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# Optimization of electromagnetic energy in cold crucible used for directional solidification of TiAl alloy

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ABSTRACT

Directionally solidified TiAl alloys are one of the most potential candidate for turbine blade in advanced aircraft engines. Electromagnetic (EM) cold crucible directional solidification (CCDS) is a novel technique for preparing large-size TiAl ingot without chemical contamination. In order to improve EM utilization, first the utilization of EM energy in CCDS was evaluated. Then based on the numerical calculation, the absorption power in TiAl alloy that induced by EM energy and the uniformity of EM field were studied, which contributes to the configuration design. Results indicated that the energy utilization in CCDS is improved by optimizing crucible configuration, the start-up power per square mm significantly decreases from 1250 to 500 W/mm$^2$. Finally, a square cold crucible with the section 36 mm × 36 mm was fabricated via a configuration optimization and employed to directionally solidifying TiAl alloy. Both the surface quality and the microstructure were controlled in the processing window, suggesting that the optimization utilization of EM energy in CCDS has been achieved. The results can provide semi-quantitative and experimental guidelines on the crucible design and the microstructure control of TiAl alloys from the perspective of EM energy.



## 1. Introduction

To improve fuel efficiency and save energy, the application of light-weight materials and advanced fuel are highly urgent in aerospace industry [1,2]. Directionally solidified TiAl intermetallics have been expected as the most promising candidate for turbine blade in the next generation aircraft engine due to their low density and attractive properties at evaluated temperatures [3,4].

In modern industries, electromagnetic (EM) energy play an important role in heating, power generation and materials preparation [5–7]. For example, many reactive and refractory materials are widely prepared using EM cold crucible [8]. In recent years, a novel bottomless cold crucible has been developed to continuous melting and directional solidifying TiAl alloys, which attracts close attentions [9,10]. It is acknowledged that the utilization of EM energy is the key issue in cold crucible directional solidification (CCDS). The design of crucible configuration is actually based on how to utilize the EM energy more effectively. Umbrasko et al. found that the power utilization can be heightened by increasing crucible height/diameter (H/D) ratio [11]. The application of an additional DC field can largely reduce heat loss [12].

The EM energy in CCDS not only influence the thermal process but also the shaping and the microstructure [13]. It transfers into the thermal energy in charge and affects the shape of solidification interface and the grain growth by changing the temperature and flow field [14,15]. Again, the multi-physical fields in cold crucible induced by EM energy would influence each other [16,17].

Therefore, from the perspective of EM energy, how to design an optimal configuration of cold crucible is the key for heightening the EM utilization and successfully controlling the microstructure of TiAl alloys. In the current paper, the utilization of EM energy in cold crucible applied to directional solidification were systematically investigated. First, the physical fundamentals and the role of EM energy in CCDS were analyzed and discussed. Then a numerical model was established to investigate the absorption power in skin layer that induced by EM energy and the uniformity of EM field in cold crucible. Further, the development of crucible configuration

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and the optimization guidelines were proposed. Last, the DS-TiAl ingots were successfully prepared using an optimized cold crucible.

## 2. Physical fundamentals of cold crucible melting and solidification

### 2.1. Physical fundamental and processing principle

The working principle of a conventional CCIM is presented in Fig. 1(a). The starting materials are staked in the copper crucible in induction heating. In contrast, both the feeding and the pulling are required for CCDS, as illustrated in Fig. 1(b). The continuous melting and directional solidification can be achieved by feeding the raw rod and pulling the solidified ingot simultaneously, which was carefully described in Ref. [13].

Materials in cold crucible would be induction-heated under the action of EM energy. The charge temperature gradually increases and an amount of melt appears at final. Then a solid skull forms due to the chilling of water-cooled wall. The current frequency ($f$) in heating process is a key parameter and the critical frequency ($f$) should be not less than $3 \times 10^6\ \rho/d^2$ [18]. $\rho$ and $d$ is the resistivity and the diameter of heated cylinder respectively. Actually, $f$ is generally lower than 10 MHz. In melting process, massive thermal energy induced by EM energy gradually generates in the skin layer. A portion of thermal energy is taken away by water-cooled wall, and the left portion is absorbed in charge. It was proposed that a proper power factor (cos $\varphi$) should be adopted for the induction melting [18]:

$$\cos\phi = P_m(m)/\eta \cdot P_i \tag{1}$$

$$m = d\Big/\sqrt{2}\delta \tag{2}$$

where, $P_m$ is the released power in melt, which is a function depending on the $m$, as expressed in (2). $P_i$ is the power in the induction coil, $\eta$ is a constant and $\delta$ is the skin depth. The $P_m$ can be significantly increased once the melt height is close to the coil height and the value of $m$ is within the range of 2–7.

### 2.2. Distribution characteristics of EM field

The distribution of EM field is mainly influenced by the power parameters and the crucible configuration [19,20]. The right part in Fig. 2 shows the typical distribution characteristic of EM field in a near rectangular cold crucible. In general, the magnetic field is strong at the middle height of induction coil where the effective zone for induction heating. With the keeping away from the middle of coil, EM field gradually decreases and shapely weaken once outside the coil region. At a same height, the magnetic flux density ($B$) near the corner of in cold crucible is much stronger due to the proximity effect. Also, the slit plays a role in gathering EM energy, which causes a strong magnetic field around the silt region in cold

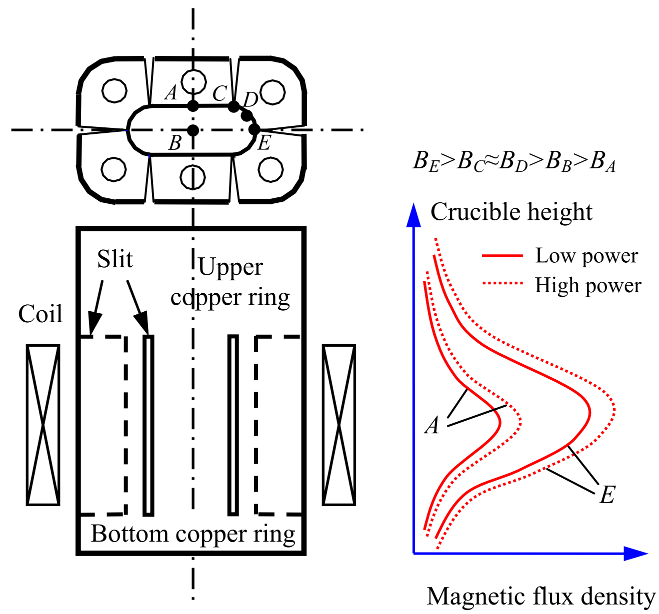


**Fig. 2.** Distribution characteristics of magnetic field in a near rectangular cold crucible.

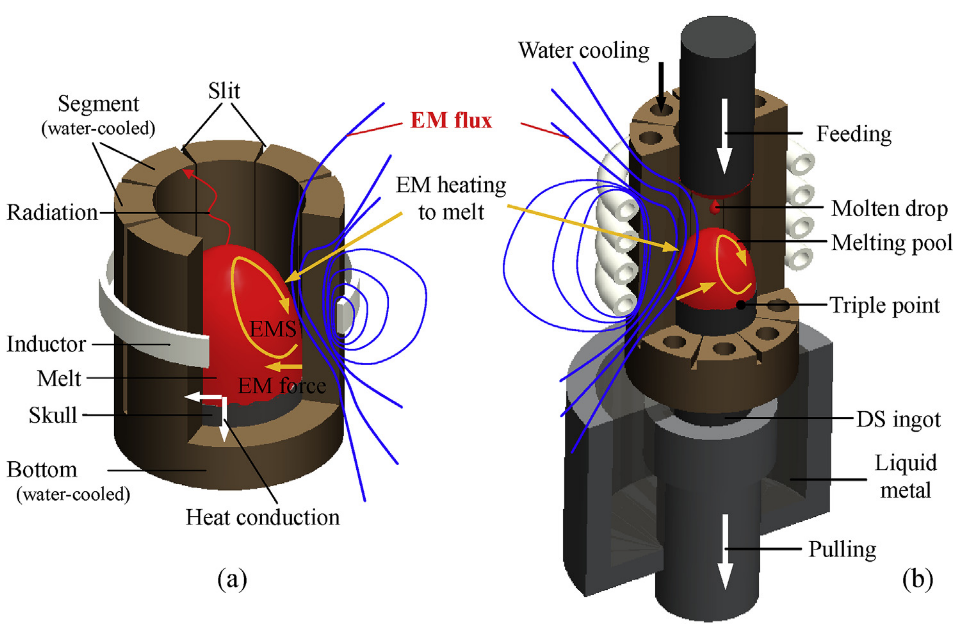


**Fig. 1.** Effect of EM energy on the cold crucible metallurgy: (a) a conventional CCIM with the water-cooled bottom type, (b) a novel bottomless type cold crucible used to continuous melting and directional solidification.