Design Method for Structure of Injection Mold Fabricated by Metal Laser Sintering

Hiroshi KORESAWA[1], Michio KOJIMA[1], Hiroyuki NARAHARA[1], Hirofumi FUKUMARU[1] and Hiroshi SUZUKI[1]
[1] Department of Mechanical Information Science and Technology,
Kyushu Institute of Technology, Japan, koresawa@mse.kyutech.ac.jp

Abstract:
This paper deals with design method for structure of injection mold fabricated by Metal Laser Sintering, which is one of the rapid prototyping technologies. This technology provides mold with more sophisticated function and improvement of formability and productivity. To realize structure of mold with these advantages, the method has been developed by following processes : (1)Specifying important structural location by optimization method. (2) Satisfying design specification using the location. It is confirmed as results of numerical experiments that suitable structure with less volume of high-density sintering, in comparison with structure fabricated by conventional process, is obtained.

Keywords: Rapid Prototyping, Metal Laser Sintering, Design of Mold and Die, Injection Molding

1. Introduction

Molds are used in the mass production of industrial products. A mold is positioned as a mother tool for the production of products; mold design is extremely important, because the quality of mold efficiency greatly influences both product function and productivity. At the same time, there is a constant demand for molds which deliver ever higher product quality, lower costs, and shorter delivery times.

Currently, in certain areas of the field of rapid prototyping technology[1], a technology has emerged in which a laser beam is made to scan upon metal powder, by means of which a thin layer is selectively sintered from the powder metal. By building up multiple layers, a three-dimensional form may be produced. In recent years, exceptional improvements have been made to this technology, which is now being applied not only at prototype formation sites but also at mass production sites. This technology is also in use at mold manufacturing sites. Molds manufactured using this technology are being used [2] in mass-production operations, and continue to prove themselves with outstanding results.

In processing technology based upon removal processes, such as are seen in processes in which work pieces are subjected to cutting work and elector discharge machining, the technology mentioned above has enabled the realization of many advantages. Some of these advantages, which were extremely difficult to realize in the past, are given in the following list. (1) It is possible to freely structure forms within the interior of pieces. For example, because of the possibility of freely laying down snaking cooling circuits within molds, it subsequently becomes possible to achieve a uniform temperature distribution throughout the surface of the mold cavity [3], which is expected to improve formability and productivity. (2) It is possible to imbue molds with even further-sophisticated capabilities. For example, it is possible to structure a porous structure which prevents the occurrence of molding defects known as burn mark, which arise in molded product forms in which it proves extremely difficult to bleed gases from within the mold cavity [4]. (3) It is possible to vary the mechanical strength of the sintered body by varying the energy density of the laser beam in use during the processing. (4) It is possible to dramatically improve freedom of mold design.

However, there are also the following defects. (1) The powder metal materials are extremely expensive. (2) Long molding times are required in order to realize high-density sintered bodies with high mechanical strength. (3) It is extremely difficult to draw up mold designs which make full use of this rapid prototyping technology.

Therefore, the objective of this research is to study mold design methods which enable the above-listed defects to be solved by achieving optimum interior structure when designing the interior structures of injection molds produced through rapid prototyping technology using powder metal materials. We herein report on our success in realizing molds which, for example, use less powder metal than other molds, but which retain the same level of structural rigidity through the comparison of numerical value experiment results and current design methods.

2. The Difficulty and Importance of Structural Design using Rapid Prototyping Technology

2.1 Difficulties Associated with Improving Design Freedom

The degree of freedom for mold designs which assume the use of process technologies based upon removal processes is extremely low due to the limits of such processing methods. On the other hand, these limits are ameliorated when using rapid prototyping technology, making it comparatively easy to realize three-dimensional structures. While demands are increasing for three-dimensional structural designs which are even more complex than conventional designs, it is also a fact that these structural designs which include complex interior structures are extremely difficult to create.

2.2 Accommodating Design Changes

One of the characteristics of mold design is adapting to frequent design changes. Simply applying conventional design methods when designing complex three-dimensional structures is almost certain to lead to lengthy design times and increased design costs.

2.3 The Importance of Determining Interior Structure

As is shown in Fig. 1, the interior structures of structural objects formed using currently-existing rapid prototyping technologies are structured in three layers throughout the object, from the surface to the interior. These three layers are known as the melt layer, the skin layer, and the core layer, respectively. The mechanical strength of each layer gradually decreases as one moves inward from the surface. The thickness of each layer is almost always determined experientially, and it is not always the case that properties such as structural strength have been optimally evaluated. This impacts the amount of powder metal materials used, the molding time and the cost of materials, among other factors, and ultimately exerts a large influence upon manufacturing costs. Therefore, it is extremely important to determine the optimum thickness of each layer in conjunction with structural evaluation.

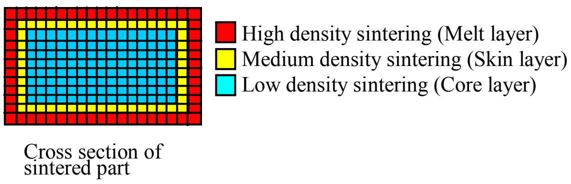


Figure 1. Inner structure of sintered part.

3. Design Methods Studied

Figure 2 shows the design techniques studied using this method. These techniques are composed of three major areas.

(A) Determination of initial analytical values: The setting of design specifications, design form and setting values for the purpose of initial internal structure and analysis (A-1).

(B) Incorporation of numerical analysis and optimized techniques: Numerical analysis is used for structural evaluation. The internal structure of structural bodies is determined by incorporating physical values and optimized techniques obtained through numerical analysis (B-1). Convergence judgments (B-2) made during analysis vary according to the designer. In consideration of cases in which there is no convergence of internal structural form, analysis frequency is repeated within parameters which do not exceed maximum repetition frequencies (B-3).

(C) Structural evaluation and re-design: Structural evaluation judgments are made by mold designers regarding stress values and displacements which may be expected to occur under design specifications (C-1).

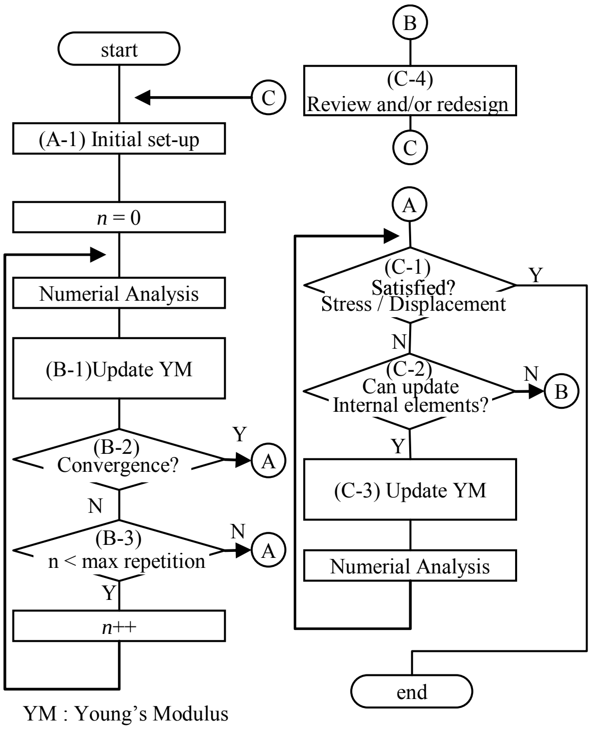


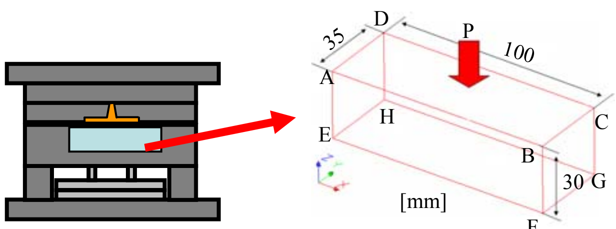
Figure 2. Design flowchart.

Design is complete when design specifications have been satisfied. If design specifications have not been satisfied, re-design is carried out using the internal structure obtained by means of optimization techniques. In this event, confirmation is made that the entire structural interior has not reached the maximum Young's Modulus (C-2). When this condition has been satisfied, the structural interior is first divided into multiple elements. Thereafter, the maximum Young's Modulus is applied for each element in the order of most to least importance for strength (C-3). Next, stress and displacement are found using repeated numerical analysis and the process begins again from (C-1), with this sequential processing being repeated. If, in (C-2), the entire structural interior has reached the maximum Young's Modulus, then a fundamental structural or design specification reexamination is carried out (C-4), and the process begins again from (A-1).

4. Numerical Experimental Model

4.1 Experimental Model

Figure 3 shows the numerical experimental model assumed for this research. A rectangular solid-form insert core built up to the moving mold half of an injection mold was assumed. It was hypothesized that an even, externally-applied molding pressure (29.7MPa) would be



(a) Injection mold (b) Insert core

Figure 3. Model for numerical experiment.

applied to A, B, C, and D of the model surface. Constraint conditions are shown in Table 1. Numerical analysis has been realized by evenly dividing the model into

Table 1 : Boundary conditions.

Injection pressure (P)	29.7 [MPa] A-B-C-D
Displacement constraint in z-direction	E-F-G-H
x-direction	A-E-H-D, B-F-G-H
y-direction	A-E-F-B, D-H-G-C

4.2 Incorporated Optimization Techniques

The optimization techniques [5] used in this research were based upon local rules. The local rules (Eq.(1)) were applied to each element. This is a technique in which stress values and target stress values obtained during numerical analysis are used to obtain a progressive structure while constantly carrying out sequential updates of Young's Modulus.

$$E^{n+1} = E^{n} \bullet f(\sigma^{n}, \sigma_{c}) \qquad (1)$$

In this equation, σ_c represents target stress, σ represents stress values obtained during analysis and E represents the Young's Modulus obtained during analysis. *n* is a subscript indicating the number of analysis iterations.

Figure 4 shows the relationship between target stress and Young's Moduli using these optimization methods. The graph is in a stepped form. This is because, in the assumed metal laser sintering combined with high-speed milling machine [2], molding is either possible or impossible depending upon the density of the laser beam in use. Furthermore, in order to simplify our evaluations, only the melt layer and the core layer were used in this experiment. Table 2 shows the Young's Moduli and the maximum allowable stress for each layer. In this research, von Mises stress was used as the stress obtainable through

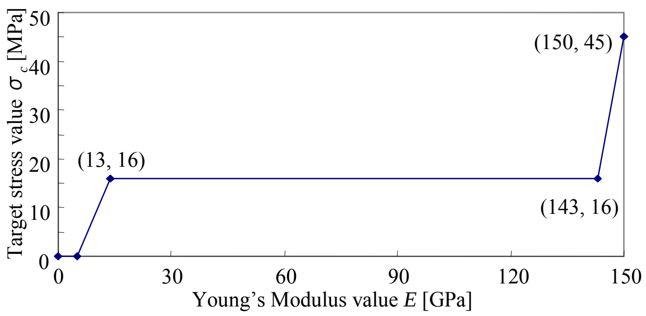


Figure 4. Relationship between target stress (σ_c) and Young's Modulus (*E*).

Table 2 : Allowable stress and Young's Modulus.

Condition of sintered part	Allowable stress [MPa]	Young's Modulus [GPa]
High density sintering (Melt layer)	45	150
Low density sintering (Core layer)	16	13

analysis.

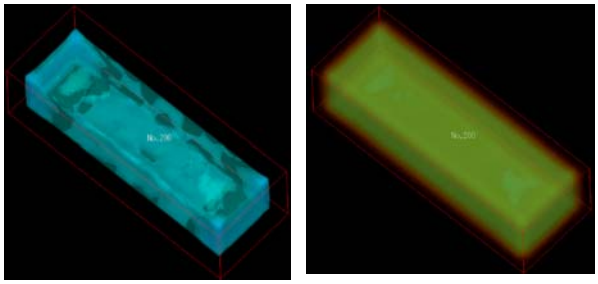
Because it is necessary to preserve mold surface form when applying extremely high molding pressure and mold clamping pressure, the surface is invariably constructed of a melt layer.

Structural optimization processes were carried out by setting the Young's Moduli in the internal structure (hereinafter, "initial structure") at analysis commencement (n = 0) at 150[MPa]. This is the Young's Modulus for the melt layer, which has the highest mechanical strength (hereinafter, "maximum Young's Modulus"). When results were obtained during processing which exceeded the maximum Young's Modulus, a forced re-design of these values was carried out and processing was continued.

5. Experiment Results and Considerations

5.1 Optimized Internal Structure

Figure 5 shows the internal structure obtained after optimization processing. In this figure, it can be confirmed that a two-layer structure was obtained. It was observed that when the Young's Moduli were within a range of from 40 to 150[GPa], the majority of high-Young's Modulus elements were located near the surface, while the internal structure was complex when the Young's Moduli were within a range of from 0 to 40[GPa].



(a) Range 0 – 40 [GPa] (b) Range 40 – 150[GPa]

Figure 5. Young's Modulus distribution in structure at the point optimization process finished (*n*=200).

Regarding convergence conditions, Fig. 6 shows the Young's Modulus frequency distribution for internal structure elements during each analysis. No major changes were observed after the step at which analysis frequency n

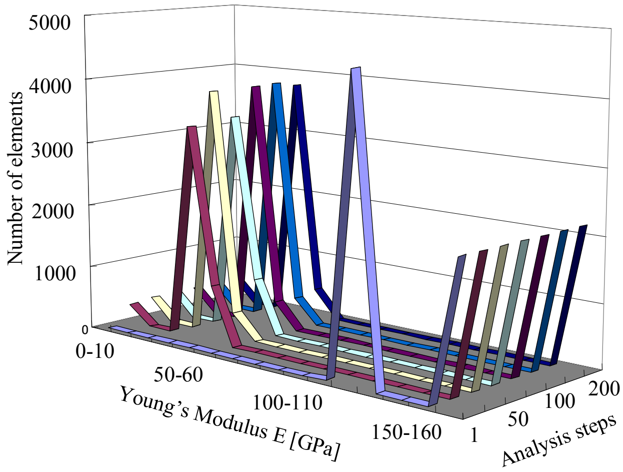


Figure 6. Transition in Young's Modulus frequency distribution on each analysis step.

= 100. Thus, we judged that the optimization processing had converged. In this experiment, we took the structure at the point in time at which analysis frequency n = 200 to be the optimized internal structure (hereinafter, "optimized structure").

5.2 Structural Evaluation and Re-Design

Figure 7 shows the frequency distribution for stress arising in the interior of the initial structure (commencement of analysis: n = 0) and the optimized structure (completion of analysis: n = 200). In comparison with the initial structure, high stress levels occurred in the optimized structure which exceeded the maximum allowable stress (45[MPa]). A re-design of the internal structure was carried out from this point. The elements used during numerical analysis were used in the division of the structure by element. Hereinafter, the structure in which the maximum Young's Moduli were forcefully exchanged at structurally important areas will be referred to as the "revised optimized structure." From these results, we were able to confirm that the maximum stress values within the structural interior decreased as the number of replaced elements increased.

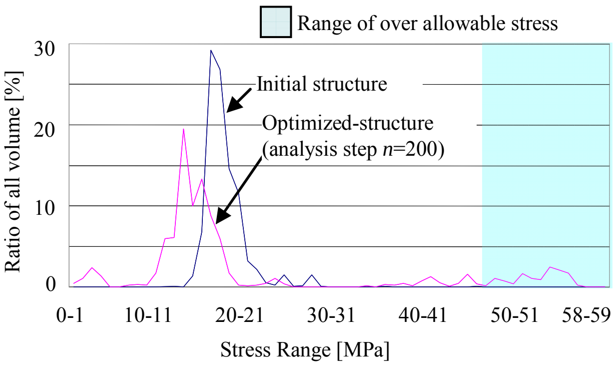


Figure 7. Stress frequency distribution on initial structure (n=0) and optimized-structure (n=200).

5.3 Comparison with Conventional Structures

The structure obtained using this technique was compared with conventional structures. In conventional structures, a melt layer is formed in a uniform thickness from the surface. The thickness of this layer is 7.5mm.

Figure 8 is a graph in which the horizontal axis shows the revised optimized structure in which maximum Young's Moduli were gradually replaced at structurally important positions. The vertical axis of this graph shows changes in maximum displacement amount and internal melt layer ratio on the insert core surface (surface ABCD). It was confirmed that the maximum displacement amount decreased in proportion to increases in elements exchanged for maximum Young's Moduli. The lowest values were obtained when all of the elements had been exchanged for maximum Young's Moduli (number of exchanged elements: 4,560).

In this comparison with conventional structures, it was confirmed that the vicinity of structures in which 500 elements (approximately 10% of the total volume) were forcefully exchanged for maximum Young's Moduli, a maximum displacement amount was obtained which was

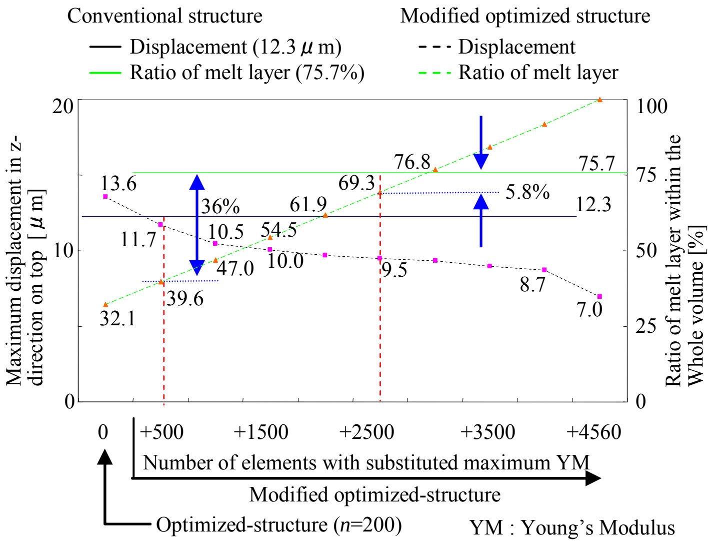
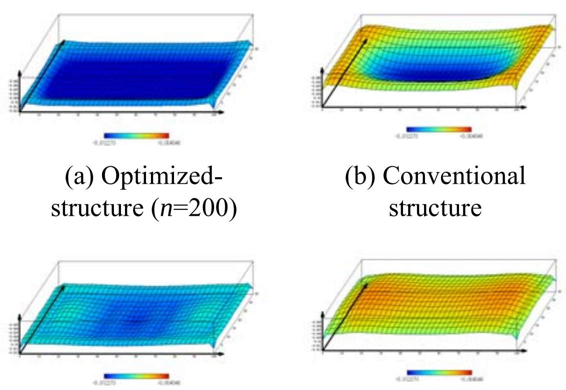


Figure 8. Changes in the maximum displacement in z-direction and the melt layer ratio within total volume when maximum Young's modulus in the revised optimized structure is substituted.

comparable to that of conventional structures. In this even t, a comparable structural rigidity was achieved at a low melt ratio of approximately 36%. However, for internal stress, more than 10% of the total number of elements exceeded the maximum allowable stress, which produced a structurally unsuitable product. Internal stresses in structures in which 2,500 elements (approximately 54% of the total volume) were forcefully exchanged for maximum Young's Moduli were at or below maximum allowable stresses, while maximum displacement amounts were lower even than that of conventional structures. In this case, a structure was achieved in which the melt layer ratio was low, at approximately 5.8%. This leads to the expectation that it will be possible to reduce the amount of powder metal used, and also to reduce machining times.

Figure 9 shows the displacement at the insert core surface (surface ABCD) for each structure. In revised optimized structures, it was confirmed that the maximum displacement amount was reduced while overall deformation was realized.



(a) Optimized-structure (n=200)

(b) Conventional structure

(n=200, +500)

(n=200, +2500)

(c) Modifeid optimized-structure

Figure 9. Displacement distribution in z-direction on top.

As is shown in Fig. 5 , by using design methods set forth in this research for extremely three-dimensional structures, structures made using the special characteristics of rapid prototyping technology allow designers to comprehensively implement their own design visions even in cases in which internal structure design changes arise which are only marginally important for the detailed design of internal structures. It is expected that these methods will allow for thorough adaptation to design changes which occur frequently during mold design.

6. Conclusion

In this research, we employed a method for designing structures achieved through the continuous laminating of layers using selective laser sintering of powder metal, which is one kind of rapid prototyping technology. Fully implementing the advantages of this technology, we studied methods for efficiently designing internal structures. The following conclusions were obtained as a result of numerical experiments carried out under the assumption of an injection mold insert core.

(1) By incorporating optimization techniques and specifying important areas from a standpoint of structural interior strength and then varying the mechanical strength (Young's Modulus) of these important areas, we were able to obtain a structural body in which it was possible to reduce both stress and displacement.

(2) We confirmed that, in comparison with structural bodies manufactured using standard techniques, it is possible to reduce melt layer ratio in structural bodies obtained using our new techniques, even when these structures possess the same level of structural rigidity.

(3) We used the physical quantities of stress and displacement to evaluate structural bodies, thus determining the melt layer structure (structural quantity) of the interiors of those structural bodies. It is expected that this will allow for appropriate decisions to be made regarding machining times and powder metal amounts.

We next plan to use metal laser sintering combined with high speed milling to manufacture the structural bodies obtained using these new techniques, and then to use these structural bodies to carry out form experiments in order to study these techniques' utility.

Acknowledgement

We would like to thank Hiroyuki Matsuura of this laboratory, Daisuke Ueda and Teruki Hayashi, who enthusiastically cooperated in this research.

Reference

[1] A., Gebhnardt, 2003, Rapid Prototyping, Hanser Publisher.

[2] Abe, S., Higashi, Y., Togeyama, H., Fuwa, I. and Yoshida N., 2007, Development of milling-combined laser metal sintering method (Combination of laser-assisted metal sintering method and the milling in one machine), J. of Japan Soc. for Precision Eng., Vol.73, No.8, pp.912-916 (in Japanese) .

[3] Yoneyama, T. and Kagawa, H., 2008, Fabrication of Cooling Channels in the Injection Molding by Laser Metal Sintering, Int. J. of Automation Technology, Vol.2, No.3, pp.162-167.

[4] Kojima, M., Narahara, H., Nakao, Y., Fukumaru, H., Koresawa, H. and Suzuki H., 2008, Permeability Characteristics and Applications of Plastic Injection Molding Fabricated by Metal Laser Sintering Combined with High Speed Milling, Int. J. of Automation Technology, Vol.2, No.3, pp.175-181.

[5] Inou, N., Shimotai, N. and Kobayashi, H., 1995, Cellular Automaton Self-Organizing a Mechanical Structure. Behavior of Total System Generated by Local Rules, Trans. Japan Soc. Mech. Eng., Vol.61, No.586 (A series), pp.1416-1422 (in Japanese).