The Evolution of Near-net-shape Ring-rolling Processes for Large Rings Made of Ti-6Al-4V

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A near-net-shape (NNS) ring-rolling process was developed to reduce the forging weight of a rolled, fan case front, ring made of Ti-6Al-4V. This was achieved by optimizing the ring-rolling process in which metallurgical and geometrical process was improved. A forging process was also developed for the manufacturing of preforms with a complex cross section in order to roll more advanced NSS rings. As a result, the weight of NSS rolled rings was reduced by 55%.

Introduction

Five countries, Japan, USA, UK, Germany and Italy, signed a collaboration agreement to jointly develop the V2500 turbofan engine in March 1983. The engine has a thrust of 25,000 to 33,000 pounds and is aimed at single-aisle civil aircraft with 150 to 180 passenger seats. The Airbus A320 is powered by two V2500 engines. A total of 2,500 engines had been sold since the beginning of sales in 1988 until the end of Dec. 2004. The production of the engines still continues steadily.

The V2500 engine uses a large, fan case, ring made of titanium alloy (Ti-6Al-4V).

Conventionally, rings with a complicated cross-sectional shape have been manufactured by machining rings with a plain cross-section rolled by a ring roll mill in our company. Our ring roll mill was too small in both power and size to produce a large ring such as the fan case. The development of a near-net shape (NNS), ring roll, technology was necessary to produce the ring with a complicated cross-sectional shape since machining from a plain shaped ring was too costly. The development of the technology reduces consumption of material and saves the machining cost significantly.

We decided to develop the technologies to produce the fan case by collective effort of the titanium division.

In Oct. 1985 we developed and installed a large ring roll for fan cases and started a test operation in 1986. A project team was organized in 1987 and started the development of NNS ring roll technologies for the fan case production. The goal was set to a "35 % reduction of the material consumed". Although the project ended in about a year and members have changed, the development effort has been continued until the present day and we have reduced the material weight to less than a half.

The production, on the other hand, has grown steadily and the total sum of delivered products has reached 3,000 pieces. The product has grown to be one of the major items of our titanium division.

This article describes the progress of the manufacturing process for the fan case front, which gave momentum to the development of NNS rolling technology. Also described is the NNS rolling technology of a tapered ring for the IPC (Intermediate Pressure Compressor) of the TRENT900 which powers Airbus A380.

1. Outline of fan case ring

Figure 1 shows the cross-section of the V2500 turbofan engine. The engine includes a number of parts made of titanium, and the fan case made of Ti-6Al-4V alloy is a large ring with diameter of 1,700 mm and total length of 1,150 mm. The fan case is made of a fan case front (approx. 770 mm long) and a rear (approx. 400 mm long) joined together by laser beam welding.

The shipping shape of the fan case front is shown in **Photo 1**. The fan case front is a large ring with outer diameter of 1,700 mm, minimum wall thickness of approx. 20 mm and height of approx. 770 mm and has a complex cross sectional shape with varying inner and outer diameters

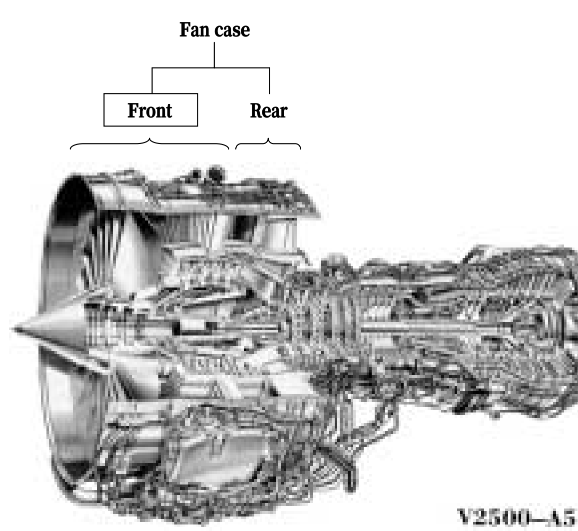

Fig. 1 Cross section of V2500 turbo fan engine

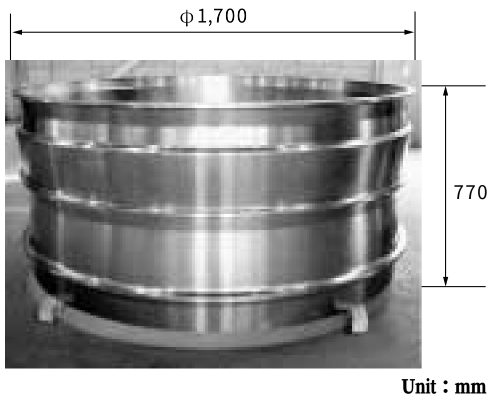

Photo 1 Shipment shape of fan case front

along the axis. [1)]

2. Manufacturing process of titanium alloy ring

Figure 2 shows the manufacturing process of the front ring. An ingot is forged into a billet in a round bar form having specified dimensions. The billet is cut to a specified length to be used as a forging material. A hole is pierced by hot forging at the center of the cut billet. The pierced billet is expanded in the diameter by hot forging the material in the wall thickness direction to form a rough preform which is ring-rolled in the peripheral direction to a specified diameter. The ring-rolled product is heat treated, machined and shipped after inspection and testing performed on test pieces taken from extra material.

3. Installation of large ring-roll mill

A ring roll mill consists of four kinds of rolls as shown in **Figure 3**. The king roll (KR) is a driving roll and rotates the ring-shaped material in the peripheral direction. The mandrel roll (MR) is a pressing roll that moves toward the KR at a specified speed. The material between the KR and MR is pressed in the thickness direction and elongates in the peripheral direction to expand the diameter. The centering roll (CR) ensures circularity of the ring by applying bending force to the material. The axial rolls (AR) confine the elongations in the height directions during the rolling.

We installed a large ring roll mill in 1985. The ring roll mill is featured by its height of 850 mm, which accommodates the size of a large fan case front, and also by the force of 800 ton which enables forming of a complicated cross sectional shape. **Table 1** summarizes the specification of the ring roll mill.

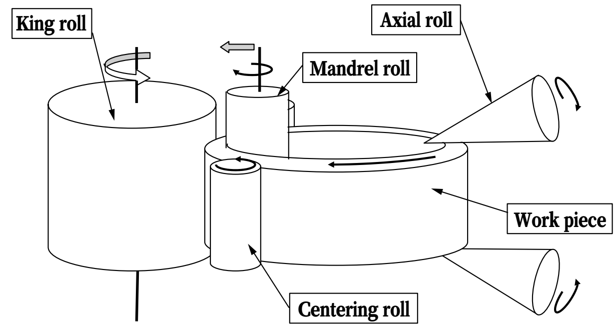

Fig. 3 Ring rolling mill

Table 1 Outline of ring rolling mill

Rolled dimension	Outside dia.	Max. 3,000 mm
	Wall thickness	Min. 30 mm
	Height	Max. 850 mm
Weight of material		Max. 5,000 kg
Pressing force		Max. 7.8 MN

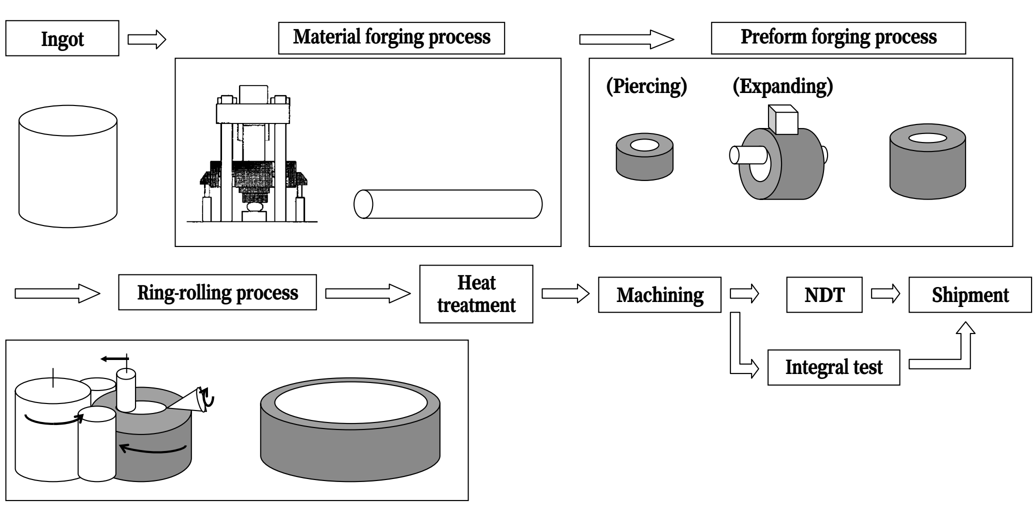

Fig. 2 Manufacturing process of ring rolled products

4. History of the ring roll technology for fan case front

When the large, ring roll mill was installed, rings with complicated cross-sections were machined from rings with simple cross-sections.

The conventional method of machining from simple cross-sections was not feasible for the volume production of the fan case front because of its high cost.

A project team was organized in 1987 with members from the Corporate Research Laboratory (Materials Research Laboratory, Mechanical Engineering Research Laboratory), Machinery Division (Cast and Forged Steel Plant, Machining Plant) and Titanium Division, to reduce the material cost (quantity of the material consumed) which was the largest cost factor. The goal was set to a "35% reduction of the material consumed".

4.1 Optimization of stable operation technology

In the ring rolling of a large diameter ring with thin wall, extra material is put on the products to compensate for the variations in diameter, circularity (difference between the largest and smallest diameters) and cylindricity (difference in the top and bottom inner diameters) to prevent the dimensional failing of the final product. For example, in the case of the fan case front, an excessive pressing of the ring wall by 0.1 mm expands the diameter by approx. 8 mm. The precision of ring rolling had to be improved first before developing the technology of NNS ring rolling.

Generally the precision of ring rolling is determined by outer diameter, circularity and cylindricity. Filling of ribs is added in case of the forming of rings with complex cross section. The outer diameter and circularity are determined mainly by the operational conditions of the rolls, and the cylindricity and filling are affected mainly by the shapes of the rolls and preforms.[2)]

(1) Outer diameter

The diameter of a ring being rolled does not represent the true diameter of the ring because the ring under rolling is elastically deformed by the pressure from the CR and AR. Also, when the feed rate of MR is high, the diameter becomes larger than the target diameter because of the remaining pressure after the MR is stopped. Besides, since the rings are rolled hot, the cold dimension is affected by the final temperature of the hot rolling due to thermal expansion.

To improve the precision of the diameter, the force exerted by the CR was optimized and the AR was released slightly before the end of rolling to minimize the deformation before and after the rolling. In addition, the feed rate of MR was reduced to minimize the remaining pressure and the final rolling temperature was optimized to minimize fluctuation of thermal contraction.[2)]

(2) Circularity

The circularity of a ring is determined by the repeated bending caused by the CR and MR. **Figure 4** shows the relation between the bending stress caused by the CR and circularity of rings with rectangular cross sections. Low bending stresses do not have enough force to correct the circularity. However, if the bending stress becomes too high, the circularity deteriorates due to the residual bending stress at the end of rolling. The force exerted by the CR was found to work best at a level slightly higher than the proof strength of the material.[2)]

(3) Cylindricity

The cylindricity is affected more by the shapes of rolls and preforms than by the rolling conditions described above.

Inferior cylindricity is a result of non-uniform rolling reduction in the height direction. In case of a ring with rectangular cross section, the control of cylindricity is rather easy because the mass is distributed uniformly in the height direction; however, in case of rings with complicated cross-sectional shapes, the rolling reduction is hard to maintain uniform in the height direction because of their non-uniform volume distribution.[2)]

This issue was resolved by the following design criteria. Ring rolled products were considered to comprise two equal portions of upper and lower having almost equal average weights. The upper and lower portions were designed to be symmetric as much as possible

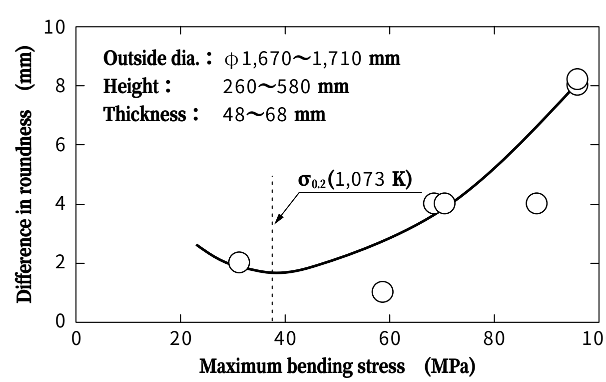

Fig. 4 Effect of bending stress of centering roll on roundness

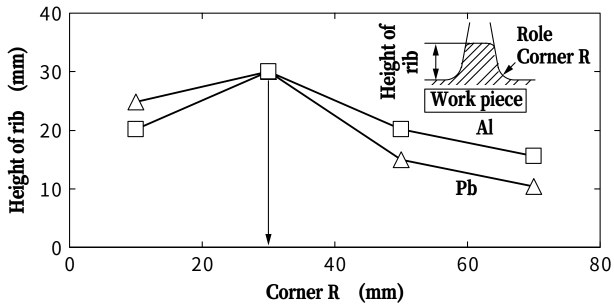

Fig. 5 Effect of corner R on height of rib

to make the rolling reduction almost equal through the height direction assuming there was no material flow in between the two portions.

(4) Filling of ribs

In the ring rolling, the thickness of the wall becomes thinner and the rib height becomes lower as the rolling proceeds. The material flow vertical to the rolled surface does not fill the groove of the roll. This is different from the forging in which the vertical material flow fills in the cavity of dies to form protruded shapes. The height of the ribs in the ring rolling is determined by the sum of the filling process and the subsequent reduction process. Experiments were conducted on a small bench scale to clarify the effect of roll shapes on the formation of ribs and determine the adequate roll shapes. **Figure 5** shows a result of a small scale experiment using lead and aluminum to determine the effect of the corner radius on the rib heights. The larger corner radius allows more flow to form the rib, however, excessively large corner radius results in lower rib height due to the increase of the rib volume. The corner radius of around 30 mm was considered to be appropriate.[2)]

The project activity has optimized operating conditions, enabled ring rolling of complex cross-section and achieved 15% reduction of the material consumed.

4.2 Development of NNS rolling technology

After establishing a stable ring rolling operation, we started the development of NNS ring rolling technology in 1991.

To roll complex cross-section shapes in near net shape, more flow of material to the axial direction is required to fill in the ribs. The material flows into the ribs increasing the weights of the ribs while reducing the weights of their vicinities. The material flow in the axial direction was evaluated in detail on portions of preforms and rings parted in the axial direction. As a result it was estimated that more material could be flowed into the ribs than had been considered previously.

For further advancement of NNS rolling, more material flow is required also in the axial direction. The conventional ring rolling using only finish roll has a limited material flow in the axial direction. A new rolling process using multiple rollers has been developed to achieve NNS.

The NNS rolling increases the variation of volume distribution in the axial direction, which results in the variation of rolling reduction in the axial direction and deteriorates the cylindricity. The design criteria were reviewed to improve the cylindricity.

Based on the conventional ring rolling (upper and lower portions), the material was considered to flow from the middle portion to upper and lower portions. The design criteria were reviewed in the following manner. The ring rolled products were considered to comprise three portions of upper, middle and lower, with smaller volume in the middle portion and larger volumes in the upper and lower portions. Almost equal weights were allocated to the upper and lower portions so that the volume distribution of all the three portions becomes uniform after rolling. As a result the rolling reduction of the three portions became uniform improving the cylindricity. **Figure 6** compares the volume distributions of ring rolled products.[3)]

The material consumption was reduced by 45% with additional improvements including piercing of the forged material by pressing, and revising of the metallurgical manufacturing process.

4.3 Development of preform forging technology

The material flow in axial direction is limited in

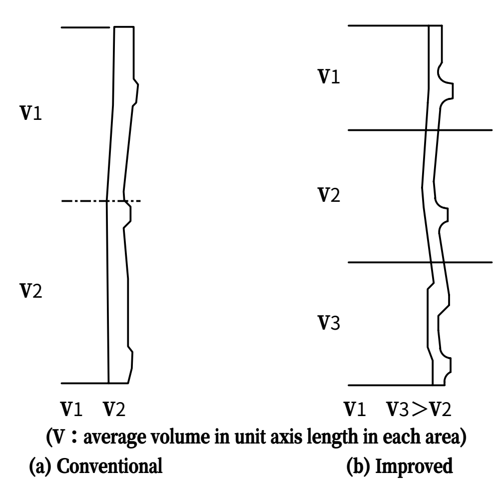

Fig. 6 Comparison of volume distribution in axis direction between conventional and improved rolled rings

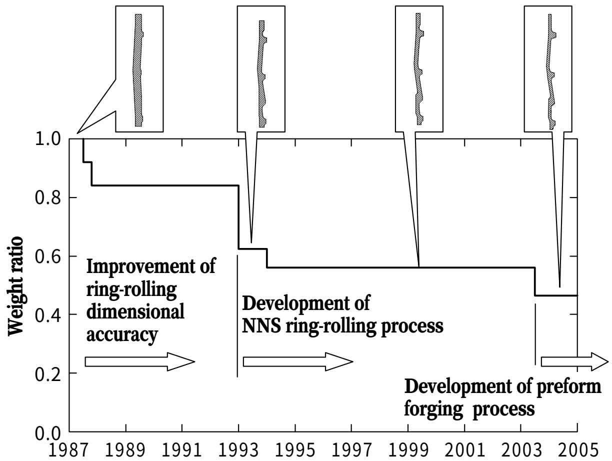

Fig. 7 Transition of weight and shape of NNS ring

Photo 2 Shipment shape of intermediate pressure compressor case

the ring rolling of preforms having rectangular cross sections. We started development of the forging technology for making preforms with complex cross-sections to make the NNS products.

Forging of preforms with complex cross-section requires dimensional accuracy and high efficiency within the limit of press capacity. The die forging improves accuracy but requires a large forging load. On the other hand, free forging requires long process time to assure accuracy. We conducted deformation analyses considering the forging load and filling of ribs and developed a free forging process to produce preforms with accurate dimensions at a high efficiency. The preforms produced by the forging process were ring rolled to NNS. As a result, the consumption of the material was reduced by 55% compared to that at the beginning of the project.

Figure 7 shows the transitions of weight and shape of NNS rings. The development of NNS ring roll technology has reduced the wall thickness and has made the cross- sectional shapes more complex.

The manufacturing cost of the product was pursued in depth and has been reduced significantly. In addition to the reduction in the material consumption described above, ingot cost was reduced by the development of a new melting technology which allows recycling of scraps generated in the machining process. New developments in material structure control technologies eliminated a few process steps from the billet-making process and perform-making process. The machining time was shortened by optimization of cutting conditions.

We currently hold a 100% market share of the product, which has become one of the major items of our division.

5. Extension of ring rolling technology

In 2003 we succeeded in receiving an order of another large ring product, the IPC case for the TRENT900 engine, and started production. Four of those engines are used to power a new large airliner, Airbus A380 (double-decker, standard passenger seats 555, max. 800), of which commercial flight is planned in 2006.

The case is featured by its conical shape and outer ribs with relatively smaller diameter of approx. 1,200 mm and height of approx. 500 mm (**Photo 2**).

Conventionally, there are two methods of producing a conical ring. One is to machine from a rolled ring with rectangular cross section and the other is to roll a ring of circular truncated cone from a preform of an analogous shape. The former method suffers from low yield and the latter faces difficulty of making the preform in circular truncated cone. We have developed a new process of rolling a tapered ring of circular truncated cone from a preform having a rectangular cross section. The NSS ring products have been produced in the shape of a circular truncated cone with outer ribs.[4)]

Conclusions

Since we received the first order of the fan case front for the V2500 engine, we have developed and installed our own large ring-roll mill and started the development of NSS ring production technologies. Cooperation from other departments including the Technical Development Group, Cast and Forged Steel Factory and Kobelco Research Institute, Inc. helped us to continue the technical development. The large ring product, which currently enjoys significantly reduced cost and 100% market share, has grown to one of our major items of titanium products.

It is a product resulting from the foresight of our predecessors and of our continuous development effort.

Moreover, it has provided technological basis for the development of the TRENT900/IPC case which won us a new order after cost competition with overseas manufacturers.

We will continue development of large rings including the TRENT1000/IPC case for the B787 to further establish our global position in large rolled rings.

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