Study on parallel fabrication in additive manufacturing  
(Connector design considering anisotropic strength by deposition direction)

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Abstract
This paper deals with a fabrication method in additive manufacturing (AM). Generally, a large model must be segmented into some parts featuring connector shapes in case that its size is over the fabrication area of AM device. However, the connector portion of each segment is usually the weakest portion in strength because it becomes thinner or narrower than the original shape. In this study, the connector design and fabrication method is investigated in consideration of the strength depending on the deposition direction in AM. Since the most parts fabricated by AM with plastic materials have anisotropic property in strength, the strength of the part can be designed by the build orientation in AM. In this paper, after the concept of the parallel fabrication that is the basis of the segmentation planning is introduced, the anisotropy of strength is evaluated with tensile and fracture tests. Then, the factor of fracturing is discussed by using stress simulation with the finite element method. Finally, the appropriate connector design is proposed and the effectivity is discussed.

Key words: Additive manufacturing, Segmentation, Strength, Anisotropy, Deposition direction, Connector

1. Introduction

Additive Manufacturing (AM) has been developed as a rapid prototyping method because it can fabricate directly shape models without molds. In recent years, demands for larger plastic models, of which size is more than 1m, is increasing. Such large model must be separated into some segments in case that its size is over the fabrication area of AM device. These models are usually segmented manually in stage of 3D-CAD modeling. The method of segmentation depends on experience of the operator, and there is no established rule. If the method of segmentation is regularized, not only the operational efficiency but also productivity by automated assembling of segmented model will be improved.

We have proposed the concept called “Parallel Fabrication” (PF), in which an entire model is segmented on the basis of regularized rule, fabricated by AM devices, and assembled into the entire object again (Tateno, 2015). In this paper, connector design of pipe shape is picked up as the first step to build the design method for PF. The connector design looks like easy but it is not if we consider the strength because the objects fabricated with AM have anisotropic property depending on deposition direction. The simulation method considering these properties has not been explored. In this paper, the detail of PF is introduced in chapter 2, fracture tests are conducted in chapter 3 to get basic data for simulation. In chapter 4, by comparing the simulation results and experimental results, comprehension methods of simulation results are considered. Finally, as an example of PF method on simple structure, connector design of pipe shape is proposed, in which the connector strength is enhanced by arranging
deposition direction in fabrication process with AM.

2. Parallel Fabrication

2.1 Necessity of Parallel Fabrication

A large model must be separated into some segments in case that its size is over the fabrication area of AM device. The segments are assembled into entire shape after they are fabricated. Each segmented parts often have connector portions to make assembling easy and correct. There are some software to support the segmentation featuring connector portions, but such software don’t take into account strength of material. In the past, AM has been applied to relatively small prototyping parts, so the strength of connected parts was not so important. In contrast, since nowadays many large and functional plastic models are fabricated with AM, the strength of connector portions between segmented parts becomes large problem.

Parallel Fabrication (PF) method will have advantages shown below.

(1) Models which are too large for existing AM devices can be made by many general AM devices. Large AM devices have enough work areas to make general and relatively large size models, but large models often consume long time and maintenance costs become severe problem. General AM devices have too small work areas to make large models, but operating costs are relatively small.

(2) Productivity of AM will be improved with parallel processing of multiple AM devices. Generally, productivity of AM is less than that of machining process because processing speed of AM are slow. Parallel Fabrication can accelerate processing speed by using multiple devices parallel to fabricate portions of the model.

(3) Mechanical properties of the model can be adjusted by assembling the segments, which are made by different materials and made in different conditions. Each segments of an entire model can be made by each material and made in each condition. Then, we can give specific characteristics, which are impossible with single material.

However, assembled models are often weak at connecting portions. Design analysis methods to enhance the strength of connecting portion must be explored to make efficient use of PF.

2.2 Connector design and fabrication for Parallel Fabrication

In this study, we propose a connector design analysis and fabrication method for PF in consideration of deposition direction. The target of this method is structures with pipes because it is a simple shape and used in many applications, and the method can be expanded to shell structures, which can be separated into cylindrical segments in PF. The pipe structures may be reinforced by ribs in inner hollow space, but it is hard to put rib in connector portion because it have interference with another connector. Therefore, it is expected to develop design and fabrication methods of connector portion to enhance strength without any additional volume to the entire model.

The strength of segments fabricated with AM mainly depend on two factors, which are shape and processing conditions. The shape of connector portion is very important because it depends on the outline shape of the models. In this paper, the shapes of segments and connector portions are assumed as shown in Fig. 1 to simplify the problem. The segment shape is a simple straight pipe and has at least one connector portion. The connector is also a pipe shape and consists of convex and concave shape. The convex connector, which has narrow end, is inserted into concave connector, which has the same diameter as the original pipe.

![Fig.1 Combination between convex and concave connector](image_url)
2.3 Related researches

In AM process, because of its principle making object layer by layer, the deposition direction affects mechanical property as geometric accuracy and strength, and productivity as processing time and consumption of support material. Many researches regarding optimization of orientation of models in AM process have been done (Pandey, 2007). For example, there are researches on selection of the preferred direction in consideration of multiple criteria of productivity (Frank, 1995), complexity of support structure (Lan, 1997), process time including preprocessing and postprocessing (Alexander, 2009), geometric tolerances (Paul, 2011), and optimization of these evaluation items using GA (Genetic Algorithm) (Amar, 2012). However, these research targets are to fabricate one entire model at a time in one AM device. There are few researches regarding segmented parts, which are assumed to be assembled.

3. Experiments

First, some experiments are conducted to understand the actual property of objects fabricated with AM. The experimental data will be used in FEM analysis to comprehend the main factor of fracturing.

In this paper, results of three types of experiment are conducted.
1) Tensile tests
2) Fracture tests of single pipe
3) Fracture tests of connected pipes

3.1 Test pieces

3.1.1 Tensile test

The objects fabricated with AM have anisotropy of allowable tensile stress according to the deposition direction. The tensile tests are conducted on several conditions with changing deposition direction of test pieces.

The shape of test pieces for tensile tests is shown in Fig. 2. This shape is designed so that the fracturing load is suitable to measurement range of the tensile testing machine.

![Test piece drawing](image)

Fig. 2 Shape of test piece for tensile testing

3.1.2 Fracture tests of single pipe

As the first step to understand fracture conditions, simple shape of single pipe is prepared. Fig. 3 shows the shape of single pile. The fracture tests are also conducted on several conditions with changing deposition direction of test pieces.

![Test piece drawing](image)

Fig. 3 Shape of single pipe for fracture test
3.1.3 Fracture tests of connected pipe

Fig. 4 shows two type of shapes, which are connected and used for the fracture tests. The convex connector (Fig. 4(b)) is inserted into the concave connector (Fig. 4(a)). The thickness of connector portions is set at 2 mm, which is the same as the single pipe’s one for approximating stress conditions each other. The thickness of pipe bodies is set at 4 mm so that inner and outer diameters of assembled parts are unified throughout the pipe. Fit tolerance of the pipes is set empirically.

![Fig. 4 Shape of assembly pipe for fracture test](image)

These test pieces were fabricated with a material jetting type AM device (Connex 350, Stratasys Ltd.). The used material is a kind of acryl resin (VeroWhitePlus, Stratasys Ltd.), of which the ultimate tensile strength is 50-65 MPa and the modulus of elasticity is 2000-3000 MPa in catalog. The material is injected from nozzle and cured by UV light. The resolution of the device is 300×300dpi and the layer thickness of the device was set to 32μm (DM mode).

Each shape was fabricated in 3 setting of deposition direction as shown in Fig. 5, which illustrates layout in fabrication. Arrows indicate coordinate axes defined on the upper side of the model. Fig. 5(a) shows Flat condition, in which xz-plane of the coordinate system becomes the deposition layer. Fig. 5(b) shows Horizontal condition, in which yz-plane of the coordinate system becomes the deposition layer. Fig. 5(c) shows Vertical condition, in which xy-plane of the coordinate system becomes the deposition layer. The horizontal plane in drawings of Fig. 2, Fig. 3 and Fig. 4 corresponds to xz-plane of objects. Thick arrows in Fig. 5 indicate the layer deposition direction for each condition. In case of pipe shape, Flat and Horizontal conditions are same actually.

![Fig. 5 Object layout of each build orientation](image)

3.2 Tensile test

Tensile tests to investigate anisotropy of tensile strength were executed by using a small universal tester,(LSC-1/300-2, Tokyo Sikenki co.ltd). The full scale range of the testing machine is 1000N. Four test pieces were fabricated on each layout condition and tested. Tension speed was set at 3mm/min.

The average fracturing stress of each layout condition are shown in Fig. 6 as a bar graph and error bars shows standard deviations. As the result, fracturing stresses of Flat and Horizontal conditions were approximately 50MPa. It is reasonable that the results of these two conditions are similar because layer conditions in this tensile test are same. In contrast, the fracturing stress of Vertical condition, in which deposition direction was along tensile stress, was approximately 25MPa. The reason of the difference was thought that each layer is cured at the same time and the strength in one layer is stronger than adhesive force between layers.
Fig. 6 Fracturing stress of test piece fabricated in each layout

Fig. 7 Photograph of fractural surface in each build orientation

Fig. 7 shows the microscopic of fracture surface for each condition. The small photo at upper right area of each microscopic photo is side view of the fractured edge. Every test piece was fractured orthogonal to tensile direction. The fracture surfaces in Flat and Horizontal conditions were relatively rough while it was smooth in Vertical condition. It seems that layer was peeled by tensile stress in Vertical condition.

### 3.3 Single pipe test

Compressive fracture tests were conducted with single pipe-type pieces shown in Fig. 3 by using small universal tester (LSC-1/300-2, Tokyo Sikenki co.,ltd). In order to concentrate moment stress near the center point, three point bending method was adopted. Each test piece was put on supports, which have a distance of 64mm, and located so as y-axis of the piece upward. Loading point was set at the center of the piece. Fig. 8 shows an overview of tests and Fig. 9 shows apparatus of the test.
These tests were carried out to investigate the effects of deposition directions on the structural strength. The coordinate system shown in Fig. 8 indicates local coordinate system defined on the target model. Thick arrows in Fig. 8 indicate deposition directions of three conditions, which are Flat, Horizontal, and Vertical condition.

Four test pieces were made for each condition. Compression speed in the fracture test was set at 3mm/min. The largest load during the compression is regarded as the fracturing load.

The test results of average fracturing stress for each layout condition are shown in Fig.10 as a bar graph. Error bars show standard deviations. From the results, fracturing stresses of Flat and Vertical conditions were approximately 540N and 630N, respectively. In contrast, fracturing stress of Horizontal condition was approximately 230N, which is lower than that of other conditions. The 630N and 230N are used as fracturing load in the simulation shown in the next chapter.

Fig.11 shows fractured form of the test pieces. In this figure, the convex and concave pair parts are placed apart so that the fractured form of each part can be observed. The circle plot means the loading point and the square plot in Fig.11(C) means the estimated loading point on disappeared fragments. In Flat and Horizontal conditions, fracture propagated from loading point in the direction to peel layers. In Vertical condition, fracture propagated in two different directions along to and orthogonal to the deposition direction. Moreover, since the fracture spreads in complex directions near the loading point, some fragments fried away.

![Fracture test results of maximum strength](image1)

3.4 Connected pipe test

Compressive fracture tests were conducted with connected pipes shown in Fig.4 as well as section 3.3. Fig.8 shows an overview of tests and Fig.9 shows apparatus of the test.

![Photograph of fractured form of the assembly test piece](image2)
Four test pieces were made for each condition. Fig.12 shows the test results of average fracturing load for each layout condition as a bar graph. Error bars show standard deviations. Fig.12 includes the result of Combination condition in addition to three conditions, which are Flat, Horizontal, Vertical condition. In Combination condition, a convex connector piece in Flat condition and a concave connector piece in Vertical condition were combined to demonstrate the proposal that is explained in chapter 5.

From the results, fracturing load of Horizontal condition was lower than that of other conditions. The result is same as single pipe tests. In contrast, fracturing load of Combination condition was highest in four conditions.

Fig.13 shows photos of pairs of fractured connectors from the top view. In Flat and Horizontal conditions, fracture propagated from the loading point in direction to peel layers as well as single pipe tests. In Vertical condition, fracture propagated around the root of convex connector. It is interesting that the convex connector was cut out in only Vertical condition. In Combination condition, fracture began at the loading point and spread around the root of concave connector.

In order to examine the results, FEM simulations are carried out.

4. FEM simulation

FEM simulations of the fracture tests is executed to analyze the stress distribution on the condition of fracturing load by comparing the results of simulations with the results of experiments.

4.1 Shapes and conditions of FEM Simulations

Single pipe and connected pipe models were modified for FEM simulations. Half cylinder shapes, which have 5mm of diameter, were added at loading point and support points to simulate the metal fixtures in practice. The interference amount between the half cylinder and the pipe model was set so that the contact area was similar with actual one, which was measured by an experiment with binding carbon copying paper between the fixture and the test piece.

Fig.14 and Fig.15 show the modified shapes of single pipe and connected pipes. The load was set on the upper surface of half cylinder shapes at load point. The half cylinder shapes at support points were set as a hinge support rotating around the center axes of the cylinder. FEM mesh was generated automatically as quadratic tetrahedral elements and the mean size of the mesh was 2.4mm. The simulation was executed as elasto-static analysis and Young's module was assumed as isotropic material because there wasn’t enough data about anisotropy of stiffness.

(a) Front and side view of drawing
(b) Isometric view of model
Fig.14 Drawings of single pipe model for simulation

(a) Front and side view of drawing
(b) Isometric view of model
Fig.15 Drawings of assembly pipe model for simulation
The value of Young’s module in the simulation was set at 3000MPa, which is standard as acrylic resin used in experiments.

4.2 Single pipe Simulations

From the experimental results of single pipe, the fracturing load of Horizontal model and Vertical model were approximately 230N and 630N, respectively. The simulation uses the same conditions to compare the simulation results with experimental results. Then, stress distribution is examined to know the main factor of fracture.

4.2.1 Horizontal model

The simulation of Horizontal model was carried out in condition that the load was set at 230N, which is the fracturing load gained by the experiment of Horizontal model. The deposition direction of Horizontal model is parallel to x-axis. Then, it can be predicted that the pipe fractures when the tensile stress in direction to x-axis, which is parallel to deposition direction, reaches 25MPa or the tensile stress in direction to y-axis or z-axis, which is orthogonal to deposition direction, reaches 50MPa.

Fig.16 shows stress distribution charts in such conditions. The top part of color bar is expanded and shown in the box placed at bottom of the figure. Figures show isometric view of the model, Fig.16(a) shows the colored area, in which the tensile stress of x-axis direction exceeds 25MPa as the allowable stress. Fig.16(b) shows the colored area, in which the tensile stress of z-axis direction exceeds 50MPa. Since the tensile stress of y-axis direction of the results is relatively small, the stress is not shown in Fig.16. Color bars shown in the right of pictures are color range of the stress. The top value of bars means the maximum main stress and the arrow at the left of bars shows the threshold (25MPa or 50MPa).

From the simulation results shown in Fig.16(a), the area, in which the tensile stress of x-axis exceeds 25MPa, exists near the load point while the tensile stress of z-axis doesn't reach 50MPa in case of 230N load. The result shows that the fracture may occur because the tensile stress of x-axis exceeds 25MPa. Moreover, the simulation result can explain the fracture form of experimental result shown in Fig.11(b) as the fracture began near the load point.
4.2.2 Vertical model
The simulation of Vertical model in case of 630N load is carried out. The deposition direction of Vertical model is parallel to z-axis. It can be predictable that the pipe fractures when the tensile stress in direction to z-axis reaches 25MPa or the tensile stress in direction to x-axis or y-axis reaches 50MPa.

Fig.17 shows stress distribution charts in such conditions. Fig.17(a) shows the colored area, in which the tensile stress of x-axis direction exceeds 50MPa. Fig.17(b) shows the colored area, in which the tensile stress of z-axis direction exceeds 25Pa. From the results shown in Fig.17(a), the area, in which the tensile stress of x-axis exceeds 50MPa, exists near the loading point, and the area, in which the tensile stress of z-axis exceeds 25MPa, exists near the loading point and the support points. The simulation results that tensile stresses of both x-axis and z-axis reaches the allowable stresses can explain the experimental results that the fracture form became complex as shown in Fig.11(c).

4.3 Connected pipe simulations
Next, the simulation of connected pipe models is executed. Stress distribution of the simulation is examined to know the important factor of fracture. The assembled model consists of concave and convex part models. The half cylinder shapes are added at loading point and support points as well as single pipe model. The outer diameter of concave parts is same as that of single pipe. The thickness of convex and concave connector is same with the thickness of single pile. The part contact condition is defined as sliding contact. From the experimental results of connected pipes, the fracture load of Horizontal model and Vertical model were approximately 370N and 640N, respectively. The simulation was executed in the same condition of experiments.

4.3.1 Horizontal model
Fig.18 shows stress distribution of the simulation in case that the load was set at 230N. Fig.18(a) shows the colored area, in which the tensile stress of x-axis direction exceeds 25MPa, exists near the end of concave connector. Fig.18(b) shows the colored area, in which the main stress of z-axis direction exceeds 50MPa, does not exist. Then, the simulation result of Horizontal model explains that the fracture occurs because the tensile stress of x-axis, which is parallel to deposition direction, exceeds 25MPa. Moreover, Fig18(a) can explain the experimental result shown in Fig.13(b) as that the fracture began at the upper side of the end of concave connector.

(a) Main stress of x-axis direction (more than 25MPa)  (b) Main stress of z-axis direction (more than 50MPa)
Fig.18 Simulation result of tensile stress in case that 370N load is applied to the assembly pipe

4.3.2 Vertical model
Fig.19 shows stress distribution of the simulation in case that the load was set at 640N. Fig.19(a) shows the colored area, in which the tensile stress of x-axis direction exceeds 50MPa, exists near the end of concave connector. Fig.19(b) shows the colored area, in which the tensile stress of z-axis direction exceeds 25MPa, exists in convex connector. Then, two types of fracture can be available, which are to begin at the end of concave connector and to begin at the root of convex connector. The latter case explains the reason that the convex connector was cut as shown in Fig.13(c).
In general, the principal main stress direction is the most important information to predict the area, in which fracture begins. Fig. 20 shows principal main stress distribution of concave connector in case of 370N load. Arrows in the figure indicate main stress directions and arrows’ color shows the principal main stress. The Maximum principal main stress appears at the upper side of the end of concave connector, which is same as the tensile stress of x-axis direction. Fig. 21 shows principal main stress distribution of convex connector in case of 370N load. The maximum principal main stress appears at the underside of the root of convex connector, which is same with the tensile stress of z-axis direction. Therefore, the important factor of fracture is regarded as the maximum principal main stress. The beginning point of fracture can be predicted by comparing the principal main stress and the allowable stress in direction to the principal main stress.
4.3.3 Combination model

In Combination condition, the deposition direction of concave connector and convex connector are set along to z-axis and y-axis, respectively. The fracture load was approximately 870N from the result of connected pipes tests. Fig.22 shows stress distribution in convex connector of the simulation that the load was set at 870N, which is the fracturing load gained by the experiment of Combination model.

Fig.22(a) and Fig.22(b) shows the colored area, in which the tensile stress of x-axis and z-axis direction exceeds 50MPa, respectively. Because allowable stresses of convex connector in direction to x-axis and z-axis are both 50MPa, there is no area that tensile stress reaches the allowable stress. This explains why Combination model is stronger than Vertical model. On the other hand, Fig.22(c) shows that the area, in which the tensile stress of x-axis direction exceeds 25MPa, exists near the end of convex connector. It shows that the convex connector can fracture if the deposition direction of convex connector is along to x-axis, which is just Horizontal model. This result shows that we should note that the best combination depends on the load in use.

4.4 Discussion about the results of simulations

Comparison between the results of simulations the results of experiments suggests the following:

(1) The fracture of pipe structure fabricated AM can be explained with the relationship between allowable stress and tensile stress to each direction.

(2) If compressive load is applied to connected portion, tensile stress occurs in direction to expand the aperture in concave connector and to bend the root of convex connector.

(3) The strength of connected portion can be enhanced by setting deposition direction properly.

5. Discussion on connector design

Generally, tensile strength of plastic materials is extremely weaker than compressive strength. Additionally in previous chapter, we found that the principal main stress is the most important factor to discuss about fracture, and the allowable tensile stress of AM materials is different depending on the deposition direction. The degree of anisotropy of tensile strength are varying according to AM devices, materials, and conditions. Therefore, we propose the connector design analysis and fabrication method for Parallel Fabrication that includes:

1) Prediction of principal tensile stress direction by using FEM simulations

2) Adjustment of deposition direction to be orthogonal to principal tensile stress direction
As regards pipe shape, each segment needs convex or concave connector to connect. However, the appropriate deposition directions are different between convex and concave connectors from strength point of view. The segments, which have convex connector, should be fabricated as Flat or Horizontal condition and the segments, which have concave connector, should be fabricated as Vertical condition. It may be a novel way that the segments having the concave connector is fabricated in short length for reducing the processing time of deposition. Fig.23 shows the example of the connector design. This is the fabrication method proposed.

On the fabrication condition in Fig.23, the parameter L1 and L2 depend on the diameter of pipe, the thickness of connector, and other conditions of shape. Therefore, these parameters should be decided as following steps.

Step 1: Calculating the maximum main stress in the deposition direction of convex and concave segments respectively on the required load condition.
Step 2: Comparing the maximum main stress in the deposition direction with the allowable stress in corresponding direction.
Step 3: Adjust L1 and L2 for the maximum main stress to become lower than the allowable stress.
Step 4: If the sufficient L1 or L2 is not found, increase the number of segments and redo from Step 1 until the sufficient L1 and L2 are found.

This fabrication method including the FEM analysis can be applied to shell structure of elongated shape, which has a hollow space enclosed by the outer body such as an exoskeleton body. For example, robot arm bodies are candidates as the application because they usually have a large size that needs to be separated for fabrication, and they require strong strength and light weight. The development of applications is the next step of this study.

6. Conclusions
   (1) As the way to make large models with AM process, Parallel Fabrication (PF) is introduced. Then, the connector design and fabrication method in consideration of deposition direction are proposed to enhance connector strength.
   (2) Compressive fracture tests of pipe structures were executed and the effect of deposition direction on the fracture load was investigated.
   (3) FEM simulations were carried out and it showed that the simulations can estimate the fracturing load and the beginning point of fracture by analyzing the principal main stress.
   (4) As a design example, pipe shape connector design and fabrication method is proposed.

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