#25-071
2025 AFS Proceedings ©American Foundry Society

Avoiding Defects Appearing During Shutdown Phase in Vacuum Arc Remelting Using Process Modeling

Ole Koeser
Calcom ESI SA, Lausanne, Switzerland

Vahid Rastegar
Materion Corporation, Newton, Massachusetts, USA

Swapnil Salokhe
ESI NA, Farmington Hills, Michigan, USA

ABSTRACT

This article addresses production challenges faced by Materion, a specialist in niobium alloys for aerospace, defense, and semiconductor applications, due to large shrinkage cavities in vacuum arc remelted ingots. Despite efforts to minimize these defects, they continued to affect productivity. To investigate the root causes, a modeling approach using ProCAST casting simulation software was employed to simulate the vacuum arc remelting process. The study identified excessive heat loss during the shutdown phase as a primary factor contributing to defects. By adjusting the duration of this phase, the simulation showed a significant reduction in shrinkage-related voids, leading to defect-free ingots. This work highlights the critical role of process modeling in optimizing production efficiency and quality in high-performance materials manufacturing.

Keywords: vacuum arc remelting, niobium alloys, shrinkage cavities, production efficiency, process modeling, defect mitigation, shutdown phase, semiconductors, casting simulation software

INTRODUCTION

A leading producer of specialty materials uses the vacuum arc remelting process to manufacture high-quality ingots of niobium alloys for aerospace, defense, and semiconductor applications. Under specific ingot geometries and process parameters large shrinkage cavities at the top of the produced ingots were observed which are impacting the productivity of the process (Figure 1). Despite diligent efforts, minimizing or eliminating these defects has been difficult, posing an obstacle to production efficiency.

To address the production issue, it was decided to use finite element process modeling to simulate the principal aspects of the specific volume arc remelting process to identify the potential root causes of the defect creation and, subsequently, identify viable solutions for mitigation.

This paper presents the modeling approach that enabled the identification of the root causes of the observed defects and identified the critical process parameters that were the origin of the issue. Figure 1 provides a visual representation of the observed shrinkage cavities. The diameter of the ingots was 26 cm. The defects had a size of multiple cm and appeared at the top section of the ingot around 5-10 cm away from the ingot top surface.

Furthermore, by adapting the process conditions it was possible to remove the current obstacles in the vacuum arc remelting and to deliver a defect-free product.

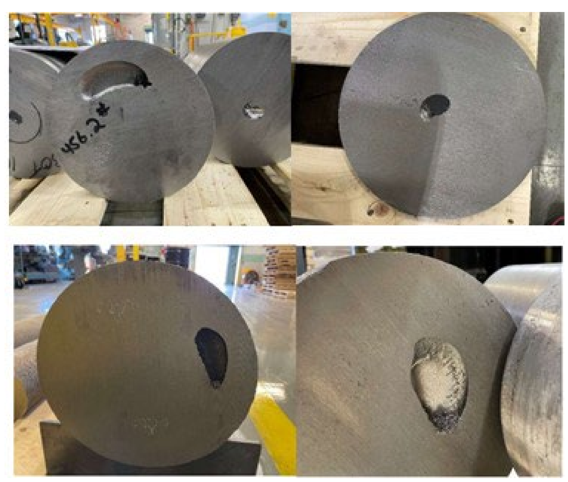

Figure 1. Visual representation of the shrinkage cavities found in the ingots. (Artwork courtesy of Materion.)

VACUUM ARC REMELTING PROCESS–SPECIFIC PROCESS PARAMETERS

The principal arrangement of the vacuum arc remelting process and its components is depicted in Figure 2. At its core, the process involves the controlled interaction between the consumable electrode and the ingot below, regulated by a voltage. This voltage initiates an electric arc, melting the material at the base of the electrode, which then forms liquid metal droplets that coalesce into a molten pool. During solidification, the metal undergoes purification, ultimately forming an ingot.

The process is governed by electrical parameters defining arc properties and melt rate, as well as cooling through the copper mold.

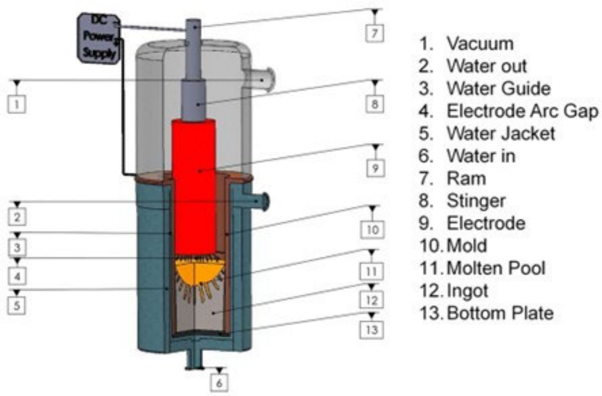

Figure 2. The principal geometry and setup of the vacuum arc remelting process.[1]

BASIC MODEL SETUP

The model setup used the geometrical representation of the process is indicated in Figure 3. The geometry consists of the copper mold, the ingot and the gap between electrode and ingot. On the right side of Figure 3 the finite element mesh of the main part of the geometry is shown (tetrahedral elements). In the modeling, the surrounding vacuum volume is meshed (not shown here).

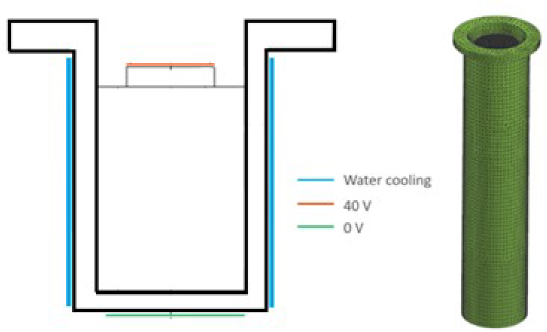

Figure 3. Left side shows geometry (drawing not to scale) used for the modeling case including ingot, Cu-mold and gap volume between electrode and ingot. The right side shows the FEM mesh representation mold. The locations of the main electrical (voltage) and thermal (water cooling) boundary conditions are also indicated.

Material properties: For the alloy material only very limited material data was available. For the study, the following properties (Table 1) were assumed:

Table 1. Material Properties for Nb Alloy

Thermal conductivity	38	W/mK
cp	0,3433	kJ/kg*K
Density	9000	Kg/m3
Tliq	2370	degrees C
Tsol	2330	degrees C
Magnetic permeability (vacuum)	1,257E-06	Henry/m
Electrical conductivity	3167000	S/m

The copper mold material properties are publicly available. For this reason, they are not indicated here.

Thermal boundary conditions:

- Interface condition ingot-mold: 500 W/m2*K
- Heat boundary condition mold surface:
  - 5000 W/m2*K, Text 15°C (locations–blue area Figure 3)

Electrical boundary conditions:

- Top of the gap area: 40 V
- Bottom of the mold: 0 V

(Locations refer to orange and green areas in Figure 3)

MODELING APPROACH AND RESULTS

The modeling approach divides the process into two process steps. In the first step, the stable thermal and electromagnetic situation during the ingot creation is simulated. In the second step, the switch-off phase is described together with defect prediction. Both models are performed in a chaining manner. For the second modeling of the switch-off phase, the temperature distribution from the first simulation is used as an initial condition.

THE PRINCIPAL RESULTS –
MAIN PROCESS STEP INGOT CREATION

Figure 4 shows the principal electromagnetic results from the main process step of the ingot building. The current distribution in the system ingot/mold is shown in Figure 4 -left side, middle. As the conductivity of the copper is much higher than the niobium alloy, the current tends to flow very soon in the direction of the copper material in the direction of the electrical zero potential. Figure 4-right side, shows the corresponding joule heat density distribution which is dominant in the area of the melt pool.

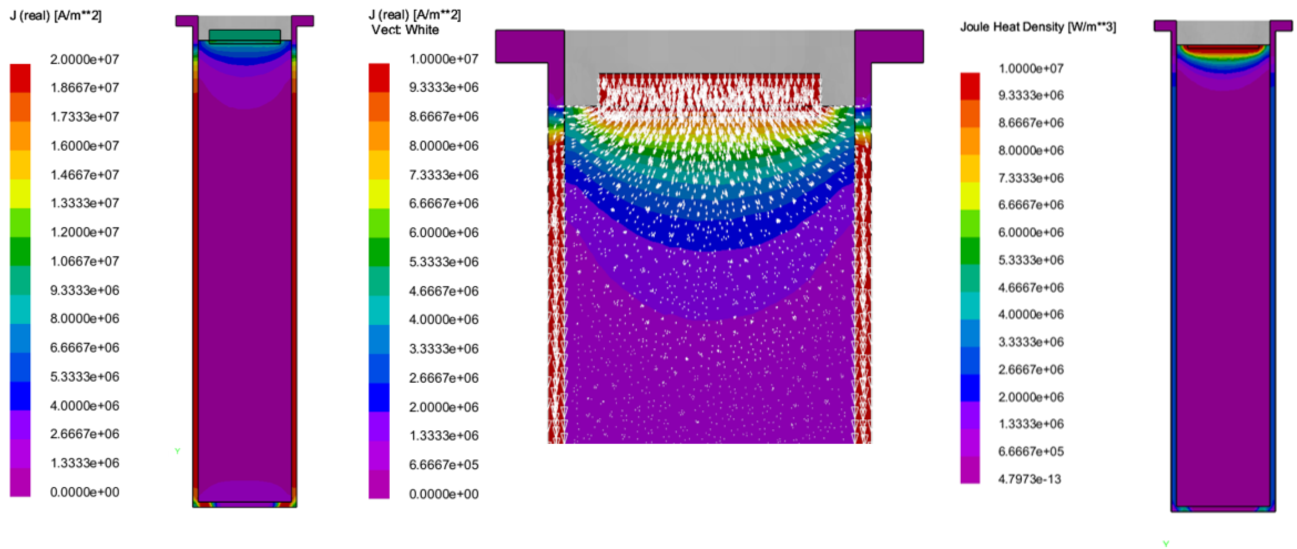

Figure 4. Electromagnetic modeling results in main process step ingot creation.

Figure 5 shows the main thermal results during the ingot creation. On the left side the temperature distribution is shown while the right side displays the corresponding fraction solid distribution. The principal shape of the weld pool is very visible.

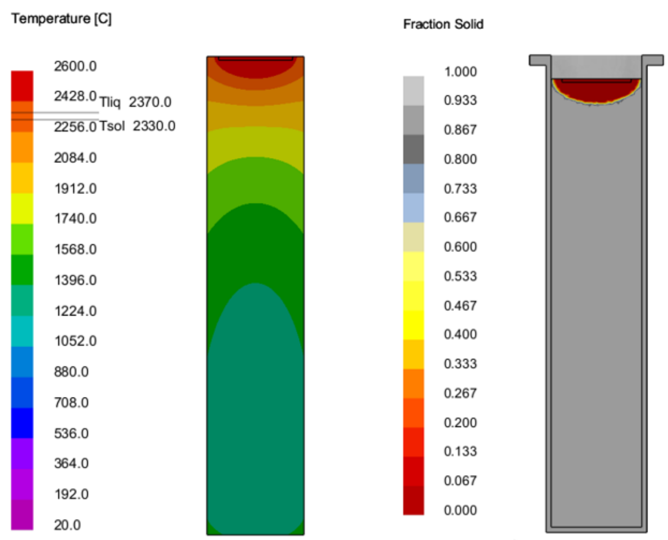

Figure 5. Thermal modeling results of main process step ingot creation. Left side temperature, right side fraction solid.

THE PRINCIPAL RESULTS IN THE MODELING – SHUTDOWN PHASE

Figure 6 shows the solidification pattern during the shutdown phase of the process at the end of the ingot building. The pattern is due to the strong heat loss at the surface of the ingot by radiation which is very dominant as the temperature of the liquid metal is very high. This leads to defect creation which is caused by alloy shrinkage (Figure 6-left side). The modeled defect is in line with the holes that are observed in production.

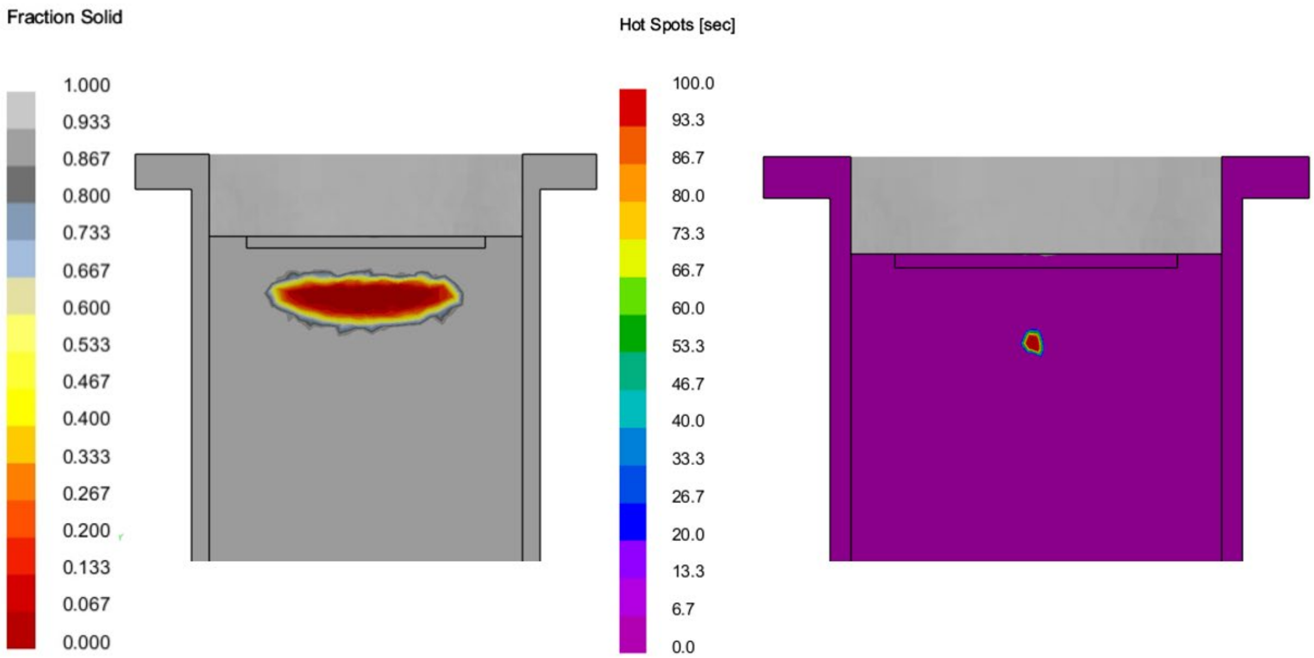

Figure 6. Solidification patterns and corresponding defect creation.

MODELING RESULTS – IMPROVED SHUTDOWN PHASE

In order to prevent the shrinkage defect the duration of the shutdown phase was increased by a factor of three. In this case, the last point of solidification can be observed at the top of the ingot. In this case, the creation of shrinkage related voids is eliminated from the production process.

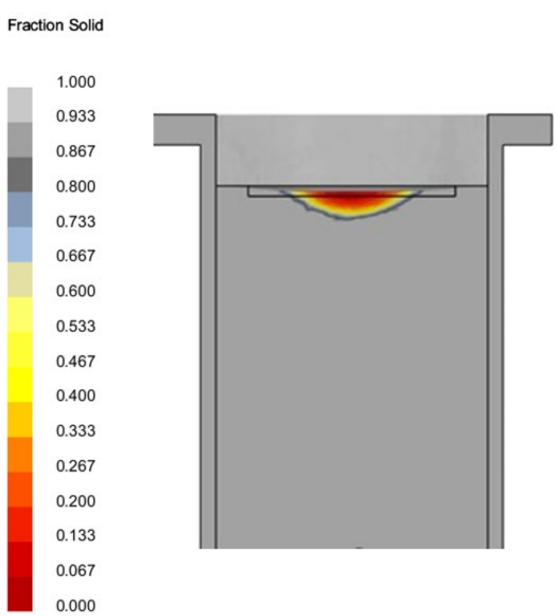

Figure 7. Solidification pattern with alternative switch off condition.

SUMMARY AND CONCLUSION

The presented modeling study successfully identified the root cause of large-hole defects observed in a vacuum arc remelting process, pinpointing excessive heat loss during the shutdown phase as a primary factor.

By adjusting the shutdown phase duration, the modeling results demonstrated the potential to eliminate shrinkage-related defects and produce defect-free ingots, thereby enhancing production efficiency and product quality. The findings underscore the importance of process modeling in optimizing vacuum arc remelting operations, enabling the mitigation of defects and delivering high-quality niobium alloys for critical applications in aerospace, defense, and semiconductor industries.

REFERENCE

1. Karimi-Sibaki, E., Kharicha, A., Wu, M. et al., "A Parametric Study of the Vacuum Arc Remelting (VAR) Process: Effects of Arc Radius, Side-Arcing, and Gas Cooling," *Metall Mater Trans B,* 51, 222–235 (2020).