al. (Ref. 4).

The consequence for the welding industry is that input power (P_{in}) has always been used instead of net power (P_{net}) to control heat input, although the correlation between them is open for interpretation or unknown. For example, as was reported by Malin in 1969 for gas tungsten arc (GTA) and plasma arc (PA) welding (Ref. 3), P_{net} has a nonlinear relationship with P_{in}. For example, in GTA welding with all other conditions equal, just increasing P_{in} even in a narrow range (from 1.38 to 2.30 kW) decreases thermal efficiency from 75 to 67%. This trend is corroborated by Niles in 1975 (Ref. 5), Smartt in 1986 (Ref. 6), and other researchers. This means that increasing P_{in} results in an increasingly smaller increase in net power. In other words, P_{in} is not an accurate substitute for P_{net}.

Researchers in their models have to rely on inaccurate data as well. In fact, modeling of thermal conditions in metals caused by welding (thermal cycles, temperature fields, cooling rates) has reached amazing sophistication in recent years. The modern models account for even subtle changes caused by physical and metallurgical phenomena, such as gravitational, electromagnetic, and buoyancy forces, surface tension, etc. However, this sophistication can enhance the accuracy of a model only if P_{net} is determined accurately. For example, P_{net} is the main thermal characteristic of any model describing cooling rate. However, it is determined with a great deal of uncertainty, as well illustrated in the *Welding Handbook* (Ref. 1). Here, the data obtained by different investigators at similar welding conditions in GTA welding are compared. For example, at current I = 200 A, reported thermal efficiency varies from 55 to 87%. A model that relies on such data will have limited predictive capability.

In other words, the most important parameter of the welding process is not controlled. For over 70 years, welding engineers and scientists have been aware of this

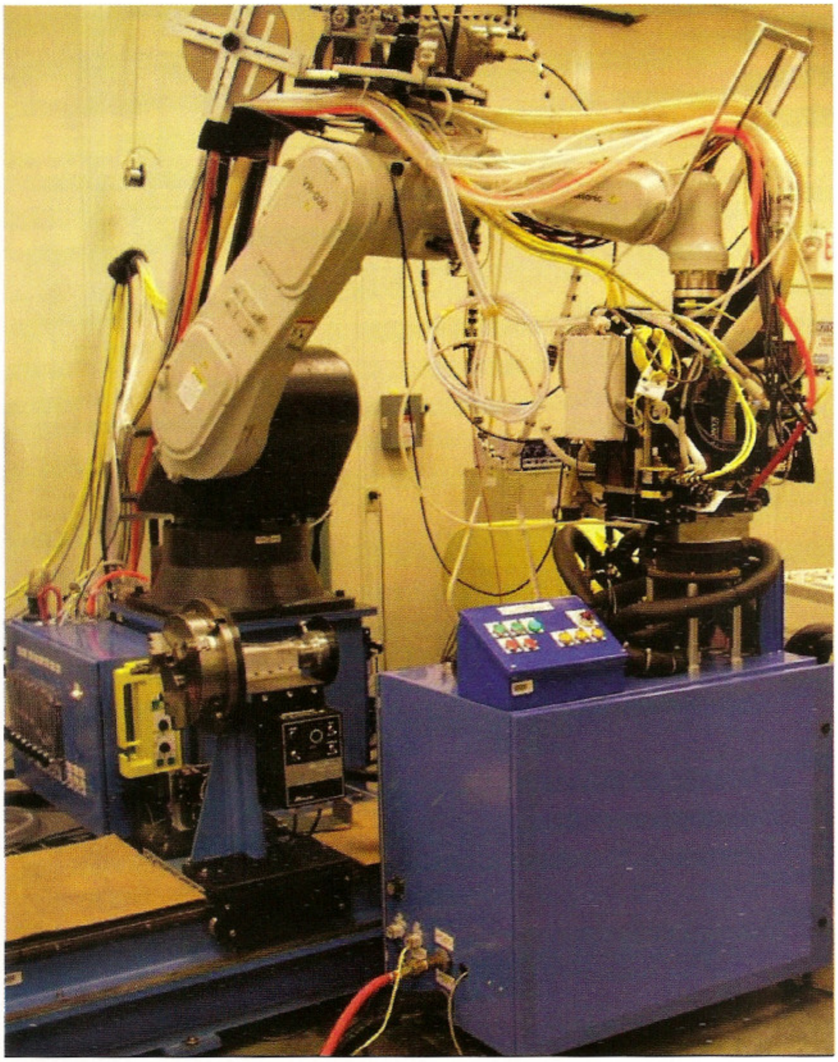


Fig. 2 — Power measurement calorimetric system (PMCS) in action. Heat source: high-power direct diode laser (HPDDL). The 4-kW laser head is mounted on a wrist of a robot.

fact. Meanwhile, unexplained deviations from specified weld quality may occur in repetitive production even if a strict control of all variables (including P_{in}) is maintained. If P_{net} changes, this phenomenon occurs unnoticed in production because it cannot be measured or detected.

Methods of Measuring Net Power

Various devices were developed by researchers over the years for measuring P_{net} mostly to determine thermal efficiency of different welding processes to support an individual modeling effort. Most of them are based on a principle of calorimetry. Typically, each researcher develops a device to pursue a specific research goal. These devices differ by principle of operation, design, and operating conditions. Often, the experimental conditions used by researchers differ and sometimes are far from those encountered in practical applications. The result is a great scatter of data that are difficult to compare.

In recent years, Seebeck Envelope Calorimeter (SEC) was used to determine P_{net} in GTA welding by DuPont, et al. (Ref. 7). It was also used by Giedt, et al. (Ref. 4) and Fuerschbach (Ref. 8) in laser beam welding.

The SEC is based on the gradient layer temperature principle: the flow of heat through a solid produces a definable temperature gradient in the direction of heat flow. In the SEC, small temperature differences across the gradient layer are sensed by multijunction thermopiles imbedded in the walls of the calorimeter. The outputs of these thermopiles are then a measure of the heat flow rather than of temperature. The calorimeter output signal is sensed across a single pair of output leads that vary in a linear manner with the heat flow rate. The resulting integrated voltage output signal is directly proportional to the thermal energy released during the weld cooling cycle.

Although designed for biomedical research, the SEC was tried in welding research because of its high accuracy demonstrated in bioscience applications and because it is the only product commercially available. Just weld a 90-mm (3½-in.) specimen, transfer it into the calorimeter, and the latter starts producing a voltage output. However, the SEC has some serious drawbacks in practical welding applications.

The SEC is not a turnkey device. It needs some additional equipment to function properly and obtain data on net power. For example, a chiller that circulates cooling water and maintains it at a constant temperature, peripheral devices, data-acquisition and processing hardware and software, etc.

The SEC is a laboratory instrument rather than a production device. It requires about 6 h to make one measurement (Ref. 1). This makes it more suitable for research rather than for practical applications.

The SEC does not account for the energy lost during welding and transfer of the specimen into the calorimeter (about 15 s). These losses of energy may occur due to radiation of and evaporation from a molten weld pool, and convection. The researchers estimated theoretically that the lost energy is about 2% (Ref. 5). However, the magnitude of the lost energy depends on many factors, including physical properties and size of the welded specimen, welding speed, ambient temperature, welding and transfer time, etc. Typically, this energy is neglected introducing an error of measurement up to 2%.

The SEC does not differentiate between transient and "quasi-stationary" energies. Each weld includes a main zone where a so-called "quasi-stationary" (moving) temperature field has been established. The objective of any calorimetric device is to measure the quasi-stationary energy transferred to a welded specimen. However, a weld contains also two transient zones. The first zone is at the start of a weld where input power is gradually raised from zero to nominal. The second is at the end of a weld where input power is gradually falling from nominal to zero. The maximum length that the SEC can accommodate is about 90 mm (3½ in.). For such a short weld, the transient zone may constitute up to 15% of the weld length (or cycle time). Nevertheless, the nominal and transient energies are averaged by the SEC and may introduce an additional source of error of up to 7%.

There are no data in literature on actual accuracy of the SEC in welding ap-

2. *Conceptualized and designed by V. Malin.*

plications. The above analysis suggests that it may reach 9% under unfavorable circumstances.

Power Measurement with Calorimetric System

The above analysis outlines the main requirements for design of a more practical and accurate calorimetric device for industrial welding and cladding applications. Following this analysis, the power measurement calorimetric system (PMCS[2]) was developed to meet these requirements.

The PMCS is a turnkey device generating data on net power in watts (rather than voltage output signal). It measures with a production-oriented speed of 3–5 min per measurement (vs. 6 h).

It measures while the arc/laser beam is on and, thus, does not require transfer of the specimen into the calorimeter. As a result, the energy losses during transfer time (due to radiation, evaporation, and convection) do not influence the final results of measurements.

It measures the "quasi-stationary" net power only. As a result, the transient power does not influence the final results of measurements.

It measures the net power with an accuracy of ± 1.5% (vs. 7–9%). To maintain the high accuracy, the PMCS is equipped with a special calibration device that allows its accuracy to be checked periodically and taking only several minutes.

For even higher accuracy, the PMCS is capable of measuring the ambient temperature T_0 and allows corresponding corrections to be made if T_0 deviates from the recommended temperature of measurement.

Although the PMCS was originally designed for measuring the net power in HPDD laser beams, it can be used for other types of laser beams, including Nd: YAG and CO_2. It is designed to tolerate the beam focused at or below the surface of the simulated substrate of the calorimeter in keyhole mode. It can be used for GTA or plasma arc welding applications as well. The development of the PMCS pursued the following objectives:

To accurately determine net power of the laser beam arc for accurate control of heat input in industrial environment.

To detect and offset gradual loss of input laser power.

To determine thermal efficiency of the laser beam/welding arc.

Description of the PMCS

Design of PMCS

The PMC system is based on the principles described in Ref. 3. A prototype PMC system is shown in Fig. 1. It is designed for measuring the amount of energy transferred to a substrate by the incident arc or laser beam. It consists of three main components as shown in Fig. 1: 1) calorimeter, 2) control system, and 3) water supply system.

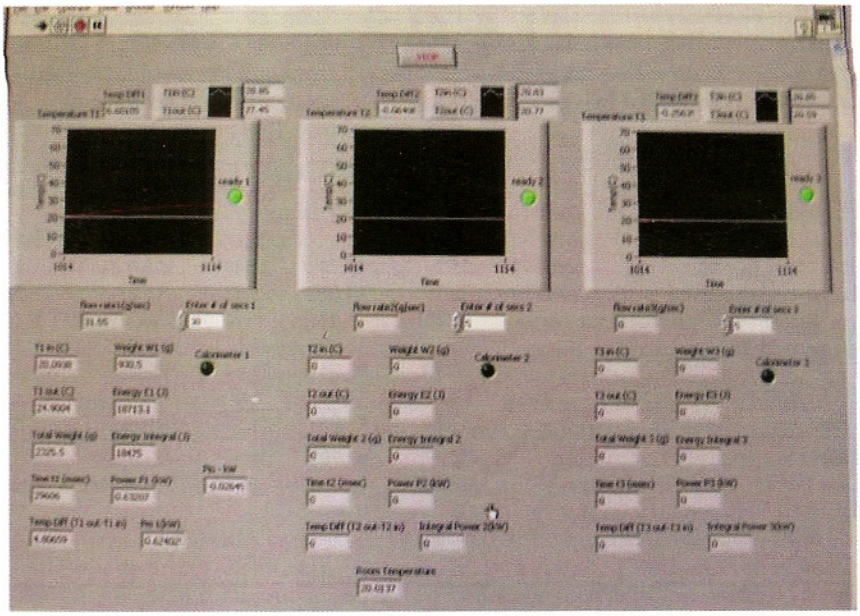


Fig. 3 — A computer screen displays data during net power measurements using Power Measurement Calorimetric System (PMCS).

The calorimeter is mounted on top of the control cabinet. It is designed as a well-insulated copper cylinder covered with a removable disk-substrate. The disk-substrate is cooled by running water.

The control system consists of the electrical, water distribution, data-acquisition, and pressure/temperature control safety systems contained in a production-oriented enclosure. The temperatures of the input water entering the calorimeter (T_{in}) and the output water exiting the calorimeter (T_{out}) are measured by the resistance temperature detectors (RTD). Mass of water m is measured by electronic scales. The data-acquisition system and specially designed software allow the input data to be displayed on the screen of a computer monitor. These data include 1) input data (water temperatures T_{in} and T_{out}, and mass m) and 2) calculated output data, including water flow rate G, measured energy E_m (in joules), and measured net power P_m (in watts).

The water supply system contains the chiller that circulates the water through the system at a constant flow rate and pressure. The temperature of the water exiting the chiller can be preset, automatically controlled, and maintained constant. The system does not allow the fluctuation of water temperature entering the calorimeter during calorimetric procedure to exceed ± 0.2°C.

The safety system shuts down the PMCS if water temperature exceeds the safe level of 70°C (158°F) or safe pressure 75 lb/in.^{2}.

The system is designed to work as a standalone portable unit. It can be brought to a desired location on the production floor. The PMCS can be integrated into a central control system and the pendant allows it to be controlled from a remote location.

Operating Procedure

The operating procedure consists of preliminary and calorimetric procedures. Figure 2 shows the PMCS in action during net power measurements of the HPDD laser beam.

The preliminary procedure starts with setting up the welding torch or the laser head over the disk substrate. To simulate conditions specified for actual welding or cladding, the disk substrate is made of the specified material. Also, a small amount of specified filler metal may be pre-placed under the arc or beam to simulate dissimilar-metal welding applications. The arc or the laser beam is struck in the center of the disk substrate. When the filler metal and the substrate are melted, it creates a weld pool. The pool is shielded from the atmosphere by argon.

The water temperatures T_{in} and T_{out} are measured by RTDs. The data are sampled at a specified frequency of 120 Hz and transmitted through an Ethernet link to a PC. The data are processed by a special software of the data-acquisition sys-

Table 1 — Typical Data Obtained in PMCS Testing Program (Series # 3-05-24, T_0 = 22°C)

Run #	Start Time (min)	T_{in} °C	T_{out} °C	ΔT °C	m (gram)	P_c (Watt)	P_m (Watt)	A_c (%)	E_c (%)
1	0	22.00	43.20	21.20	930.5	2,897	2,790	96.31	3.69
2	9	22.01	43.14	21.13	929.5	2,892	2,777	96.02	3.98
3	14	22.06	43.26	21.20	927.5	2,893	2,780	96.09	3.91
4	23	22.12	43.37	21.25	926.0	2,899	2,781	95.93	4.07
5	30	22.15	43.63	21.48	923.5	2,902	2,804	96.62	3.38
6	45	22.24	43.72	21.48	928.0	2,909	2,817	96.84	3.16
7	59	22.28	44.01	21.73	919.5	2,919	2,817	96.51	3.49
8	67	22.28	44.02	21.74	920.5	2,913	2,829	97.12	2.88
9	73	22.31	43.99	21.68	919.0	2,910	2,816	96.77	3.23
10	81	22.30	43.94	21.64	929.5	2,909	2,843	97.73	3.27
11	87	22.32	44.01	21.69	912.5	2,896	2,797	96.58	3.42
12	95	22.34	44.06	21.72	916.0	2,902	2,814	96.97	3.03
AVG		22.20	43.70	21.5	923.5	2,903.0	2,805.0	96.62	3.46
STD		0.13	0.36	0.24	5.92	8.52	20.85	0.51	
STD/AVG, %		0.6	0.8	1.1	0.6	0.3	0.7	0.5	
SCATTER		0.34	0.92	0.61	18.0	27.0	66.0	1.19	
SCATTER, %		1.5	2.1	2.8	1.9	0.9	2.4	1.2	

Legend: Time — Elapsed start time of each run; T_{in} — temperature of water entering the Calibration system; T_{out} — temperature of water exiting the PMCS calorimeter; $\Delta T = T_{out} - T_{in}$; m — mass of water passing through the calorimeter; P_c — input calibration electrical power; P_m — net input power of water measured by the PMCS; A_c — calibration efficiency (P_m/P_c x 100%); E_c — calibration error (100% - A_c); T_0 — ambient temperature; AVG — average; STD — standard deviation; Scatter — difference between maximum and minimum values.

Table 2 — Instrumentation and Calculation Errors in PMCS Testing Program (Series # 3-05-24, T_0 = 22°C)

Error		T_{in}	T_{out}	ΔT	m	P_c	P_m
Per measurement	(±)	0.10°C	0.15°C	0.25°C	0.5g		
Aver (60 measurements)	(±)	0.013°C	0.019°C	0.032°C			
Average (12 runs)		22.34°C	44.06°C	21.72°C	923.5g		
Relative error	(±)	0.06%	0.04%	0.1%	0.05%	0.03%	0.15%

tem. The data-acquisition system calculates temperature gradient ΔT as follows:

$$\Delta T = T_{out} - T_{in} \text{ (°C)} \tag{4}$$

The operator watches the output temperature-time function $T_{out} = f(t)$ on the screen of a monitor. At first, T_{out} is rising rapidly, then it slows down. When T_{out} becomes stable, a thermal equilibrium is established between the heat transferred by the laser beam into the substrate and the heat removed by the water. Normally, it takes about 1–2 min depending on heat conductivity of the substrate.

When the thermal equilibrium is reached (T_{out} does not change), the operator pushes the start button and starts the calorimetric procedure. Temperatures T_{in} and T_{out} and mass m are displayed continuously on the monitor screen and recorded. The calorimetric procedure continues for a calorimetric period t equals 30 s. When t is up, data recording stops and the operator turns off the heat source.

The data on ΔT values are integrated over time t. At the end of the calorimetric procedure, the measured energy Q_{net} and the corresponding measured net power P_{net} that are transferred to the water are calculated using the following formulas:

$$Q_m = C\, m\, \Delta T \text{ (joules)} \tag{5}$$

$$P_m = Q_m/t \text{ (watts)} \tag{6}$$

where C = specific heat of water (J/g °C)
m = mass of water passing through calorimeter for time of measurement (gram)
T_{out} = temperature of water entering the calorimeter (°C)
T_{in} = temperature of water exiting the calorimeter (°C)
t = time of measurement (s)

Final ΔT, Q_m, and P_m values are displayed on the monitor screen at the end of the calorimetric procedure as shown in Fig. 3.

Calibration System

To ensure and maintain high accuracy of the measurements, an optional calibration unit is added to the PMCS as shown in Fig. 1. The calibration system (CS) allows the accuracy of the PMCS to be verified without using an arc or laser beam energy source.

The CS includes electrical heaters that supply a constant flow of electrical power of 1.5 or 3 kW (nominal) to the incoming (cold) water running through the CS. The input (calibration) electric power P_c is measured by a precision wattmeter. The data-acquisition system of the CS is sampling the power P_c with a specified frequency of 120 Hz. When the thermal equilibrium is reached (T_{out} does not change), the operator starts the calorimetric procedure. During the calorimetric procedure, 60 measurements were made and integrated (averaged) over the calorimetric time period t = 30 s to determine P_c.

At the same time, the water coming out of the CS (hot water) is running through the calorimeter of the PMCS. During the calorimetric procedure, the data-acquisition system of the PMCS is sampling the temperatures of cold and hot water with the same frequency 120 Hz. Similarly, 60 measurements are made by the PMCS and integrated (averaged) over the same time period t (30 s) to determine (measured) net power P_m. Values of both P_c and P_m are compared to calculate two calibration parameters: 1) calibration efficiency A_c and 2) calibration error E_c. Both parameters are calculated as follows:

$$A_c = P_m/P_c \times 100\% \quad (7)$$

$$E_c = 100 - A_c\ (\%) \quad (8)$$

The P_c and A_c values are displayed on the screen of the monitor at the end of the calibration procedure, which takes from 3 to 5 min.

Testing of PMCS

To determine the accuracy and repeatability of the PMCS, a special testing program was implemented using the calibration system. Thousands of measurements, hundreds of test runs, and numerous test series were conducted during the testing program. During each 30-s test run, the data-acquisition system makes and records 60 measurements. Each series of tests consists of 5–12 runs with an interval of 5–15 minutes between the runs. Time intervals of about 15–30 minutes were made between the test series. Water was circulating through the calorimeter continuously during each series. As an example, the results of test series # 3-05-24 are shown in Table 1. The data from 12 consecutive runs were obtained with intervals of 5–15 minutes over 1½ h at the outside temperature T_0 = 22°C (71.6 °F).

The detailed results of these tests are discussed in Ref. 9. The analysis of Table 1 shows fairly repeatable results of measurements judging by a low standard deviation STD. In fact, fluctuations from average STD/AVG is 1.1% max. Still, a small portion (3.46%) of supplied input power is not accounted for. The analyses show that this happens due to three types of error.

Instrumentation errors are introduced by the devices measuring temperature, mass of water, and electric power. Calculation errors are introduced as a result of calculation of temperature gradient ΔT, net energy Q_m, net power P_m, and calibration efficiency A_c. The data show that both errors introduce a relatively small (0.15%) error in determination of P_m as summarized in Table 2.

It was found that most of the unaccounted energy is the energy lost due to heat exchange between the calorimeter and the environment through insulation creating a systematic error. The minimum power loss that was recorded during the testing program can be considered a calorimeter constant (loss through insulation) and can be accounted for if more accurate measurements are required (in research, for example).

Another error may be introduced due to the effect of environment. All precision temperature-measuring devices are sensitive to the environment in which they operate. It is recommended that the PMCS be used in a temperature-controlled environment (a heated or air-conditioned room) at a recommended temperature of 22°C (71.6°F).

However, this may not be always possible in a production environment. To determine the error caused by T_0 on the results of measurements, the PMCS was tested at T_0 varying from 20.5° to 27.8°C (69°–82°F) as measured by an RTD. Several series of tests were conducted and the obtained data were analyzed. It was found that error occurs in net power determination if T_0 deviates from the recommended 22°C (71.6°F). A special algorithm was developed to compensate for this error in the recommended range of ambient temperatures within 20°–24°C (68°–75°F).

Models of the PMC System

Two types of the PMCS are designed, the basic and the research models.

The basic (1-water line) model is production oriented, and it measures the net power only. It is designated for users who perform laser/arc welding or cladding, heat-treating, surface modification, and direct metal deposition, to produce accurate and repeatable results. Also, it can be used by fabricators of critical components that require strict control over net heat input, including critical components for aerospace industry and components made of heat-sensitive steels (HY-100, HY130) for the Navy.

The research (3-line) model of the PMC system (Fig. 1) is designed for research purposes. In addition to measuring P_{net}, it is capable of measuring the amount of energy lost during calorimetry (due to laser beam reflection, weld pool radiation, and heat convection). For this purpose, the auxiliary calorimetric system is added to the basic model of the PMC system. It consists of four identical, flat heat exchangers insulated from each other. They are assembled together forming a double-walled square copper tube cooled by water. The assembly is installed on top of the basic calorimeter around the laser beam so that the beam is in the center. If the inlets and outlets of all four heat exchangers are connected in sequence, they act as one calorimeter absorbing all the energy lost around the laser beam. If each pair of opposite heat exchangers is connected in sequence, two calorimeters are formed that absorb lost energy reflected in two perpendicular directions separately. This feature can be used for measuring lost energy along and across the rectangular beam in HPDD lasers. The 3-line PMC system operates as a 1-line (basic model) if both auxiliary calorimeters are not used. The control, data-acquisition, and safety systems of the research model contain three sets of components to control three water lines. As a result, this model is much larger in size than the basic model. Three calorimeters operate one at a time. The measurement procedure for each auxiliary calorimeter is similar to that for the basic calorimeter.

Application of PMCS

The main application of the PMCS is to directly measure power transferred to the substrate (net power) by various welding and nonwelding heat sources for the purpose of controlling heat input and, thus, obtaining products of higher and more repeatable quality.

The heat sources may include various types of multikilowatt lasers (high-power direct diode, Nd:YAG or CO_2) and welding arcs (gas tungsten arc or plasma transferred arc). It may be possible to use the PMCS for other concentrated sources of heat associated with non-arc welding processes such as oxyfuel welding, friction stir welding, etc.

PMCS can be used for other important applications such as determination of net power in nonwelding processes, i.e., heat-treatment and laser surface modification; in-process net power control in rapid 3-D direct metal deposition; calibration of input laser power gradually degrading over time; and research in thermal efficiency of various welding and nonwelding heat sources.

There may be some other applications unknown so far due to novelty of the product.

Possible Users of PMCS

Potential users of the PMCS may include regulating agencies issuing codes and specifications and/or monitoring their application such as NAVSEA, NASA, FHWA, NIST, and others.

Engineering professional societies such as AWS, ASME, and others may be interested parties in promoting the switch from traditional input power to net power control practice.

Fabricators involved in automatic welding of heat-sensitive steel or thin-wall critical structures, or operating under codes or specifications (aerospace manufacturers, defense contractors, shipyards, auto manufacturers, and others) may be interested in improving weld quality and repeatability.

Research and educational institutions, including universities, government national laboratories, and corporate research centers, may be interested in improving their modeling capabilities.

How PMCS is Used

Switching from traditional input power to net power control does not change established production routine, just the criteria for process control. Similar to a traditional determination of optimal range of input power ($P_{in\ opt}$), optimal range of net power ($P_{net\ opt}$) is also determined using procedure qualification tests. The optimal is the range that allows acceptable (optimal) weld quality to be obtained. The optimal net power $P_{net\ opt}$ can be determined by PMCS in a laboratory using the same production laser/arc welding equipment, if available. If not, the PMCS is used on the production floor. For close simulation of production conditions, the disk of the calorimeter should be made of the same material as the actual parts; the same production input power, laser head height, or arc length, etc., should be used. Then, $P_{net\ opt}$ is specified in welding procedure specification and inspected using the PMCS on a regular basis (once a day or twice a week) depending on production conditions, critical nature of the parts, and laser/arc welding equipment used. If regular inspections show that P_{net} is close to or out of the optimal range boundaries, then the input power is adjusted until P_{net} is within the optimal range. By maintaining P_{net} constant, weld quality and repeatability can be maintained as well.

Predictions

It is envisioned that in the near future, significant changes may occur in the welding industry as a direct result of introduction of the PMCS technology.

Thousands of the PMC systems or similar devices could be in operation all over the world. Welding engineers and welders will be using the PMCS to measure net power directly, accurately, and quickly for calibration or in-process control of heat input in arc or laser welding in addition to or instead of ammeters and voltmeters or other devices used for determining input power.

The PMCS allows researchers and scientists to collect accurate data on the thermal efficiency of various welding and laser processes applied to different metals to improve the predictive capability of their models.

The PMCS could impact regulating government agencies (NASA, NAVSEA, Federal Highway Administration, and others) and professional societies. Net power might be included in welding codes and specifications as a mandatory variable to control heat input instead of input power.

The PMCS could change the welding industry as well: net power might replace input power in welding procedure specifications to control heat input.

More predictable and repeatable weld quality can be obtained in welding critical components, including weld geometry, penetration, dilution, microstructure, and other metallurgical and mechanical properties.

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References

1. *Welding Handbook*, 8th edition, Vol. 1, Welding Technology, p. 68, American Welding Society, Miami, Fla.

2. Kramer, R., Schwede, H., Valker, B., Hansel, K., and Clos, M. 2003. Laser power measurements in industrial environment. *Proceedings of the 22nd International Congress on Application of Lasers and Electro-Optics* (ICALEO 2003), paper 805, p. 72.

3. Malin, V. E. 1969. A study of thermal characteristics of constricted alternate-current arc. *Svarochnoe Proizvodstvo* (Welding Production), No. 9, pp. 3–5.

4. Giedt, W. T., Tallerico, L. N., and Fuershbach, R. W. 1989. GTA welding efficiency: Calorimetric and temperature field measurements. *Welding Journal* 68(1): 28-s to 32-s.

5. Niles, R. W., and Jackson, C. E. 1975. Weld thermal efficiency of the GTAW processes. *Welding Journal* 54(1): 26-s to 32-s.

6. Smartt, H. B., Stuart, J. A., and Einerson, C. J. 1986. Heat transfer efficiency in gas tungsten arc welding. ASM Metals/Materials Technology Series, No 8511-011, 1–14, ASM International, Materials Park, Ohio.

7. DuPont, J. N., and Marder, A. R. 1995. Thermal efficiency of arc welding processes. *Welding Journal* 74(12): 406-s to 416-s.

8. Fuerschbach, P. W. 1996. Measurement and prediction of energy transfer efficiency in laser beam welding. *Welding Journal* 75(1): 24-s to 34-s.

9. Malin, V., and Sciammarella, F. 2004. Calorimetric system for measuring net power in laser beam and arc welding. *Proceedings of the 23rd International Congress on Application of Lasers and Electro-Optics*, (ICALEO 2004), San Francisco, Calif., Paper #1005.