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Paper:

High-Efficiency Machining Strategy for Non-Uniformly Shaped Workpiece Using On-Machine Measurement

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Non-uniformly shaped workpieces made of such materials as ceramic and cast metal can prevent higher-efficiency machining from being achieved in the conventional process due to large deviation of removal stock. Therefore, this paper proposes a novel method to achieve a high-efficiency machining strategy for non-uniformly shaped workpieces using on-machine measurement. This method utilizes on-machine measurement of a workpiece placed at an arbitrary position on a machine table as a machining pre-process. The product shape is arranged in the workpiece shape, and NC program for machining is generated based on the on-machine measurement data. The proposed method can be expected to be reasonable for a large-size product that requires long machining time because of long initial setup time and air-cutting in machining. A case study using numerical experiment was carried out. The results showed that our proposed method reduced total manufacturing time including on-machine measurement.

Keywords: high-efficiency machining, on-machine measurement, large-size products, force monitoring, adaptive control

1. Introduction

Workpieces made of such materials as ceramic and cast metal often have relatively large shape deviation due to their production processes. This can be a serious issue in the machining of non-uniformly shaped workpieces, particularly in large-size products, because it can prevent higher-efficiency machining from being achieved in the conventional process, where a standard datum plane must firstly be fabricated. This generates a large deviation of removal stock. In this case, the air-cutting time, which is defined as the time when the tool is not cutting the workpiece, becomes longer because a tool path must be generated based on the maximum deviation of the removal stock. As the product size becomes larger, the difference of the removal stock becomes longer and machining efficiency becomes lower. Therefore, the fabrication of a reasonable tool path adequate for the workpiece shape is recommended to perform higher-efficiency manufacturing. The present CAD/CAM systems in commercial usage focus on tool path generation for high speed and precision machining for complex-shaped products. However, they do not pay attention to the overall machining efficiency by adjusting the tool path based on such a non-uniformly shaped workpiece. Various monitoring and control technologies in processes [1–5] and an intelligent machine tool have been developed in recent years [6–8]. The authors evaluated cutting force monitoring in end-milling processes using internal sensors in a linear motor driven machining center [9] and showed the effect of an adaptive control machining system by monitoring the grinding force with an internal sensor that used a motor current signal of a machine tool [10]. Furthermore, on-machine measurement technology has been developed with a high-precision machine tool and measurement sensors. Research on on-machine measurement technology in the machining process has been conducted [11–13]. However, their main purpose is to improve machining accuracy by compensation based on measurement, not on machining efficiency. Therefore, the present study proposes a novel method to reduce the machining time for non-uniformly shaped workpieces using on-machine measurement as a machining pre-process. This novel method is expected to be applied to the intelligent machine tool operations.

2. Proposed Strategy for Higher-Efficiency Machining Using On-Machine Measurement

In this study, the product shape is assumed to be a plane and only its periphery face must be machined. The flow of conventional machining processes for a large workpiece is illustrated in **Fig. 1**.

- The workpiece is placed on the machine table and adjusted to its axes using the three datum points of its profile (**Fig. 1(a)**).
- The datum faces that are parallel with the X and Y axes are fabricated by machining (**Fig. 1(b)**).
- The origin of the NC program is set based on the datum face, and the workpiece is machined with a tool path along the periphery of the product (**Fig. 1(c)**).

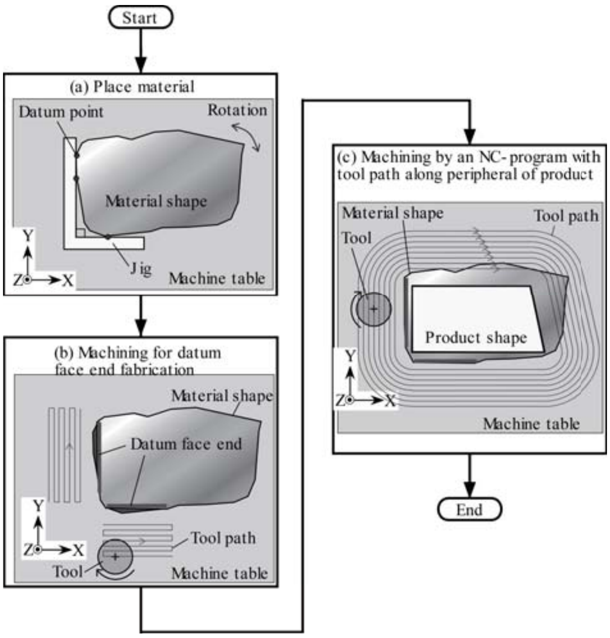


Fig. 1. Flow of conventional machining process.

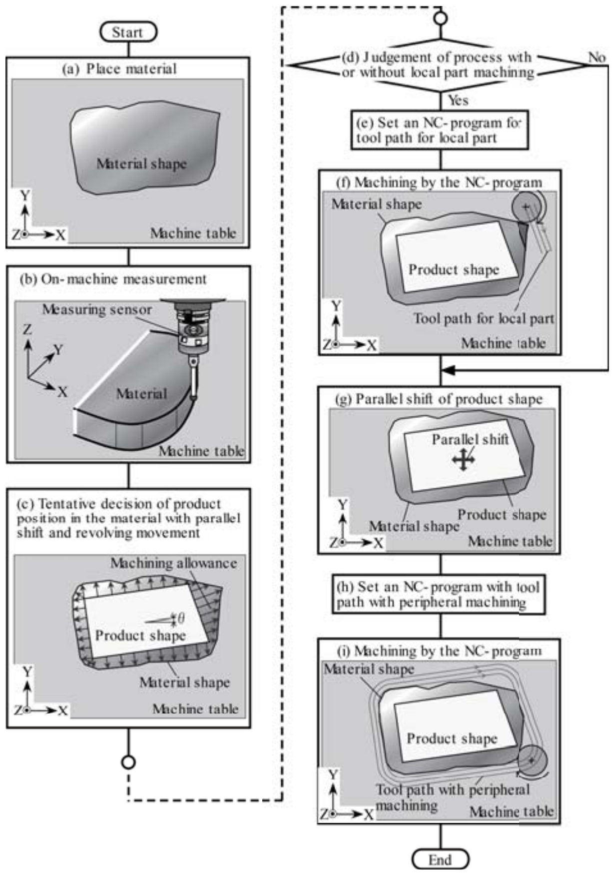
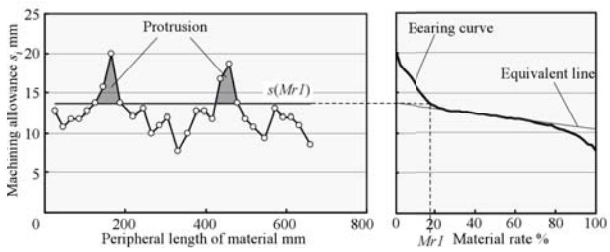


Fig. 2. Flow of proposed machining process.



(a) distribution of machining allowance (b) bearing curve

Fig. 3. Extraction of cusp part.

In this method, the initial setup takes a long time because the workpiece size and weight are large. Also, a large variation of machining allowance occurs because the product layout in the workpiece must be determined as just one pattern with the datum faces. Air cutting time lengthens because the tool path is generated based on the maximum machining allowance. Moreover, the machining efficiency becomes lower because the deviation of the machining allowance increases with larger products.

Therefore, we propose a new method that contains the following four main processes. The first acquires the coordinate data of the non-uniformly shaped workpiece profile by on-machine measurement. The second is layout adjustment of the product shape in the workpiece before machining. The third generates a tool path in the machining. The fourth is machining the workpiece. This process takes time not only for machining but also for on-machine measurement of the workpiece profile and arrangement of the product shape in the workpiece. The measurement time increases when the expression accuracy is improved by setting more measurement points. The time for arranging the product position increases when the position accuracy is improved for shorter machining time.

Hence, this method finds a reasonable product position in the workpiece as an approximated solution that demonstrates maximum effect to reduce the total manufacturing time based on a balance between machining and measurement times. The detailed flows of the proposed method are shown in **Fig. 2**.

- A uniform-shaped workpiece is non-selectively located on the machine table (**Fig. 2(a)**).
- On-machine measurement acquires the workpiece profile data as the coordinate data of the machine tool (**Fig. 2(b)**).
- The product shape from the CAD data is arranged in the workpiece shape by parallel shift and rotary movements to calculate the machining allowance distribution (**Fig. 2(c)**). The centers of the gravity of the workpiece and the product shape are calculated. The product shape is moved in parallel since its gravity matches the workpiece's gravity. Next, the product shape is rotated to minimize the variation of the machining allowance distribution.
- The next step is a judgment about whether a process with or without local machining is needed (**Fig. 2(d)**). The cusp is extracted after the layout of the above product shape. **Fig. 3** shows an example of the cusp-part extraction. For machining allowance, we prepared a bearing curve based on the surface quality evaluation parameters determined in JIS B 0671-2: 2002 (ISO 13565-2: 1996). An equivalent line is drawn on it. The parts with larger machining

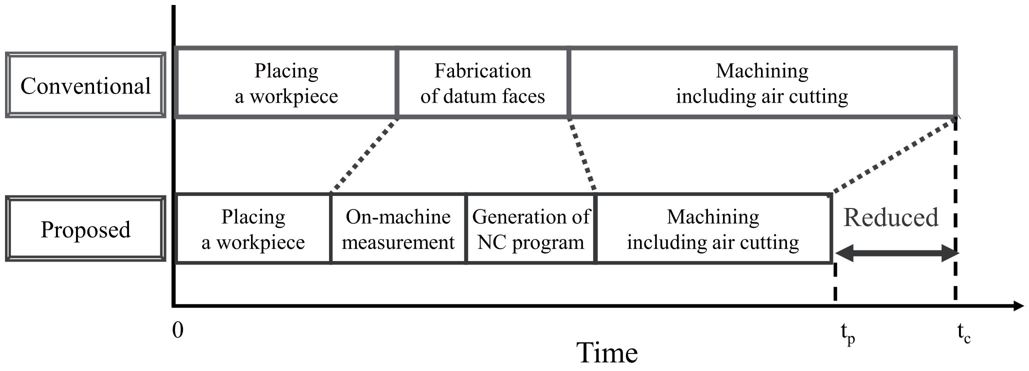
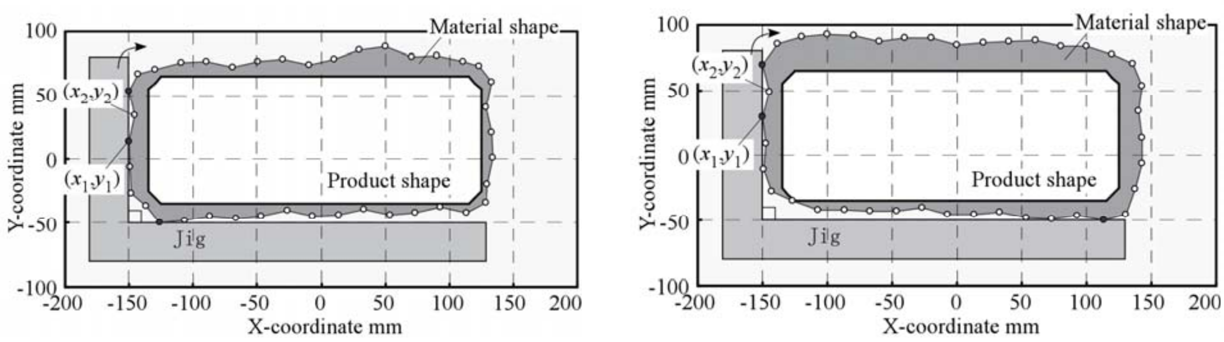
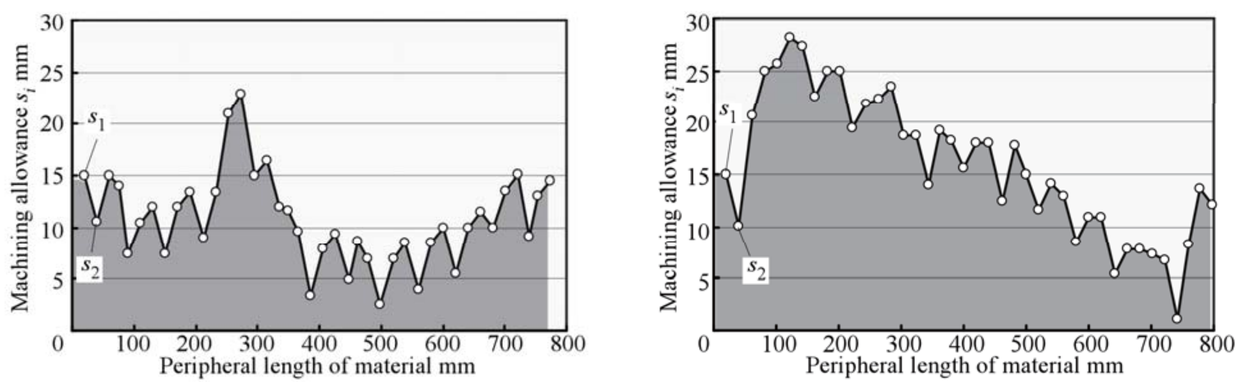


Fig. 4. Conceptual time chart that shows effect of proposed method.



(a) Model A (b) Model B

Fig. 5. Models for case study (Initial position).



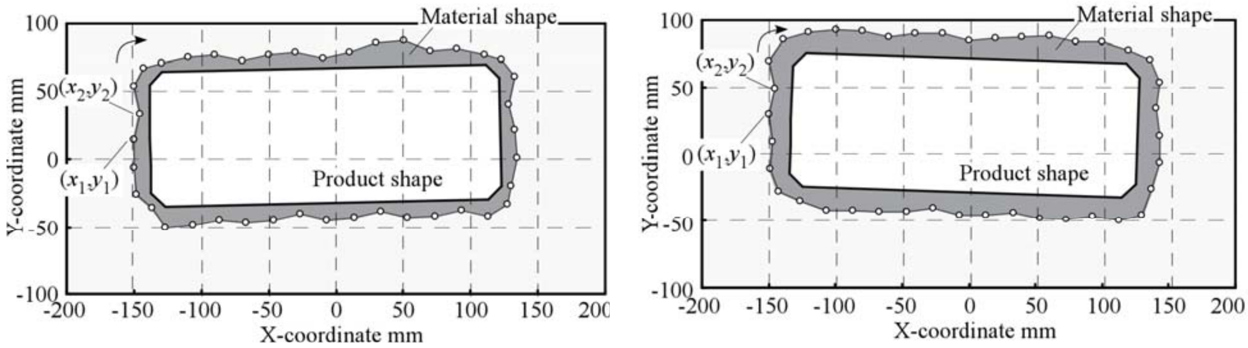
(a) Model A (b) Model B

Fig. 6. Machining allowance distribution by conventional method.

allowance than s(Mr1) are defined as cusp parts. The s(Mr1) is a machining allowance where the value of the material ratio on the equivalent line is 0. The machining time is estimated regardless whether the machining is done for the extracted cusp parts. The judgment of the next process is decided based on its time diminishing effect.

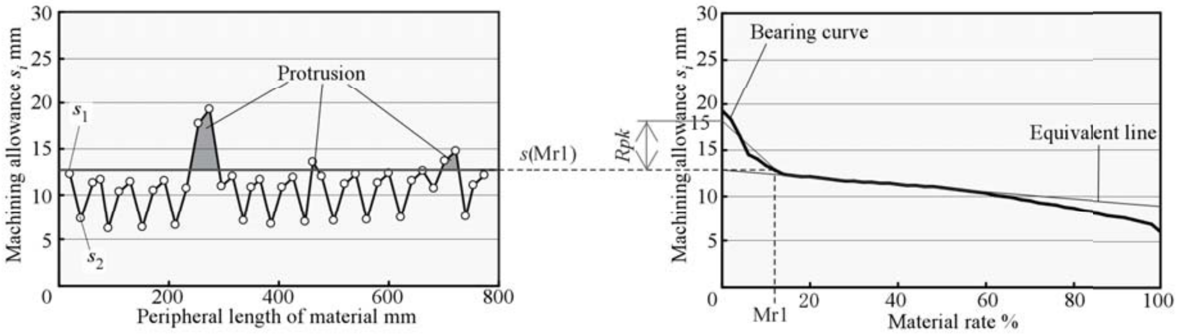
- A tool path for the local part machining is prepared if needed (**Fig. 2(e)**).
- Local part machining is carried out (**Fig. 2(f)**).
- The product shape is shifted to minimize the maximum machining allowance of the remaining workpiece shape (**Fig. 2(g)**).
- A tool path for peripheral machining is generated based on the determined product shape position (**Fig. 2(h)**).
- Machining is carried out using the tool path (**Fig. 2(i)**).

Here, **Fig. 4** illustrates a conceptual time chart comparing both the conventional and proposed methods. In the proposed method, placing a workpiece and machining including air-cutting time are drastically reduced, although on-machine measurement and generation of NC program time are added. Therefore, we expect to reduce the effective total process time.

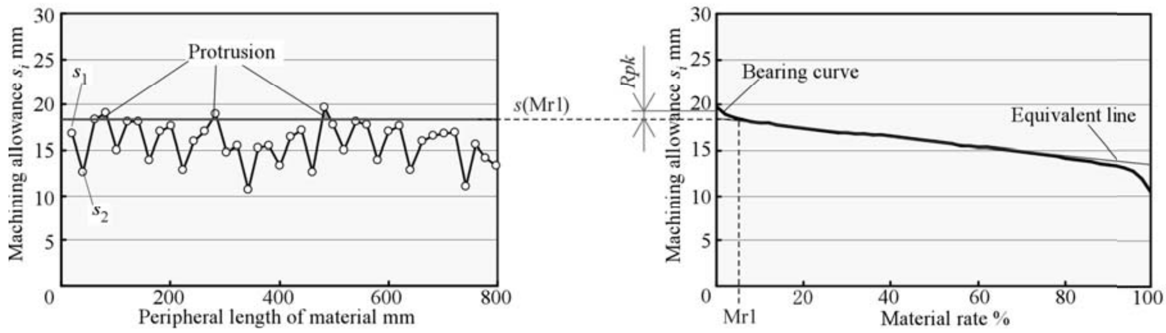


(a) Model A (b) Model B

Fig. 7. Layout of product shape after parallel shift and rotary movement in **Fig. 2(c)**.

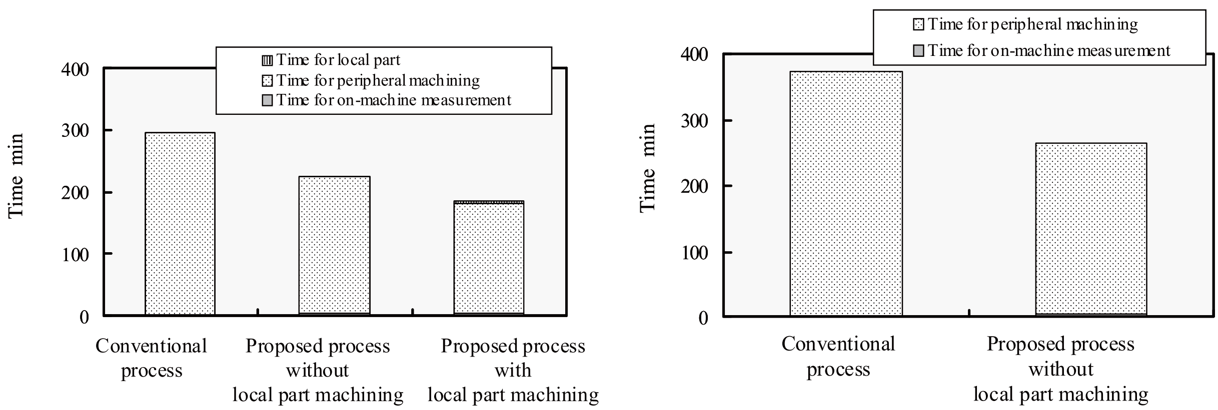


(a) model A



(b) model B

Fig. 8. Extraction of protrusion in machining allowance distribution.



(a) model A (b) model B

Fig. 9. Effect of shortening machining time by proposed method.

3. Case Study by Numerical Experiments

To verify the effect of our proposed method, we compared it with the conventional one in a case study by numerical experiments. We assumed the following in this case study. The object shape was a plane, and the machined faces were the periphery of the workpiece. The tool feed speed was 400 mm/min, and the depth of the cut was 0.15 mm constant, considering the actual grinding of ceramics workpieces using a 10 mm diameter electroplated diamond wheel. We had two models (**Fig. 5**).

Figure 6 shows the machining allowance distribution of the conventional method. The allowance at each point was estimated as the total depth of cut, which was calculated by the product of the depth of cut multiplied by the number of machining times to reach the product face. A large maximum machining allowance of about 30 mm or less was found with its deviation (**Fig. 6**). This result indicates that it takes a long time to complete the manufacturing because round machining starts far from the workpiece periphery faces and has long air-cutting time when the conventional method was applied.

Figure 7 shows the result of the proposed method. This is after the on-machine measurement process mentioned in **Fig. 2(b)**. The following are the conditions: 40 measurement points, 5 mm in 50 mm/min approach distance to workpiece and escape in 1000 mm/min, and total peripheral movement length is about 800 mm in 1000 mm/min. The coordinate value (x_i, y_i) at each point on the non-uniformly shaped workpiece on the machine table can be acquired by the on-machine measurement. Then, the coordinate values of the gravity of the workpiece were calculated. Parallel shift of the product shape was performed based on its gravity position with that of the workpiece. Rotary movement was carried out to minimize the machining allowance. Searching for the extremal points by the steepest descent method was demonstrated to minimize the average deviation of the machining allowance. **Fig. 8** shows the estimated machining allowance distribution. The maximum machining allowance, which is approximately 20 mm or less, is clearly reduced after the process. Since its distribution approaches flatness, it has little deviation. For model A, reducing the machining time is expected by applying local part machining. However, it cannot be done for model B. We calculated the time-reducing effect by applying local machining and compared it with the conventional; model A clearly showed the effect, but not model B. Therefore, local part machining was carried out for model A, but not for B.

Figure 9 shows the machining time. We confirmed that applying our proposed method is effective. The machining time was reduced by about 24% by changing the layout of the product shape without local part machining and 37% by adding local part machining for model A. Nevertheless, both schemes have on-machine processes. Model B shows about 31% of the machining time reduction. These verify the effect of the proposed method.

4. Conclusion

In this paper, we proposed a novel method for high-efficiency machining of large-size product using on-machine measurement and applied it to a grinding process of a large ceramic product. In a case study, numerical experiments showed that this proposed strategy outperformed the conventional method. A huge time-reducing effect is expected when the product size increases. However, improving the method for three-dimensional-shaped products is future work. Such an application is possible in principal, but the balance with on-machine measurement is a concern. Achieving a mathematic model to evaluate the optimal index for locating and orienting the product shape in the workpiece shape is also future work.

This method might be able to integrate adaptive control machining by monitoring grinding or cutting force because inevitable deviation remains when the on-machine measurement point is reduced to decrease the total machining time. Using this adaptive control machining integrated with on-machine measurement technology is expected to achieve higher-efficiency machining for manufacturing large products from non-uniformly shaped workpieces.

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