A LABVIEW^{TM} BASED AUTOMATED TEST SYSTEM FOR SPARKS CURRENT AND VOLTAGE MEASUREMENT: AN APPLICATION TO THE WIRE ELECTRICAL DISCHARGE MACHINING PROCESS

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Abstract. *Wire electrical discharge machining (WEDM) is widely used in the manufacturing of precision parts with intricate profiles, generally made of hard materials which are difficult to machine through conventional processes. The efficiency of the metal removal, along with the surface finishing, is the common objective of several researches in WEDM improvement. The performance is governed by factors such as the dielectric properties, flushing condition, wire tensioning and feed rate, raw material constitution and thickness, pulse peak voltage, on-time and duty-cycle factor. The sparking behavior, that can be monitored through voltage and current waveforms, directly reflects this performance. This paper depicts an automated test system specially designed to acquire voltage and current data, perform signals processing tasks and present relevant information, such as total energy transfer and average discharge times. It consists of a computer-based instrumentation system interfaced to high performance hardware, a LabVIEW^{TM} software application and special apparatus for in loco current measurement. Preliminary results on E25 Grade tungsten carbide machined with brass wire were obtained varying the isoenergetic pulse discharge times, using a previously optimized WEDM operational combination for the other parameters. The resulting cutting rates and a process performance indicator are presented as a function of the discharge time .*

Keywords*: Wire Electrical Discharge Machining, Automated Test System, Current and Voltage Measurement*

1. INTRODUCTION

Spark current and voltage measurements require high speed data acquisition systems. The automation of current and voltage waveforms acquisition, analysis and presentation provides a useful and productive toolset to be used in the optimization of operational conditions in the Wire Electrical Discharge Machining (WEDM) process, widely used to obtain intricate profiles in hard materials.

In this non-conventional machining technique, material is removed through the application of a pulsed electrical discharge between cathode and anode, which are separated by a small gap where a temporary, high energy density plasma channel is formed, and is responsible for melting small amounts of material each pulse cycle. The debris are solidified and removed by a flushing system during the pulse interval time. The sparking cycles between the continuously fed wire and the work piece progressively produce a cut along its thickness following a previously defined path and thus obtaining a desired geometry. Among the frontiers of WEDM research nowadays (Ho *et al*) is one of great interest: the study of the effects of machining parameters on the cutting rate V_W (mm^2/min). Process productivity and surface finishing are a consequence of the concomitant conditions and parameters used. According to (Scott *et al apud* Ho *et al*), the discharge current, pulse duration and pulse frequency are the most important parameters to influence the productivity. In the industrial environment, combinations of parameters are usually taken from WEDM machine builders' technological tables, with little or no room for customizations 'out of the table'.

In the Electrical Discharge Machining (EDM) process, voltage and current signals characteristic parameters have the standard shapes and designations shown in Figure 1. These shapes change in some degree in the WEDM process, where information can rather be extracted from pulse trains statistics. In the here reproduced Figure 2, (Liao and Woo) illustrated examples of WEDM pulse forms. According to these authors, many of the pulses are not normal discharges, but short circuits and arcs. (Watanabe *et al apud* Liao *et al*) proposed a classification for WEDM signals according to the considered ongoing phenomenon (normal discharge, short circuit, arc). The arc discharges have waveform shapes close to the normal discharge, making the differentiation yet possible but harder. These authors also developed a discrimination system based on the elapsed time between the rising of the gap voltage and the beginning of the ignition current. Since a recurrent occurrence of arcs or short circuits may indicate that wire breakage is near, the statistical analysis of recent data in real time allied to special inference algorithms could be used to feedback the power supply and prevent a machine stop. This concept was used by (Cabanes *et al*) to develop a solution for on-line prevention of wire breakage.

The current and voltage waveforms don't have a regular, periodical behavior. Despite being settable on the machine, interval (t_0) and discharge (t_e) times vary during the processing period as the gap conditions change. Sometimes a long delay (very above the set t_0) in open circuit voltage level is observed before the breakdown. Evaluating the t_e exclusively in the normal pulses requires the preliminary application of a pulse classification criteria to the pulse trains.
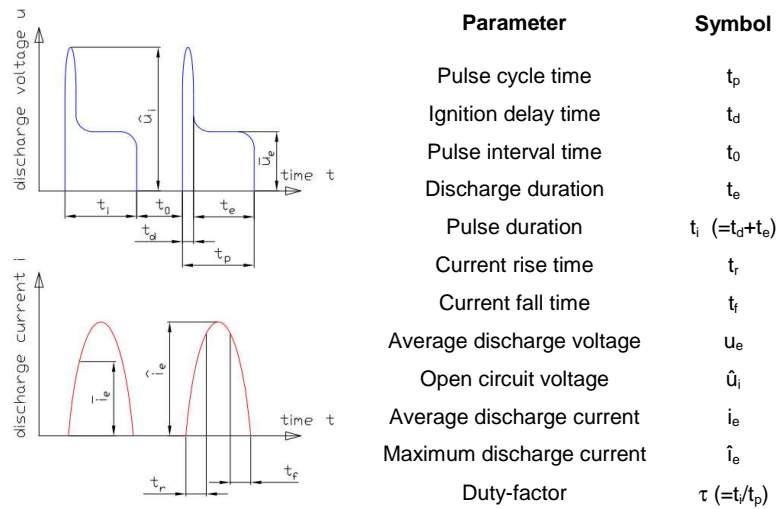
Parameter	Symbol
Pulse cycle time	t_p
Ignition delay time	t_d
Pulse interval time	t_0
Discharge duration	t_e
Pulse duration	t_i $(=t_d+t_e)$
Current rise time	t_r
Current fall time	t_f
Average discharge voltage	u_e
Open circuit voltage	$\hat{u}_i$
Average discharge current	i_e
Maximum discharge current	$\hat{i}_e$
Duty-factor	τ $(=t_i/t_p)$

Figure 1. Parameters of current and voltage waveforms in the EDM process.

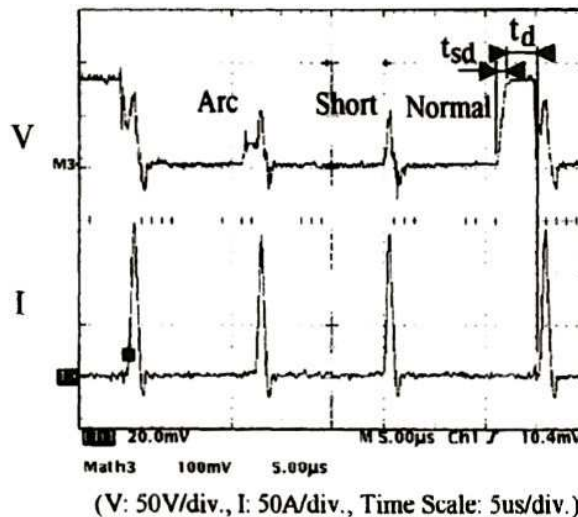
(V: 50V/div., I: 50A/div., Time Scale: 5us/div.)

Figure 2. Arc, short circuit and normal discharge events (Liao and Woo).

Actually, correlating the underlying physical phenomena that occur in the discharge gap to a combination of process parameters and the work piece material through a physical model is an extremely difficult task, being WEDM rather studied experimentally, given its stochastic character. The performance is governed by factors such as (but not limited to): dielectric properties, flushing condition, wire tensioning and feed rate, raw material constitution and thickness, pulse peak voltage, on-time, duty-cycle factor. Nevertheless, researching the combined effects of the several parameters that influence WEDM process, taking a satisfactory number of levels for each, results in a very high quantity of combinations. (Mahapatra and Patnaik) used the Taguchi method to minimize the number of experiments, and genetic algorithms as well, in optimization efforts.

Measuring current and voltage directly in the power circuitry of a commercial brand machine may be risky, possibly leading to unsafe operation or damage to high cost equipment. In this work, to go around this difficulty a special apparatus was designed to allow *in loco* current measurements with minimum intervention. To evaluate the net energy consumption, the real voltage and current waveforms are multiplied and the result integrated along the processing period. It's possible to quantify a process performance indicator (PPI) dividing the cut area by the product between total energy and machining time.

In this present paper, tungsten carbide was chosen as the work piece material. This is a common choice in the manufacturing of tooling for stamping operations, and its high hardness makes WEDM the most indicated machining option from both technical and economical criteria. The objective of this work is, using an automated test system, to study the relation between the pulse discharge time t_e and the process productivity, analyzing the cutting rates and the PPI to find the best value for t_e.

2. AUTOMATED TEST SYSTEM FOR SPARKS CURRENT AND VOLTAGE MEASUREMENT

Designing an automated test system implies integrating a system attending requirements in three layers: hardware, software and physical system (Mendes *et al*). The degree of automation and the context of each application may vary the importance or relevance of each layer, but they shall typically be present.

Voltage and current waveforms in high speed events are captured with high data acquisition rates and compatible sensors. In these cases, the hardware represents major part of system cost. For this project, a high performance interfaced oscilloscope and wide band current and voltage measurement probes were employed. The integration with a computer was implemented through a GPIB interface. Functionality was implemented in a software application using the LabVIEW[TM] platform (National Instruments).

2.1. Hardware components

Figure 3 shows the hardware components integration in a scheme. The voltage measurement probe used was a P5100 250MHz bandwidth, limited to 2500V (DC + peak AC), with 100x attenuation factor (Tektronix, Inc.). For current measurement, it was used the probe Tektronix[TM] TCP202, 50MHz bandwidth, capable to measure up to 15A (DC + peakAC); above this level, a maximum [peak current][pulse width] product of 500 A.µs limits the operation.

The Tektronix[TM] P5100 high voltage and TCP202 current probes are attached to the Tektronix[TM] TDS644B model oscilloscope, connected with a laptop computer through a GPIB interface (National Instruments[TM] USB-to-GPIB adapter).

A feed-through accessory was designed for the cables and wires safe connection to the WEDM machine through one of its side walls.
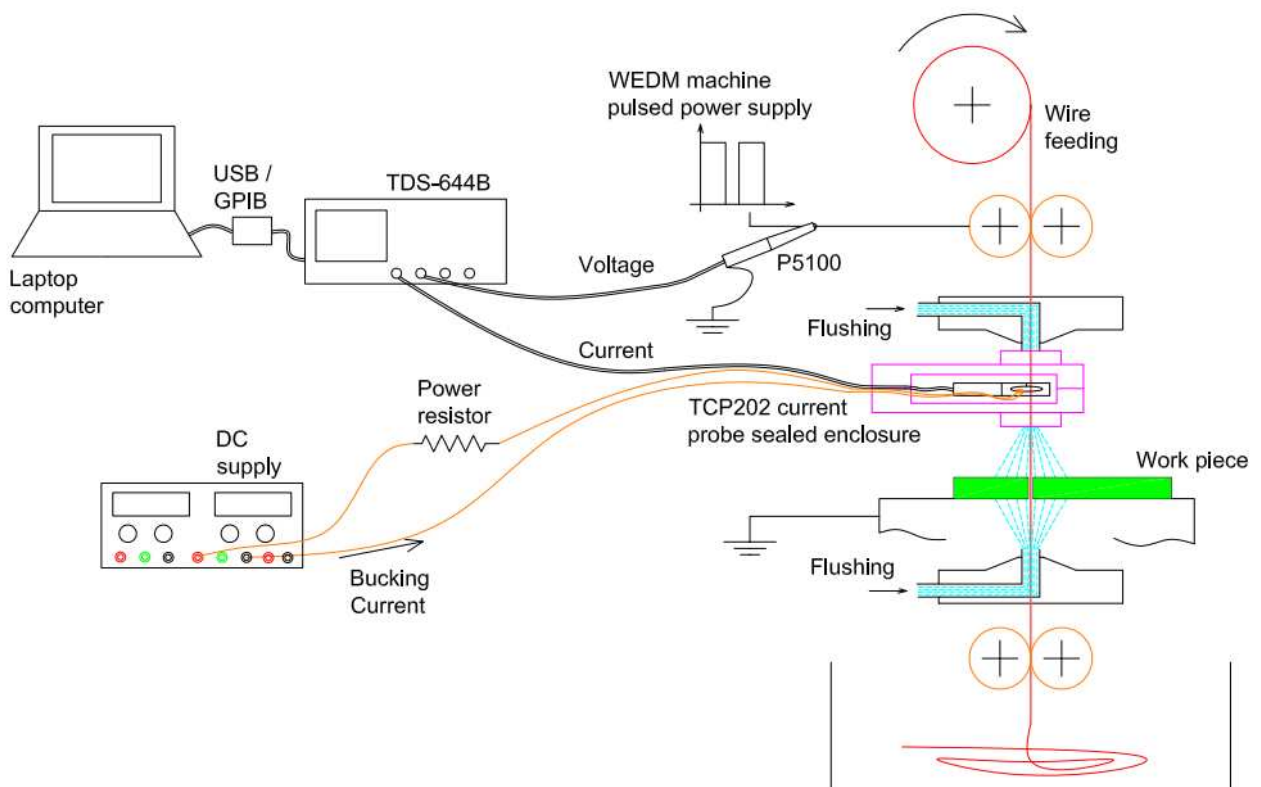

Figure 3. Integration of the hardware components used to measure current and voltage in the WEDM process.

To improve the measurement range of the current sensor, a bucking current circuit was added to the system. Eight turns of enameled copper wire were wounded in the current sensor to produce a constant DC current in opposed direction to the WEDM (process) one, raising the measurable current limit up to 8A in safe conditions. The actual bucking current value is the product between the number of turns in the coil and the current set through a variable power supply. After acquisition, the bucking current is subtracted from the measurement data via software. This procedure allowed capturing peaks of pulses situated up to 8A above the original sensor limit.

2.2. The LabVIEW™ software application

The experimental procedure to study the WEDM process through the behavior of real current and voltage waveforms with enough data sampling requires such an amount of computational tasks that justifies its automation. Starting from a set of requirements, several functionalities were implemented in a sofware application, named 'ArcVIEW', developed on the LabVIEW platform, and listed in Table 1.

Table 1. Functionalities of the 'ArcVIEW' software application.

Functionalities	Configurable parameters
Current and voltage waveforms capturing parameters configuration	Sampling rate; sample length; trigger level
Capture modes (single shot or periodical)	Waveforms capturing periodicity
File operations (save, open)	Data saving folder, files format
Filtering	Passband (lowpass), filter type
Spectrum analysis (FFT)	
Current pulses detection, width determination and fix of flat top pulses (peaks reconstruction)	Detection levels (two, horizontal), top cutoff level
Power, energy, discharge duration and current/voltage statistics	
Batch analysis and tabulation of results	Acquired data folder
Report generation	Format (.pdf, .html)
Waveforms clipping	Start/end moments

In the periodical capture mode, the acquired waveforms are automatically transferred to the computer during the experimentation sessions are stored in a selected folder, in a cyclic process as shown in Figure 4.
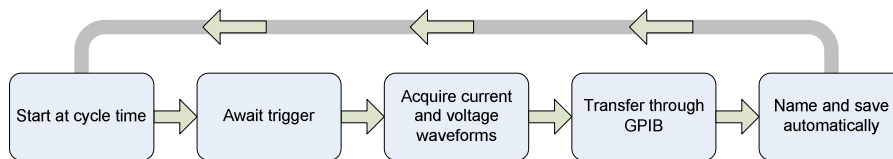

Figure 4. Automatic data acquisition and storage loop.

After the machining task is finished, at the user command the files are batch processed to extract the desired information from the raw data, following the steps shown in Figure 5.
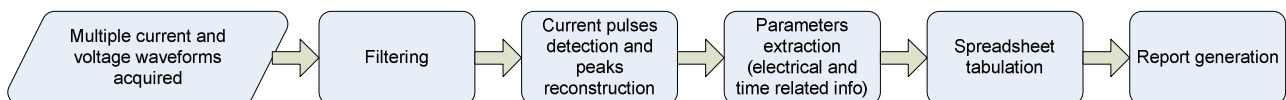

Figure 5. Batch current and voltage signals processing.

Mostly, the current peaks observed in the WEDM process well exceed the maximum rating of the TCP202. Substitution of this probe for another one with the same or broader bandwidth, and higher maximum current capabilities, requires an expensive investment. This limitation problem was solved through signal analysis and processing, using a heuristic technique for peaks reconstruction. Figure 6 illustrates the peak reconstruction process.

The algorithm takes two user defined horizontal lines (crossing levels) and locates their intersections with the pulses, registering the start and end crossings times for each pulse and line; the four points marked for each pulse this way are used to adjust two lines to the rise and fall pulse sides, whose intersection is the missed peaks' top. Then, using the same acquisition interval time and the flat region current value (the known limit), an interpolation procedure is run to calculate the curve points that will replace the saturated potion of the current signal. This process has been tested in some non-flattened pulses (i.e., pulses with maximum below the sensor saturation limit), where it could be verified that the approach pulse results very close to the real one. This favorable result is just as expected, because the peaks can be approximated by a triangular shape. Finally, whenever a capture starts in the middle of a pulse, the algorithm detects the incomplete pulse and clips the problematic border of the file, enabling it to be processed.
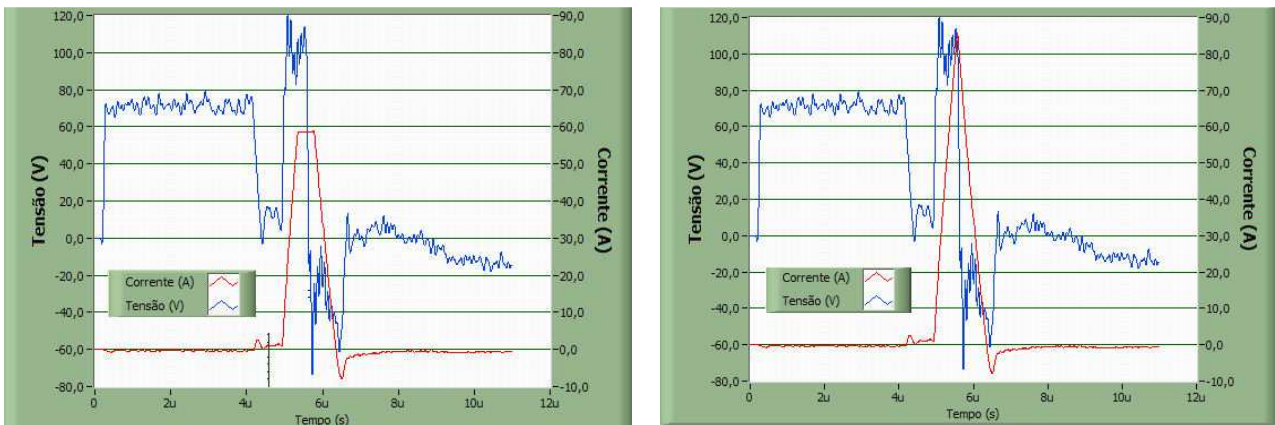
Figure 6. Reconstruction of the current pulse peak cut off due to sensor saturation.

The four reference memories for waveforms recording available in the TDS644B oscilloscope are managed in two pairs, being the currently in-use one selectable by the user, and giving some versatility to comparative analysis. Each memory is capable of storing 15000 points, compromising the time length of an acquisition with the user selectable sampling rate.

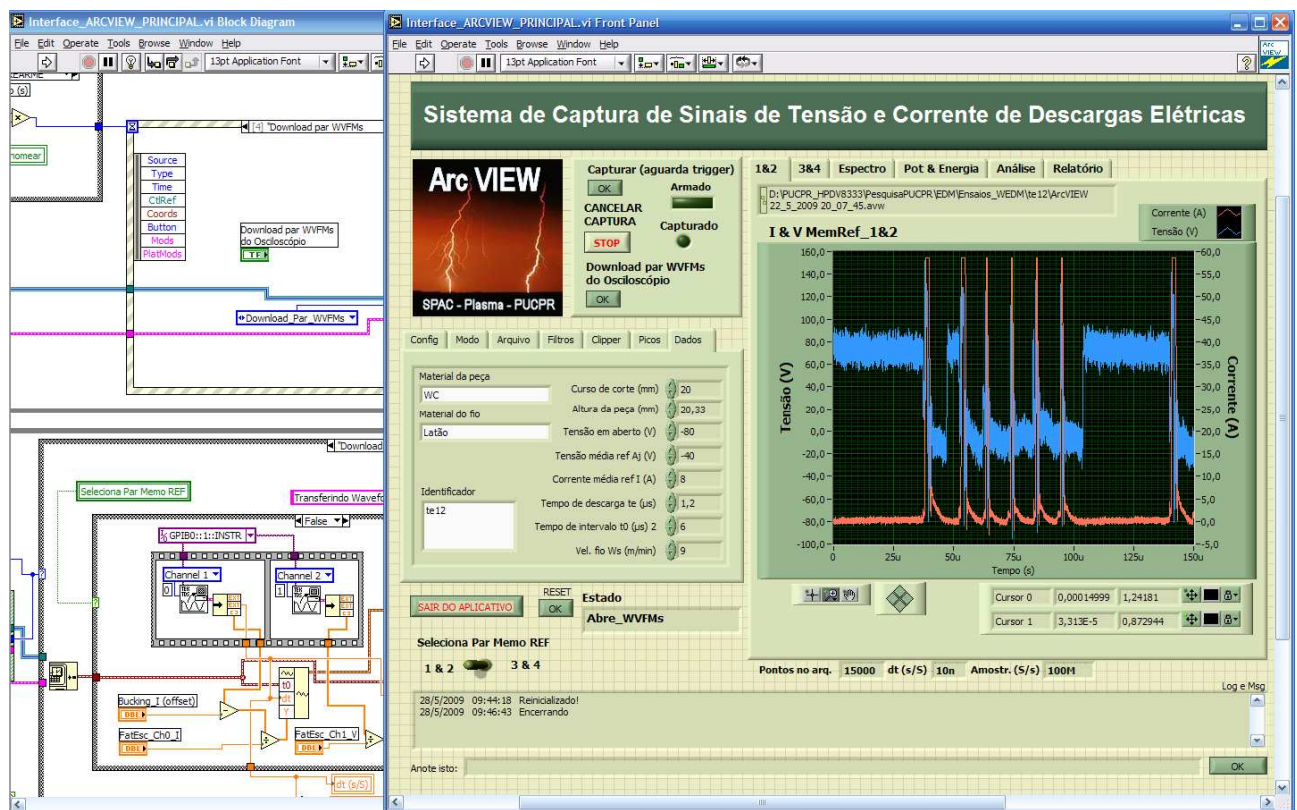The application software user-friendly interface is shown in Figure 7.

Figure 7. ArcVIEW user interface – front panel and (partial) block diagram.

2.3. The current probe sealed enclosure device

The TCP-202 probe is protected from the pressurized flushing water by a special apparatus designed as a sealed device, which bypasses the flow around the probe and leaves passage to the running wire. This device has been specially engineered to operate under the 8 bar (top and bottom) local flushing water pressure. Its assembly on the machine is made with compatible adapters - upstream, for mechanical attachment and water inlet, and downstream, where the original outlet flushing nozzle was moved to. The device design and its assembly in work position are shown in Figure 8.
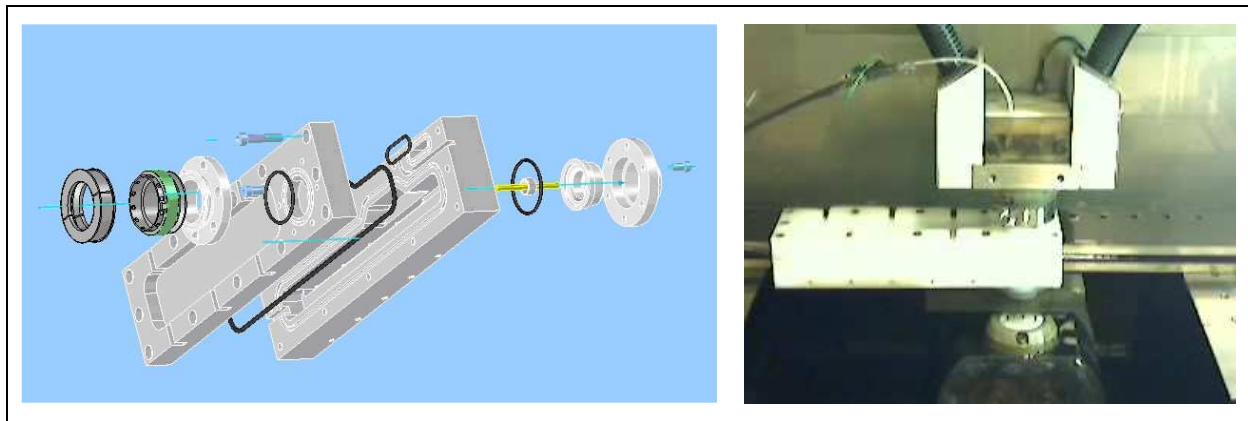
Figure 8. Sealed enclosure device design and its assembly in the WEDM machine (sensor inside).

4. EXPERIMENTAL SETUP

4.1. The WEDM machine

A Charmilles Robofil 290 5-axes CNC WEDM machine (Charmilles Techonologies) in LAUS / PUCPR was used in the tests. It is shown together with the main specifications in Figure 9.
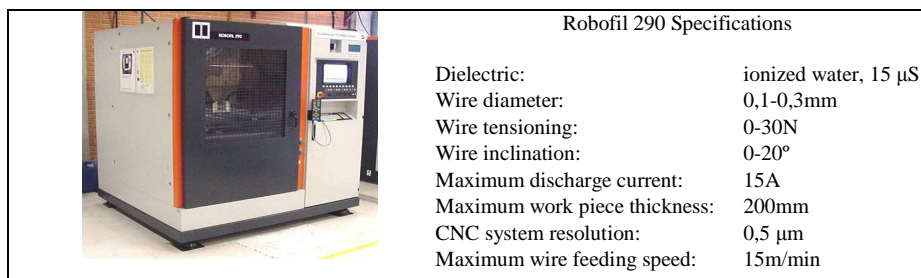

Robofil 290 Specifications	
Dielectric:	ionized water, 15 μS
Wire diameter:	0,1-0,3mm
Wire tensioning:	0-30N
Wire inclination:	0-20º
Maximum discharge current:	15A
Maximum work piece thickness:	200mm
CNC system resolution:	0,5 μm
Maximum wire feeding speed:	15m/min

Figure 9. Robofil 290 WEDM machine.

4.2. The E25 Grade tungsten carbide

The E25 Grade WC 20,33mm thick stock material used in the experiments presents the properties in Table 2.

Table 2. Properties and composition of E25 Grade tungsten carbide.

E25 GRADE carbide	Values	units
WC content	88,2	%
Ni+Co content	11,5	%
Average grain size	2,5	μm
Rockwell Hardness HRA	89,2	-
Density	14,3	-
Vickers Hardness HV30	1240	-
Transversal tensile strength	3500	MPa

4.3. Machine setup parameters and procedure

The cutting rate was measured as function of discharge time t_e, under the WEDM machine setup shown in Table 3, taken from an investigation conducted by (Amorim and Teixeira), where the cutting rate V_W (mm^2/min) was measured in the machining of H40S WC versus the variation of the interval time t_0 (μs), wire feeding speed W_s (m/min), and average reference pulse voltage A_j (V). Those tests were performed using both brass and copper wire, and provided an experimental indication of optimum parameters. Their values for brass wire provided the highest cutting rates and were used to setup the WEDM machine. The discharge time was set up varying between 0,6 and 1,2μs in 0,2μs steps. A CNC program was executed to perform a 25mm straight cut starting from the work piece border. Data collection was done between 5 and 25mm, to avoid the expectable difference of machining conditions close to the border. Under each t_e

setup, two repetitions were executed (a and b). All waveforms were acquired at 100MS/s acquisition rate and are 150µs long. The acquisitions cycle time was set to 10s.

Table 3. Robofil 290 parameters setup for E25 Grade WC cutting rate tests.

Parameter	Values	units
Wire feeding speed W_s	9,0	m/min
Interval time t_0	6,0	µs
Average voltage A_j	40	V
Average current I_0	8	A
Open circuit voltage	80	V
Brass wire diameter ϕ	0,25	mm
Wire tension	10	N
Discharge time t_e	0,6 / 0,8 / 1,0 / 1,2	µs
Pulse mode	Isoenergetic	-

Applying the FFT analysis resources available in the ArcVIEW software on some preliminary captures, the 10MHz cut off frequency for the lowpass filter to be applied to both current and voltage waveforms was selected. The filtering allows a simplification of the pulse detection algorithm, that otherwise may detect short period oscillations in the pulses' rise and fall ramps, requiring a secondary verification routine to eliminate false positives. Current sensor saturation level was found to be 58,5A (Figure 10, left graph), value used in the peaks reconstruction algorithm. Corrected peaks and cleaner signals (Figure 10, right graph) result from the signals processing.
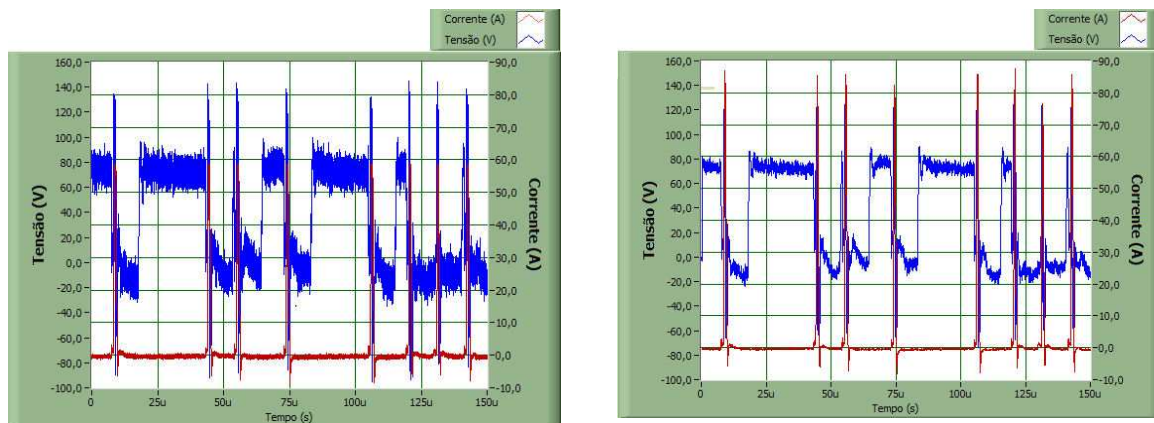

Figure 10. Typical current and voltage waveforms during the WEDM operation, before and after processing.

5. RESULTS AND DISCUSSION

Results from the tests are presented in Table 4.

Table 4. Tests results tabulation.

Test id	Pulses detected [#]	Captures [#]	Setup t_e [µs]	Cutting rate Vw [mm²/min]	Cutting time [min]	Average te [µs]	Std dev [µs]	Average power [W]	Std dev [W]	Total energy [kJ]	Process performance indicator - PPI [mm²/(min*kJ)]
te06a	506	52	0,6	49,4	8,2	0,63	0,03	151,8	39,4	75,0	0,66
te06b	463	50	0,6	49,7	8,2	0,63	0,03	129,6	31,8	62,8	0,78
te08a	383	42	0,8	60,5	6,7	0,73	0,07	192,4	64,1	77,5	0,78
te08b	386	41	0,8	61,3	6,6	0,72	0,06	185,5	54,5	73,8	0,83
te10a	328	37	1,0	67,2	6,1	0,77	0,10	224,7	83,1	81,6	0,82
te10b	302	33	1,0	69,7	5,8	0,77	0,12	244,8	112,2	81,2	0,81
te12a	278	34	1,2	73,0	5,6	0,88	0,14	300,5	112,2	100,4	0,73
te12b	294	36	1,2	72,0	5,7	0,85	0,13	290,5	128,9	98,5	0,73

The number of pulses, their widths and spacing great variability observed in the captured waveforms corroborate the stochastic behavior of the WEDM process. During the tests, wire breakage events occurred few times, and always in the beginning of the tests. If wire breakage is persistent, any process productivity analysis looses major part of its value.

The average power verified along all acquisitions is multiplied by the cutting time to compute the total energy of each test. The PPI is then calculated for the $406,6mm^2$ cuts on the WC work piece, as the area cut per kJ and minute. This indicator can be understood as an economical measure of the process. The $t_e=1,2\mu s$ condition produced the fastest cuttings, whilst the highest PPI was calculated in the $t_e=1,0\mu s$ one. Cutting rates and the PPI are shown in bar graphs in Figures 10 and 11, respectively.

The average t_e differs from the setup one, as it includes every detected pulse in the computation. The explanation for this fact may include the variable incidence of arcs and short circuits, which increase the difference, as this events add values lower than the setup one to the average calculation. Also, a growing standard deviation is verified.

Average power values show an expected growth with increasing discharge times, and are related to the shorter machining times. The high standard deviations indicate the need for longer data collection periods, but the interpretation of the values is still valid for comparison purposes.
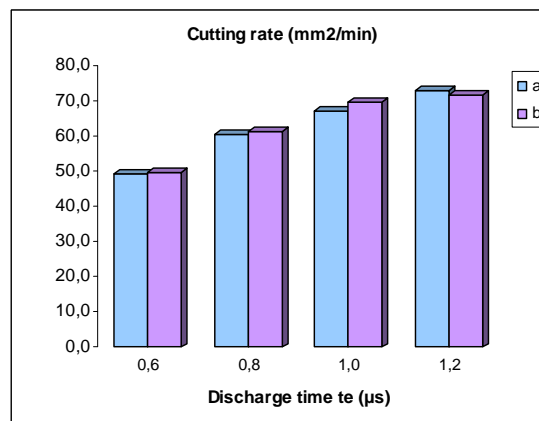

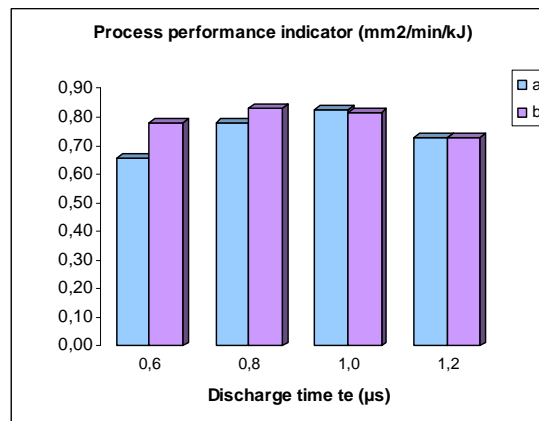Figure 11. Cutting rates observed.

Figure 12. Process performance indicators (PPI's) calculated.

6. CONCLUSIONS

A solution for *in-loco* current measurement in the WEDM process environment was successfully designed and implemented. The automated test system used for the data acquisition, processing, presentation and storage allowed the execution of the experiments in a shorter time and with a near human intervention free procedure. A heuristic algorithm has been developed to identify sparks' current pulses and reconstruct their tops when saturation of the sensor occurs.

A potential improvement to this system is the implementation of a pulse classification algorithm and its integration with the WEDM machine, allowing the run of large scale pre-programmed experiments to map performance and provide on-line signals analysis and statistics to be used in the feedback of operational parameters.

The highest cutting rate for E25 grade WC was attained with te=1,2μs, and the best performance, considering machining time and energy consumption, with te=1,0μs.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Amorim, F., Teixeira, C., 2005. "Eletroerosão por fio de metal duro utilizado para ferrramentas de estampagem", Proceedings of the 3rd Brazilian Congress of Fabrication Engineering, Vol. 1, pp 1-9.

Cabanes, I., Portillo E., Marcos M., Sánchez, J. A., 2008, "On-line prevention of wire breakage in wire electro-discharge machining", Robotics and Computer-Integrated Manufacturing, No. 24 pp. 287-298.

Charmilles Tehnologies, 2009. 15 Mar 2009, <http://www.agie-charmilles.com>

Ho, K. H., Newman, S. T., Rahimifard, S., Allen, R. D., 2004. "State of the art in wire electrical discharge machining (WEDM)", International Journal of Machine Tools & Manufacture, No. 44 pp. 1247-1259.

Liao, Y. S. and Woo, J. C., 1997. "The effects of machining settings on the behavior of pulse trains in the WEDM process", Journal of Materials Processing Technology, No. 71 pp. 433-439.

Liao, Y. S., Cheng, M. P., Liao, K. W., 2009. "An on-line pulse train analysis of the wire-EDM process", Journal of Materials Processing Technology, No. 209 pp.4417-4422.

Mahapatra, S. S., Patnaik, A., 2006. "Parametric Optimization of Wire Electrical Discharge Machining (WEDM) Process Using Taguchi Method", Brazilian Association of Mechanical Sciences, No. 4, Vol. XXIII, pp. 422-429.

Mendes, L. A., Back, N., Oliveira, G. H. C., 2009. "Designing automated test systems: An adapted methodology inspired on Pahl and Beitz's systematic approach", Robotics and Computer Integrated Manufacturing,
<http://dx.doi.org/10.1016/j.rcim.2009.04.006>

National Instruments, 2009. 15 Mar 2009, < http://www.ni.com>

Scott, D., Boyina, S., Rajurkar, K. P., 1991. "Analysis and optimization of parameter combination in wire electrical discharge machining", International Journal of Production Research, No. 29, Vol. 11, pp. 2189-2207.

Tektronix, Inc., 2009. 15 Mar 2009, < http://www.tektronix.com>

Watanabe, H., Stato, T., Suzuki, I., 1990. "WEDM monitoring with a statistical pulse classification method", Ann. CIRP No. 39, Vol. 1, pp. 175-178.

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