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Forming Simulation and Experiment for Progressive Fabrication Process of Inner Fin in Heat Exchanger

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〈Abstract〉

In this study, a progressive process was performed to fabricate the inner fin of a high-efficiency heat exchanger. A forming simulation was also carried out on the concavo-convex of the inner fin, forming a simulation based on elastic-plastic finite element method. The forming analysis where the speed of the press descended and ascended was set to five seconds showed that the effective stress was at a maximum of about 69 MPa in the curved portion where the bending occurred. Therefore, the die was designed based on the simulation results, and the inner fin die was installed on the 400-ton capacity press. After that, the inner fin fabrication experiment was conducted under the same condition as the simulation. Crack was not found from the curved portion of the concavo-convex of the inner fin. The profile of the concavo-convex of the prepared inner fin measured 6.7~6.8 mm in depth, 2.65~2.7 mm in width, and 0.3 mm in thickness.

Keywords : Inner Fin, Heat Exchanger, Progressive Process, Forming Simulation

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1. Introduction

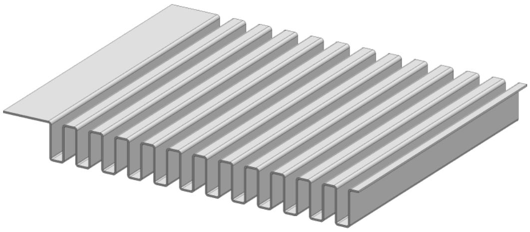
In modern society, heat exchangers are widely used not only in the automobile industry, in the space industry, and in factory automation equipment, but also in general household air conditioners and refrigerators. A heat exchanger is a device that allows two fluids to exchange heat with each other [1,2]. Inner fin, which is among the core parts of the heat exchanger, is a product where a concave-convex channel is inserted in a pattern form on a thin plate. A heat exchanger inner fin is a product in which one fluid moves and transfers heat to another fluid without physical contact. Since the heat exchange is conducted mainly in the inner fin, the shape of the inner fin should be uniform and should have a constant gap. In addition, the inner fin should be composed of a material having excellent thermal conductivity and should have a mechanical strength to some extent. Pinto proposed the optimum design condition considering the necessary parameters during the design of the heat exchanger [3].

The inner fin is manufactured through a plastic forming process. Bae and four other researchers carried out the material test and structural analysis for the thin plate of the high-performance, plate-shaped heat exchanger and fabricated the inner fin using a simple forming process [4]. Jain et al. analyzed the internal speed and temperature distribution of the plate type heat exchanger [5]. Since the inner fin of the heat exchanger is used by stacking about more than 100 sheets, it is manufactured by a press forming process to save material and to improve productivity. To achieve a high-performance heat exchanger, the thickness of the inner fin should be less. However, it is not possible to form a concavo-convex shape by press for the entire thin plate because a concavo-convex portion may be cracked or ruptured, or a concavo-convex shape cannot be formed into a right-angle due to spring-back. This is why a progressive forming method which forms a concavo-convex plate one by one should be applied to form a thin plate. In this study, a device that can manufacture the inner fin of the concavo-convex plate uses a general universal press machine. The adopted device is comprised of uncoiler, feeder, press, and dies.

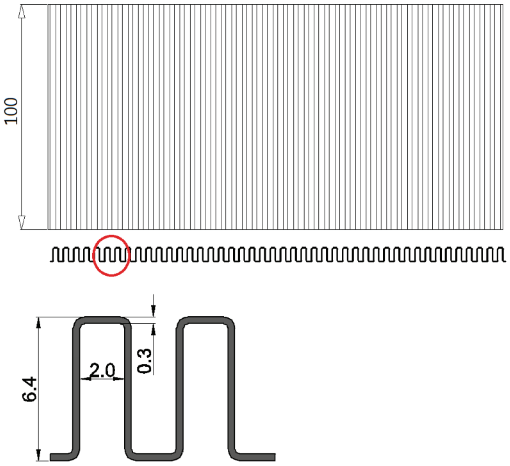
2. Experiment and Simulation Method

2.1 Design of Inner Fin Shape

Figure 1 shows the 3D and 2D drawings of the inner fin part of a heat exchanger. The 3D shape was modeled using a CAD program, while 2D drawing was sketched using a drafting function. The cross-sectional shape of the inner fin was formed by arranging numerous concavo-convex shapes uniformly. The depth of the concavo-convex shape was designed to be 6 mm, its width was designed to be 2.0, and the concavo-convex shape was made to have a right angle to raise the efficiency of the heat exchanger's heat transformation. In addition, the thickness of the inner fin was designed to be 0.3 mm because more than 100 sheets of inner fin should be stacked.



3D

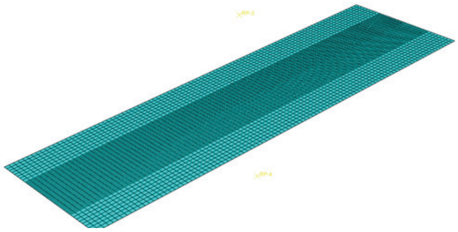


2D

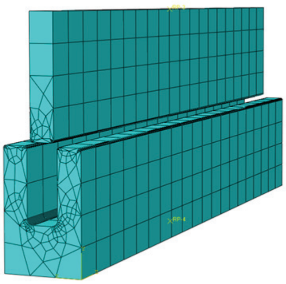
Fig. 1 Inner fin of heat exchanger

2.2 Simulation Condition

A forming analysis was performed using a plastic analysis program based on the elastic-plastic finite element method. The modeling file of dies and specimens was loaded into the molding analysis program to form the concavo-convex shape from the specimen. The data of the tensile test of the inner fin material made of pure aluminum was input to the forming analysis program data input device. A finite element mesh should be formed for the die and the specimen in order to perform the finite element analysis. The smaller the lattice size of the element, the larger the number of elements and the longer the analysis time that is required, but the higher the accuracy of the analysis. Because the computer calculates stress and strain for each element, the number of elements and the time required for the analysis are longer. On the contrary, if the lattice size of the element is increased, the number of gratings is decreased, the analysis time is shortened, and the accuracy of the analysis is impaired. Therefore, it is necessary to divide the elements so that the appropriate analysis time and some accurate analysis results are obtained. Figure 2 shows the mesh setting. The mesh of the specimen was divided into small portions of the central portion where the forming was intensively performed, and both portions were divided into relatively large meshes. In the case of the die, the curvature part is divided into smaller meshes and the straight part is divided into larger parts.



Blank



Die

Fig. 2 Mesh generation of blank and die

Figure 3 shows the boundary condition of the die and the material. The boundary condition was set similarly as the actual forming condition. The lower die was fixed to the press (six reaction forces were imposed) and was set to compress the specimen while the lower die was descended. The condition was set to compress the specimen while the upper die moved with the speed of 6 mm/s. Between the die and the material, non-rubbing condition was applied.

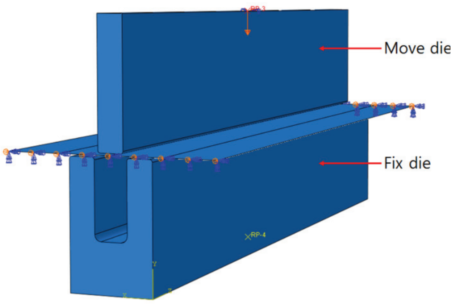


Fig. 3 Boundary condition between die and blank

2.3 Experiment Condition

Figure 4 shows the operation process in which the concavo-convex shape of the inner fin is formed using the progressive forming method to manufacture the inner fin of the heat exchanger. The pure aluminum plate wound as coil shape was hung and inserted to the feeder. The plate which passes the feeder is inserted into the die which is installed on the press as one concavo-convex shape is formed.

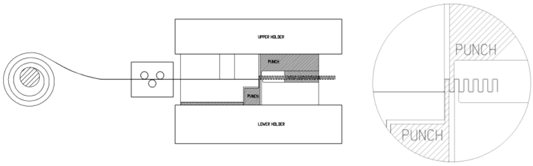
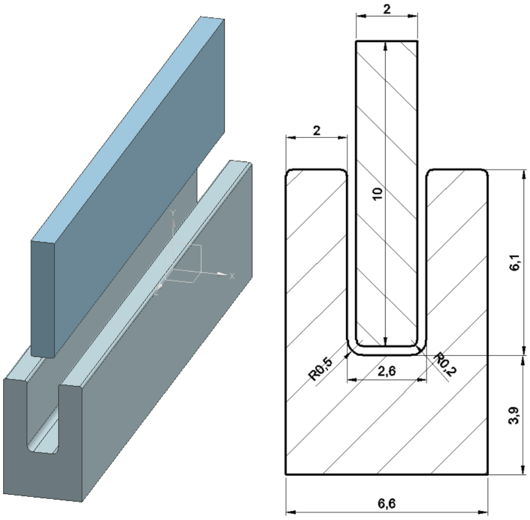


Fig. 4 Fabrication process of inner fin

Figure 5 shows the shape of the core die that forms a concavo-convex shape. Because the clearance between the upper die and the lower die was designed as zero (0), thickness was shrunk when the plate was formed to a concavo-convex shape. From the forming result, the radius of curvature of the upper die was designed to be R0.2 and R0.5 for the lower die.



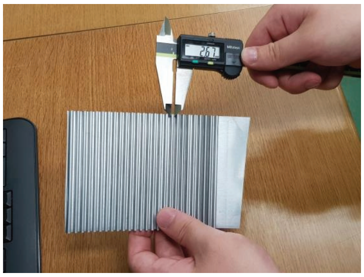
3D 2D

Fig. 5 Core die of inner fin

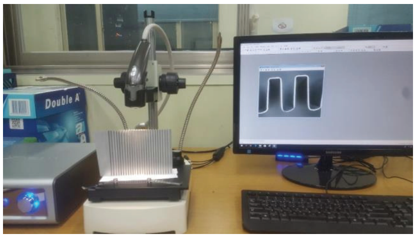
The inner fin die was installed on the 400-ton universal press. It consists of the uncoiler on which aluminum plate coil can be hung, a feeder that injects the plate into the die, and a press die that forms the concavo-convex portion. On the die and plate material, liquid lubricant was not applied. One end of the plate was bound to the feeder, while other parts were set as free. Since one end of the plate was bound to the feeder, it would not fall when the upper die presses the plate. The feeder pushes the material into the die until the pitch of the concavo-convex shape (4.6 mm) is achieved correctly. After forming one concavo-convex shape on the plate by the descended upper die, the feeder again pushes the plate into the die by as much as 4.6 mm once the upper die ascends to the upper direction. By repeating the process above, the concavo-convex shape is formed into the inner fin.

2.4 Analysis of Experiment

The width and height, as well as the flatness of the inner fin, were measured using Vernier calipers and video-microscope. Figure 6 shows how the shape of the concavo-convex part is measured through Vernier calipers and video-microscope.



Vernier callipers



Digital microscope

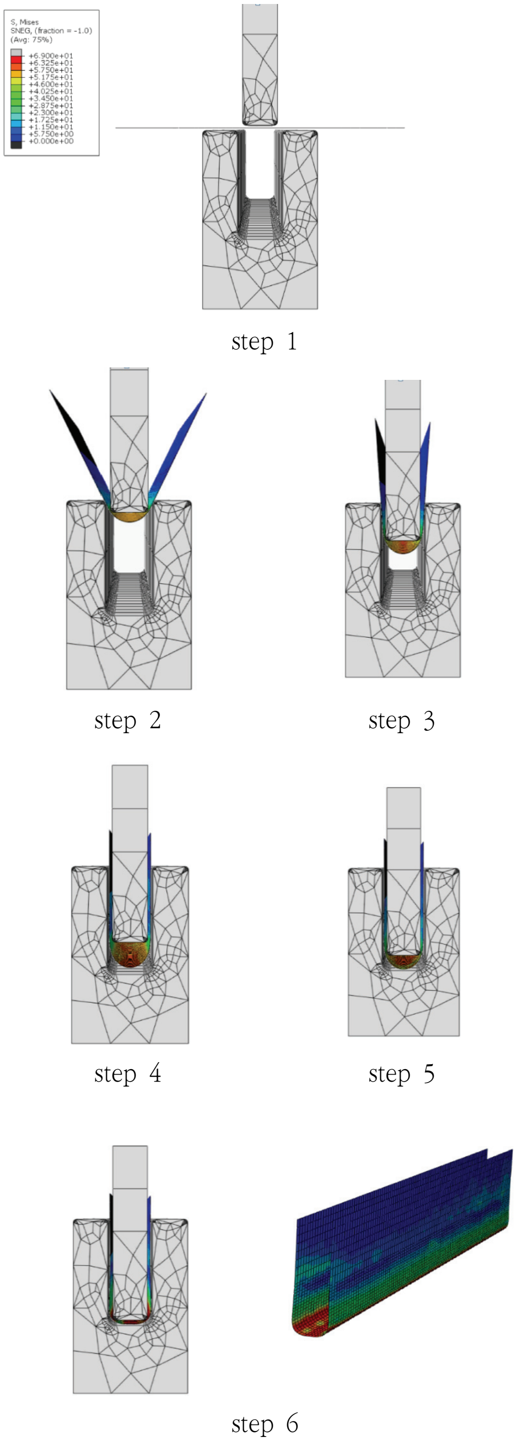
Fig. 6 Measurement of inner fin

Three specimens were measured for the width and height whereas five samples were taken for the concavo-convex shape of the inner fin. The flatness was expressed as a difference between the highest gap and the lowest gap of the clearance measured from the inner fin and the bottom while the inner fin was laid on the flat surface. For the measurement of the flatness, three samples were taken.

3. Experiment and Simulation Results

3.1 Forming Simulation

Figure 7 shows the analysis results of the concavo-convex forming at the inner fin by stages. The analysis results were drawn as Von-Mises stress (effective stress) values. When the upper die entered the lower die while pressing the plate (stage 2), the plate became bent into a V shape, and the effective stress of 57 MPa was generated from the bent portion. The effective stress increased at the curved part while the plate was further pushed into the lower die. In Stage 4, the effective stress at the curve was about 69 MPa. In Stage 4, the curvature of the plate reached the bottom of the lower die before the upper die reached the groove bottom. When the upper die reached the groove bottom, the plate was compressed in Stage 6. At this time, effective stress was increased at both edges. During forming, the portion where the effective stress was generated at maximum was the curved part which was bent. The stress at this spot was lower than 69 MPa. Since the tensile strength of the plate was 96 MPa, there was little



step 1

step 2

step 3

step 4

step 5

step 6

Fig. 7 Forming steps of simulation results possibility of breakage occurring in the plate during actual forming.

Figure 8 is the graph of the applied load drawn from the analysis results when the concavo-convex portion of the inner fin was formed. The capacity of the press to be used in the forming experiment can be determined from the analysis results required for forming. From the graph, it can be anticipated that when the plate enters the groove of the die, it becomes bent to a V shape and the largest load of 150 N is consumed. After the plate entered the groove of the lower die, the required load was sharply decreased. When the plate was further inserted to the groove at about a half, there was no force to be used for strain; that is, once the plate started entering the groove of the die, plastic deformation of the plate was completed, and when it reached half of the groove, the upper die played a role of pushing the material downward.

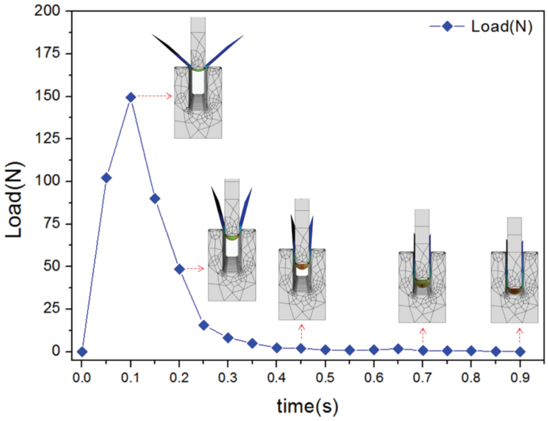


Fig. 8 Forming load curve vs time

3.2 Forming Experiment

3.2.1 Formability

It took 55 seconds to render the inner fin at a length of 50.6 mm (11 no. of concavo-convex) upon pressing descended and ascended for 5 sec. This test was repeated 20 times, with the defect examined for the prepared samples through a video-microscope test. Table 1 shows the formability results when the speed of the descended and ascended press was set to 5 sec. No defect was found by video-microscope for all 20 samples. This result satisfies the quantitative target of 5 % defect set in this study. Since there was no defect found from all the 20 samples, the defect rate became zero (0) %. Figure 9 shows the inner fin prepared by setting the descending and ascending press speed to 5 sec.

Table 1. Results of fabrication about 5 seconds of press speed

No.	Defect	No.	Defect
1	x	11	x
2	x	12	x
3	x	13	x
4	x	14	x
5	x	15	x
6	x	16	x
7	x	17	x
8	x	18	x
9	x	19	x
10	x	20	x

Fig. 9 Fabricated 20 inner fins

3.2.2 Cross-Section Shape of the Concavo-Convex

The cross-sectional shape of the inner fin samples prepared by setting the descending and ascending press speed to 5 sec (55.2 mm/min) were measured. Table 2 shows the height and width of the concavo-convex shapes of the samples, which were measured by Vernier calipers and video-microscope. The measured values did not differ much in either instrument. The height of the concavo-convex was 6.7 mm to 6.8 mm, and the width was 2.65 mm to 2.7 mm. The ideal width and height of the concavo-convex part were 2.6 mm and 6.4 mm (size of the fabricated die). However, the width of the formed concavo-convex was wider by around 0.05 mm. It is because the concavo-convex widened after forming due to spring-back. The height of the concavo-convex was also higher by around 0.3 mm than that of the ideal case. The reason is that the top of the convex-concave became projected when the next concavo-convex was formed after forming one concavo-convex. Since there was no device implemented to make the plate adhere to the lower die, the top of the next concavo-convex became projected while the next concavo-convex was formed. Such phenomenon could be confirmed from the forming analysis result.

Table 3 shows the flatness values measured by Vernier calipers and video-microscope. There was no significant difference in the values measured by Vernier calipers and video-microscope. The flatness values were in a range of 2.51 mm to 2.62 mm.

Table 2. Height and width of concavo-convex (unit : mm)

	Type of measurement	Position				
		1	2	3	4	5
H	Vernier callipers	6.76	6.76	6.71	6.78	6.84
	Digital microscope	6.74	6.67	6.70	6.58	6.53
W	Vernier callipers	2.67	2.69	2.67	2.67	2.73
	Digital microscope	2.67	2.60	2.65	2.67	2.71

Table 3. Flatness of inner fin (unit : mm)

Type of measurement	Flatness
Vernier callipers	2.52
Digital microscope	2.53

4. Conclusions

The shape of the inner fin derived from the forming analysis program based on the elastic-plastic finite element method was the same as that of the inner fin obtained through the actual pressing operation.

1. The speed at which the press was descended and ascended was set to 5 sec, and it took 55 sec to manufacture the inner fin length of 50.6 mm (11 concavo-convex).
2. As a result of the Von-Mises stress (effective stress) value, the position where the effective stress was mostly generated at the time of forming was the curved portion where the bending occurred, and the stress at this portion was 69 MPa or less.
3. When the plate entered the groove of the lower die, the V-shaped bending deformation occurred, the largest load was applied, and its size was 150 N.
4. The height of the concavo-convex of the manufactured heat exchanger inner fins was 6.7 to 6.8 mm, the width was 2.65 to 2.7 mm, and the flatness was 2.51 to 2.62 mm.

Acknowledgement

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