

New Methods to Look at an Old Technology: Innovations to Diagnose Thermal Plasmas

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Received: 31 July 2014 / Accepted: 16 December 2014 / Published online: 27 December 2014
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Abstract The use and development of diagnostics for thermal plasmas is motivated by the industrial importance of thermal plasma applications like welding, cutting or thermal spraying. While the physical fundamentals of plasma diagnostics were introduced decades ago new technologies allow to perform a more detailed analysis of the mentioned applications with increased spatial and temporal resolution, enabling the investigation of complex processes thereby moving the focus from pure plasma to plasma-material diagnostics. An attempt is made to demonstrate current and future possibilities provided by technical progress using “old physics” with the help of few examples. The examples introduced here focus mostly on welding applications and include the use of high-speed cameras for the spectrally resolved analysis of plasma radiation and two-color pyrometry. In addition the use of Thomson scattering in gas metal arc welding is proposed as well as the use of magnetic field measurements for non-intrusive current density measurements.

Keywords Plasma diagnostics · Welding · Thermal spraying · Thermal plasmas

Introduction

Thermal plasmas are an “old” technology. Experimental papers describing technical applications are dating back to the early twentieth century and the diagnostics of plasmas is certainly as old as the technology itself. In the beginning diagnostics were used to understand the fundamentals of plasma physics, leading to new theories and knowledge. Nowadays physical principles are well understood, many publications have been written

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about various measurement techniques, addressing their strengths and weaknesses, numerous review articles have been published thus the question might be asked: “Is there still a need for new developments?” In order to answer this question one has to look at the current trends in plasma technology. A main application of thermal plasmas can be found in material processing. May it be welding, cutting, thermal spraying or waste treatment—in these fields the physical understanding of the plasma has progressed significantly, which is expressed by the amount of numerical simulations which deliver impressive results thus one might argue that we are already in a post-diagnostic area. Usually for these applications the currently proclaimed use of diagnostics is limited to verification of a model or—once a cost effective system is developed—to process control. Similar things are true for lighting applications, in this field most of the recent work has been concentrated on investigating plasma electrode interactions, here as well the understanding has progressed allowing modeling to take the lead in new development, with the diagnostics presumably becoming an assisting tool.

Nevertheless new developments are still necessary as there are still challenges ahead. As mentioned, modelling and simulation have progressed significantly but there is still one major problem. An ideal process can be modelled, but most plasma processes are not ideal, at least not for long. Electrode phenomena lead to unforeseeable attachment behavior, metal vapor disturbs current conduction in the plasma or even the always interesting question why a process works perfectly well in one location on this planet but not in a different spot may make a closer look at thermal plasmas worthwhile.

This paper is intended to provide new perspectives for plasma diagnostics, hence new ideas for what can be done. Using a few measurement techniques an attempt will be made to show possibilities for improvement for the two old plasma applications thermal spraying and welding but only after a short review as to where the current state-of-the-art stands.

State of the Art

The main source of information about electrically driven technical processes is always provided by voltage and current measurements. Even though this is a standard technology, which is excellently described in [1] care has to be taken when high frequency measurements are made or even at what location those measurements take place. Additionally grounding and shielding measures [2] have to be taken.

Thermal plasma diagnostics may be categorized in various ways, for example by usage (process control or fundamental research), by working principle (optical, electrical etc.) or by interaction with the plasma (intrusive, non-intrusive). Most fundamental diagnostics principles are well-known and have been described in detail in previous publications thus this paper will only provide a short summary.

In thermal plasma applications numerous additional diagnostics for process control have been developed. These technologies are supposed to provide on-line information about the quality of the product, like the weld seam or the produced coating. Thus frequently plasma parameters are not measured. In applications like thermal spraying many systems concentrate on the characteristics of the particles that are heated and accelerated inside a plasma. Parameters like temperature of particles, velocity and trajectory are recorded, standards are defined and deviations from said standards are used to interact with the process often with the help of artificial neural networks. The control systems have been developed for and are used in industrial environments, displaying robust, user-friendly interfaces. Most of these systems (PIV, PFI, DPV 2000 etc.) [3] are based on optical

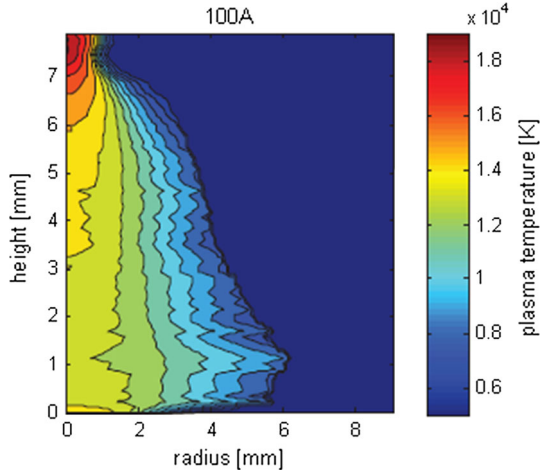
detection of either luminous particles or illuminated particles, which show up as traces on the acquired image. These traces or the integration over traces from particle bundles are used to determine the above mentioned parameters. Similar camera based control systems have been developed for the welding process where for example the evaluation of weld pool geometry is used to provide quality surveillance [4]. As an alternative to cameras the weld defects can also be detected through use of spectrally filtered photodiode signals of the plasma radiation [5].

However, while process control is certainly important one cannot expect to obtain scientific information. Apart from process control there have been numerous applications of high technology diagnostic systems that require significant knowledge and which are suited for laboratory environments only (e.g. [6]), but help to further the physical understanding of the investigated plasma processes. Looking at a few systems an attempt will be made to show how the incorporation of new technologies provides an enormous amount of additional information.

Plasma diagnostics using spectroscopy have been around for a while and are used to determine densities and temperatures of the various plasma species. The fundamentals of spectroscopic techniques are discussed in detail in [7]. The basic principle is the spectrally resolved measurement of plasma radiation which can be performed using spectrographs, monochromators or narrow band filters in combinations with adequate recording devices like photo multiplier tubes, cameras, photo diodes etc. From the shape and intensity of the emitted radiation (line width, shape, self absorption etc.), not only the plasma parameters can be determined but also the plasma composition or the local electric field data that can be used to be compared to modelling results [8]. However, in order to evaluate the data acquired significant information is necessary for example for the transition probability of excited states or what kind of transition the radiation detected can be assigned to. These data are provided in publically available databases like [9], with the thus obtained information about temperature and density parameters like conductivity of the plasma can be determined using publications like [10].

Certainly spectroscopy has profited in recent years from advances made in detector technology and camera development, respectively, allowing more sensitive measurements. But one especially important feature is the possibility to obtain detailed information about transient (i.e. unstable) processes with the camera based analysis of plasma radiation. With the use of interference filters and a setup of mirrors synchronous imaging of an arc at two different wavelength intervals onto a single camera chip of a high-speed camera is possible with high spatial and temporal resolution, resulting in a full 2D image of the plasma in two different spectral bands. This principle can of course also be performed using two synchronized cameras [11]. The thus measured side-on radiances result from the local emission coefficients integrated along the line of sight through the arc. These can be reconstructed in cylindrical coordinates by the inverse Abel transformation under the assumption of axial symmetry. For each corresponding pixels of the two acquired images local emission ratios can be calculated. These values are compared with calculated emission ratios within the filter widths yielding the local plasma temperature. The temperature dependency of each calculated emission coefficient for corresponding spectral interval as well as the resulting ratio are described in detail in [12] and are also shown using a tomographic analysis in [13]. An example of the camera-system-obtained temperature distribution inside the TIG arc is shown in Fig. 1. Due to the fact that a high-speed camera is used high temporal resolution can be achieved.

Fig. 1 Plasma temperatures in a TIG process operated with a DC current of 100 A with argon as shielding gas. The contour plots show the radial and axial decrease of temperature from the hot cathode region. Each surface color corresponds to a temperature interval of 1,000 K



The TIG arc in this experiment was recorded with 33,000 fps. However, this method has its limitation once the assumption of LTE or adequate optical density of the plasma is violated.

While most spectroscopic analyses imply the investigation of an optically thin medium in local thermal equilibrium—which is not always true, even for thermal plasmas—Thomson scattering (TS) could be used as a well-established diagnostic for simultaneous measurement of electron temperature and density without the assumption of LTE in plasmas [14]. This technique does not require the knowledge of the gas composition, so it can be applied for diagnostics of gas mixtures.

Temperature and density measurements using Thomson laser scattering have been extensively used since the theory of electron density fluctuations in plasmas was first established by Salpeter [15] in the 1960s. The principle of TS may be explained by looking at a Doppler-shift. The light from a laser is scattered by free electrons, which due to their thermal velocity and the collective movement in the plasma is shifted from the original laser wavelength.

To derive values for the electron temperature and the density from the scattered light intensities, the experimental line profile has to be fitted with a theoretical line shape. According to the theory, the scattered power is proportional to the spectral density function $S(k, \nu)$, approximating the plasma as an electron gas with a neutralizing background of positive charges. As mentioned before, to obtain electron temperature and electron density measurement, we need to match the experimental line profile with the calculated one by properly adjusting the values for T_e and n_e . This nonlinear fitting is performed using the Levenberg–Marquardt algorithm [16].

Although already applied to techniques like plasma spraying and gas tungsten arc welding (GTAW) only few works investigated the use of TS for atmospheric discharges for example in the technologically more likely event of the presence of metal vapor [17] like in gas metal arc welding (GMAW) processes. This is mostly due to the unstable nature of the GMAW process, which does not allow long data acquisition times commonly used in TS.

Anyhow, the GMAW process poses many challenges for diagnostics. A plasma is ignited between a wire electrode and a flat workpiece (the wire usually acting as the anode). The wire is melting leading to the formation of droplets which travel through the

plasma to the workpiece becoming part of the weld seam. Metal vapor is produced mostly close to the droplet formation zone and becomes part of the plasma. The influence of this vapor on plasma conductivity and current flow is nicely described in [18]. In order to predict the amount of metal vapor and the quality of the seam the temperature of the droplet and how it develops while traveling through a plasma are important parameters. Here we already see an example of how plasma diagnostics evolves into plasma process diagnostics. In order to measure droplet temperature in the presence of a plasma the thermal radiation from the droplet has to be detected. From this signal and the emissivity of the material the temperature can be determined. However the emissivity of the molten droplet is not known with sufficient accuracy and can vary locally due to oxidation, temperature variations and surface texture. Using two-color pyrometry surface temperature can be determined without knowledge about the emissivity [19–21]. Assuming grey body radiation the knowledge of the absolute emissivity can be omitted due to the use of intensity ratios. Using the assumption that the emissivity ϵ_1 and ϵ_2 at the wavelengths chosen does not differ significantly the temperature of the droplet can be described by

$$T = \frac{h_c/K_B(1/\lambda_2 - 1/\lambda_1)}{\ln(SR(\lambda_1, \lambda_2)) + 5 \times \ln(\lambda_2/\lambda_1)},$$

where h is the Planck constant, c the speed of light, k_B the Boltzmann constant and SR (λ_1, λ_2) the ratio of radiances at λ_1 and λ_2 .

Apart from being able to take the plasma radiation into account this pyrometry method needs to have a high temporal resolution to determine the temperature development during the trajectory of the droplet. To perform this pyrometry an optical setup similar to the one shown in Fig. 2 and as previously described for the 2D spectroscopy is used. The object of interest is observed through an objective. The collected light is divided into two beams by a mirror prism. Both beams are projected onto a low light performance CMOS image sensor of a high-speed camera by two mirrors. In both beam paths an interference filter of different wavelengths is placed, producing a single image on the sensor chip displaying two images of the same droplet (Fig. 2). The surface temperature of the observed object is determined by ratio generation of the intensity at both wavelengths.

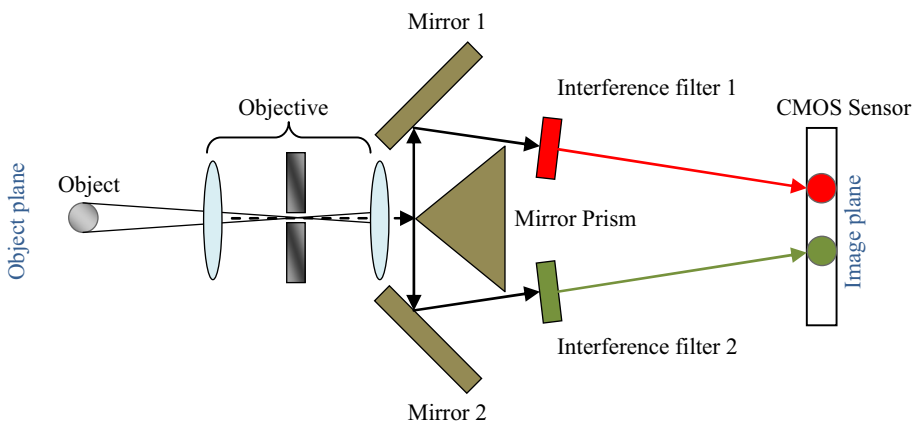


Fig. 2 Schematics of the setup of the two-color pyrometry

Using this setup the droplet can be observed with high temporal resolution, given by the optical acquisition system. Two-color pyrometer measurements show especially for low wire feed rates that the droplet is not heated uniformly by the arc. The bottom, where apparently most of the arc energy is deposited during current conduction before detachment, is hotter than the top part of the droplet, where it detaches from the wire. On the trajectory to the workpiece the droplet temperature equalizes with the result that the average temperature decreases, Fig. 3 [22].

This high-speed pyrometry provides significant information about the plasma material interaction on a very small timescale, but for understanding surface chemistry more information is needed.

These are just a few examples of how the use of modern technology already enhances the investigation of thermal plasma applications but there is still room for innovations.

Current Developments

Before an attempt is made to sketch new possibilities for innovative diagnostic systems a basic problem which is frequently overlooked will have to be addressed. With the tendency to develop new and innovative processes for thermal plasmas using progress made in power electronic (i.e. pulsed processes, fast AC processes) the measurement of current and voltage is becoming more challenging as well. Just to provide a small example one may look at the welding process. When the plasma is transferred from the molten material to the cold material (workpiece is being welded) the cathodic electron emission mechanism changes from thermionic to thermo-field or pure field emission leading to the formation of so-called arc spots. These arc spots can be observed by optical means and should also be detectable in the current and/or voltage measurement. The time scale of arc spot formation is similar to the well-known mechanisms in vacuum and can thus be assumed to be in the MHz range. Including a small inductance in the measurement circuit may have a serious effect on the integrity of the signals recorded. In Fig. 4 the influence of an added inductance can be observed.

It is obvious the inductances as small as 1 μH already distort the acquired signal significantly. Thus the rules of high frequency measurement technology will increasingly have to find their way into thermal plasma diagnostics. Rules like impedance matching, the choice of adequate sampling rate and thus the avoidance of aliasing artefacts should be

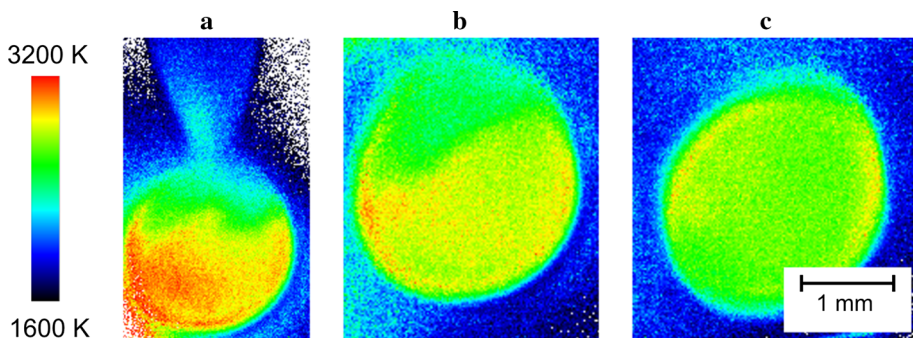


Fig. 3 Temperature distribution of the droplet surface while traveling to the workpiece, before detachment (a), after detachment (b), at height of cathode (workpiece) (c)

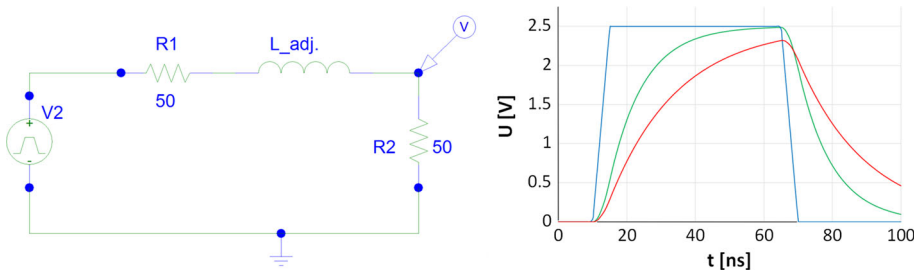


Fig. 4 Measurement circuit with a variable inductance L (left); influence of the inductance in the circuit on signal integrity (right). Original signal at (V): blue, signal distorted by $1 \mu\text{H}$ inductance in series w/R1: green, signal distorted by $2 \mu\text{H}$ inductance in series with w/R1: red

well-known to each researcher dealing with thermal plasma technology. Electrical Engineering textbooks provide ample information.

While process control systems are addressed earlier in this paper the focus of discussing new and innovative possibilities for thermal plasma diagnostics will concentrate on more elaborate systems. This is mostly due to the fact that the use of process control requires high reliability and low cost. Thus these systems can only follow scientific developments but hardly lead to innovations.

As explained earlier, diagnostic systems for thermal plasmas are well developed for scientific purposes, with stable plasmas and well defined boundary conditions. For high-speed applications gaining more ground recently, however, more improvements are needed to adapt to real life applications. In thermal spraying tomography is used frequently for the analysis of plasma jets. Since the data acquisition for a high resolution tomographic investigation takes a significant amount of time as many images of the plasma have to be taken from various observation angles the assumption is made that the jet is stable and long integration times are used to obtain an averaged image of the plasma jet. Similar approaches are taken in scattering measurements where the cross section is usually very small ($0.665 \times 10^{-24} \text{ cm}^2$ for TS) which means that averaging over many measurements i.e. long time constants improves the signal-to-noise ratio and thus the measurement quality. In order to be able to perform these long duration measurements up to now in welding very often scenarios are analyzed which have little to do with actual welding operation. Sometimes the workpiece is replaced by non-melting material in order to obtain high process stability. The welding distance may be set to a fixed distance. Gas and material combinations are selected to be able to perform spectroscopic analyses where a lot of information is easily available (e.g. using pure Argon as a welding gas).

Thus the main challenge for innovative diagnostics will be to provide data for actual commercial processes with the goal to provide information about:

- Fast changes in the behavior of plasmas.
- Interaction of plasmas with material.
- Obtaining information about plasmas that occur in industrial environments.

possibilities to gather this information will be suggested as follows.

Based on the single-camera, two-images system described earlier in this paper, a poor-man's tomography can be designed. Looking at the target to be analyzed with two beam paths at a 90° angle with respect to each other allows for gathering 3D information without the assumption for rotational symmetry. This will enable omitting the Abel inversion,

which due to the assumption of a certain radiation profile (very often Gaussian) is a cause of error as most technical plasmas are not rotationally symmetric. This is especially true for plasma welding and cutting applications where the plasma is moved across the material to be treated. In order to be close to a tomographic analysis at least six viewpoints will have to be recorded simultaneously but even with just one camera and two images significant information for process analysis can be gathered. In Fig. 5 an example is shown of a pulsed GMAW process with simultaneous acquisition of Argon radiation, metal vapor radiation and droplet formation, synchronized with current and voltage data of the welding process [22]. Using this kind of observation technique the occurrence of metal vapor can be determined in dependence on droplet formation and the influence of metal vapor on Ar radiation (i.e. current path) can be investigated. Such techniques are especially useful for industrial processes where the occurrence of metal vapor is seen as source of possible health risks for the operator. Minimizing metal vapor might lead to lower nano-particle formation in the vicinity of the welding process.

Using spectrally resolved imaging the spreading of metal vapor in the pulsed GMAW process can be observed (Fig. 5) and by using side-on spectroscopy the temperature in the plasma can be determined. However, as this requires an Abel inversion and taking into account that a welding plasma is hardly rotationally symmetric temperatures of the plasma should be determined by tomographic means using at least four different viewing angles detecting two wavelengths each similar to the work by Hlína [23]. For the simultaneous analysis of plasma gas and metal vapor, the work shown in Fig. 5 should be extended to look tomographically at two vapor lines and two plasma gas lines. Again certain assumptions—as mentioned before—are needed to do this.

A group in Greifswald (INP) has performed pure side-on measurements and found that the observable metal (Fe) core in the center of the plasma has a significantly lower temperature $\sim 9,000$ K than the surrounding argon plasma ($\sim 13,000$ K), which also leads to a significantly lower conductivity in the plasma core compared to the fringes, suggesting a current flow which is reduced in the center of the plasma [18]. While these measurements have been verified by numeric modelling there may still be additional investigations necessary. Apart from the validity of rotational symmetry one may argue that the optical density of the metal vapor core (Fig. 6) is too high to assume an optically thin plasma. Thus new methods for verifying these data should be developed.

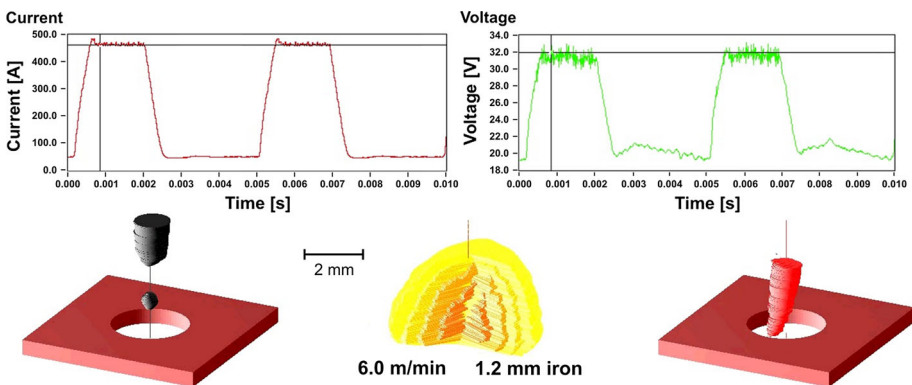
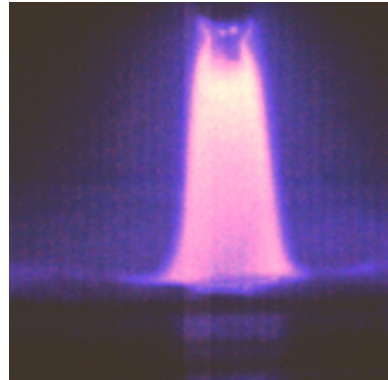


Fig. 5 High-speed 3D images of droplet formation (*bottom left*), Ar radiation (*bottom, center*) and metal vapor radiation (*bottom right*) recorded synchronously to current (*top left*) and voltage (*top right*) [22]. Image acquisition speed: 8,333 fps

Fig. 6 Metal core pulsed GMAW (with friendly permission by INP Greifswald), center with high amount of metal vapor radiation, fringes Ar radiation (*blue*)



One way to verify this measurement might be the use of high-speed Thomson scattering, which in the case of pulsed GMAW needs to provide sufficient temporal resolution, i.e. data acquisition during a few pulses only at well-defined acquisition times. This means that a stable process needs to be guaranteed for only few pulses and that measurements in the plasma are always taking place at a certain time with respect to the droplet position inside the plasma. Due to advances in camera technology and electronics these challenges can be met. Sufficiently high quantum efficiency of the detection system is needed.

The setup as shown in Fig. 7 was used to investigate a pulsed GMAW process with one droplet per pulse detachment. In general it is possible to obtain measurements from a single laser pulse using such a setup. However in order to improve the signal to noise ratio the scattering signal generated by several laser shots is accumulated on the CCD chip of the camera. On the short time range the GMAW process is sufficiently stable to average of a few pulses. However on the long time range the behavior of the arc will change. Hence in

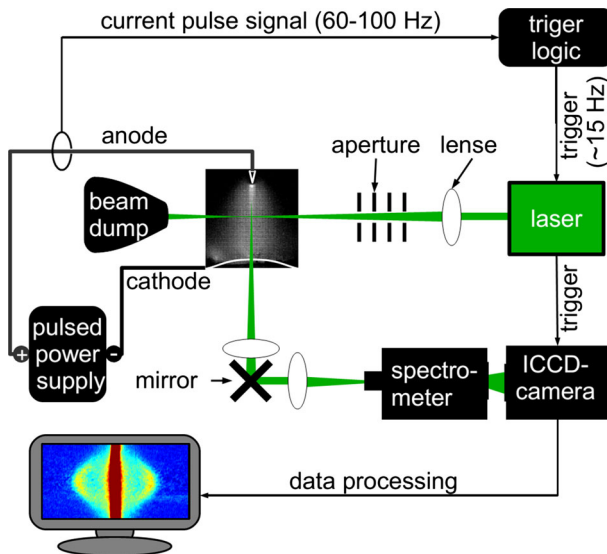


Fig. 7 TS setup for investigation of GMAW process

order to ensure comparable results the signal is integrated during five laser pulses in the high current phase and 20 laser pulses in the low current phase. An additional high-speed camera was installed for the arc shape visualization. By doing this it was in addition possible to optically verify that the arc shape did not change considerably during the signal integration procedure. For the TS signal detection the image intensifier of the ICCD camera is activated for 5 ns per pulse to minimize the plasma background radiation. In order to minimize the CCD readout noise the on-chip accumulation function of the ICCD camera is used. Additionally the background radiation is recorded by keeping the experimental conditions and the trigger time of the GMAW pulse but by blocking the path of the laser radiation.

With this kind of setup electron temperature measurements were performed without the assumption of rotational symmetry. Resulting temperature development for a pulsed GMAW process is shown in Fig. 8 [24].

Making single shot TS a standard diagnostics will be a major challenge but will also help provide reliable data for many transient processes. Up to now it has not been possible to verify the temperature minimum as measured by spectroscopy due to technical problems with the used wavelength (532 nm) for the Fe wire/Ar plasma gas combination. Certainly using single shot TS may require additional attention to the possible problem of plasma heating by the laser due to inverse bremsstrahlung. Fortunately, due to the fact that this is a linear process, the heating effect can be eliminated by extrapolation (i.e. measuring the electron temperature with laser power variation) as described by Fincke [25]. However, as studies have shown [26, 27] this kind of extrapolation has to be complemented by taking into account the dependency of laser absorption on electron temperature, which changes during the laser pulse. Thus the initial electron temperature has to be determined by studying the temporal evolution of T during the laser pulse and then by extrapolating the results to the origin of the pulse. In order to do this the temporal evolution of the laser pulse has to be taken into account as well [28]. Heating has been considered for lower laser

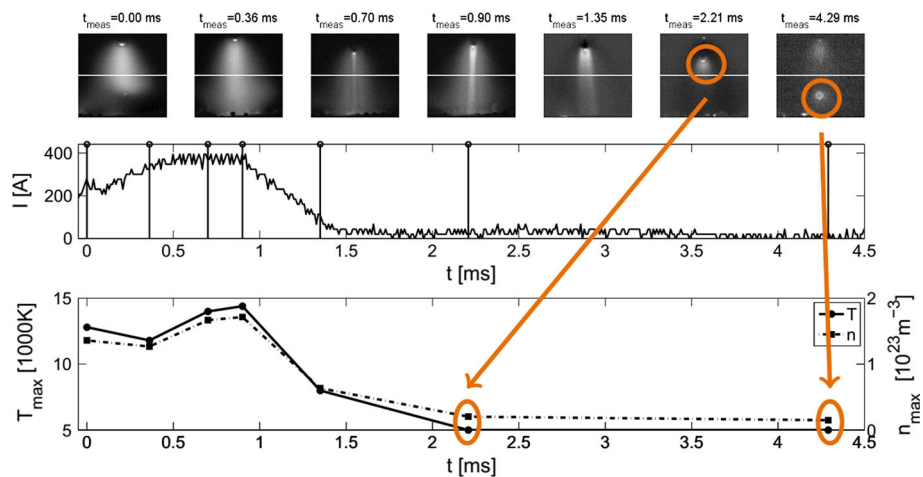


Fig. 8 Results of TS measurements for Al wire/Ar gas combination (electron temperature and density (*bottom*) during a pulsed GMAW process. The *line* in the images (*top*) gives the position of the laser, the *vertical lines* in the current display (*center*) the time of data acquisition during the current pulse, the *circles* mark the droplet position in the high-speed images and in the measurement results

power in [29], and was proven to be negligible. If however, for single shot operation laser power will have to be increased significantly, the evaluation of the laser heating may require an additional experimental effort. In order to be able to compensate laser heating most likely calibration measurements will have to be performed on a mock-up experimental setup providing constant plasma parameters, which are similar to the object investigated. Another possibility would involve a simultaneous spectroscopy/scattering experiment through which at least the consistency of plasma in the measurement is confirmed allowing to compare TS results obtained with varying laser power.

Now certainly a non-intrusive method to determine current density in the plasma would be a way to verify the above mentioned spectroscopic measurements as a current minimum in the plasma center was predicted. Even though one might argue that this is not plasma diagnostics it may definitely verify plasma diagnostics. One possible approach to determine current density in a plasma could be the measurement of magnetic fields produced by the current flow similar to the work in fusion research [30]. Advances in electronics manufacturing allow for the production of hall probes which can determine not only the magnitude of a magnetic field but also the *x*–*y*–*z* components on a very small footprint, enabling local *B*-field measurements with high spatial and temporal resolution. In order to use these sensors for example in the GMAW process some innovation has to be applied as well: A first approach would be to arrange the hall probes around the plasma column in order to deduce the current density in the plasma column. Assuming a certain current distribution in the plasma column the *B*-field at a fixed location, where a hall probe may be placed, could be calculated using the Biot–Savart Law. Using an iterative approach the measurement signal of numerous hall probes may thus lead to a current density distribution inside the plasma column. In order to show the validity of this approach the variation of a *B*-field signal in a fixed spot for a varying current density distribution at a constant total current is shown in Fig. 9. Here discrete conductors are assumed.

While it is obvious that the changes are small they may still be of some merit to this application. The accuracy will improve, if the probes can be placed closer to the plasma or even inside the plasma. First attempts have been made moving a cooled *B*-probe through the fringes of the plasma. Using Gauss’ Law the included current inside a circular contour can be determined as a function of the radius: $\oint_{\mu_0} \vec{B} \cdot d\vec{s} = I_{enclosed}$.

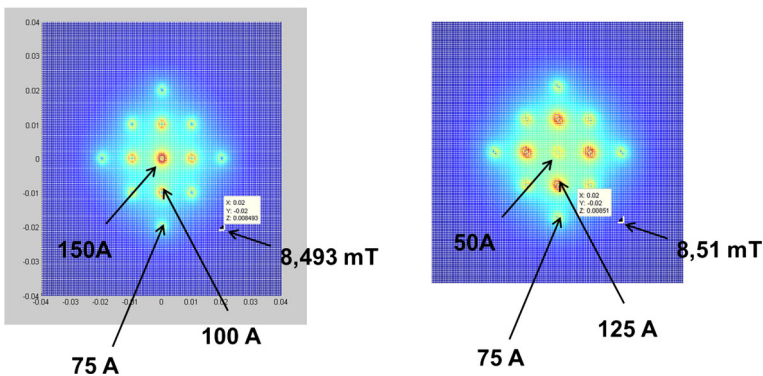


Fig. 9 Magnetic field distribution calculated resulting from varying current distribution of a total current of 1,150 A. In the *left* image the center conductor has a current 150 A which is reduced to 50 A in the *right* image

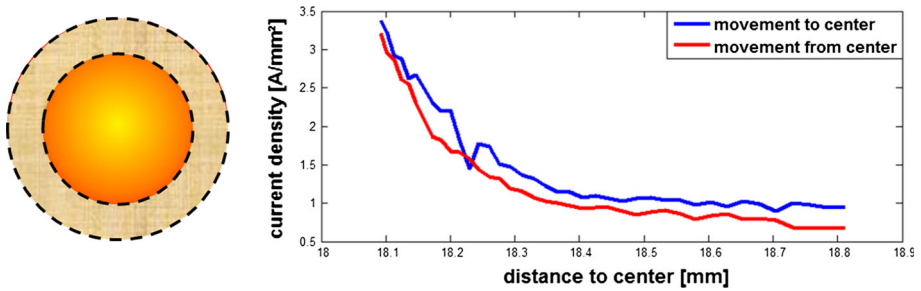


Fig. 10 Current density measured in rotationally symmetric plasma inside outer area of arc footprint (*left image*)

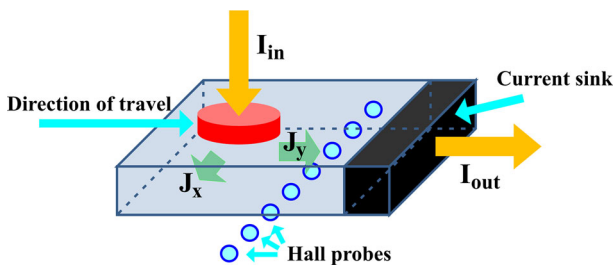


Fig. 11 Principle of B -field evaluation underneath workpiece by means of a hall probe array. Current input (*magenta circle*)

By determining the B -field at two different radii the current included in the area between the two radii can be determined. Assuming rotational symmetry the current density in this area can be calculated (Fig. 10) by $J = (I_{r_2} - I_{r_1}) / \pi(r_2^2 - r_1^2)$

Another ansatz is used to determine the current density in the footprint of the plasma by measuring the current in the workpiece.

Once the arc travels across the workpiece in y -direction the current is flowing from the footprint of the arc to the attachment point of the return cable of the current circuit acting as a current sink as seen in Fig. 11. If the footprint of the arc current has a distinctive shape the current density inside the workpiece is influenced. This can be seen using the following example: A current of 100 A is flowing through the workpiece. This current is flowing in either the y -direction (direct path to current sink) or in x -direction (Fig. 11).

If now the assumption is made that the current is distributed across a cylindrical surface (arc footprint) changes in this distribution will lead to a change in current density inside the workpiece and thus to a change of the B -field produced by this current density. In Fig. 12, the change of current density in x -direction is depicted along a line in x -direction right underneath the center of the footprint. While in one case the current is distributed evenly across the footprint of the arc in two other cases the center of the arc does not conduct any current including a variation of the size of the non-conductive area (similar to the condition in the GMAW scenario described above). It can be seen from an electrostatic model that the shape of the current density in x -direction changes even though the total current transferred through the footprint remains constant. This change should be recordable using small sensitive hall probes. The data proves the applicability of this method. An inverse

Fig. 12 Current density J_x along the hall probe array shown in Fig. 11 for solid cylinder (blue), donut with 1 cm diameter current free area in the center (orange) and 2 cm diameter current free area in the center (green)

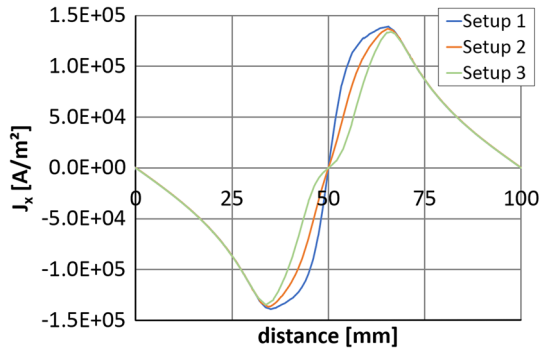
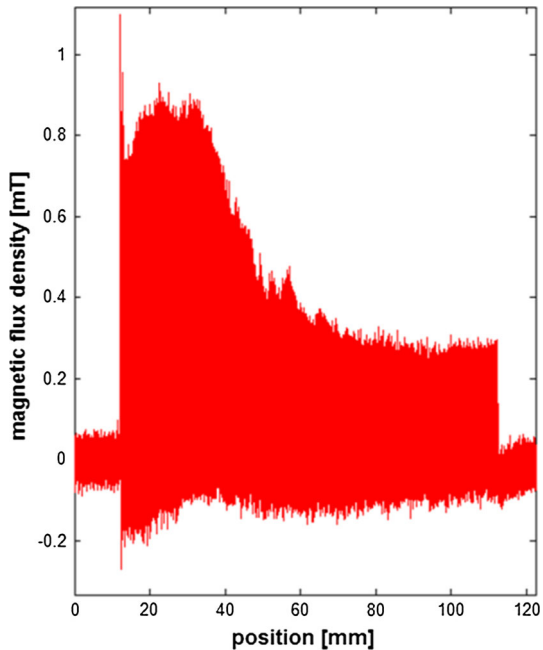


Fig. 13 Measured B -field in y -direction for traveling arc footprint as sketched in Fig. 11



modelling approach should be taken to quantitatively determine the current density in the footprint.

An actual measurement of the magnetic flux is given in Fig. 13, where the result of a hall probe signal (y -direction) underneath a workpiece in the case of GMAW is shown, while the arc is moved across the workpiece in y -direction. The higher magnetic flux in the left part of the signal is due to the arc being on the left of the hall probe (Fig. 11), thus all the current flows across the area where the hall probe is placed underneath. With increasing travel the current drops as more current will be able to flow to the current sink without having to cross the hall probe sensitive area.

One last example for how plasma diagnostics might provide important data and evolve into process diagnostics is the use of additional information provided by two-color

pyrometry. In thermal spraying particles are inserted into a so-called plasma jet. Plasma jet temperature can be analyzed by tomography as shown in previous works [31] and particle temperature may be measured by two-color pyrometry (side-on or tomographically), which is just determined by the amount of equipment that is available. The particles inside the jet are molten and also surface chemistry might take place (oxidation), which of course influences the quality of the coating. Thus it would be interesting to know if and how such surface chemistry during interaction with the plasma takes place. It is currently possible to determine the trajectory of a single particle with a camera system. With the known trajectory it should be able to find the particle downstream in a second camera system. Thus two-color pyrometry would be able to provide information about the development of particle surface temperature. Additionally at the same time it would be possible by recording the intensity of the measured radiation in the two used wavelength intervals to record a change in emissivity of the particle. However, the assumption for this is that the emissivity changes due to surface chemistry and not due to cooling or heating of the particle, but this could be ensured with the two-color pyrometry. Using for example information about emissivity changes [32] due to oxidation the measured information could be used to determine the change of oxidation during flight.

In order to verify the measurements obtained by this technology an additional method to determine the composition of sprayed particles in-flight might be useful. Using the LIBS (laser-induced breakdown spectroscopy) [33] technology in thermal spray may provide the information necessary.

Future

High-speed camera development will drive optical thermal plasma investigations. High frame rates ($>10^5$ fps) at full resolution will allow to investigate plasma processes in great detail at high speeds. Spectrally resolved imaging will provide information about material plasma interaction up to the specifics of current attachment and surface chemistry. However, the main problem will be the analysis of the data. It should be well known that effects like aliasing even appear in optical imaging, displaying artefacts which might be suitable for fancy physical explanation but are just not real. Thus Nyquist sampling criteria have to be applied to avoid Moiré effects, features that need to be seen require at least twice the sampling resolution of the size of the sample. Sensitivities of the CCD need to be taken into account as well. Usually spectral sensitivity ranges from 300 nm to 1 μm with a significant difference between back-illuminated CCDs and front-illuminated CCDs, but for example two-color pyrometry at around 1 μm wavelength is hardly possible using regular CCDs. In addition issues like pixel cross-talk need to be taken into account and certainly the adequate optical imaging is the key. Optical aberration is and will remain the biggest source of error.

With the progress of laser technology the use of lasers as a standard tool for analysis will become more likely. Scattering methods to analyze plasma velocity, plasma composition, magnetic field (faraday rotation) or refractive index of the plasma to determine density will move from the use in the high investment fusion technology to “low cost” thermal plasmas wherever the plasma parameters allow such measurements. However due to the plasma radiation especially in the presence of metal vapor and at high currents, it might be necessary to perform such measurements in the UV rather than in the visible range to ensure that the plasma is optically thin in the region of interest. Looking at the most common tool for plasma analysis the Nd:YAG Laser that means that a wavelength of

266 nm will have to be applied, this subsequently forces the use of fused silica optics and adequate detectors.

Another aspect that will require more attention in future is the resolution of smaller features within the plasma, which may include the analysis of cathodic arc spots [34] and the formation or movement of nano-particles inside the plasma, which occurs involuntarily in GMAW or intentionally in nano-particle suspension spraying. Observation using far-field microscopes (telescopes) certainly suffers from sampling issues as mentioned above but is—no matter how careful the experiment is designed—controlled by the Rayleigh criterion limiting the resolution to about 0.5 of the used wavelength, which implies that using visible light only a range of particles down to ~ 250 nm can be observed. Even that is not possible in most experimental arrangements, which is not sufficient for many applications. Collective movement of smaller particles may definitely be observed using scattering but the identification of an individual particle requires the use of shorter wavelengths. But here we arrive at a problematic stage. At wavelengths below 200 nm radiation is absorbed in molecular oxygen and below 100 nm radiation only propagates in vacuum, both conditions that do not match well with the approach to analyze commercial systems. Thus the next step would be to use X-rays [35]. The use of X-rays could be advantageous due to the possibility to analyze the material side of the plasma-material interactions as well [36]. Weld pool imaging would be possible and numerous other possibilities like X-ray TS could be performed. However for commercial applications there are many barriers for using X-ray sources. The most promising approach in science would probably be the production of X-rays with the help of laser produced plasmas in the vicinity of the region to be investigated. This is a standard technology in fusion [37] which also provides temporal resolution and could be applied to thermal plasma research as well.

Discussion

The examples described in this paper are supposed to show that diagnostics of thermal plasma processes is still a very challenging subject with numerous possibilities for innovations. The trend moves from fundamental research for the understanding of thermal plasmas to the wide field of understanding material-plasma interaction.

In order to achieve that goal experiments with actual commercial systems will have to be performed to understand and help to solve the problems that occur within industrial processes. This may include the influence of surface chemistry on current transfer and arc attachment. Even though—especially in the lighting industry—sophisticated models have been developed to predict the shape of the current attachment [38], these models do not include the influence that chemical reactions or surface structure variation on a micrometer scale might have on the near electrode layer. However the influence of surface preparation (roughness, chemistry) has been observed, thus these effects will have to be evaluated. Additionally the influence of the metal vapor production and material contamination is still something to be analyzed in more detail. New processes using new material combinations with fast electronic control systems need to be investigated. Thus there is still a significant amount of diagnostic analysis to be done to help understand plasma physics and chemistry. That may be in the form of interferometry (2D or 3D), scattering (single shot for fast unstable processes), high-speed camera systems (temporal development analysis), material oxidation, X-rays (to analyze weld pools and dense plasmas), hall probes (for current density measurements), intelligent cameras for process control (weld pool diagnostic), near

electrode diagnostics using microscopy and RF electrical measurements to finally solve the problem why a process might work well in Europe but not in SE Asia.

Certainly the examples given in this paper are by no way a complete list of all the methods that profit from technological advances. Many research institutions worldwide are currently investigating thermal plasmas and many approaches to understand the involved physical processes are made. However one should not forget that the use of new technologies involves almost always knowledge that has been around for decades.

Acknowledgments The authors wish to thank Dr. Joachim Heberlein (1939–2014) for leading the way in thermal plasma diagnostics. The development of many diagnostics mentioned here was funded in part by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Grant SCHE 428/10-1 und SCHE 428/8-1.

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