

Three-Dimensional Fabrication of Metallic Parts and Molds Using Hybrid Process of Powder Layer Compaction and Milling

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Abstract

In order to produce three-dimensional models with cemented carbide powders, a freeform fabrication method named Layered Compaction Manufacturing (LCM), which is a hybrid process of powder compaction and CNC milling in layer-by-layer additive manner, is proposed. The feasibility of the LCM process is confirmed by making a WC-9wt%Co carbide model. The connecting strength between the layers of the model after sintering is evaluated by the bending test. It is found that the transverse strength of the sintered products is higher than 2 GPa.

A WC-9wt%Co model with inside channels for temperature control is successfully fabricated using a paraffin wax as a sacrificial material in the LCM process.

Keywords: Layer manufacturing; Powder compaction; Milling; Carbide; Channel

1. Introduction

With increasing demand for improving the accuracy of dimension and the quality of molded precision products such as optical lenses, temperature control is required for molds and dies because thermal and elastic distortion of the tool cannot be neglected. WC-Co alloys are extremely useful for such an application due to its small thermal expansion and high elastic modulus as well as its high resistance to wear. However, it is difficult to produce molds and dies with internal cooling and/or heating channels by conventional machining. Layer manufacturing techniques such as selective laser sintering (SLS) [1-2], three-dimensional printing (3DP) [3], and a hybrid process with conventional milling [4-6] are under development. Although these techniques enable fabrication of metallic models with complicated geometry such as the internal channels directly from powders or molten metals [3, 7], they cannot be used for WC-Co carbide tools because the resulting mechanical strengths and relative density are not high [8].

In this study, a solid freeform fabrication method named Layered Compaction Manufacturing (LCM), which is a hybrid process combining powder compaction and CNC milling in a layer-by-layer additive manner, is proposed in order to achieve molds and dies made of carbides with internal cooling and/or heating channels. The feasibility of the LCM process is evaluated by making WC-9wt%Co carbide cubes, and the connecting strength between the layers of the model after sintering is measured by the three-point bending test. Furthermore, a model with inside channels, which has a potential to realize molds and dies with temperature control, is presented.

2. Principle of the proposed process (LCM)

The procedure for the Layered Compaction Manufacturing (LCM) is shown in Figure 1. First, the sliced data of a designed solid model is prepared with a CAD/CAM system. Then, the green model is formed using a compacting tool composed of a container, a lower punch, and an upper punch. After the powder metal is supplied into the container, the thin powder layer is compacted and grooves are milled according to the coordinate information of the slice data. The created grooves are filled with a molten material with a low-melting point, e.g. paraffin wax, as sacrificial material (separator) to separate the model part, or to create cavities. A layered green object which consists of the model part and the unnecessary parts is obtained by repeating these processes to the final layer of the slice data. Then, the unnecessary parts are removed from the model part by remelting the separator. At this time, the cavities such as internal channels are also created in the model because the separator is completely removed from the grooves. Finally, the green model is sintered, and the removed powder is reused.

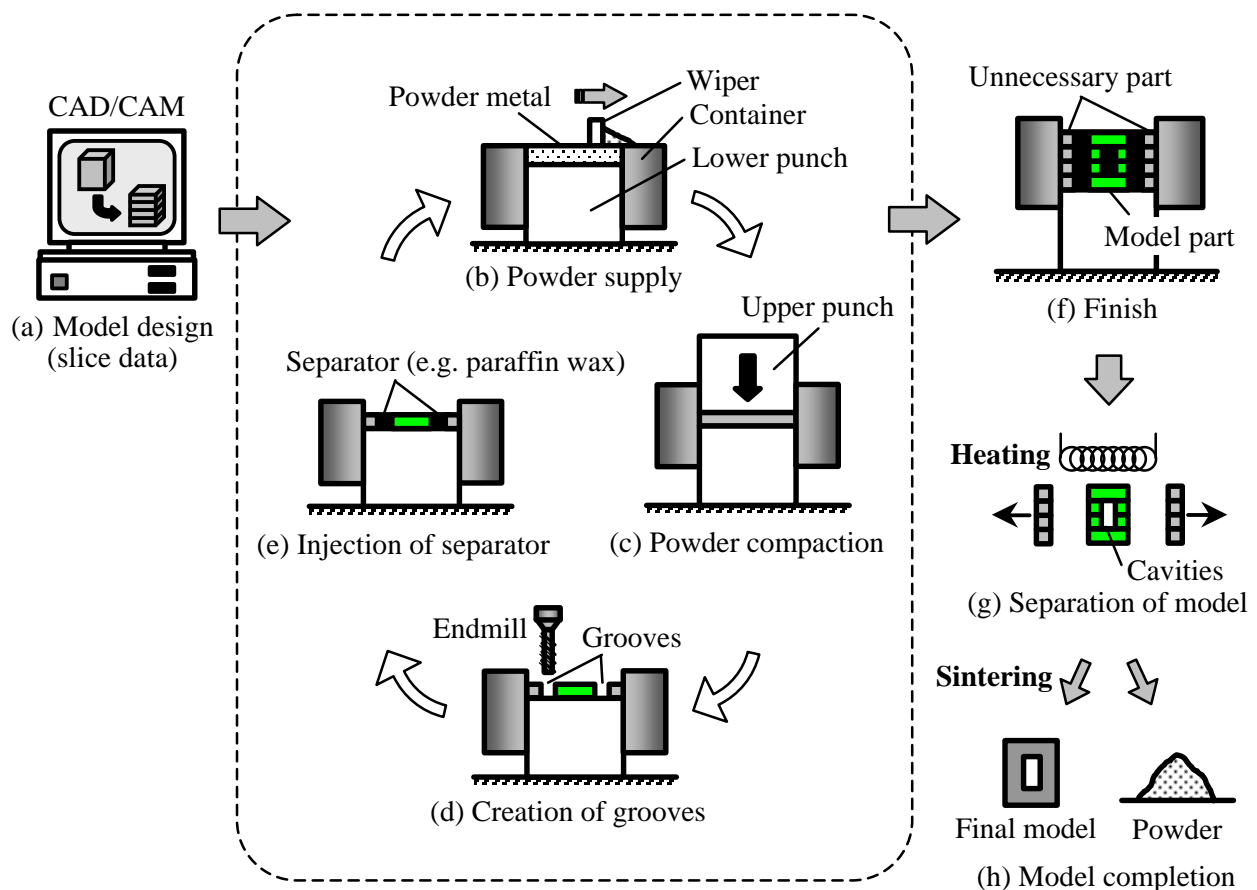


Figure 1. Fabrication procedure of the LCM process combining powder compaction and milling in a layer-by-layer additive manner.

3. Materials and apparatus

In this study, WC-9wt%Co carbide powder with a particle size of 1-3 μm was used, and paraffin wax with a melting temperature of about 332 K was utilized as the separator. The WC-9wt%Co carbide is widely used for cutting tools and dies due to its high mechanical properties and high resistance to wear. The relative densities of the compacted green state and the sintered state against the compacting pressure are shown in Figure 2. At each compacting pressure, the sintered density is very close to 100%.

For powder compaction, a tool composed of a container with an inner diameter of 40 mm, a lower punch, and an upper punch was used (Figure 3). The grooves were created using a CNC milling machine (CAMM-3 PNC3000, Roland DG Ltd.) with a diameter of 1.2 mm endmill coated with diamond.

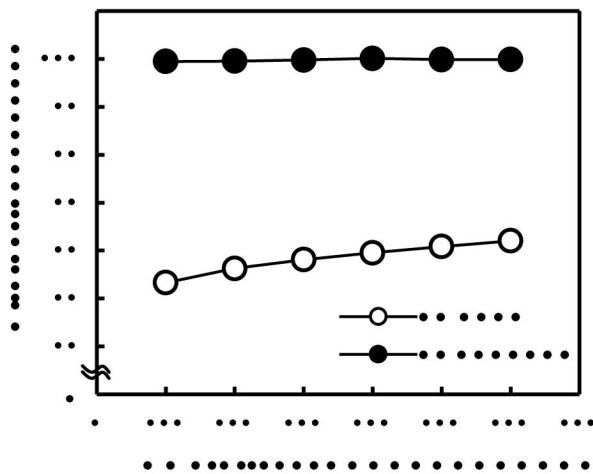


Figure 2. Relative densities of the WC-9wt%Co powder compacted at various pressures.

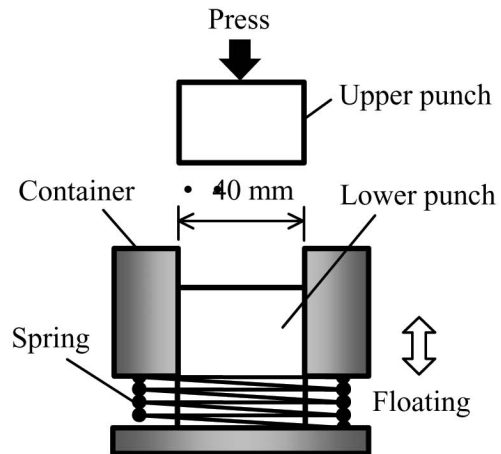


Figure 3. Tool for the powder compaction.

4. Evaluation of the LCM process

4.1 Process performance

The feasibility of the proposed method was evaluated by fabricating a WC-9wt% Co carbide cube shown in Figure 4. The total number of the layers is four, and the thickness of each layer is 1 mm. The compacting pressure is 200 MPa.

Figure 5a shows the created first layer. The subjects in the photographs represent the milled grooves according to the two-

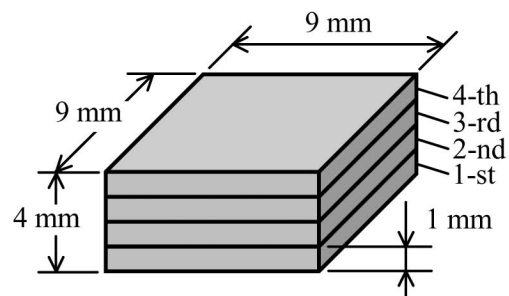


Figure 4. Schematic drawing of the designed model (cube).

dimensional profile of the cube (top row) and the grooves filled with paraffin wax (bottom row). The wax was filled after heating to about 413 K in order to improve the wettability with the compacted WC-9wt%Co powder. Although the supplied wax penetrates into the compacted carbide layer, it is completely dewaxed in the sintering processes. The excessive paraffin wax was removed by milling after solidification. Figure 5b shows the green object composed of the cube and the unnecessary part when the layered compaction is finished. By removing the unnecessary parts, the final green cube was obtained (Figure 5c). The cube was easily separated by remelting the wax in the grooves. The time required for creating the green cube was about 2 hours. These results suggest that the proposed method enables easy fabrication of carbide models with free shapes.

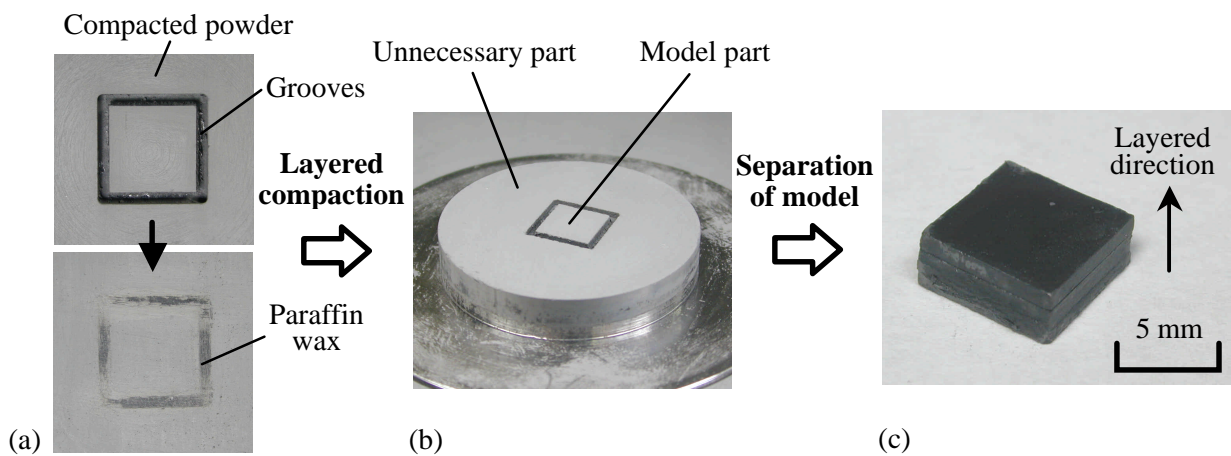


Figure 5. WC-9wt%Co green cube fabricated using the LCM process. (a) First layer. (b) Green object when the layered compaction is finished. (c) Final green cube.

4.2 Mechanical properties

In order to evaluate the connecting strength between the layers of the sintered model fabricated by the proposed method, the transverse strength of the layered specimens was measured after sintering by the three-point bending test. The results were compared with those of the conventionally compacted specimens (non-layered). The shape of the layered specimen used in the test is shown in Figure 6. The thickness of the layers around the center of the specimen, which is the breaking point in the bending test, is about 1 mm. The cross-section of the specimens is grounded to 8 mm×3.6 mm after sintering at 1623 K. The span between the supporting points is 20 mm.

The transverse strengths of the layered and

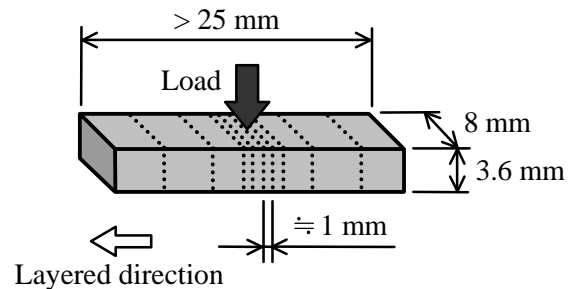


Figure 6. Layered specimen after sintering for the three-point bending test.

non-layered specimens compacted at various pressures are shown in Figure 7. The strength of the layered specimens is lower than that of the non-layered specimens by 5 to 30% at each compacting pressure. However, it is found that the transverse strength of the layered products after sintering is higher than 2 GPa, which is sufficiently high for the alloy. Figure 8 shows the microstructure of the layered specimen at the boundary between the layers. Metallographical defects and microcracks are not observed. These results indicate that the proposed method allows fabrication of the models with sufficiently high mechanical strength from the WC-Co powders.

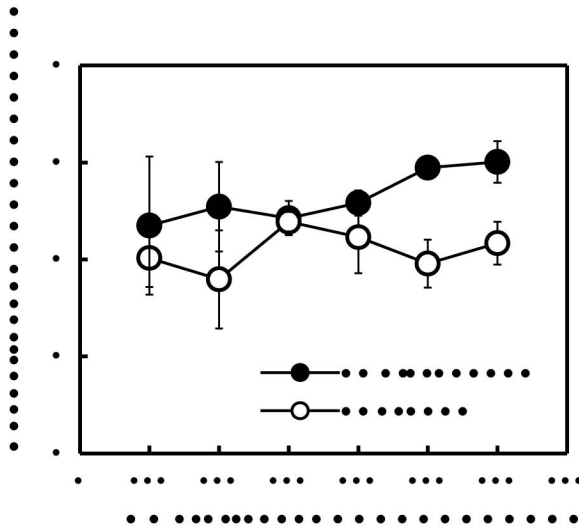


Figure 7. Transverse strength of the layered and non-layered specimens at various compacting pressures.

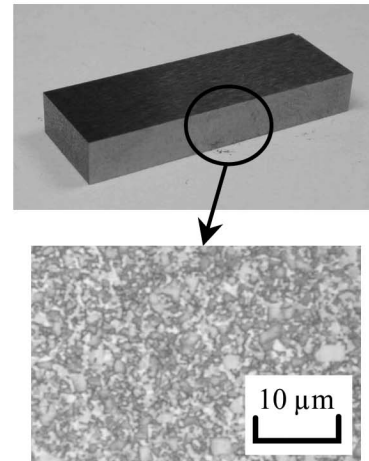


Figure 8. Microstructure of the layered specimen at the boundary between the layers.

5. Application of the method to model with inside channels

5.1 Model design

A model with inside channels, which has a potential to realize molds and dies with temperature control, was fabricated from the WC-9wt%Co carbide powder by the LCM process. The designed model is schematically shown in Figure 9. The internal channels are composed of the channel 1 and channel 2 located in the lower and upper part of the model, respectively. These channels are connected with the channel 3 in the middle of the model. The cross-section of the channels before sintering is 1.2 mm wide \times 1 mm high. The designed model is numerically decomposed to five layers as shown in Figure 9b, and the thickness of each layer is 1 mm. The channel 1, channel 2, and channel 3 are created in the second, fourth, and third layer, respectively. The compacting pressure is 200 MPa.

For fabricating the internal channels, the grooves corresponding to the channels are milled, and then they are filled with paraffin wax. After the layered compaction is finished, the wax is removed from the grooves by heating the green model in the furnace at about 363 K for 5 minutes. Finally, the green model is sintered at about 1623 K for 7 hours.

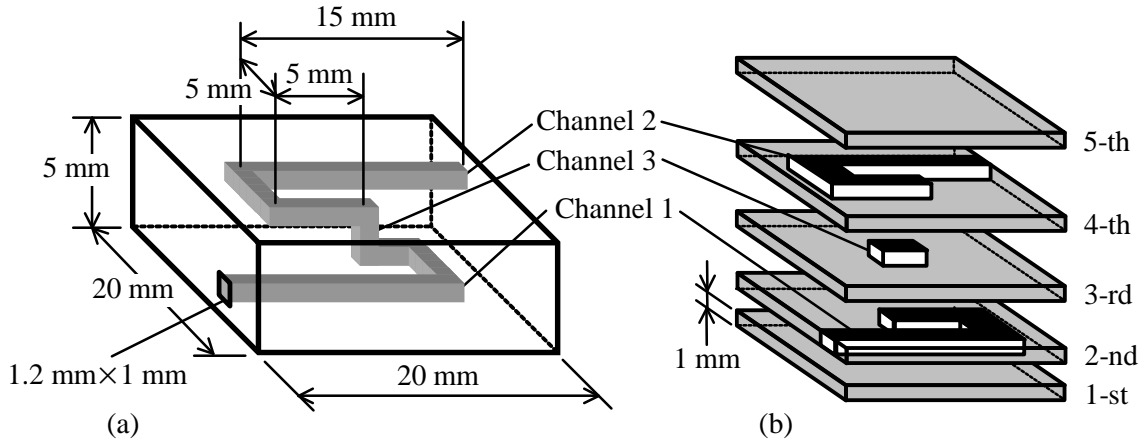


Figure 9. Schematic drawing of the model with inside channels (a) and its layer construction (b).

5.2 Results and Discussion

The green model produced by the LCM process is shown in Figure 10. The photograph in the left shows the top view of the fabricated second layer. The paraffin wax filled in the grooves shapes the channel 1. The final green model is shown in Figure 10b. The time required for producing the green model was about 4 hours.

The cross-section of the internal channels before/after sintering is shown in Figure 11. By heating the green model in the furnace, the paraffin wax is completely removed from the grooves and the internal channels are obtained (Figure 11a). After sintering, the channels maintain their shapes (Figure 11b). These results indicate that the LCM process enables fabrication of complicated geometry such as the internal channels, which is difficult to be realized with the conventional machining method.

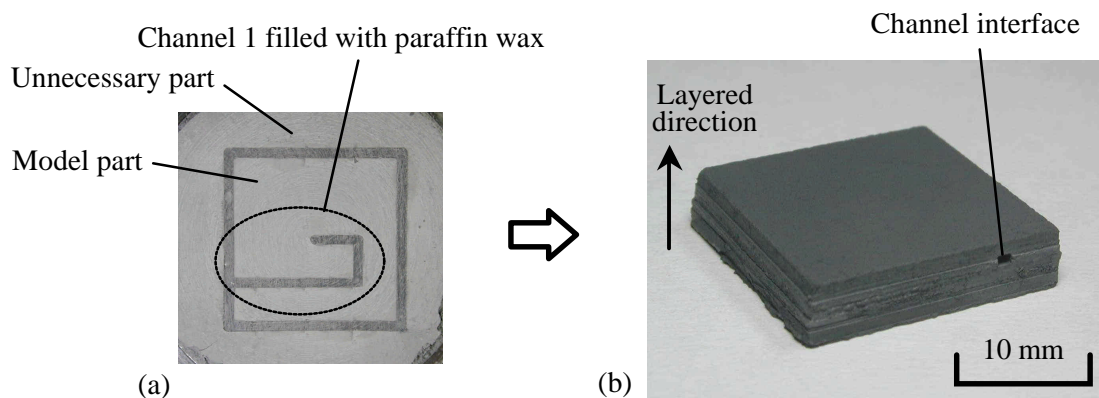


Figure 10. WC-9wt%Co green model with inside channels fabricated using the LCM process. (a) Top view of the second layer. (b) Complete view of the final green model.

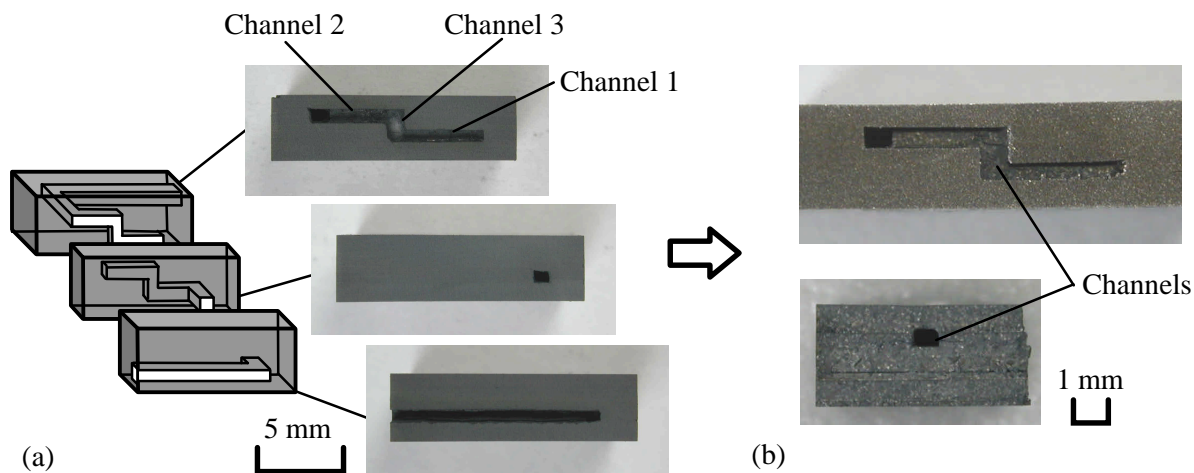


Figure 11. Cross-sectional view of the internal channels. (a) Green model. (b) Sintered model.

6. Conclusions

Layered Compaction Manufacturing (LCM) process has been developed in order to produce three-dimensional models with cemented carbide powders. The feasibility of the LCM process has been evaluated using a WC-9wt%Co powder, and following results have been obtained.

- (1) By making WC-9wt%Co carbide cubes, it is confirmed that the proposed method enables easy fabrication of the near-net-shape carbide models.
- (2) The connecting strength between the layers of the sintered model made of WC-9wt%Co powder has been measured by the three-point bending test. It is found that the transverse strength of the sintered products is higher than 2 GPa, which is sufficiently high for WC-Co alloys.
- (3) A model with inside channels, which is difficult to be realized with the conventional machining method, has been successfully fabricated using a paraffin wax as a sacrificial material (separator). This result suggests that the LCM method allows fabrication of molds and dies with inside channels for temperature control.

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