Currently electromagnetic fields are applied to the forming and processing of materials in the following aspects: highly purifying materials, changing structures, improving mechanical properties, improving precision of forming, reducing (possibly eliminating) contamination, and shortening the technological processes [1, 2]. In these applications, induction melting and electromagnetic stirring are successfully used. Because the electromagnetic field induces an electromagnetic force on the melt, the liquid metal in the cold crucible (either in a mold or not) is constrained to some shape during continuous forming and solidification. This is called electromagnetic constraint forming technique [3].

Titanium alloys can be contaminated and suffer from ingredient segregation, microstructure coarsening, poor mechanical properties, and poor performance because of its high melting point, high chemical activities and high alloying element content in melting and casting [4]. Cold crucible induction melting provides an efficient way of melting titanium alloys and preparing high performance materials. However, there are some problems that need to be resolved in controlling the forming and properties. Vives [6] applied the copper cold crucible with slits in an alternating magnetic field to continuous casting. In China electromagnetic continuous casting of aluminum alloys and steel showed that the ingots have perfect surfaces and refined grains [7, 8]. Continuous casting of multicrystalline silicon and titanium alloys were reported in France and Japan respectively [9, 10]. Cold crucible electromagnetic casting is affected by the electromagnetic field, temperature field, flow field and other factors; especially strong cooling of the crucible inner wall. As cold crucible electromagnetic casting and directional solidification are different to other techniques, we studied the effect of technical parameters and the formation of hot cracks in this paper.

1 Experimental apparatus and method

1.1 Experimental apparatus

The experimental apparatus is a multi-functional continuous casting and directional solidification apparatus with a cold crucible, schematically shown in Fig. 1 (a). It includes a melting system, movement system, controlling system, cooling system, and vacuum system. The melting system includes a cold crucible (with 8 vertical slits) and a water cooled induction coil (supplied with a 50 kHz frequency current from a transistor generator) surrounding the crucible as shown in Fig. 1 (b). This is the key part of the apparatus for induction melting and electromagnetic constraint. In order for titanium alloys to not be contaminated and oxidized, the vacuum system can be evacuated and filled with argon gas many times. A temperature gradient for directional solidification is established by strong cooling from low melting point liquid metal in the bottom.

The raw materials used in this experiment are Ti6Al4V alloys. The apparatus includes both a mechanical withdrawal system and a mechanical feeder that can each be controlled at different velocities, allowing continuous melting and forming to be realized using the power supply.

1.2 Experimental method

The quality of a newly formed ingot is decided by technical parameters, which include power supply, coil turns, coil position, pedestal position, withdrawal velocity, and cooling intensity. Two
groups of experiments were designed. The first was to study the effects of key technical parameters (withdrawal velocity, power, coil turns, pedestal height in the coil) on surface quality. The second was to investigate the effects of the liquid metal for cooling and the coat on the crucible inner wall on surface quality using the optimized parameters condition obtained from the first group of experiments. The power frequency is 50 kHz. Power is gradually transmitted to the charge until it reaches a given value, the supply of raw materials and the continuous withdrawal of the ingot can be started 5 minutes later, when a liquid metal dome with a suitable shape has formed in the argon atmosphere. The newly formed ingots all have a length of about 120 mm.

2 Surface qualities of the ingots

2.1 Effect of technical parameters

Different titanium ingots with 30 mm diameter were prepared under the above mentioned conditions, and are shown in Fig. 2. These ingots were very different in surface quality; some are crack free, while some have many cracks homogeneously distributed. It was found that the power was the most important factor affecting the formation of cracks.

2.2 Effect of cooling conditions

In order to research the effects of the cooling liquid metal and the heat holding of the coat on the surface quality, four ingots were cast under the conditions of having, or not having, cooling liquid metal and coat with the optimized parameters, as show in Fig. 3. It was seen that the ingots with perfect surface quality (smooth and crack free) were cast with coat. Crack free ingots were cast under liquid metal cooling condition, but some little creases appear on the surface.

Fig. 2  Surface quality of ingots cast under different parameters

(a) 5/50/4/4 (b) 3/50/3/2 (c) 3/55/4/3 (d) 3/60/5/4 (e) 5/55/5/2
withdrawal velocity, mm.min⁻¹/power, kW/coil turns/pedestal height, cm

Fig. 3  Effect of cooling liquid metal and coat on surface quality

(a) 3/no/yes (b) 3/yes/no (c) 3/no/yes (d) 3/yes/yes
coil turns / cooling liquid metal / coat

3 Structure of ingots

Ingots obtained in the first group of experiments were sectioned and polished, and then etched using a solution of 5%HF-5%HNO₃-90%H₂O by volume, and their macrostructures are shown in Fig. 4. There are many differences between these ingots in their grain size and growth direction. The grains are like ears, long and flat. The internal quality of those ingots cast by cold crucible electromagnetic constraint forming is whole and dense, having no shrinkage cavity, dross inclusion, gas hole or other usual casting defects. This proves that this technique can improve the internal quality of castings. By examining the macrostructure, it appears that under equal velocity conditions, grain size is almost unchanged with increase of power. However, under equal power conditions, grain size decreases considerably, the growth direction deviates from the withdrawal direction, and the
continuity of grain growth decreases with increase of velocity. When withdrawn at a slower growth rate, the ingots have relatively large columnar structure which is parallel to the withdrawal direction (as Fig. 4a), and this indicates that this technique can be used for directional solidification.

4 Mechanism of macroscopic defect forming

The effects of technical parameters on surface quality were investigated and the results are: the number of coil turns is the most important, followed by power, withdrawal velocity, and the pedestal height.

In cold crucible directional solidification, because the ingot is round, there is only alloy inner blocking when solidification causes contraction. The main reason for crack forming is an external force. Cracks will appear when the friction between the crucible inner wall and the mushy zone of the forming ingot is bigger than the strength of the mushy zone. The friction is decided by the friction coefficient and pressure. In our study friction coefficient is constant, so the friction is dependent on the pressure. When other conditions are steady, current density in the coil and electromagnetic field intensity decrease with an increase in the number of coil turns. So electromagnetic pressure decreases and the pressure between the liquid metal and crucible inner wall increases, resulting in the friction increasing and more cracks forming. The effect of the power can be divided into two aspects: the first is that the height of the meniscus increases with an increase in the power, leading to the hydrostatic pressure increasing; the second is that the electromagnetic pressure increases with an increase in the power. These have opposite effects. From our experimental results the height of the meniscus is the main factor, because the increment in the hydrostatic pressure is much greater than that in electromagnetic pressure for the same increase in the power. The friction increases, and so do cracks. The withdrawal velocity and pedestal height both have less effects on the friction.

The effect of cooling liquid metal on crack formation is realized by an increase in the cooling velocity and cooling intensity. Both of these reduce the mushy zone’s volume and the contact area between the mushy zone and the crucible inner wall, so the friction decreases and cracks decrease. The coat has an important effect on cracks. The mushy zone volume and the friction coefficient will be greatly decreased when the inner wall is coated, so crack formation will be decreased as well. In addition, the coat will reduce the lateral heat transfer during solidification, which leads to more heat conduction in the axial direction that is necessary for directional solidification.

From the effects of technical parameters on macrostructures, it can be seen that withdrawal velocity is the most important factor, followed by the pedestal height, other parameters have little effects. Structure is decided by the solidification; the shape and size of grain mainly depend on solid-liquid interface which is decided by heat transfer.

Solid-liquid interfaces obtained by quick cooling of ingots cast under different conditions are shown in Fig. 5. They become more concave with increase in velocity. Because the thermal conductivity of Ti6Al4V is very low, the latent heat released during solidification cannot be conducted in the axial direction quickly enough. At the same time the liquid metal will be solidified from the side, so the liquid-solid interface is concave. At a lower velocity, there is enough time for heat to be conducted in the axial direction, so the heat distribution in the horizontal direction is almost even, and the liquid-solid interface is near to planar. The liquid-solid interface will be planar when the heat conducted in the axial direction is equal to the heat released from solidification. Restricted by the strong cooling of cold crucible inner wall (soft contact between liquid metal and inner wall) in cold crucible directional solidification, the magnitude and the distribution of heat energy is very important, so the balance of the power and the withdrawal velocity is necessary for directional solidification.

Through analysis above mentioned, the relationships among process parameters, flux, and cooling agent having influence on surface quality and microstructure were concluded, and then the optimum scheme was designed. Figure 6 is the titanium alloys ingot cast under some parameters with no crack and surface smooth.

5 Conclusions

Cold crucible electromagnetic constraint and directional solidification can realize the melting of titanium alloys, constraining the liquid metal by electromagnetic force, keeping soft contact between the liquid metal and crucible inner wall,
This technique is applied to titanium alloys melting without contamination, casting, structure control, etc., now, and will have wide prospective applications in the future.

References


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