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The investment casting technology of Ti products

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Abstract

In 1994, the golf club head of Ti-alloy was produced by casting for the first time in Daido Castings. And then, any kind of Ti-alloy casting parts have been produced such as motorcycle, automotive and sports applications. In particular, TiAl turbine wheel of turbocharger have been attracted attention in automotive application, because that product has a good potential to improve the fuel efficiency.

In this paper, Ti-alloy casting technologies and mechanism of Levicast which is our original melting and casting method for Ti-alloys are explained in details.

Additionally, properties and producing process of TiAl turbine wheel are explained in details.

1. Introduction

Titanium has been recognized as a familiar metal material these days. Because of its lightweight, high corrosion resistance and strength, titanium and titanium alloys are often used for sporting goods we directly touch, such as a golf club head, bicycle and motorcycle parts.

Titanium aluminum alloy has lighter weight and higher heat resistance than titanium alloy. For turbocharger for automobile, TiAl alloy turbine wheel has been in practical use since 1999. Daido Castings has been producing TiAl wheels since then. Our mass production line of titanium products, especially titanium casting technology has been making a great contribution to wide spreading TiAl alloy wheels in the market.

This paper presents our titanium mass production line including Levicast(1) process, our unique process combining Levitation Melting method and Counter Gravity Casting process, and what the drawbacks of conventional titanium casting process, vacuum arc melting and centrifugal casting method(2), as well as our newly developed material for TiAl turbine wheels.

2. Daido Castings' titanium casting history

By 1993, Daido Steel's R & D had been making various trials of titanium precision casting products. Using 2kg Levicast equipment, trial products of golf head, bicycle parts, implant bone, turbine wheel etc. had already been realized. In 1994, Precision Casting Division was newly set up featuring Levicast, one and only titanium precision casting method, and entered titanium golf head market.

We introduced 10kg Levicast equipment. In 1998, total number of shipped golf head reached up to 1 million. At the same time, production of exhaust valves for motorcycle started. It was widely recognized that “thin-wall” or “light-weight” equals “Levicast”.

In 1999, production of TiAl turbine wheels for passenger vehicle turbocharger started. In 2001, production base was transferred from Nagoya to Nakatsuigawa, Gifu pref. to incorporate the titanium production process into the already operated automatic line of Ni-based alloy turbine wheel.

In 2008, we retreated from golf head market and targeted TiAl turbine wheels as our
main product. Now we are trying further improvement to create world wide market of TiAl wheel.

3. Production process of TiAl turbine rotor in Daido.

Fig.1 shows our production process.

![Production Process Diagram]

Our die design enables turbine wheel to have very good balance based on our more than 15 year’s experience. Thanks to it, we gained a great deal of trust from our customers. We are now trying to apply another new technology to improve balance further. Model process is incorporated in the Ni-based alloy turbine wheel line. For titanium products, special molding material is used which has stable slurry condition, plus special program is installed in the molding robots, to make molds with high and stable quality.

Casting process features Levicast equipment.

There are three advantages in Levicast.

1. Contamination free melting: oxygen content of TiAl cast is around 500ppm.
2. Thin-wall casting: minimum blade tip thickness of TiAl turbine wheel is 0.50mm.
3. Higher productivity than conventional process: short cycle meting and casting.

On machining process, TiAl turbine wheel is machined before brazing it to shaft on brazing process. TiAl is a difficult-to-cut material. Based on our year’s experience of machining tools and conditions, we realized high and stable quality.

Fig.2 shows our original brazing method for TiAl. We call it PIB process\(^{(5)}\). PIB means Pressurized Induction Braizing. First, filler metal sets between TiAl T/W and alloy steel shaft. After setting, only brazed area is heated by induction heating under pressurized condition in argon atmosphere to block oxidation.

There are three characteristics of PIB process.

1. Direct brazing of TiAl T/W and alloy steel shafts
2. High joint strength
3. Short cycle brazing
Fig. 2 Schematic Illustration of Pressurized Induction Brazing Process

Fig. 3 shows joint strength using various filler metals. Among them, we tested three metals to evaluate joint strength between TiAl and steel from RT to 500 degree C: Ag-base, Ti-base and Ni-base. The Ni-based filler metal's strength is the highest among the three. In addition, that of Ni-based matches the strength of TiAl.

Fig. 3 Joint Strength using Various Filler Metal

Fig. 4 shows the brazed interface used Ni-based filler metal. The thickness of the interface is about 10μm. No defects like void were found on it. Based on this result, Ni-based filler metal was selected for mass production. We have produced more than 80,000 turbine rotors since 2003. Turbine rotors produced by this method have caused no trouble in the market so far.
TiAl T/W has been developed in collaboration with Daido steel’s R & D section. Mainly, Daido steel was in charge of alloy development, such as alloy design, structure, some properties, while Daido castings was in charge of manufacturing technologies, such as mold making, melting, casting and brazing process. Now Daido group support the customers in various ways regarding TiAl alloy. (Fig.5)

4. Levicast process
4.1. Conventional titanium casting method
Melting point of pure titanium is 1,670 deg C. It is much higher than that of pure iron. And it is very active material under melting condition. Therefore, Titanium is not possible to be melted in a ceramic crucible which is used for steel; generally, water-cooled copper crucible is used. Between inside of the crucible and titanium, solidified shell of titanium is created and works as a molten metal container to prevent crucible from damage, molten metal from contamination. It is called Skull Melting process because of the shape of the shell.

Fig.1 shows oxidation level of pure titanium melt by induction heating in various kinds of crucibles in 99.9999% argon atmosphere. Inner diameter of crucible was 30mm. Holding time after meltdown was 3 minutes.
Before meltdown it was 0.2%. But after meltdown it was 0.5%, even if yttria(Y₂O₃) is used which is the most stable oxidized material. In the other materials which are less stable than yttria, contamination was much worse\(^{(4)}\).
Fig. 6 Contamination of Titanium after Melting in Various Crucible

Fig. 7 shows conventional titanium casting device. Skull Melting process causes high heat loss. It prevents extra heat of molten metal, so miss-run often occurs. In order to solve this problem, centrifugal force of about 50G is generally used. However, it makes casting process complicating, and requires high strength of mold. It leads to high mold manufacturing cost. In addition, this process requires expensive consumable electrode billet as melting material. It is also necessary to do all work in a vacuum to make arc work stable. Many casting gates lead to low as-cast yield rate. To solve all these problems and realize mass production of titanium precision casting products, fundamental change was necessary.

![Fig. 7 Conventional Titanium Casting Device](image)

**4.2. Principle of Levitation Melting method**

Heat loss can be lowered greatly by making the area small where molten metal contacts the water-cooled crucible. Initial type of Levitation Melting method’s goal was “Full Levitation” : to make molten metal fully levitated by electromagnetic force. Fig. 8a shows the principle of full-levitation method using coils for the purpose of some experiment.  

High frequency alternating current through the coil generates inductive current of 180 degrees out of phase on the surface of the metal. Between these currents, Lorentz’s repulsing force according to Biot-Savart’s law are generated. It makes the metal afloat. However, because electromagnetic force doesn’t work to the bottom of the metal, only metal drop which is little enough to keep its shape by surface tension can be fully levitated.
Fig. 8 Principle of Levitation Melting

Fig. 8b shows the principle of the semi-levitation method applied to practical industrial operation\(^{(7)}\). There is no limit to maximum melting volume in theory because solidified shell at the bottom supports molten metal itself. The water-cooled copper crucible has vertical slits around it for electrical insulation and the eddy current is generated in the molten metal. Then molten metal stands up by the means of electromagnetic pressure, not contacting the wall of the crucible. It means less contacting area and less heat loss than in Skull Melting process. All kinds of shape of melting material can be used including reasonable scrap. Chemical composition and temperature of molten metal keeps completely constant by electromagnetic stirring. Because it can be operated whether in vacuum or in inert gas, it is easy to handle melting material or molds.

Fig. 9 shows 10kg of molten titanium under the electrical power of 450kW by our developed Levicast equipment. The bottom of metal touches the crucible, while the side does not touch it. The temperature of the metal reaches the targeted value in less than one minute and extra heat can be controlled in the range of 50-100 deg C. It realizes very high repeatability of molten metal temperature.

Fig. 9 Molten Metal Inside the Furnace

4.3. Structure of casting device

Fig. 10 shows the outline of the device. Atmosphere in the crucible is Argon under atmospheric pressure. The mold chamber can be moved, keeping airtight. So it is easy to change the ceramic molds, keeping the atmosphere with no contamination. The electrical power is 450kW, frequency is 15kHz. Melting volume is about 10kg, quite little volume compared to its power. Then it realizes to make the casting time very short, up to about 2 minutes.
5. Development of TiAl alloy and turbine wheel production technology

5.1. Market trend of turbocharger

Fig.11 shows estimation of production volume of turbocharger. (8)

The number of vehicle equipped with turbocharger has steadily grown in the world market since around 2006.

One of the reasons is the fact that because main effect of turbocharger is to increase power output, engine size can be downsized.

Now, Turbocharger is recognized as a good technology to improve fuel efficiency.

Installation rate of turbocharger for diesel engine is almost 100%. On the other hand, especially in Europe and other countries the rate for gasoline engine has been increased.

5.2. Why TiAl turbine wheel?

In Fig.12, horizontal axis represents engine rpm and vertical axis represents torque.

The torque of vehicle equipped with turbocharger is bigger than that of non-turbo vehicle. However, problem of convectional turbocharger is lower torque in low engine speed: turbo lag. In order to solve turbo lag, new turbo systems were developed by many turbo and vehicle makers: VGT (Variable Geometry Turbo) in diesel engine, two stage turbo or twin
charger in gasoline engine. In turbo system, TiAl has a big potential to improve its performance because TiAl wheel weighs half of super alloy turbine wheel. Moreover, a single TiAl turbo may be able to replace two stage turbo or twin charger.

Fig.13 shows the response of TiAl and super alloy turbine wheel. TiAl turbo realizes better acceleration response than super alloy turbo by about 26%. In the near future TiAl turbo will be selected the best turbo system for improving fuel efficiency.

Fig.12 Torque of Vehicle Equipped with Turbocharger  Fig.13 Response of T/W

5.3. History of TiAl turbine wheel development by Daido group.

Fig.14 shows history of development of TiAl turbine wheel by Daido group. We have developed not only alloys, but also casting process and joining process of turbine wheel and steel shaft. Now we have some original manufacturing technologies of TiAl products. We started the first publication concerning TiAl turbochargers in 1987. TiAl turbocharger has been applied for race car in 1998, and for passenger vehicle in 1999. Our original TiAl alloy has been applied for passenger vehicle in gasoline engine from 2003 to 2010. Recently, another alloy has been developed. Now we have produced more than 120,000 turbine wheels since 1998 including DAT-TA1 and other alloys.

![Fig.14 History of Development of TiAl Turbine Wheel by Daido Group](image-url)
5.4. New demand for turbocharger

Recently, direct injection, turbo and stoichiometric combustion technologies are applied in combination to improve fuel efficiency in gasoline engine. As a result, the exhaust gas temperature increased up to max.1050 deg C. New demand for material for high temperature use was created.

Generally, Ni-based super alloy is used for turbine wheel material. The alloy most commonly used is IN713C.

However, at high temperature over 1000 deg C is applied Mar-M246 or 247. Our conventional TiAl, DAT-TA1(Ti-33.5Al-4.8Nb-1.0Cr-0.2Si), can be applied up to 950deg C, but not higher. So, we needed to develop new alloy for higher temperature use. (Fig.15)

![Figure 15: New demand for turbocharger](image)

Table 1. Chemical composition of materials for turbine wheel

<table>
<thead>
<tr>
<th>Alloy type</th>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Chemical composition(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cr</td>
</tr>
<tr>
<td>Ni-based superalloy</td>
<td>GMR235</td>
<td>7.9</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>IN713C</td>
<td>7.9</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>Mar-M246</td>
<td>8.5</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>Mar-M247</td>
<td>8.5</td>
<td>8.3</td>
</tr>
<tr>
<td>TiAl</td>
<td>DAT-TA1</td>
<td>3.9</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>DAT-TA2</td>
<td>4.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

5.5. The concept of new TiAl alloy design

Features of this design is: increased creep strength, phase stability at high temperature and improved oxidation resistance. We developed DAT-TA2. Based on DAT-TA1, Al and Nb were optimized and C was added to achieve higher temperature strength. Nb and Si were optimized to increase oxidation resistance. Si was increased and C was added to gain more creep resistance. Finally, Nb and C was optimized to keep good manufacturability. This is the super new alloy, DAT-TA2. (Fig.16)
To keep same castability as conventional DAT-TA1, the chemical composition was adjusted. As a result, DAT-TA2 has columnar structure with TiAl/Ti₃Al lamellar structure as figure 17.

![Microstructure of DAT-TA2](image)

**Fig.17 Macro/Microstructure of DAT-TA2**

5.6. Mechanical Properties of DAT-TA2

Fig.18 shows high temperature tensile strength. Mechanical properties were evaluated using about 10mm diameter as-cast bar specimens, not turbine wheel. DAT-TA2 has higher tensile strength and 0.2% proof stress than DAT-TA1. Those of DAT-TA2 are lower compared to Ni-based super-alloy at low temperature, but they become equal at high temperatures. Fig.19 shows creep rupture property. That of DAT-TA2 is higher than that of DAT-TA1, but lower than that of Ni-based super-alloy.
Generally centrifugal force is loaded by rotation system such as turbine wheel. So we evaluated specific strength. In this case, we define specific properties as strength or stress divided by density.

Fig.20 shows specific strength. By specific strength, DAT-TA2 is the highest in all alloys from low to high temperatures. Fig.21 shows specific creep rapture property. Considering density, DAT-TA2 is the most excellent creep rapture property.

In our test, test pieces are exposed to cyclic conditions of heating and cooling. Cyclic number is 200 cycles, and test atmosphere is under air. Considering that oxygen in exhaust gas is lower than in air, this test condition is thought to be severer than the case where turbine wheel is used in practical use.

DAT-TA1 and DAT-TA2 were drastically improved compared with a binary TiAl alloy. DAT-TA2 has higher oxidation resistance than DAT-TA1. That of DAT-TA2 is equivalent to that of Ni-based super-alloy up to 1000°C in air. (Fig.22)
5.7. Development of next alloy
Considering properties of each, DAT-TA1 is suitable for diesel engine or gasoline engine at low temperature up to 950deg C, while DAT-TA2 will be suitable for gasoline engine around 1000deg C. Turbine wheel made of DAT-TA2 is currently under evaluation by our customers and we hear some of them gained good results we expected. Now, we are going to next step: to develop next alloy which has further excellent high temperature properties. (Fig.23)

6. Conclusion
(1) TiAl has been used as the turbine wheel of turbocharger of passenger vehicle engines without any trouble since 1998 in Japan. This fact demonstrated that TiAl has enough reliability as a structural material.
(2) TiAl is a promising lightweight material which is useful for energy saving technology in the field of automotive and aerospace industries. To widen practical use of TiAl, it is necessary to develop not only high performance materials but also low cost mass production technology.
(3) Daido Castings is making a great effort in order to widen practical use of TiAl in
future.
(4) Development of new big-volume Levicast(30kg) has already been completed. Further improvement project of our mass production line is now under way.
(5) TiAl turbine wheel market will expand drastically by our stable production and supply.

References
(1) Daido Steel CO., LTD. : Japanese Patent No.2725639,3044598
(3) Daido Steel CO., LTD. : Japanese Patent No.3829388
(8) CSM worldwide: Auto industry prediction report 2010-2015