# VANE MACHINING BY THE BALL-END-MILL FOR THE NEW RFQ IN THE J-PARC LINAC

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*Abstract*

The fabrication of a new RFQ has been started for the J-PARC linac. The RFQ cavity is divided into three unit tanks. Each unit tank consists of two major vanes and two minor vanes, all of which are brazed together. To reduce the cost and time required to develop a special formed bit for the vane modulation machining, a numerical controlled machine using a conventional ball-end-mill was adopted for the vane modulation cutting instead of a wheel shaped cutter. Dimension accuracy was confirmed by cutting test pieces. The finished surface seems smooth enough for the RFQ requirements. Our results using ball-end-mill machining for the vanes will be described.

## RFQ IN THE J-PARC LINAC

The J-PARC RFQ is a four-vane type cavity used to accelerate a negative hydrogen beam from 50 keV to 3 MeV with peak current of 30mA. The RF duty factor is 3% (600 μs at50 Hz).

We started preparing a backup RFQ in case the current RFQ ran into trouble. The beam dynamics design is unchanged, but the mechanical design and fabrication methods are quite different. The engineering design started at the beginning of 2009 and fabrication last summer [1].

Since the shape of the vane modulation is a complex curved surface, two-dimensional machining using specially formed milling cutters with a wheel profile is the usually adopted machining method. To reduce the expense and time requirement for the development of a special cutter, we tried three-dimensional machining using a commercially supplied ball-end-mill for the vane modulation machining.

In this paper, the detailed machining procedure and results of the vane machining are described together with some topics that arose during the fabrication.

## RFQ DESIGN

Table 1 shows the main RFQ design parameters. The material of the vane is high-purity oxygen-free copper with HIP (Hot Isostatic Pressing). The RFQ cavity is divided into three unit tanks. Each tank (about 1 m long) will be integrated together on a platform after the brazing of the major and the minor vanes. Schematic drawings of the vanes are shown in Fig. 1.

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Table 1: Main RFQ Parameters

| | |
|---|---|
| Frequency [MHz] | 324 |
| Inter-vane voltage[kV] | 82.9 |
| Max. surface field [MV/m] | 31.6(1.77 Kilpatrick) |
| Ave. bore radius [mm] | 3.7 |
| Vane-tip curvature [mm] | 0.89r0 (3.293mm) |
| Vane length [mm] | 3172.1 |
| Number of cells | 294 + (transition cell, FFS) |

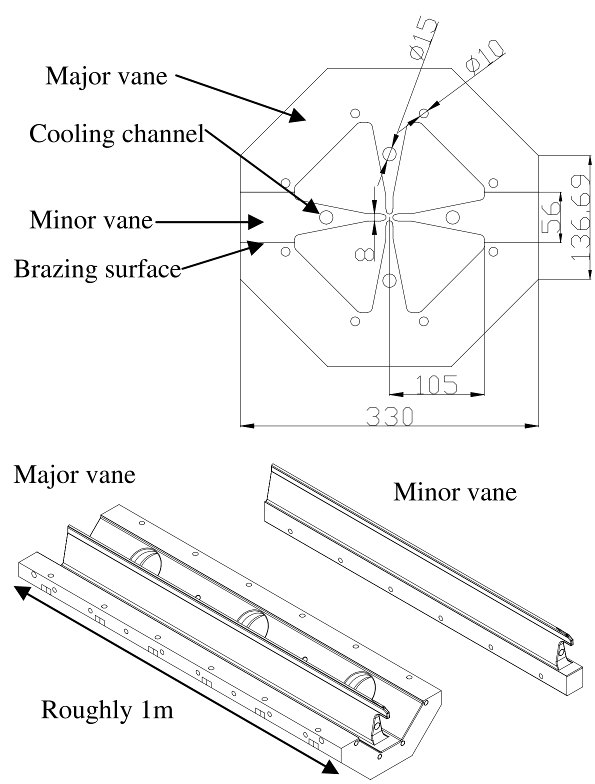



Figure 1: Schematic drawings of the unit tank vanes. The cooling channel was machined by gun-drill and plugged by electron beam welding.

## TEST MACHINING USING THE BALL-END-MILL

To evaluate the performance of end-mill machining, several machining tests have been done. Figure 2 shows a full-size aluminium model to check the dimension accuracy. Using a three-dimensional coordinate

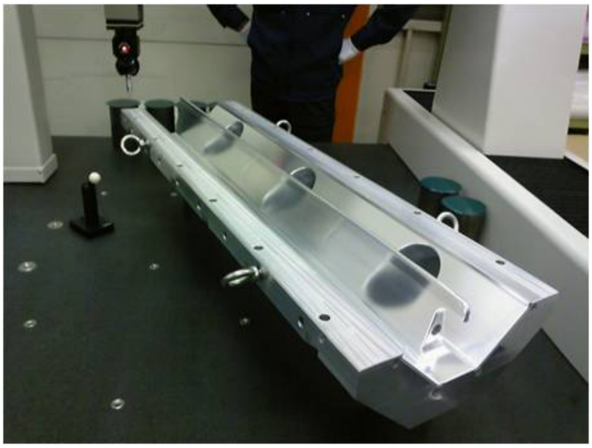


Figure 2: Aluminium test milling cut model.

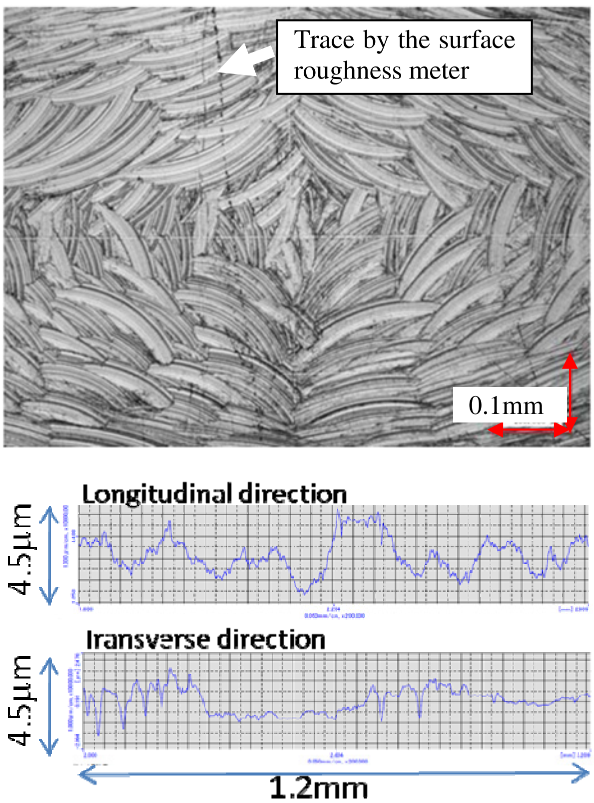



Figure 3: Top: is a close-up photo of the vane tip. The material of this TP is annealed oxygen-free copper. The cutter mark left by the ball-end-mill machining can be clearly seen. Bottom: trace is the measured surface roughness of the vane modulation. Typical surface roughness is 0.8μm.

measuring machine (CMM), the dimensional error in the cross-sectional shape was 0.03 mm. The accuracy of the vane-tip curvature (design:3.293mm) was less than 0.01mm. The shape error of the modulation curve was 0.01 mm. Although the dimensional accuracy of the cross-sectional shape was tolerable, the height of the modulation ridge line was short more than 0.05mm. In order to correct this machining error, the final machining for the modulation carried out in several-step process with the measurement of the vane height.

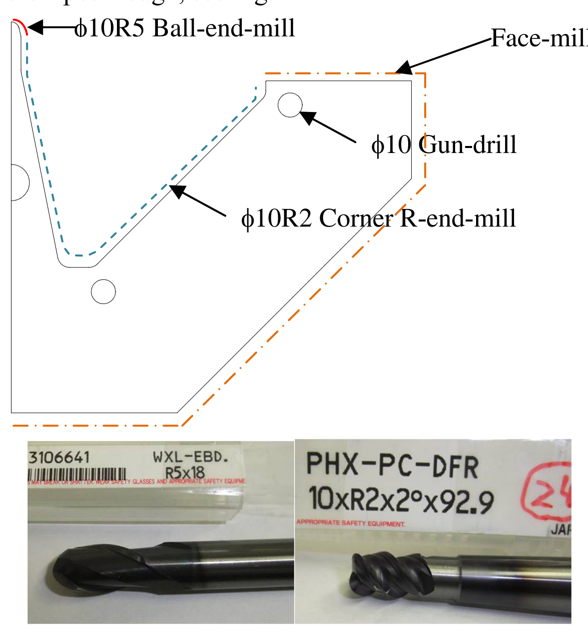
The expected surface roughness of the vane modulation surface was also checked by machining small test pieces (TPs) made of annealed oxygen-free copper. Figure 3 shows a close-up view of the modulation surface. The surface roughness is typically 0.8 μm (Ra). In this test, the curvature of the ball-end mill was 5 mm.

## VANE MACHINING

The vane machining process is summarized as follows.

- Very rough machining (residual metal: 4 mm ).
- Deep hole processing for cooling channels.
- Rough machining (residual metal: 1 mm ).
- Annealing.
- Semi-final machining (residual metal: 0.2 mm).
- Final machining (0.2mm -> 0.14mm -> 0.08mm -> finish).
- Surface treatment by chemical polishing.

The complete cross sectional shape was machined out by using three kinds of end-mills. A ball-end mill was used for the modulation, a face-mill was used for the flat brazing surface, and a corner-R-end-mill was used for the V-shaped trough, see Fig. 4.




ϕ10R5 Ball-end-mill ϕ10R2 Corner R-end-mill

Figure 4: Tools for the machining.

Figure 5 is a photo taken during the vane machining. The stage moves in the horizontal plane and the end-mill moves vertically. The main feed direction of the stage is in the longitudinal direction. The dimensional accuracy of the brazing surface and the modulation is quite important, however, in the test a large machining error was observed in the height of the modulation ridge line. To avoid that, we introduced three semi-final machining steps before finishing the modulation surface. In each step, the modulation machining program was the same as the final

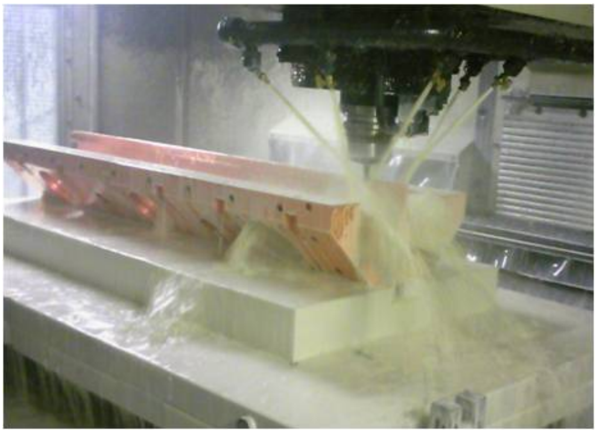


Figure 5: Ball-end-mill machining of the RFQ modulation.

finishing process. The residual metal to be removed decreased from 0.2mm to 0.14mm to 0.08mm. After the every semi-final machining step, the height of the modulation ridge was measured by a contact probe on the machining center. Based on these measurements, we could put in a compensating correction for the finishing.

Table 2: Results of the Measured Height Error

| vane | | | yyyy /mm/dd | Error at | | | Correction for finishing |
|---|---|---|---|---|---|---|---|
| | | | | 0.20 | 0.14 | 0.08 | |
| Unit 1 | maj. | 1 | 2010/2/3 | 0.01 | 0.02 | 0.01 | 0.02 |
| | | 2 | 2010/2/8 | 0.02 | 0.04 | 0.05 | 0.06 |
| | min. | 1 | 2010/2/18 | 0.01 | 0.04 | 0.03 | 0.04 |
| | | 2 | 2010/2/22 | 0.05 | 0.07 | 0.06 | 0.06 |
| Unit 2 | maj. | 1 | 2010/8/9 | 0.03 | 0.03 | 0.03 | 0.03 |
| | | 2 | 2010/8/16 | 0.05 | 0.06 | 0.07 | 0.07 |
| | min. | 1 | 2010/8/23 | 0.07 | 0.03 | 0.04 | 0.04 |
| | | 2 | 2010/8/30 | 0.02 | 0.02 | 0.02 | 0.03 |
| Unit 3 | maj. | 1 | 2010/7/12 | 0.04 | 0.05 | 0.04 | 0.04 |
| | | 2 | 2010/7/20 | 0.02 | 0.04 | 0.05 | 0.06 |
| | min. | 1 | 2010/7/26 | -0.01 | 0.02 | 0.03 | 0.04 |
| | | 2 | 2010/7/30 | 0.02 | 0.03 | 0.01 | 0.02 |

Table 2 shows the results of the measured height error at semi-final steps and the value of the correction for finishing. Positive value is in the over-cutting direction. We think that these errors are induced from the fluctuation of the environmental temperature of the factory and the thermal expansion of the spindle head.

Figure 6 shows the modulation height error of the minor vane of the units 2 and 3 measured by CMM after finishing. The dimensional error seems to be a combination of the modulation shape (about 0.01mm), curvature of the vane (0.015mm), and height offset (0.02mm). We think that the offset error is caused by the accuracy of the measurement by the contact probe on the machining center.

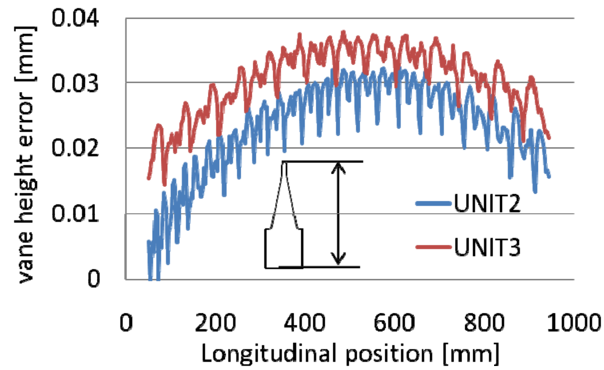



Figure 6: Measured dimensional error of the vane height.

## VANE DEFORMATION AFTER THE MACHINING

After the machining, the vanes were transported to the brazing factory where they were assembled. During the assembling, we found a warpage of the vane of about 0.08mm in one of the minor vanes. During their transport, the vane were mounted on a backbone (H-section steel) made of stainless-steel as shown in Fig. 7. The flatness of this backbone was within 0.12 mm. Therefore, we remade the backbone to increase the strength of the structure and improve its flatness. After doing that, we did not find any more of this kind of vane deformation.

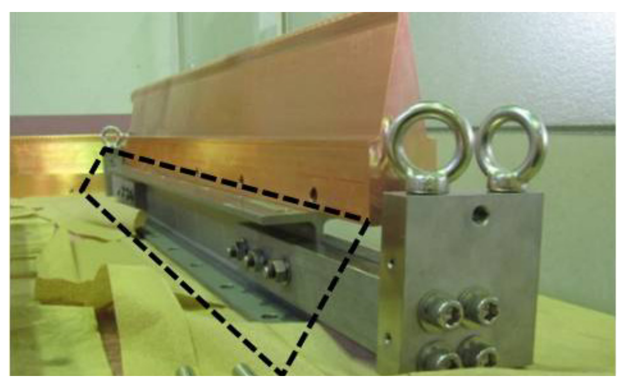


Figure 7: Vanes are bolted on the backbone during the transportation.

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## REFERENCES

[1] T. Morishita et al., "Fabrication of the New RFQ for the J-PARC Linac", Proc. of 2010 International Particle Accelerator Conference, Kyoto, Japan, p. 783 (2010).