Machining Technology for Large Impellers of Centrifugal Compressors

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The impellers of centrifugal compressors are becoming larger, requiring machining efficiency to be improved in accordance with the characteristics of 5-axis machining centers and work shapes. Now, the machining time has been reduced by using contour machining, a cutting-resistance-leveling system and a method for predicting chatter vibrations. This paper describes the recent measures taken to improve the machining of large impellers.

Introduction

Recently, the centrifugal compressors used for air-separation units, for example, have been increasing in size and the demand for them is growing. Accordingly, their impellers, the major components, are becoming larger, requiring a long machining time. Hence, the reduction of machining time is an urgent issue in preventing extended delivery times and avoiding a high milling cost.

The impellers of centrifugal compressors rotate at high speeds and must be both highly accurate and strong. Hence, they are mainly shaped by machining. An impeller has blades, each twisted three-dimensionally into a complex shape extending over an adjacent blade in order to achieve a high pressure ratio and high efficiency. These impellers are difficult to machine with the simultaneous 3-axis/4-axis control machining centers generally used for die machining and require machining by simultaneous 5-axis control machining centers.

In an attempt to select a machining method that matches the characteristics of simultaneous 5-axis control machining centers and the work shapes, thus developing a highly efficient method for machining larger impellers, Kobe Steel has adopted simulation technology, which has grown remarkably in recent years. The following is an outline of the machining technology worked on recently.

1. Machining of impeller blades

The shapes of impeller blades are determined optimally after repeating fluid performance analysis, strength/vibration analysis, etc., so as to satisfy all the required specifications from the aspects of performance, strength, vibration and structure. A solid model with typical impeller shape and the names of impeller parts are shown in **Fig. 1**.

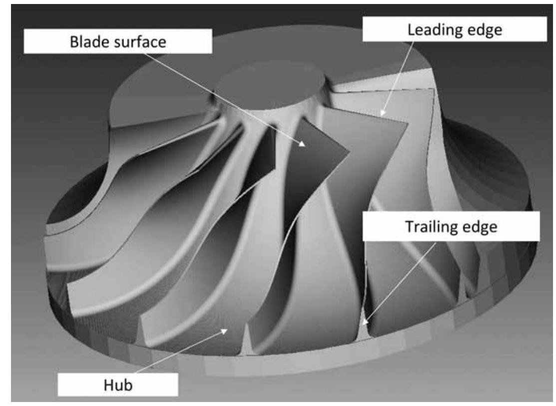

Fig. 1 Solid model of impeller

Free-form surfaces, such as those of impellers, are machined by simultaneous 5-axis machining centers. Simultaneous 5-axis machining centers feature three linear axes and two rotary axes, which are simultaneously controlled in order to adjust the tool attitude as needed to enable the machining of parts with complex 3-dimensional shapes. On the other hand, the 3-dimensional interference between a tool (principal axis) and work/jig must be taken into account, and tool loci must be determined so as to avoid machining at the dead point of each ball end mill, the point at which the circumferential speed of the cutting edge at the tip becomes zero. This makes the preparation of NC programs especially difficult.

Impeller materials include stainless steel that is mainly selected for its strength and corrosion resistance. For example, a titanium alloy with a high specific strength is used for impellers that run at high circumferential speeds. Stainless steel and titanium alloy have poor machinability and are generally referred to as difficult-to-cut materials. In addition, they have thermal conductivities lower than those of other steels, which leads to cutting heat accumulating on the cutting tips, accelerating the deterioration of the tool tips and shortening the tool life. This also adversely affects the finish accuracy of the work piece.

The following summarizes the problems with impeller blade machining:

i) Machining a 3-dimensional shape involves a constantly changing cutting depth and varying cutting resistance.
ii) Structurally, simultaneous 5-axis machining centers have low machine stiffness around their rotary axes and are generally not suitable for

heavy cutting.

iii) Each work piece has a thin shape and, in addition, long tools are used, which promotes chatter vibration, making it difficult to increase the machining speed.

The following measures were taken to solve these problems and to improve the machining efficiency. They are, respectively, i) adopting a technique for leveling cutting resistance, ii) adopting contour machining, and iii) using a tool with variable pitch and variable lead angle and adopting a prediction technique for chatter vibration. The following is an outline of what has been done.

2. Measures for improving rough-machining efficiency of impeller blades

2.1 Technique for leveling cutting resistance

Conventionally, a tapered ball end mill made of high-speed steel as shown in **Fig. 2** was used for the rough machining of impeller blades. As impellers have become larger, the tools for rough machining have increased in size, accompanying an increased cutting depth and, consequently, increased cutting resistance. This has made machines more likely to stop due to overloading and caused tools to break during machining. As a result, machining conditions such as the cutting depth and feed rate must be eased, making it difficult to improve machining efficiency by simply using larger tools.

A possible cause of tool breakage, other than increased cutting depth and the associated increase in cutting resistance, is the increased tool length, adapted in order to avoid interference between a work piece and the machine during the machining of impeller blades. Such a tool is more likely to deflect. In addition, the machining of complex 3-dimensional shapes such as impellers involves a cutting depth and tool attitude that change constantly, along with a constant change in cutting resistance. To prevent tools from breaking, machining must be performed under cutting conditions that are eased to maintain the resistance as low as possible, which poses the problem of increased machining time.

Hence, in order to reduce the variation in cutting resistance, a technique for leveling cutting resistance has been adopted. A system adapting this technique is shown in **Fig. 3**. This system employs a cutting-resistance model in accordance with the materials, tool-shape data, a material shape model and an NC program (tool loci) to geometrically calculate the amount of contact between the material and tool. This enables the calculation of cutting resistance in chronological order.

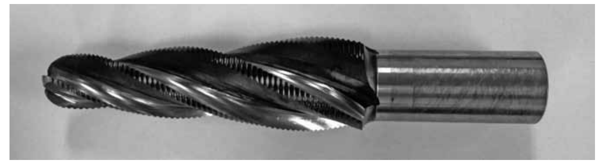

Fig. 2 Tapered ball end mill made of high-speed steel for roughening

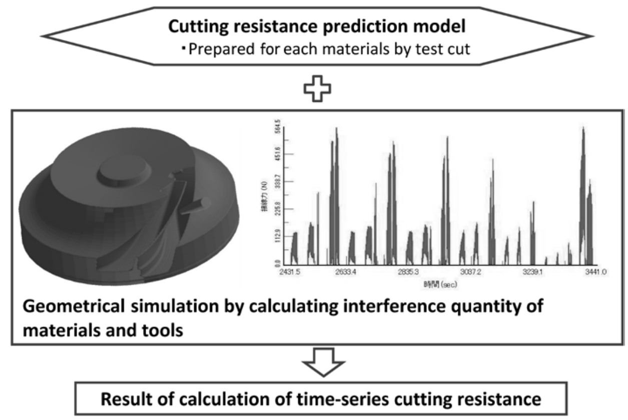

Fig. 3 Conceptual diagram of cutting-resistance-leveling system

In addition, inputting the threshold for maximum cutting resistance and executing recalculation enable the leveling of cutting resistance. This makes it possible to reduce the feed rate for portions with high cutting resistance in order to decrease the cutting resistance and to raise the feed rate for portions with low cutting resistance, which increases the cutting resistance. As a result, the variation in cutting resistance can now be suppressed without changing tool loci. An example of cutting-resistance leveling is shown in **Fig. 4**. It should be noted that the thresholds for cutting resistance have been compiled in a database after test machining in accordance with material, tool size and cutting depth.

This cutting-resistance leveling has stabilized the machining. As a result, the feed rate has been improved by approximately 60%, and the cutting depth has been increased by 25% in the radial direction and by approximately 30% in the axial direction. In addition, the stabilized variation in cutting resistance has decreased the risk of biting due to tool deflection and tool breakage, enabling the reduction of the allowance for finish machining from the conventional 2mm to 1mm. Hence, the finish machining time has also been reduced significantly.

2.2 Contour machining

Contour machining is used mainly for complex shapes such as dies. The machining is conducted

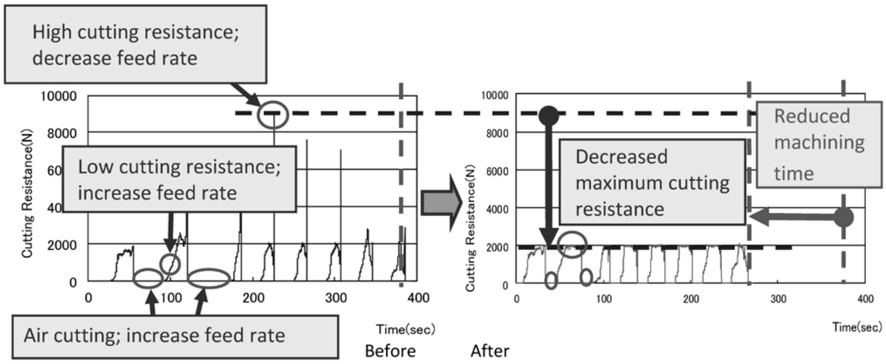

Fig. 4 Example of cutting-resistance leveling

while keeping a constant cutting depth in the axial direction and is thus accomplished with a small cutting depth and high feed rate, which enables highly efficient rough machining even for complex shapes. In such machining with a small cutting depth and high feed rate, more cutting resistance is imposed in the axial direction, or the direction of the principal axis of the machine, while decreasing the cutting resistance imposed in the radial direction. Therefore, even when tools with long protrusion are used, as in the machining of impeller blades, roughness failure due to the lack of tool rigidity can be avoided, as well as the deterioration of tool life; the result is highly efficient machining. In addition, 5-axis machines can run while fixing the rotary axes with low rigidity, which is expected to enable tools with long protrusion to be used with sufficient rigidity to ensure stable machining.

Although contour machining is expected to realize highly efficient machining, its application to impellers requires 3-dimensional determinations of machining ranges and optimum tool attitudes to prevent undercut while avoiding interference between complex-shaped blades and tools. In conventional computer aided machining (CAM), the angles of tool attitudes are roughly designated to prepare the passes for contour machining, and the adequacy of the machining range must be verified repeatedly, which makes it difficult to use conventional methods for preparing NC programs for contour machining. **Fig. 5** shows an example of how a geometrical cutting surface is designed to determine the tool attitude.

On the other hand, the recent development of 3D-CAD/CAM has enabled the machining range and optimum tool attitude to be designated visually on 3D models, permitting the preparation and verification of optimum machining passes in a short period of time. This, as a result, has realized efficient machining with a small cutting depth and high feed rate along the surface shapes of blades for the maximum machining range.

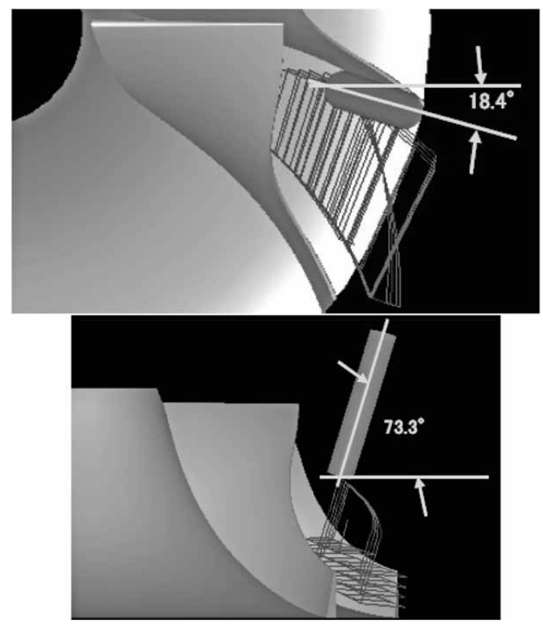

Fig. 5 Example of tool attitude

Compared with the conventional rough machining using a tapered ball end mill made of high-speed steel, machining with a small cutting depth and high feed rate results in a small cutting depth; however, the use of ultra-hard material for the cutting tip can increase the feed rate by a factor of 20 with an expected increase in the amount of chips discharged. On the other hand, due to the small cutting depth, the machining must be conducted with a tool with a rather large diameter. Therefore, a decision was made to adopt this method for the rough machining on the side of trailing edges, which have ample interspaces in between the blades.

Further, a radius cutter with a cutting tip made of ultra-hard material can now be used in place of the tapered ball end mill of high-speed steel used for conventional rough machining, which has shortened the machining time by 17% on average.

3. Measures for improving finish machining efficiency of impeller blades

3.1 Tool with variable pitch and variable lead angle

Fig. 6 schematically shows the machining methods used on leading edges. Cutting with the lateral face of a tool (i.e., flank milling) reduces the number of passes and thus shortens the machining time; however, the lateral face of the tool comes in contact with each leading edge throughout its entire length all at the same time, which results in large cutting resistance. In addition, the work is thin-walled and possesses low rigidity, which causes chatter vibration around the leading edge; this poses a problem in obtaining favorable surface roughness. Therefore, thrust machining using the round chamfer at the tool tip (i.e., point milling) has been adapted to reduce the cutting resistance; this has increased the number of passes and decreased the machining efficiency.

To achieve highly efficient machining, a tool was developed for preventing chatter vibration during flank milling.[quote] There are two types of chatter vibration: namely, forced chatter vibration and self-excited chatter vibration. The large vibration that occurs during machining is mostly attributable to regenerative chatter vibration, a type of self-excited chatter vibration.

Fig. 7 shows the generation mechanism of chatter vibration during cutting.[unquote 1)] During cutting, the relative motion of the work piece and tool generates a slight unevenness on the cutting surface. In addition,[quote] the phase difference between the previously machined wavy surface and currently machined wavy surface causes the cutting thickness (i.e., amount of cutting: the interspace between the solid line and dashed line in the figure) to change periodically (Fig. 7a). This turns into a periodical variation in cutting resistance. Once this vibration exceeds a certain level, it begins to grow, leading to regenerative chatter vibration.

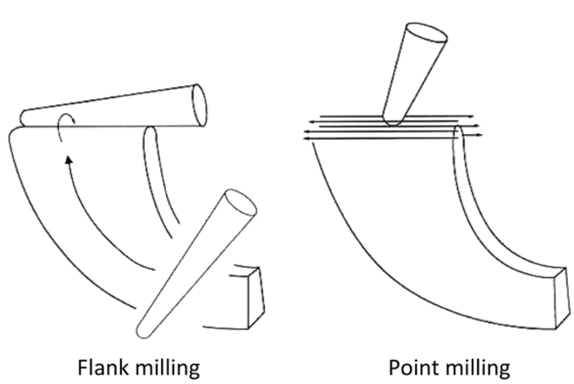

Fig. 6 Flank milling and point milling

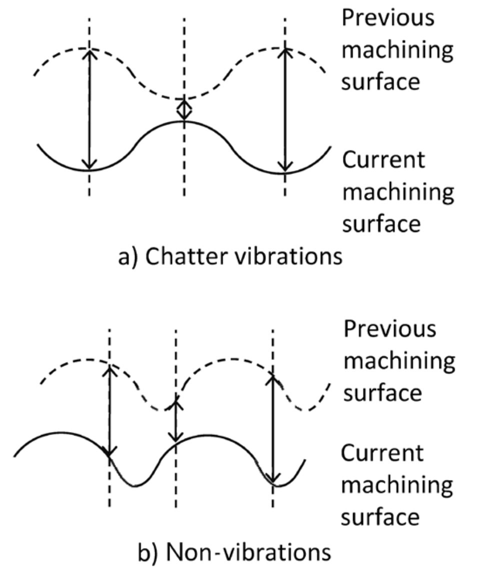

Fig. 7 Mechanism of chatter vibrations in cutting[1)]

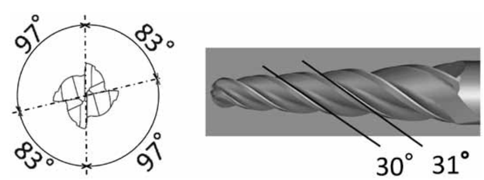

Fig. 8 Milling cutter with variable pitch and variable lead angle

In order to suppress this, it is effective to change the periodicity and/or the regularity of the cutting thickness by, for example, varying the cutting-edge intervals (Fig. 7b).[unquote 1)] This theory has been introduced into the development of a tool with variable pitch and variable lead angle for machining impeller blades. As a result, chatter vibration during the flank milling of the leading edges can now be prevented while yielding satisfactory surface roughness. **Fig. 8** shows the tool with variable pitch and variable lead angle.

3.2 Technique for predicting chatter vibration

Hub surfaces are machined using tools with long protrusion. Thus, an attempt to increase machining speed and/or cutting depth causes chatter vibration to occur, posing a problem in satisfying the surface roughness required. Hence, a study was conducted to adopt a technique for predicting chatter vibration in order to pursue optimum machining conditions for preventing chatter vibration and improving machining efficiency.

This technique predicts the theoretical limit of machining conditions that cause chatter vibration. For the material properties of the work piece, a preliminary 2-dimensional cutting experiment is conducted to determine the relationships among the rake angle, tool tilt angle and cutting resistance value. Next, a cutting force model taking into account the geometrical relationship between the tool (cutting edge) and work piece is used to calculate the value of the cutting resistance. Meanwhile, in order to determine the dynamic characteristics of the tool and machine, the spring constant and viscosity coefficient of the system are determined by conducting excitation experiment of the end mill on the machine. The cutting force and the dynamic characteristics with a tool attached are used to predict the theoretical limit of machining conditions that cause chatter vibration.

In general, the tools used for machining impeller blades come in all different lengths, since they are repolished each time after use. On the other hand, the lengths of the tools used for hub surface machining remain unchanged, since they are of a shrink-fit type whose ball end mill at the tip can be changed, which means that a change of work piece does not affect the dynamic characteristics of the tool. Hence, this prediction technique has been adopted. **Fig. 9** shows a predicted curve for chatter vibration based on this technique. Adopting the technique for the prediction of chatter vibration has enabled an increase in the cutting depth in the axial direction from 0.4mm to 1mm and in the tool revolution from 1,280rpm to 3,200rpm to achieve machining without chattering.

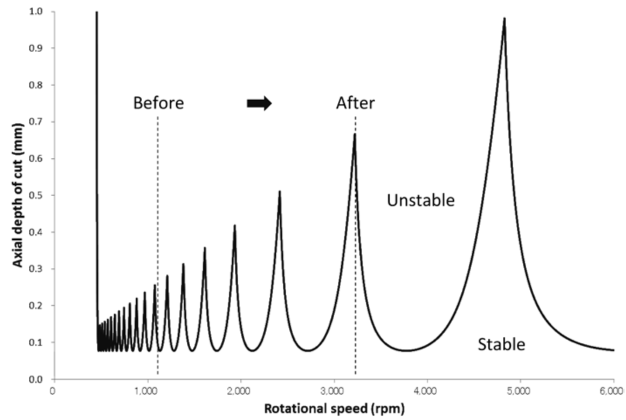

Fig. 9 Improvement of cutting conditions by predicting chatter vibrations

Conclusions

This paper has introduced the problems encountered during the machining of large impellers made by Kobe Steel. It has been demonstrated that these problems can be resolved by optimizing the tools, machining method and machining conditions for large impellers, thereby significantly shortening the machining time. Impellers are likely to become larger, and their machining is expected to become more challenging. Kobe Steel will strive to adopt state-of-the-art machining technologies while maintaining quality and shortening the machining time.

References

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