Rapid Manufacturing of Microscale Thin-walled Structures using a Phase Change Work-holding Method

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High-speed machining is a very useful tool and one of the most effective rapid manufacturing processes. This study sought to produce various high-speed machining materials with excellent quality and dimensional accuracy. However, high-speed machining is not suitable for microscale thin-walled structures because the structure stiffness lacks the ability to resist the cutting force. This paper proposes a new method that is able to rapidly produce very thin-walled structures. This method consists of high-speed machining followed by filling. A strong work-holding force results from the solidification of the filling materials. Low-melting point metal alloys are used to minimize the thermal effects during phase changes and to hold the arbitrarily shaped thin-walled structures quickly during the high-speed machining. We demonstrate some applications, such as thin-walled cylinders and hemispherical shells, to verify the usefulness of this method and compare the analyzed dimensional accuracy of typical parts of the structures.

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1. Introduction

Various manufacturing stages are required to produce precision molds and dies quickly. Of these stages, the final finishing processes, such as fine machining, polishing, and electrical discharge machining (EDM), consume the majority of the total manufacturing time and often take more time than the rough machining processes. To obtain microscale thin-walled structures, it is first necessary to manufacture the EDM electrode, but this consumes much time and money. Recently, as the main spindle and feed speeds have increased, high-speed machining has rapidly replaced the final finishing processes. Therefore, multi-functional high-speed, high-performance machining is being developed to meet the needs of customers by shortening the cycle time of trial products and achieving high-quality final products.[1,2]

This paper proposes a new rapid manufacturing process for thin-walled structures that was developed from high-speed machining with phase-change filling. Phase-change filling that uses low-melting point metal alloys is more effective at holding the work-piece when manufacturing thin-walled structures with arbitrary shapes compared to traditional methods.

This technique produces a strong work-holding force because the filling resistance is created only by the phase changes.[3,4] Very thin-walled structures can be produced easily and quickly using this method, and they do not have any deformation in the heat affected zone (HAZ) because of the low-melting point of the metal alloys. Therefore, the EDM process that was traditionally used to make very thin-walled structures is now being replaced by the process discussed here, enabling precision dies and molds to be manufactured at a lower cost within a short period. In order to demonstrate the feasibility of this process, some same parts were manufactured and analyzed in this study.

2. Filling process

2.1 Low-melting point metal

We propose the following criteria to obtain the optimal filling metal from low-melting-point metals: the metal must be environmental friendly, have no HAZ, and produce a minimal difference of temperature when solidified from the solid to liquid states, and the process must be easy to automate to obtain greater flexibility. Bi-42Sn metal, which is Pb-free, was selected from the metals listed in Table 1, which were considered based on their cost, melting point, coefficient of thermal expansion (CTE), and environmental friendliness.[5]

2.2 Filling resistance experiment

The extracting method of a universal tensile machine (UTM) was used to measure the filling resistance in this study. To minimize the dynamic effect, we controlled the tensile speed at 0.01 mm/s, which is in the range of a quasi-steady state. The dimensions of the bath and extracting circular bar for the filling resistance test are shown in Fig. 2, while Fig. 3 shows the change in the filling resistance according to the filling immersion depth. The resistance increased sharply as the filling depth became deeper. Fig. 4 shows that a maximum filling resistance of 3.45 kN was observed at a depth of 70.0 mm under these experimental conditions. Previous studies estimated that these values were very high compared to high-speed machining forces. Therefore, based on these experimental results, the filling resistance is sufficient to hold thin-walled structures during high-speed machining.

Table 1 Mechanical properties of various filling materials

	Metal Cost/Kg (US $)	Melting Range(°C)	Tensile Strength(MPa)	Elongation (%)	Wetting Angle(°)	CTE ($\times 10^{-6}$/K)
Sn-37Pb	5.87	183	19 (20°C)	-	-	21
Bi-42Sn	7.79	139	41	20 (20°C)	43±8 (195°C)	15
Sn-20In-2.8Ag	51.63	179 - 189	46.9	47	44±8 (220°C)	20
Sn-9Zn	7.99	199	64.8	*45	*37±7 (215°C)	-
Sn-5Sb	8.36	232 - 240	31 (20°C)	25 (20°C)	37 (-)	-

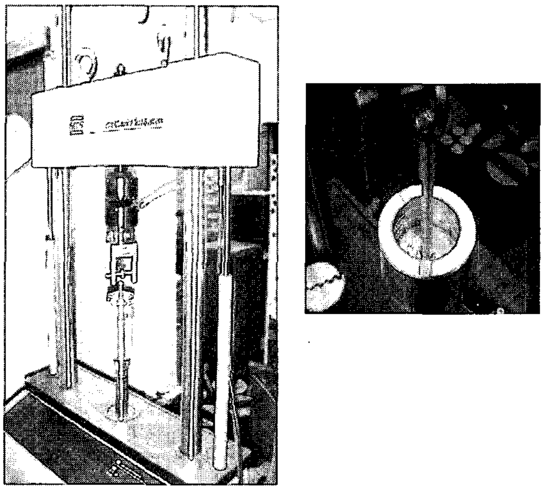


Fig. 1 Experimental set-up for the work-holding force test on a universal tensile machine

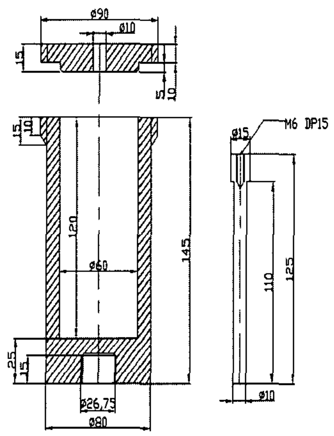


Fig. 2 Dimensions of the work-holding force test device

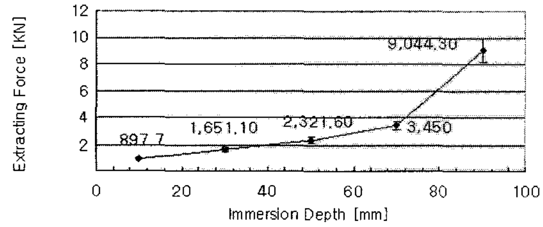


Fig. 3 Work-holding force versus immersion depth

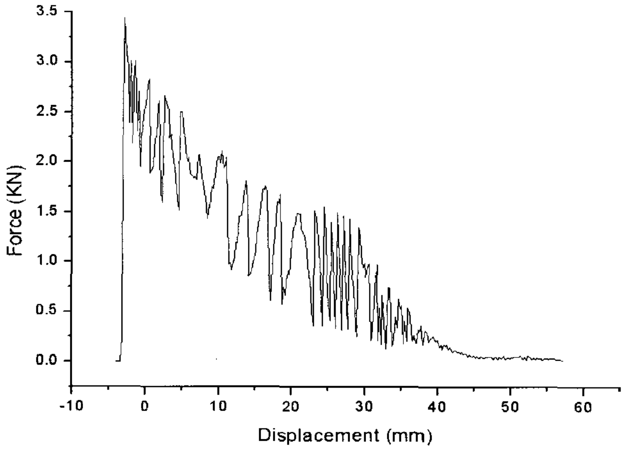


Fig. 4 Change in the work-holding force at an immersion depth of 70 mm

3. Manufacturing process

3.1 Process design for microscale thin-walled structures

Until now, the production of thin walls required for precision dies and trial products depended on the electrode accuracy of the EDM. In this paper, we demonstrate how to make microscale thin walls using high-speed machining only. Previously, a manufactured thin-walled structure with a thickness of 1.0 mm and a height of 10.0 mm (ratio of height to thickness: 10) was reported. In order to realize very thin walled structures, we propose a new rapid manufacturing process for high-speed machining with phase change filling, as illustrated in Fig. 5.

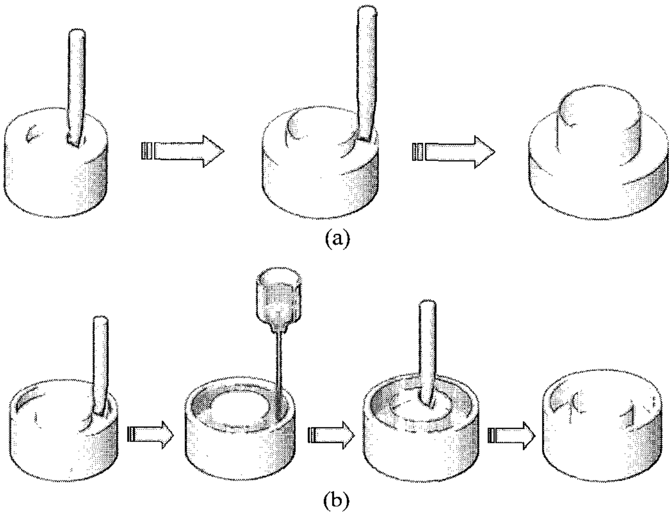


Fig. 5 Schematic diagrams of high-speed machining of a thin-walled cylinder (a) without filling and (b) with filling

As shown in the figure, the process procedure is very simple. First, the inner (or outer) side of the thin wall is machined. Then, the cavity of the inner (or outer) side is filled with a low-melting point metal alloy. The filling metal is solidified to hold the thin wall, as detailed in the previous section. Then, the outer (or inner) side of the thin wall is machined, and the thin wall is obtained by melting the solidified filling metal. This procedure has been used to manufacture a microscale thin wall with a higher degree of accuracy than conventional methods.

3.2 Manufacturing thin-walled cylindrical shells

Thin-walled cylinders were first machined using a developed

HisRP machine, which had a thickness set to 10.0 mm. [6, 7, 8] To obtain these experimental results, we used a spindle revolution speed of 50,000 rpm, a feed rate of 6,000 mm/min, and a flat-end mill tool diameter of 10.0 mm. Figs. 6 and 7 show the finished wall structures for thicknesses of 35, 20, and 10 μm without the filling process, and for thicknesses of 35 and 10 μm with the filling process. We summarized these results in Fig. 8. In this figure, cases I through V refer to the respective manufactured examples without and with filling shown in Figs. 6 and 7. When filling was not used, we obtained maximum errors for the height of 0.9%, diameter of 0.9%, and thickness of typically 8.0% – 16.0%, except for the worst thickness error, which was 74.0% for a wall thickness of 10 μm. These results show that the maximum attainable thickness was about 35 μm in the examples without filling. In the examples with filling, we obtained maximum errors for the height of 1.5%, diameter of 0.2%, and thickness of no more than 3.8%.

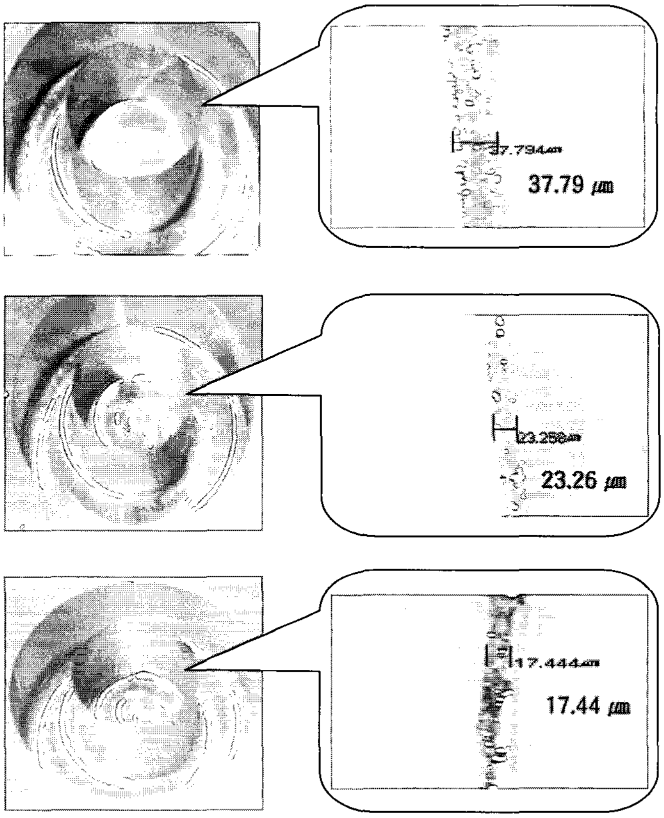


Fig. 6 Thin-walled cylinders machined without filling: (a) Case I, $t = 0.035$ mm, (b) Case II, $t = 0.020$ mm, (c) Case III, $t = 0.010$ mm

3.3 Manufacturing thin-walled hemispherical shells

Thin-walled hemispheres, which are a more complex shape, were manufactured to verify the feasibility of the proposed process. Different values for the minimum wall thickness of the machined hemispheres compared to those of the cylinder were chosen because the tool paths used for the hemispheres were three-dimensional and much different from those used for the cylinder. In addition, we introduced a bridge in some of our tests to hold the thin-walled hemispheres; this connected the hemisphere and the work-piece directly, as shown in Fig. 9. The minimum wall thicknesses of the hemisphere ranged from 500 μm without the bridge to 35 μm with the bridge. The diameter of the hemispheres was 21.0 mm. The error in the diameter ranged between 0.5 – 6.6% for Case I (see Fig. 10), which had no bridge, and between 0.5 – 2.0% for Cases II and III (see Fig. 11), which had bridges. The corresponding thickness error was 6.0% for Case I and 1.1 – 1.2% for Cases II and III. As summarized in Fig. 12, we were able to rapidly manufacture a three-dimensional thin-walled structure with a minimum wall thickness of 35 μm using high-speed machining by making use of filling and bridges.

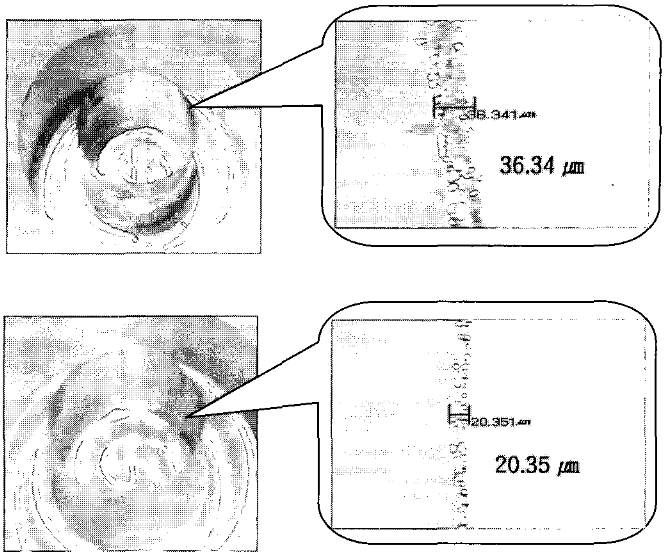
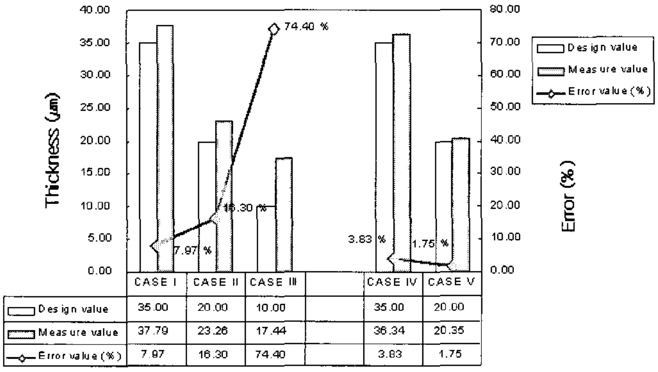
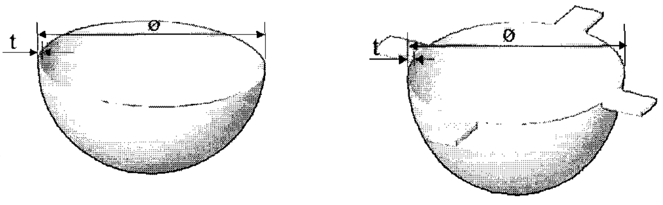


Fig. 7 Thin-walled cylinders machined with filling: (a) Case IV, $t = 0.035$ mm, (b) Case V, $t = 0.020$ mm



	CASE I	CASE II	CASE III		CASE IV	CASE V
Design value	35.00	20.00	10.00		35.00	20.00
Measure value	37.79	23.26	17.44		36.34	20.35
Error value (%)	7.97	16.30	74.40		3.83	1.75

Fig. 8 Measured thickness and errors in the thin-walled cylinders



(a) (b)

Fig. 9 CAD models of hemispherical shells (a) without bridges and (b) with bridges

4. Conclusions

This paper proposed a new rapid manufacturing process for high-speed machining with filling to produce microscale thin-walled structures. Thin-walled cylinders and hemispheres were manufactured to demonstrate the application possibilities of this process. The following conclusions were drawn from this experiment.

First, traditional manufacturing methods produced cylinder wall thickness errors exceeding 10% when the wall thickness was 35 μm. By contrast, the proposed process could be used to manufacture cylinder walls that were only 20 μm thick with an error of just 5.0%.

Second, when this process was used to manufacture thin-walled hemispheres, which are three-dimensional structures, the wall thickness was limited to 500 μm with a thickness error of 6.0%. By using bridges, a wall thickness of 35 μm could be manufactured to within a 2.0% error. The results demonstrated that it was important for three-dimensional thin-walled structures to be held by bridges during the filling process. The next stage of this research will be to test our proposed process using various applications, such as dies and trial metal products that have more complex shaped structures with very thin walls.

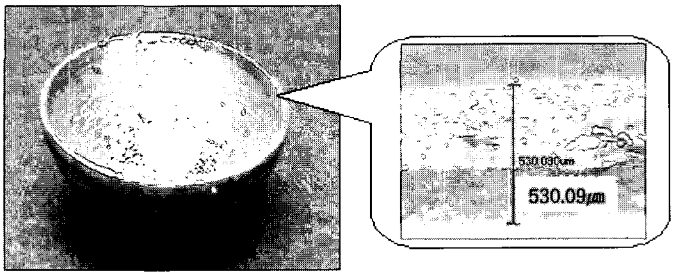
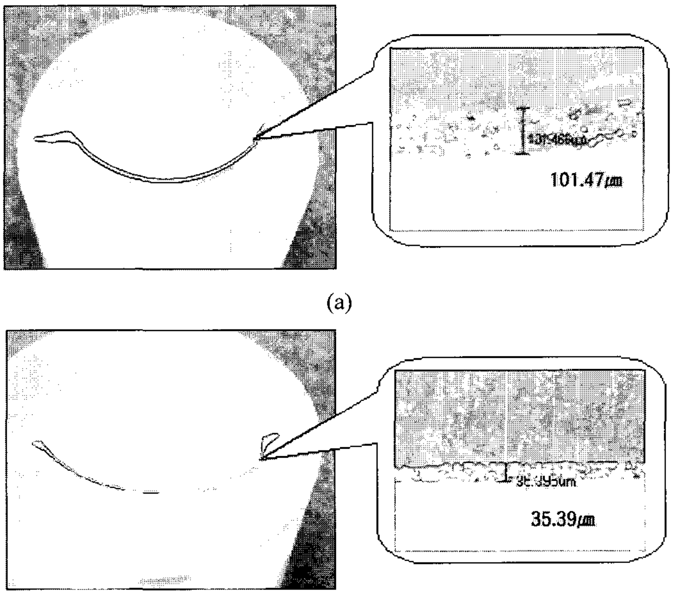


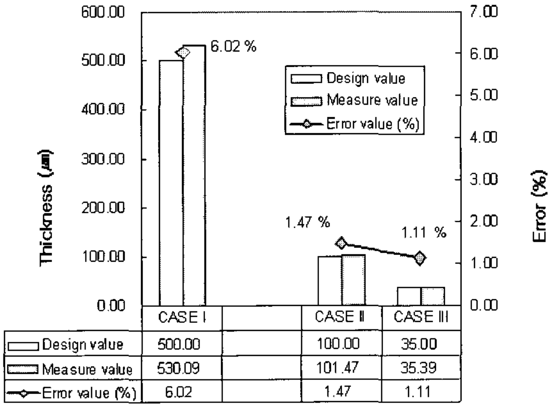
Fig. 10 A hemispherical shell without bridges: Case I, $t = 0.500$ mm



(a)

(b)

Fig. 11 A hemispherical shell with bridges: (a) Case II, $t = 0.100$ mm, and (b) Case III, $t = 0.035$ mm



	CASE I		CASE II	CASE III
Design value	500.00		100.00	35.00
Measure value	530.09		101.47	35.39
Error value (%)	6.02		1.47	1.11

Fig. 12 Measured thicknesses and errors of the hemispherical shells

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