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Characterization of the behaviour of the electric arc during VAR of a Ti alloy

P Chapelle[1], C Noël[1], A Risacher[1], J Jourdan[1], J Jourdan[2] and A Jardy[1]
[1]Institut Jean Lamour - UMR 7198 CNRS/Université de Lorraine,
Laboratory of Excellence DAMAS, CS 50840, 54011 Nancy Cedex, France
[2]Timet Savoie, Avenue Paul Girod, 73400 Ugine, France

E-mail: pierre.chapelle@univ-lorraine.fr

Abstract. In this paper, we report experimental results based on the direct observation of the electric arc behaviour during vacuum arc remelting of a Ti alloy. These results were obtained in a specifically instrumented industrial furnace using high speed framing camera and optical emission spectroscopy, for a current density level of the order of 10 A/cm^2 and a gap length of a few centimetres. It was observed that the arc exhibits a similar operating regime to that described in the literature for the case of Inconel 718 and Zr alloy electrodes. The arc structure corresponds essentially to that of a diffuse metal vapor arc with separate and rapidly moving cathode spots. Several critical parameters of the cathode spots, including their current, size and velocity, and of the interelectrode plasma were evaluated. Also, the interactions between the arc operation and the transfer of metal drops in the interelectrode gap were investigated. Three modes of transfer of the liquid metal drops in the interelectrode gap have been identified depending on the gap length: drop falling, drip short and drop erosion induced by the cathode spots.

1. Introduction

The Vacuum Arc Remelting process is an important technology for refining reactive metallic ingots, such as titanium and zirconium alloys. In this process, heating and melting of the metal is achieved with the help of a metal vapor electric arc established between a consumable electrode (cathode) and a molten metal pool that forms on top of an ingot (anode) which solidifies into a water cooled copper mold. To help metal producers to meet new requirements on process performance and ingot quality, it becomes increasingly important to have a more comprehensive understanding of the electric arc behaviour and more generally of all the phenomena taking place in the interelectrode region. In particular, knowledge of the arc behaviour is important for the proper modelling of the heat flux and electric current distributions provided by the arc at the ingot top surface, which determine to a large extent the solidification conditions of the metal, and thus the final ingot quality.

Despite its importance, the information on the arc behaviour are currently very limited due to the experimental constraints caused by the design of VAR furnaces which does not allow to directly observe or easily access with sensors the arc during a melt. Only two works dealing with direct optical investigation of the arc were reported in the literature. The first observations were made by Zanner and his colleagues in the 1980s [1,2] investigating the melts of Ni based superalloys, while, more recently, observations applied to the melt of a Zr alloy were performed by some of the present authors [3]. These investigations were done by installing on an existing furnace a purposely developed module to visualize the arc. Very similar results were obtained for both types of alloy. The main result was that under standard melting practice the arc takes on a so-called diffuse appearance, the arc being composed of multiple fast moving cathode spots distributed over the electrode surface. The sequence of events controlling the transfer of metal in the interelectrode gap was also investigated in these studies, with particular interest in the transient short circuits and arc extinction caused by the metal dropping at short gap lengths.

In the present study, we describe similar experiments carried out while melting a Ti alloy electrode. First, we report observations made with a high-speed video camera of the appearance and evolution of the electric arc, as long as estimations of the main parameters of the cathode spots. A special attention is put on the influence of an external axial magnetic field on the cathode spot distribution. Then, we present the evaluation of some plasma parameters, like excitation temperatures and relative densities, measured using optical emission spectroscopy. Finally, we describe the various modes of transfer of the metal between the electrode and the ingot observed as a function of the gap distance and their interactions with the arc behaviour. We present in particular a new mode of transfer of the metal identified for very small gap distances, which had not been reported in earlier works. A more detailed report on the experiments described in the current work is given in [4].

2. Experimental setup

The experiments were performed in cooperation with the CEZUS company using the previously developed setup described in [3]. An industrial VAR furnace was equipped with an additional water-cooled cylindrical chamber, referred to as the module of observation of the electric arc (figure 1). This module, placed between the crucible and the upper vacuum chamber, was equipped with three horizontal (or slightly inclined) viewing tubes that allow to directly observe the arc in a configuration close to that of an actual remelting operation. During an experiment, an electric arc was sustained between an electrode and an initial ingot with a height greater than that of the crucible, so that the arc region was in the horizontal alignment of the viewing ports. The ingot diameter was smaller than that of the crucible to prevent contact between the side of the ingot and the uncooled flanges of the crucible and the observation module. This configuration implied to limit the size of the liquid pool formed at the uncooled ingot top. The duration of an experiment was thus limited to a few minutes.

All experiments were performed with a 160 mm diameter electrode and a 280 mm diameter ingot both in Ti-6Al-4V, except two experiments during which a Ti-10V-2Fe-3Al electrode was used in order to study the influence of the alloy composition. Melting parameters were as follows: the arc voltage was varied between 27 V and 37.1 V, the arc current between 2 kA and 6.1 kA and the gap length between 2.1 cm and 7 cm. Moreover, some experiments were performed applying a vertical magnetic field (the intensity of the field was 15 G) produced by an inductor coil placed around the observation module. Phenomena in the interelectrode region and at the electrode surface were observed with a high-speed video camera (Photron SA5) using frame rates up to 10^5 frames per second. The high-speed video camera was synchronized with the high frequency (up to 200 kHz) recording of the arc voltage to analyze the electrical signatures associated to the metal transfer mechanisms. Besides arc visualization, we also investigated the plasma emission by optical emission spectroscopy using a Jobin Yvon spectrometer (TRIAX 550) equipped with a 1200 grooves/mm grating blazed at 250 nm and an ICCD detector. The observed spectral domain ranged from 270 nm to 540 nm.

3. Results

3.1. Arc structure

Similarly to the observations reported in the case of Ni based and Zr alloy electrodes, the arc appearance during the melt of a titanium alloy appeared to correspond to the diffuse regime, which characterizes "classical" vacuum arcs established between two solid electrode surfaces at low current densities (employed for example in vacuum circuit breakers) [5]. As can be seen in figure 2, the arc was composed of a set of simultaneously operating cathode spots, moving at a high velocity across the electrode bottom end surface and on a fraction of the electrode lateral surface. Each spot was a site of emission of a jet of plasma composed of metal vapor particles originating from the cathode. These plasma jets mixed near the cathode surface to form a diffuse and weakly luminous plasma, which filled approximately homogeneously the interelectrode region. The anode did not play an active role in the discharge.

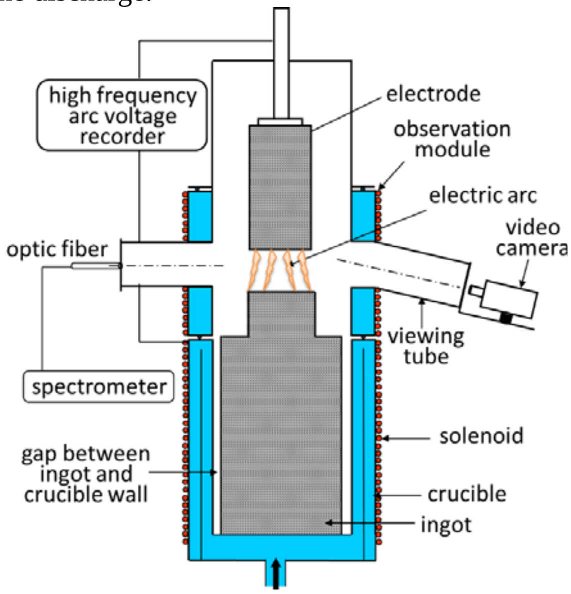

Figure 1. Experimental set-up implemented on an industrial VAR unit.

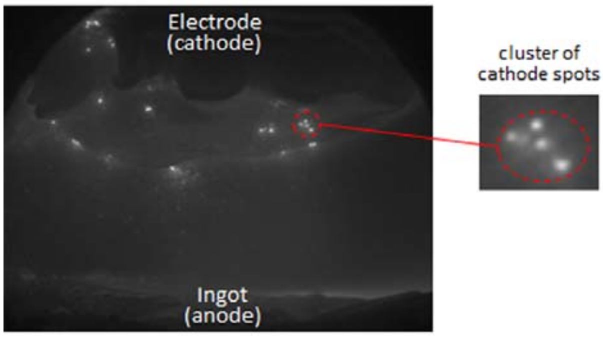

Figure 2. Video image (recorded at 5700 frames/s with an exposure time of 10 µs) of the electric arc.

A more detailed insight into the structure of the arc showed that the arc was composed of at least two structural levels.

- The first level was that of cathode spots. The average current per spot was found to be of the order of 100 A. The size of a spot was estimated to be several hundred micrometers and its apparent velocity over the cathode surface turned out to be of the order of 1 to 10 m/s. As shown in table 1, our results are close to those obtained for the melt of a zirconium alloy and are globally coherent with the spot parameters reported for "classical" vacuum arcs between solid electrode surfaces [6].
- At a larger length scale, a second level of structuration of the arc was observed, corresponding to the formation of clusters of cathode spots. These clusters were most often of small size, with a number of spots per cluster varying between 2 and 13 (for an average value equals to 3.9). The number and the arrangement of the spots inside a cluster were unstable. The clusters might spontaneously extinguish and frequently divide into smaller clusters which tended then to repel each other. It seems that the division of clusters was caused by the increase of the number of the spots inside the cluster. The clusters were characterized by a non-steady and complex dynamic behaviour. They had 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.

Table 1. Estimated parameters of the cathode spots.

	Electrode	Properties of the cathode spots			Number of spots / cluster
		Diameter (μm)	Average current (A)	Apparent velocity (m/s)	
Measurements in a VAR furnace	Zy4 [3]	-	76 - 190	1 - 10	2 - 5
	Ti-6Al-4V	629 ± 141	~100	1 - 10	2 - 13
Vacuum arc between two solid surfaces	Ti [6]	411 ± 66	33,5	30	9 ± 3

The influence of an external axial magnetic field on the arc distribution was investigated by following the proportion of spots present at the electrode tip during the melt (i.e. the ratio of the number of spots present at the electrode tip to the total number of spots present both at the electrode tip and on the electrode side surface). This parameter was obtained with the help of an image processing program capable of detecting automatically on each video image the position of all the cathodes spots present on the surface of the electrode. Figure 3 shows that parameter in the form of a distribution function. As shown in this figure, the proportion of spots under the electrode tended to be larger when a magnetic field was applied. Also, the situations where all the spots were established on the lateral surface (no spots under the electrode) were less frequent when a magnetic field was applied. These observations suggest that the application of an axial magnetic field allowed a better confinement of the arc under the electrode, by promoting the location of the spots at the electrode tip instead of the lateral surface. Note that a similar effect of the application of an axial magnetic field is reported in vacuum arc circuit breaker studies [7].

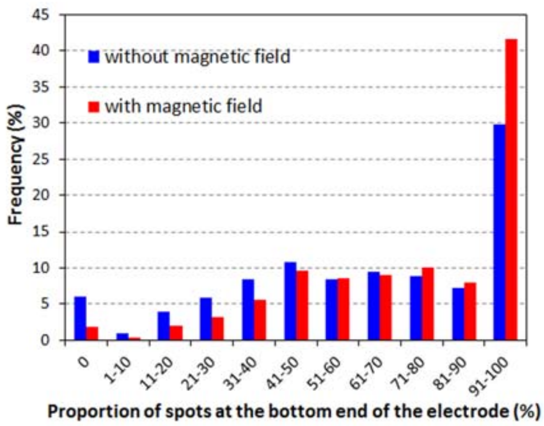

Figure 3. Influence of an external axial magnetic field on the proportion of cathode spots at the electrode tip.

3.2. Plasma parameters

The spectroscopic data provided information on the nature of the excited species (atoms and ions) present in the plasma and has allowed us to determine their excitation temperature. They have also been used to estimate the relative proportion of singly ionized titanium particles with respect to titanium atoms, which gives an indication on the ionization degree of the plasma. Details and equations regarding the processing methods of the spectroscopic data may be found in [4].

The presence of a large number of spectral lines due to singly ionized titanium particles was noted in the emission spectrum of the plasma (suggesting that it was the dominant species in the plasma). Titanium was also present as atoms and (yet to a much lesser extent) in the form of ions Ti^{2+}. The emission spectrum contained also spectral lines due to each of the main alloy elements (Al, V and Fe). These elements were present both as atoms and singly charged ions (doubly ionized particles were also observed in the case of vanadium).

Table 2 summarizes the values of the excitation temperature of Ti atoms and Ti^+ ions determined for the two investigated alloys. Only the excitation temperature of Ti atoms and Ti^+ ions could be determined, as the number of spectral lines observed for the other species was insufficient to perform such a calculation. The temperature of Ti^+ ions exceeded (1.5 to 2 times) that of Ti atoms. This difference may be related to differences in the spatial distributions of the two species. Indeed, it is expected that Ti^+ ions were mostly produced in the plasma jets emitted by the cathode spots, while Ti atoms originated predominantly from the volatilization of the metal from the liquid film at the base of the cathode and from the surface of the liquid pool on the anode side. No significant influence of the alloy composition on the two calculated temperatures is observed.

Table 2. Estimation from the spectroscopic data of the excitation temperatures of Ti atoms and Ti^+ ions and of the density ratio of Ti^+ ions and Ti atoms.

alloy		Ti-6Al-4V	Ti-10V-2Fe-3Al
Arc voltage (V)		31.2	31.4
Melting current (kA)		3.95	4.55
Gap length (cm)		4.4	4.6
T_{exc} (K)	**Ti**	**6615** ± 928	**6963** ± 1741
	Ti^+	**11387** ± 1509	**11266** ± 1161
n_{Ti+} / n_{Ti}		**24.24** ± 4.14	**8.81** ± 1.91

Table 2 shows also the estimated values of the Ti^+ ions to Ti atoms density ratio. It must be pointed out that, contrary to the calculation of the temperatures which relies on the measurement of the intensity of a large number of spectral lines, the calculation of the density ratio relies on the measurement of the intensity of only two spectral lines. This may explain the limited accuracy of the calculation of the density ratio and the important standard deviations obtained. The density of Ti^+ was much larger (approximately one order of magnitude greater) than the density of titanium neutral particles. The spectroscopic data did not allow us to calculate the true ionisation rate of the plasma. This would require to take into account all ion and neutral species in the plasma and to determine the excitation temperature of each of them. However, the very large values of the ratio of the densities of Ti^+ ions and Ti atoms obtained here and the dominant presence of spectral lines due to these two species in the emission spectrum of the plasma suggest that the plasma was strongly ionized.

3.3. Metal transfer

Three different modes of transfer through the interelectrode gap of the liquid metal drops created at the electrode tip have been observed depending on the gap length. Moreover, the shorter the gap length, the more important the influence of the arc on the transfer mechanisms.

1) For large value of the gap length (greater than about 6 cm), the metal drops were allowed to develop with, in general, negligible activity of the spots on the drop surface. Metal drops 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. The only interaction with the arc occurred immediately after the drop breakup. A fine filament of metal was left hanging under the electrode, which was quickly eroded under the action of the cathode spots, as the spots tended to accumulate on the filament surface. The total duration of the transfer sequence was typically of the order of several hundred milliseconds.

2) For values of the gap length between 2 cm and 6 cm, the transfer of metal drops involved predominantly a phenomenon called a drip short, which corresponds to the formation of a transient short-circuit caused by the momentary contact of the metal drop with the surface of the metal bath. Such transfer sequence was very similar to that described in the literature for the case of Ni based and zirconium alloy electrodes.

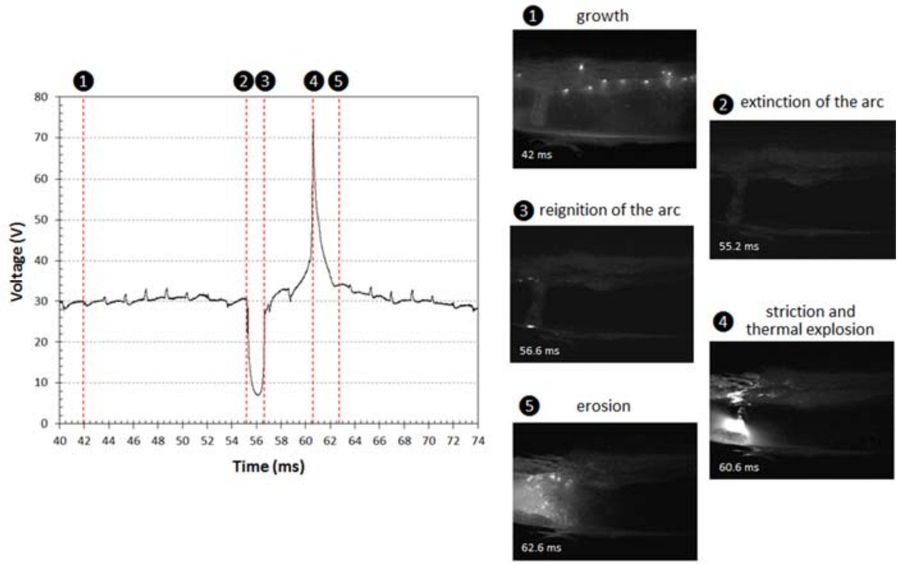

Figure 4. Transfer of a liquid metal drop with a drip-short and the electrical signature associated (gap = 3.6 cm).

Figure 4 shows an example of such a transfer sequence as well as its electrical signature. Note that we describe here the most commonly observed drip short sequence. Slight variations of the sequence are described in [4]. The sequence started with the relatively slow growth of a protuberance of metal, with negligible influence of the arc (image 1). The growing protuberance ended up touching the surface of the ingot metal bath, causing a short-circuit (the voltage dropped consequently to a small value) and the extinction of the arc (image 2). After a short time interval, the bridge of liquid metal connecting the electrode to the ingot broke near the ingot. This was followed immediately by the reignition of the arc between the bottom end of the protuberance and the ingot (image 3). As the cathode spots tended to remain concentrated at the tip of the protuberance resulting in a highly luminous plasma (constricted arc), some local narrowing (pinching effect) of the protuberance was observed. This pinching effect developed until causing a thermal explosion of the metal in the narrow region and the transfer of the bottom part of the protuberance to the ingot (image 4). This phenomenon may be attributed to the fact that an important fraction if not all of the electric current flowed through the protuberance, which induced within the protuberance some intense compressive magnetic forces and Joule heating. The constriction of the arc under the protuberance was responsible for an increase of the voltage level, with a peak value coinciding with the thermal explosion of the protuberance. Eventually, the cathode spots spread over the entire electrode surface and the remaining portion of the protuberance was finally transferred to the ingot by progressive erosion under the action of the cathode spots (image 5).

3) For a gap length value of 2 cm, a specific mode of transfer was observed, which had not been reported in previous studies. The metal drops were generally unable to develop up to a stage where they produce a drip short. 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 the growing protuberances and causing their progressive erosion. Such erosion took the form of small volumes of metal being torn off from the protuberance and tiny droplets of metal emitted by the spots.

Often the action of the spots was not continuous, but repetitive, with interruptions related to the establishment of the spots on other protuberances.

4. Conclusions

Visualization experiments of the arc behaviour and metal transfer mechanisms during the vacuum remelting of titanium alloys have been reported for the first time. Similarly to the results obtained for the melts of Ni based and Zr alloys, the arc was observed to operate in a diffuse mode, characterized by the presence over the electrode surface of a collection of small and fast moving cathode spots. The values of the basic parameters of the cathode spots estimated in this work are comparable to the values measured for cathode spots established on a titanium solid surface. The application of an axial magnetic field has been found to stabilize the arc under the electrode, limiting the establishment of the cathode spots on the side surface of the electrode. The spectroscopic investigation has revealed that the metal vapor plasma is mostly composed of Ti atom and Ti^+ ions, the density of the latter being significantly higher than that of atomic titanium. Three distinct modes of transfer of the metal drops have been identified, namely for decreasing gap length: dripping, drip-short and arc controlled erosion of metal drops. This third mode, which had not been described in earlier studies, was observed for very short gap length (about 2 cm)

5. Acknowledgments

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