Melting and Casting Technologies for Titanium Aluminide Intermetallics

Daisuke MATSUWAKA[*1] · Tomohiro NISHIMURA[*2] · Fumiaki KUDO[*3] · Yuuzo MORIKAWA[*4] · Hitoshi ISHIDA[*2]

[*1] Application Technology Center, Technical Development Group
[*2] Materials Research Laboratory, Technical Development Group
[*3] Kobelco Research Institute, Inc.
[*4] Production Department, Titanium Plant, Titanium Unit, Advanced Materials Business

Abstract

Alloys based on the titanium aluminide (TiAl) intermetallic compound are lightweight and have excellent high temperature strength and oxidation resistance. Therefore, they are being increasingly used in low-pressure turbine blades of jet engines for commercial aircraft, against the backdrop of fuel consumption reduction needs and the like. Kobe Steel has been working on the development of a manufacturing technology for TiAl material with international competitiveness, devised a melt deoxidation method utilizing the phenomenon of decreased oxygen solubility when high concentration aluminum is added, and achieved an oxygen concentration of 0.03 mass% or less. The company has also realized a narrow composition range (Al content ±0.3 mass%) and improved casting yield (+25% or higher compared with the conventional method) by constructing a melting and casting process using the cold crucible induction melting (CCIM) method. This paper also details the technology for recycling titanium scrap and describes future prospects.

Introduction

Alloy based on titanium aluminide (hereinafter referred to as "TiAl alloy") is light weight, with a density about half that of a Ni-based alloy, and has excellent high-temperature strength and oxidation resistance. Thanks to this, it is increasingly adopted for the low-pressure turbine blades of commercial aircraft jet engines to meet the recent need to reduce fuel consumption and CO_2 emissions.[1), 2)]

The 48-2-2 alloy (Ti-48Al-2Cr-2Nb at.%), the current de facto standard for TiAl alloy, was developed by the General Electric Company. After that, pioneering research and development was vigorously carried out in the 1990s, including work by Takeyama et al., showing the guiding principle for the structural design of the alloy for forging,[3)-5)] and practical applications of TiAl alloys are progressing in Europe, which is highly environment-conscious. In the future, as the practical applications progress further, they are expected to be adopted more widely in next-generation aircraft engines and may possibly spread to other fields.[6)-8)]

In Japan, the Cross-ministerial Strategic Innovation Promotion Program (hereinafter referred to as "SIP"), led by the Cabinet Office, has promoted structural design guidelines and the development of manufacturing technology to improve heat resistance (Innovative Design and Production Technology of Novel TiAl Alloys for Jet-engine Applications).[9)]

This paper presents various issues in the manufacturing technology of TiAl alloy material (melting, casting and recycling) and describes the achievements and future prospects of Kobe Steel's efforts to establish its mass production technology.

1. Manufacturing technology of TiAl base material

1.1 Typical melting and casting process and technical issues

The melting and casting technology of TiAl alloy includes special melting processes such as vacuum arc remelting (hereinafter referred to as "VAR") adopted for titanium and titanium alloys, electron beam melting, plasma arc melting (hereinafter referred to as "PAM"), vacuum induction melting, and cold crucible induction melting (hereinafter referred to as "CCIM").[10)]

High quality is required for TiAl alloy due to its applications. This raises issues especially in ensuring compositional uniformity, which greatly affects the material structure (and thus affects product characteristics), and in reducing casting defects. In order to satisfy such high quality requirements, GfE mbH (Germany), the world's largest company in the field, melts the material by the VAR method and then casts it using a centrifugal casting method.[11)] In addition, since the raw materials are expensive, recycling scrap with a view to cost reduction is expected to become more important in the future as the alloy's applications to aircraft engines expand.

1.2 Melting and casting technology by CCIM method

Table 1 compares the respective technical issues associated with the processes introduced in the previous section. As shown in this table, the CCIM method is considered to be the most suitable, as regards scrap recycling and compositional uniformity, for the melting and casting process of TiAl alloy. Hence, this paper introduces the results of past efforts in the CCIM method.

As mentioned above, in the melting of TiAl alloy, it is most important to keep its components at predetermined concentrations. The CCIM is a method in which an object is strongly agitated by induction heating to be uniformly melted (**Fig. 1**). Since a split-type water-cooled copper crucible is used as the melting container, a solidification skull (solidified shell) is formed in the part that comes into contact with the water-cooled copper. Taking this phenomenon into consideration, Kobe Steel has optimized the arrangement of the raw materials, composition and order of addition, in advance. These efforts have enabled a narrow-width control (± 0.3 mass% of the target) of the Al concentration in the TiAl alloy when an identical composition is melted continuously. On the other hand, in order to improve the quality and to reduce the cost of TiAl alloy castings, it is effective to improve the yield of sound material by reducing the casting defects in the material. Kobe Steel has developed a technology to produce sound material without casting defects by controlling the casting rate in the melting process based on the CCIM method and has successfully improved the yield by 25% or more compared with the conventional method, which involves tilting the water-cooled copper crucible to pour the molten metal into a mold installed below.

1.3 Recycling technology for TiAl alloy scrap

The greatest obstacle in recycling titanium scrap is the increase in impurity elements, one of the main impurity impurities being oxygen. Various techniques have been attempted to deoxidize titanium,[12)-16)] however, the deoxidation of titanium is thermodynamically difficult.

In the case of TiAl alloy also, industrial recycling is limited to the scrap that occurs in-house, and there are various problems in the practical application of recycling excessively contaminated scrap. For this reason, high-grade raw materials with a low oxygen

Table 1 Comparison of technical issues in melting processes for TiAl alloy

Melting process	Atmosphere	Heat source	Homogeneity & composition controllability	Scrap recycle	Total
VAR (skull melt-pour)	Vacuum	Arc	△ : Fair ・double/triple melt required ・evaporation loss (Al, Cr, etc.)	△ : Limited flexibility for electrode preparation	△ Fair
EBM	High vacuum	Electron beam	× : No good ・high evaporation loss (Al, Cr, etc.)	○ : Normal flexibility	× Bad
PAM	Inert-gas	Plasma arc	○ : Good ・depend on blended compositions of additional materials	○ : Normal flexibility	○ Good
CCIM	Inert-gas	Induction heating	◎ : Excellent ・strong magnetic stirring	◎ : High flexibility	◎ Excellent

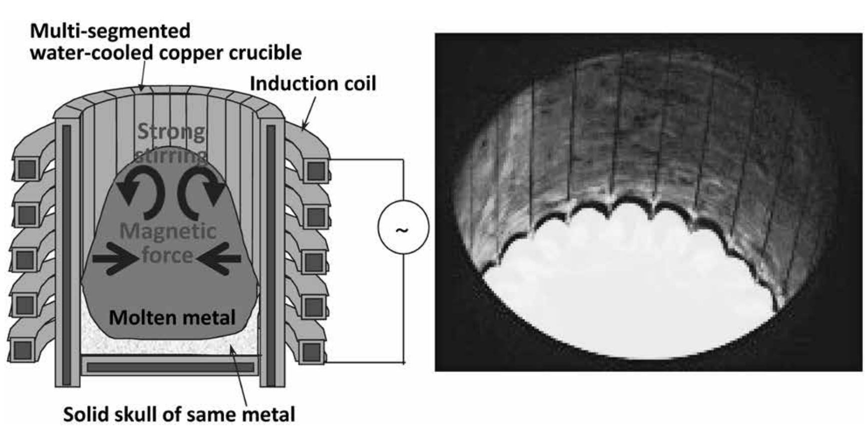

Fig. 1 Schematic diagram of cold crucible induction melting (CCIM)

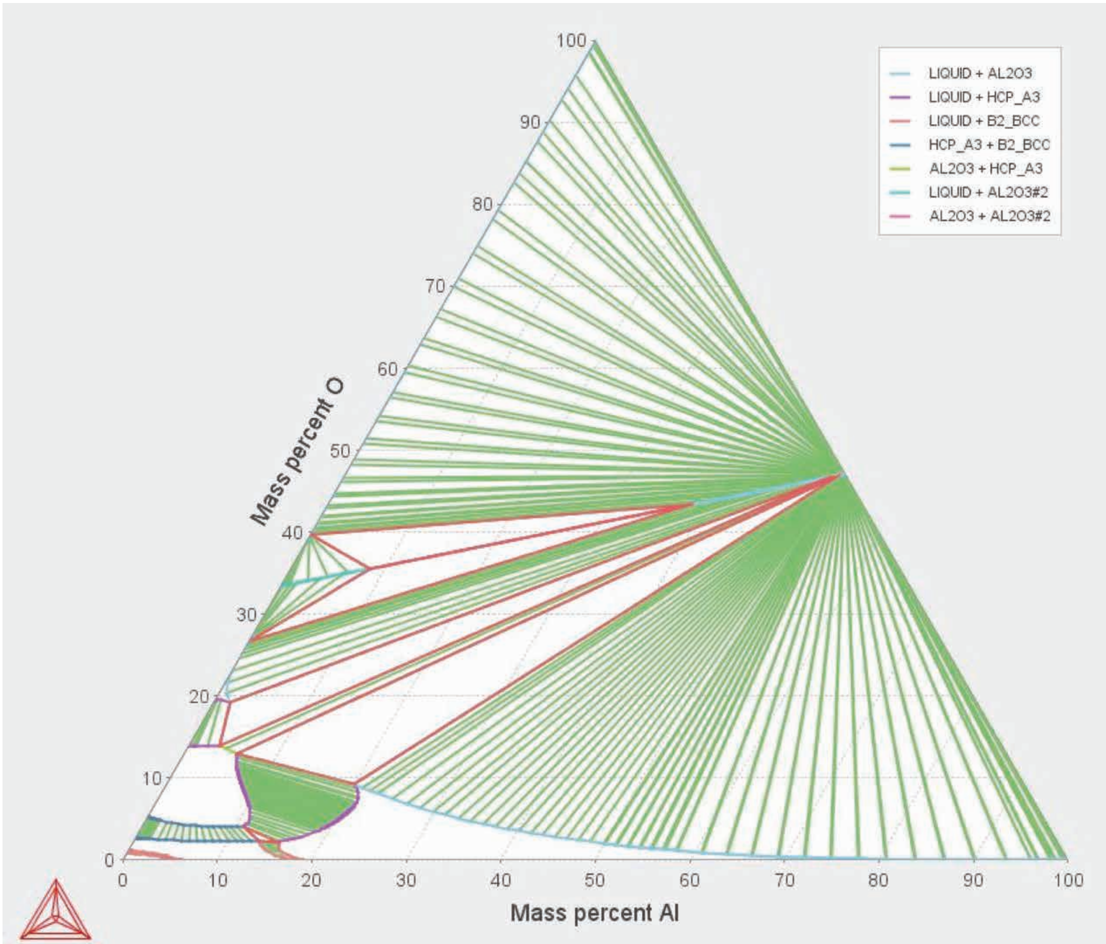

Fig. 2 Ternary isothermal section of Ti-Al-O at 1,973K (calculated by Thermo-Calc)

concentration must be used as the raw materials for TiAl alloy, which is an active metal like titanium.

Hence, Kobe Steel has focused on this thermodynamical feature: the oxygen solubility in the intermetallic compound decreases significantly when the aluminum concentration in a general TiAl alloy is higher than 30-40 mass% and the company has verified the feasibility of performing deoxidation by adding aluminum during TiAl alloy melting (**Fig. 2**). The results are shown in **Fig. 3**. TiAl alloy containing 0.8 mass% oxygen was melted with PAM or CCIM and metallic Al was added. As a result, it has been clarified that deoxidation down to 0.1 mass% or less can be achieved in the high Al concentration region of more than 40 mass%. The product of this deoxidation reaction has been confirmed to be Al_2O_3.

Then, flux was added to separate the molten TiAl alloy from Al_2O_3, in addition to further reducing the oxygen concentration. For the flux, the CaO-CaF_2 system was selected because of its low melting point (easy to melt, with high reactivity) and its high solubility of Al_2O_3. **Fig. 4** shows the results when the flux is added. Comparison of the oxygen

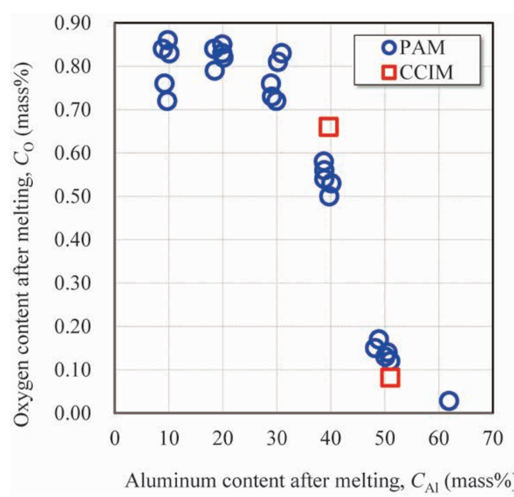

Fig. 3 Effect of aluminum content on deoxidation behavior in molten TiAl alloy

concentrations with and without flux addition at a given Al concentration shows that the oxygen concentration has been reduced by the flux addition, as intended. When no flux is added, the deoxidation product Al_2O_3 (spot-like precipitates in the upper photograph of **Fig. 5**) is scattered in the TiAl alloy, which makes it difficult to separate it from the alloy

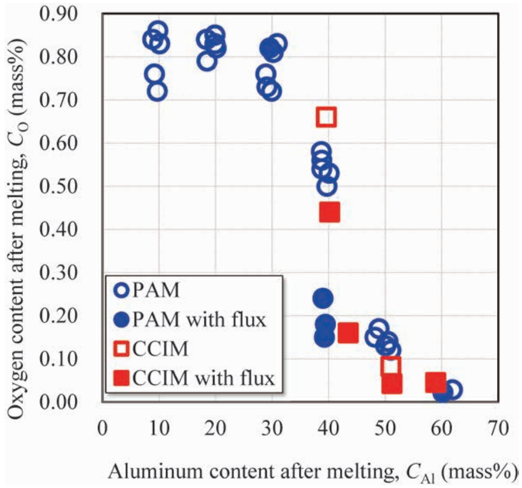

Fig. 4 Effect of flux addition

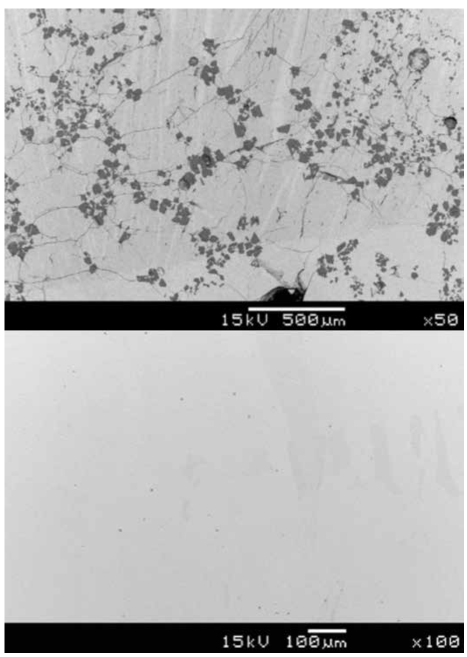

Fig. 5 SEM images of sample cross-sections after melting without flux (upper) and with flux (lower)

after deoxidation. On the other hand, the addition of the flux has been confirmed to eliminate Al_2O_3 from the TiAl alloy solidified after melting (Fig. 5, lower photograph). This is considered to be the result of Al_2O_3 being absorbed in the molten flux. Also, when the obtained TiAl alloy with a high Al concentration is added with Ti for composition adjustment and to dilute the Al concentration, the remaining Al_2O_3 has been confirmed to decompose (dissolve in TiAl alloy again), verifying the points made in this discussion.

The recycling technology utilizing this principle for scrap with highly dissolved oxygen (hereinafter referred to as the "high-Al melt deoxidation method") has a fast reaction rate because the deoxidation reaction proceeds during melting. In the case of the TiAl alloy, the additive amount

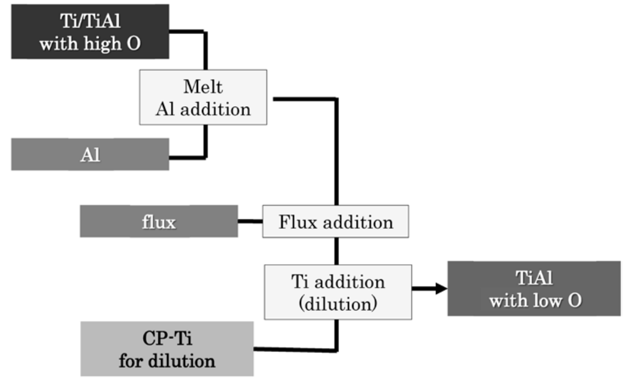

Fig. 6 Schematic diagram for TiAl alloy deoxidation process

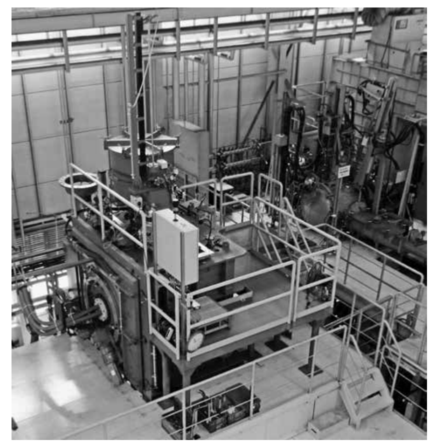

Fig. 7 Appearance of pilot-scale CCIM furnace

of Ti (amount of dilution of Al concentration) can be small, so future development for practical applications is expected. **Fig. 6** shows a schematic diagram of this process.

2. Efforts to establish mass production technology

As mentioned at the beginning, Kobe Steel has been working on the development of "high-grade, low-cost ingot manufacturing technology" by CCIM in the SIP project, "Development of innovative manufacturing process for TiAl Blade." The company has used pilot-scale CCIM equipment (**Fig. 7**), which was introduced for the purpose of establishing the technology for mass production and has demonstrated a narrow width control of Al concentration by optimizing the melting conditions to achieve high quality, the reduction of casting defects and improvement of yield by optimizing casting conditions.

3. Future prospects

The aircraft industry is expected to continue to grow at an annual rate of approximately 5%, and the market for TiAl alloy is expected to expand.

To further expand the adoption of TiAl alloy, it is most important to produce the material with higher quality at a lower cost. In particular, the recycling of scrap containing expensive elements is expected to become ever more important. Hence, Kobe Steel believes that the high-Al melt deoxidation method and the CCIM method, which is not restricted by the shape of the scrap, can be promising as mass production technology.

As the additive manufacturing technology is disseminated and the understanding of its merits and demerits progresses, it is expected that the demand for TiAl alloy powder will increase sharply as the conversion from the current manufacturing technology (precision casting, isothermal forging, total machining, etc.) occurs. High-grade, low-cost material manufacturing technology is also indispensable for powder production. For these future issues, Kobe Steel plans to participate in the "Development of Powder Manufacturing Process and Basic Technologies for High Performance TiAl based Alloy Turbine Blades" in "Material Revolution by Integrated material Development System," which is one of the subjects of the second phase of SIP, to continue to upgrade TiAl alloy as a basic technology for mass production.

Conclusions

Attempts have been made to develop the melting and casting processes for low-cost high-quality TiAl alloy, and the following results have been obtained:

(1) Optimizing the composition, arrangement and addition order of raw materials has enabled a narrow width control of Al concentration in TiAl alloy (± 0.3 mass% of the target) when an identical composition is melted continuously.

(2) Controlling the casting rate has improved the yield of sound material without casting defects by 25% or more compared with the conventional method.

(3) A melt deoxidation process has been devised on the basis of the phenomenon of oxygen solubility in the intermetallic compound decreasing as the Al concentration increases.

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