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Systematic Investigation of the Temperature Field in Atmospheric Plasma Processing (APP)

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Abstract. The application of functional layers has increased constantly over the last decades [1]. Coating processes like plasma spraying allow efficient processing of metal or oxide particles, and have already found their application in various sectors of industries. Ultra fine cleaning, surface activation or surface modification with the plasma arc are currently also under investigation. In the scope of this work the influence of four different main parameters - current, working distance, feed speed and gas flow - on the arc temperature field was investigated. Due to the complex and different interactions of these parameters on the temperature field, the temperature distribution in steel and aluminium sheets was systematically examined. Furthermore, the relationship between the measured surface temperatures and the wettability of the substrates is being discussed.
To generate the required data, two different experimental setups were used. First, the spatial heat distribution of the plasma arc was measured with a special arrangement of thermocouples. Second, the temperature fields during the plasma surface treatment of DC01 and Al 6082 substrates was measured. In addition to measurements with NiCr-Ni thermocouples an investigation with an IR-Camera was performed. After the plasma surface treatment, the resulting wettability was determined by contact angle measurement.
The obtained results and especially the measured temperature fields will be used in a next step to validate numerical simulations with SYSWELD and ANSYS CFX, which will be used for process optimization.

1 Introduction

Besides chemical or mechanical surface treatments, the application of atmospheric plasma processing (APP) is a popular pre-treatment in coating and joining technology. During APP the substrate is put under a thermal cycle which is performed by a plasma torch. After the pre-treatment is completed, the subsequent coating process starts. APP leads to an ultra-fine cleaned surface, which significantly improves the layer quality after coating [2]. The pre-treatment reduces pores and improves the wettability as well as the morphology of the final layer. To take advantage of these benefits, it is important to gain a better understanding of the process parameters and their interactions. Besides the local heat input of the plasma torch, the surface condition after APP is highly time-dependent [2]. Heat input and time are crucial factors for process control, especially in coating applications. To obtain the measurement data, the time dependence as well as the interaction of the parameters, variable parameters had to be defined. These parameters comprise electric current (I), working distance (a), feed speed (v) and plasma gas flow (argon flow rate).

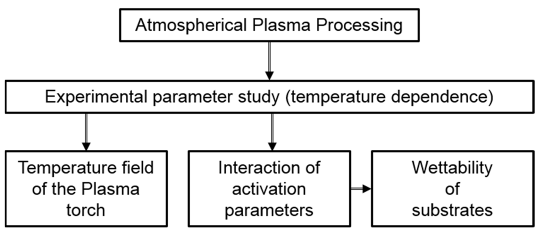

Figure 1 - Sequence of the temperature investigation

Figure 1 shows a schematic sketch of the temperature investigation sequence. The experimental investigation is set up in two main sequences. First, the spatial heat distribution of the plasma arc is measured. Second, the temperature fields of two different substrate materials during APP are investigated. Based on application-oriented coatings for automotive industries the focus of the parameter study lies on steel substrates. Additionally, the consequence of APP of steel sheets concerning changes in wettability is being discussed. The spatial heat distribution, the temperature fields of the substrates and the surface energies are important data serving as boundary conditions in numerical simulations.

2 Spatial temperature distribution of the plasma arc

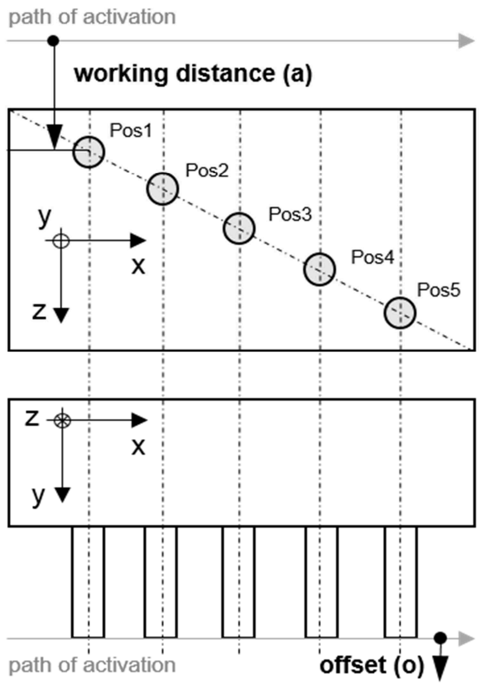

Figure 2 - Experimental setup of the spatial temperature distribution measurement with thermocouples

Inocon Technologie GmbH performs APP with their patented plasma torch. To investigate the temperature distribution, a spatial arrangement of thermocouples was used. A solid block of steel was milled and thermocouples were positioned in ceramic cylinders. According to Figure 2, five positions (Pos1 to Pos5) were chosen to measure the transient temperatures at these locations. During all measurements two main plasma torch parameters - electric current and argon gas flow - were kept constant while two parameters were varied systematically. An initial path of activation was created with these parameters.

2.1 Experimental procedure and results

The initial path of activation was set on the front surface of the ceramic cylinders and in a working distance (a) of 25 mm. The tips of the thermocouples were set at the face of the ceramic cylinders. To get the spatial results, the paths were defined by an offset value (o), which was increased in direction of the y-axis (Figure 2), as well as by a stepwise reduction of the working distance (a).

Table 1 shows the value ranges of the variables. Figure 3 shows the results of the measurements.

Table 1 - Parameter range of the spatial heat distribution tests

	min	max
working distance (mm)	12	25
offset (mm)	0	0.3

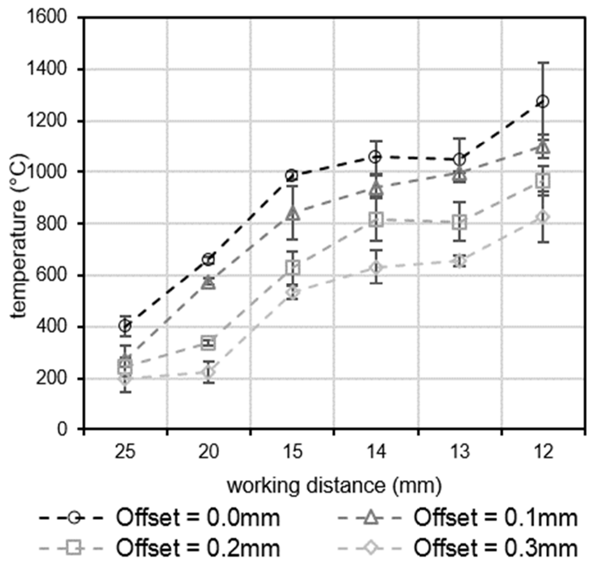

Figure 3 - Spatial temperature distribution in dependence of working distance and offset (I = 100 A, argon flow rate = 10 l/min)

3 Systematic investigation of the temperature field on steel and aluminium substrates

Based on the previous results the second experiment took place. Therefore, two different substrate materials were used.

3.1 Substrate materials

The materials used are steel (DC01) and aluminium (Al 6082) sheets with a dimension of 200x100x1.5 mm. The surface condition of the steel substrates is “as received”. These types of material are commonly used in automotive and ship building industries. Due to difficulties while applying the thermocouples concerning the natural Al_2O_3 passive layer, the aluminium sheets were pickled. Table 2 shows the nominal chemical composition of the substrate materials.

Table 2 - Chemical composition of the substrate materials

mat. [3]	C	P	S	Mn	Ti
DC01	0.12	0.045	0.045	0.6	-

mat. [4]	Si	Fe	Cu	Mn	Mg	Cr	Zn	other	Ti	Al
Al 6082	0.7-1.3	0.5	0.1	0.4-1.2	0.6-1.2	0.25	0.2	0.15	0.1	balance

3.2 Experimental procedure

To measure the temperature fields experimentally, six K-thermocouples were applied on the top and two on the bottom surface of the substrates. The activation path was set in the centre of the substrate sample (Figure 4).

The activation path represents the trajectory of the plasma torch. To ensure a stable plasma arc during APP and gather reproducible measurement signals, a stabilisation period of 5 seconds in a distance of 20 mm in front of the substrate was chosen.
The main goals of the systematic investigation are the transient temperature, the interaction of the parameters, as well as the peak temperatures during APP.

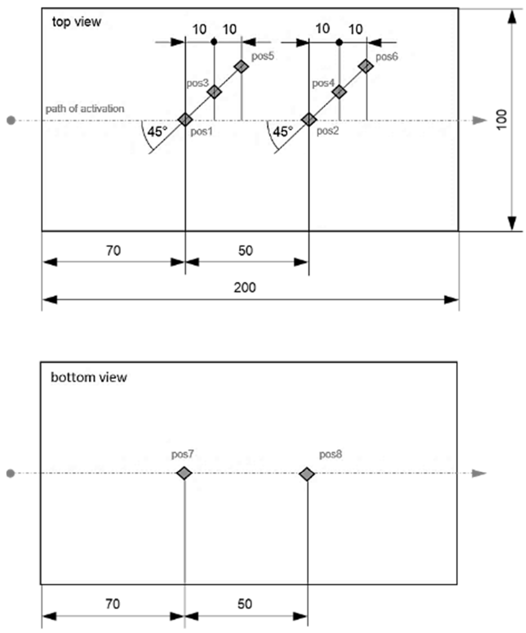

Figure 4 - Thermocouple positions on substrates

3.3 APP on steel substrates

For the systematic investigation of temperature fields, a basic parameter set was defined (electric current = 100 A, working distance = 20 mm, feed speed = 50 mm/s and argon flow rate = 10 l/min). In one experiment, three parameters were kept constant while one parameter was systematically varied. Table 3 shows the range of the variable parameters for the experiment. Figure 5 shows the impact of the investigated parameters on the resulting peak temperature in the centre of the substrate specimen (Pos2).

Table 3 – Parameter range of the experiment

	min	max
electric current (A)	50	200
working distance (mm)	15	30
feed speed (mm/s)	25	100
argon flow rate (l/min)	5	20

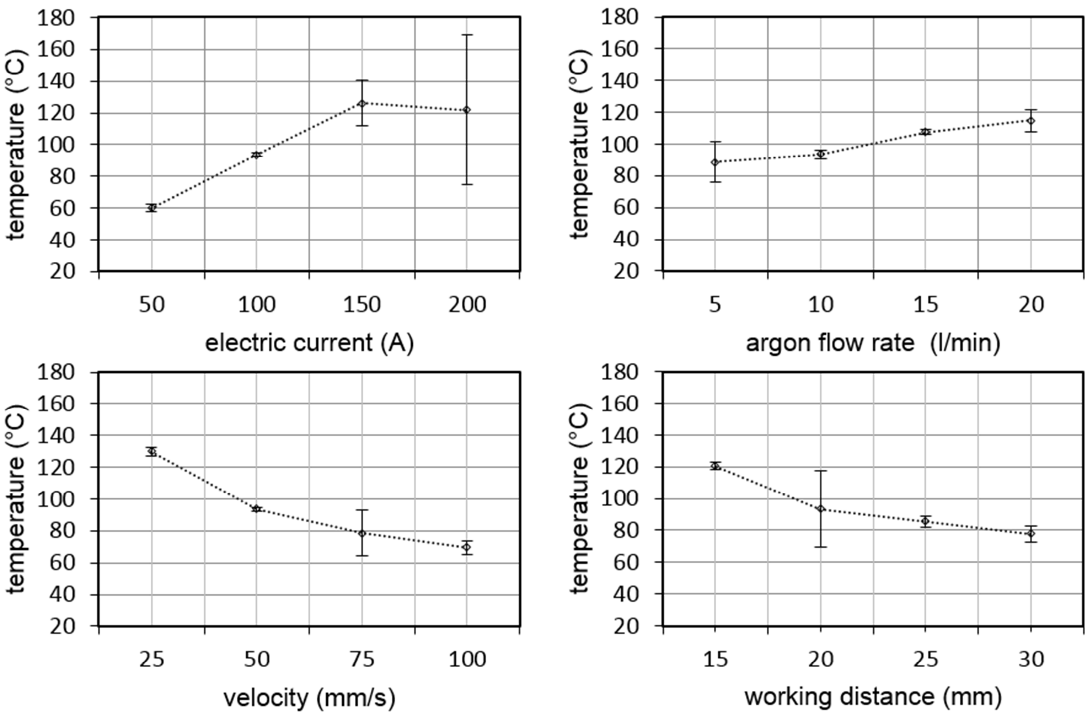

Figure 5 - Peak temperatures during plasma activation according to the parameters electric current, working distance, feed speed and gas flow

3.4 APP on aluminium substrates

To measure the temperature fields of Al 6082, the same experimental setup was used. As mentioned before, the aluminium was pickled before applying the thermocouples. However, just three K-thermocouples were used; two thermocouples on the top (Pos1, Pos2) and one on the bottom surface (Pos3). The positions of the thermocouples are the same as on the steel substrate. Figure 6 shows the peak temperatures of all positions measured.

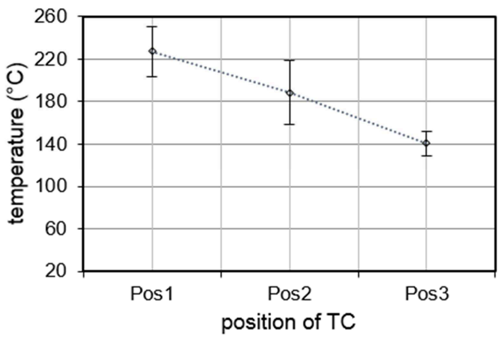

Figure 6 - Peak temperatures of the aluminium substrate (basic parameters)

3.5 Infrared Camera measurements

Additionally to the thermocouples, the temperature was also measured using a FLIR 2102 Infrared Camera (IRC). The used main parameters of the IRC measurement are shown in Table 4. These parameters are the emissivity (ε), the distance of IRC to the object, the humidity and the ambient temperature. To achieve the emissivity value of 0.92 according [5], the substrates were blackened with an acetylene burner. In Figure 7, the temperatures which were measured by using two different methods are compared.

Table 4 – IRC parameters

ε	distance (m)	hum. (%)	amb. Temp. (°C)
0.92	1	27	26

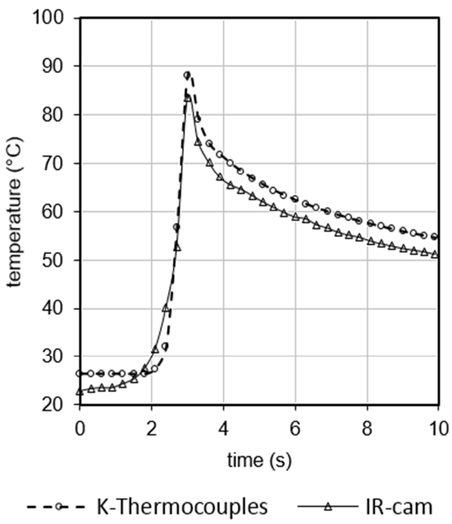

Figure 7 - Comparison of IR and TC measurement during APP (I = 100 A, a = 20 mm, v = 50 mm/s, argon flow rate = 10 l/min)

4 Wettability

A common experimental procedure to examine the wettability, which is highly dependent on the previously measured temperature fields, is contact angle measurement. The optically measured contact angle reflects an APP - dependent surface condition. In order to be able to measure the surface energy by determining the respective contact angle, two different liquids (deionized water and diiodomethane) are necessary [6]. The tests were performed at the Institute of Chemistry of Materials (Graz University of Technology) on the Drop Shape Analyzer 100 under constant conditions. After an exposure time of 20 min in air, the time dependence of the APP was investigated. The APP parameters used are shown in Table 5. Within this data the time-dependent contact angle can be plotted (Figure 8) and compared with the as received surface condition (t>>).

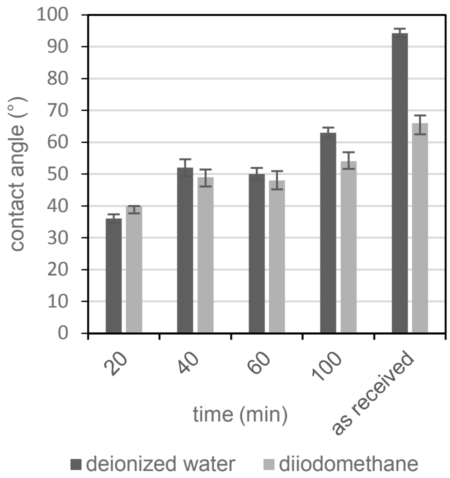

Figure 8 – Contact angle in order to discrete time steps

Table 5 - APP parameters for contact angle measurement

electric current (A)	working distance (mm)	feed speed (mm/s)	Argon (l/min)
100	10	50	10

5 Discussion

5.1 Temperature field

The investigation of the plasma arc shows a temperature gradient in horizontal and vertical direction. An offset of 0.3 mm leads to an absolute temperature reduction of 675 K to 338 K at a = 25 mm in horizontal direction. The same trend can be observed at all measurement points. In vertical direction, the temperature curve shows a bell-shaped behaviour. Due to the melting temperature of the thermocouples and a plasma arc length of 12mm, an investigation limit was reached with this measurement setup. The highest temperature ($\overline{x}$ = 1250 °C) was measured at the tip of the plasma arc (a = 12 mm; o = 0 mm).

5.2 Temperature field of steel and aluminium substrates

The systematic investigation reveal that Varying the electric current and the feed speed leads to the biggest changes regarding the peak temperature.

It was shown that an electric current of 200 A leads to a unstable situation, resulting in a higher standard deviation for the measured temperatures. The reason has not been investigated yet.

Changing the gas flow leads to the lowest temperature changes. The temperature levels on Al 6082 substrate are significantly higher than on the steel substrates. A good agreement between IRC and thermocouple temperature measurements was observed. Therefore, future measurements can be performed with the less time consuming IRC setup.

5.2 Wettability of steel substrates

APP shows a significant improvement of the wetting behaviour compared to the initial condition as due to the APP the contact angle of e.g. deionized water could be decreased by 62%. The results also show a clear trend concerning the time-dependent behaviour of APP. Therefore, a systematic parameter study is under development.

6 Conclusion

The temperature distribution of the plasma arc was measured with thermocouples and IRC. The resulting temperature fields on steel (DC01) and aluminium (Al 6082) substrates were measured successfully. Contact angles and surface energies could be measured. The contact angle measurements clearly showed that APP is a suitable possibility for surface preparation and modification, and brings a great benefit regarding wettability. Therefore, APP has a significant impact on the subsequent coating processes. The experiments performed showed clear trends and results, which can be used to validate numerical simulations for further process development.

References

[1] R. Heimann, *Plasma Spray Coating*. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA, 2008.

[2] S. Tang, O.-J. Kwon, N. Lu, and H.-S. Choi, “Surface characteristics of AISI 304L stainless steel after an atmospheric pressure plasma treatment,” *Surface and Coatings Technology*, vol. 195. pp. 298–306, 2005.

[3] S. Stahl, “data sheet - DC01,” 2015. [Online]. Available: http://www.bauforumstahl.de/upload/publications/kaltgewalzte_Feinbleche_aus_weichen_St%C3%A4hlen_DC01.pdf. [Accessed: 07-Dec-2015].

[4] Haeuselmann, “data sheet - EN AW 6082,” 2015. [Online]. Available: http://www.haeuselmann.ch/webautor-data/23/EN6082.pdf. [Accessed: 07-Dec-2015].

[5] R. Marek and K. Nitsche, *Praxis der Wärmeübertragung*. Leipzig: Carl Hanser Verlag GmbH & Co.KG.

[6] D. Y. Kwok and a. W. Neumann, *Contact angle measurement and contact angle interpretation*, vol. 81, no. 3. 1999.