Electron beam melting toward defects-free titanium alloys

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Abstract

Titanium alloys used for rotating parts of aeroplanes must meet the strict standards of quality, so that it is required to demonstrate that electron beam melting is capable of producing defects-free ingots. However, complete elimination by dissolution of low density inclusions (LDI) having high nitrogen content would be difficult, so that a new way of eliminating LDI was needed. Therefore, control of a state of the molten titanium flow with the aide of Marangoni flow induced by electron beam has been studied, and the effects on eliminating LDI have been verified.

1. Introduction

Since it was introduced in 1980s, electron beam cold hearth melting [1] has been used to produce not only commercially pure titanium products but also aerospace-quality products. Among of them, titanium alloys used for rotating parts of aeroplanes must meet strict standards of quality, so that it is required to demonstrate that electron beam melting is capable of producing defects-free ingots. There are two kinds of inclusions (see table 1) to be eliminated. One is high density inclusions (HDI) such as WC tool bits and other refractory metals. The other is low density inclusions (LDI) such as nitrided sponge particles and burned sponge particles. Since density of HDI is greater than that of molten titanium (e.g., Ti-6Al-4V≒3920 [kg/m³]), they can sink in the molten titanium (pool) and can be trapped in the skull (solidified titanium formed on a crucible). On the other hand, LDI can have density lower than molten titanium, so that they do not sink but can move inside or on the surface of the pool. In order to eliminate those kinds of LDI, removal by dissolution is often used, but complete removal of LDI having high nitrogen content might be impossible [2, 3]. Therefore, a new way of eliminating LDI has been studied.

Table 1 Type of inclusions

Type	Kind of inclusion	Density [kg/m ³]	Melting point [°C]
HDI	WC tool bits	15630	2870
	A piece of W	19250	3422
LDI	Nitrided sponge particles	Irregular (True density 5400)	1670(0%N)－ 3000(15%N)
	Burned sponge particles	Irregular	1670

2. Methodology

It is well known that there is a temperature gradient on the surface of a fluid, and thus Marangoni flow is induced. Therefore, some area of a molten titanium in a hearth is intensively heated by electron beam (hereafter, we call Intensive Heating (IH)), and thus Marangoni flow originating the heated area is generated. Based on the fact, we considered the control of a state of the molten titanium flow with the aide of the Marangoni flow, and inclusions coming to the area got stuck in front of the area (see figure 1).

Figure 1 Mechanism of removing LDI

3. Verification of effectiveness of IH by numerical simulation

In order to verify that Intensive Heating can really get LDI stuck in front of the heated area, a computational model describing a molten titanium flow and behaviour of inclusions in a molten titanium has been developed [4-6].

3.1. Computational model

Equations describing molten metal flow are shown:

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) &= 0 \\ \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) &= -\nabla p + \nabla \cdot \bar{\bar{\tau}} + \rho \vec{g} - \rho \beta' (T - T_0) \vec{g} + \frac{(1 - \beta)^2}{\beta^3} A_{\text{mesh}} \vec{v} \\ \bar{\bar{\tau}} &= \mu \left(\nabla \vec{v} + \nabla \vec{v}^T - \frac{2}{3} \nabla \cdot \vec{v} I \right) \\ \frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\rho \vec{v} H) &= \nabla \cdot (\lambda \nabla T) \\ H &= c_p T + \beta L \\ \left\{ \begin{array}{ll} \beta = 0 & \text{if } T < T_{\text{Solid}} \\ \beta = 1 & \text{if } T > T_{\text{Liquid}} \\ \beta = \frac{T - T_{\text{Solid}}}{T_{\text{Liquid}} - T_{\text{Solid}}} & \text{if } T_{\text{Solid}} < T < T_{\text{Liquid}} \end{array} \right. \end{aligned}$$

Here, t is time, ρ is density, $\vec{v}$ is velocity vector, p is pressure, $\bar{\bar{\tau}}$ is stress tensor, μ is viscosity, I is unit $\vec{g}$ is gravitational acceleration, $\beta' (= 1.73 \cdot 10^{-4} [1/K])$ is thermal expansion coefficient, $T_0 (= 1923 [K])$ is re temperature, β is liquid fraction, $A_{\text{mesh}} = 10^5$, H is enthalpy, λ is thermal conductivity, T is temperature specific heat, $L (= 286 [kJ/kg])$ is latent heat, $T_{\text{Solid}} (= 1913 [K])$ is solidus temperature, $T_{\text{Liquid}} (= 1923 [K])$ is liquidus temperature. The values of c_p and λ are summarized in Appendix A.

Equations describing the behaviour of inclusions in a fluid are shown:

$$\frac{d\vec{u}_p}{dt} = \frac{\vec{v} - \vec{u}_p}{\tau_r} + \frac{\vec{g}(\rho_p - \rho)}{\rho_p}$$

$$\tau_r = \frac{\rho_p d_p^2}{18\mu} \frac{24}{C_d Re}$$

$$Re = \frac{\rho d_p |\vec{u}_p - \vec{u}|}{\mu}$$

Here, the first term of the right hand side of (7) represents drag force. τ_r is relaxation time, $\vec{u}_p$ is particle (incl) velocity vector, ρ_p is particle density, d_p is particle diameter, C_d is drag force coefficient [7], Re is Reynolds number defined by equation (9).

Moreover, heat flux given to the surface of molten titanium is described by the following equations:

$$q = \alpha q_0 \exp\left(-\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2}\right) - C_1 C_2 (T^4 - T_\infty^4)$$

$$Q = \alpha q_0 \int_{\text{all } x} \int_{\text{all } y} \exp\left(-\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2}\right) dx dy$$

Here, q is heat flux given to the pool surface. The first term of (10) is heat flux by electron beam and the second term is heat flux by radiation. $\alpha (= 0.7)$ is coefficient representing heat efficiency, (x, y) represents the position on the surface, (x_0, y_0) is beam spot, $\sigma (= 7.5[\text{mm}])$ is standard deviation, $C_1 (= 0.4)$ is external emissivity, $C_2 (= 10^{-8} [\text{W}/\text{m}^2 \text{K}^4])$ is Stefan-Boltzmann constant, T_∞ is external radiation temperature, Q is heat of electron beam.

3.2. Numerical Conditions

Flow of a molten titanium and behaviour of LDI moving on the surface of the pool was investigated under the following numerical conditions:

n Electron beam

- Heat, Scan velocity: 0.25 [MW], 1.6 [m/s]

n LDI

- Diameter, Density: 5.0 [mm], 3528 [kg/m³] (c.f., Molten Ti-6Al-4V: 3920 [kg/m³])
- Nitrogen content: ∞ (It was assumed that LDI did not dissolve.)

3.3. Numerical Results

Behaviour of LDI without Intensive Heating is shown in figure 2. In the figure, molten titanium flows from the left to the right, so that the solid lines in figure 2(b) representing LDI path on the surface of the pool are reaching to the lip where refined molten titanium is poured to a mold. This result indicates that LDI cannot be eliminated, and there is a risk that LDI contaminate ingots.

On the other hand, behavior of LDI with IH is shown in figure 3. In the calculation, IH was carried out at the center of the hearth, so that the surface temperature becomes greater than other. Because of this temperature gradient, Marangoni flow is induced and LDI coming from the left get stuck in front of the hotter area and cannot move to the lip. This result does not change even if the position of beam spot changes as shown in state 1 to 3 in figure 3.

Figure 2 Behavior of LDI without IH

Figure 3 Behavior of LDI with IH

4. Verification of effectiveness of IH by experiments

Experiments to verify the effects in actual facilities have been carried out. In the experiments, carbon tracer particles were used instead of true LDI because the density is much less than that of molten titanium. And then we mixed them with raw materials. Time transition of carbon tracer particles in molten titanium is shown in figure 4. In the figure, the molten titanium in the cold hearth flowed from the upstream side to the downstream side, so that carbon tracer particles behaved in the same manner. In the case of a heat pattern without IH (see figure 4(a)), the particle was not eliminated and flowed to a mold. On the other hand, in the case of a heat pattern with IH (see figure 4(b)), the particle got stuck in front of the IH area and was not able to flow to the mold. Therefore, the effects of Intensive Heating on eliminating LDI have been confirmed.

Fig. 4 Experimental Results to verify the effect of Intensive Heating

5. Conclusion

Titanium alloys used for rotating parts of aeroplanes must meet strict standards of quality, so that it is required to demonstrate that electron beam melting is capable of producing defects-free ingots. However, complete elimination by dissolution of LDI having high nitrogen content would be difficult, so that a new way of eliminating LDI was needed. Therefore, control of a state of the molten titanium flow with the aide of Marangoni flow induced by Intensive Heating has been studied and effects on eliminating LDI has been verified by the numerical simulations and the experiments using actual electron beam facility and carbon tracer particles.

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Appendix A Properties of Ti-6Al-4V

Properties of Ti-6Al-4V using in the numerical simulations (see section 3) are shown in table 2. μ assumed to be described in the polynomial form: $\mu = 0.03856 - 2.85243 \cdot 10^{-5}T + 5.45115 \cdot 10^{-9}T^2$.

Table 2 Properties of Ti-6Al-4V

Temperature [K]	Specific heat [J/kgK]	Thermal conductivity [W/mK]
298	546	7.0
373	562	7.45
473	584	8.75
573	606	10.15
673	629	11.35
773	651	12.6
873	673	14.2
973	694	15.5
1073	714	17.8
1173	734	20.2
1267	753	22.7
1269	641	19.3
1373	660	21.0
1473	678	22.9
1573	696	23.7
1673	714	24.6
1773	732	25.8
1873	750	27.0
1922	759	28.4
1924	831	33.4