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Improvement of formability for fabricating thin continuously corrugated structures in sheet metal forming process †

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Abstract

A stamping process is widely used for fabricating various sheet metal parts for vehicles, airplanes, and electronic devices by the merit of low processing cost and high productivity. Recently, the use of thin sheets with a corrugated structure for sheet metal parts has rapidly increased for use in energy management devices, such as heat exchangers, separators in fuel cells, and many others. However, it is not easy to make thin corrugated structures directly using a single-step stamping process due to their geometrical complexity and very thin thickness. To solve this problem, a multi-step stamping (MSS) process that includes a heat treatment process to improve formability is proposed in this work: the sequential process is the initial stamping, heat treatment, and final shaping. By the proposed method, we achieved successful results in fabricating thin corrugated structures with an average thickness of 75 μm and increased formability of about 31% compared to the single-step stamping process. Such structures can be used in a plate-type heat exchanger requiring low weight and a compact shape.

Keywords: Multi-step stamping; Multi-step tensile test; Plate type heat exchanger; Corrugated structure; High aspect ratio structure

1. Introduction

The sheet metal forming process is well-known and widely used for making a variety of complicated sheet metal applications in automobiles, aircrafts, ship-building, and electronics [1]. The stampings have remarkable accuracy and good finish in deformed shapes, and they also have excellent mechanical properties compared to those of other fabrication processes. Especially for manufacturing plate-type heat exchangers, this process is commonly utilized to make thin and wide corrugated structures because of the merits of low-cost and mass production, as well as a reduction of material loss [2-5]. The deformed corrugated plates are stacked up in a volumetric heat exchanger in which heat transfer occurs by flowing high and low temperature fluid through each layer.

However, a heat exchanger used in an aircraft needs to be compact and lightweight for energy saving. Therefore, it is necessary that the plate, a component of a heat exchanger, has a narrow corrugated structure with a high aspect ratio to ensure a sufficient flow rate according to the flow paths. In general, a heat exchanger composed of thinner plates performs better because of an increased amount of heat exchange between the hot and cold sides [6-11]. These structures are also expected to be utilized in various energy devices, for example, a separator used in fuel cells [12-14].

However, from the viewpoint of manufacturing technology, it is not easy to make these functional plates using a single stamping process because of geometrical constraints such as in narrow continuously corrugated structures. A novel approach is proposed in this work using multi-step stamping (MSS) that includes heat treatment for improving formability. In the MSS process, a thin plate with an initial thickness of 100 μm was used to fabricate the target corrugated structures that had a sine-curve shape with a 1.5 mm depth and 3.3 mm width (see Fig. 8). However, this is not a common way to apply the MSS process in sheet metal forming, so there are few research reports on the topic, especially the MSS assisted by heat treatment for improving formability. To understand the material behavior during the MSS and after heat treatment, we conducted experimental studies such as a multi-step tensile test, and performed a finite element analysis to study the process parameters and discover a way to increase formability.

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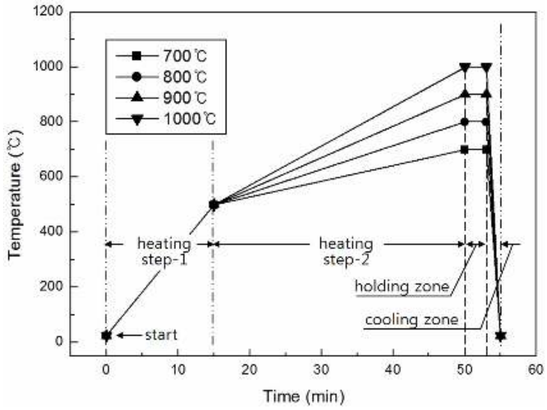

Fig. 1. Scheduling of heat treatment: temperature versus time schedule.

2. Experimental test for material properties

2.1 Mechanical properties depending on heat treatment conditions

The tensile test is widely used to evaluate the formability of a material using an elongation ratio. We used the fundamental tensile test to find the change of material properties of STS 304-1/2H according to heat treatment conditions and to know the best temperature range for heat treatment. Specimens with a thickness of 100 μm were prepared by cutting them out vertically to the rolling direction, and the tension rate was the identical condition of 2 mm/min in all tensile tests. In general, recrystallization of an austenite structure of STS 304-1/2H occurs under a temperature range of 1010 to 1120°C [15]. Therefore, considering achieving thin specimens, we chose heat treatment conditions below the reference temperature: 700, 800, 900, and 1000°C. After heat treatment with the given conditions, the vacuum furnace power was turned off, and the specimen was cooled to room temperature with injection nitrogen gas inside of the furnace. In the heat treatment, a vacuum furnace should be used to prevent a specimen from oxidation and formation of scales in its surface. The detailed scheduling of time to temperature in the heat treatment is shown in Fig. 1.

Fig. 2 shows the tensile test results obtained from the five types of specimens with different heat treatment conditions. The heat treated specimens have larger elongation values and lower yield stresses than the original material (‘initial material’ in Fig. 2); as is well known, this result confirms that formability can be improved using heat treatment. For the 700 and 800°C heat treated specimens, the value of yield stress was reduced 5 and 15%, respectively. For the heat treatment at 900°C and 1000°C, the yield stress was reduced rapidly by 50 and 60%, respectively. Further, the elongation increased to approximately 39 to 89% over the original material that was not heat treated. Table 1 summarizes the change in material properties according to the heat treatment conditions.

However, as shown in Fig. 1, the elongation increased dramatically above 900°C, compared to lower temperatures. To understand the reason, we observed the microstructure of each specimen, as depicted in Fig. 3. The grain size of the specimens was in the range of 23 to 24 μm on average at heat treatment conditions of 700, 800°C, and in the original material. There was not a large change in size, and was similar to that of the original material, whereas, above 900°C, the grain size was increased to about 37 μm due to the recrystallization

Table 1. Comparison of mechanical properties under various heat treatment conditions: Y.S, T.S, and EL stand for yield stress, tensile stress, and elongation, respectively.

STS304-1/2H	Y.S (MPa)	T.S (MPa)	EL (%)	Hardness (Hv)
Original	651	852	38	270
700°C	619	845	53	259
800°C	552	827	57	237
900°C	323	725	63	155
1000°C	265	663	72	141

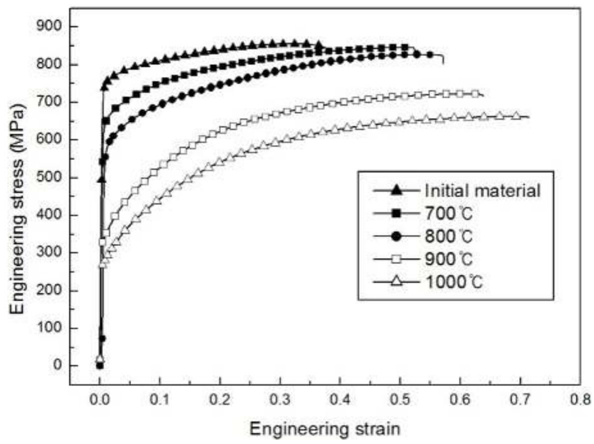

Fig. 2. Tensile test results of the engineering stress-strain curve of STS 304-1/2H obtained using various specimens that were heat-treated under various temperature conditions.

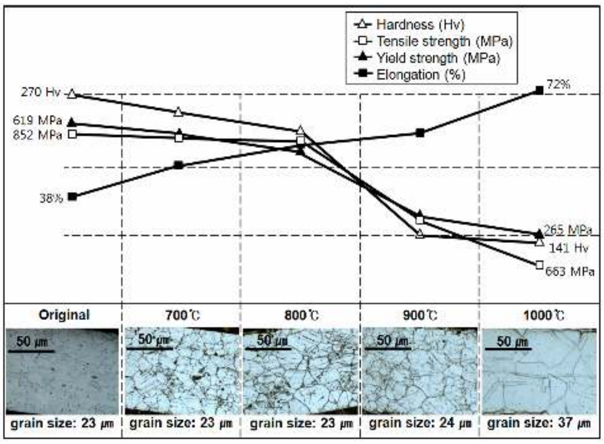

Fig. 3. Variation of mechanical material properties including hardness, tensile strength, yield strength, and elongation after heat treatment with different temperature conditions: 700, 800, 900 and 1000°C.

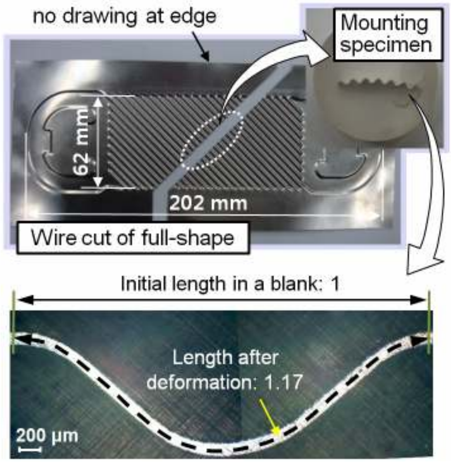

Fig. 4. Photographic images of a deformed specimen; wire cut full-shape of a deformed corrugated structure, and comparison of the original blank length (value: 1) and the deformed length of a cross-section (value: 1.17) in a unit cell: length ratio = 1:1.17. And the size of full shape is 202 mm in a horizontal direction and 62 mm in a vertical direction.

effect. In addition, the hardness of the raw material was 270 Hv, but it was reduced to 48%, which is 141 Hv, after heat-treatment (see Fig. 3). Among the results of the tensile test, we found that the best condition for improving formability seems to be heat treatment at 1000°C. At this condition, the plastic deformability is improved by the reduction of the tensile stress and increase of elongation.

2.2 Multi-step tensile test for evaluation of formability

We conducted a novel tensile test (multi-step tensile test (MST)) to evaluate formability by considering real material behaviors in the MSS process. As is well known, the total strain is dependent on the incremental deformation paths, so using the MST, the amount of deformation limit in each step can be assumed during the multi-step forming process. Also, the total amount of strain can be evaluated with considering intermediate heat treatment between forming steps by the MST. The multi-step forming process is widely applied in bulk metal forming, whereas for sheet metal forming, it is rarely used to increase formability. At the intermediate step between cold forming processes, the heat treatment technique is often used to eliminate residual stress on the inside of a workpiece.

To consider the whole material behavior and to evaluate the formability of sheet metal during MSS, the elongation obtained at each stamping-step was applied as a tensile condition in the MST test. Therefore, to do the MST test, we defined the maximum tension in the first stamping step. As shown in Fig. 4, which is the cross section part of the deformed full plate, the successfully stamped shape has a maximum shape ratio (width vs. depth) of 1:1.17. This means that the sheet is stretched to an amount of 17% in the first stamping process. As previously mentioned, continuously corrugated structures

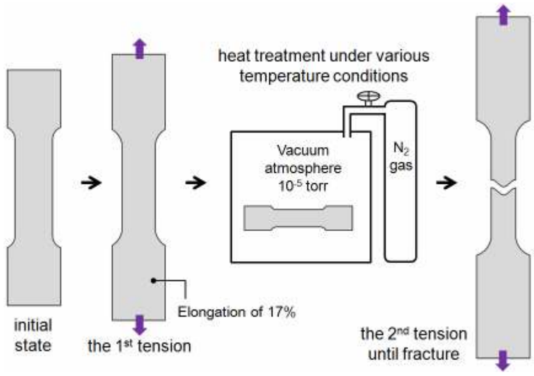

Fig. 5. Schematic process of the multi-step tensile (MST) test method.

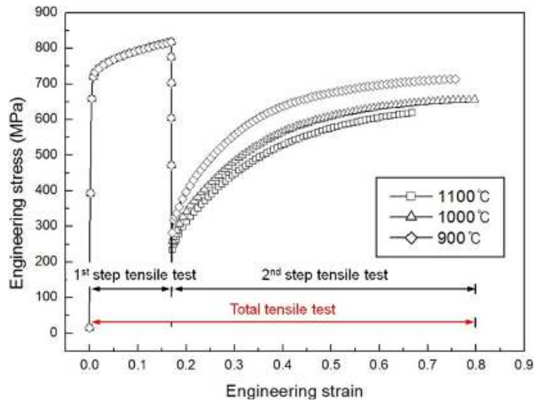

Fig. 6. Multi-step tensile test results: engineering stress-strain curve of STS304-1/2H under various heat treatment conditions.

topologically restrain each other, so there is no drawing at the edge of a blank sheet. For this reason, all deformed corrugated shapes come from stretch forming only. Therefore, it is possible to assume that the amount of maximum elongation of the local area is 17% in the first stamping process.

Based on the obtained elongation data from experiments, we conducted the MST test as depicted in Fig. 5: the first elongation of the specimen to 17%; then heat treatment under the temperature conditions of 900, 1000, and 1100°C, respectively; and finally, the second tensile test until the specimen broke to know the maximum elongation. In other words, the tensile specimen was made according to test standards and was elongated, increasing the 50 mm of the initial gauge length to 58.5 mm (17% elongation) in the tensile test machine. The tested specimens were put in a vacuum furnace for the heat treatment at different temperature conditions. In the previous section of the material test, we made the heat treatment with a maximum temperature of 1000°C, but this time the heating temperature was increased up to 1100°C to determine the variation of elongation of a specimen over 1000°C. As the final step in the MST test, the heat treated specimen was elongated again until it was broken to determine the maximum total elongation through the MST test. The results of the MST test are shown in Fig. 6 and summarized in Table

Table 2. Comparison of mechanical properties of the multi-step tensile test: Y.S, T.S, and EL stand for yield stress, tensile stress, and elongation, respectively. The amount of 17% in EL is obtained from the first stamping process.

STS304-1/2H	Y.S (MPa)	T.S (MPa)	EL (%)	Total EL (%) [17%+EL]
900°C	314	713	59.3	76.3
1000°C	267	656	63.7	80.7
1100°C	247	620	51.0	68.0

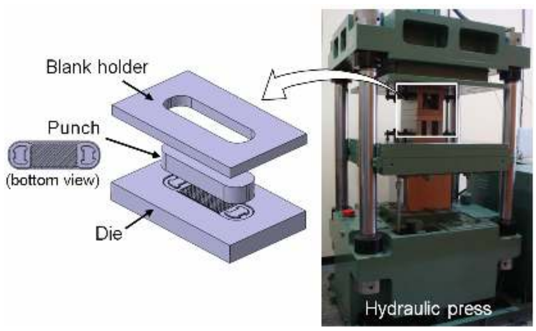

Fig. 7. Experimental setup of a rig for the stamping test, and the shapes of molds are punch, die, and blank holder.

2. The total elongation from the first tension to the second tension reached 80.7% at heat treatment under 1000°C in the intermediate step. For heat treatment at 1100°C, the total elongation was shorter due to a change of material properties that occurred by precipitation hardening [16]. The supersaturated solid solution decomposes with temperature ranging 1000 to 1065°C for most stainless steels. As the hardness increases during precipitation, so does the susceptibility to hydrogen embrittlement; therefore, the elongation is decreased after precipitation hardening. Compared to the results from the fundamental tensile test, the maximum elongations in the MST are increased: from 63% to 76.3% and 72% to 80.7% in case of heat treating temperature of 900°C and 1000°C, respectively. Thus, when manufacturing corrugated structures in thin sheets with a 100 µm thickness, as designed in this work, work hardening that occurs after the first forming step can be eliminated by heat treatment at 1000°C through a vacuum heat treatment furnace. The total amount of deformation might also be improved by the serial process of MSS: the first stamping, heat treatment, and the second stamping.

3. Fabrication of continuously corrugated structures

3.1 Experimental setup

The experimental rig used to fabricate thin corrugated structures is shown in Fig. 7. The maximum loading of 150,000 kgf was allowable by using hydraulic cylinders in the rig. The shapes of molds, including punch, die, and blank holder, are shown in the left-side of Fig. 7. A rectangular blank with a 100 µm thickness is put on the die, and the blank holder presses the blank down to prevent out-of-plane bending at the edge of a blank. For stamping, the punch is moved down on the fixed blank. The pressure of the punch and blank holder is controlled using a hydraulic system. In the case of stamping corrugated structures, the blank holding force scarcely influences the deformability of a blank because of its complicated shape; however, the stamping force directly affects the formability.

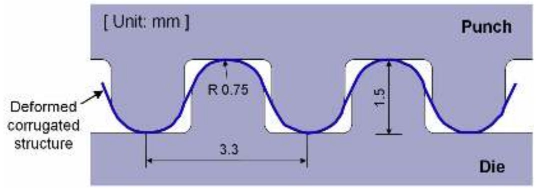

Fig. 8. Schematic view of the shape and dimension of the mold: matched punch and die, deformed corrugated structure from a blank sheet.

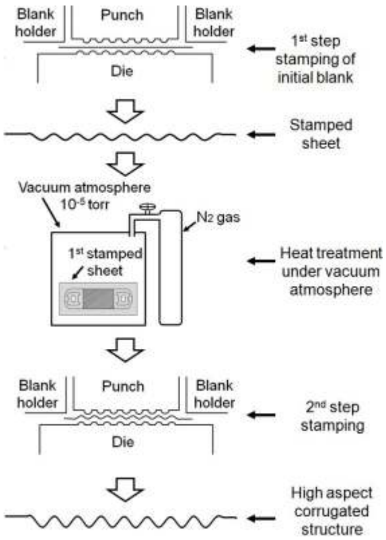

Fig. 9. Schematic diagram of the multi-step stamping (MSS) procedure.

The details of the shape of molds (punch and die) in the final stamping stage are depicted in Fig. 8 with the dimensions as follows: the corrugate height is 1.5 mm with a radius of 0.75 mm, and the width of the corrugated space is 3.3 mm.

3.2 Fabrication of high aspect ratio corrugated structures using MSS

To the best of our knowledge, it has been rare to fabricate complex corrugated structures on very thin sheets using a single stamping process. In this work, to fabricate continuously corrugated structures on sheet metal having a thickness of 100 µm, we used the MSS process as depicted in Fig. 9. For the evaluation of the process parameters before real stamping experiments, a finite element (FE) analysis was employed using a commercial code, PAM-STAMP. In the FE analysis, all components including blank holder, punch, die, and blank are considered, and the boundary conditions were given as

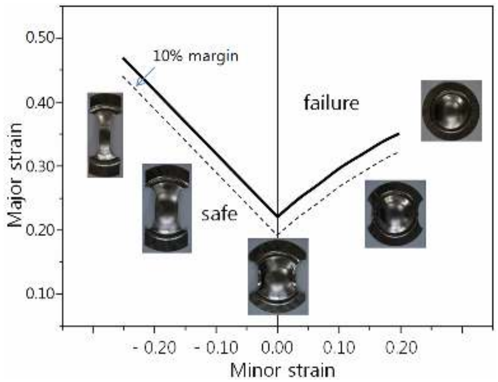

Fig. 10 Schematic diagram of the view of the forming limit curve (FLC) for STS304-1/2H.

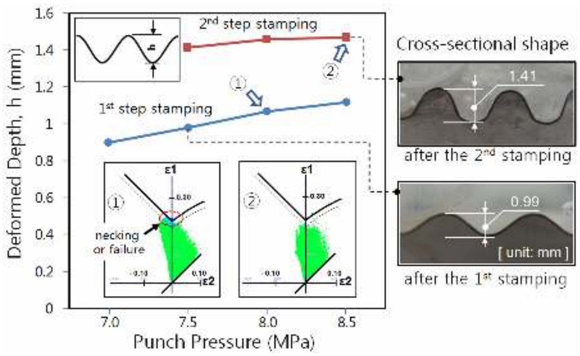

Fig. 11. Comparison of the deformed depth (h) according to punch pressure between the first and the second step stamping process; the upper insets are photographs of cross-section of corrugated structures, and the lower insets show the forming limit diagrams at the critical punch pressure of 8.0 MPa (in the first stamping) and 8.5 MPa (in the second stamping), respectively.

follows: the die was fixed, and the blank holder and punch were moved along the vertical direction by controlling the pressure. For the evaluation of formability in the analysis, a forming limit diagram (FLD) of the STS304-1/2H sheet was obtained using experiments, as shown in Fig. 10 [17-22].

In the analysis results of the first stamping process shown in Fig. 11, it was possible to stamp corrugated structures successfully without crack until a punch pressure of about 7.5 MPa. In this case, the maximum deformed depth of a corrugated structure was 0.99 mm. However, the FLD revealed that at a punch pressure over 7.5 MPa all cases failed. The blank holding pressure, which rarely influenced the formability in this work, was given as the fixed value of 4.5 MPa in the all cases. From the first step stamping process, the forming ratio (η), which is defined in Eq. (1) as comparison of the target height (h_t) and deformed maximum height of the corrugated structure (h_c), was approximately 66%;

$$\text{forming ratio } (\eta) = (h_c / h_t)\cdot 100 \text{ } (\%) \quad (1)$$

where the target height is 1.5 mm.

As such, the target forming height of 1.50 mm was not obtained with a single step forming process alone due to the work hardening effect. Therefore, in this study, the hardening that occurred in the forming process was removed using a heat treatment of annealing to extend the forming limit in the next step. Then, the second-step stamping analysis was performed to get the shape of the high aspect ratio corrugated structures. In the analysis of the second step stamping process, we considered the material properties of a sheet as ones obtained from the tensile test using the heat treated specimen. We also assumed that the work hardening effect was perfectly eliminated by the heat treatment, so the residual stress value was set as 'zero' in the second step stamping analysis. The results of the second forming analysis with the maximum forming depth with the FLD are summarized in Fig. 11. Here, at a punch pressure of 8.5 MPa, the forming depth improved but it also caused breaks. In addition, when the punch pressure was 7.5 MPa, breaks did not occur but the forming depth was not sufficient. On the other hand when the punch pressure reached 8 MPa, breaks did not occur at a forming depth of 1.46 mm and a forming ratio of 97%. Compared to the single-step forming, the forming depth was increased by 0.47 mm in the second-step stamping. Then, based on the single-step forming, forming depth was improved by about 47%.

The insets in Fig. 10 show the changes in depth of the corrugated structure obtained from the first and second-step stamping. For observing the cross-section of the deformed plate, it was cut in the vertical direction of the corrugation to measure the corrugated structure shape and the distribution of thickness. Surface polish treatment was conducted on each plate after mounting. Then, through optical microscope, the forming depth and sectional view of the corrugated structure were observed. As shown, the deformed depth was clearly increased; therefore, we can conclude from the results that the MSS is an effective way to make high aspect ratio corrugated structures.

4. Results and discussion

The comparison in the variation of the forming depth obtained from the finite element analysis through the experimental MSS is shown in Fig. 12. Defining the corrugation depth of 1.50 mm as the 100% forming ratio, in the results from the MSS analysis, a corrugation depth of 1.47 mm was found with a 97.3% forming ratio under the conditions in which breaks did not occur in the sheet. However, the corrugation forming depth was found to be 1.41 mm in the MSS experiment, indicating a forming ratio of 94.0%. The gap between the two values was about 3.3%, which seemed to come from the difference in real conditions, especially the setting value of residual stress after the first-step stamping in the analysis. And the forming ratio after the second step stamping is largely increased compared to the first stamping result from 66% to 94% (the difference reaches about 28%). Also, from the results of tensile test, the maximum elongation is increased from 38% (original specimen) to 80.7% (from the MST). Thus, it is

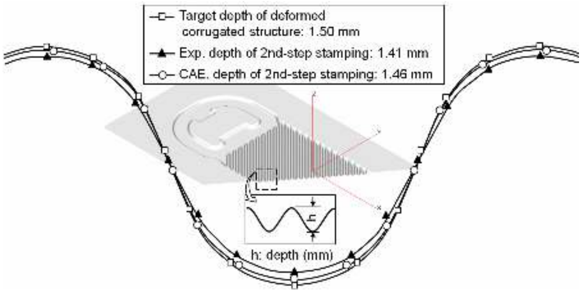

Fig. 12. Comparison of experiment stamping and forming analysis of multi-step stamping.

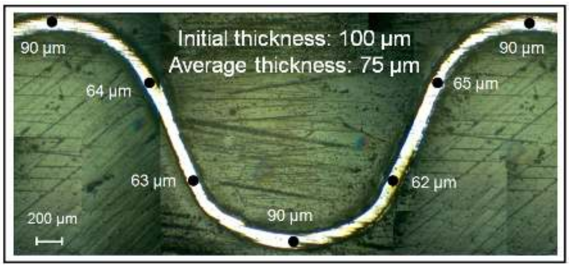

Fig. 13. Optical micrographic image of the deformed corrugated structure: thickness variation after the second step stamping.

possible to conclude that the proposed MST test can be used to estimate the formability of multi-step stamping process in case of stretching dominant material behavior, even though there are some gaps between both tensile test and stamping results.

The plate with an initial thickness of 100 μm, after the MSS experiment, showed a change in thickness of the shape and a reduction in thickness as shown in Fig. 13. The average thickness of 7 points was 75 μm, showing a reduction of 25% in thickness compared to the initial material. The minimum thickness in the corrugated structure was about 63 μm. This may have been caused by the occurrence of considerable stretching in the plane deformation condition, increasing the corrugation depth. The difference of a local thickness can be improved with optimization of process parameters such as blank holding force, lubrication conditions, punch force and speed.

5. Conclusion

The following conclusions were made about the manufacturing of continuously corrugated structures using a thin sheet of 100 μm thickness. To fabricate corrugated structures that can be used in various heat management devices, a multi-step stamping process was proposed by a linking heat treatment technique to increase the formability. The experimental results of multi-step tensile tests confirmed that the multi-step stamping process improves the formability of a thin sheet up to 80.7% in elongation, when the specimen is heat treated at appropriate temperature conditions. The multi-step tensile test proposed here seems to be an effective way to evaluate the formability or elongation of a test material. In the multi-step stamping process, the temperature condition of the heat treatment was defined by the multi-step tensile test. For the heat treatment, 1000°C, which is near the re-crystallization temperature of the original material, was found to be the most effective. A complex corrugated structure was successfully fabricated with an improvement of formability of 47% compared to a single-step stamping process. The thickness variation of deformed structures was in a range of 62 to 90 μm. The maximum reduction rate of thickness was about 38%, which is a considerable amount considering the thin initial thickness of 100 μm and the cold-state stamping condition. In summary, the proposed tensile test and multi-step stamping process can be utilized to evaluate the increase of formability and to fabricate complicated sheet products such as continuously corrugated structures using very thin sheet.

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