EXPERIMENTAL AND NUMERICAL ANALYSIS OF DISTORTIONS AFTER ENAMEL COATING PROCESS ON OVEN CATALYTIC SIDE PANEL SHEETS

by

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Sheet metal materials are used in many sectors due to their good mechanical properties and weight/strength ratios. The use of sheet metal materials is common in household appliances and built-in ovens manufacturers. The final stage process in the manufacture of panels from sheet metal is usually coating. Sheet panels used in built-in ovens are usually enameled to be corrosion resistant and more hygienic. However, the heat treatment in the enamel coating process causes distortions in sheet metals. In this study, experimental and numerical investigations were carried out in order to minimize the distortions and thermal stresses that occur after the enamel coating on the oven side panel. The ANSYS 2020 R2 program was used for numerical analysis. The DC04EK cold rolled sheet in EN 10209 standard was used for the panel sheet used in the experiments. Panel sheets were produced as flat and formed, and enamel coated under the same conditions. The differences between the two sheets after the coating process were examined. The distortions and thermal stresses were smaller in the formed sheets. Maximum distortion was measured as 6.35 mm in flat sheet and 4.68 mm in formed sheet metal. The distortion in the formed sheet was approximately 25% less than the flat sheet. In numerical analysis, on the other hand, formed sheet distortion was 30% less than flat sheet. When the experimental results and numerical results are examined, it is seen that the forms given to the sheets minimize the distortions and stresses.

Key words: *thermal distortion, sheet metal, finite element method, heat treatment*

Introduction

Sheet metal forming is the process of forming materials using mold tools with the logic of plastic deformation of thin materials. Since these materials are low-weight and high strength materials, they have become the main raw material of many sectors. It is encountered in applications in many fields such as aviation, space industry, automotive and household appliances industries. Especially the panels of household appliances (refrigerator, oven, *etc.*) are produced from these sheet metals [1-3]. The DC04EK cold rolled sheet metal is widely used in the production of panels. In order to obtain panels, sheet metals go through different processes such as cutting, bending, drilling and spinning [4-6]. After ensuring the dimensional and shaped integrity of the panels, coating is done according to the conditions of use. Enamel coating is usually applied to the panels operating under high temperature to be corrosion re-

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sistant and better in terms of hygiene [7, 8]. In the enamel coating process, sheet metals are heat treated in furnaces under high temperature for better curing of the coating [9]. The biggest problem here is the distortion of the panels after heat treatment. This distortion causes the product not to be in the desired dimensions. Therefore, the distortions should be minimal. High distortion rates negatively affect both the visual and function of the product and make it difficult to assemble.

The effect of thermal processes on the material is generally studied on fuels [10-12]. When the literature is examined, no study has been found on the distortions that occur in sheet metals after enamel coating. In the studies on the distortion of sheet metals, the distortions that occur in the sheets after the welding process have been investigated [13-16].

As a result of the development of technology and the increase in demands, process improvements were needed in the sheet metal forming sector, as in other sectors. Production speed is very important in industries where mass production flow is high. Like the selection of materials to be preferred before production, the mold tools and process design steps to be used must be adapted to this change quickly. Using the trial/error method to respond to this change is not a viable and sustainable method in terms of both time and cost. For this reason, computer aided engineering tools are used today. The most frequently used method among these tools is the finite element analysis method (FEM) [17].

The FEM was first used by large automotive companies in the late 1970's to examine whether tearing and writhing occur in sheet metal forming processes. Today, the main purpose of the simulations. The main purpose of the simulations made today is to observe and interpret the strength, behavioral properties of the sheet material to be shaped under different conditions such as stress, vibration and deflection. In order to obtain a successful result in the analysis, it is necessary to establish a finite element mesh, to determine the boundary conditions well, to choose the workpiece material correctly and to model it correctly [18].

In this study, the distortions of DC04EK cold rolled sheet metal panels after enamel coating were investigated experimentally and numerically. It is aimed to minimize the distortions that occur after heat treatment. In order to keep the distortion at a minimum level, the flat sheet was formed and the distortion difference between the flat sheet and the formed sheets was compared. The distortion was lower in formed panels and the desired result was achieved in the study.

Experimental procedure

The side panel sheets used in oven manufacturing are coated with enamel to be more resistant to corrosion and to have a long service life. The side panel sheets used in oven manufacturing are coated with enamel to be more resistant to corrosion and to have a long service life. In the enamel coating process, the panels are kept in ovens at high temperatures. Distortions occur on the surface of the panels coming out of the furnace due to thermal stresses during cooling. In order to calculate these distortions and make correct planning during the production stages, flat sheet panels were formed before enamel coating. The distortion differences between the enamel coated flat sheet and the formed sheet were investigated experimentally. In addition, the distortion of uncoated flat and formed sheet metal after heat treatment was examined and the effect of enamel coating on distortion was also examined. In order to see the accuracy of the experimental results, enamel coated flat sheet and formed sheet metals were numerically analyzed using the finite element method. Thus, the effect of the form given to the sheet on the distortion was observed. Experimental results and numerical analysis results were compared. The ANSYS 2020 R2 program was used for numerical analysis. The experimental scheme used in the study is given in fig. 1.

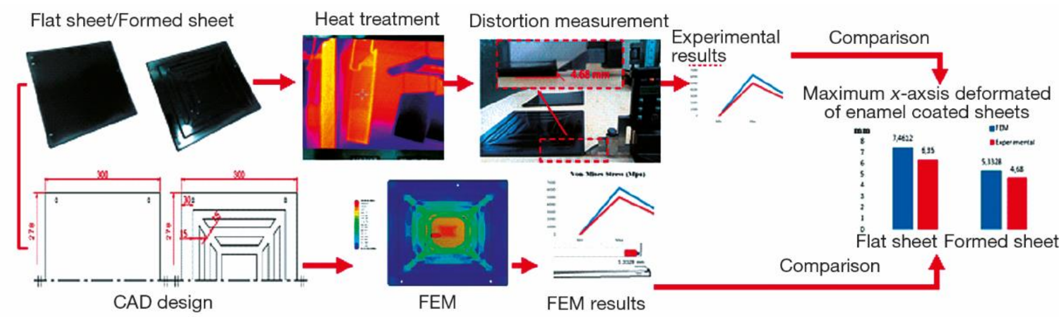

Figure 1. Schematic picture of the experimental set-up

Materials

In the study, two different workpieces as flat sheet and formed sheet with the dimensions of 300 × 278 × 0.6 mm were used. The sheet quality, material thickness and rolling direction of the parts used in the experiments are the same. The sample materials are DC04EK quality manufacturing steel sheet material in EN 10209 standards with a thickness of 0.6 mm, which is suitable for drawing, resistant to aging, suitable for extra deep drawing and enamel coating [19].

The 20 of each sample type were produced. As an experimental result, the measurement of the sample, which is close to the average value in the measurements, is given. Distortions that occur during the processes on the samples are neglected until the enamel coating. Sheet materials were processed in different molds and shaped as flat and formed, then enamel coating was applied.

Before enamel coating, the samples were washed with special chemicals to remove oil and dirt and dried at 145 °C. After enamel coating was applied on the dried samples at room temperature, they were kept in the heat treatment furnace at 830 °C for 25 minutes. Enamel coating thickness is between 0.15-0.16 mm. The distortions occurring in both samples after coating were examined.

Modelling of finite elements

In the numerical study, using the finite element method to compare the experimental results, primarily solid models of flat and formed sheet materials were created in the Solidworks program. The ANSYS 2020 R2 program was used for finite element analysis. Analyzes were made after 0.15 mm enamel coating was applied to the model within the program. In order to analyze the structural deformation on the part due to the exposure of the materials to high temperature changes in the enamel process, a steady-state thermal analysis was performed at the temperature values of 830 °C to which the part was exposed, and the effect of the temperature on the material was evaluated by static structural analysis. The initial temperature was accepted as the ambient temperature of 22 °C. The stresses on the surface of the samples due to temperature differences were investigated by static structural analysis.

Material properties. For the finite element model, the technical properties of the DC04EK steel material used in the oven panel are given in tab. 1.

Table 1. Mechanical properties of the DC04EK steel

Mechanical property								
Tensile strength [MPa]	Yield strength [MPa]	Elongation at break [%]	Young's modulus [GPa]	Poisson's ratio	Density [gcm^{-3}]	Thermal conductivity [$Wm^{-1}K^{-1}$]	Thermal expansion coefficient [10^{-6} per °C]	Electrical resistance [μΩcm]
270-350	220	36	200	0.287	7.8	25.1	10.4	61

Mesh generation and boundary conditions. In order to analyze the parts, meshing was applied to their surfaces. For this, mesh metric criteria were used. It is necessary to evaluate all criteria in terms of mesh quality. Evaluation of 3 criteria (skewness, orthogonal quality, and aspect ratio) in order of importance is sufficient to determine mesh quality [20]. Mesh was made considering these three criteria. In the numerical studies, the hexagonal mesh structure consisting of square/cube elements, which is considered the most ideal in terms of element quality, was used. Aspect ratio criterion, one of the mesh metric quality criteria, was used to increase the quality level of the mesh structure used and to obtain more accurate and sensitive solutions. By reducing the size of the elements from 20 mm to 2 mm, they were selected in an acceptable range and optimum quality values were obtained. Flat sheet sample consists of 62371 elements and 125969 nodes. The mesh structure of the formed sheet sample consists of 152096 elements and 305860 nodes. Mesh images of flat and formed sheet samples are given in fig. 2.

In the experimental study, the sheet metal panels are hung with hooks from the two holes on the upper part. In order to create the same conditions as in the experimental study, the sheet panels were fixed through two holes in the finite element analysis as shown in fig. 2.

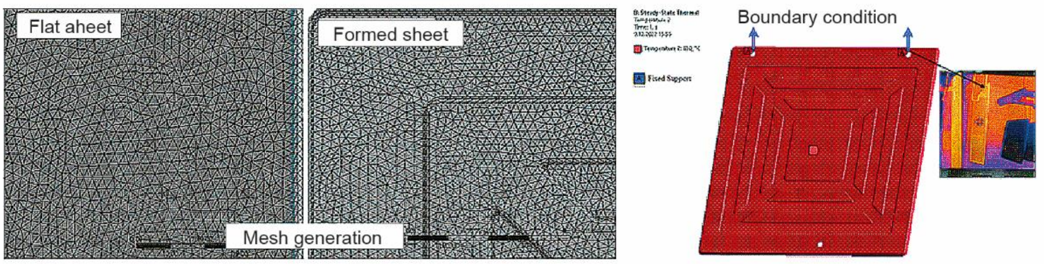

Figure 2. Mesh and boundary condition image of samples

Experimental and numerical results

Experimental results

First of all, flat and formed sheets were heat treated without enamel coating in order to see the effect of the enamel coating on distortion. The distortions occurring in both sheets were measured. The measurement of distortions was made using a measuring gauge on a flat table. The corner with the highest distortion in sheet materials was measured. In fig. 3, the measurement of distortions in uncoated flat and formed sheets is given.

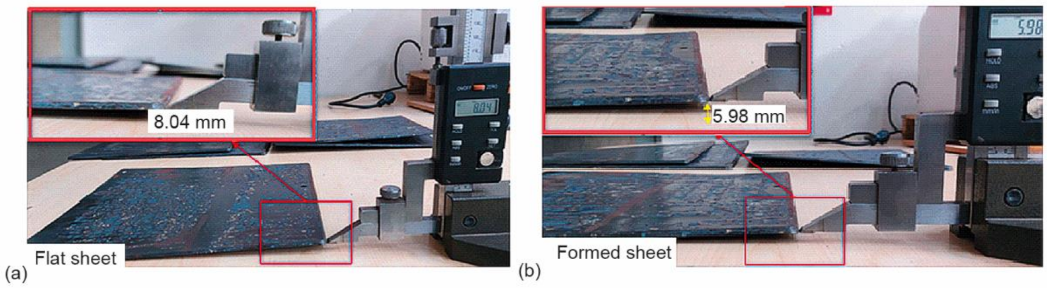

Figure 3. Experimental distortion measurement of uncoated flat and formed sheets

While the maximum deformation in the *x*-axis was measured as 8.04 mm in the flat sheet without enamel coating, the maximum deformation in the shaped sheet was measured as 5.98 mm. When the effect of the form given to the sheet metal is examined without the effect of the enamel coating on the uncoated sheets, the maximum distortion was approximately 25% less thanks to the form given to the flat sheet.

The distortions that occur in the enamel coated sheets after the uncoated sheets were measured experimentally. In both flat sheet and formed sheet metal, the maximum distortion occurred at the opposite corners of the fixed edge. In fig. 4, the maximum distortion measurements of the enamel coated flat and formed sheet are given. The maximum distortion was measured as 6.35 mm in flat sheet and 4.68 mm in formed sheet metal. The distortion that occurred in the enamel-coated sheet metal was approximately 25% less than the flat sheet.

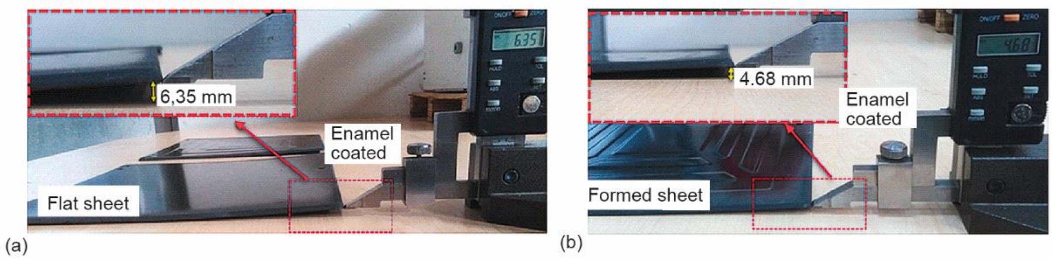

Figure 4. Experimental distortion measurement of enamel coated flat and formed sheets

In fig. 5, the bar graph of the distortion rates of enamel coated and uncoated sheets is given. According to the graph, it is seen that the distortion is more in the uncoated sheets. It has been observed that enamel coating reduces the distortion in sheet materials. Thanks to the form given to the sheets in both coated and uncoated sheets, the distortions were approximately 25% less than in the flat sheet.

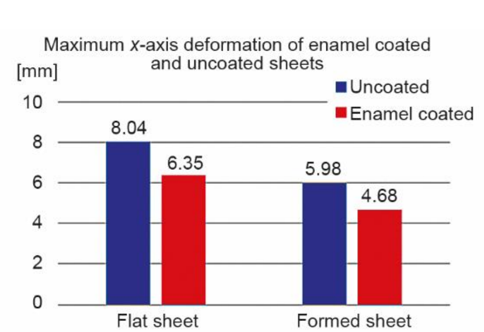

Figure 5. Distortion graph of coated/uncoated flat and formed sheets

Microcracks that may occur on the enamel coating reduce the corrosion resistance of the material. The material, which corrodes quickly, both reduces its service life and creates negative effects in terms of hygiene. Figure 6 shows the cracks in the enamel coating on the samples. Since the sheet plates were distorted from their corners in the same direction, the cracks in the coating occurred on the line where the distortions met. Microcrack examined photos along the line. While microcracks were formed along the line in the flat sheet, no microcracks were detected in the formed sheet. The reason for this is that, thanks to the form given to the sheet, the forms create resistance against stresses and the distortion is less than that of the flat sheet.

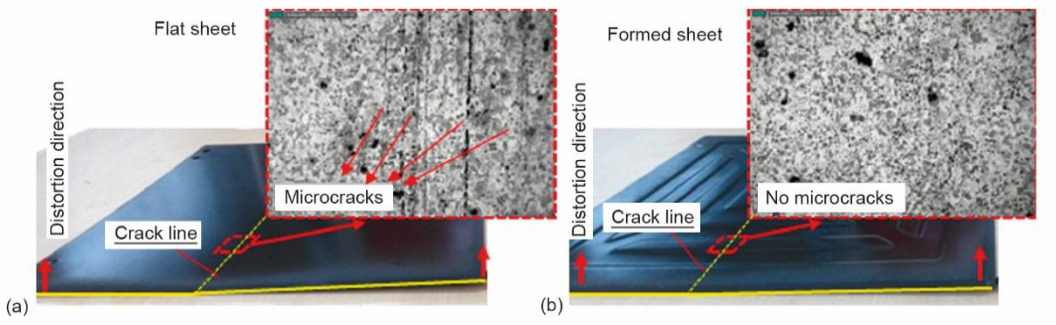

Figure 6. Microcracks on enamel coated of flat and formed sheets

Finite element results

Since the aim of the study is to minimize the distortions that occur in the sheet metal after enamel coating, only the distortion of flat and formed sheet materials after enamel coating was investigated in the FEM.

The heat flow analysis of the flat and formed sheet in the results of the thermal analysis is given in fig. 7. The heat flux density is measured as the energy transfer rate per a given area in a given time [Wmm^{-2}]. After the sheet materials are kept at 830 °C for 25 minutes, they are taken out of the oven and cooled at 22 °C. When fig. 7 is examined, the temperature distribution on the surface of the sheet materials occurs from the center outward. Cooling takes place from the outer part of the samples towards the centre. Since the thermal conduction in flat sheet is faster towards the short side, it does not show an even distribution. For this reason, the distortion was large due to the thermal stresses. In the formed sheet material, on the other hand, the temperature distribution was more regular on the sheet surface due to the forms. In addition, the form structures minimized the thermal stresses, and the distortions were smaller. It has been observed that the forms that serve as a support distribute the heat more regularly on the material surface.

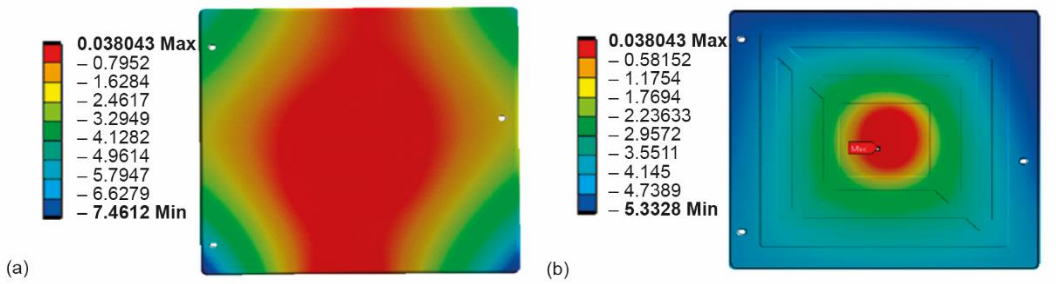

Figure 7. Thermal analysis of coated flat and formed sheet metals

Von Mises stress is a value calculated to determine whether the structure has undergone plastic deformation under any loading condition. The sample enters the enamel curing oven by hanging it from two holes on its surface with hanger apparatus. In fig. 8, Von Mises analysis results of flat and formed sheet metal are given. The maximum stress in the flat sheet was 5123.7 MPa and the highest stresses were observed at the corners of the sheet.

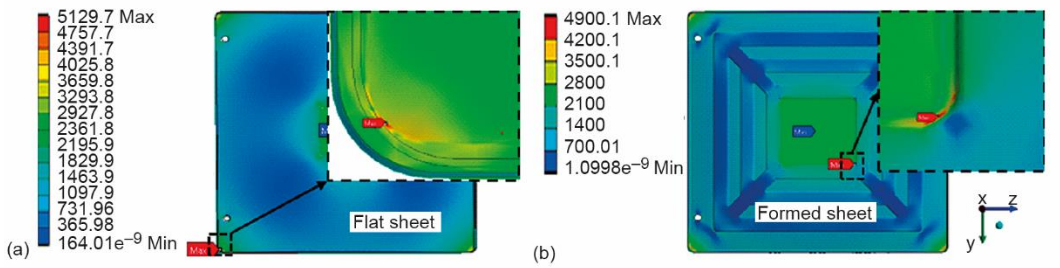

Figure 8. Von-Mises stresses of flat and formed sheet in FEM

The process of giving geometrical form to the sample increased the surface area of the sheet. With the forming process applied to the flat sheet material with a single surface area, four different surface areas were formed. Stresses occur on each surface due to temperature. Since different stress surfaces are formed on each surface on the geometric form, compression occurs in smaller places in stress analysis. These stresses can also be considered as residual stresses. As a result of the formation of different stress surfaces in different axes, on different surfaces, complementary or absorbing stresses occur. These stresses can vary depending on the surface and direction. For example, if there is a stress in the *x-y* direction, the geometric form on the symmetrical side can create another stress in the opposite direction in the *x-y* direction, minimizing or eliminating the stress in the middle. It has been observed that the different surface areas on the part have a stress-relieving effect and accordingly, the amount of distortion is less than the flat sheet metal part. The maximum stress in the formed sheet was 4900.1 MPa. In fig. 9, the maximum and average Von-Mises stresses occurring in flat and formed sheets are given.

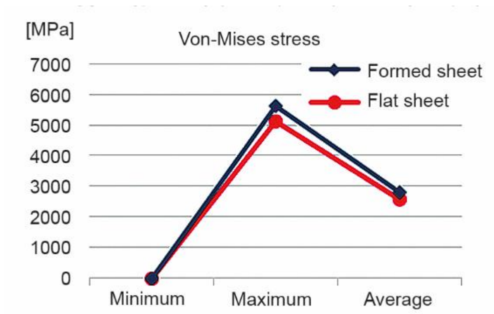

Figure 9. Von-Mises graph of flat and formed sheet

Different stresses occurred on the part in different regions with the effect of 830 °C temperature that the first piece before it was healed was exposed to in the enamel process. These stresses caused structural defects and distortions on the part. The FEM analyzes also support this result. The maximum deformations in the *x*-axis of flat and formed parts in FEM analysis are given in fig. 10. In the FEM analysis, as in the experimental results, the distortion was higher in the flat sheet. In flat sheet metal, the maximum distortion in the *x*-axis occurred at the opposite corner of the hanger holes with 7.4612 mm. In the formed sheet, the most distortion was again in the same corner. According to the FEM analysis, the maximum distortion in the *x*-axis of the formed sheet was 5.3328 mm. The distortion was 2 mm smaller than the flat sheet. In other words, approximately 30% less distortion occurred than flat sheet.

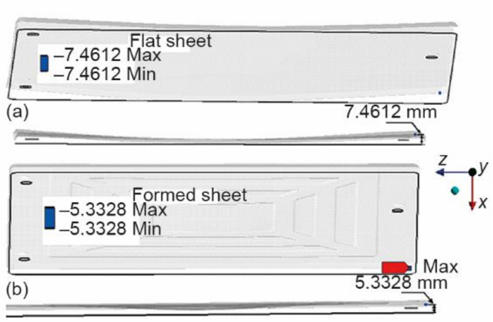

Figure 10. Distortion values of flat and formed sheet in FEM

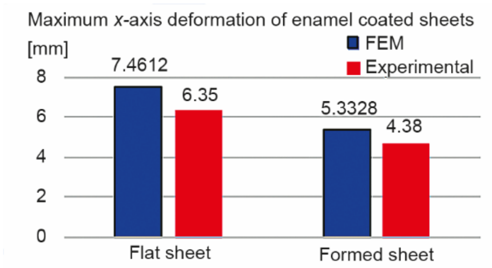

Figure 11. Distortion graph of FEM and experimental results

In fig. 11, the graph of the experimental and FEM analysis results of the maximum deformations of the samples in the *x*-axis is given. According to the graph, the experimental results obtained were close to the FEM results. Experimental results were approximately 15% smaller than the FEM results for both flat and formed sheets. These results show that the experimental study is at the desired level.

Conclusion

In this study, the distortion behavior of 0.6 mm thick DC04EK quality side panel sheet used in built-in ovens due to thermal stresses after the enamel process was investigated. The results of the experimental and numerical analysis data were evaluated in this study, which was carried out for two different parts of the same material quality with flat and formed geometric structures. Both parts were cured in an oven at 830 °C for 25 minutes after enamel coating. The pieces coming out of the oven were cooled at room temperature. Experimentally, both parts were subjected to the same enamel line process and the applied analysis conditions were kept the same. As a result of the analyzes, it has been proven that the distortions that occur on the flat sheet are noticeably higher than the sheet designed with the formed. The distortion ratio (8.04/5.98 mm) between the flat and formed sheets without enamel coating, and the distortion ratio between the enamel coated sheets (6.35/4.68 mm) were almost the same. In coated and uncoated sheets, formed sheet distortions were approximately 25% less than flat sheet metals. According to the distortion results, it can be said that the enamel coating has a reducing effect on distortion. In the FEM analyzes made considering the enamel coated sheets, the distortion of both flat and formed sheets was 15% less than the FEM results. The FEM results show parallelism with experimental results. In addition, the Von-Mises stress in the flat sheet was higher than in the formed sheet. As a result, it has been observed both experimentally and numerically that the stresses occurring in the geometrically formed sheet metal panel are less than the flat sheet panel, and accordingly, the total structural change on the part is less.

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