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Technical Note

LARGE—A Plasma Torch for Surface Chemistry Applications and CVD Processes—A Status Report

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The LARGE (*LONG ARG GE*NERATOR) is a new generation DC-plasma torch featuring an extended arc which is operated with a perpendicular gas flow to create a wide (up to 45 cm) plasma jet well suited for large area plasma processing. Using plasma diagnostic systems like high speed imaging, enthalpy probe, emission spectroscopy, and tomography, the LARGE produced plasma jet characteristics have been measured and sources of instability have been identified. With a simple model/simulation of the system LARGE III-150 and numerous experimental results, a new nozzle configuration and geometry (LARGE IV-150) has been designed, which produces a more homogenous plasma jet. These improvements enable the standard applications of the LARGE plasma torch (CVD coating process and surface activation process) to operate with higher efficiency.

Keywords advantages of TS, diagnostics and control, influence of process parameters, influence of spray parameters, plasma spray forming, stability of TS process, TS coating process

1. Introduction

Chemical vapor deposition (CVD) processes are promising paths toward more cost-effective technologies for wide area coatings on strips or sheets of steel, glass, polymeric web, etc.

In order for economic coating technologies to be compatible with industrial requirements, the following aspects need to be addressed (Ref 1, 2):

- Availability of scalable wide-area plasma sources
- Stability of plasma jets without fluctuations
- PE-CVD process for continuous air-to-air conditions
- Characterization of coatings/deposition rate

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The DC plasma source LARGE (Ref 3-6) was developed and evaluated for continuous plasma-enhanced (PE) CVD under atmospheric pressure. The LARGE is characterized by two rod-shaped electrodes arranged opposite to each other on a common axis with adjustable distance (up to 45 cm) (Fig. 1).

The name of the linear DC arc jet plasma source LARGE stands for *LONG ARG GE*NERATOR. Added to the name is usually a code where the first part indicates the development/application number and the second part the length of the plasma sheet in mm (e.g. LARGE III-150 = version 3, 150 mm length). Table 1 shows a detailed overview of the basic parameters used to operate LARGE III-150 as a standard module. Using multiple modules, a LARGE III-300 or LARGE III-450 can be constructed.

Different from conventional torch systems the plasma gas is injected laterally to the linear electrical arc stretching along the torch axis. Passing through the arc, the gas transferred into the plasma state leaves the torch as a flat homogenous plasma flow. Shrouding the electrodes with inert gases allows to use any desired plasma gas composition in order to set plasma specific parameters, as temperature, radical, or ion densities. Moreover, plasma chemical reactions are initiated. Conventional DC plasma generators are built by conical cathode and concentrically hollow anode. Because of the limited spot size of the plasma jet, the treatment of large surfaces or band materials requires a scanning process of the torch. The goal for the LARGE development was to have access to a flat, homogenous plasma sheet in order to enable plasma chemistry for large surface technologies and to minimize any non-uniformity of the treatment (Fig. 2). In this case, the arc is ignited between these two electrodes while plasma gas is fed through axially, resulting in an emanating plasma jet exhibiting a rectangular shape of distinct width, height, and length.

Fig. 1 Picture of LARGE III-150

Table 1 Basic parameters of LARGE III-150 and LARGE IV-150

Parameter	Range
Plasma gas	O_2, H_2, He, Ar, N_2, CH_2
Current	$I = 10\text{-}100$ A
Voltage	$U = 100\text{-}300$ V
Electrical power (linear power density)	1-30 kW (7-2 kW/cm)
Gas flow	10-100 slpm
Gas temperature at the exit of the torch	100-3500 °C

2. Principle and Operation of the Linear DC Arc Jet Plasma Source LARGE

The ignition of the arc over a long distance is crucial to the operation of the LARGE. The arc is initially ignited over a short distance and subsequently elongated step-by-step by opening of semiconductor switches (CIPASS—*C*ombined *I*gnition by *P*ilot *A*rcing and *S*uccessive *S*witching). The principle is shown in Fig. 3. All cascade plates can be connected through semiconductor switches to the anode potential of the power supply (Ref 5, 6). Having closed all switches the controller starts the ignition process of a high-voltage power supply in order to ignite a pilot arc between the cathode and the first cascade plate. Subsequent opening of the switches forces the anodic arc root to move step-by-step toward the anode. In this way, controlled by the CIPASS system, the arc is elongated until it reaches the anode, completing the ignition process. The DC power supply (TOPCON) has been developed for operation of the LARGE. The voltage and power range of up to several hundreds of kW, together with a fast response, makes this power supply a suitable tool for plasma applications.

The plasma gas is injected perpendicular to the torch axis. Passing through the arc, the gas is transferred to the plasma state and leaves the torch laterally through a flat slit. A main characteristic of the LARGE torch is the innovative form to stabilize the long plasma arc. In the case without a cross-flow of cold gas, the arc is

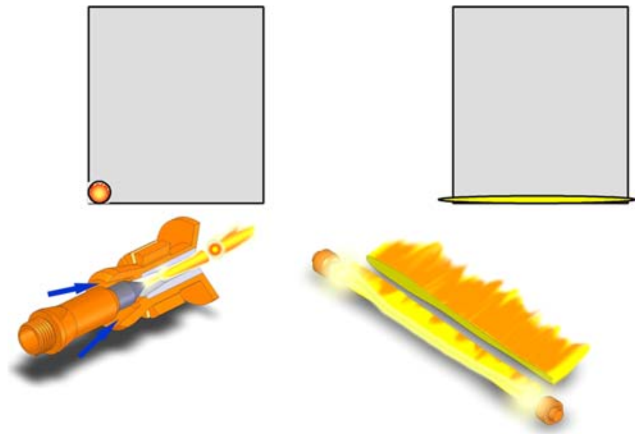

Fig. 2 Scanning treatment of planar surfaces by a conventional plasma torch and flat plasma geometry (LARGE)

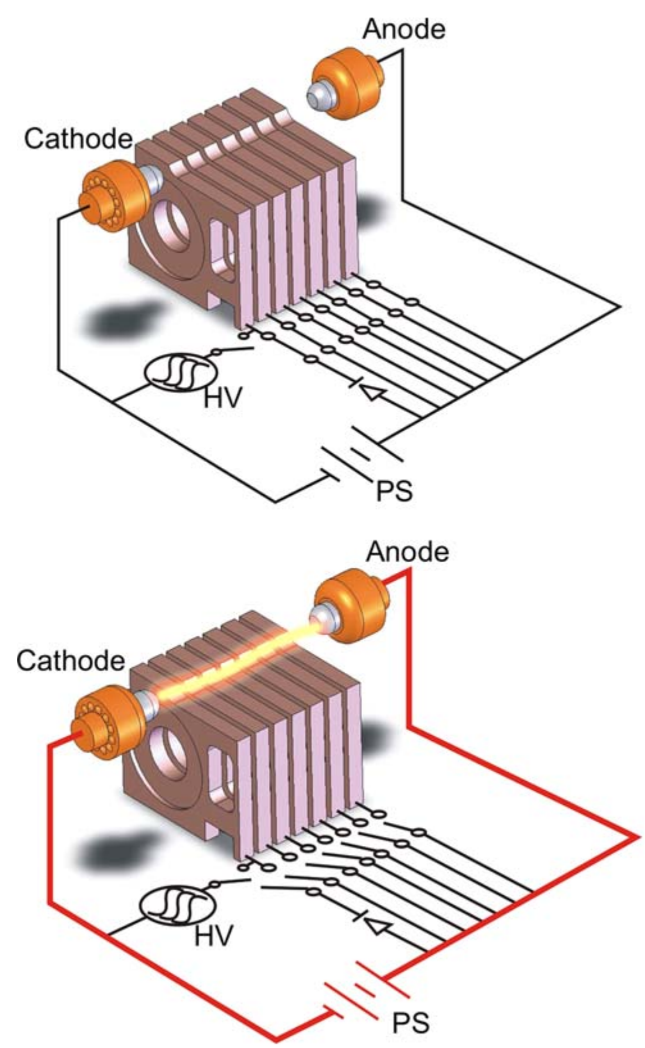

Fig. 3 Principle of the CIPASS method, before and after LARGE ignition (HV, high voltage power supply; PS, power supply)

wall-stabilized: according to the Steenbeck's principle, a transferred arc adjusts itself to a configuration of minimum power (Ref 7). For the LARGE torch, consisting of a straight arc connecting both electrodes, the minimum power configuration corresponds to a straight arc line. The additional cross flow of the cold plasma gas produces, due to the viscous force, a global bending of the arc downstream, curvature which has to be compensated. This compensation is achieved by the Lorentz force (Ref 8, 9) created by a the interaction of the electric current of the plasma arc to the strong magnetic field produced by two long permanent magnets located above and below the plasma arc (Fig. 4).

The torch system LARGE can be operated under low pressure as well as under atmospheric pressure conditions. The torch is water cooled and has a thermal efficiency of about 40-60% depending on the operating parameters. The torch behavior is controlled by two different gas flows: the plasma gas and additionally a gas flow surrounding the electrodes to ensure a fixed arc attachment point. As electrode gas typically inert gas flows of 2 × 1.5 slpm argon shroud the cathode and the anode. This shrouding of the electrodes permits the use of almost any desired gas mixture as plasma gas as any oxidation of the electrodes can be avoided. Actual plasma gas flows (Ar, H_2, N_2, O_2, CO_2,CH_4,…) are in the range from 0.5 to 5 slpm per centimeter plasma jet width. The utilization of chemical reactive gases, which are partly transferred to radicals, ions, and molecule fragments, allows the torch to be operated in CVD and surface treatment processes.

3. Experimental Diagnostics

Electrical, acoustical, magnetical, and optical measurements (Ref 8, 10) have been carried out on the system LARGE to elucidate the operating parameter range and to clarify the specific plasma jet properties.

As a preliminary diagnostic, the distribution of the magnetic field produced by the long magnets at the torch outlet was measured by means of a Tesla probe (Fig. 4). Characteristic for this distribution is the rapid decrease in the magnetic strength at locations near the cathode/anode.

To qualify the plasma source LARGE, information about the homogeneity of the broad plasma jet is necessary. Therefore, measurements of the integral light emission were taken as indicator. A CCD camera is mounted to look straight down to the plasma jet. The video data is transmitted to a personal computer to analyze the plasma jet contour. If the plasma jet is deviating from the desired contour, gas flow controlling valves can adjust the flow rate. A periodic variation of the integral light emission of the plasma jet is observed (Fig. 7, above) by the gas

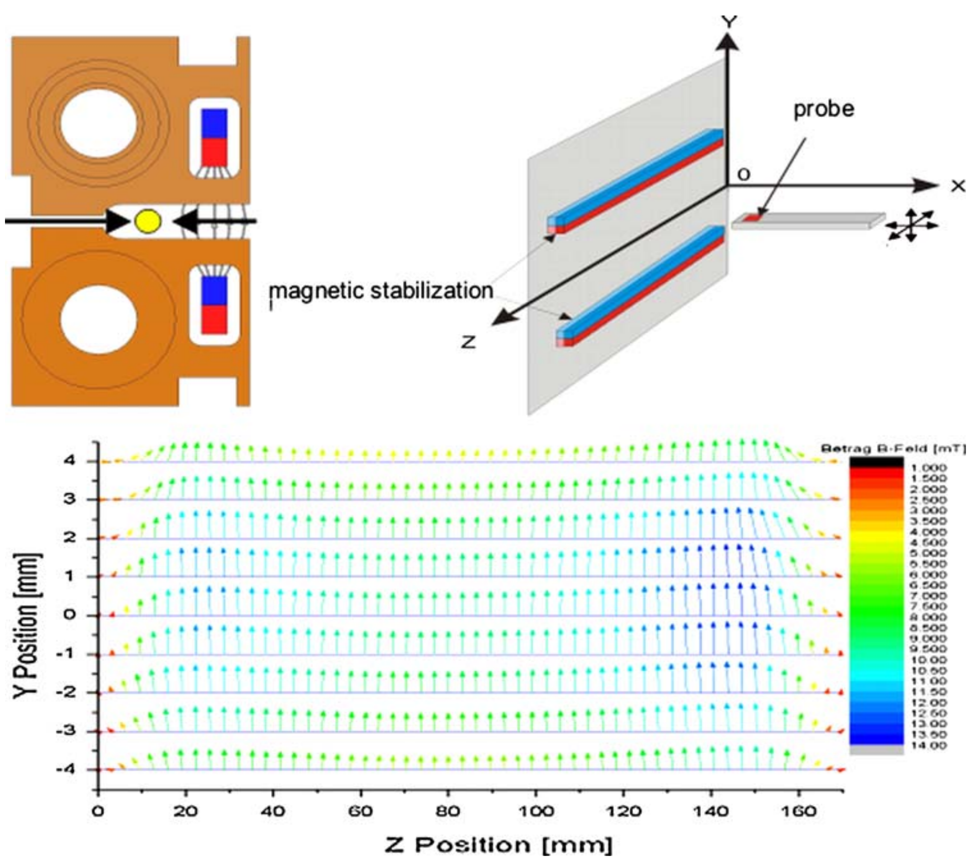

Fig. 4 Principle of arc stabilization and dependence on temperature of conductivity and tesla-probe measurement of the magnetic field B_y und B_z in a distance of 14 mm

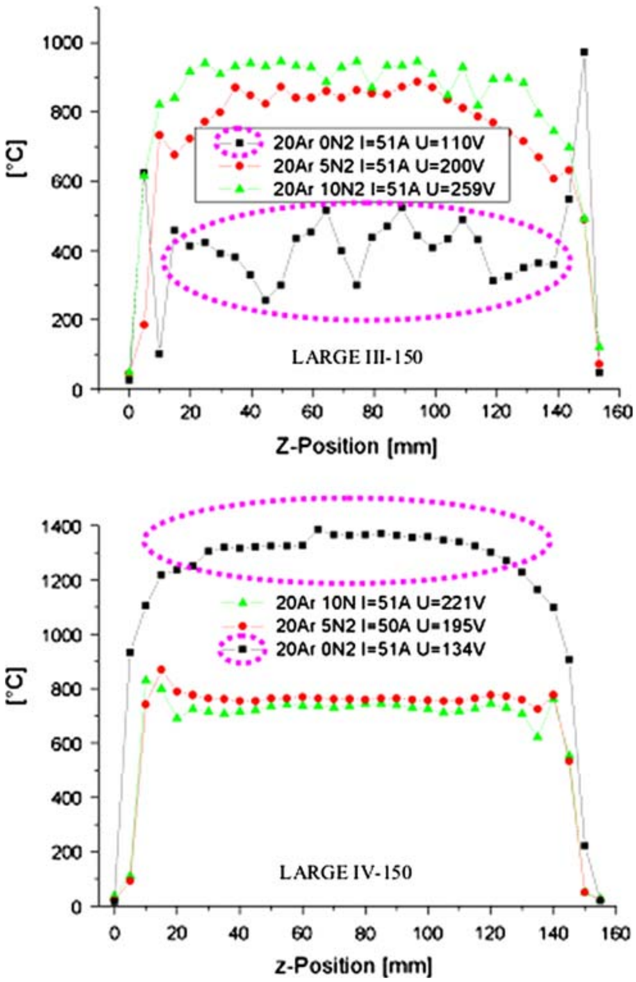

Fig. 5 Distribution of temperature measured with enthalpy probe at a location 4 mm downstream for LARGE III-150 (above) and LARGE IV-150 (below)

injection through discrete ports. An improved gas divider is already in production which is supposed to reduce these fluctuations. The new gas divider will inject the plasma gas as linear constant sheet overcoming the constraints of discrete gas injection. Additionally, plasma jet temperatures and plasma jet velocities were measured using an enthalpy probe (Tekna-ENP 04 in combination with probe type ENP-476). In comparison to the imaging technique mentioned above, which produces a 2D image, the enthalpy probe is a 3D spatially resolving method. As the plasma source LARGE generally makes use of gas mixtures, a quadruple mass spectrometer (Balzers QMG311) was used to determine the gas composition. However, the overall length of the extraction system impedes the determination of radical concentrations, e.g. of ozone in oxygen containing gas mixtures, due to rapid chemical reactions at atmospheric pressure. These concentrations have to be measured with spatially resolving optical techniques. The resulting temperature distribution can be seen in Fig. 5, and detailed results can be found in Ref 3. This topic will be the subject to a latter publication comparing enthalpy probe measurements to spectroscopic investigations. So far only qualitative information about the optical emission spectrum (OES) has been gathered (Ref 8, 11, 12). The optical emission spectroscopy signal was recorded by an optical cable to a SpectraPro-0.275 Meter Digital Scanning Mono-chromator (Acton Research Corporation). The OES spectrum of a pure Ar plasma is shown in Fig. 6.

4. Modeling and Simulation of the LARGE

By means of the software package ANSYS, a simple model was developed to calculate the flow without interaction to the magnetic field and assuming a laminar flow (Ref 8, 10, 13). The objective is to evaluate the fluctuations and instabilities of the produced plasma jet as influenced by the nozzle geometry. The goal was to design a new nozzle to produce a more homogenous plasma jet (Fig. 7).

The velocity distribution of the cold gas flow (LARGE III-150) was calculated by using software ANSYS. In Fig. 7 (middle), the momentum of the cool gas flow during its travel through the plasma canal is depicted for the LARGE III-150. The resulting velocity distribution displays a well pronounced vortex previous to the torch outlet. This effect may be responsible for the inhomogeneous plasma flow issuing from the torch, just as experimentally measured in the temperature distribution by means of the enthalpy probe (Fig. 5, above). In order to reduce this effect, a new modification of the cascade plates has been modeled. Herein, the arc is constricted into a small semicircular cavity in the upper cascade plates and the gas flow is pushed into this cavity through a slight elevation in the lower cascade plates (Fig. 7 and 8, below). This cascade plate modification corresponds to the improved model LARGE IV-150. This new design shows improved behavior for continuous wide-area PE CVD processing (Ref 1, 3) through better stability, even though a lower jet temperature has to be taken into account. In Fig. 8, examples of the gas flow profile, at different locations and with special nozzle geometries, are depicted. The LARGE IV-150 source featuring the new nozzle design limited the fluctuations significantly at the exit (measurement location 2).

5. Results and Conclusions

In the torch system LARGE, the arrangement of the anode and the cathode opposite to each other on a common axis leads to a substantially different plasma jet compared to conventional torch systems. Utilizing this flat, broad plasma jet brings advantages particularly if large-scale workpieces have to be treated. By shrouding the electrodes with inert gases, reactive plasma gases can be used for plasma chemical reactions in the central part of the torch. Electrical measurements show the stability of the discharge and constant power consumption. Noise

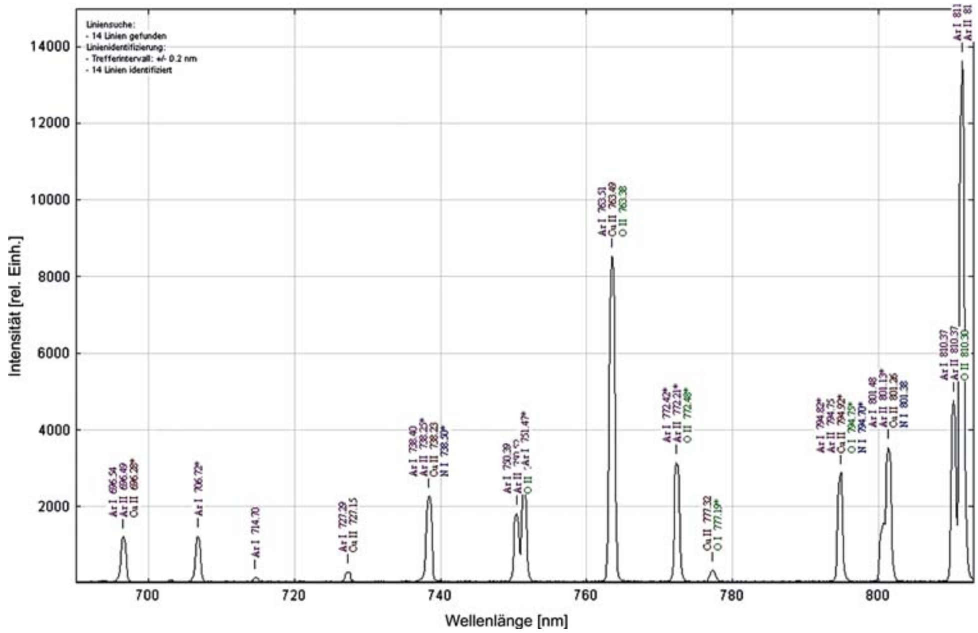

Fig. 6 Emission spectroscopy investigation of LARGE III-150, 20 slpm Ar, $I = 50$ A

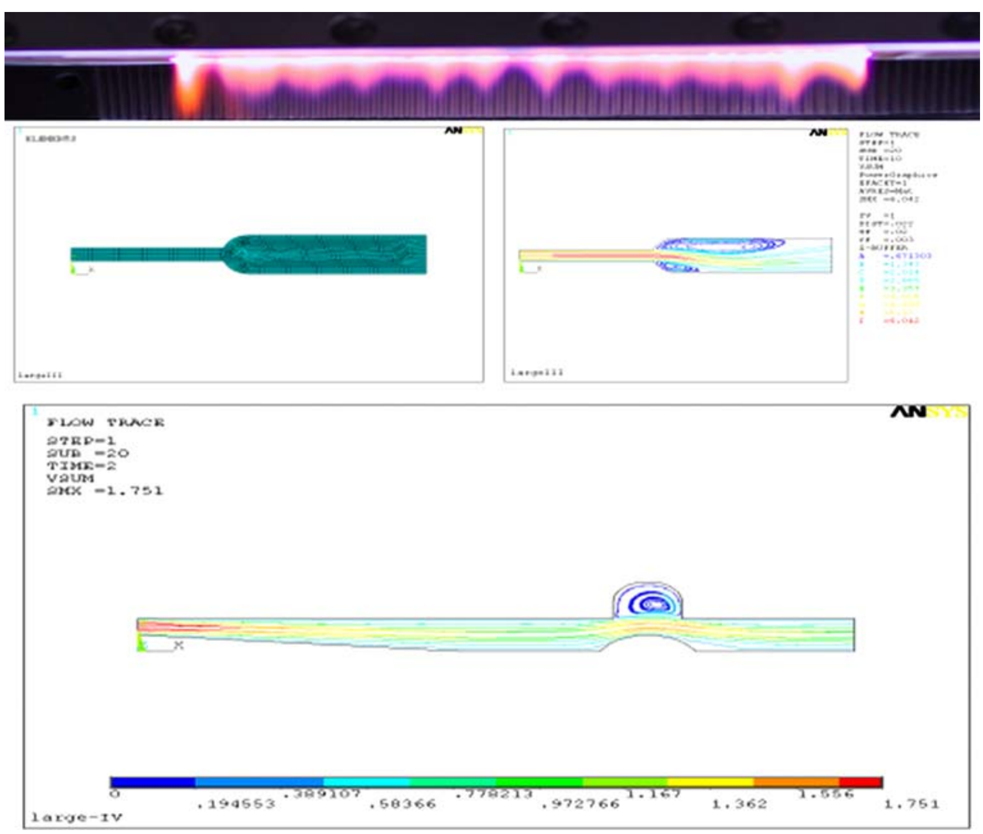

Fig. 7 Fluctuations and instabilities of plasma jet measured with CCD camera, LARGE III-150 (above). Simulated velocity distribution in LARGE III-150 (middle) and LARGE IV-150 (below)

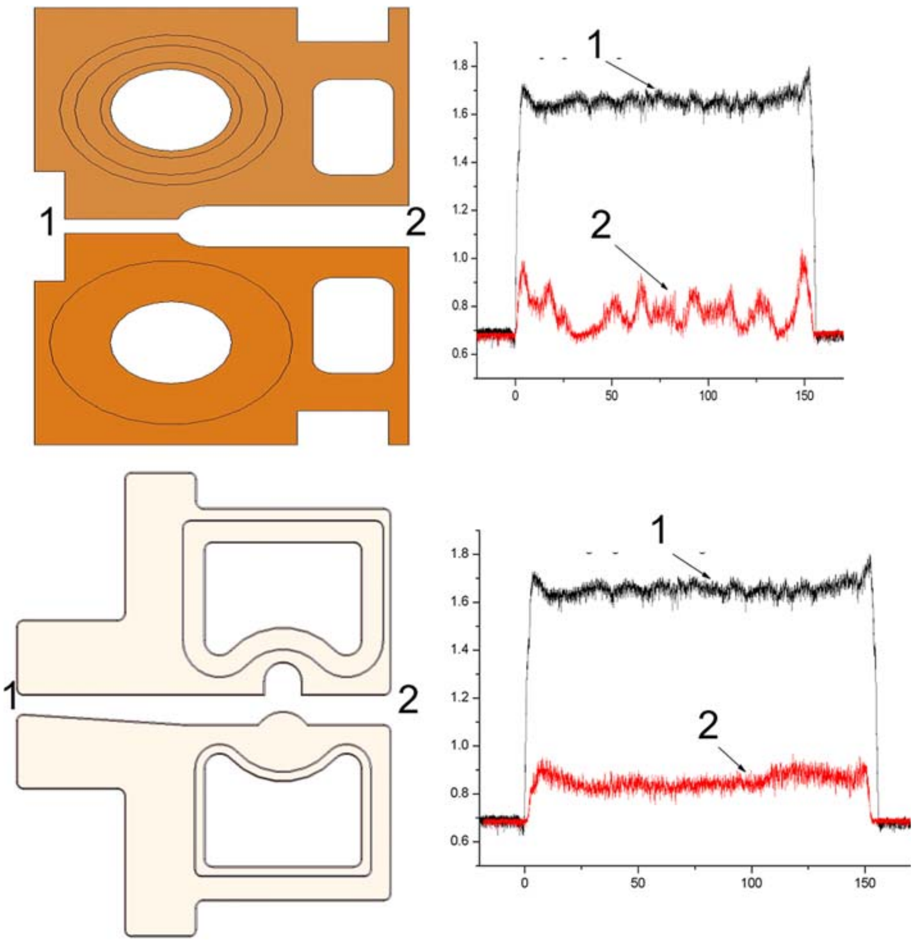

Fig. 8 LARGE III-150 geometry and velocity of gas flow on different measurement locations 1/2, and LARGE IV-150 geometry and velocity of gas flow on different measurement locations 1/2

levels of the torch are remarkably low (<80 dB(A)). Optical and enthalpy probe measurements show fluctuations of the plasma jet, which appear to be correlated to the plasma gas injection through discrete ports. An improved design of the gas divider with a homogeneous plasma gas injection system should provide better stability.

The potential application range of the newly developed Arc Jet-CVD technology was evaluated by screening studies on several substrates. Plasma pretreatment was found to be very efficient for improving layer adhesion (Ref 1, 2). More optical and enthalpy probe measurements as well as modeling will be used to find out the optimum nozzle geometry for present and future applications.

References

1. V. Hopfe, D. Rogler, G. Maeder, I. Dani, K. Landes, E. Theophile, M. Dzulko, C. Rohrer, and C. Reichhold, Linear Extended ArcJet CVD – A New PECVD Approach for Continuous Wide Area Coating Under Atmospheric Pressure, *Chem. Vapor Depos.*, 2005, **11**, p S.510-S.522
2. M. Koppers and E. Theophile, umweltgerechtes Verfahren zur Folienbehandlung und Folien-kaschierung im Atmosphärenplasma, BMBF – gefördertes Projekt, öffentlicher Endbericht, 2006
3. E. Theophile, ''Entwicklung eines Plasmagenerators mit atmosphärischem DC-Langlichtbogen zur Modifikation von Werkstoff-oberflächen,'' Dissertation UniBw München, 2006
4. R. Hartmann, G. Kraut, and K. Landes, CIPASS—An Ignition Method for the Innovative Plasma Torch ''LARGE'', *Eur. Phys. J. Appl. Phys.*, 1999, **8**, p 253
5. R. Hartmann, J. Zierhut, and K. Landes, European Patent 97810823, 1997
6. TOPCON, http://www.regatron.ch/
7. Th. Peters, Über den Zusammenhang des Steenbeckschen Minimumprinzips mit dem thermodynamischen Prinzip der minimalen Entropieerzeugung, *Zeitschrift für Physik*, 1956, **144**, p 612-631
8. R. Huddlestone and S. Leonard, *Plasma Diagnostic Techniques*, Academic Press, New York, San Francisco, London, 1965
9. H. Rosenbauer, ''Messung der durch ein Quermagnetfeld erzeugten Gasströmung in einem wandstabilisierten Niederstrombogen,'' Dissertation, Technische Universität München, 1970
10. M. Boulos, P. Fauchais, and E. Pfender, *Thermal Plasmas – Fundamentals and Applications*
11. R. Payling and P. Larkins, *Optical Emission Lines of the Elements*, Wiley Verlag, Chichester, 2000
12. A. Capetti and E. Pfender, Probe Measurements in Argon Plasma Jets Operated in Ambient Argon, *Plasma Chem. Plasma Process.*, 1989, **9**(2), p 329-341
13. T. Drabek, Numerische Simulation der turbulenten Strömung in ebenen Diffusoren, Diplomarbeit, TU Wien, 2001