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유한요소해석에 의한 하니컴 코어의 성형공정에 관한 연구

한규택#

A Study on the Forming Process of Honeycomb Core by Finite Element Analysis

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ABSTRACT

In this paper, research on the manufacturing technology of hexagonal structure core is investigated. Also the optimal forming process of the honeycomb core is developed and the rolling process is analyzed using finite element code, DEFORM^{TM}-3D. The standard honeycomb has a uniform hexagonal structure defined by the material, cell size, cell wall thickness and bulk density. Honeycomb core products can be made from any thin, flat material. The most common cell configuration is the hexagon but there are many other shapes for special applications. Because of the precision shape and the thin thickness, the honeycomb core is not easy to manufacture in the metal forming process. Through this study it was confirmed that after the rolling process, the section of honeycomb close to the standard shape can be obtained. This result is reflected to the manufacturing process design for the honeycomb core.

Key Words : Honeycomb Core, Manufacturing Process, Finite Element Analysis, Hexagonal Structure

1. Introduction

Honeycomb products are typically lighter in weight than corresponding solid products, use less material, are less expensive to manufacture and utilize, and provide satisfactory durability and strength for most applications. Honeycomb core products are typically custom made for the particular application. Honeycomb core products, for example, are typically used in the wings and ailerons of airplanes. This typically requires hard tooling, for cutting the core to an exact shape and/or bending it to a final form. In addition, foam splice lines are utilized to attach pieces of honeycomb core portions together, which degrade the overall performance levels. Often, the honeycomb products require forming to the final shape which typically includes the use of heat to soften the cells. This usually leads to degradation in overall material structural properties and a weaker assembly. Honeycomb core products also typically require time consuming

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validation and verification testing, particularly relative to radar energy absorption[1].

Honeycomb's lightweight, high-strength properties and environmental durability have satisfied a broad range of applications. It has also been a catalyst for the invention of entirely new products. Honeycomb has proven a highly versatile material in the fabrication of complex assemblies requiring simple and compound curvatures. With its superior strength-to-weight ratio, honeycomb has enhanced the performance of aircraft, space vehicles, satellites and other important products of the aerospace and defense industries. The standard honeycomb has a uniform hexagonal structure defined by the material, cell size, cell wall thickness and bulk density. The main constructional materials are aluminum, glass fiber reinforced plastic and aramid paper. Among them, aluminum and aramid paper (Nomex™) honeycomb are commonly used in engineering applications[2-5].

There have been studies concerned with honeycomb products, but there has been no study that tried to analyze manufacturing process using computer simulation and the results are reflected to manufacturing process design for the honeycomb core. The final objective of this study is to develop the new manufacturing process of honeycomb core.

Because of the whole process is very complicate, in this study only forming process of honeycomb seal is simulated using finite element analysis to find the optimum shape of honeycomb seal for turbine. Due to the honeycomb seal is used at high temperature, the corrugation process is applied in this simulation.

2. Definition of hexagonal honeycomb

The schematics of a commercial honeycomb with curved walls at the intersection points and a straight-walled honeycomb are shown in Fig. 1a and b, respectively.

Fig. 2 shows the isolated unit cell that includes five distinct segments: two vertical straight portions; an inclined straight portion and two curved portions.

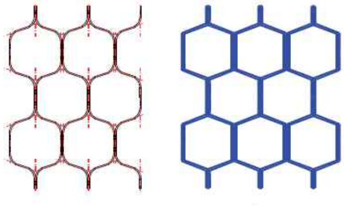


Fig. 1 Regular hexagonal honeycomb structure: (a) commercial honeycomb with curved walls at the intersection points; (b) theoretical honeycomb with straight walls

The angle defining the fillet is described in terms of the nominal inclination for the general honeycomb; i.e., θ. This angle changes as θ changes and takes the value of $\left(\frac{\pi}{2}-\theta\right)$ as shown in Fig. 2. The inner fillet radius is $\left(R-\frac{t}{2}\right)$ and the outer radius is $\left(R+\frac{t}{2}\right)$, where R is the centerline fillet radius, and t is the wall thickness.

The cross-sectional properties, i.e., area and moment of inertia remain constant throughout the curved portion of the wall and the curvature affects the length of the straight portions of the walls.

segment 1 in Fig. 2 does have a length that is reduced by half of the vertical projection of curved segment 2 from its nominal length of $\frac{L}{2}$, which is equal to $Rtan\left(\frac{\pi/2-\theta}{2}\right)$. Thus, segment 1 has a length of $\left(\frac{L}{2}-Rtan\left(\frac{\pi/2-\theta}{2}\right)\right)$. This length physically represents the half length of the attached walls of the commercial honeycombs. Segment 2 will in turn have a length tracing the angle of $\left(\frac{\pi}{2}-\theta\right)$. Segment 3 has a nominal length of L, which is then reduced due to the curvature at its ends and has a length of $\left(L-2Rthan\left(\frac{\pi/2-\theta}{2}\right)\right)$. Segments 4 and 5 have the same lengths of segments 2 and 1, respectively.

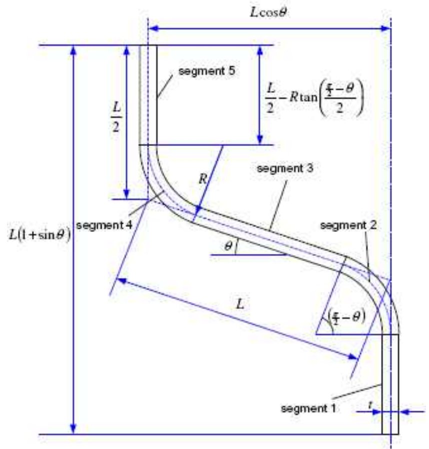


Fig. 2 A general hexagonal honeycomb with curved walls at the intersection points

There are five basic ways of making honeycomb adhesive bonding, resistance welding, brazing, diffusion bonding and thermal fusion[1]. These methods are based on how the nodes are attached. By far the most common manufacturing method is adhesive bonding; perhaps as much as 95% of the honeycomb cores are made this way. Resistance welding, brazing or diffusion bonding are only used on cores that must see high temperatures or severe environmental conditions as it is much more expensive to manufacture core by these processes.

The corrugation method is the original technique used to fabricate honeycomb core. Although it is labor intensive, this method is still used for making high density metallic and some nonmetallic cores. In the corrugation process the sheets are first corrugated, then adhesive is applied to the nodes and the sheets are stacked and cured in an oven. Since only light pressure can be applied to the stacked block the node adhesive is much thicker than the expanded core.

3. Manufacturing of honeycomb

The Fig. 3 shows the honeycomb seal made from honeycomb core. It is widely used in the gas turbine. In this case the honeycomb is shaped by the punch process, each ring of the honeycomb core consists of 16 segments honeycomb members.

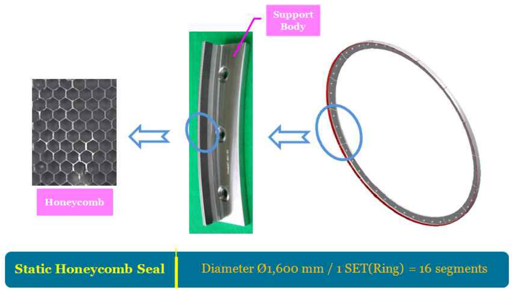


Fig. 3 Honeycomb seal

Fig. 4 shows the welding process of the honeycomb core.

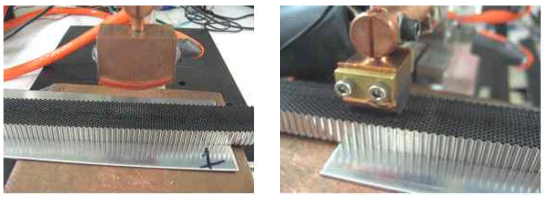


Fig. 4 Welding process of the honeycomb core

And Fig. 5 shows the whole process using the corrugate rolling process to make the honeycomb seal. In Fig. 5, the whole honeycomb seal process is divided into four parts: the corrugation process, cutting process, welding process, brazing process. The corrugation process, illustrated in Fig. 6, is the original technique used to fabricate honeycomb core. In the corrugation process, the sheet is involved into two gears to form the honeycomb shape. In the cutting process, the sheet after the corrugation process will be divided into several parts and each width is the honeycomb width. The divided sheets are stacked into a honeycomb shape. In the welding process the honeycomb bends to a honeycomb core. Then the brazing process combines honeycomb core, brazing filler mental and back steel (support body) into a honeycomb seal.

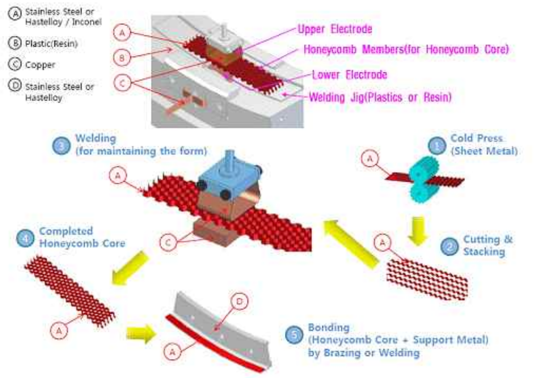


Fig. 5 Manufacturing process to make honeycomb seal

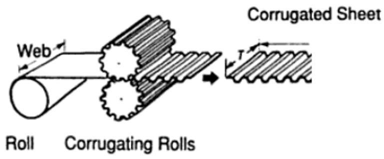


Fig. 6 Corrugate rolling process

4. Simulation

In this research, numerical approach for modeling the behavior of honeycomb is studied. The part of the honeycomb is modeled using the commercial S/W, CATIA. Also, the factors of the parameter of optimal forming process are developed and the corrugation process is analyzed. The corrugation process is simulated using finite element code, DEFORM^{TM}-3D. The specification and material property of the honeycomb are shown in Table 1 and Table 2.

Table 1 Specification of honeycomb

Edge Length	4mm
Width	4mm
Cell wall thickness	0.1mm
Half-Hexagonal Size	3.2mm
Centerline fillet radius	0.02mm
Material	Inconel-718

Table 2 Material properties of honeycomb

Density	8.19g/cm^3
Tensile strength	1240MPa
Yield point	1036MPa
Elongation in 50mm	12%
Hardness	36HRc

In this study, the corrugate rolling process is simulated and discussed. The honeycomb member shape is the basic of the honeycomb core. The corrugate rolling process is very important in the whole process. According to Fig. 6, the gear is applied in the simulation. Also, in order to keep the sheet at the horizontal plane, a guide is necessary in the simulation. The sheet material is assumed rigid-plastic. Also the gear and guide are assumed to the rigid body. Fig. 7 is the assembly of modeling element.

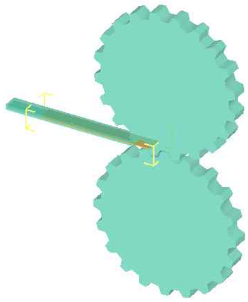


Fig. 7 Assembly of modeling elements

There are many factors to effect the shape of the honeycomb in the simulation. In order to simplify the simulation, first of all, the sheet of 0.3mm thickness is applied. And then, the sheet of 0.1mm thickness is applied. Because of the honeycomb shape fully depends on the gear shape, and the honeycomb angle is easy to reach in the simulation. The first factor I want to raise is the difference between addendum angle(α) and dedendum angle(β). The angle of theoretical honeycomb is 120°. But according to the gear, the addendum angle and dedendum angle is different. That means it is impossible that not only the addendum angle equals to 120° but also the dedendum angle equals to 120°. For the honeycomb shape is close to the standard shape, between addendum and dedendum, which one has to equal to 120°. In order to find the solution, two cases are established. Case 1 is α=120°, Case 2 is β =120°.

Fig. 8 and Fig. 9 show the schematic gear shape of Case 1 and Case 2 respectively. It is easy to find that when α_1=120°, β_1=129°, when β_2=120°, α_2=111°.

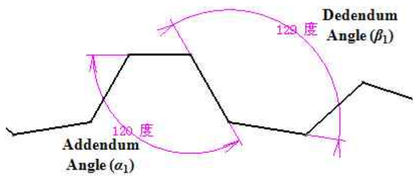


Fig. 8 Schematic gear shape of Case 1

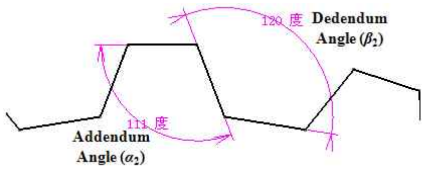


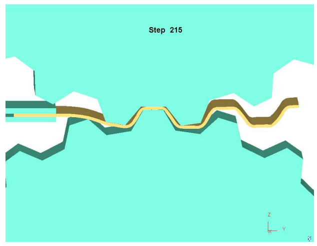
Fig. 9 Schematic gear shape of Case 2

In order to simplify the simulation, the initial sheet thickness (t) is 0.3mm, the vertical gear clearance(c_v) is 0.3mm. Also a fillet(R) of 0.02mm on he addendum face is applied to cut down the stress concentration. The parameter is shown in Table 3.

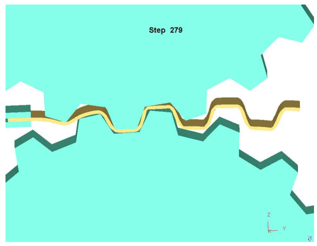
Table 3 Process parameter in the simulation

	Case 1	Case 2
Sheet Thickness (t)	0.3mm	0.3mm
Number of the teeth (N)	20	20
Fillet on the addendum face (R)	0.02mm	0.02mm
Addendum angle (α)	120°	111°
Dedendum angle (β)	129°	120°
Vertical gear clearance (c_v)	0.3mm	0.3mm

In this part, the main purpose is to find out the honeycomb shape which is close to the standard shape in these two conditions. Then result of the shape is shown in Fig. 10.



(a) Case 1



(b) Case 2

Fig. 10 Shape of Case 1 and Case 2 after simulation

From Fig. 10 we can see that the honeycomb shape after rolling process is influenced by the dedendum and addendum angle of gear.

5. Result and discussions

Fig. 11, we can estimate that the honeycomb corner radius is larger than the fillet on the addendum face of the Case 2. Then in the corrugation process, there is a limit of honeycomb corner radius, even though the addendum face fillet is 0.02mm or little, the honeycomb corner radius would not be reduced. Then it is worth to discuss whether the honeycomb corner radius is changed if the addendum face fillet is enlarged.

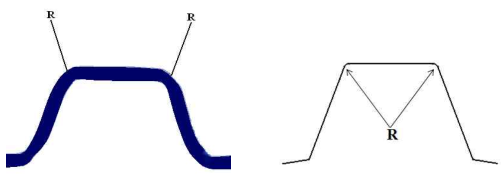


Fig. 11 Comparison between honeycomb corner and gear corner in Case 2

Analyzed results of Case 2 that dedendum angle is 120°, R is 0.02mm, are shown in Fig. 12.

From the stress distribution and stress histogram of Fig. 12, it is possible to conclude that the stress distribution in the entrance area is similar, but in the rolling area it is small. Also according to the stress histogram, the average effective stress is small, which confirms the opinions insisted.

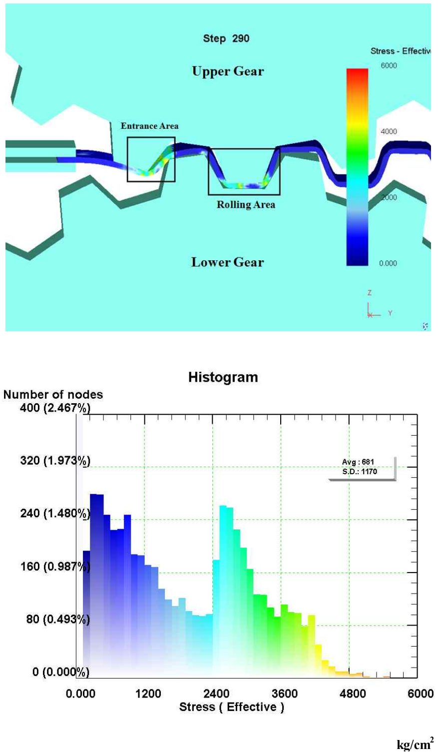


Fig. 12 Stress distribution and histogram of Case 2

6. Conclusions

In order to make a honeycomb using Inconel which is applied to the honeycomb seal, the corrugation process is used to investigate the feasibility of the honeycomb manufacturing. The process is simulated using commercial software, DEFORM-3D^{TM}. Because of the thin thickness of the sheet, the sheet is easily bended in the process. The purpose of the simulation is to find an optimum design to obtain a honeycomb which is close to the standard honeycomb shape.

The fillet on the honeycomb corner is almost same to honeycomb corner radius. As R increases, the fillet on the honeycomb corner increases, and the stress distribution in the rolling area is small. So a large fillet on the addendum face can reduce the stress concentration to extend the gear life and avoid the sheet fracture. The sheet initial location affects the entrance angle in the simulation. It is a best way to change the entrance angle without changing the number of the gear teeth. The proper sheet initial can reduce the stress concentration at the entrance point. The gear initial location affect the sheet how to involve into the gear, the better way is to bend a corner than turn a corner while the sheet is being involved into the gear.

Through this study it was confirmed that after the rolling process, the section of honeycomb close to the standard shape can be obtained. The results obtained are reflected to the manufacturing process design for the honeycomb core. Also research results can be extended to apply to the manufacturing of various honeycomb products.

Acknowledgement

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