Title	Dexterous Machining of Unstable Thin Plate
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Citation	Procedia CIRP (2017), 63: 324-329
Issue Date	2017
URL	http://hdl.handle.net/2433/234961
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Type	Journal Article
Textversion	publisher

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ScienceDirect
Procedia CIRP 63 (2017) 324 – 329
www.elsevier.com/locate/procedia

The 50th CIRP Conference on Manufacturing Systems

Dexterous Machining of Unstable Thin Plate

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Abstract

In recent years, miniaturization and light weightedness are required for industrial products as well as high functionality. Thin plates are appropriate in terms of weight, however they are usually difficult to produce only by cutting operation due to the deformation by cutting force or vibration of the thin plate. This study deals with the machining of a twisted thin plate, whose height, width and thickness are 50 mm, 30 mm and 0.1 mm respectively, without using any auxiliary tool. Such a thin plate with high aspect ratio is easily broken down by the cutting force. Thus, the machining of thin plate with high aspect ratio is approached by devising a tool path strategy in this study. As the cutting force easily allows for deformation of twisted thin plate with high aspect ratio, two methods are devised with regard to the generation of the tool path, the method with a supporting frame and the peeling method so that the stiffness of the plate can be kept high. Then, the actual machining of thin plate with high aspect ratio, made of aluminum alloy, was realized without any breakage. As a result, it is found that such cutting method allows the possibility of fabricating such a twisted thin plate.

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Keywords: : Dexterous machining, Twisted thin plate, High aspect ratio

1. Introduction

Modern industrial products with complicated shape consist of a number of simple parts and elements to realize their function. These parts and elements must be manufactured whilst considering inter-compatibility between them. Products are commercialized by combining them with each other. However, in craftworks, the compatibility is not considered, and the complicated shape is often processed as it is by a skilled person. The skilled person copes with such craftworks by making use of innumerable know-how such as the cutting condition suitable for the machining, the fixture of materials, the preparation for special jig and tool, etc. Know-how owned by skilled persons is often thought to be implicit knowledge. If such an implicit knowledge, for example, the know-how such as the fixture of materials and the cutting condition, could be converted to explicit knowledge that can be expressed as an algorithm and technological procedure, it may be possible to produce the products and parts with highly added value like craftworks.

Such machining is called "Dexterous Machining" [1], which can be categorized into four areas as follows,

(1) Machining very complicated shapes [2] [3] [4]
(2) Machining extremely difficult-to-grip/maintain work-pieces
(3) Machining very hard/soft materials [5,6]
(4) Machining very unstable shapes

This study deals with the machining of easily deformable thin plates as part of the "Dexterous Machining" theme.

The turbine blade-shape has high aspect ratio of 500 with twisted plate, as shown in Fig. 1. Thus, the breakage of the thin plate may take place due to the deformation by cutting force and forced vibration.

In the study, two machining methods are proposed to create such a thin plate by using a multi-tasking machine tool [7]. One is to complete the workpiece shape by giving a supporting frame surrounding it and by removing a supporting frame from a workpiece shape after machining. The other is to machine the thin plate like peeling the down words from the upper part.

It is expected that accurate machining can be carried out by these two methods, while suppressing the workpiece

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doi:10.1016/j.procir.2017.03.321

deformation and the chatter vibration, without decreasing stiffness of the thin plate workpiece.

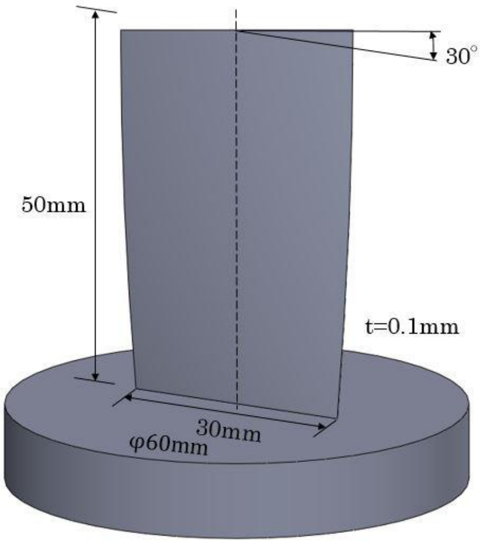


Fig. 1. Example of unstable shape like turbine blade.

2. Machining method with supporting frame

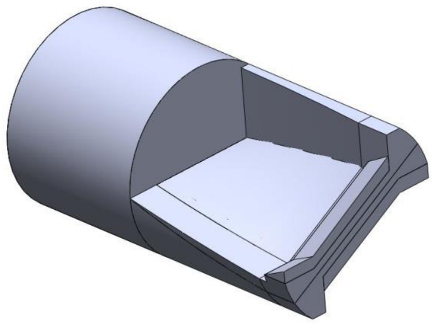
2.1. Outline of machining method

Let us introduce how to add a supporting frame to the workpiece. In making a thin unstable shape with a high aspect ratio, the portion near the root is better machined than the other end in terms of the form accuracy and the surface finish. It is because the portion near the root has increased stiffness. The supporting frame is added in 3D CAD system, taking account of the following two conditions;

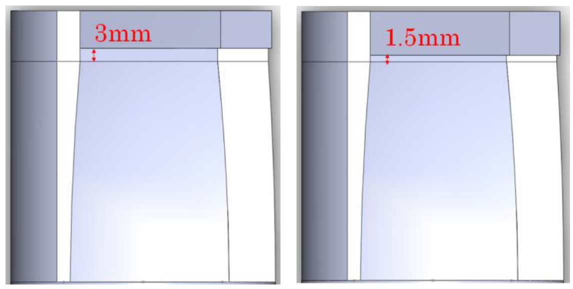
(a) The supporting frame can be cut off from the finished thin plate.

(b) The supporting frame must be added so that the cutting tool can machine the thin plate, while keeping the tool attitude inclined by 30 degrees to both sides against the feed direction, in order to reduce the amount of bending of the thin plate.

Figure 2 shows the shape satisfying the above conditions. To confirm the effectiveness of the supporting frame, analysis by use of Solidworks Finite Element Modelling (FEM) was performed regarding the models with and without the supporting frame. The deformation and strain of the models are compared under the condition that the cutting force is applied at the tip of the thin plate from the direction normal to the plate surface by 30 degrees. The plate thickness is assumed to be 1.3 mm, considering the plate thickness of the rough finishing. The analysis conditions are listed in Table 1. The material used in the simulation and cutting experiment is aluminium alloy A1060, the properties of which are also listed in Table 1.



(a) Whole view of turbine model with frame

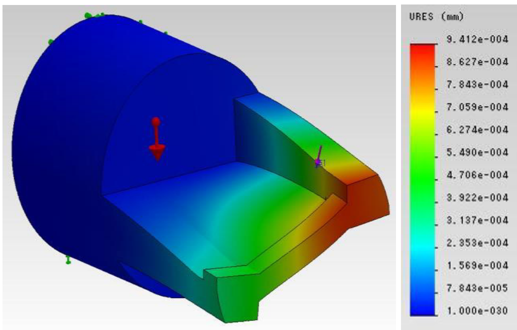


(b) Front view (c) Back view

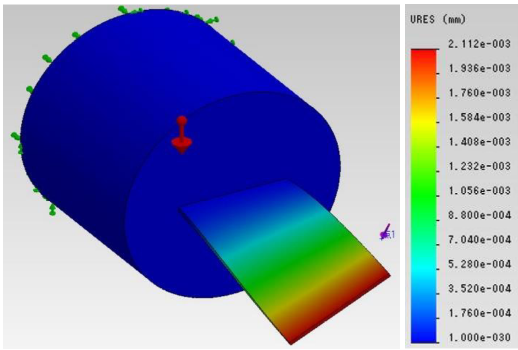
Fig. 2. The turbine blade with frame.

Table1 Analysis Conditions

Maximum element size	0.60 mm
Tolerance	0.03 mm
Load	5 N
Workpiece Material	A1060
Young's modulus	$6.9e^{10}$N/m^2
Poisson's ratio	0.33
Density	2700kg/m^3



(a) With frame



(b) With out frame

Fig. 3. FEM simulation.

The analysis result is shown in Fig. 3. The maximum deformation is 0.94 µm with supporting frame, and 2.1 µm without, which demonstrates the effectiveness of the supporting frame.

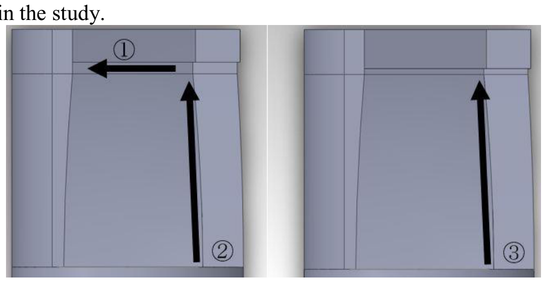
2.2. Tool path generation

Roughing is carried out until the plate reaches 3.0 mm in thickness. In rough-finishing, the machining is done until the plate thickness becomes 1.3 mm. In finishing, the machining is performed on both sides of the thin plate by turns, with the cutting tool inclined by 30 degrees sideward from the normal with respect to the feed direction. At the time, the machining is done in up-cut.

In the next stage, a cut-off operation is carried out to remove the thin plate from the supporting frame. It was recognized in the preparatory experiments that the thin plate was broken when the circumference of the plate is cut off from the supporting frame at once. Thus, the cut-off operation is done according to such order as illustrated in Fig. 5.

The removal of the supporting frame after the cut-off operation is performed as follows: the cross beam at first, then side beams, so that the supporting frame cannot make contact with the thin plate.

In regard with the tool path generation and NC data generation, a commercial CAM system (ESPRIT: DP Technology) and the programming language Python were used in the study.



(a) Front view (b) Back view

Fig. 4. Cut off order to remove the shape from the frame.

3. Peeling method

3.1. Outline of machining method

Breakage of the thin plate may take place due to the deformation by cutting force and forced vibration. Cutting force may cause the bending and deformation of a thin and twisted shape. Therefore, as shown in Fig. 5, workpiece deformation of the thin plate shape will be suppressed by peeling it downwards from the upper part. At the same time, successive machining of the front and back surface is carried out with a small pick feed and a relatively large depth of cut, in order to prevent deformation of the thin plate.

3.2. Tool path generation

Rough machining is performed until the thin plate becomes 4.0 mm in thickness. Then side cutting is performed to reduce the amount of finishing, which reduces deformation by the side cutting force in finishing. Rough-finishing before peeling is performed until the thin plate becomes 3.5 mm in thickness, so that the unevenness of the surface by roughing can be eliminated. The finishing, called peeling method, is performed downwards from the upper part, similarly to the machining with supporting frame.

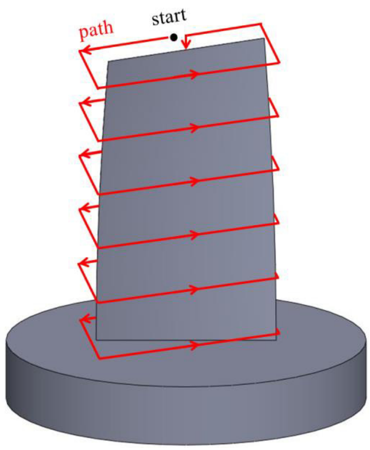


Fig. 5. Machining method.

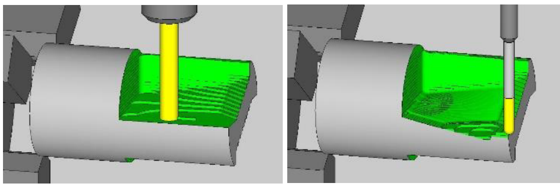
4. Machining experiments and results

In machining experiments, a 5-axis multi-tasking machine tool (YAMAZAKI MAZAK; INTEGREX i-150) was used.

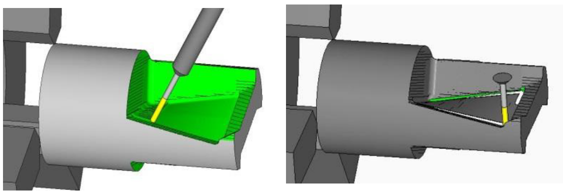
4.1. Machining method with a supporting frame

Figure 6 shows the simulation at each stage from roughing to finishing. The tools were: ϕ10 mm flat end mill for roughing and removing the frame, ϕ6 mm ball end mill for rough-finishing, ϕ3 mm ball end mill for finishing and cutting off from the frame. Figure 7 shows the actual machining at each stage according to Fig. 6. The machining conditions in this methodology are listed in Table 2. Machining time was 16 minutes for roughing, 21 minutes for rough-finishing and 45 minutes for finishing, respectively. Besides, it takes 2 minutes for cutting the frame off and 18 minutes for removing the frame. The total machining time is thus 102 minutes. Figure 8 shows the machined workpiece shape.

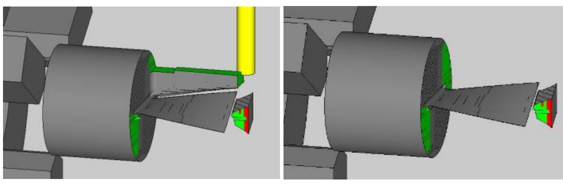
The result of thickness measurement of the thin plate by a micrometer was 0.147 mm at the tip, 0.109 mm in the middle and 0.100 mm at the root, respectively. It can be seen that the actual thickness of the plate is a little bit thicker than the design of 0.1 mm. It is due to the high rigidity by adding the supporting frame. The measured result of the surface roughness was 0.225 μm (Ra) on average, 0.282 μm (Ra); at the tip of the plate, 0.25 μm (Ra) in the middle and 0.142 μm (Ra) at the root, respectively. It was observed that the shape was well created, as seen in Figure 8.



(a) Roughing (b) Rough-finishing



(c) Finishing (d) Cut-off from frame

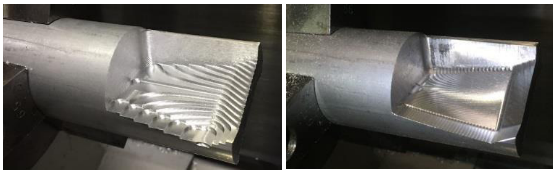


(e) Frame removed (f) Machined result

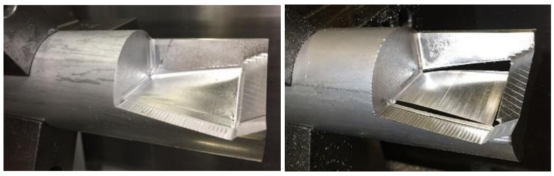
Fig. 6. Machining simulation at each stage.

Table 2. Cutting condition.

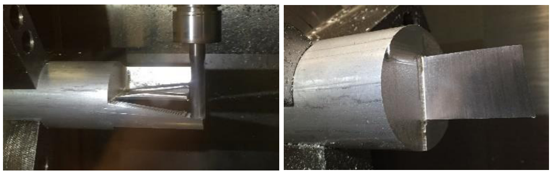
	Spindle rot. (rpm)	Feed rate (mm/min)	Depth of cut(mm)	Pick feed (mm)
Roughing	4000	2400	1.5	-
Rough-finishing	8000	2000	0.3	-
Finishing	8500	300	0.6	0.35
Cut-off from frame	10000	50	1.5	-
Frame removed	4000	1500	1.5	-



(a) Roughing (b) Rough-finishing



(c) Finishing (d) Cut-off from frame



(e) Frame removed (f) Machined result

Fig. 7. Machined results at each stage.

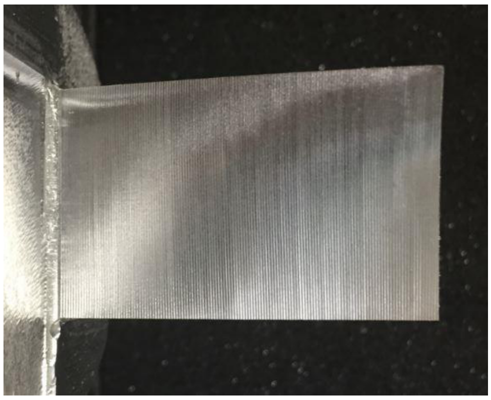
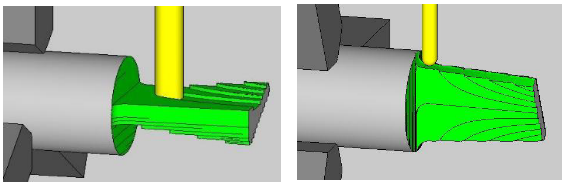


Fig. 8. Finished shape.

4.2. Peeling method

Figure 9 shows the simulation at each stage from roughing to side cutting [8]. The tools were: ϕ10 mm flat end mill for roughing, ϕ6 mm ball end mill for side cutting and rough-finishing, ϕ3 mm ball end mill for finishing. Figure 10 shows the actual machining at each stage according to Fig. 9. The machining conditions in this methodology are listed in Table 3. Machining time was 15 minutes for roughing, 20 minutes for side cutting, 121 minutes for rough-finishing and 505 minutes for finishing, respectively. The total machining time was thus 661 minutes. Figure 11 shows the machined workpiece shape.

The result of thickness measurement of the thin plate by a micrometer was 0.112 mm at the tip, 0.114 mm in the middle and 0.108 mm at the root, respectively. The measured result of the surface roughness was 0.200 μm (Ra) on average, 0.151 μm (Ra) at the tip of the plate, 0.207 μm (Ra) in the middle and 0.243 μm (Ra) at the root, respectively. This method can achieve a workpiece shape closer to the design.

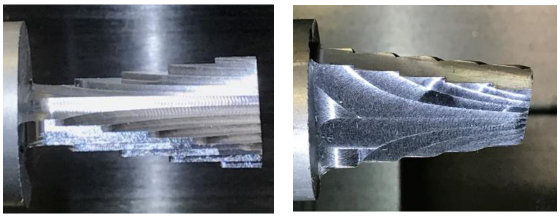


(a)Roughing (b)Side cutting

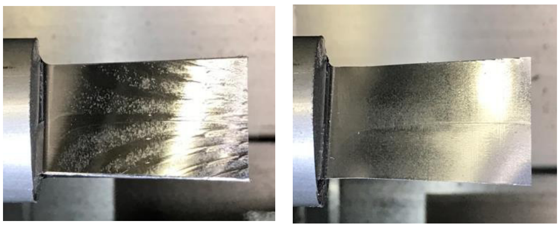
Fig. 9. Machining simulation at each stage.

Table 3. Cutting condition.

	Spindle rot. (rpm)	Feed rate (mm/min)	Depth of cut(mm)	Pick feed (mm)
Roughing	2800	1000	1.5	-
Side cutting	12000	800	0.1	0.05
Rough-finishing	12000	500	0.25	0.25
Finishing	12000	200	1.7	0.0625



(a) Roughing (b) Side cutting



(c) Rough-finishing (d) Machined result

Fig. 10. Machining results at each stage.

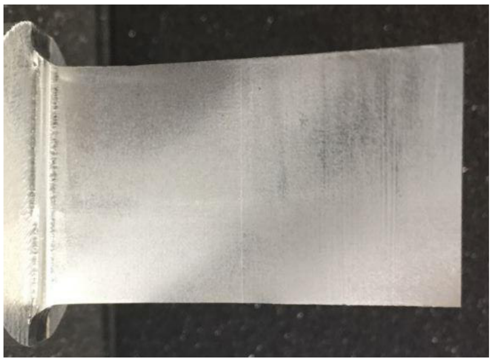


Fig. 11. Finished shape.

4.3. Comparison of two machining methods

Let us compare the two machining methods for curved thin plate with high aspect ratio, using the abbreviations S: with a supporting frame, and P: Peeling. As was mentioned, the machining time of S is 102 min, however that of P is 505 min. Although S is 4.9 times faster than P, The thickness distribution and final surface roughness are almost same in S and P. Judging from the consideration, it is found that the machining method with a supporting frame is effective.

5. Conclusion

Two methods were proposed to create a thin twisted plate with high aspect ratio of 500. The study is summarized as follows:

(1) It was found that the machining method consisting of adding a supporting frame opens the possibility of machining a thin plate with high aspect ratio, however the shape is a little bit curled due to the difficulty of cutting the supporting frame off.
(2) It was proved that the peeling method can create a thin twisted plate with high aspect ratio, whereby the cutting tool does not make contact with the finished portion at all, albeit with a longer machining time.

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