

Development of Fixture Jig for High-precision Turbine Blade Machining

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ABSTRACT

A machining jig optimized for high-precision machining of turbine blades, which are principal parts in aviation gas turbine engines, was developed. The objective was methods of manufacturing that are high-precision, low-cost, environmentally considerate, and capable of application to mass production.

Turbine blades are airfoil parts with three-dimensional geometry, and they are the most important parts in determining the performance of high-speed engines. They are manufactured by precision casting because they employ large amounts of heat-resistant alloys that are difficult-to-machine materials. The blade attachment part has a special shape and requires high precision, and is therefore finished by precision machining. It used to be that low-melting-point alloys would be poured into a fixture jig, using the airfoil surface geometry as a reference, and the piece would then be machined. However, fixing the blade in place and removing it involved a high-temperature dissolution process, and the labor required for the manual steps made this method unsuitable for mass production.

An alternative material was sought in the recyclable, low-cost resins used in motor vehicles. The resin jigs were in a compact form machined to standards that would allow multiple blocks to be placed on the machining equipment; the material could be formed simply using the insert molding manufacturing process; it possesses the rigidity to allow high-precision machining; removal of the jig after machining would not result in blade deformation; and the resin should be recyclable. Based on experimentation, PPA was selected as the material and adopted for the fixture jig.

1. Introduction

A gas turbine engine is made up of a compressor, a combustor, and a turbine. These engines are used to propel aircraft as well as to drive propellers, generators, vehicles, and so on. Air being taken in continuously is pressurized in the compressor after which fuel is added and then ignited in the combustor, yielding combustion gas that contains high energy from combustion. This combustion gas is then directed into the turbine, where part of the energy is extracted in the form of rotary movement. This rotary output is the source of power that drives the compressor. The turbine blades (hereafter referred to as blades) are among the parts that make up the turbine, and they consist of an airfoil portion on which the combustion gas acts and a tree portion that is mounted on a disk. This tree portion is designed and formed to hold the blade to the disk and to withstand centrifugal force when the turbine is rotating. That portion is called the tree because it resembles a Christmas tree in shape, and since it is a critical part, it

requires surface roughness and dimensional accuracy on the micron order. There are also blades that have a structure called a shroud at the outside end of the airfoil such that the shrouds form a ring around the periphery when the blades are mounted on the disk. This structure helps keep gas from escaping and helps prevent resonant vibration in the blades (Fig. 1).

A heat-resistant Ni-base alloy is used for the blades. Creep strength against centrifugal force is important. Therefore, the rate of solidification is regulated during the precision casting process so that there will be no crystal grain boundaries transverse to the tensile stress, thus yielding a single crystal or a directionally solidified material. Heat-resistant alloys have low thermal conductivity and are rigid, tough, difficult-to-machine materials. Consequently, cutting tools experience large amounts of wear, and machining costs are higher. Blades are also difficult parts to position and immobilize for machining, making them a factor in increased manufacturing cost.

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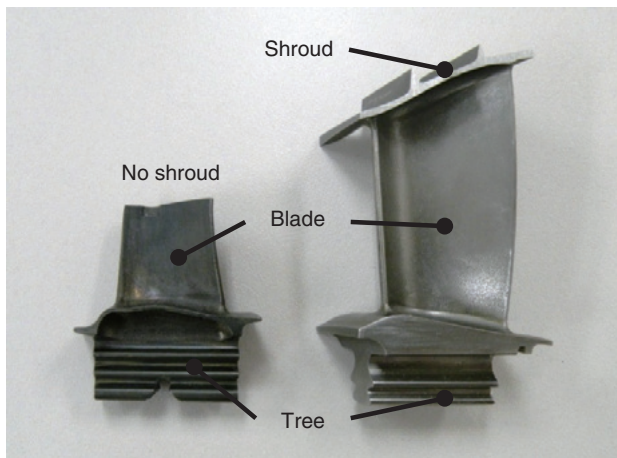


Fig. 1 Image of turbine blade

2. Blade Machining Process

2.1. Overview of the Process

First, an ingot of heat-resistant alloy is heated and melted in a vacuum and precision cast to create blade material. The blade material is then positioned using a fixture jig, and the tree and shroud portions are machined. Dimensional inspections are carried out during this process. After machining, the fixture jig used to immobilize the blade is removed, burr is removed, the surface is polished, and the piece undergoes a washing process. A completion inspection is then conducted. The airfoil portion satisfies the design requirements for dimensional accuracy and surface roughness in the precision casting state, so no machining of it is done and the material is used as it is. The tree and shroud portions cannot satisfy the design requirements the way they are as they come out of precision casting, so they go through the finishing process by machining.

2.2. Former Method of Immobilizing Blades and Issues Involved

The only place that can be used to immobilize the tree portion and the shroud portion for machining is the airfoil portion, which does not undergo machining. If the piece is held in place by means of the airfoil directly, however, the airfoil may be deformed, so machining cannot be performed in that way. Consequently, a fixture jig that can hold the airfoil and not deform it is needed. The fixture jig is attached using the airfoil as reference, and it serves as a retainer during machining.

There are different methods of using the fixture jig. In one, the piece is held by clamping the airfoil part with a form jig, and in the other, the airfoil part is enfolded in some kind of immobilizing material. The method of clamping it with a form jig necessitates preparation of the same number of jigs as blades that will be machined simultaneously, for each type of blade. This means that the initial jig fabrication cost is high. This method is also unable to deal with variations

in the dimensions of the airfoil portion created by precision casting, and it can cause damage to the airfoil surface when clamping it. It can also happen that the position slips during machining due to inadequate immobilization, so that dimensional errors occur. Consequently, the method of enfolding the airfoil portion in an immobilizing material was adopted, and a low-melting-point alloy that dissolves at approximately 200°C was used as the immobilizing material. However, when the blades were being immobilized, and when the low-melting-point alloy was being removed after machining, it was necessary to heat and then cool the blades and the low-melting-point alloy, and the long lead time was an issue. When removing the material, the alloy foreign matter that remained on the blades had to be removed by hand, further lengthening the lead time. Other issues included the fact that the low-melting-point alloys are heavy and not easy to handle, and that the materials cost was high.

3. Immobilizing the Blades with Resin

3.1. Immobilization by Fiber-Reinforced Thermoplastic (FRTP)

Consideration of a fixture jig that is more inexpensive, lighter, and allows lead time to be shortened resulted in the decision to replace low-melting-point alloys with fiber reinforced thermoplastic (FRTP) as the immobilizing material. Thermoplastic cools and solidifies rapidly, and it can immobilize a blade with insert molding within several minutes. Another company has applied for a patent on a method of immobilizing blades using resin that is not fiber-reinforced, but the use of FRTP (hereafter resin) can enhance the rigidity of the fixture jig. The fixture jig does not deform even under a greater machining load, which means that the blade machining conditions can be made better and enhanced machining efficiency and quality can be expected.

In order to select a resin, it was necessary to perform a comprehensive evaluation and judgment of formability, blade machining efficiency, ease in removal of the resin, and resin material costs. The suitability of resins cannot be judged solely by their characteristic values alone. Therefore, a number of resin types were selected, subjected to tests of forming and removal, and judged accordingly. This article will focus on forming of the blades before machining and on removal after machining, which are characteristics of this process. Tests of forming were conducted first. The characteristic values of resins vary greatly with the state of forming. Formed items were therefore observed, the dimensions were measured, and the molding conditions were set to optimal levels for demonstrating resin performance. Tests of removal were then conducted and resin removal methods were decided. Figure 2 shows the blade materials and the external appearance of the resin fixture.

3.2. Forming Mold

The blade material is made by precision casting with a dimensional tolerance greater than 0.05 mm. Consequently,

it was necessary to set the gap between the blade material and the mold to be greater than the 0.05 mm thought to enable insert molding. This gap became a cause of resin leakage, and it caused a deterioration in resin dimensions and mechanical properties. It was necessary to address these issues by means of the molding conditions (Fig. 3).

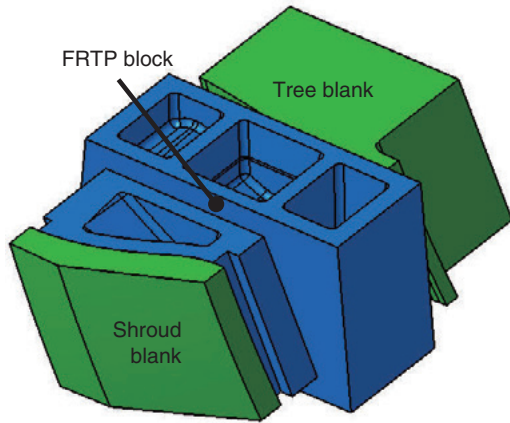


Fig. 2 Overview of turbine blade with F RTP block

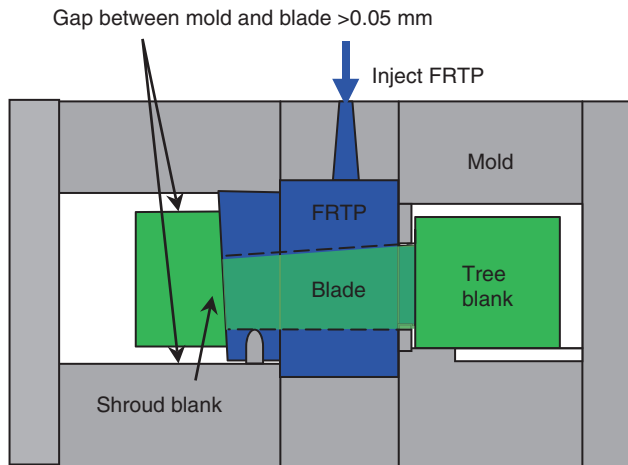


Fig. 3 Section view of insert mold

4. Immobilization of the Blades

4.1. Selection of the Resin

Consideration of the below items in connection with selection of the resin resulted in identification of three candidates for immobilizing material. These are polyphthalamide (PPA) reinforced with glass fibers, polylactic acid (PLA) reinforced with bamboo fibers, and polypropylene (PP) reinforced with glass fibers (Table 1).

(1) Chemical resistance

This is the resistance of a resin to chemicals. Resins that are not attacked by and do not have their properties changed by the cutting fluids, cleaning fluids, oils, and other such substances employed are used.

Table 1 Material data sheet of selected F RTPs

	PPA	PLA	PP
Resin content	Polyphthalamide	Polylactic acid	Polypropylene
Fiber content	Glass	Bamboo	Glass
Fiber weight ratio (%)	45	60	40
Density (kg/m ³)	1560	1390	1220
Young's modulus (GPa)	13.8	4.4	9.5
Charpy absorbed energy (kJ/m ²)	10.3	3.3	37
Mold shrinkage (%)	0.6	0.3	0.7

(2) Coefficient of elasticity

This is a mechanical property that serves as an indicator of the rigidity of the fixture jig. The larger the value, the smaller the amount of jig deformation when a load is applied.

(3) Cost

Commercially available resins that are reasonable in cost, readily obtainable, and distributed in large volumes are used.

(4) Mold shrinkage

This value affects the dimensional accuracy and deformation of the formed item. The smaller the value, the less the amount of shrinkage during solidification. Lower anisotropy is preferable.

(5) Impact strength

This value is an indicator used to judge susceptibility to cracking when the resin is removed. It indicates the amount of energy required to destroy the resin when an impact load is applied to it. Resins with smaller values are considered to be more susceptible to cracking.

(6) Environmental suitability

Resins that impose a lower environmental burden are used. Resins are judged on whether or not they can be recycled, whether or not they are biodegradable, and other such properties of materials that are readily disposable.

4.2. Molding Conditions

Resin for forming should ideally have positive flowability, should fill the mold from corner to corner under low pressure and in a short time, and should cool and solidify evenly. In the blade insert molding that is the subject here, however, there was a large gap between the blade material and the mold, as discussed above, and resin leakage occurred under the molding conditions recommended by the resin manufacturer. An effort was therefore made to lower the resin flowability in the vicinity of the gap in order

to help prevent resin leakage. Conceivable methods for lowering the resin flowability were lowering the melting temperature and lowering the temperature of the mold. The method of lowering the melting temperature reduced resin flowability so that it was necessary to increase the injection pressure, which was at cross-purposes with prevention of resin leakage. Lowering the melting temperature also increased the likelihood of embrittlement due to insufficient melting. The method of lowering the melting temperature was therefore judged to be inappropriate. The method of lowering the mold temperature does not have drawbacks like those noted above. Ordinarily, no change is made to the mold temperature, but this represented a new attempt at localized control of the flowability of resin in contact with the mold without increasing the injection pressure. It was therefore determined possible that this could broaden the range of applicability of injection molding.

The following four molding conditions are parameters that should be adjusted:

(1) Resin temperature and resin injection pressure

Higher figures for both resin temperature and injection pressure yield more favorable resin flowability. This makes forming and filling easier to perform, but the resin becomes more susceptible to leaking. The resin temperature is set relatively high to where there is no resin leakage and in the range within which the resin does not undergo thermal decomposition. The resin injection pressure is to be set starting at a low figure, and is to be adjusted according to filling conditions.

(2) Mold temperature

When the mold temperature is higher, the resin inside the mold is less likely to cool and the resin flowability is more favorable, so that it is easier for the resin to fill the mold. In general, the mold temperature is set somewhat higher than the glass transition temperature of the resin, but the resin is then more susceptible to leaking. This also results in greater shrinkage of the resin during cooling, which can cause sinking to occur. The mold temperature is therefore to be set at a level as low as possible while still maintaining sufficient resin flowability for filling.

(3) Injection speed

Higher injection speeds mean that the resin is fed into the interior of the mold more quickly. The resin retains positive flowability while filling the mold, so that the filling density is greater, as is the mold shape repeatability. At higher injection speeds, however, the resin is more susceptible to leaking. The injection speed is to be set to a high level in the range within which resin leakage will not occur.

(4) Holding pressure

Higher holding pressures allow the resin to be fed in without interruption while it is solidifying, so that the filling density is greater. However, the resin becomes more susceptible to leaking. Furthermore, the application of excessive holding pressure will cause the residual stress in the resin interior to increase, resulting in deformation when separated from the mold. The holding pressure is to be set

high at a level that does not cause resin leaking and where deformation does not occur.

In order to help prevent the occurrence of resin leakage, the mold temperature this time was set somewhat low, the injection speed was adjusted to be as high as possible in the range within which mold leakage would not occur, and tests were conducted to determine the optimal conditions. Raising the injection speed results in the resin filling the interior of the mold before resin flowability decreases. This results in positive resin uniformity and reproducibility of the product shape. The relationship between mold temperature and injection speed will be described using the example of PPA (Fig. 4).

The glass transition temperature of the PPA used was 123°C, and the manufacturer's recommended mold temperature was 135°C or higher. The present testing, however, was conducted with the mold temperature set at 100°C and 120°C. The testing with a mold temperature of 100°C resulted in insufficient filling and a defect in appearance called a weld line, which is a remnant of the boundary line where two bodies of cooled resin come into contact with each other. The injection speed was raised higher in an attempt to ameliorate the defect, but resin leaking occurred at a point before the defect was eliminated. The resin flowability therefore was not enhanced and it was not possible to fill the mold sufficiently. When insufficient filling occurs, the mechanical properties of the resin cannot be fully brought out. It was judged, therefore, that appropriate conditions could not be set at a mold temperature of 100°C.

At a mold temperature of 120°C, the increased temperature of the mold enhanced resin flowability and also enabled its control. Raising the injection speed eliminated the resin filling insufficiency and the weld line at a point before resin leaking occurred. The results of the testing clearly showed the injection speeds that adversely impacted resin leaking and process yield rate, and made it possible to discern the optimal injection speed.

Next, the relationship between the holding pressure and resin injection pressure will be described using the

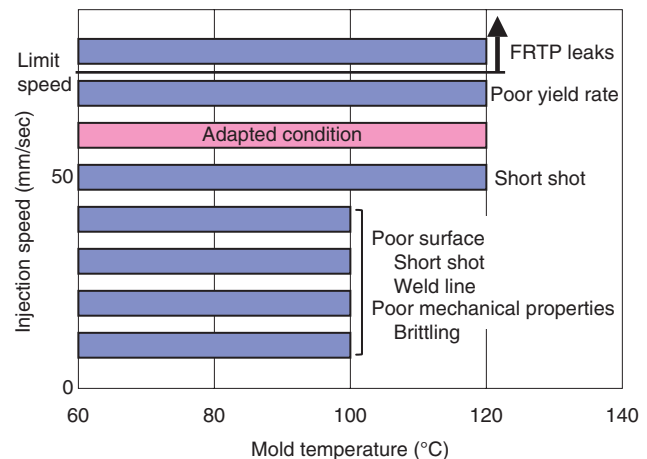


Fig. 4 Injection speed - mold temperature diagram

examples of PP and PPA. Injection molding can be divided into the injection process of filling the mold with resin and the cooling process of solidifying the resin. The pressure applied in order to extrude the resin in the injection process is termed the injection pressure, and the pressure applied during the solidification process is the holding pressure.

The resin shrinks during cooling and solidification. When this shrinking causes a gap to form between the mold and the resin filling the mold, the rate at which the resin not in contact with the mold cools becomes slower than that rate of the resin that is in contact with the mold. This difference in the cooling rate causes residual stress in the interior of the resin, and this can cause deformation of the formed product. Feeding in additional resin can be an effective countermeasure for this, if the resin is maintained in a state of flowability.

The injection pressure is decided by a comprehensive consideration of the type of resin, the melting temperature, the mold temperature, the mold geometry, and other such factors. Here, the forming is being controlled by means of the injection speed, and the injection pressure was set to as low a level as possible. The holding pressure enhances the resin filling density and contributes to retention of contact with the mold. This factor is important in the insert molding of blades, therefore, in order to keep the resin and blade in close contact and immobilize the blade securely. Consequently, the holding pressure was set as high as possible within the range that would not cause leaking of resin but would allow a favorable yield rate.

Tests were conducted on the relationship between injection pressure and holding pressure in PP and PPA (Fig. 5). The test results for PP will be explained first. The glass transition temperature of PP is lower than the ambient temperature, and adequate flowability is shown even when the mold is at room temperature. Testing to confirm the status of resin filling was therefore carried out with the injection pressure set to a somewhat low 50 MPa, and the holding pressure raised from 20 MPa, which was below that injection pressure. Even with the holding pressure set to the same 50 MPa as the injection pressure, shrinkage still resulted in major sinking, and insufficient filling and deformation

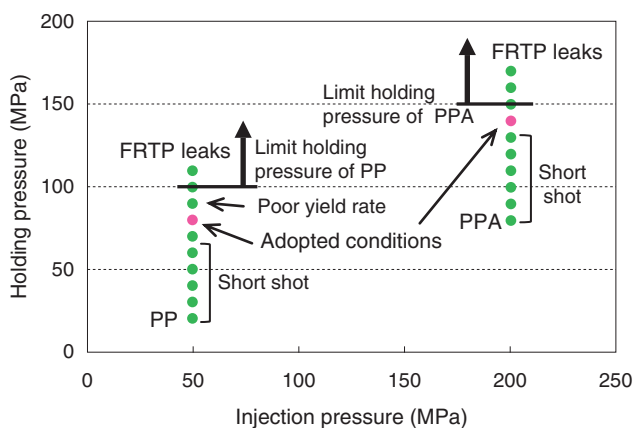


Fig. 5 Holding pressure - injection pressure diagram

occurred. It was determined that when the holding pressure was raised higher than the injection pressure, however, the sinking was ameliorated and resin leaking did not occur until the holding pressure reached 100 MPa. In light of the yield rate, a holding pressure of 80 MPa was finally adopted.

Next, the results of PPA testing will be described. With PPA, the mold temperature is lower than the glass transition temperature, and the injection speed is also set somewhat lower. Consequently, the flowability is conspicuously reduced. The injection pressure was then set to 200 MPa, which is somewhat higher than the manufacturer's recommended value, and the holding pressure was raised from 80 MPa, which was lower than the injection pressure, as in the case of the PP, to check the filling status. With the holding pressure at 80 MPa, the filling was somewhat insufficient and deformation was observed, but these were ameliorated as the holding pressure was raised. Resin leaking was confirmed to occur when the holding pressure exceeded 150 MPa. In light of the yield rate, therefore, it was judged that 140 MPa would be the optimal value. This value is lower than the injection pressure.

The forming tests conducted in this way made it possible to set molding conditions that would not result in resin leaking with either PPA, PP, or PLA. Figure 6 shows the example of insert molding of a blade with a PPA fixture.

The selection of a resin was made according to the judgment regarding removal of the resin.

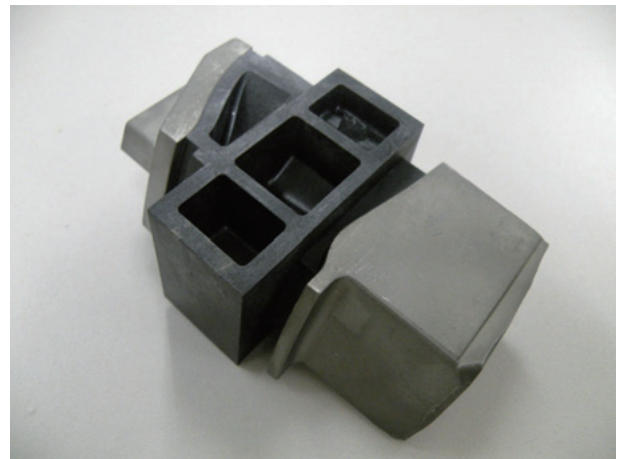


Fig. 6 Turbine blade with F RTP block

5. Resin Removal

5.1. Method of Removal

The resin that has immobilized a blade must be removed safely, simply, and in a short time after machining. The following five methods of removing the resin were compared and considered. The breaking method was judged to provide the greatest work efficiency because it did not cause any temperature change in the blade or resin and it allowed easier handling.

(1) Burning

This is a method of igniting the resin and burning it. The blades are heated to a high temperature, so there are concerns about oxidation, pollution, deformation, and so on. There are safety-related issues, as well, and it becomes impossible to recycle the resin.

(2) Heating

In this method, the resin is heated by placing the blade in a furnace or by some other such means, where it is melted and removed. This requires removal of resin that adheres to the blade surface. It is possible to recycle the resin.

(3) Chemical treatment

This method employs chemicals, ultraviolet radiation, or other such means to embrittle the resin and remove it. The process takes a long time and it requires extensive equipment to assure worker safety, making this method more costly. It is not possible to recycle the resin.

(4) Cooling

This method uses liquid nitrogen or other such means to cool the resin and cause embrittlement so it can be removed. It requires a refrigerant and necessitates measures to assure worker safety. It is possible to recycle the resin.

(5) Breaking

In this method, a load is applied to the resin to break it so it can be removed. There is no temperature change and the method is easy to handle. It is possible to recycle the resin. However, the blade must not be deformed by the load applied to the resin during removal.

5.2. Resin Removal by Breaking

The method of removing resin by breaking presupposes that the blade will not be deformed. Consequently, it is necessary to reduce the load applied to the resin.

Testing was carried out on blades without shrouds or undercuts. A hydraulic hand press was used to apply a load directly to the resin, and cracks were made to spread from wedge-shaped notches made in the bottom surface of the resin by the tensile stress of bending (Fig. 7).

The load this required for breaking in the case of PPA was 1800 N, for PLA 500 N, and for PP 1500 N. No adhesion of resin to blades nor deformation of blades was observed

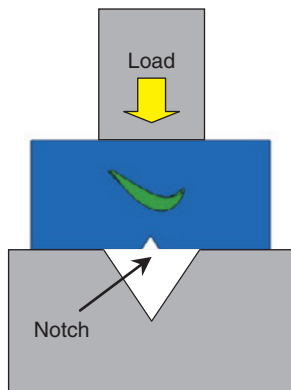


Fig. 7 Breaking method with notch

with either PPA, PLA, or PP. The cracks that formed in the PPA and PLA spread instantaneously from the front edge of the airfoil cross-section to the opposite side so that the resin broke into two pieces that could be removed from the blade as they were. With the PPA, the application of a load caused the hand press cylinder to press several millimeters into the resin block. After the PPA deformed, cracks formed in the notches and the PPA broke apart. The PLA showed particular fragility, such that the resin block broke apart even before it had been pushed in to any extent at all, allowing removal from the blade. With the PP, the progress of cracking stopped partway through. Even if the wedges were pressed in to apply further load, the resin only deformed and it could not be removed from the blade. The blade could not be removed solely with the process employing a hydraulic hand press, so the resin was broken manually and removed. The PP was judged to be a disadvantageous resin for purposes of removal and was therefore removed as a candidate material (Fig. 8).

No deformation of the blades occurred in this testing. However, the breaking method uses deformation of the resin block to cause cracks to form at the notches. In the case of blades with low rigidity, therefore, there is concern about possible deformation of the blade, so this method was judged to be impractical. Use of resin breaking methods that would not be affected by blade rigidity was studied, and the method of breaking the resin by applying a load locally was devised. The following test was performed using PPA and PLA. Wedges were pressed into the notches made in the top and bottom surfaces of the resin and load was applied locally. When this is done, the notches made in the resin serve as guides for the wedges (Fig. 9).



Fig. 8 Results of breaking method with notch

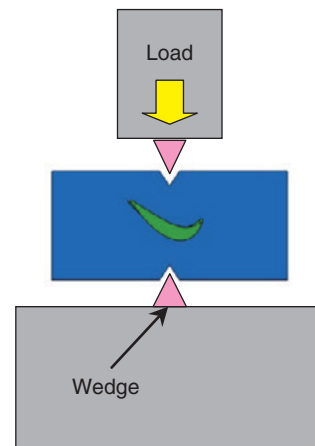


Fig. 9 Breaking method with 2 wedges

Table 2 Comparison of breaking load

	Breaking load	
	Notch	2 wedges
PPA	1800 N	100 N
PLA	500 N	30 N
PP	1500 N	N/A

Results of the testing showed that the load necessary for breaking the PPA was 100 N or less, for the PLA it was approximately 30 N, and there was no deformation in the blades after removal (Table 2). This was a significantly smaller load than was applied for breaking in the preceding tests, and the deformation in the resin when cracks formed was localized and smaller. It was found that the method of using wedges to apply a load caused cracks to form in the PPA and PLA, enabling breaking.

5.3. Examination of the Number of Breaks

The discussion to this point has covered blades that do not have shrouds. However, the actual blades have shrouds that extend around the outer periphery, and some undercutting is therefore involved. In the case of blades with shrouds, the inside part of the shroud and the airfoil surface side of the blade have an undercut shape. Because of this undercutting, the resin cannot be removed with two breaks. The approach of breaking the resin apart into smaller pieces in order to remove the resin from the undercut portions was examined.

Breaking the resin into three pieces was considered first. The PPA and PLA had wedges placed at one location on the top surface of the resin and at two places on the bottom surface. Figure 10 shows a simplified view of the jig when breaking takes place.

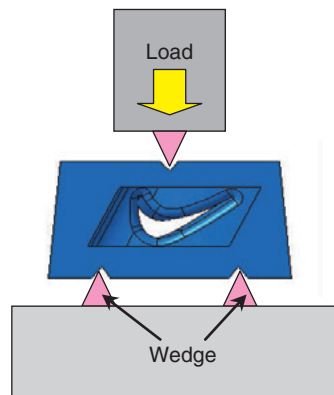


Fig. 10 Breaking method with 3 wedges from 2 sides

Table 3 Results of breaking method with 3 wedges from 2 sides

	Breaking load	Results	Yield rate (%)
PPA	500 N	Crack was unstable. Half of blocks were left.	50
PLA	50 N	Crack was unstable. 90% of blocks were left.	10

The breaking was unstable with both the PPA and PLA, and there were cases in which the resin could not be removed. The yield rate was approximately 50% with the PPA and approximately 10% with the PLA (Table 3). Wedges were placed at two locations on the bottom side, but cracks formed at only one or the other of the wedges on the left and right, while no cracks at all formed at the other of the two wedges. In the testing, symmetrical formation of cracks at both wedges at left and right on the bottom surface of the resin occurred only rarely. Cracking proceeded asymmetrically left and right (Fig. 11).

With the PLA, discoloration and adhesion of resin to the blade airfoil surface was observed. This phenomenon was not found on blades without shrouds, and it is considered to have occurred due to differences in the mold and the molding conditions in the case of blades with shrouds. As a result, it was judged the PLA was unsuitable for blades with shrouds, and PLA was removed from the candidate materials.

Based on the results from the method of breaking the resin into three parts, it was determined that there were issues with the method of placing wedges at two locations on one surface. The placement of the wedges was therefore reexamined with a view to causing stable cracking. The method of using four surfaces of the resin with a wedge placed at one location on each surface was therefore adopted. Calculation of the stress distribution by means of the finite element method (FEM) showed that increases in stress in the vicinity of the wedges occurred locally with this method, and it was anticipated that deformation of the block would be limited and there

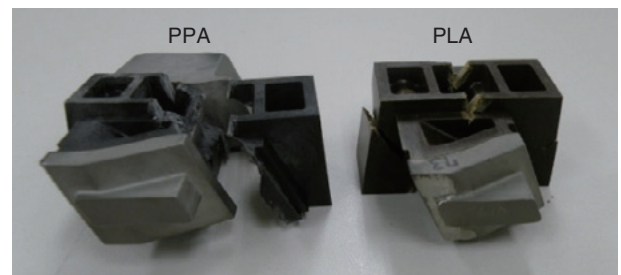


Fig. 11 Result of breaking method with 3 wedges from 2 sides

would be no impact on the blades (Fig. 12).

A special jig was fabricated to enable application of a load to four surfaces in a single process using a hand press. This is a mechanism that uses the descending motion of a cylinder to sandwich the resin from top and bottom and from left and right (Fig. 13).

The test with wedges placed at one location each on four surfaces was conducted only with the PPA. The load of 200 N applied in the test resulted in uniform cracks forming on all four sides, and it was able to produce stable breaking. The resin at the problematic undercut portions was also successfully removed. Repetition of the testing confirmed that stable cracking would occur (Fig. 14). Moreover, the

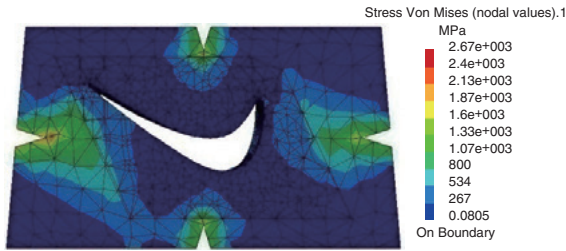


Fig. 12 Stress contour of F RTP block

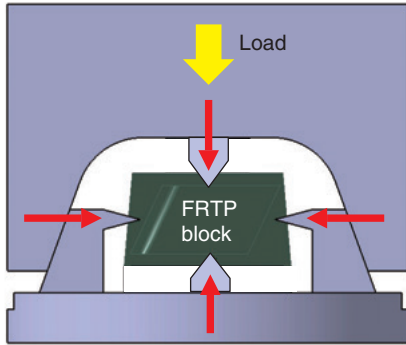


Fig. 13 Breaking method with 4 wedges from 4 sides

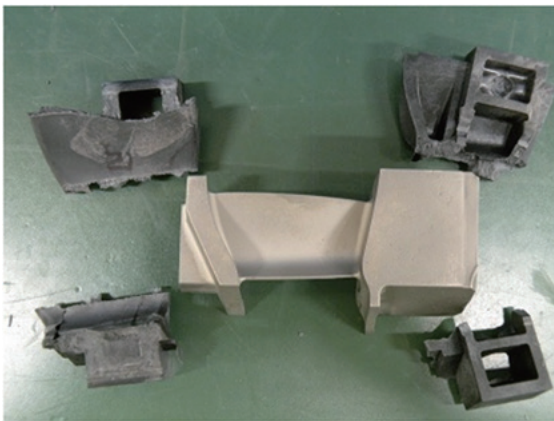


Fig. 14 Result of breaking method with 4 wedges from 4 sides

time required for the process of removing the resin was approximately one minute, and it was confirmed that the resin could be removed from a blade safely and in a short time. This breaking method was therefore adopted, and PPA, which had been demonstrated in resin removal testing as readily developing progressive cracks and not adhering to the blade, was selected as the blade immobilizing material.

6. Conclusion

- (1) The optimal conditions were found for the process of immobilizing blades using resin, for locally controlling the flowability of the resin that is in contact with the mold surface during insert molding, and for forming the piece without leaking of resin from the gap between it and the mold.
- (2) A method was found for breaking the resin apart to safely and efficiently remove it from the blade using a hand press and a special jig. This method also facilitates recycling of the resin.
- (3) PPA, PP, and PLA were selected as materials for use in immobilizing the blade. Testing performed to compare them by forming, machining, and resin removal resulted in selection of PPA as the optimal material.

The above made it possible to replace low-melting-point alloy with PPA as the material for the blade fixture jig. The process was thereby simplified and shortened, and it became possible to reduce the cost for fixing the blade. The weight reduction also enhanced the handling of the item during work.

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