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## 2-D modelling of longitudinal and radial segregations in vacuum arc remelting of titanium alloys

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***Abstract :** A model of heat and mass transfers in vacuum arc remelting process is used to simulate the remelting of TA6V ingots on an industrial scale. The model enables to calculate the shape and depth of the liquid pool, as well as the oxygen segregation caused by liquid/solid partition. Computed results are presented for different preparations of electrode.*

### INTRODUCTION

The Compagnie Européenne du Zirconium Cezus has been using Vacuum Arc Remelting furnaces for the processing of Titanium and Zirconium alloys on an industrial scale for more than thirty years. It has been known for a long time, that because of the coexistence of both liquid and solid phases (figure 1), zone refining would occur during the ingot remelting in VAR processing. This induces both longitudinal and radial solute segregation at the scale of the ingot. For Titanium alloys, used in jet engines, it results in a reduced control of the  $\alpha$ - $\beta$  allotropic phase transition temperature, which is highly dependent on the analytical composition (mostly through the alphagene effect of Oxygen). This temperature appears to be a critical parameter of the thermomechanical treatments that follow the production of the ingot, and will provide the metal with its final mechanical properties.

In this study, we compare the results in terms of oxygen content heterogeneity between three kinds of electrodes. We first consider an homogeneous electrode where oxygen is perfectly and equally introduced. The results constitute our reference. We then study an industrial electrode where alloying elements are concentrated locally in each compact. Finally, we model the behaviour of what we call a compensated electrode, where the solute initial repartition is determined in order to minimize the zone refining effect. We examine how efficient such a technique can be, and we quantify its effects on the radial solute homogeneity.

### MATHEMATICAL MODELLING OF MASS TRANSFER IN VAR PROCESSING

To simulate the remelting of the ingots, we used a mathematical model developed at the School of Mines of Nancy <sup>(1,2)</sup>. The model is based on the numerical solution of the transient state heat transfer equation in the cylindrical ingot. The approach of the study was to assume that the thermal problem is independent from the mass transfer, whereas the latter will depend on the thermal behavior of the ingot. It provides us with all the required thermal parameters, and their evolution during the three remeltings of the VAR ingot.

#### Model assumptions and mass transfer equation

The model assumptions are the following ones :

- the liquid pool is analytically homogeneous,
- thermodynamic equilibrium is reached at the solid/liquid interface,
- the effective partition coefficient is constant during the remelting and switches to the value of 1 once the electrical arc is turned off,
- solid state diffusion is neglected,
- volatilization of alloying elements is not considered.

The mass balance in the liquid pool can therefore be written as follow :

$$\frac{\partial V_L C_L}{\partial t} = v_f C_e - \frac{\partial}{\partial t} \int_{\text{solid}} C_s dV_s \quad (1)$$

where the indexes L, s, e refer respectively to liquid, solid and electrode, and  $v_f$  is the melting rate. The liquid pool volume  $V_L$  is a critical parameter, equivalent to a dilution term, and was determined by the heat transfer simulations.

As seen in equation (1), the solute repartition in the electrode influences the solute repartition in the ingot. Provided the initial electrode solute repartition, this equation is solved three times in order to simulate the actual remelting route for titanium alloys which comprises three melts. The model was validated in earlier works <sup>(2,3)</sup> on industrial measurements and best fit was obtained with a constant effective partition coefficient of oxygen in titanium of 1.06. All following simulations were made using this value.

## LONGITUDINAL SEGREGATIONS

### *Remelting of an homogeneous electrode. Understanding of the basic phenomenon*

Figure 2.a presents the average oxygen content across a section for each of the three melts. The combination of the dilution in the liquid pool and the solid/liquid partition results in a decrease of the oxygen content on top of the first ingot. This ingot is then tilted and remelted. The remains of the first melt segregation can be observed at the bottom of the second ingot where dilution is not important enough to remove this defect. A new segregation is generated on top of the second ingot. Same mechanism occurs in the third melt. The top segregation of the second melt is slightly diluted. The third melt top segregation adds up to the remains of the first melt segregation to accentuate the intensity of the segregation. The final oxygen content distribution consists in a disymetric bell shaped curve. This curve was observed experimentally in earlier works on an industrial production of Ti-6Al-4V <sup>(2,3)</sup>.

### *Remelting of a compensated electrode. Industrial practice*

The way actual industrial electrodes are prepared results in an initial electrode where the alloying element repartition is far from being homogeneous. We simulated such an industrial practice. The initial electrode was divided in 28 compacts. In each of them the total necessary oxygen content for the compact was concentrated in its center part on a fraction of 35% of the compact height. As seen on figure 2.b, the first melt still carries the initial heterogeneity. The number of waves observed on the oxygen content corresponds exactly to the number of compacts. At the beginning, the oscillations are very important and reach rapidly a steady state. This state corresponds to the steady state of the liquid pool volume which determines the dilution of the material incoming from the electrode being melted. After the second melt, the oscillations have completely disappeared. The resulting oxygen profile can be superposed to the second melt one obtained in the previous simulation, and this within 2 ppm. Same conclusions can be applied to the final oxygen content profile.

### *Remelting of a compensated electrode*

As mentioned earlier, the remelting of an homogeneous or a compacted electrode results in a disymmetrical and non constant oxygen content distribution. We examined ways of reducing this heterogeneity by modifying the initial repartition in the electrode in order to compensate the segregation occurring during the processing route. Figure 2.c presents the result of such a practice where the predicted

bottom and top oxygen deficits were compensated by adding oxygen in the electrode end compacts. One can see that it results in a very high oxygen content at both extremities of the first ingot. By the play of the following zone refinings and dilutions, the final oxygen content is smooth and closer to the aimed oxygen content all along the ingot as in the regular processing route. As a result, longitudinal segregations are reduced by a factor 2.

## RADIAL SEGREGATIONS

### *Remelting of an homogeneous electrode*

The results for the final ingot presented in figure 3.a reveal that the oxygen content increases from center to outside of the ingot in the upper two-thirds of the ingot. It results both from the pronounced bell shape and the lower oxygen content of the liquid pool. The sharp discontinuity corresponding to the presence of the final liquid pool can be easily observed. In the lower third, the general aspect of the radial distribution is reversed. Oxygen content decreases from center to outside of the ingot. But the amplitude of the segregation is much smaller than in the upper part. Indeed the radial segregation gets more and more intense along the ingot height, because of the increasing distortion of the liquid pool shape, almost flat at the beginning and V-shaped at the end of the melt. Maximum radial segregation occurs on top of the ingot. The same profile is obtained with a compacted electrode, once the initial heterogeneities are damped.

### *Remelting of a compensated electrode*

Using a compensated electrode, the general trends observed in the previous case are reversed (see figure 3.b). In the upper part, the oxygen content is higher on the center line than outside. The presence of the final liquid pool can still be observed and corresponds once more to a sharp decrease in the oxygen content. The profile presents a maximum, corresponding to the local boundary of the final liquid pool and the oxygen enrichment of the electrode. In the lower part of the ingot, the oxygen content is slightly lower on the center line as outside. Segregation intensity remains more important on top than at the ingot bottom. As a result of the compensation, radial segregations are reduced by one third.

## CONCLUSIONS

The simulation of the solute behavior in a triple VAR processing route enables us to understand the phenomena occurring in solute redistribution. When remelting an homogeneous electrode, zone refining results in a disymetric bell shaped oxygen content distribution along the ingot length. The liquid pool curvature generates radial segregations. Their sense reverses between the bottom driven by the second melt and the top driven by the third melt. Their intensity increases from bottom to top, as do the liquid pool curvature. When considering an industrial compacted electrode, it is seen that the oxygen content oscillations issued from the localisation of the oxygen in the compacts of the electrode are totally damped after only two melts. Finally, an optimised practice of the alloying elements compensation technique in the initial electrode enables to reduce longitudinal segregation by a factor 2 and radial segregation by 30% in the final ingot. This tends to prove that everything made to reduce longitudinal segregations will contribute to reduce radial segregations.

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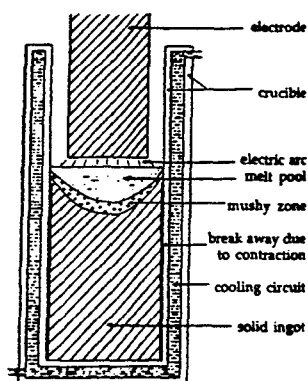


Figure 1: Schematic representation of the VAR process

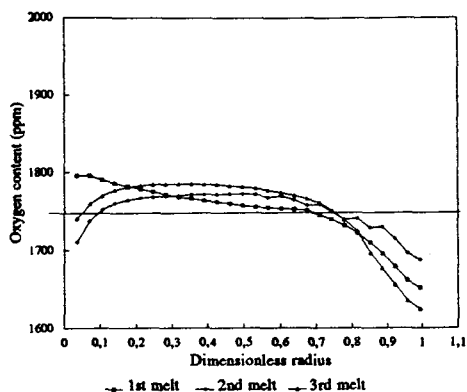


Figure 2.a: Homogeneous electrode

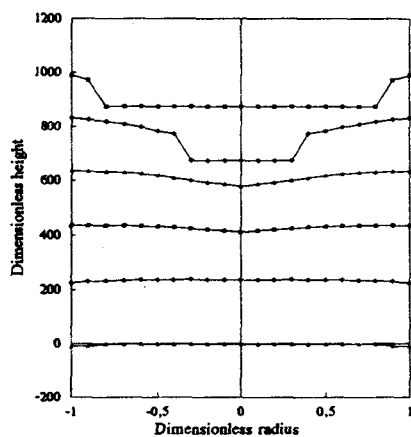


Figure 3.A: Homogeneous electrode

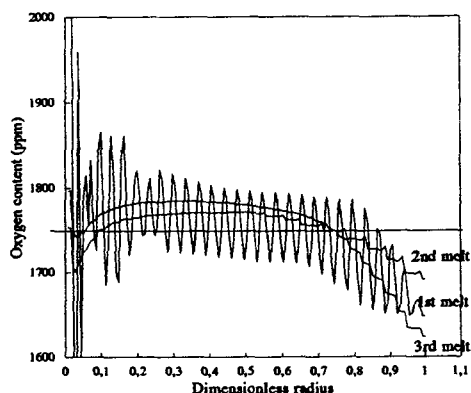


Figure 2.b: Compacted electrode

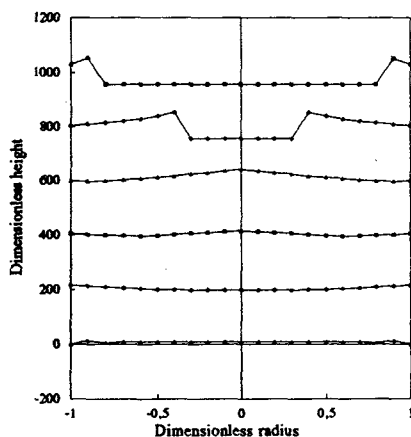


Figure 3.b: Compensated electrode

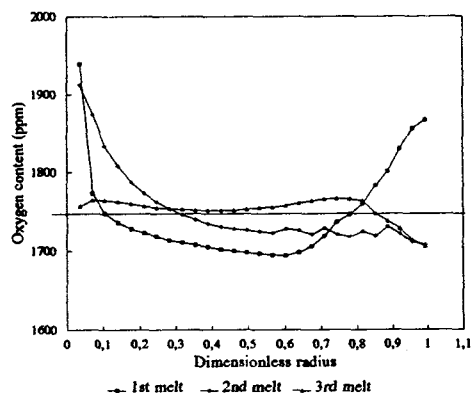


Figure 2.c: Compensated electrode

Figure 3: Map of the oxygen content in the final ingot for different electrodes

Figure 2: Evolution of the oxygen content during triple remelting of different initial electrodes