Stability of the Indirect Plasmatron in the Plasma Spray Coating Process

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Abstract: **Plasma spray coating is vanguard technology for obtaining new quality of the materials. The technology with electric arc is the most versatile from all thermal spray processes. One of the main parameters of this process is stability. The stability of the process plasma spray coating depends on many factors which are heterogeneous by their nature. Studying of such random and fast process is possible with the system for data acquisition (DAQ).**

Keywords: **plasma spray coating, electric arc, stability, DAQ.**

1. Introduction

The process of plasma spray coating is rapidly changing and random by its nature. Stability of the electric arc in the chamber of the plasmatron depends on different factors which are versatile: length of the electric arc, debit and type of the mixture of plasma generating gases, nominal current and input electrical power in the process, debit of the metal powder for coating, heat transfer etc. Many of these technological parameters depend on the regime of operation of the plasma spray coating equipment. Except of variation of these regime parameters, for establishing the electric arc and its stability in the space and during the time, the most important role has construction of the plasmatron - form and type of the electric arc chamber and cathode, profile of the plasmatron nozzle and manner of carrying in the plasma generating gas i.e. construction of the gas distribution bushing [1], [2].

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For assessment of the process stability, it is important to define it and find correct mathematical expression of this parameter. The system of the plasmatron's chamber and the power source form unit, which can be examined as one couple due to their electrical interaction each other. This means that stability of such a system is a function of the output current-voltage characteristics of the power source and with the electric arc [7].

Studying this process requires measuring in real time of instant values which characterize it. This can be done with the help of multichannel data acquisition (DAQ) system [8]. To receive detailed information for the process within indirect plasmatron it is necessary to measure simultaneously instant values of the electric arc current – I_L and drop of the voltage on it, respectively on the plasmatron's electrodes (anode and cathode) - U_{AC}.

This report presents definition and expression of the stability in indirect plasmatron and one advanced way to appreciate it with the help of DAQ system.

2. Definition of the stability in the process of plasma spray coating

The models of the electric arc are very different, but basic mathematical expression of the arc is:

$$\vartheta = \frac{dg}{dt} = -g + \frac{i}{\varphi(i)}, \quad (1)$$

where *g* – is conductivity, *i* – is current, θ – thermal time constant of the arc, $\varphi(i)$ – dependence of the voltage from current. Obviously voltage current characteristics are given with expression:

$$u = k.i^m, \quad (2)$$

where *k* - is proportional coefficient, *m* - is exponent coefficient. Then (1) is transformed in:

$$\vartheta\frac{dg}{dt} = -g + \frac{i^{1-m}}{k}. \quad (3)$$

The criterion for stability depends on the model of the electric arc and the type of influence over it. For model (3) and simplified circuit with electromotive voltage and active resistance, this criterion is much known as the Kaufman's criterion:

$$R + \frac{du}{di} = R + R_d > 0\,, \qquad (4)$$

where R – is active resistance and R_d – differential resistance in the circuit of the electrical arc.

For some models the criterion for stability can be expressed with:

$$R + cR_d > 0, \qquad c = 2/(1-m)\,, \qquad (5)$$

where m can be in the interval [-1;0] if in output circuit is connected inductive element (for example choke). This will increase stability of the system [7].

The electric arc is such a type of the load which doesn't save energy during the operation of the plasmatron. Power source must cover stabile and one-way transfer of the energy to the electric arc. Continuous and smooth discharge of the electric arc in the plasmatron's chamber greatly depends on the voltage stability. When power source and electric arc are examined as a connected couple, then we must take into account both current-voltage characteristics.

What must be current-voltage characteristic of the power source to maintain stable operation of the couple power source - electric arc? The main condition of this is:

$$K_{ST} = \left(\frac{dU_{arc}}{dI_{arc}} - \frac{dU_{ps}}{dI_{ps}} \right) > 0\,, \qquad (6)$$

where K_{ST} - is coefficient of the stability of the couple power source - electric arc, dU_{arc}/dI_{arc} - differential resistance of the electric arc, dU_{ps}/dI_{ps} - differential resistance of the power source.

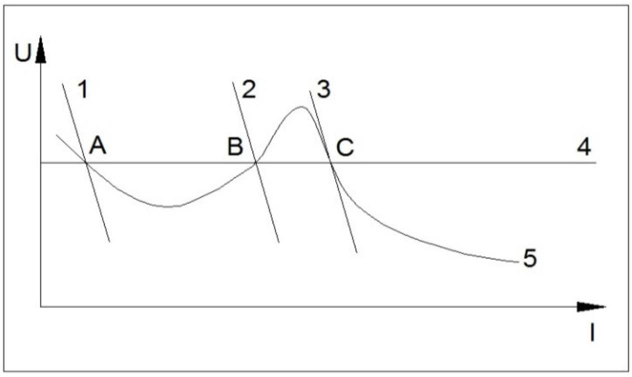

Figure 1. Current-voltage characteristic of the electric arc discharge (5), voltage source(4) and current source (1, 2, 3).

In the figure 1. is shown current-voltage characteristic of the electric arc discharge (5) and power sourcing (1, 2, 3, 4). In the points A and C differential resistance of the electric arc is negative (decreasing slope of the curve). Stability of the system is retained in case of greater negative slop of the characteristic of the power source. Then absolute value of differential resistance of the power source - dU_{ps}/dI_{ps} is greater than differential resistance of the electric arc - dI_{arc}/dI_{arc} and K_{ST} will be positive. The greater is difference between them the bigger is $K_{ST.}$

Theoretically the biggest differential resistance has current source $dU_{ps} / dI_{ps} \to \infty$, which allows obtaining of the high K_{ST}. Practically the electrical net is a voltage source, therefore power source converter must not only transform the energy from AC to DC, but to form output current-voltage characteristic with big negative slope i.e. current source.

All this influences on the system's stability and resultant differential resistance in the circuit can be assessed with the Kaufman's criterion, respectively with the coefficient of stability - K_{ST}. Therefore to obtain K_{ST} (which is proportional of the resultant differential resistance in the system) is important, firstly to measure instant values of the working current and voltage of the plasmatron and then to calculate resultant differential resistance. The active resistance in the output circuit obviously always is positive and then K_{ST} will represent assessment of the system's stability [7].

3. Main regimes and calculations of the differential resistance of the power source

The main technological parameters for the observed regimes are: debit of the main plasma gas (argon) - Q_{Ar}, debit of the additional plasma gas (nitrogen) – Q_N, working current – I_L and debit of the metal coating powder Q_{MP}.

For the experiments, the main regimes of the operation of the plasmatron include changing of the three technological parameters: working current (I_L), debit of main plasma gas – argon (Q_{Ar}), debit of additional plasma gas – nitrogen (Q_N) [3].

Table 1 shows the numbers of these regimes for three levels of variation of the technological parameters above.

Table 1.Technological parameters for the regimes from R1 to R27

I,A	Q_{Ar}=20 l/min. Q_N,l/min	Q_{Ar}=30 l/min. Q_N,l/min	Q_{Ar}=40 l/min. Q_N,l/min
	0 (R1)	0 (R10)	0 (R19)
300	2 (R2)	2 (R11)	2 (R20)
	4 (R3)	4 (R12)	4 (R21)
	0 (R4)	0 (R13)	0 (R22)
400	2 (R5)	2 (R14)	2 (R23)
	4 (R6)	4 (R15)	4 (R24)
	0 (R7)	0 (R16)	0 (R25)
500	2(R8)	2 (R17)	2 (R26)
	4 (R9)	4 (R18)	4 (R27)

For obtaining differential resistance of the source, it is necessary to have dependence between voltage and current, which is received from preliminary measurements. In the table 2 are shown data for differential resistance for the main current regimes, based on the current-voltage characteristic. Data are received for three levels of the debit of the additional plasma gas - nitrogen (0, 2 and 4l/min).

Table 2. Differential resistance (in mΩ) of the source during different debit of the nitrogen plasma gas (Q_N=0 - 4 l/min.)

I A	Q_N=0 l/min	Q_N=2 l/min	Q_N=4 l/min
300	-20	-20	-20
350	-10	-10	-10
400	10	0	-20
450	20	10	0
500	20	10	20

This data represent differential resistance for the main working current interval on this characteristic of the source in mΩ. Differential resistance of the system in some points tends to be zero, which means that current-voltage characteristic in that area is approximately parallel to the x-axis (current axis).

4. Wiring diagram of the used DAQ system

Due to the stochastic character, big slope and levels of the observed signals, its necessery to be used voltage deviders. This ensures security and correct measurement of the values. Signals must be reduced to the level between 0-10V, which is the range of the input channels of the DAQ system.

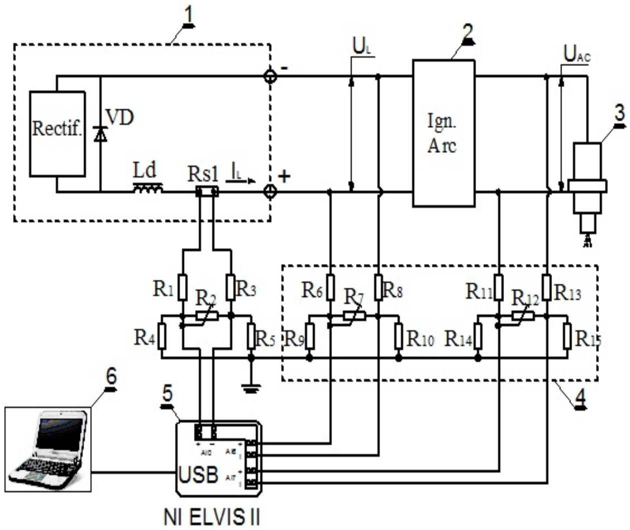

Figure 2. Wiring diagram of the DAQ system and used measuring shunt and voltage dividers for transformation of the signals
1 - power source; 2 - arc ignition block; 3 -plasmatron; 4 - votage divider; 5 - DAQ module; 6 – computer with LabVIEW software.

The measurement channels of the DAQ system for monitoring of the process are adjusted to be differential. They are connected to the shunt of the plasmatron source (R_{S1}) for current measurement (I_L) and between plasmatron's electrodes - anode and cathode for voltage measurement - U_{AC} (figure 2.). Any unbalance in the inputs due to the attenuators is filtered with the help of the software. The main units in figure 2. are: 1 - power source (rectifier), 2 - block for electric arc ignition, 3 - plasmatron, 4 - voltage dividers for current and voltage measurements, 5 - DAQ system (NI ELVIS II), 6 - computer with LabVIEW software [5,8].

5. Measurements of differential resistance (R_d) and stability coefficient (K_{ST}) in the system of the plasmatron

The measurement signals of the main observed values – I_L and U_{AC} have random character of alteration. They have rapid change of the level and big slope of the increasing and decreasing fronts [4], [6]. In figure 3. are shown graphics of the voltage, current and differential resistance for one of the regimes of the operation of the plasmatron. Corresponding graphic of the resistance on the same regime is shown in figure 4. (in ohms).

During the experiments it was discovered, that energy passed during the time from the power source to the electric arc is not constant (figure 5.). It was observed, that there are periods with high level of the current, which determine small resistance [4,6].

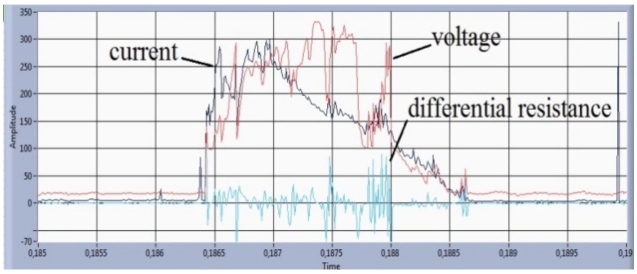

Figure 3. Voltage(U_{AK}, V) current(I_L, A) and differential resistance (R_D, Ω) in time domain .

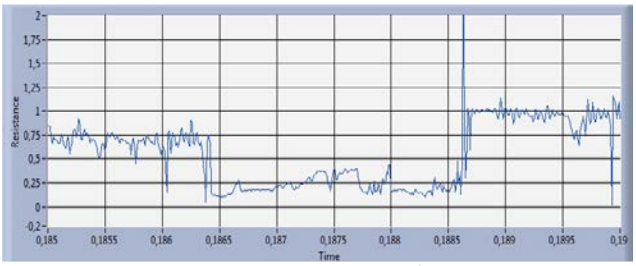

Figure 4. Time domain graphic of the resistance (R_{PS}, Ω) corresponding to the signals from figure 3.

Those are periods with high level of the energy released from electric arc. This process is periodic with time of period T=6,6ms, which corresponds to the frequency of the rectifier's output pulsations due to the three phase power source (300Hz).

This effect largely determines stability of the process. Low level of the resistance with combination of high level of the negative differential resistance in the system can reduce K_{ST} to the stage of breaking the electric arc.

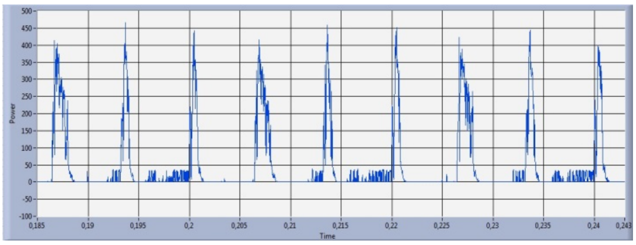

Figure 5. Time domain graphic of the power (P_{out}, kW), consumed of the plasmatron

In tables 3. and 4. below are shown data obtained for output source resistance (R_{PS}), output differential resistance (R_D), its maximum (R_{Dmax}) and minimum (R_{Dmin}) values and its absolute deviation (ΔR, ΔR_D). It is calculated K_{ST}, its absolute and relative tolerances (ΔK_{ST}, δK_{ST}). Table 3 represents the main regimes by debit of the coating powder Q_{MP}=400gr/h. and table 4 by Q_{MP}=800gr/h.

Stability of the system power source - electric arc is going down during the increasing of the current - from 361 mΩ to 100 mΩ. At the same time its fluctuations are growing up with adding of nitrogen in the plasma gas mixture – from 20,78% to 76% in comparison with its average value.

Table 3. Obtained data for R_{PS}, R_D and K_{ST} and its tolerances by debit of the coating powder Q_{MP}=400gr/h.

mΩ	P1	P3	P4	P6	P7	P9
R_{PS}	-20	-20	10	-20	20	20
R	820	840	550	530	340	420
R_{min}	300	280	200	180	160	150
R_{max}	1550	1550	1050	950	740	800
ΔR	1250	1270	850	770	680	650
R_D	339	257	260	135	218	115
R_{DMIN}	284	163	247	95	193	80
R_{DMAX}	361	269	279	192	242	152
ΔR_D	77	133	30	97	49	72
K_{ST}	359	277	250	155	198	95
ΔK_{ST}	77	133	30	97	49	72
δK_{CT},%	21,45	48,01	12,00	62,58	24,75	75,79

Table 4. Obtained data for R_{PS}, R_D and K_{ST} and its tolerances by debit of the coating powder Q_{MP}=800gr/h.

mΩ	P1	P3	P4	P6	P7	P9
R_{PS}	-20	-20	10	-20	20	20
R	820	860	560	430	330	410
R_{min}	270	300	200	170	150	100
R_{max}	1500	1600	1050	970	720	740
ΔR	1230	1300	850	800	570	640
R_D	341	245	276	145	209	120
R_{DMIN}	300	193	226	111	179	82
R_{DMAX}	373	327	331	196	240	158
ΔR_D	75	134	105	85	61	76
K_{ST}	361	265	266	165	189	100
ΔK_{ST}	75	134	105	85	61	76
δK_{CT},%	20,78	50,57	39,47	51,52	32,28	76,00

Figures 6. and 7. show values of the resistances R_{PS} and stability coefficients K_{ST} during regimes R1 - R9 according to the values of the debit of the metal powder (Q_{MP}=400gr/h. (fig.6) and Q_{MP}=800gr/h. (fig.7)).

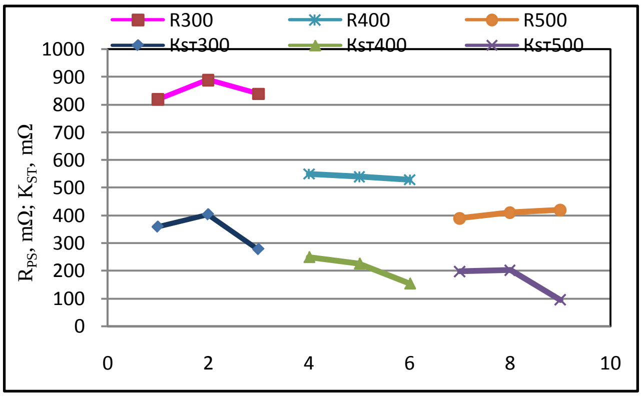

Figure 6. Stability coefficient (K_{ST}) and resistance in the output circuit of the plasmatron (R_{PS}) by regimes R1 – R9 by Q_{MP}=400gr/h.

Stability coefficient decreases with increasing of the I_L. For every current range (300A, 400A or 500A), graphics of the K_{ST} shows maximum for debit of the nitrogen - Q_N=2 l/min.

Therefore for this type of the plasmatron's construction, exists optimum of the plasma gas mixture which ensures maximum stability in the system. This dependence slightly alters with variation of the metal powder in the process (fig.7.) [3].

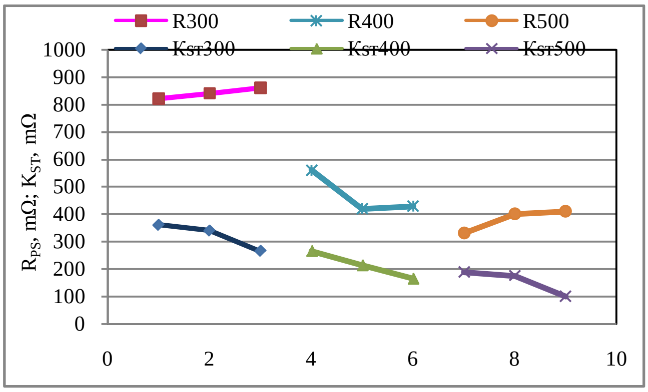

Figure 7. Stability coefficient (K_{ST}) and resistance in the output circuit of the plasmatron (R_{PS}) by regimes R1 – R9 by Q_{MP}=800gr/h.

Stability coefficient also can be examined as dependence on the each single main technological parameter of the regime. Figures 8. – 10. show dependences of the stability on the Q_{MP}, I_L and Q_N respectively.

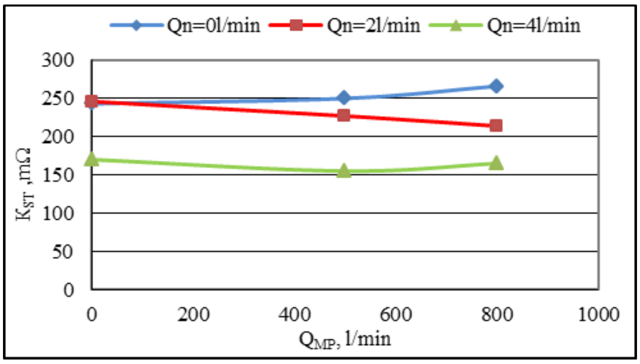

Figure 8. Stability coefficient (K_{ST}) as a function of the debit of the metal powder (Q_{MP})

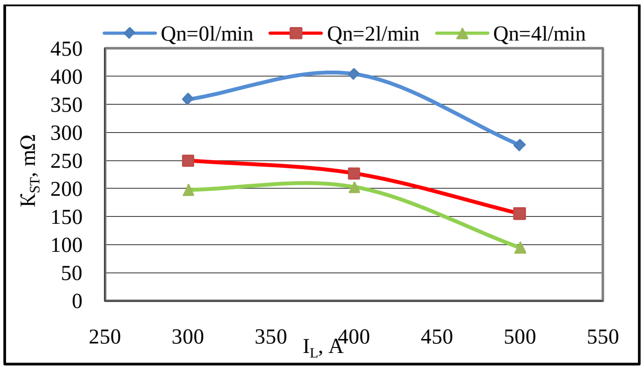

Figure 9. Stability coefficient (K_{ST}) as a function of the working current (I_L)

From graphics in the figures 8. – 10. it is apparent that the main parameters, which influence on the K_{ST} are working current (I_L) and debit of the nitrogen (Q_N). Debit of the metal powder for plasma spray coating doesn't change too much K_{ST}. The bigger current in the output circuit is equivalent of less resistance, which reduces K_{ST}. At the other hand, adding nitrogen (which has bigger specific enthalpy than argon) as second plasma gas, increases energy of the arc, but generates fluctuations with bigger amplitude and slope. This disturbs smoothness of the output parameters (I_L, U_{AC}) and reduces K_{ST}.

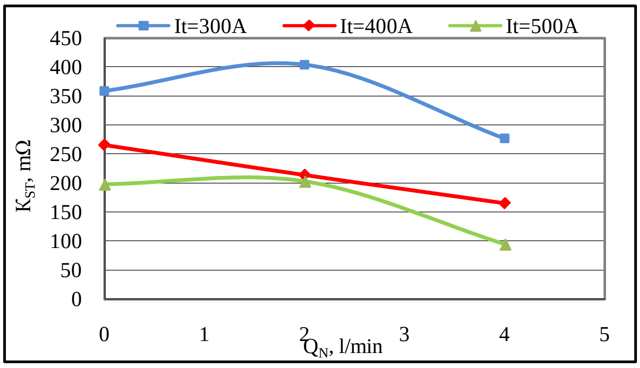

Figure 10. Stability coefficient (K_{ST}) as a function of the debit of the additional plasma gas – nitrogen (Q_N)

6. Conclusion

This method for monitoring of the plasma spray coating system shows excellent results for studying of this type of random processes and constructions. In this manner, with using of high sampling frequency, can be revealed fast fluctuations and also influence of the main technological parameters in the process.

From the received data it was found, that the coefficient of stability of the system changes vary more than 4 times within working current interval - from 400 mΩ to 95 mΩ. The main parameters which can exchange output characteristic of the process (power and voltage of the electric arc, and amplitude and slope of its fluctuations) are working current (I_L) and debit of plasma gas (Q_N) with high level of specific enthalpy (nitrogen). Debit of the metal powder, influence on the K_{ST} of the system due to its phase transition and changing of the plasma stream through the nozzle. This effect is smaller than the influence of the nitrogen plasma gas.

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