

On the Origin of the White Spot Defect in Vacuum Arc Remelted Ingots

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INTRODUCTION

Author's aim – another attempt to wipe blank spots (in Russian we say: “white spots”) from the map, which name is:

“The problem of white spot”



White spot – several facts to explain:

- **Nb content in white spots is less than in the base metal, in Alloy 718 it varies from 2.5 to 5.0 percent;**
- **unusually low Nb (<1%) was revealed in white spots in VAR ingot of Alloy 718 melted at a very long arc gap (X. Wang et. al);**



White spot – several facts to explain:

- **“in many cases discrete white spots have a concentration gradient of Nb between the surface and center with increased Nb in the center”**

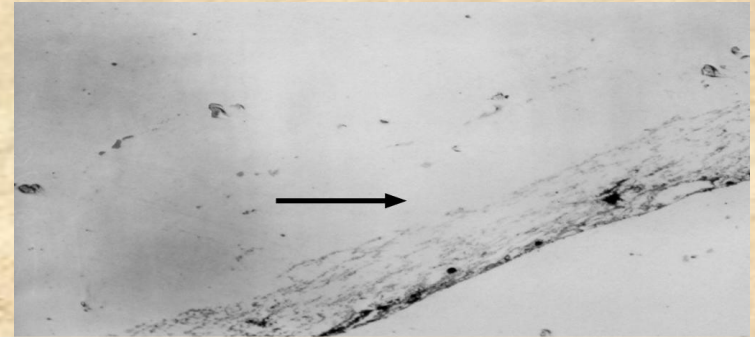
(F. Zanner et. al);

- **no dirty white spots are present in the ESR ingots of Alloy 718 – it is a privilege of VAR-process.**



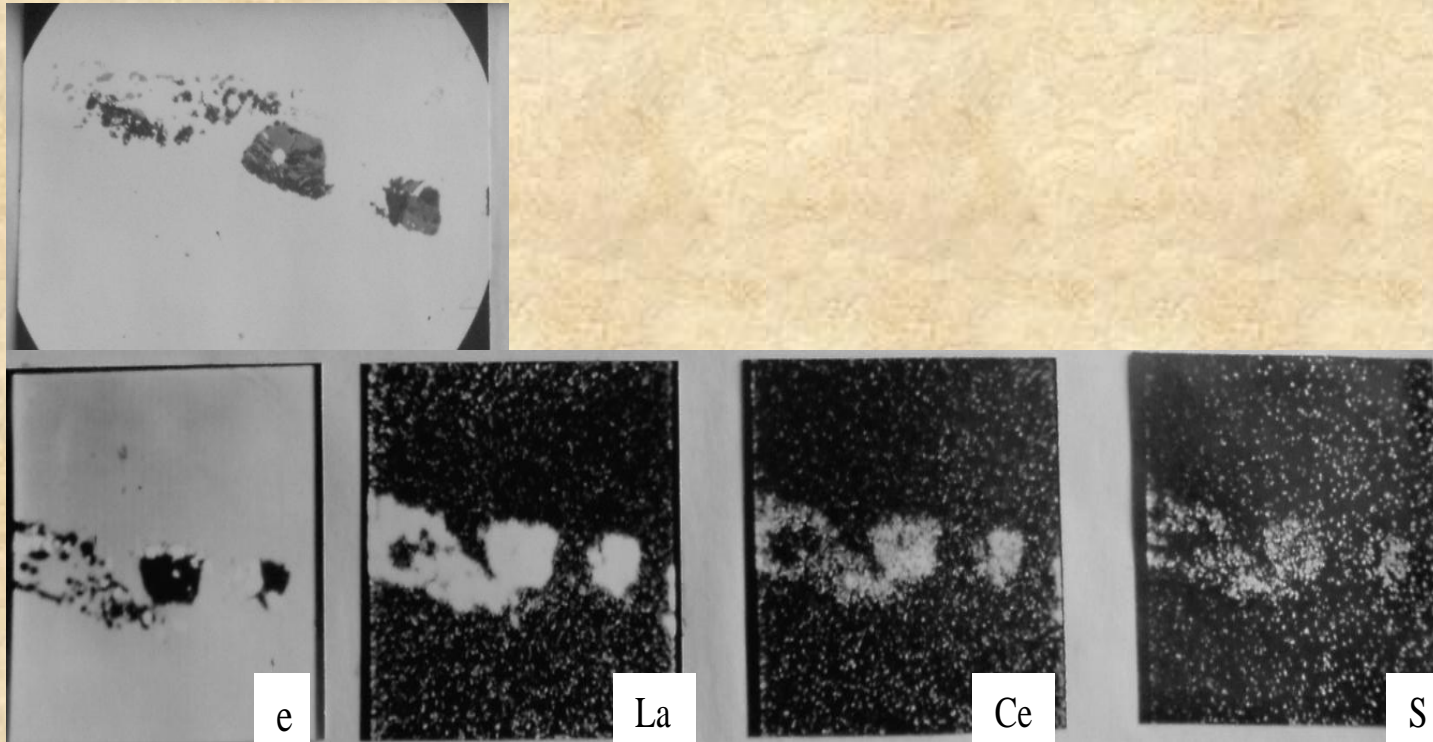
Nonmetallic inclusions fringing the non-etching zone of the white spot

White spots (WS) are often accompanied by strings of inclusions. It was observed that strings are situated mostly at the bottom side of non-etching zone.



Arrow indicates to the non-etching zone

Inclusions composition in the WS-area (RE sulfides and oxysulfides)



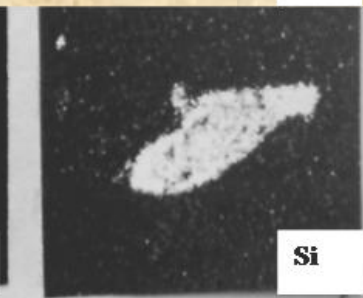
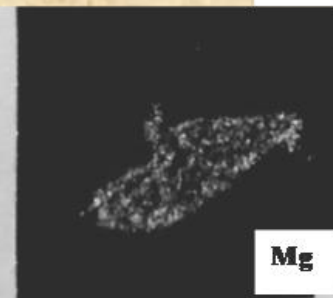
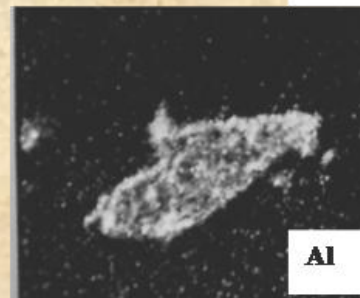
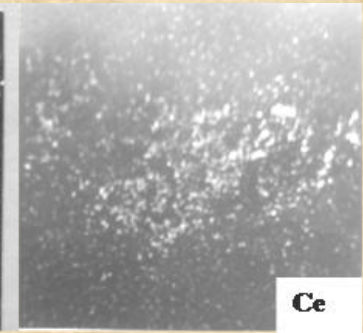
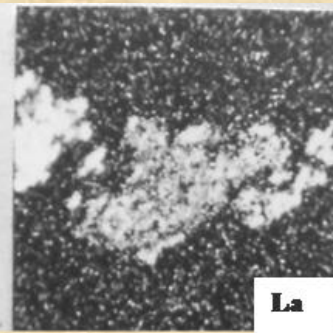
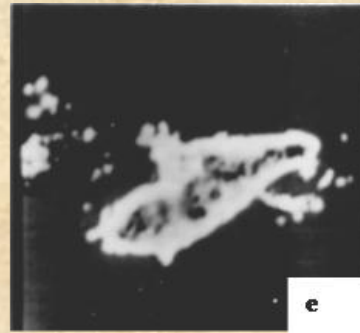
An origin of inclusions in the WS-area

These inclusions originate from slag entrapped to electrode. Slag consists of oxides of Si, Mg, Al, Ce, La and sulfides of Ce and La.

Composition of slag is shown at the next slide.



Slag from electrode



Transformation of slag on the pool surface

During remelt slag is separated to the bath surface and gradually loses Si, Mg and even Al by the following reactions of reduction:

- $3\text{SiO}_2 + 2(\text{Ce,La}) = 2(\text{Ce,La})_2\text{O}_3 + 3\text{Si}$
- $\text{Al}_2\text{O}_3 + (\text{Ce,La}) = (\text{Ce,La})_2\text{O}_3 + 2\text{Al}$
- $3\text{MgO} + 2(\text{Ce,La}) = (\text{Ce,La})_2\text{O}_3 + 3\text{Mg}$



Probable sources of WS

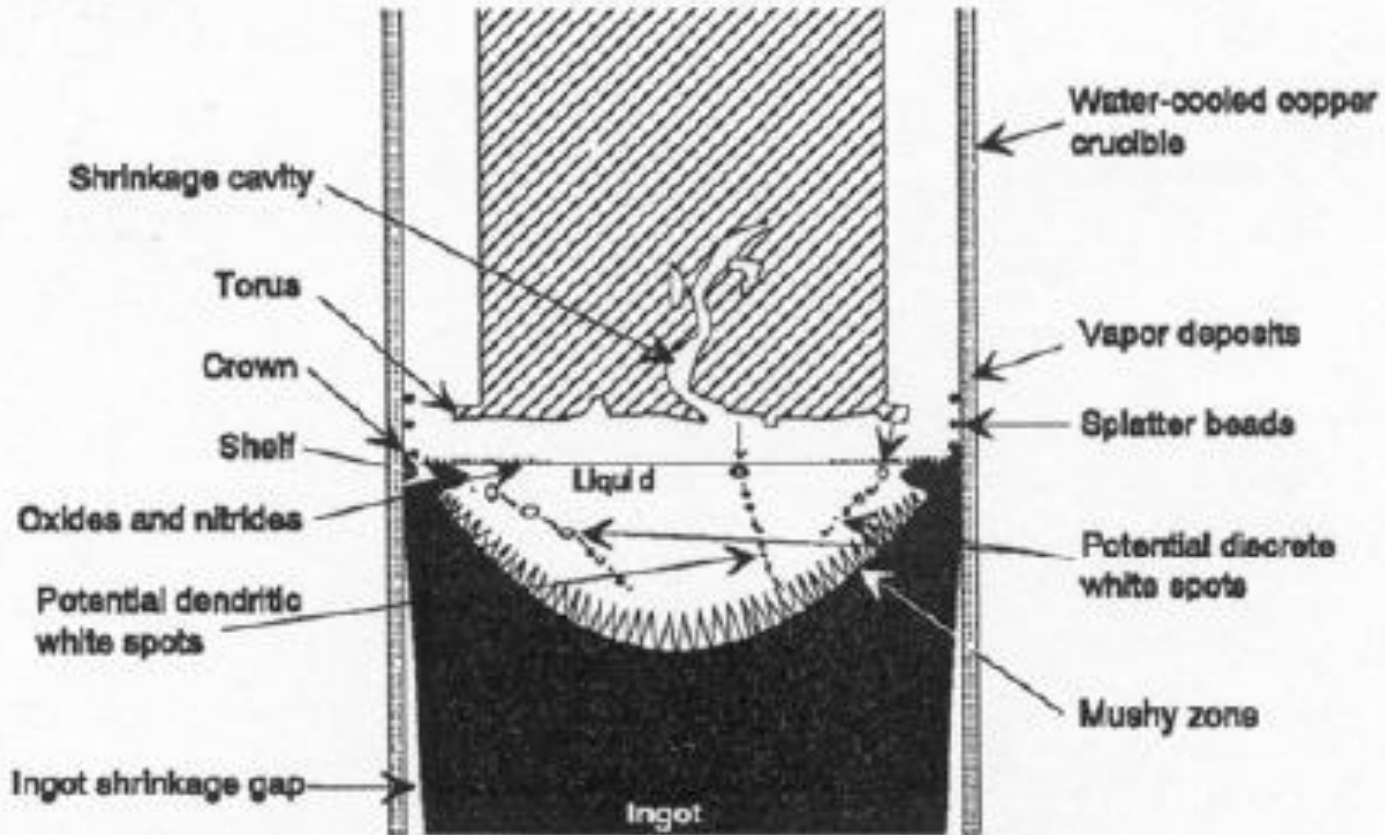
Several potential sources of WS are usually considered:

- **shelf at the edge of the molten pool under its surface;**
- **dendrites from the cavities of electrode;**
- **torus at the lower edge of electrode.**

However all these sources are not evident.

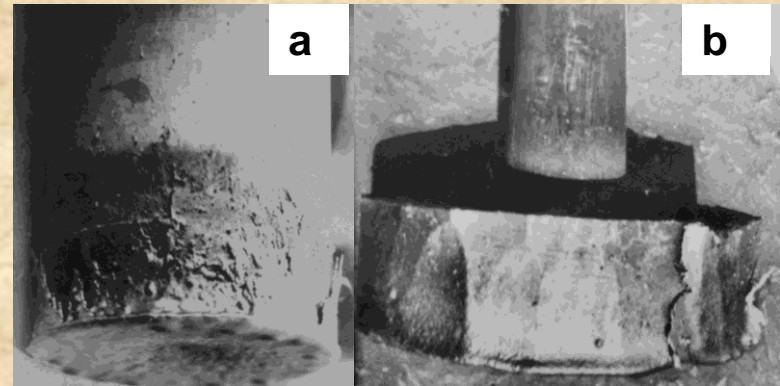


Probable sources of WS (L.A. Jackman et al.)



The most probable source of WS

- Watching the process of remelt, one may see occasional outbursts of the liquid metal from melting zone.
- As a result spatters appear at the side surface of electrode. Spatters and electrode composition is the same.



**Spatters appearance:
at the middle part (a)
and before the end
of remelt (b)**

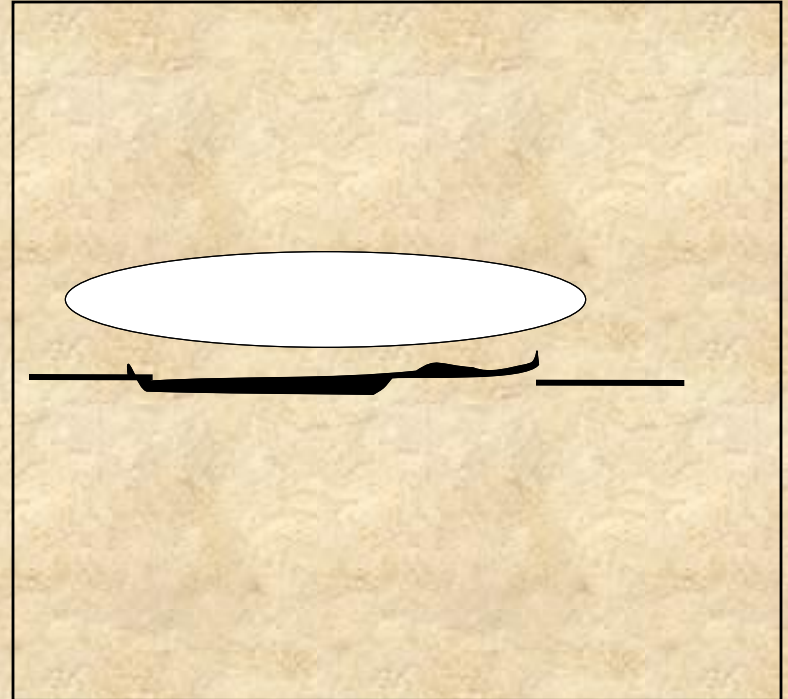
Fate of spatters

Sooner or later spatters are cut by the arc from the electrode and fall down to the pool. We have to explain in what way solid metal particles of a middle chemistry falling to the liquid pool «are losing» some part of Nb and carbon. Words «are losing» are quoted not accidentally: this decrease is likely the result of renewal of the outer layer of heterogeneous particles.



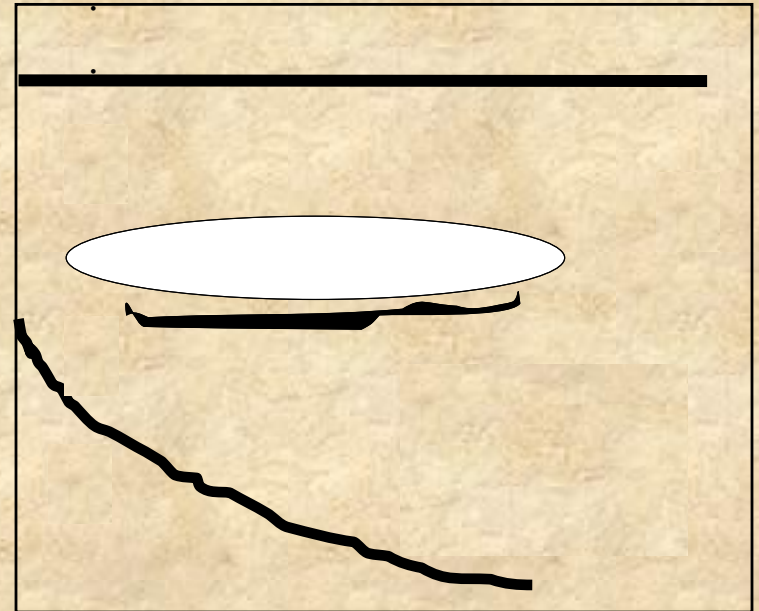
Fate of spatters – step 1

**Spatter is falling
to the pool surface
where it contacts the
floating slag particles.**



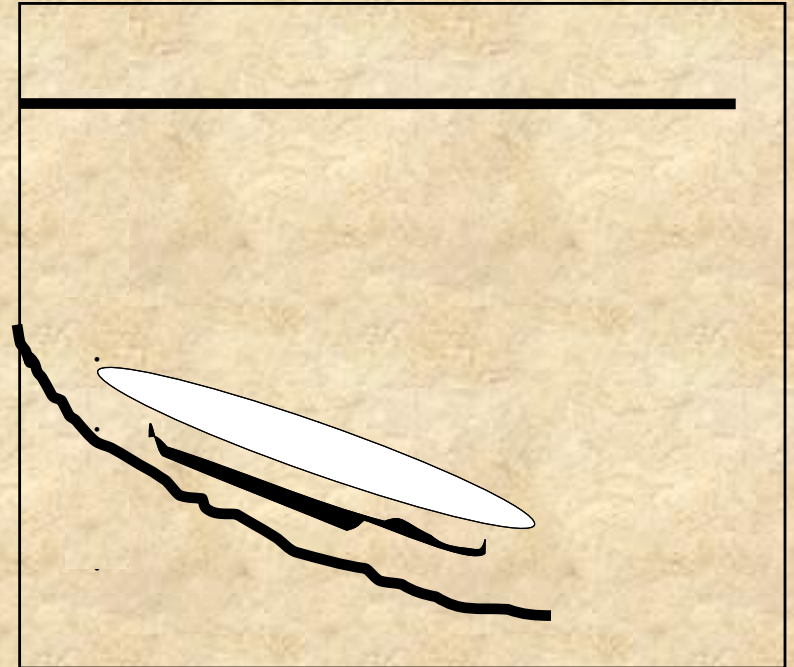
Fate of spatters – step 2

- Spatter with slag particles adhered is sinking from the pool surface to its deep layers.
- Temperature of spatter is high enough for its partial melting.



Fate of spatters – step 3

Near the mushy zone the rests of the particles remain for some time surrounded by the liquid metal at a liquidus point and acquire the same temperature.



Fate of spatters – step 3

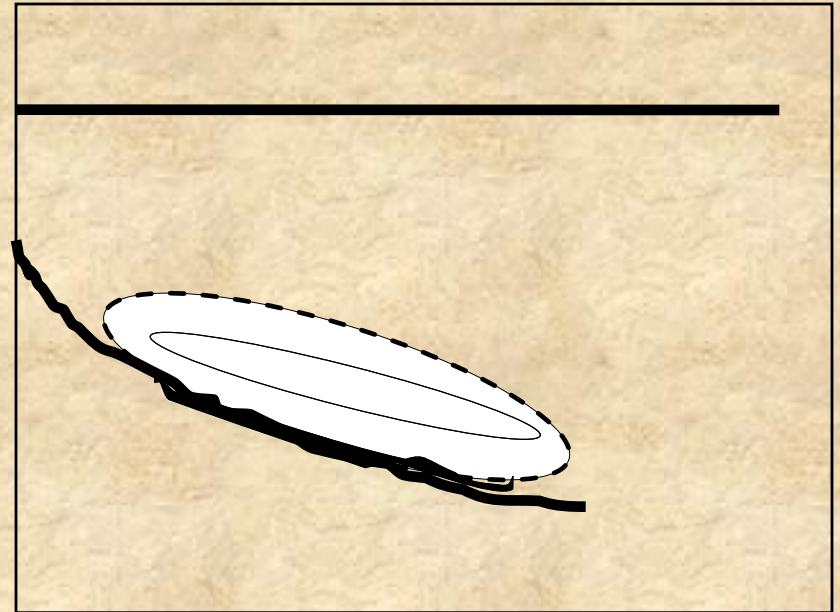
Somewhat of balance comes: the liquid phase has no excess of heat to melt the particle, and the solid phase is unable to withdraw latent solidification heat from surrounding liquid.

Equilibrium isothermal solidification is only possible in these conditions. Just like at any other solid and liquid interface, continuous process of atoms exchange is going.



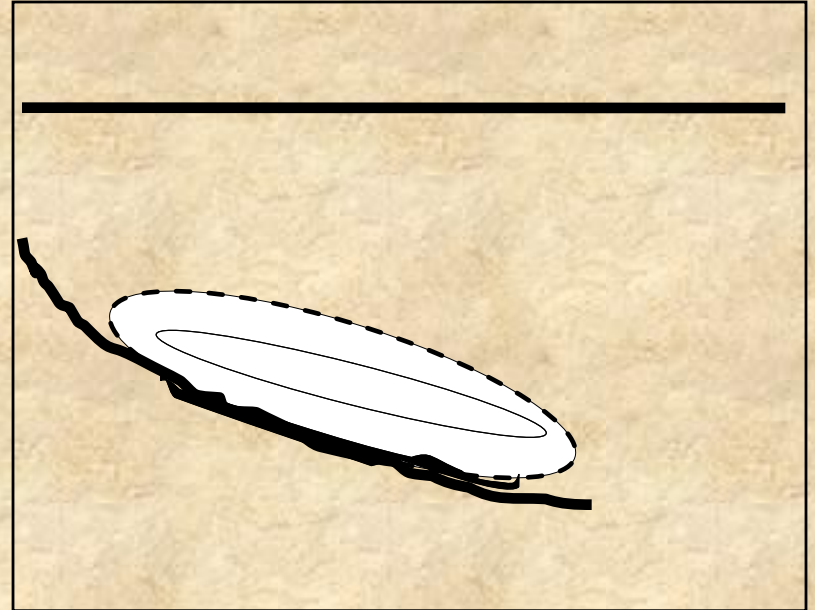
Fate of spatters – step 4

The result of such exchange is the growth of solid phase layer leaned by elements lowering the melting point and enrichment by the same elements of the liquid phase boundary layer.



Fate of spatters – step 4

This mechanism allows explaining appearance of Nb concentration gradient inside of the particle with increase to its center.



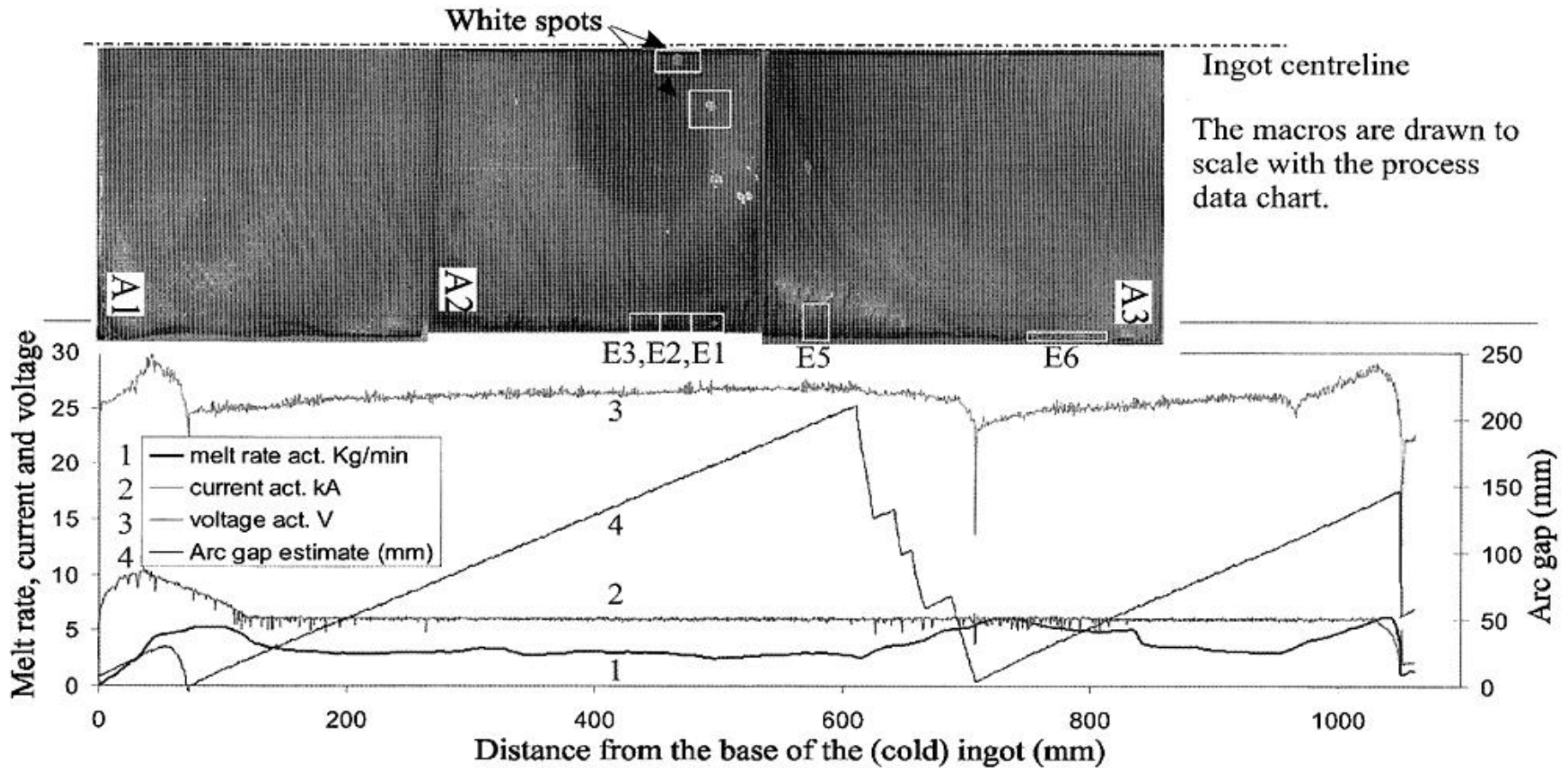
Long arc and white spot

Now let us consider a special case – “white spots” revealed by Dr. Wang and co-authors in the VAR ingot remelted at unusually long arc gap.

In this experiment the gap elongated gradually as a result of occasional electrode stoppage. In several hours the movement of electrode resumed and the gap rapidly diminished. Authors have illustrated all this by the picture shown at the next slide.



VAR process data and ingot macrostructure (X. Wang et. al)



Some comments to white spots in the “long gap ingot”

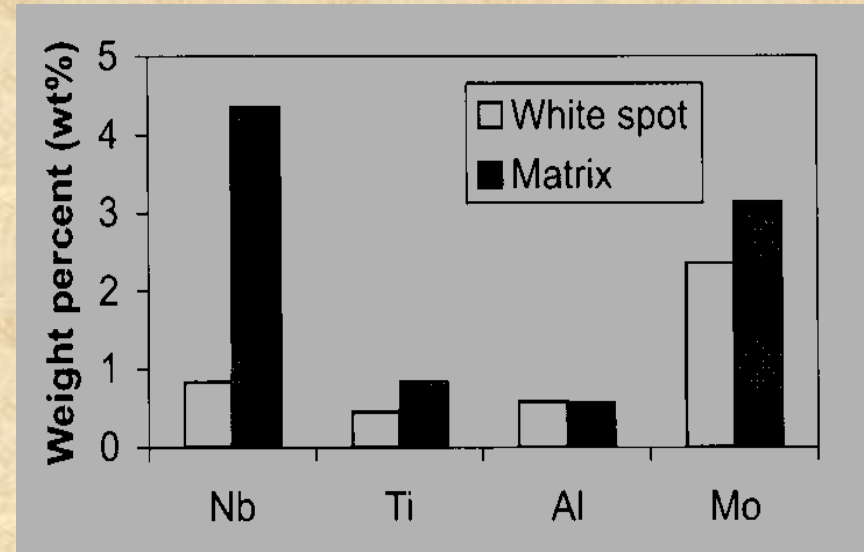
- **All defects revealed are situated at one the same area near the level corresponding to the maximum arc gap.**
- **Moreover, their position coincides with the bottom part of the liquid pool at the moment when the gap reached its maximum and began rapidly diminish.**
- **Neither before this moment nor after it no white spots had appeared.**



Comparison of WS and matrix composition (X. Wang et. al)

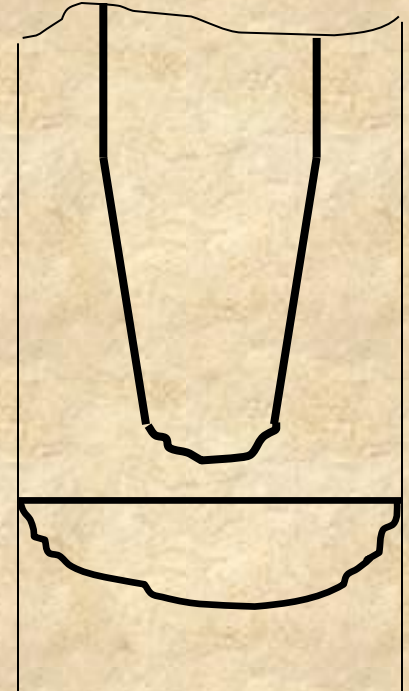
An important peculiarity of the “long gap WS” is unusually low Nb (<1%).

The reason will be discussed at several next slides.



Form of unmovable electrode

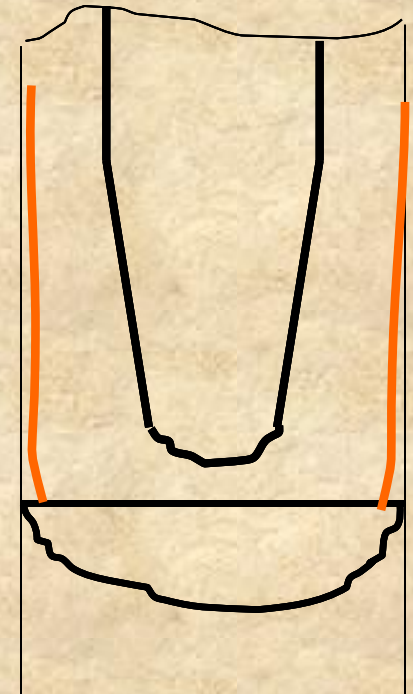
- During remelt of unmovable electrode its form is changed from cylinder to cone.
- Calculation made at mold dia. 500 mm and electrode dia. 430 mm (at melt rate 3 kg/min) gives the approximate values:
arc gap – 100...50 mm.
height of conical part –260...380 mm;
- Approx. 15...20 % of melting occurs at the electrode side surface.



Form of electrode and crown behavior

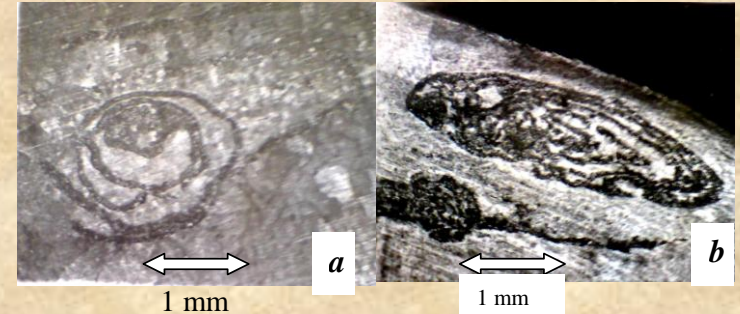
Conical form of electrode influences the height and the thickness of crown:

- **crown is very thin (<1 mm) and high;**
- **it is prone to curling at the change of heating conditions;**
- **one of the reasons for such change is abrupt diminishing of the arc gap.**



Crown defect (spiral) in VAR ingot

- Curling of the crown leads to its heating and falling of some fragments to the pool;
- Due to their form defects revealed in ingots were named “spiral” and due to their origin – “crown”;
- Defect usually is not accompanied by metal discontinuity. It is fixed due to strings of nonmetallic inclusions.



“Crown” defect in the Ni-base superalloy

Nonmetallic inclusions in defect spiral

Inclusions in defect “spiral” and in the crown are titanium nitrides. Laminated pattern of inclusions is typical for particles condensed from vapor.



Additional comments to white spots in the “long gap ingot”

- **Location of defects in the ingot hints that they are formed in period of rapid diminishing of the arc gap. So it is quite probable that we are dealing here not with the WS but with the “crown” defect.**
- **Vapor origin of defects is also strongly confirmed by extra low Nb content along with reduced Ti and Mo in defect area.**
- **As it may be seen from the next table these three elements have the highest boiling points in the row of metals – components of Alloy 718.**



Comparison of boiling points of several metals

Element	Mn	Cr	Fe	Ni	Ti	Mo	Nb
Boiling point, °C	2061	2672	2861	2913	3287	4612	4742



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Conclusions-1

- **Spatters on the side surface of an electrode, which arise episodically as a result of gases outburst from the cast electrode cavities, are considered as the most probable source of the white spot defect.**
- **The particles of spatters, when falling to the liquid pool, entrain slag film from the pool surface to its deep layers.**



Conclusions-2

- **There is evident conformity of composition between inclusions in the white spot area and slag in the electrode.**
- **Short gap, rather than medium or even long one, promotes spatters formation, preventing free outlet of gases from under the electrode. This in turn leads to white spot occurrence.**



Conclusions-3

Partial loss of Nb in the WS against its middle content in Alloy 718 may be explained by a process including isothermal diffusion controlled solidification with forming of Nb-lean layer.



Conclusions-4

- **Defects in the VAR ingot of Alloy 718, melted at extremely long gap, are probably not the white spots, but of a crown type.**
- **Thin and high crown formed at a long gap mainly by vaporization of metal contains little Nb – element with very high boiling point. It explains extra low Nb concentration in defects area.**



Conclusions-5

Additional argument for crown origin of “long gap” defects is the fact that all of them are situated in one and the same part of the ingot, solidified during arc shortening, just at the beginning of this process. Rapid change of the gap alters abruptly conditions of the crown heating, and it leads to the buckling of the thin crown and to falling of its particles into the pool.



Thank You!



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