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Observation of the electric arc behaviour in VAR

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Abstract

This study investigates, at different scales, the electric arc during Vacuum Arc Remelting of metallic alloys. First observations – very short timescale – were obtained in a specifically instrumented industrial furnace using high speed framing camera and optical emission spectroscopy, during the remelting of Ti alloys. Also, the interactions between the arc and the transfer of metal drops in the interelectrode gap were investigated. A second set of experiments – large timescale – consisted in characterizing the dynamics of the arc during actual heats under various operating conditions. Measurements of the luminosity recorded during actual Zr or Ni-based remeltings indicate that a periodic asymmetric behaviour takes place. The influence of such a behaviour on the electrode melting and ingot growing processes was simulated and some results are presented and discussed.

Key words: Vacuum Arc Remelting, Electric arc, Optical investigation

Introduction

The Vacuum Arc Remelting (VAR) process is an important technology for refining high added-value metallic ingots, such as steels, Ni-based superalloys, Ti alloys and Zr alloys.

Heating and melting of the metal is achieved with the help of a metal vapor electric arc established between the consumable electrode (cathode) and the molten metal pool that forms on top of an ingot (anode), which solidifies into a water-cooled copper mold (see Figure 1). Despite its importance, information on the arc is currently very limited due to the design of VAR furnaces that does not allow direct observation of the arc during a melt. Only two works dealing with direct optical investigation were reported in the literature. In the 1980s, first observation was made at Sandia National Laboratories [1,2] concerning the melt of Ni-based superalloys while, more recently, observation of the melt of a Zr alloy was performed by the present authors [3]. These investigations were achieved by installing on an existing furnace a dedicated apparatus equipped with a high speed video camera, in order to visualize the arc at a short timescale.

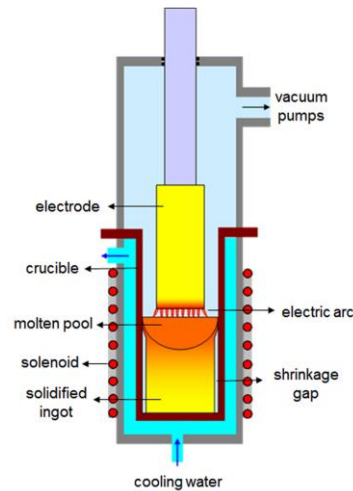


Fig. 1: Schematic representation of the VAR process.

In both cases, the arc behaviour was found to be similar to the diffuse mode of a vacuum arc created between cold solid electrodes. The arc consists of several dispersed clusters of cathode spots moving over the whole surface of the cathode. Such a behaviour seems to imply that the energy transferred from the arc to the cathode and ingot is distributed uniformly, so axisymmetry would be expected at the macro-scale. However, from measurements of the luminosity and magnetic field, several authors [4,5] have suggested that the center of gravity of the arc was off-centered and not immobile.

A thorough understanding of the dynamics of the arc is important for a proper control of the process performance and ingot quality. The spatial and temporal distribution of the arc determines the energy and electric current inputs to the ingot top surface, which control to a great extent the quality of the remelted products. In the frame of an ANR research programme associating Institut Jean Lamour and three major French VAR users (Timet Savoie, Areva NP and Aubert&Duval), new experiments were carried out to visualize the electric arc, at both the micro- and macro-scale, for various alloys and experimental conditions. This paper reports the most significant results and presents briefly the numerical simulation of the influence of a transient 3D behaviour.

Arc behaviour at the micro-scale

The experiments were performed in cooperation with Timet Savoie and Areva NP using the previously developed apparatus described in [3]. A full-scale VAR furnace was equipped with an additional water-cooled cylindrical chamber placed between the crucible and the upper vacuum chamber, as shown on Figure 2. This module was equipped with three horizontal (or slightly inclined) viewing tubes that allow direct observation of the arc in a configuration close to that of an actual remelting operation. All experiments used a 160 mm diameter electrode and a 280 mm diameter ingot in Ti-6Al-4V or Ti-10V-2Fe-3Al. Details on the experimental set-up is available in [6].

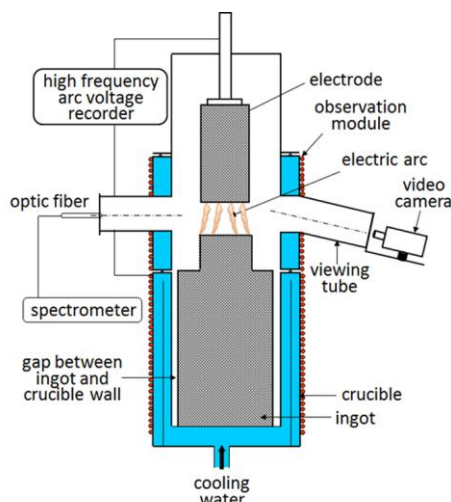


Fig. 2: Experimental device implemented on a full-scale VAR unit.

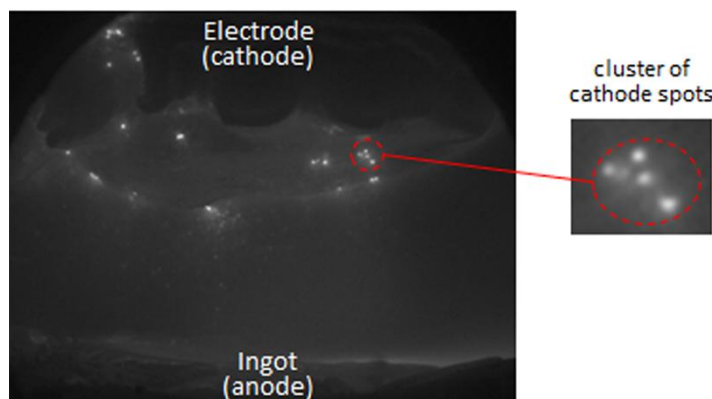


Fig. 3: Video image of the electric arc, recorded at 5700 frames/s with an exposure time of 10 μ s.

As in the case of Ni-based and Zr alloy electrodes, the arc appearance during the melt of a Ti alloy was a typical diffuse regime, which characterizes "classical" vacuum arcs established between two solid electrode surfaces at low current densities (employed for example in vacuum circuit breakers) [7]. As can be seen on figure 3, the arc was composed of a set of simultaneously operating cathode spots. The average current per spot was around 100 A while the size of a spot was estimated to be several hundred micrometres and its apparent velocity over the cathode surface of the order of 1 to 10 m/s. A characteristic time scale associated with this motion was less than 1 ms. The cathode spots gathered in clusters that were animated by an apparent random motion which tended to be preferentially oriented towards the edge of the electrode. After reaching the edge, the clusters moved along the side surface of the electrode over a few centimetres, and finally extinguished. The application of an axial magnetic field was found to stabilize the arc under the electrode, limiting the establishment of the cathode spots on the side surface.

Each spot was a site of emission of a plasma jet composed of metal vapor particles. These plasma jets mixed near the cathode surface to form a diffuse and weakly luminous plasma, which filled homogeneously the interelectrode region. The anode did not play an active role in the discharge. A spectroscopic investigation revealed that the metal vapour plasma was mostly composed of Ti atom and Ti^+ ions.

Interactions of the spots with the melted material were found to be highly dependent on the arc length; the shorter the arc length, the more important the influence of the arc on the transfer mechanisms. Indeed, three different transfer modes of the drops created at the cathode tip through the interelectrode gap could be observed. For a large arc length (> 6 cm), the metal drops were allowed to develop with a negligible activity of the spots on their surface. They grew first by accumulation of metal and then by stretching and eventually ended up falling off into the liquid pool under the effect of gravity. In the case of an intermediate arc length (between 2 cm and 6 cm), the transfer of metal drops involved predominantly the well-known "drip short" sequence, in which a short-circuit was caused by the momentary contact of the metal drop with the surface of the metal bath. Such transfer sequence was very similar to that previously described in the literature [1-3]. However, for a short arc length, (< 2 cm), a specific mode of transfer was observed, which had not been reported in previous studies. The metal drops were unable to develop. Metal transfer was strongly affected by the arc and occurred mostly under the physical action of the cathode spots locating themselves preferentially on the surface of growing protuberances and causing their progressive erosion.

Arc behaviour at the macro-scale

Despite their interest for understanding the physics of the electric arc, the experiments reported above cannot be directly linked to a simulation of the process, with the aim of optimizing the remelting parameters, due to the very small characteristic time scale. By integrating the observed motion over time, the influence of the arc on both electrode and ingot was roughly simulated by the present authors [8]. Because of the apparent random location of the birth of cathode spots and their high velocity at the cathode tip, such integration led to a uniform distribution of current and thermal power, hence an axisymmetric behaviour.

However, it has been reported that the arc often does not behave axisymmetrically at the macroscopic scale. Based on measurements of the luminosity and magnetic field created by the arc, Ward et al. [4] suggested that the centre of gravity of the arc was off-centred and rotated in a time-averaged sense around the electrode axis, so that part of the arc could be assimilated to a rotating spot. A 3D model of the ingot pool [5] concluded that the hydrodynamic behaviour of the melt pool and ingot solidification process could be greatly influenced by such an ensemble arc macroscopic motion. Therefore, we report new visual investigations of the dynamic behaviour of the electric arc during actual VAR heats. These experiments were achieved in close connection with Areva NP (Zr alloy) and Aubert & Duval (Ni-based superalloy) under various operating conditions. Video cameras positioned on top of the furnace chamber were used to film the annulus gap between the electrode and crucible wall (see figure 4).

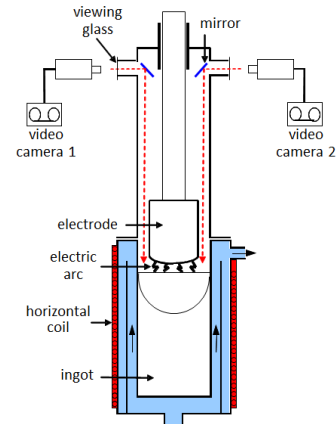


Fig. 4: VAR furnace equipped with two video cameras.

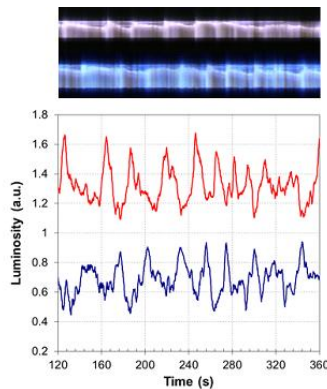


Fig. 5: Typical luminosity variations observed for two diametrically opposite regions.

In the case of a Zr alloy remelting, the treatment of the films, detailed in [9], revealed that the observed luminosity at a given position fluctuated quite regularly, as shown on figure 5. Furthermore, variations of luminosity in two diametrically opposite regions were essentially in phase opposition. A frequency analysis concluded to a periodic behaviour, hence an apparent macroscopic motion of the centre of gravity of the arc across the electrode surface, with a period of around 30 s. This phenomenon was observed for all the melt conditions tested, including various external stirrings. Furthermore, similar results, although less conclusive, were drawn concerning the remelting of Inconel 718.

It must be stated that the reasons for such a macroscopic motion of the arc are still not known. The most striking feature remains the large time constant of this motion, much greater than any micro-scale which could be linked to the behaviour of cathode spots (see above) and does not correspond either to any obvious time scale of the VAR process.

Numerical simulation of the effect of an asymmetric unsteady arc

As stated previously, computational models based on a 2D axisymmetric geometry [10,11] might not be sufficient to describe accurately the ingot and cathode evolution. To account for an unsteady asymmetric behaviour of the arc at the macro-scale (ensemble arc motion), specific 3D models have been developed at IJL. The models consider the existence of a so-called 'arc-spot' liable to rotate on the base of the cathode. The total power transferred to each electrode is the sum of a part distributed uniformly all over the electrode surface and a 'spot' part concentrated in a small area. A 3D home-made finite volume model of the heat transfer in the cathode and subsequent tip melting was developed first. It simulates the consumption of melted material by removing mesh cells from the computational domain, as soon as the computed temperature reaches a prescribed value, slightly higher than the liquidus of the alloy. The initial mesh is typically composed of 2,700,000 cells (100-90-300 in r - θ - z directions).

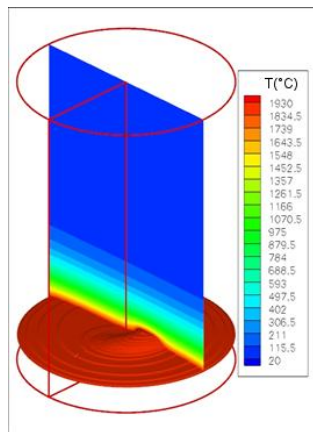


Fig. 6: Example of electrode temperature map, showing the influence of arc-spot motion.

In order to represent the influence of such an arc-spot on the ingot growth, and following the pioneering work by Bojarevics et al. [5], we have recently started to build a 3D model of the continuous growth and solidification of the remelted ingot. Written in the open-source platform OpenFOAM, the model is a classical CFD representation of coupled fluid flow and heat transfer in the liquid pool, mushy zone and solidified ingot. First results, as shown on figure 7, are very promising. As an example, the importance of transient Marangoni driven flow caused by a local superheat could not be evidenced by 2D VAR models because of their assumption of axisymmetric heat input at the free ingot surface.



Fig. 7: Example of computed temperature map and velocity field on the ingot free surface.

Conclusion

Through experimental observation, especially the optical investigation, of the VAR electric arc at two different space and time scales, a deeper understanding of the arc behaviour has been obtained. Some important features, such as the precise influence of an external magnetic field on the location of the cathode spots, as well as the reason for the asymmetric global dynamics frequently observed at the macro-scale, are not well solved yet. However, recently developed numerical models already enable us to link the physics of the arc to the actual phenomena that are responsible for the quality of the remelted products.

Acknowledgments

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