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# Study on Flexibly-Reconfigurable Roll Forming Process for Multi-Curved Surface of Sheet Metal

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*In order to manufacture three dimensional sheet metal parts for small-quantity batch production, several flexible forming technologies, including multi-point forming (MPF), have been made as alternatives to the conventional die forming one. However, the existing alternatives cause defects like dimples and wrinkles on the sheet metal during forming, due to their discrete punches. Long setup time and additional post-processing, like machining, of the products limits the feasibility of these technologies. The alternative processes may not be suitable for a skin structure in the aerospace industry, which requires precision machining. To alleviate these limitations, a new sheet metal forming process, named flexibly-reconfigurable roll forming (FRRF) process is proposed. This innovative technology utilizes adjustable punches mounted on two reconfigurable rollers. The shape of the reconfigurable rollers is maneuvered by the adjustable punches. Additional privilege of this innovation is that the blank size is unrestricted in its longitudinal direction. In this paper, the method and procedures of the FRRF process are presented. The feasibility of this FRRF process is demonstrated by finite element simulations of various shapes of convex, saddle, and twist-type surfaces which are typical to multi-curved shapes used in sheet metal forming.*

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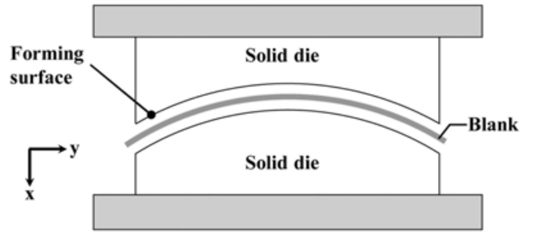
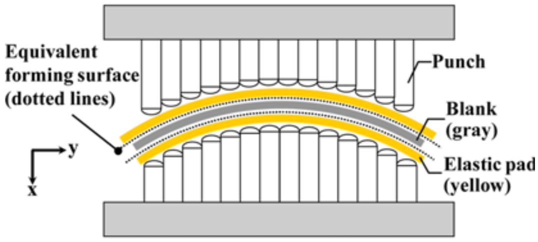
## 1. Introduction

Generally, a sheet metal forming process for a three-dimensional curved sheet has been carried out by using a die and press machine tool, which are matched to the objective surface of the product, as shown in Fig. 1(a). However, it is still difficult to make this conventional die forming process economically efficient because of the additional production cost incurred by the development and management of the forming tool. In particular, it is not suitable for small-quantity batch production used in industries such as: aerospace, shipbuilding, and free-form construction.

In the shipbuilding industry, many different curved steel plates used for hull structures have been fabricated with a conventional line heating method, which uses a high-temperature heat source to form a gradual curvature by thermal deformation.[1,2] This is truly a nonproductive process since most forming procedures are conducted manually by skilled experts. Thus, it takes a long time to make the required products. The manufacture of aircraft skin structures, which are typically formed using a stretch forming process, requires a large number of solid dies due to the various shapes of aircraft parts. This can raise the unit cost of production owing to the management required for the forming dies. In recent years, both automobiles and rapid transit trains have required a greater variety of curved sheet metal components for skin structures due to demands from producers and consumers. This can also cause economic losses when using the conventional die forming process. Therefore, many investigations on flexible forming technologies, including multi-point sandwich forming, fluid or elastomer dieless forming, and incremental roll forming, have been carried out to replace the existing process with new sheet metal forming processes.[3-9] Among these, the multi-point forming (MPF) process, which consists of a set of height-adjustable hemispherical discrete punches and an elastic cushion, has been developed as an alternative to the conventional die forming process, as shown in Fig. 1(b). The MPF process can make various equivalent forming surfaces using a single die set, instead of solid dies. Thus, the MPF process is more appropriate for small-quantity batch production and can also reduce the cost and time required for production compared to the conventional die forming process. However, the MPF process may create some defects such as dimples and wrinkles (as shown in Fig. 2) on the sheet metal, depending on the material properties, objective



(a) Conventional die forming process



(b) Multi-point forming process

Fig. 1 Schematic diagrams of conventional die forming process and multi-point die forming process

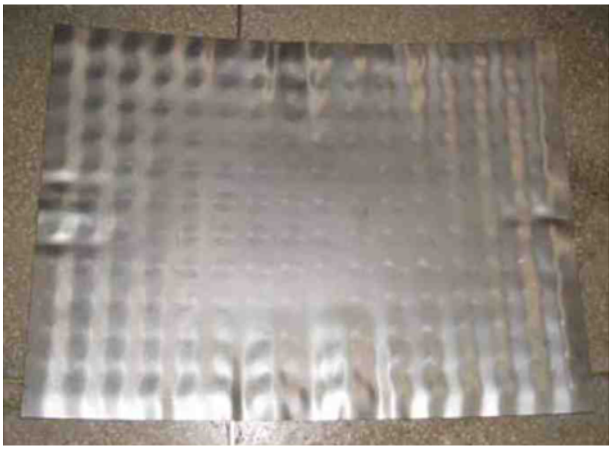


Fig. 2 Example of sheet metal with dimples and wrinkles formed by using multi-point forming process

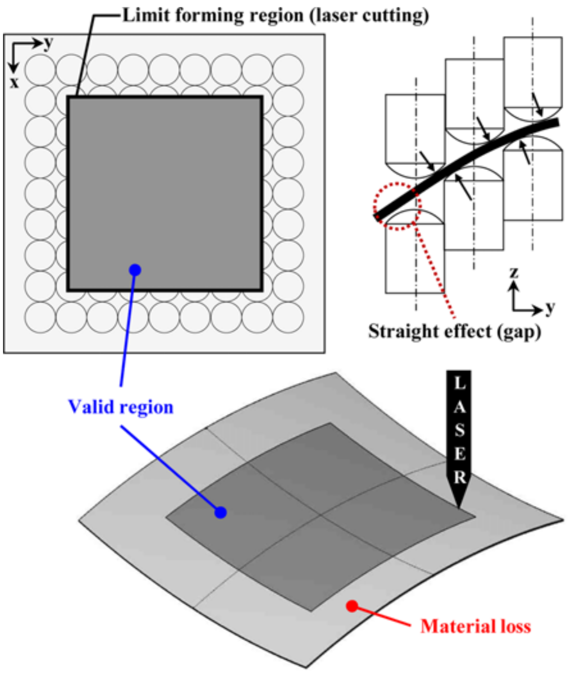


Fig. 3 Forming errors at edge of sheet metal

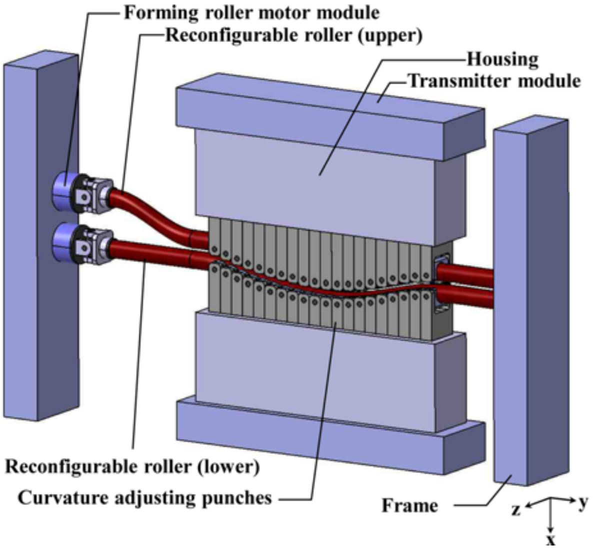


Fig. 4 Schematic view of FRRF apparatus

curvature, and thickness of the sheet metal. These defects inherently result from the irregular gap between the sheet metal and the punches since the forming surface is formed by discrete punches. In order to overcome these defects, an elastic pad that is reusable as a result of its hyper-elastic material behavior is usually used for smoothing the discrete forming surface, and a larger number of smaller punches are used.[10] Nevertheless, this still does not provide sufficient solutions for the aerospace industry, which requires precision machining. In addition, additional machining outside of the formed region on the sheet metal is required due to the discontinuous surface, as shown in Fig. 3, which can also cause material losses.[11]

In this paper, a new sheet metal forming process, called flexibly-reconfigurable roll forming (FRRF) process, is proposed to solve the problems of the existing processes for three-dimensional curved sheet metal.[12] As shown in Fig. 4, this innovative process utilizes curvature adjusting punches and upper and lower reconfigurable rollers as forming tools, where the shape of each reconfigurable roller can be changed in the vertical direction. It is also equipped with motors that can supply sufficient torque to both the curvature adjusting punch module and reconfigurable rollers. In contrast to the MPF process, the size of the blank for this process is unrestricted in the longitudinal direction just as with the typical roll forming process. Therefore, this process can reduce the additional production cost incurred by the material losses and use of a smaller apparatus compared with MPF, and it can remarkably minimize the forming errors, as stated above, because of the comparatively continuous forming surface. In this paper, the method and procedure of the FRRF process are presented. The feasibility has also been demonstrated through the numerical simulations of the proposed FRRF process by describing convex, saddle, and twist-type surfaces, which are the typical multi-curved shapes formed in a sheet metal forming.

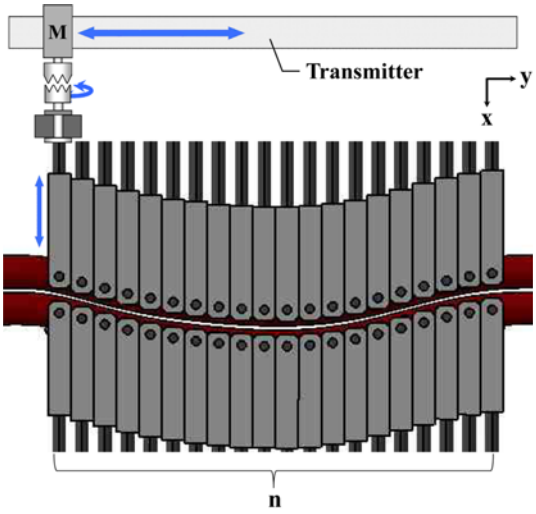


Fig. 5 Illustration of reconfigurable multi-punch array

## 2. Method and procedure of FRRF process

In contrast with the typical roll forming method, the FRRF process utilizes reconfigurable rollers as forming tools. The reconfigurable rollers are the essential component that allows the manufacturing of various shapes without remaking and revising unlike in conventional solid die forming. The initial blank is inserted between these reconfigurable rollers, which are arranged vertically, and then, the blank is formed by being forced out by the rotation of the rollers. In this procedure, the shape of a formed sheet metal is determined by the curvature of the reconfigurable rollers and continuously varying gap between them.

As shown in Fig. 5, the curvature of the rollers is adjusted by using different lengths for the multi-punch array, which are controlled by the revolution counts of motors. The number of motors used for this forming tool can be equal to the number of adjustable punches. Otherwise, one or more motors can be used to adjust the length of a punch by installing a transmitter. As shown in Fig. 6, a curvature adjusting punch consists an outer housing and internal rod. To adjust the punch length, the outer housing and the internal rod have internal and external threads, respectively. The other part of the internal rod, which is not connected to the outer housing, is joined to the motor, as mentioned earlier. The opposite side of the outer housing has a roller guide that supports the consecutive bending of the reconfigurable rollers. The roller guide is equipped with an easily replaceable bush which is necessary since the bush is affected by mechanical abrasion despite its low-friction coating. The reconfigurable rollers are rotated by the forming roller motors on both ends. In addition, the FRRF apparatus has frames, housings, and so forth for attaching other components, including those mentioned above.

Various three dimensional curved shapes, including the three typical kinds previously mentioned, can be made based on the curvatures in both the transverse (y-axis) and longitudinal (z-axis) directions, as illustrated in Fig. 7. The curvature in the transverse direction is related to the different lengths of the curvature adjusting punch array. The curvature in the longitudinal direction, on the other hand, is caused by the difference in the applied strains on the sheet metal. This strain difference essentially comes from the difference in the sizes of the gaps between the upper and the lower reconfigurable rollers, depending on the location. For instance, the final product has a convex-type surface if the applied strain on the center of the blank is larger than that at the edges during the forming process, whereas the reverse configuration is true for saddle-type surface.[12]

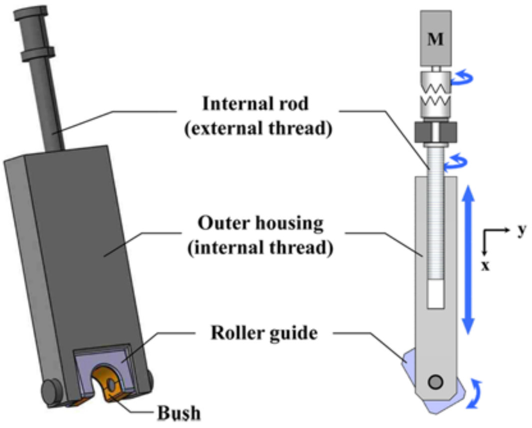


Fig. 6 Punch assembly and its mechanism

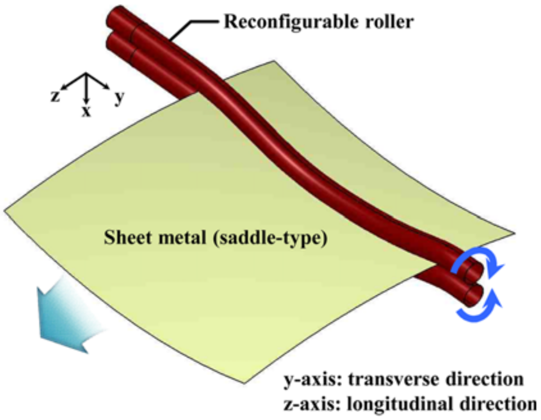


Fig. 7 Graphical explanation of FRRF process

## 3. Geometrical and Numerical Modeling for FE Simulations

In the FRRF process, the forming location is simply described by using a piece of sheet metal, along with the upper and lower reconfigurable rollers. As shown in Fig. 8, the geometrical shapes with respect to the sheet metal and rollers can be expressed in terms of quadratic curves, which indicate the neutral axis of the sheet metal and rotation axes of the upper and lower reconfigurable rollers. In this figure, subscripts $b$, $u$, and $l$ denote the sheet metal, upper reconfigurable roller, and lower reconfigurable roller, respectively. In this paper, three design parameters are defined for geometrical modeling. These parameters, which are relevant to the shape of a multi-curved piece of sheet metal, are the radius of curvature ($R_{b,c}$), included angle ($\theta_{tip}$) between the center and the tip of the sheet metal, and eccentricity ($e_b$) of the neutral axis of the sheet metal. The radius of curvature and the

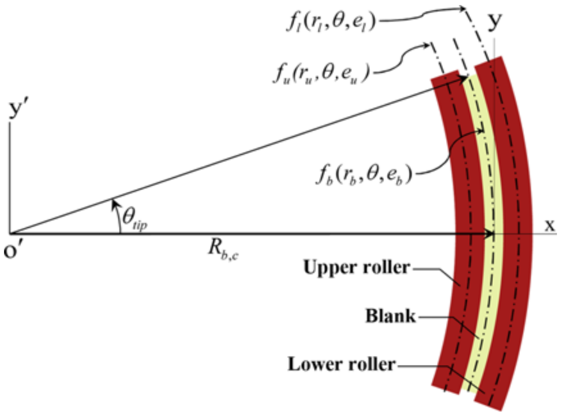


Fig. 8 Geometrical relation of blank and reconfigurable rollers

included angle are used to determine the curvature and shape of the sheet metal with respect to the transverse direction. Continuously varying gap between the reconfigurable rollers affects the shape of the sheet metal in the longitudinal direction. The eccentricity allows the forming tool to generate multi-curved sheet metal with non-circular arc, which has a curvature that varies with the distance from the center of the sheet metal in the transverse direction.

To simulate the typical multi-curved shapes such as convex, saddle, and twist-type surfaces, different design parameters are applied for each shape. In this paper, the curvature radius, eccentricity, and included angle are set at 300 mm, 0, and 10°, respectively, in the convex and saddle-type surface cases. The curvature radius for the twist-type surface is 600 mm. The value of the included angle for the twist-type surface is set to be equal to that used in the other cases.

Simulations for the three typical multi-curved shapes are implemented through ABAQUS, which is a widely used commercial software for finite element simulation. The simulations are performed in two phases. The first phase involves inserting a piece of sheet metal between the reconfigurable rollers and holding it there. The second phase involves rotating the reconfigurable rollers to push the sheet metal out. One of the simulation models is represented in Fig. 9.

The vertically arranged rollers are split into numerous rings, as shown in Fig. 9. Each of these rings has a diameter of 20 mm and a width of 2 mm in these simulations. A determination of the locations of every ring is conducted during the first phase, and every ring is arranged in the direction of the tangent along the quadratic curves, which are the rotation axes of the reconfigurable rollers. Therefore, the total number of rings required for the simulations is determined by the values of the design parameters. The translational and rotational motions of the rings are conducted according to the local coordinates, which consider the center of each ring as the origin during the simulations. In other words, every origin for the local coordinates is located on the quadratic curves. Meanwhile, the number of revolutions of the reconfigurable rollers is set depending on the length of the sheet metal in the longitudinal direction.

The size of the initial blank is 105 × 105 × 1 mm$^3$, considering both the radius of curvature and the included angle, as previously decided. The blank elements consist of 4 layers of solid type elements in the thickness direction for the simulations using the FRRF process. Al 2024-T4, a relatively soft material, is used as the sheet metal, and it is assumed to be an elasto-plastic material. The material properties used in simulations are summarized in Table 1.

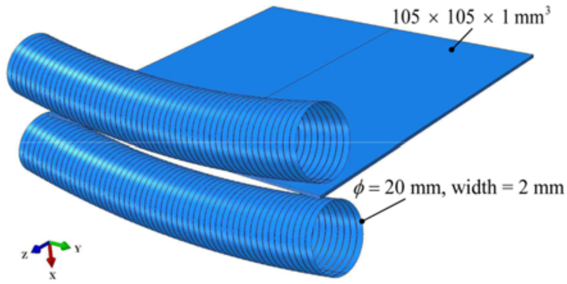


Fig. 9 Example of FE model using FRRF process

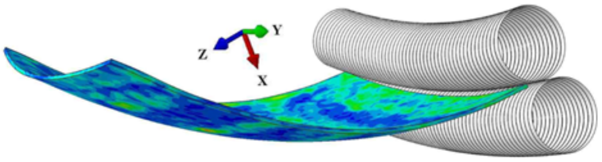
Tab1e 1 Material properties used in the simulations

| Properties (Al 2024-T4) | | Value |
|---|---|---|
| | Elastic modulus (GPa) | 73.1 |
| | Yield strength (MPa) | 250 |
| | Ultimate strength (MPa) | 430 |
| | Poisson's ratio, $v$ | 0.33 |
| | Density (kg/mm$^3$) | 2.78×10$^{-6}$ |
| $\bar{\sigma} = K\bar{\varepsilon}^n$ | Strength coefficient, $K$ (MPa) | 690 |
| | Work-hardening exponent, $n$ | 0.16 |

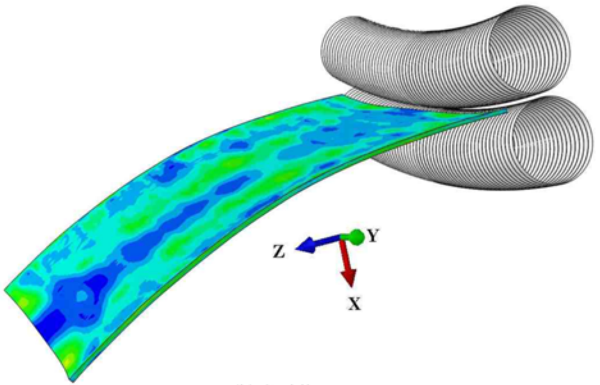
All rings constituting the reconfigurable rollers are assumed to be rigid since the deformation of every ring in contact with the blank is noticeably smaller than that of the blank, and shell type elements are used in the simulation models. In the actual process, AISI 440 stainless steel, having high modulus of elasticity (200 GPa) and yield strength (1.28 GPa), can be applicable to the reconfigurable rollers since it is capable of performing the FRRF process without plastic deformation.

## 4. Numerical Results

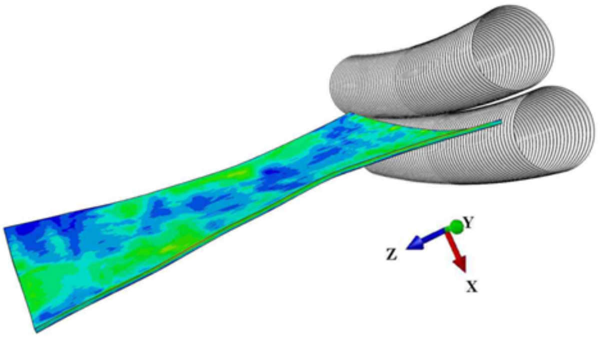
Fig. 10 describes the numerical results of the simulations for typical three-dimensional curved sheet metal shapes such as convex, saddle, and twist-type shapes using the FRRF process. These results are obtained from forming simulations where all of the rings of the reconfigurable rollers are arranged according to the respective quadratic curves and then rotated on their own axis for pushing the sheet metal out. Except for the applied boundary condition for the gap between the reconfigurable rollers, the convex and saddle-type curved sheet metal shapes are formed under the condition that the same numbers and sizes are used for the sheet metal and rings in the simulations. However, the twist-type curved sheet metal in Fig. 10(c) was obtained by using different design parameters compared to those for the other shapes in order to minimize the curvature in both the longitudinal and the transverse directions. This result of this twist- type shape indicates that both sides of the sheet metal in the longitudinal direction have a shape like a straight line when the curvature in the transverse direction is decreased as a design parameter, in relation to the curvature radius and eccentricity increase. On the other hand, a multi-curved shape having two or more curvatures can be formed by decreasing the design parameter values of the curvature radius and eccentricity.



(a) Convex-type

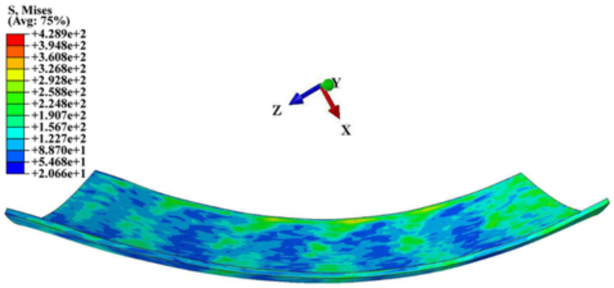


(b) Saddle-type

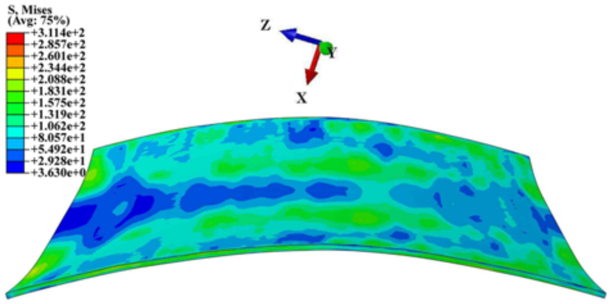


(c) Twist-type

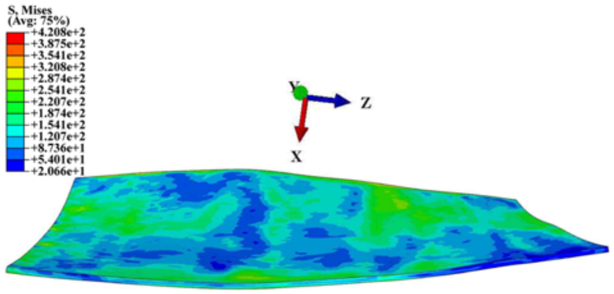
Fig. 10 Typical models of three-dimensional curved sheet metal shapes using FRRF process



(a) Convex-type



(b) Saddle-type



(c) Twist-type

Fig. 11 Stress distribution of typical three-dimensional curved sheet metal shapes obtained by using FRRF process

Fig. 11 shows the stress distribution of the three typical multi-curved shapes after the forming procedure using the FRRF process. The convex-type curved sheet metal has high stress values close to the ultimate tensile stress compared with the other shapes since the curvatures in both the transverse and the longitudinal directions overlap in the center of the sheet metal. In contrast to the convex-type sheet metal, the saddle-type curved sheet metal has a comparatively lower concentrated load since the curvatures in the transverse and longitudinal directions have the opposite signs. In the case of the twist-type curved sheet metal, it has higher values of stress near the exit of the reconfigurable rollers. This result is produced not only by the bending caused by the strain difference in the thickness direction but also by the torsional strain coming from the strain difference in the transverse direction. In these simulations, spring-back is not considered owing to focus on the feasibility of FRRF process. However, after sheet forming is involved, elastic recovery is observed in the formed side of sheet metal. This is due to the fact that the blank is not constrained by forming tools unlike other bending technologies.

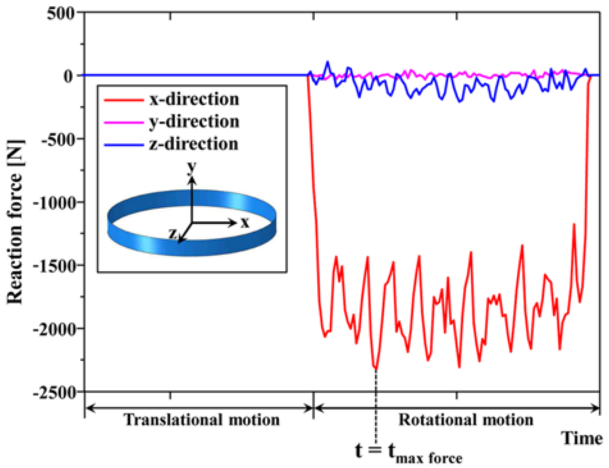
As shown in Figs. 10 and 11, there are no defects such as dimples and wrinkles, which are often produced in the MPF process for sheet metal forming. Therefore, this FRRF process can be used as an appropriate sheet metal forming method. It is also a better process for sheet metal forming since there is no additional machining outside of the forming region of the sheet metal.

In order to obtain information for fabricating an FRRF apparatus, an investigation is conducted to obtain the loads acting on the reconfigurable rollers during the entire simulation. Fig. 12(a) shows the reaction force acting on the ring with the maximum value during the entire simulation in the case of the convex-type shape with the highest value of concentrated load. The maximum value of the reaction force is 2,323 N at $t = t_{\text{max force}}$ on the lower reconfigurable roller. Fig. 12(b) describes the reaction forces acting on each ring at $t = t_{\text{max force}}$. The zeroth ring near the center of the reconfigurable roller has a maximum load for the same reason, which is the overlap of the curvatures in both directions, as previously mentioned.

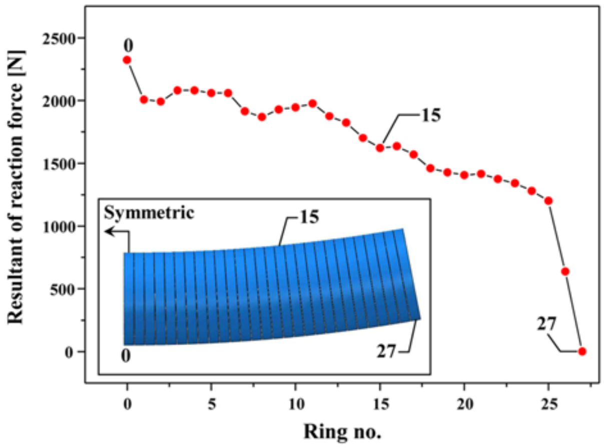
## 5. Conclusions

In this investigation, the method, apparatus, and procedure of the FRRF process for sheet metal forming were proposed. It is confirmed that the feasibility has been demonstrated through the numerical simulations of the proposed FRRF process.

The FRRF process requires uncomplicated components and a



(a) Distribution of reaction force for zeroth ring during extire forminf procedure



(b) Resultant forces of rings composing rollers at time $t_{\text{mac forcd}}$

Fig. 12 Load distribution at particular ring(a) and particular time(b) in case of convex curved sheet metal

comparatively smaller installation space. Thus, this process can reduce the production cost related to the development and maintenance of forming dies. It also requires no additional machining as a result of forming errors such as dimples and wrinkles from the forming process. Therefore, this progressive process can be used for sheet metal forming in small-quantity batch production, including applications in the shipbuilding, rapid transit train, automobile, and free-form construction industries. It can also be applied to aerospace skin structures, which require precision machining, through an intensive and steady investigation on the apparatus for the FRRF process.

In the follow-up study, based on the results, the investigation on elasto-plastic behaviors of the reconfigurable rollers will be carried out considering infinitesimal deformation of it by both numerical and experimental methodologies.

## ACKNOWLEDGEMENT

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