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Study on Reduction of Residual Stress Induced during Rapid Tooling Process - Influence of Heating Conditions on Residual Stress -

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Abstract. This paper deals with the reduction of residual stress induced during the selective laser melting with a mixture of ferrous based metal powder. To evaluate the residual stresses induced during layered manufacturing processes, a strain gauge is attached on the bottom face of the base plate. The residual stress within the consolidated structure is calculated from the amount of strain change measured by the strain gauge when the consolidated structure is cut with an end mill. The influences of base plate thickness and consolidated structure height on the residual stresses are investigated. In addition, the effect of pre-heating and post heating by a laser beam irradiation are evaluated. The results showed that the deformation of the base plate increased with the increase of the consolidated layer and the decrease of base plate thickness, and the deformation was flattened when the consolidated structure was completely removed with the end mill. The deformation was related to the induced residual stresses. The residual stress distribution within the consolidated structure in the z direction was extremely large at the top layer of the structure and the boundary between the base plate and consolidated structure. The residual stress at the first layer of the structure decreased when the base plate was heated before consolidating the deposited powder. The residual stresses decreased when each of the consolidated layers was repeatedly heated by the laser beam irradiation.

Introduction

Since Kodama introduced a new method for the automatic fabrication of a three-dimensional plastic model, various types of layered manufacturing techniques have been applied to achieve in the manufacturing of prototypes, tools and functional end products[1,2]. These techniques have been followed with the development of three dimensional CAD systems, and classified as a different new group from the forming process and the material removal process. The layered manufacturing technique with metal powder is especially remarkable because a practical use is possible for the obtained products. Recently, a multifunction machine, in which a ferrous based powder bed is selectively heated and fused by laser beam irradiation and the edge of the consolidated structure is cut with an end mill, has been developed to produce an injection molding die[3]. However, the consolidated structure formed in this machine has problems that a deformation and a micro crack are caused due to the residual stresses induced during the laser beam irradiation[4].

This paper deals with the reduction of residual stress induced during the layered manufacturing processes. To evaluate the residual stresses within the consolidated structure, a strain gauge is attached on the bottom face of the base plate. The residual stress within consolidated structure in each position is calculated from the amount of strain change measured by the strain gauge when the consolidated structure is cut layer by layer with an end mill. The influences of the thickness of the base plate and the height of consolidated structure on the residual stresses are experimentally investigated. In addition, the effect of the pre-heating by a laser beam irradiation on the base plate and the laser condition for the layered manufacturing on the reduction of the residual stress are evaluated.

Table 1 Specification of metal powder

Material		SCM, Cu, Ni
Shape		Irregular
Particle mean diamete	d	25 [μm]
Bulk density	ρ	4190 [kg/m^3]
Absorption ratio	A_r	25 [%]
Thermal conductivity	T_k	0.14 [W/m·K]

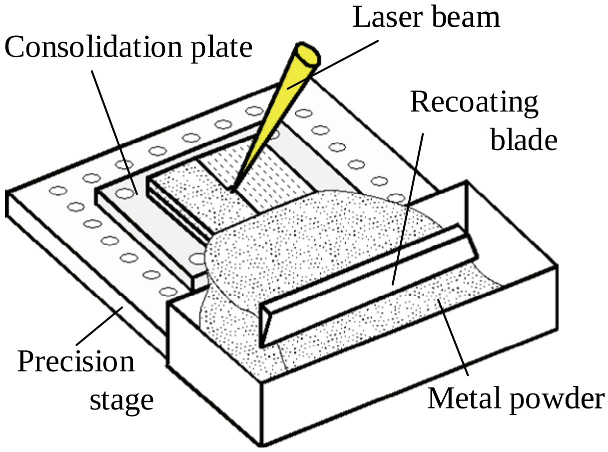

Fig. 1 Schematic illustration for consolidating metal powder

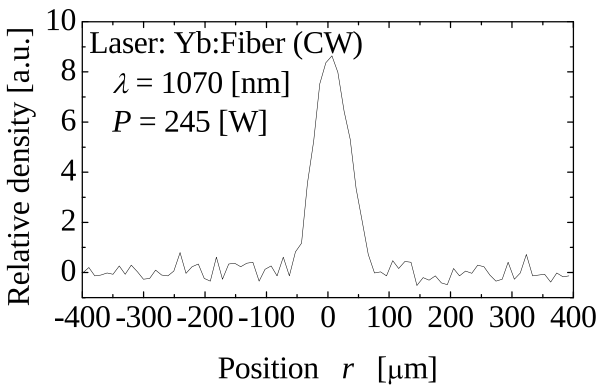

Fig. 2 Profile of laser beam

Experimental setup

Consolidation procedure The schematic illustration for consolidating a metal powder is given in Fig. 1. This system is composed of a Yb:fiber laser (IPG Photonics Corp.: YLR-SM) and the consolidation facility of a metal powder. The intensity of laser beam relative density measured by beam profile system (OPHIR Corp.: Beam star FX-50) is shown in Fig. 2. The laser beam formed a Gaussian shape and the focal diameter was ϕ=100 μm. The metal powder is deposited on the base plate at a thickness of 50 μm with a recoating blade. The laser beam then was irradiated to the powdered surface through a galvanometer mirror, and scanned on it with programmed NC data. After forming a layer of consolidation, these processes are repeatedly performed as the scan direction of laser beam is varied by 90°. In order to improve the wetting property of the melted powder, the plate surface was sandblasted with #35 of average grain size[5]. The surface roughness of the base plate was *Ra* =3.5 μm. Nitrogen is filled up within the consolidation vessel during the manufacturing processes so as to prevent the oxidization of the metal powder.

Metal powder The specification of metal powder is summarized in Table 1. The metal powder was a mixture of 70% chromium molybdenum steel powder, 20% copper alloy powder and 10% nickel powder in weight. The mean diameter of the powders mixture was d=25 μm. Since metal powder was loaded under gravity action only, its bulk density was 4190 kg/m^3[6].

Beam model for the evaluation The beam model used to measure a residual stress is shown in Fig. 3, and its consolidation conditions are summarized in Table 2. The base plate was carbon steel with a fixed size of 49 x 9 mm and its thickness was ranged 5 - 30 mm. The consolidated beam model was a fixed size of 45 x 5 mm and located at the center of the base plate. The thickness of the beam model which was varied by the number of forming layers was ranged 1 - 30 mm.

Measurement of base plate deformation The deformation caused by the consolidated structure was examined by measuring the bottom face profile of the base plate with a CCD laser displacement sensor (Keyence Corp.: LK-080) which is 49 mm of evaluation length. The influences of the base plate thickness and the consolidated structure height on the deformation are experimentally investigated.

Measurement of residual stress within consolidated structure The experimental conditions for measuring the residual stress within consolidated structure are given in Table 3. To evaluate the residual stresses induced during layered manufacturing processes, a strain gauge (Kyowa Electronic Instruments Co., Ltd.: KFG-2-120-C1-11) was attached on the bottom face at the center of the base plate. The residual stress was evaluated by measuring the dynamic strain with the strain gauge when the surface of consolidated structure was cut with an end mill. The cutting tool used was high speed steel which is 16 mm in diameter and its axial depth of cut was fixed to 0.1 mm. The cutting speed was 17.6 m/min and it is slow enough to prevent the influence of residual stress generated by the cutting process. The milling and strain measurement was alternately carried out until the whole consolidated structure was removed. The residual stress in each position was calculated from the amount of strain change measured by strain gauge[7]. In the stress calculation, the Young's module of consolidated structure was determined to be 124 GPa from a tension test.

Reduction of residual stress To investigate the influence of heat treatment to the beam model on the reduction of residual stress within the consolidated structure, the effect of preheating and post heating of the beam model was examined. Table 4 gives the experimental conditions. The preheating was performed to the base plate surface to investigate the reduction of residual stress on the base plate. The post heating was performed to the surface of consolidated structure.

Table 2 Consolidation conditions

Plate		Carbon steel (AISI 1049)
Size		49 x 9 [mm]
Thickness	t_s	5 - 30 [mm]
Consolidation		
Size		45 x 5 [mm]
Thickness	t_c	1 - 30 [mm]
Layer thickness	t	50 [μm]
Laser beam		
Laser power	P	200 [W]
Scan speed	F	440 [mm/s]
Beam diameter	ϕ	100 [μm]

Table 3 Experimental conditions for the measurement of residual stress

Strain gauge		KFG-2-120-C1-11
Gauge length	L	2 [mm]
Resistance	R	120 [Ω]
Cutting tool		EX-TIN-EDS 16
Tool material		High speed steel
Diameter	ϕ_t	16 [mm]
Shape		Flat end mill
Number of flute		2
Cutting speed	V	17.6 [m/min]
Feed	F	40 [mm/min]
Axial depth of cu	A_z	0.1 [mm]

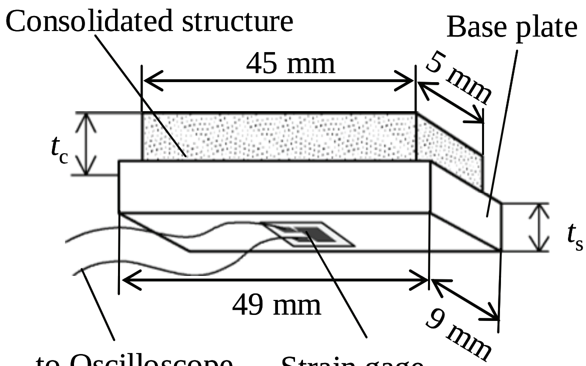

Fig. 3 Beam model for the evaluation

Results and discussions

Residual stress distribution The residual stress distribution in the layered direction of consolidated structure is shown in Fig. 5. From this graph, there were tensile stresses within the consolidated structure in each position. Additionally, the residual stress was extremely large at the top layer of the consolidated structure and at the boundary between the base plate and the consolidated structure, and its value was σ =800 MPa in each position.

Influence of layered conditions on residual stress The influence of the base plate height on the base plate deformation and the residual stress induced at the top surface is shown in Fig. 5, where the number of consolidated layers is constant of 120. The deformation height of the base plate decreased with the increase of the height of the base plate, and was then saturated to zero at the plate height of t_s

=30 mm. On the other hand, the residual stress at the top surface of consolidated structure remained almost constant in all conditions. These results showed that the residual stress at the top surface of consolidated structure had no relation to the base plate height. These were because the geometrical moment of inertia increased with the increase of the base plate height, therefore the base plate was hardly to deform by the residual stress on the top surface. In addition, the deformation of the base plate was flattened when the consolidated structure was completely removed with an end mill.

Fig. 6 showed the influences of the layered number on the base plate deformation and the residual stress at the consolidated surface under the base plate height of t_s=20 mm. The deformation height and residual stress increased with the increase of the layered number, and then became almost constant when the layered number was over 400 layers. The increase of the residual stress was due to the increase of the consolidated layer, which was equal to the laser irradiation number.

Effect of heat treatment on the reduction of residual stress When the laser beam was irradiated to the base plate surface at the laser power of 200 W, the influence of preheating on the residual stress reduction at the boundary between the base plate and the consolidated structure was indicated in Fig. 7. The residual stress at the boundary was extremely small after the laser beam was irradiated to the base plate surface, and resulted in the reduction of the deformation height.

Fig. 8 showed the variation of residual stress with the post heating of the consolidated layers. The post heating was performed in each layer after the powdered surface was consolidated by the laser beam irradiation. As shown in Fig. 8, the large residual stresses at the top layer of the consolidated structure decreased with the post heating by the laser beam irradiation although the residual stress within the consolidated structure was not influenced with the post heating.

Table 4 Experimental conditions for the residual stress releasing

Laser power	P	200 [W]
Scanning speed	F	440 [mm/s]
Beam diameter	ϕ	0.1 [mm]
Hatching pitch	H	45 [μm]
Base plate thickness	t_s	20 [mm]
Consolidation thicknes	t_c	3 [mm]

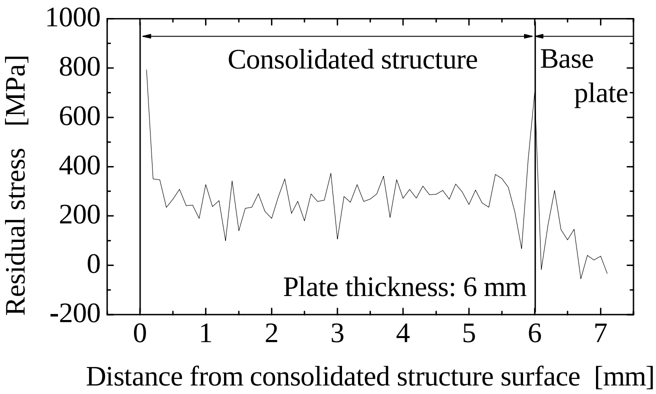

Fig. 4 Residual stress distribution

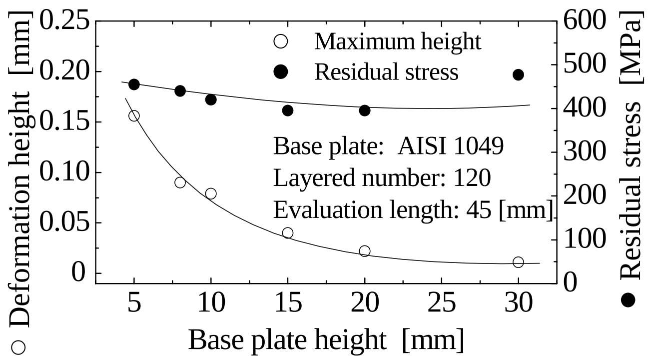

Fig. 5 Influence of base plate height on deformation and residual stress at the top surface

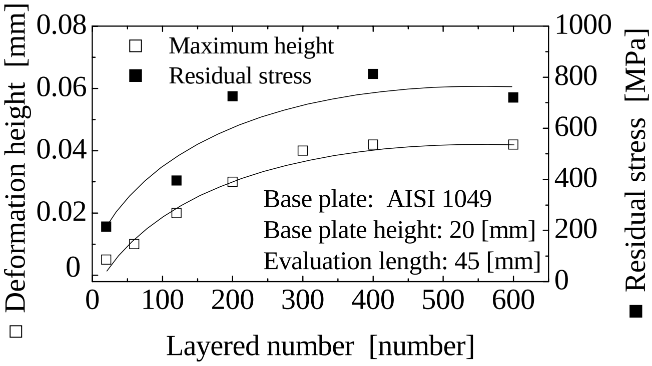

Fig. 6 Influence of layers number on deformation and residual stress
(Base plate height t_s =20 mm)

Summary

The main results obtained were as follows:

(1) There were tensile stresses within the consolidated structure and these values were extremely large at the top surface and at the boundary between the base plate and the consolidated structure.

(2) The deformation of the base plate decreased as the consolidated surface was cut with the end mill, and the surface was flattened after the consolidated structure was completely removed.

(3) The deformation of the base plate was related to the residual stress at the consolidated surface.

(4) The residual stresses at the top layer of consolidated structure and at the boundary between the base plate and the consolidated structure decreased when the heat treatment was performed with the laser beam irradiation.

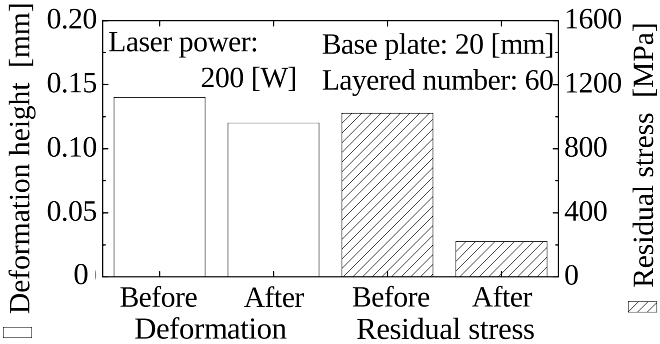

Fig. 7 Effect of preheating at the base plate on the reduction of residual stress at the boundary

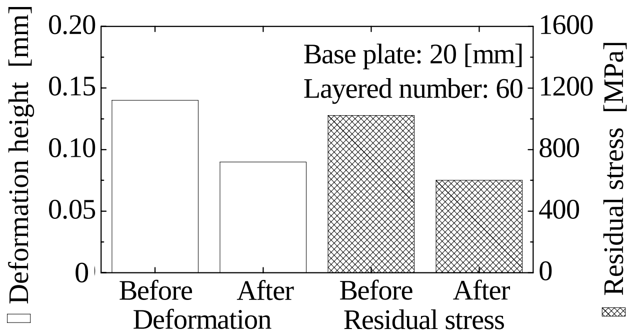

Fig. 8 Effect of post heating at the top layer on the deformation and the residual stress at the top surface

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