Thermal plasma research: a tribute to Dr Joachim Heberlein

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Abstract: A driving force in the thermal plasma community, Joachim Heberlein initiated numerous initiatives to improve understanding of plasma technologies like plasma spraying and plasma cutting. These technologies in addition with the more general subject of arc-electrode interactions will be discussed to demonstrate the impact that Jockel Heberlein's work had.

Keywords: thermal plasma, arc-electrode interaction, plasma spraying, plasma cutting

1. Joachim Heberlein (1939-2014)

The IEPC mourns the passing of Emeritus Professor and 2009 awardee of the plasma chemistry award Joachim (Jockel) V.R. Heberlein on February 17, 2014 after a long battle with ALS. Prof Heberlein was born in Berlin in 1939. He received his diploma in physics in 1966 from the University of Stuttgart. In 1967 he came to the University of Minnesota, where he received his PhD in mechanical engineering in 1975, advised by Prof (now Emeritus) Emil Pfender. Then, after working for fourteen years at Westinghouse R&D Center in Pittsburgh where he served as Manager of Applied Plasma Research, Lamp Research and Nuclear and Radiation Technology, he rejoined the Minnesota M.E. Department in 1989 as associate professor. He was promoted to professor in 1994 and was appointed Ernst Eckert Professor of Mechanical Engineering in 2000. He retired at the end of 2012 [1]. Prof Heberlein published over 140 journal papers and received 13 patents.

2. Introduction

Jockel Heberlein was a leader in thermal plasma research. During his tenure at the University of Minnesota he spearheaded developments in numerous research areas regarding thermal plasma technology. In this paper only few examples of his work will be mentioned.

Heberlein was very involved in thermal spray technology, where he focussed on plasma spray and wire arc spray technology. His goals were to overcome inherent limitations of this technology due to the unstable nature of the process, limiting particle production in the case of wire arc spray and homogeneous particle heating in the case of plasma spray, respectively. Apart from numerous experimental efforts he also performed numerical simulation to further understanding of the physical processes taking place during operation.

Another focus of his research was plasma cutting technology. This time dealing with a transferred arc where the material to be cut acts as an anode he tackled similar issues dealing with the instability of plasma devices. In a fruitful collaboration with Hypertherm Inc. he helped to improve the technology leading to new product developments and commercial success. In this area as well he combined experimental investigations with numerical simulations leading to a better grasp of the technology and paving the path to new designs and improvements.

Common to all non-RF plasma applications is the interaction of electrodes and bulk plasma. May it be as a closed system with fairly constant electrode parameters – as in the case of plasma spray or in an open system – where at least one electrode is highly unstable due to melting and movement the close proximity (~ µm) of a thermal plasma with a gas temperature of the order 10^5 K and non-consumable electrodes with a vaporization temperature below (in the case of Cu) 3000 K is always a somewhat puzzling issue. Of course Jockel was interested in this as well. He developed physical concepts to perform numerical simulations of the boundary regions of both – the anode and the cathode, where especially in the after 2000 he focussed more and more on the anode phenomena, which had been regarded as quite simple, a hypothesis Heberlein proved wrong.

This paper will try to give a few examples of Jockel's work focussing on the fields mentioned in this introduction. A summary which can by no means be regarded as even close to being complete.

3. Thermal Spray

In plasma spray technology a plasma jet is produced using so called plasma torches, consisting of a cathode and an anode which are arranged along a common axis, the cathode usually consisting of a cone shaped piece of tungsten, which points at a hollow tubular copper anode ending in a nozzle. The gas flowing between the cathode and the anode is heated by a moving arc resulting in a hot jet that is pushed out the nozzle. An example of this system is shown in Fig. 1. Particles are fed into the gas jet, heated and accelerated towards a substrate where they form a coating.

Even though plasma spray is an established technology there are still issues that, when solved, could lead to significant improvements of the process. One of the problems that Heberlein concentrated on were the instabilities in the flow, which are in part due to fluid

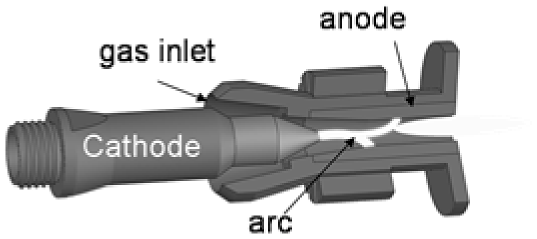

Fig. 1. F4 plasma torch, principle of operation.

dynamics and in part due to the arc movement inside the plasma torch. The jet once it leaves the nozzle, becomes turbulent, mixing with the outside atmosphere producing cold islands in the gas flow, which might trap particles [2]. Solution attempts, like the application of shroud gas flows [3] have been described but so far have not led to significant improvements. In addition the position of the anode attachment can and will change, mostly due to the strong gas flow. This is partly intentional and also enhanced by a vortex component to the axial gas flow as short residence times of the anodic arc root prevent local overheating and melting of the anode surface [4], but it also leads to variations in arc length, and thus to arc voltage/power fluctuations [5]. Significant advanced diagnostic efforts were performed under the leadership of Dr Heberlein including Thompson Scattering measurements [6] and it was shown that depending on the characteristic processing times (0.1 s – 10 ms) [7] these variations may lead to fluctuations in particle heating and influence the quality of the coating produced. Efforts to use these fluctuations to control the spray process and define proper operation conditions using fuzzy logic [8] were also part of his strategy to deal with all aspects of the process.

This also included modelling where Heberlein was involved not only with the plasma spray [9] process but all kinds of plasma torches [10].

The same diligence he did on plasma spraying was used for analysing the wire arc spray process, where an arc is struck between two wires leading to melting of the wire tips and the production of a particle beam as shown in a sample image in Fig. 2.

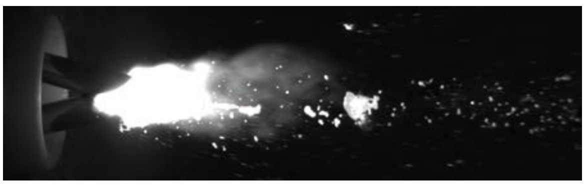

Fig. 2. Particle production in a pulsed TWAS process (source LPT, Munich).

Flow characteristics of the process were recorded in Jockel's group [11] and based on the experimental analysis a model was developed describing the distribution of the produced particles depending on flow and plasma parameters [12], a publication which is still the state-of-the-art.

Just these few examples show that Dr Heberlein was enormously involved in coating technologies which is also shown by the fact that he co-authored with Pierre Fauchais and Maher Boulos the recently published textbook Thermal Spray Fundamentals [13].

4. Plasma Cutting

From Heberlein's long lasting interest and the High Temperature Laboratories long tradition in understanding basic thermal plasma phenomena using simple TIG like experimental setups [14] it was only a matter of time until he started to put his mind on the plasma cutting process.

In this process a high current arc is transferred from a Hf cathode inside a torch through a constricting nozzle onto a workpiece which under the influence of oxidation is vaporized and cut (Fig. 3). Understanding the interaction of the plasma and the strong gas flow as well as the reactive chemistry was a challenging task.

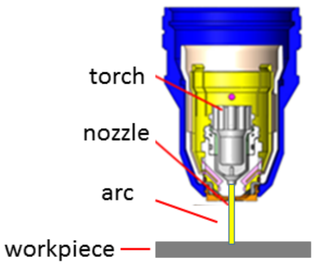

Fig. 3. Principle of plasma cutting.

Again using diagnostics in his group at the U of M methods were developed to investigate the cathode attachment during operation [15] (Fig. 4) and the influence of current ramp up and ramp down on cathode erosion was discovered.

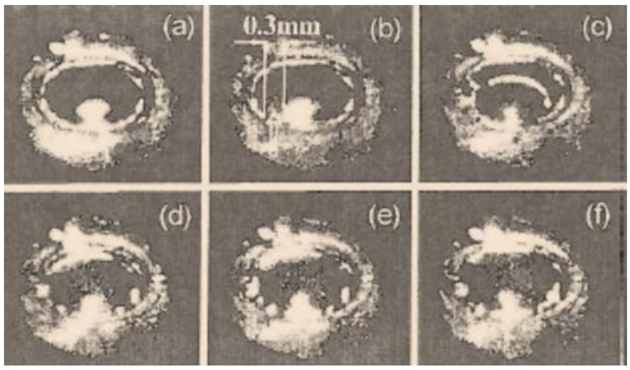

Fig. 4. Movement of molten Hf (cathode) inside torch during start phase (33 ms between frames).

More so using spectroscopy [16] the plasma was investigated and fundamental knowledge for modelling the process was gained. The model developed included a detailed study of the effect of the radiation model and the cathode current density boundary condition on the distribution of the plasma field quantities. Using this method plasma cutting torches from Hypertherm Inc. were successfully modelled [17].

5. Electrode Phenomena

In order to properly understand thermal plasma physics knowledge about the processes in the boundary is essential. Heberlein was aware of this from the start of his career, knowing that modelling a plasma source without detailed consideration of the electrode regions would neglect numerous effects that might influence the behaviour of the bulk plasma and thus the only lead to an incomplete evaluation of the performance of plasma technologies.

At first his focus was set on the cathode region with its different electron emission mechanisms, driven in part by a strong ion bombardment where the material and even the shape and surface structure of the electrode show a significant influence on plasma behaviour. Heberlein developed a theoretical model describing the influence of the arc condition and the cathode material and geometry on arc cathode erosion. For this he had to use a realistic one-dimensional sheath model in which he included an integral energy balance of the ionization zone between the sheath and the arc, supplemented by a differential energy balance of the cathode. Using the classic case of a tungsten cathode in an argon arc he obtained different values for the ion current density fraction in dependence on arc current and evaluated the major effects on the energy balance of the cathode [18], which could be used to design electrodes for various application.

However, in many plasma technological applications the commercially important electrode is the anode. In plasma cutting and TIG welding a transferred arc is used to treat a workpiece which at the same time acts as the anode for the arc. Thus it is important for the quality of the treatment how the plasma attaches this electrode. A constricted attachment would result in a localized higher heat flux density than a diffuse attachment thus Heberlein – driven by the commercial application of his work – ventured into this field as well. Starting in the 90s together with his friend and colleague Emil Pfender he started to investigate TIG-like setups [19] whereas later – during his tenure as a Humboldt fellow at the University of Bochum – he evaluated low current systems as well resulting in a review paper about anode boundaries [20].

In this paper he showed together with his friend and colleague Jürgen Mentel that the arc anode attachment of high intensity arcs is strongly affected by the fluid dynamics of the arcing arrangement and that current and heat flux densities can change significantly as diffuse to a constricted attachments may occur for similar operating parameters. He discussed the occurrence of positive and negative anode falls, postulating a dependence on the point of measurement and of course the mode of attachment.

He also used a two-dimensional CFD model coupled to a one-dimensional sheath model to simulate the processes near the anode, showing again his approach of starting a modelling effort after having experimentally evaluated the system to be investigated.

6. Summary

This brief abstract is supposed to provide a glimpse of the breadth and depth of research that Joachim Heberlein did in the field of thermal plasmas during his time at the University of Minnesota. Coming from a strong experimentally driven background he was able to combine theory and experiment as well as physics and chemistry to improve fundamental understand and commercial applications.

7. Acknowledgements

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