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Consolidation of Compacted Zircaloy Chips via Vacuum Arc Melting - Analysis of the Electric Arc

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Abstract: The main objective of this work is to present the preliminary results on the analysis of the signals arising from the electrical arc, during the vacuum arc remelting of Zircaloy electrodes, aiming the automation of the fusion process. Zircaloy electrodes were made from compacted chips resultant of the machining of Zircaloy rods. The melts were performed in a prototype (vacuum arc remelting) VAR furnace under low pressure of argon and the arc was fed by a constant DC power source. Both filtered and unfiltered signals were recorded by means of a data acquisition system. The fast Fourier transforms FFT and autocorrelation integral were used as tools for data analysis. The result showed that the events occurring within the electric arc have a strong influence on the electric signals. The analysis allowed inferring that the VAR electric arc system has mainly a chaotic behaviour and sporadic periods of linear behaviour. The conclusion of this work is that a control system may be developed, based on the modelling of the non-linear behaviour of the arc, mainly chaotic. This may allow the achievement of an automatic control for the process and yield better quality products.

Introduction

The Zircaloy is a refractory and reactive high zirconium alloy used by the Angra I and II Brazilian nuclear power plants as the main material for the fuel cladding. This material was chosen due to its low cross section for thermal neutrons and its high resistance to corrosion and high tensile strength, within the reactor operating conditions. During the fuel elements fabrication, considerable amounts of chips are produced, mainly by lathe turning. The Zircaloy used for the production of the fuel elements by the Brazilian industry is imported; this fact makes the recycling of this chips advantageous from the economical, technological and environmental point of view.

In the 1990's, a prototype of a VAR furnace was developed as a facility for the investigation on solidification and arc phenomena associated to processing of small electrodes of reactive and refractory materials. At that time, a mathematical model for the determination of the thermal distribution, the thermal gradient and the cooling rate was set up and its results well matched the experimental ones [1]. Nowadays, this prototype has been improved in order to deal with the research on the process of the melting of electrodes made from compacted Zircaloy chips.

In a VAR furnace the heat generated by an electric arc is highly concentrated in a space between the lower part of the electrode and the surface of the liquid metal pool, as seen on fig.1. The main behaviour of the arc voltage versus its length may be expressed by the Ayrton equation, see equation (1).

$$V = a + bl \qquad (1)$$

Where: a is the open circuit voltage; b is a characteristic constant of the process and; l is the arc length.

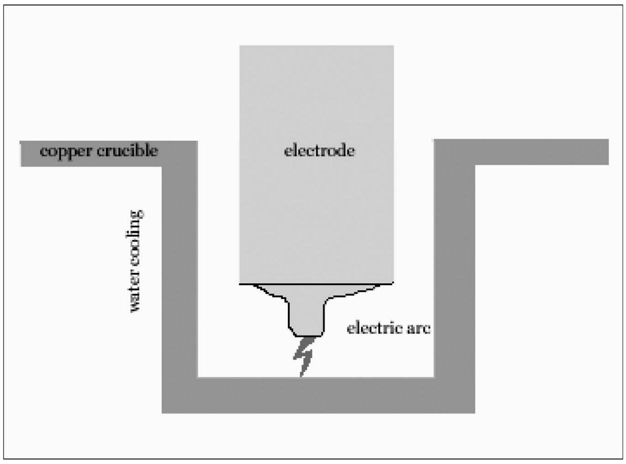

Figure 1. Scheme showing an electric arc and melting pool in VAR furnace.

Such an equation summarises the linear behaviour of the electric arc stating that the lengthier it is, higher the voltage is. This is a good starting point for a controller and in fact, this behaviour is used when operating a VAR furnace manually. Manual operations of VAR furnaces do not allow the reproduction of the melt within narrow limits. Furthermore, the constant *b* represents the influence of various aspects that can not be observed by a VAR furnace operator. These aspects are the electric arc translations on the electrode and liquid metal surface; atmosphere variations due to gas flows or variations on its composition; liquid metal transfer from the electrode to the crucible; and electromagnetic forces.

The automation of processes in the industry had a boost with the large availability of digital controllers and the application of the control theory, even for linear or non-linear phenomena. Electric arc welding deserved attention from the designers in order to cut the electrode consumption due to liquid metal spattering [2]. Electric arc industrial furnaces were also a focus of attention to promote electric arc control and attain an energy efficient process [3]. The automation of a process demands knowledge of the system itself and the relation among its variables. The essential issue on the investigation of the VAR furnace aiming its automation is the changes in the behaviour of the electric arc voltage as an answer to changes in the electric arc environment. Once the electric arc current is kept constant, arc voltage is the process variable responsible for the electrode consumption and is promptly available to VAR furnace operators. Recent investigation mentioned that in some cases electric arcs have a chaotic behaviour [4].

Well-defined time periodic signals and stochastic processes have characteristic Fourier transform functions or spectra. The periodic signals have its spectra characterised by well-defined peaks at well-defined frequencies being totally predictable at any instant. The stochastic processes exhibit spectra almost flat for all frequencies and the state of the system at any time are not predictable. These two classes do not fulfil all possible real situations. In fact, there is a class of unique characteristics in between those presented above. This class is called chaos, a flat frequency spectrum with short-term predictability dynamical, bounded system.

On dealing with dynamical systems and chaos, some remarks may be found useful. When a complex system evolving time visits a region of the phase space frequently, this region is called an attractor. Two important characteristics of this space, concerning the set theory, are the invariants under the evolution of the system: fractal dimension d_a and the Lyapunov exponent λ [5]. The topological dimension of a chaotic system is not an integer value and it is a good indication of a chaotic behaviour. The Lyapunov exponent, when is positive, shows how trajectories on the attractor, move apart. Both are independent of changes in the initial conditions of the trajectories, and both are independent of the coordinate system in which the attractor is observed. The short term predictability of chaotic systems allows the system to be modelled and the model used as the basis for a control device.

Experimental

The melts for this work were carried out in a prototype VAR furnace, developed at IPEN. This VAR is powered by a commercial DC power source at a maximum of 400 A capacity. The power source open voltage was kept at 80 V and the electric arc voltage around 17 V. The signals picked up by the data acquisition system were conditioned by resistors with a fixed bias of 1/149. The meltings were processed within an argon (analytical degree) environment. Specially designed carbon steel and copper crucibles were used allowing the video recording of the process through one of the furnace's observation window.

The electrodes used for this work were made from machined Zircaloy chips; die compacted to square section bars 0.5 m long. The density of the compacted bars was 2.29 x 10^3 (+/- 10%) kg/m^3, approximately 35% of the bulk Zircaloy density.

The data acquisition was performed by means of a microcomputer 8 bits soundboard, and INTEL® 80486, DX 4-100 MHz, 20 MB RAM, and 540 MB for the hard disk. Data acquisition rates of 10 kHz and 20 kHz were used limiting the maximum signal frequencies to 5 kHz and 10 kHz respectively, in accordance to the Nyquist´s law. The application DAQARTA [6] (Data Acquisition and Real Time Analysis) for DOS system was chosen in order to perform the data acquisition and previous data treatments. The signals were recorded right to the hard disc in the MPEG (Moving Picture Expert Group) [7] format. The processed results of various commercial applications running on Macintosh computers were compared for validation. When was necessary to perform any calculation it was used the BASIC language.

A VHS video camera was used for image capture at a 1/2000 of a second shutter velocity and manual focus. A neutral density filter was placed in front of the camera lens to dim the high intensity of the brighten arc. The digitalisation of the images was done by means of a Macintosh computer and was edited in the *Avid Videoshop 3.0* application.

Results and discussion

Three distinct electrode voltages signals regions are presented: no electrical arc; just after arc ignition; disturbed arc and metal transfer. These raw signals are presented together to its frequency spectra in order to show evolution of the process from a periodic dynamic to chaotic dynamic, see Figs. 2 to 5. These figures show the electric arc signals of 50 ms and its fast Fourier transform – FFT spectra, taken at the three different conditions. The DC power source without the presence of the electric arc can be seen in Fig. 2. A highly periodical behaviour signal is confirmed by the FFT spectrum. Just after the electric arc strike, Fig. 3, the shape of the signal changes but the FFT spectrum keeps showing its high periodicity. After enough heating of the electrode's lower tip, it melts and the melt oscillation is responsible for the non periodical signals seen on Fig. 4 and Fig. 5, whose FFT spectra show a flat behaviour. At any condition of the electric arc, there is contamination from the DC power source original periodic signals, bellow 1 kHz and at the harmonics in 4, 6 and 8 kHz. The deep potential drop seen on Fig. 4 and Fig. 5 are caused by a short circuit or almost short circuit caused by liquid metal droplet fall.

The Fig. 6 shows a sequence of pictures taken at 1/15 of a second apart. The identification of the droplet separation is signed by the voltage drop due to a short circuit in the electrode, caused by an elongated liquid metal column, extruded by the Lorentz and the gravity forces. After separation, the electric arc elongates and the voltage rises is accompanied by a light flash that can be seen at the sixth photogram. Fig 7 shows the acquired voltage versus time – V (t) x t graph during the formation and separation of the liquid metal droplet.

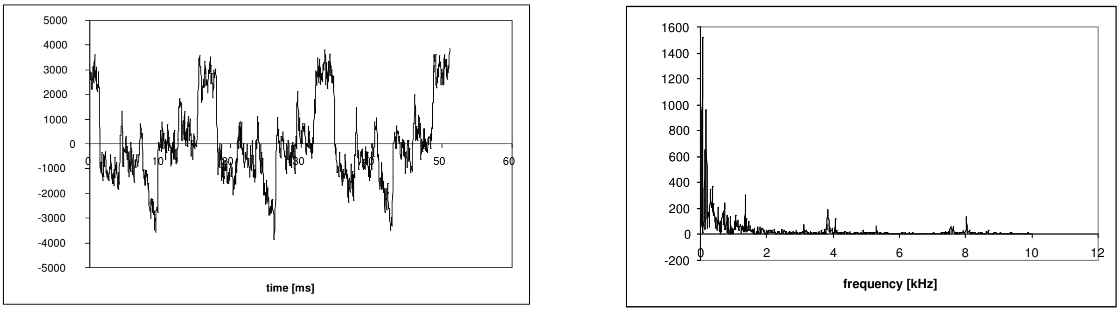

Figure 2. Graphics showing electrode voltage and FFT spectrum without the presence of the electric arc.

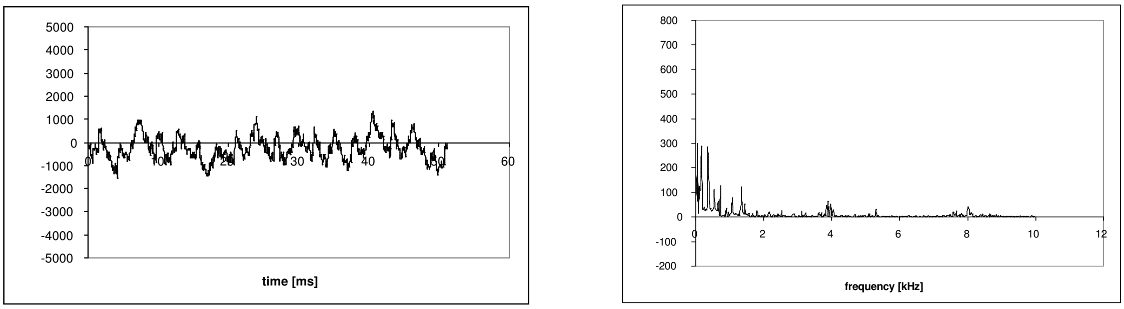

Figure 3. Electrodes voltage and FFT spectrum - no metal transfer through the electric arc.

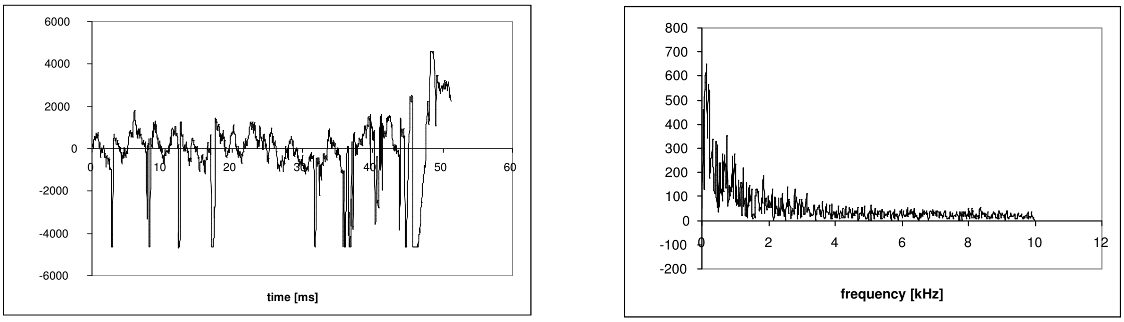

Figure 4. Electrodes voltage and FFT spectrum, perturbations on the electrode liquid metal tip surface and possible short circuit close to 45 ms.

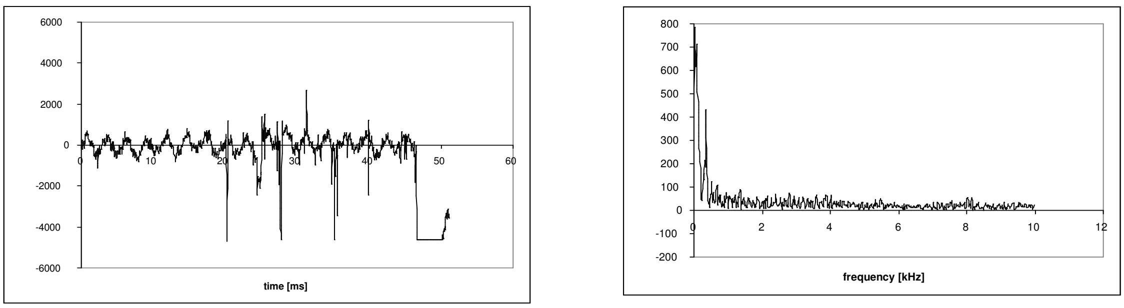

Figure 5. Electrodes voltage and FFT spectrum, indicating perturbations on the electrode liquid tip followed by a short circuit caused by metal transfer.

The signal that generates the V (t) x t graph seen on fig. 7 is used in the determination of the fractal dimension on the phase space of the dynamical system and the number of dimensions for the embedded space, homeomorphic to the original dynamic system. Fig. 8 shows the variation of the fractal dimension as a function of the distance between elements of the set obtained from the autocorrelation integral. There is a region within which the fractal dimension d_a is approximately constant, independent of the number of dimensions of the phase space.

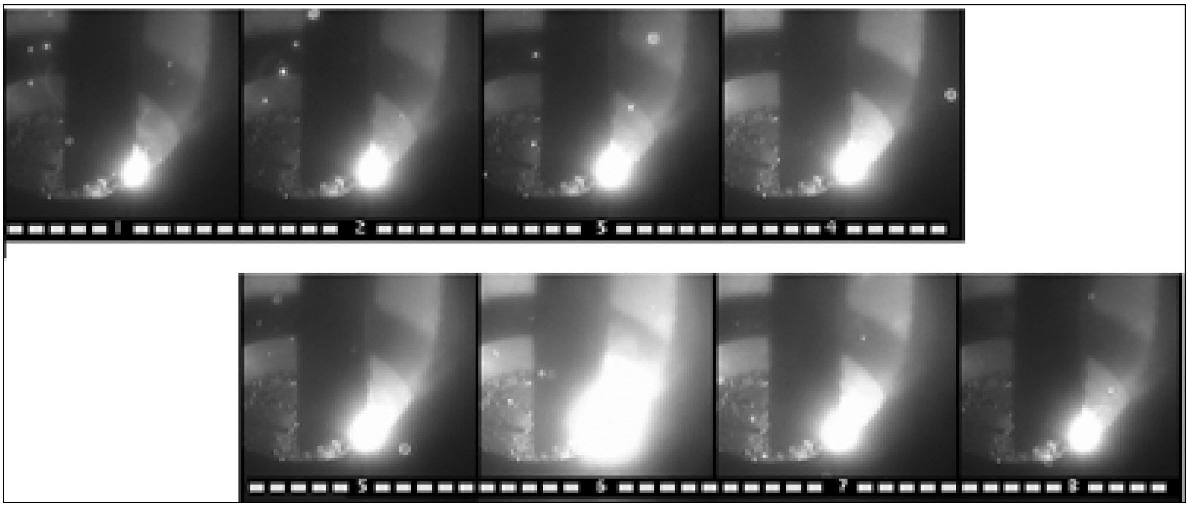

Figure 6. Sequence of photograms taken 1/15 seconds apart.

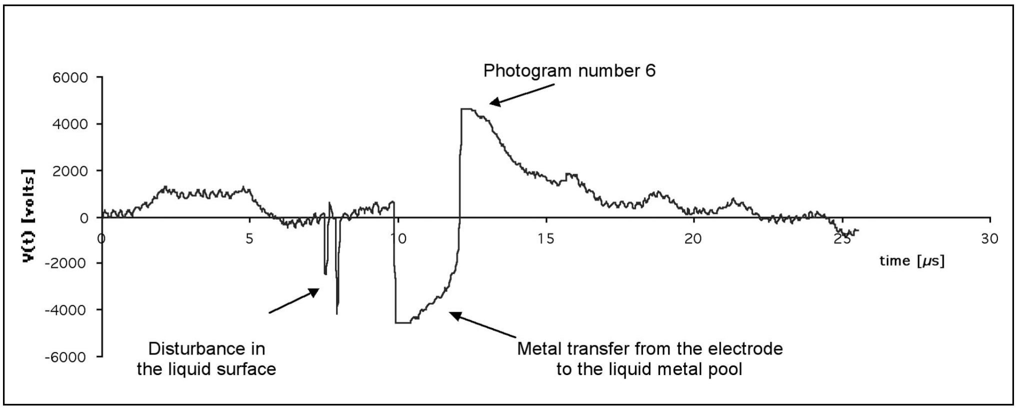

Figure 7. V (t) x t curve, showing acquired signal during the formation and separation of the liquid metal droplet.

The graphical determination of the fractal dimension of the phase space suggests a value of 2.2. Such result seems to be in accordance to the published value of 2.4 ± 0.3 for the fractal dimension of the attractor in the phase space of a non-consumable electric arc [4].

In Fig. 9, the aspect of the melted electrode tip can be seen. Just after the arc strikes, heat is generated and then electrode tip start to melt. The liquid metal didn't fall immediately, instead, capillary forces pull the melt up into the voids of the compacted chips electrode. Metal transfer starts when balance between capillary and gravity is attained. This initial transient behaviour is confirmed by means of the analysis of the voltage signals of the electric arc.

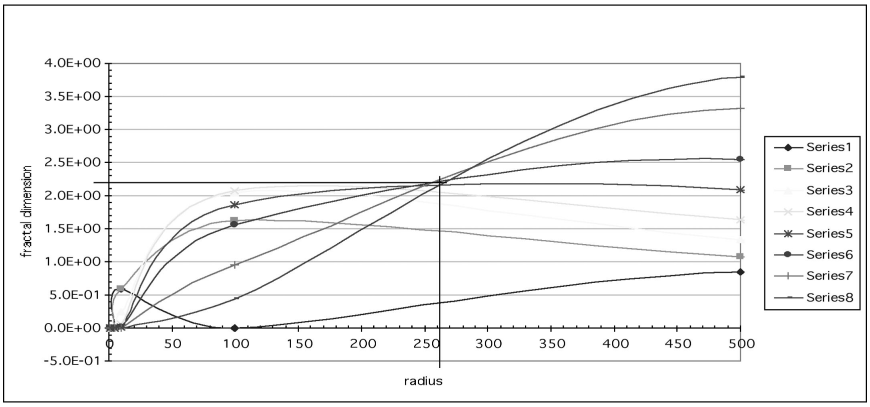

Figure 8. Graphical determination of the fractal dimension of the phase space. Each of the series is calculated for different number of dimensions of the phase space.

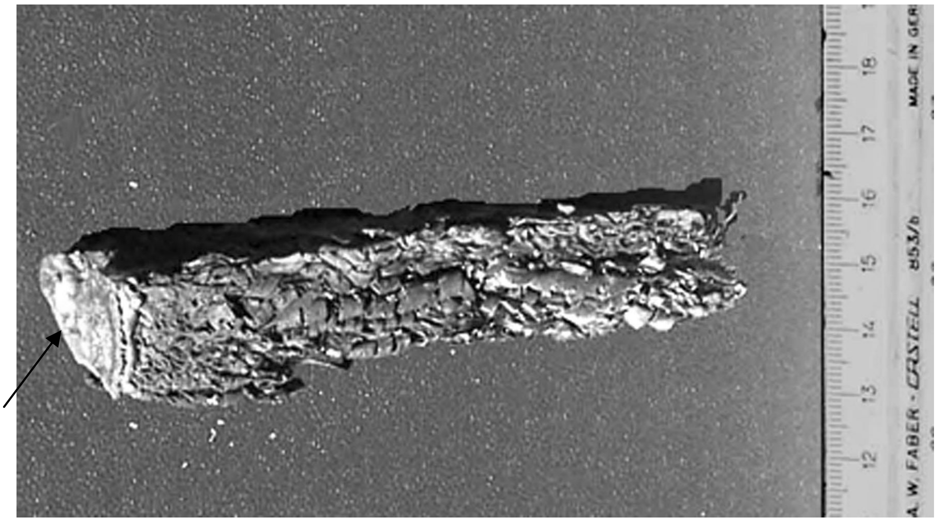

Figure 9. Compacted electrode and tip after end of the melt process. The picture shows the permeated liquid into the compacted electrode, see arrow.

Conclusions

The experiments showed that the operating condition determinate the arc behaviour. At early stages of the process, the arc is almost undisturbed and the system may be as almost linear, with a well-defined periodic signal. As the melting of the electrode occurs and liquid metal takes apart of the electrode tip, the system changes to a dynamical behaviour. The comprehension of this process is a determinant factor for system modelling and further control automation of the process.

The fractal dimension found for the disturbed electric arc strongly indicates non-linear chaotic behaviour. This behaviour may be modelled despite the fact its FFT spectrum is almost flat as the stochastic one. Artificial neural networks are indicated for this purpose.

This work focuses its attention on the behaviour of the electric arc when it is disturbed by formation of liquid metal oscillation on the liquid metal pool and electrode tip. It was found that the electric arc system is strongly dependent of the arc environment and that the analysis of the electric arc voltage signals indicates a chaotic characteristic for the VAR electric arc system.

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