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Analysis of die designs for the stamping of an automobile rear floor panel

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Industrial summary

The stamping process of manufacturing a one-piece rear floor panel of a passenger car has been investigated in the present study. An analysis of the original die design, in which a split defect occurred at the drawn-cup wall, was performed using circle-grid analysis as well as the 3-D finite-element method. The split defect is due to the large area of sheet metal under the blank-holder that limits the flow of the metal towards the cup area. An optimum die design, which consists of a separate die face and a wedge mechanism mounted in the lower die frame, was proposed to provide additional metal for the cup area and to eliminate the split defect without adding an extra operation. This optimum die design was validated by the results of circle-grid analysis performed for the first and second draw operations and also by the good-quality panels produced.

Keywords: Stamping dies; Rear floor panel; Splits; Circle-grid analysis.

1. Introduction

Splits are amongst the major defects occurring commonly in the stamping process. A lot of research effort has been made to investigate the causes of and solutions to the split problem during the last few decades [1–4], the methods used including forming-limit analysis and the finite-element method. Since Keeler and Backofen [5] first introduced the concept of forming-limit diagrams (FLDs) in 1963, they have been used widely in the analysis of sheet metal forming in press shops. The FLDs indicate the strains which lead to failure and thus provide a useful tool to determine if the forming process is likely to be prone to splitting, whilst the finite-element method can calculate the strain distributions in the stamped parts accurately and thus predict if the split defect is likely to occur.

In general, the solution to problems of splitting is to provide more metal to the critical area before the major drawing process starts. This can be achieved either by decreasing the blank-holder pressure or improving the lubrication conditions, but the most straight-forward method is to add an extra operation solely for the purpose of feeding more metal into the critical area. However, the extra operation increases the production cost by adding one more set of dies and additional man-power; and hence in reality, it should be avoided.

In the present study, an optimum die design in which a separate die face and a wedge mechanism mounted in the lower die frame is proposed to eliminate the occurrence of a split-defect in the stamping process for a one-piece floor panel of a passenger car. The special die face and wedge mechanism were designed to provide additional metal for the critical area where the split defect occurred, without adding an extra operation. Both circle-grid analysis and 3-D finite-element simulations were performed to analyze this split defect.

2. Problem description

The common design for a rear floor panel of a passenger car is usually a two-piece type, namely, welding two stamped pieces together, as shown in Fig. 1. The two-piece type design is chosen mainly due to the difficulty encountered in stamping a one-piece rear floor panel, in which a split tends to take place at the wall of the deeply drawn cup used for storing the spare tire, as shown in Fig. 2. The occurrence of the split is attributed to the substantial distance between the cup wall and one side of the blank-holder, as shown by line A–B in Fig. 3, that

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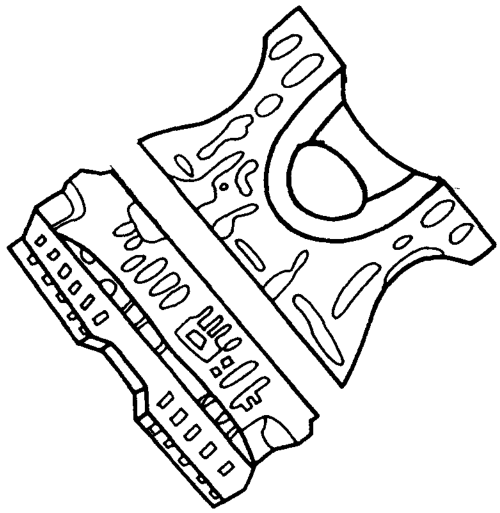

Fig. 1. A two-piece rear floor panel.

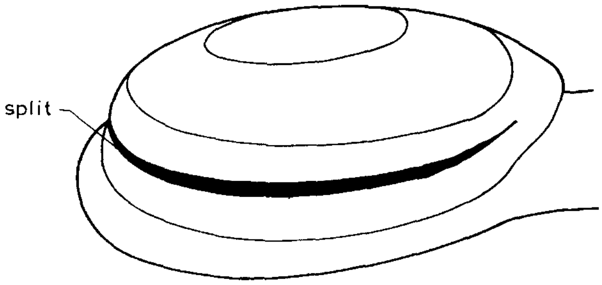

Fig. 2. A split occurring at the cup wall.

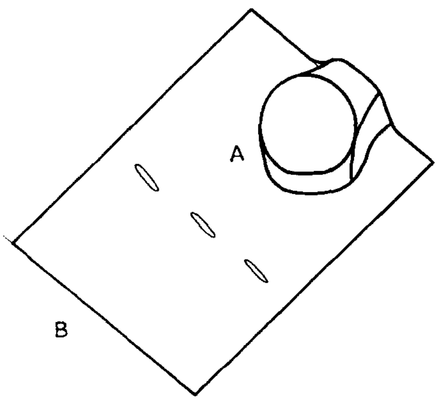

Fig. 3. The location of the drawn cup in the sheet-blank.

restricts the metal under the blank-holder from flowing into the cup area. Whilst in the two-piece design this distance is much shorter and sufficient metal can flow easily into the cup to prevent the edge of the cup from splitting, due to cost-effective considerations, a one-piece rear floor panel is always desired, so that the split problem must therefore be overcome.

The original procedure in the press shop for the production of the one-piece rear floor panel consists of four operations: first draw, second draw, trimming, and flanging. The first-draw operation was designed only to produce a cup shape, as shown in Fig. 3. As for the ribs around the cup, these were formed in the second-draw operation. Like most stamping processes, the main deformation of the rear floor panel is completed in the first-draw operation. The conventional draw process allows the punch to pull more metal into the die cavity from the blank-holder. To facilitate metal-flow, no draw beads were employed on the blank-holder surface. However, due to the large draw depth and the geometric difficulty mentioned above, a split was still found at the cup wall near the bottom after the first-draw operation, as shown in Fig. 2. The location of the split defect indicates that the considerable distance between one side of the cup wall and the blank-holder does prevent the metal from flowing towards the cup. Some efforts have been made to help the metal to flow toward the cup area. The attempt of decreasing the blank-holder pressure led to more wrinkles at the root of the cup area but without eliminating the split. Improvement of the sheet metal quality was also proven to be in vain. Extreme care taken with the lubrication conditions can ease the split problem: however, this is not cost-effective for the process of mass production. Also the large quantity of lubrication oil used in the stamping process may pollute the shop floor. Hence, the most efficient way left to solve this problem is to provide more metal for the cup area before the punch starts to form the cup. To achieve this end, modification of the blank-holder surface to form a better binder-wrap shape which provides more metal around the cup area was considered. The binder-wrap is the deformed shape of the sheet-blank at the closure of the blank-holders. However, due to the same geometrical reason, i.e. the considerable distance between the cup and one side of the blank-holder, the optimum blank-holder surface is not easy to obtain. Finally, a separate die face designed for the first-draw operation aided by a special wedge mechanism mounted in the lower die frame provided more metal for the cup area and enabled the production of sound products without split defects.

3. Analysis of the original design

The problem of splitting is usually related to the strain distribution in the critical area. The strain distribution in any cross section of the formed part is determined by two factors: one is the amount of metal-flow resulting from draw-in over the blank-holder; the other is the amount of stretch created by the contacts between the punch and the die [6]. To quantify the effect of the tooling geometry on the metal flow, the original design was analyzed by circle-grid analysis (CGA) and the finite-element method (FEM).

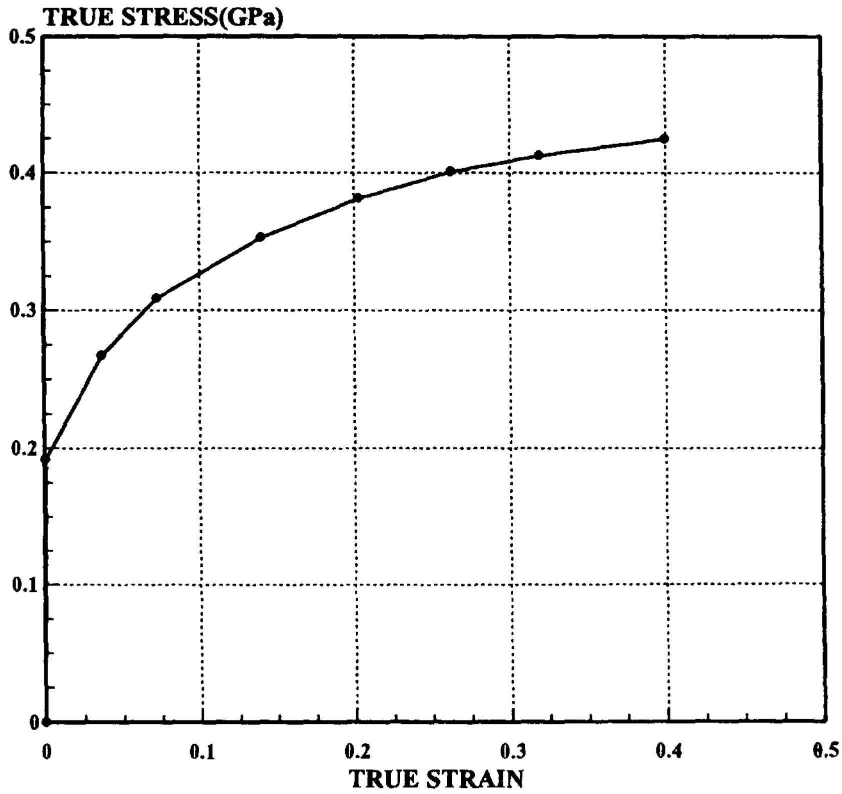

Fig. 4. The stress-strain curve for the sheet-blank.

3.1. Circle-grid analysis

Circle grid analysis has been used widely in the press shop to measure the strain distributions and thus to enable an analysis of the formability of the sheet metal by plotting the measured strains on the forming-limit diagram. The circle grids have a major advantage over the other types of grid, such as square grids, since they do not have any preferred orientations. This advantage lies in that the deformation of the circles will result in ellipses, the two principal directions being displayed clearly by the major and minor axes. The magnitudes of the principal strains can then be calculated from the measurements of the lengths of the major and minor axes. By plotting these measured major and minor strains on the forming limit diagram, the severity of areas of a formed part can be evaluated.

In the present study, a production floor-panel made using the original die design was first analyzed with circle-grid analysis. The steel sheet used for production is 0.7 mm thick and of DDQ quality, with material properties as shown in Fig. 4. The corresponding forming-limit diagram for this material provided by the steel supplier is shown by the solid curve in Fig. 5. Any area of a formed part which is deformed with the strains located on or close to this curve will tend to split. In practice, the forming-limit curve shifted down by 10%, as shown by the dashed line in Fig. 5, is used as the design curve. The area above the forming limit curve is called the failure zone; the area between the forming-limit curve and the design curve is termed the marginal zone; and the area below the design curve is named the safe zone. In general, the strain distributions in any area of a formed part should fall in the safe zone to make the stamping process stable, a stamping process being said to be stable if it is less sensitive to process variations.

Before being stamped, the critical area of the sheet-blank was imprinted with 5-mm diameter circles with 6-mm spacing between their centres. To imprint the circles the critical area of the sheet-blank was first cleaned using a special cleaner, then a stencil with the correct grid pattern was placed in position on the part. Using the electrolyte as conductor, the area covered by the stencil was marked with the grid pattern by an etching process. To prevent the marked area from rusting, a piece of cloth saturated with cleaner was used to wipe off excess electrolyte and residual oxides in the marks.

After being stamped, a split was found on the cup wall near to the top, as shown in Fig. 2. The major and minor strains of the deformed circles around the split, as shown in Fig. 6, were measured and plotted on the forming limit diagram, as shown in Fig. 7. As can be seen in this figure, the measured strains are either above or close to the

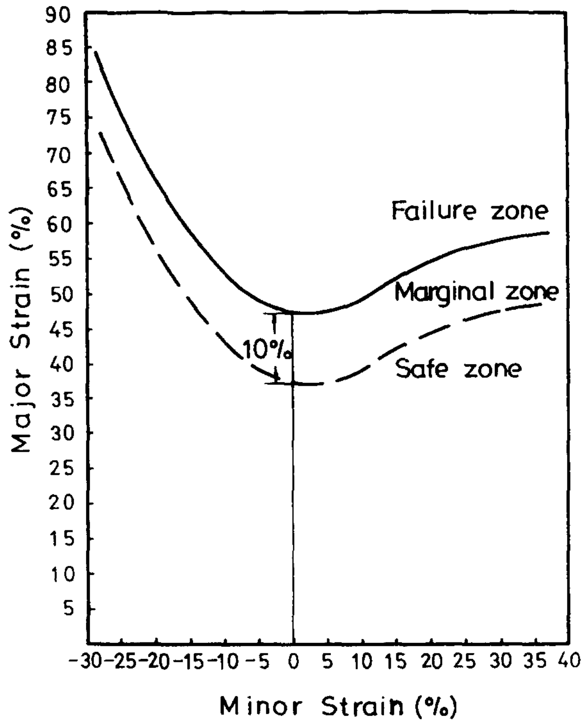

Fig. 5. The forming-limit diagram for 0.7 mm DDQ steel sheet.

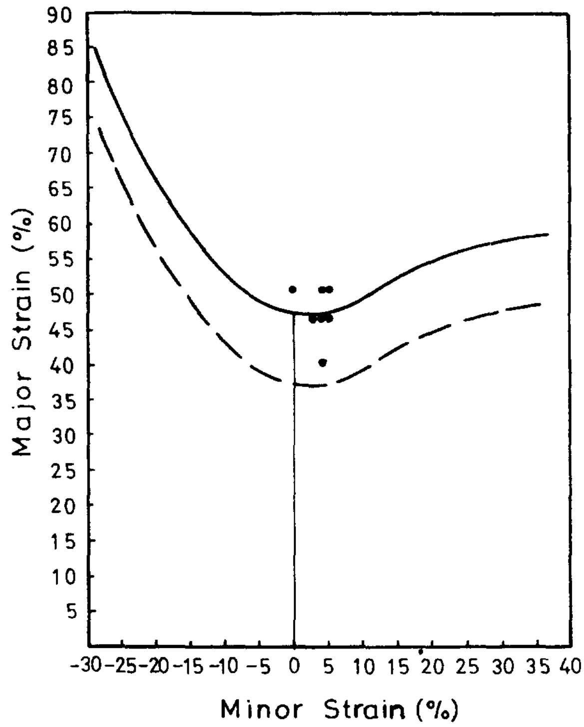

Fig. 7. Measured strains around the split.

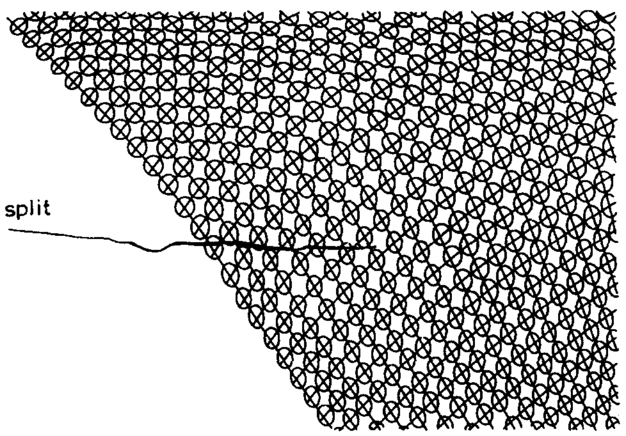

Fig. 6. Deformed circles on the sheet-blank.

forming-limit curve, and the failure is obviously due to stretching, since both the major and minor strains are positive. It is also noted that the strains are very close to the plane-strain failure mode, i.e., close to the axis on which the minor strain is zero.

The results of the circle-grid analysis indicate that the original design is very unstable. The FLD also indicates that the major strain is too large: this is consistent with the present authors' opinion that the considerable distance between the cup and one side of the blank-holder limits the flow of metal towards the cup area, resulting in the large strains. As discussed in the previous sections, the most effective method of decreasing the major strain is to provide more metal for the cup area.

3.2. Finite element analysis

To help further understanding of the deformation of the sheet-blank during the stamping process, a 3-D finite-element analysis was performed for the first-draw operation of the original design. The explicit finite-element code PAM-STAMP, which is capable of handling any arbitrary 3-D die shapes, was used to conduct the simulations. Since the 3-D die geometries, including the punch, the die cavity, the blank-holder and the draw beads, are not simplified, the finite-element program is able to simulate the actual production processes more accurately.

In order to describe the geometry of the die components, a commercial CAD program was used to construct the surface models for these components. The mesh systems required by PAM-STAMP as the input data for the die geometries were then generated by the same commercial CAD program, as shown in Fig. 8. In earlier periods, it was very difficult, if not impossible, to generate the mesh system for a complicate 3-D die shape, such as the stamping dies. However, as CAD systems are being used with increasing popularity in the die and mould industry, the above procedures to generate the mesh systems for the die geometries become trivial. Since the PAM-STAMP code treats the die components as rigid bodies, the mesh systems are used only to describe the geometries

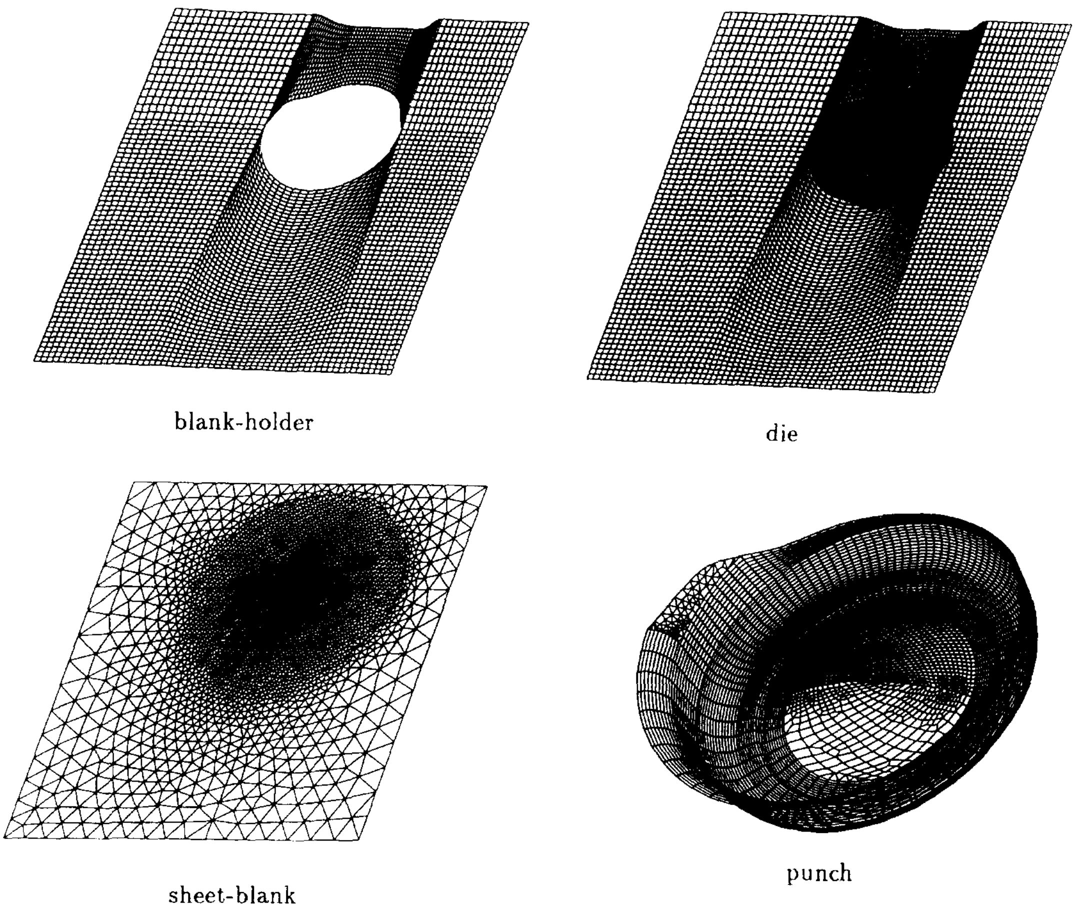

Fig. 8. Mesh system for the original die design.

of these components and not for stress analysis. In the present investigation, a mixture of 3-node triangular and 4-node rectangular elements is used to construct the mesh systems. The mesh system for the sheet-blank is also shown in Fig. 8. As seen in this figure, the mesh density is much higher in the cup area than elsewhere, since the cup area is the location where splitting occurs. The numbers of elements used in the analysis are summarized as follows: die: 9,910; punch: 5,499; blank-holder: 4,411; sheet: 4,891; total: 24,711.

The material properties used for the finite-element analysis are the same as those given in the previous section, the other operational conditions being: blank-holder pressure: 57 kPa; punch velocity: 10 m/s; punch stroke: 895 mm; and coefficient of friction: 0.12. The CPU time spent on an HP735 work-station to run a single job is about 11 100 s, the simulation results being displayed on an SGI work-station.

One of the advantages of using finite-element analysis for stamping process is that the deformed shape of the sheet-blank can be monitored throughout the stamping process, which is not possible in the real production process. Amongst the deformed shapes, the binder-wrap is the most interesting to the die designer, since it can be used to determine if the blank-holder surface has been designed properly. In the present study, the main purpose of the finite-element analysis is to investigate the deformation of the sheet-blank and the location where the split is most likely to occur. Hence, the deformed shape and the thickness contour obtained from the finite-element simulations were investigated.

The deformed mesh is shown in Fig. 9. As seen in this figure, the cup is formed without causing any wrinkling. As for the thickness contour shown in Fig. 10, the darker area represented the thinner portion of the steel sheet. It can be seen from this figure that the thinnest portion is at the cup wall near to the bottom: this location agrees with that found in the production panel. In addition, the distribution of the major and minor principal strains around the thinnest portion obtained from the finite-element simulation, as shown in Fig. 11, is very consistent with that found in the real production panel, as shown in Fig. 7. Hence, the finite-element simulation confirms the previous circle-grid analysis and is validated by the production process. With the validated process parameters, the finite-element analysis

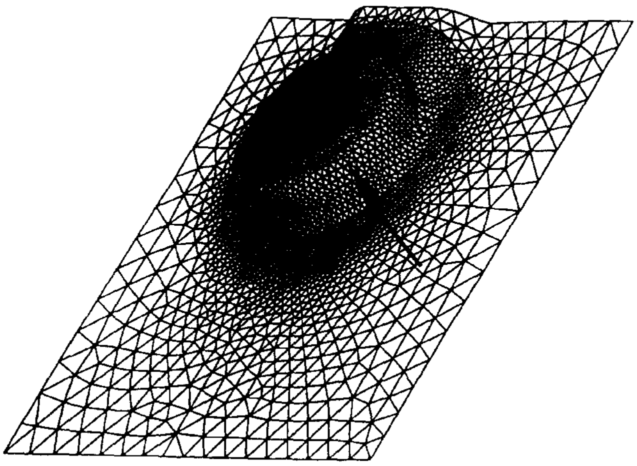

Fig. 9. Deformed shape for the original die design.

can be used for the analysis of any modified die design to substitute for the real die try-out. Compared with the real die try-out, the finite-element simulation is not only cost-effective but also time-saving, the example given in the following section demonstrating this advantage.

4. A modified die design

Since the split-defect is due to the lack of metal around the cup, one possible modification is to open the blank-holder at one side of the cup, as shown in Fig. 12, which may cause more metal to flow into the cup. The geometries of the die and the sheet-blank remain the same as in the original design and, hence, are not shown in Fig. 12. In order to validate this modification, a 3-D finite-element simulation was performed instead of re-vamping the real die. The simulation conditions were the same as those for the original design, except that the geometries of the punch and the blank-holder were changed, as shown in Fig. 12.

The distribution of the major and minor strains of the whole panel obtained from the finite-element simulation

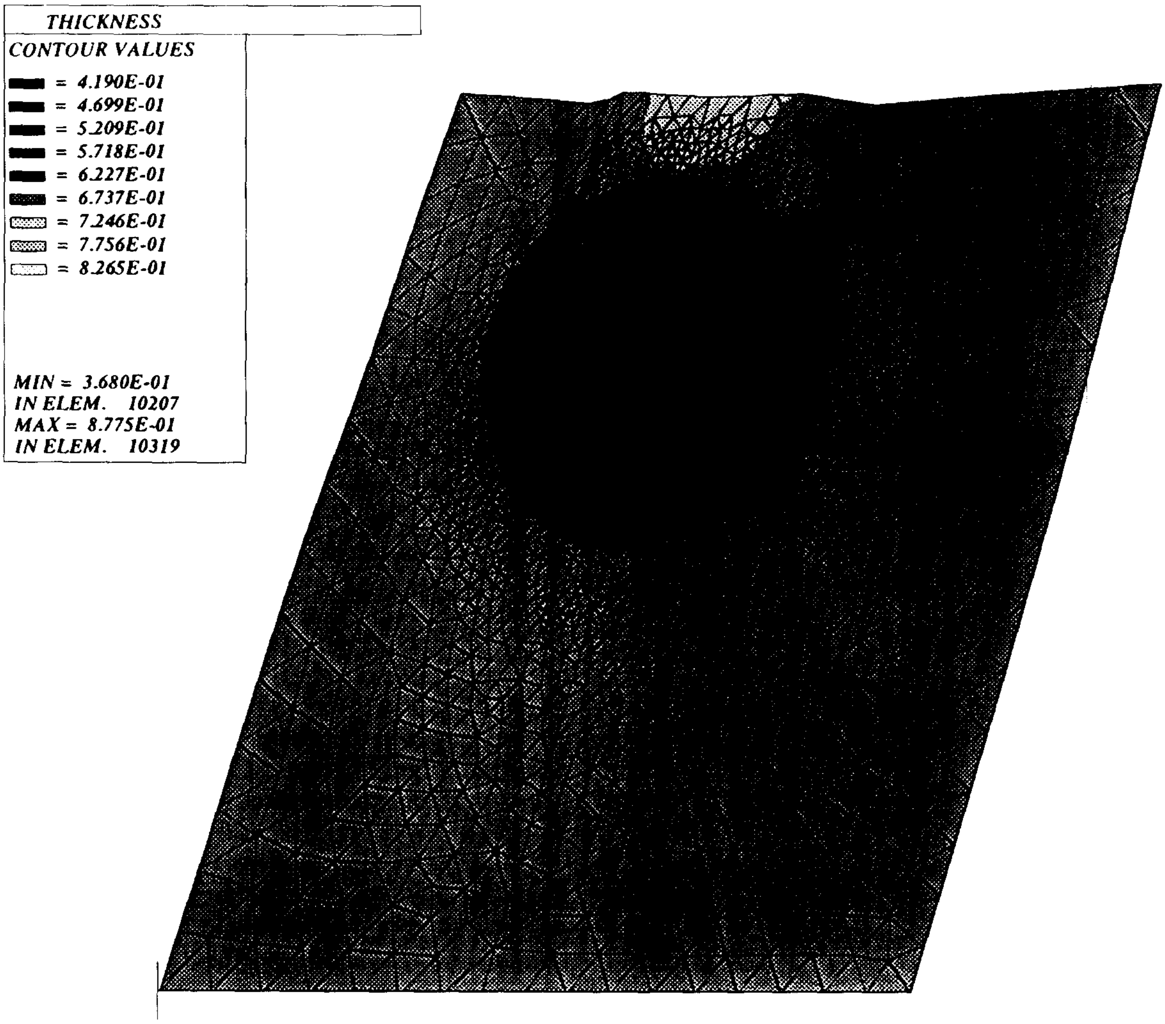

Fig. 10. Thickness contour obtained from finite-element simulation for the original die design.

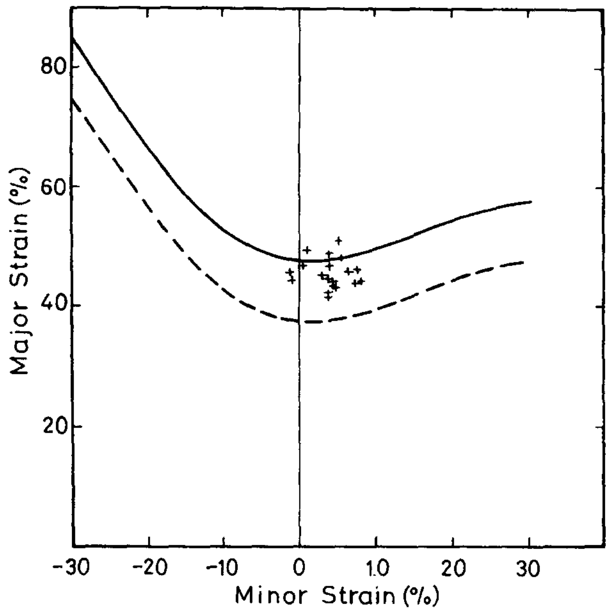

Fig. 11. The strain distribution obtained from finite-element simulation for the original die design.

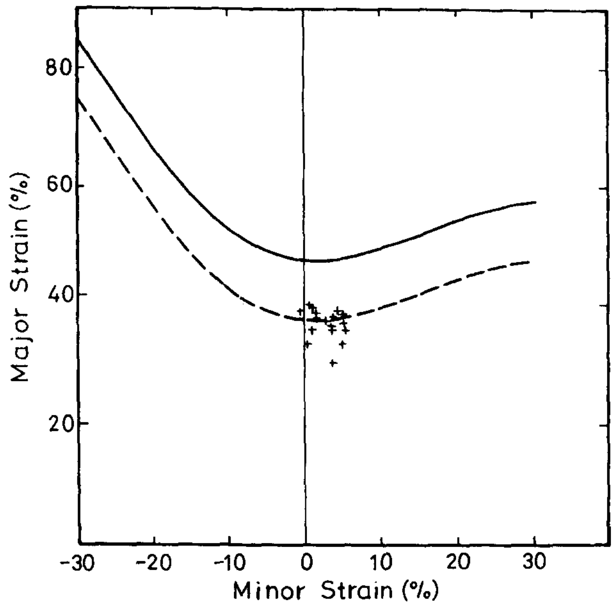

Fig. 13. The strain distribution for the modified die design.

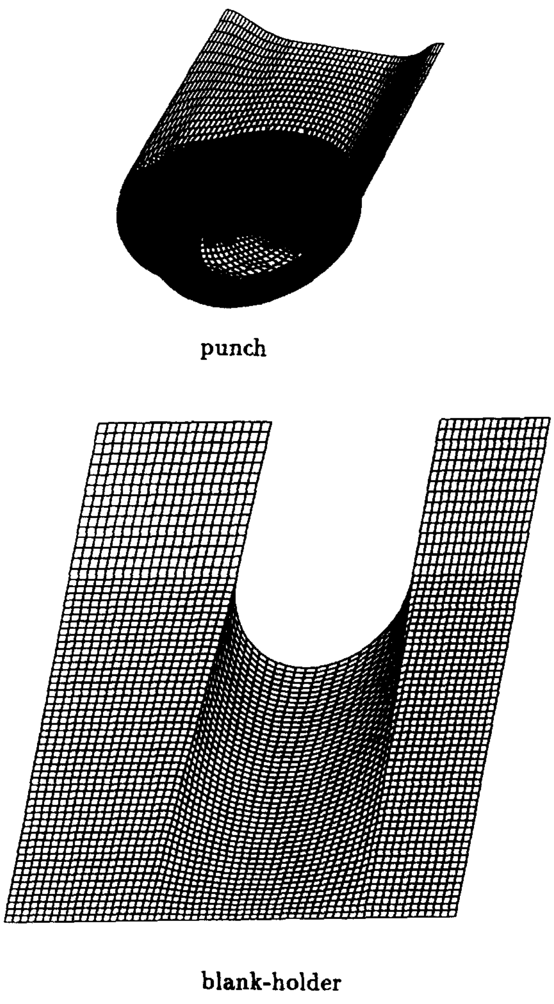

Fig. 12. The modified die design.

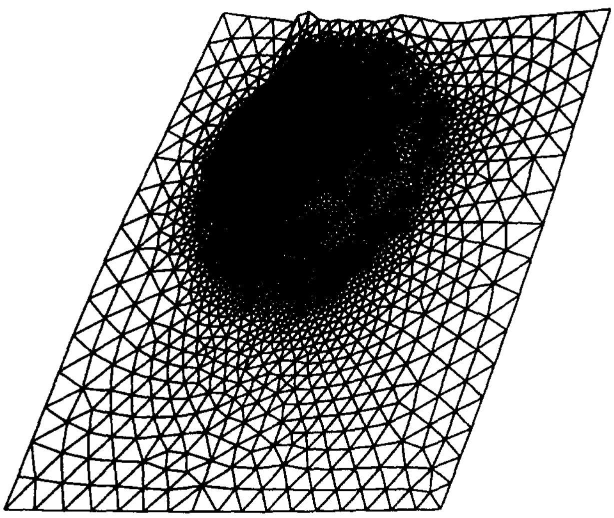

Fig. 14. The deformed shape for the modified die design.

for the modified die design is shown in Fig. 13. As seen in this figure, due to a lot of material being drawn into the cup from the unconstrained area, the strain distribution moves down a little bit but is still in the marginal area. Fig. 14 shows the deformed shape, in which serious wrinkles are observed in the unconstrained area. Although the split problem might be avoided in this modified design, the serious wrinkles are unacceptable. As a result, the modified design was not feasible according to the 3-D finite-element simulation, and the re-vamping of the real die was avoided.

5. The optimum die design

As discussed in the previous sections, the most effective method to eliminate the split-defect from the production panel is to provide more metal for the cup area. Several attempts have been made to achieve this end but only the die design depicted below has been found to be feasible and efficient.

In the press shop, the rear floor panel was stamped by a single-action press with two nitrogen cylinders supplying power to the blank-holder. In order to provide more metal for the cup area without adding an extra operation, the lower die shape was divided into two portions, as shown in Fig. 15. The middle portion of the die shape was driven by a wedge mechanism and can move up and down relative to the rest of the lower die, which remains stationary. Since the modified die shape was designed to eliminate the split-defect, the location of the movable portion was chosen at the cup area. The movable portion was driven upwards through the wedge mechanism as the blank-holder closed. At the closure of the blank-holder, the movable portion lifted the sheet-blank to a particular height, providing the cup area with more metal than that in the original design. The movable portion was then forced to move downwards when it was contacted by the top die during the die-closing process. At die closure, the movable portion was retrieved to its position and a sound part was formed.

It is obvious that the mechanism for the movable portion of the lower die provides a better binder-wrap in the cup area before the punch moves down. However, the optimum amount of additional metal provided is yet to be determined. The optimum amount of metal is defined as that with which the split defect can be eliminated without causing unacceptable wrinkles. In the present study, a simple calculation which limited the average elongation of cross-sections at the cup area to a maximum value of 20% was performed to determine this amount. According to the calculation, the movable portion of the lower die should raise 300 mm at the closure of blank-holder to provide the proper amount of metal for the cup area.

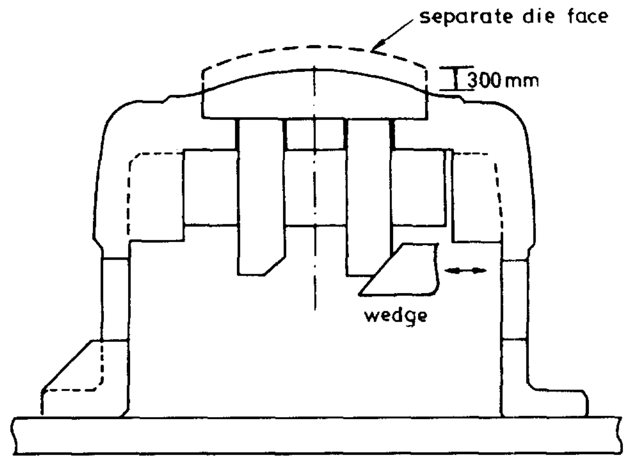

Fig. 15. The separate die face and the wedge mechanism.

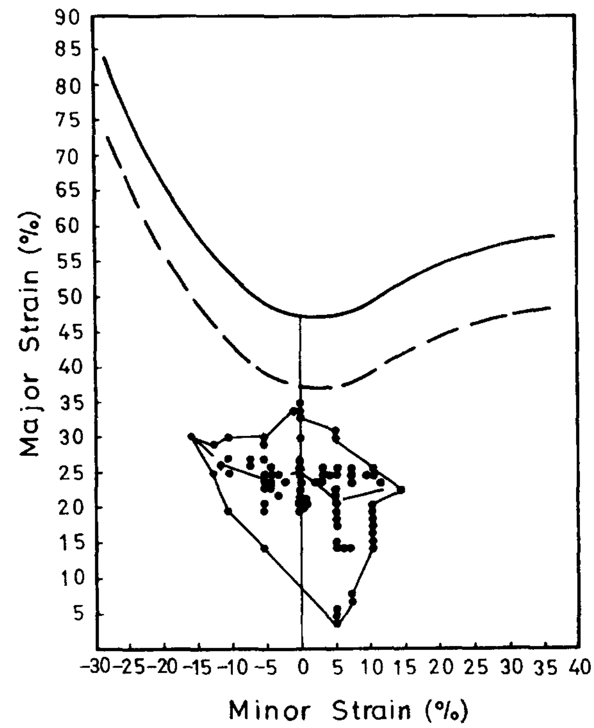

Fig. 16. Measured strains for the first draw of the optimum die design.

6. Results and discussion

A modified lower die frame corresponding to the above calculation was manufactured to validate the optimum die design. As a result, rear floor panels with good quality were obtained using the modified dies during the try-out period. To quantify the quality, circle-grid analysis was conducted again for the formed part, the circles being scribed on the same area as they were in the original design. The major and minor strains around the cup wall where the split used to occur were measured and plotted in the forming-limit diagram, as shown in Fig. 16. As seen in this figure, all the measured strains were in the safe zone, which indicates that the first-draw operation with the modified dies is very stable and is not sensitive to process variation.

In order to make the validation more complete, circle-grid analysis was performed for the second-draw operation also. In addition to forming the ribs in the panels, as shown in Fig. 1, the second-draw operation also sharpened the corner radii at the root of the cup. Thus, the second draw would stretch the cup area a little. The major and minor strains measured in the first draw and the second draw at the cup area are shown in Fig. 17. It is

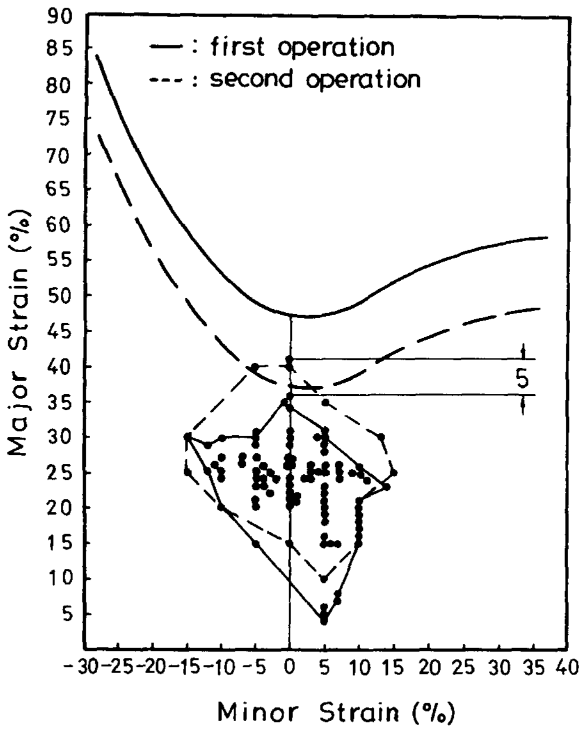

Fig. 17. Measured strains for the first- and second-draws of the optimum die design.

seen clearly in Fig. 17 that the strains are higher in the second draw, as is expected. Although several strains are in the marginal zone, most of the strains stay in the safe zone. Since the number of points falling into the marginal zone is small and their strains are still close to the design curve, the second-draw operation can also be considered stable. As for the third and forth operations, only triming and simple flanging processes are involved. Therefore, these two operations do not cause any further deformation, and need not be analyzed.

7. Summary and conclusions

A split-defect occurring in the cup area of a one-piece rear floor panel for a passenger car has been investigated in the present study. The split-defect is caused by the restraint of metal flow towards the cup area due to the long distance between the cup wall and one side of the blank-holder. In order to cope with this problem, a separate die face and a wedge mechanism were designed for the lower die to provide the binder-wrap with more metal near to the cup area at the closure of the blank-holders. The proposed die design was validated by the good-quality panels produced and also was proven cost-effective, since no extra operations were needed. This novel design showed that the optimum shape of the binder-wrap can be obtained not only by employing the proper blank-holder surface but also by changing the other components of the die face.

It is well known that circle-grid analysis (CGA) is a very useful tool in the analysis of the problem of splitting. In the present investigation, the cause of the split-defect occurring with the original design has been identified from the CGA results. Also the CGA performed for the first- and second-draw operations has shown that the optimum die design leads to a stamping process which is not sensitive to process variations, and thus the stability of the stamping process is indicated.

The 3-D finite element simulations also confirmed the analysis for the original die design. Since there is no limitation of the die geometry imposed on the 3-D finite-element analysis, the actual stamping process can be simulated more accurately. Hence, 3-D finite-element simulations can replace actual die try-outs, resulting in substantial savings in tooling cost and delivery time. A feasibility study using 3-D finite-element simulation performed in the present investigation for a modified die design has demonstrated this advantage.

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References

[1] S.P. Keeler, SAE paper 650635 (1965).
[2] Z. Marciniak and K. Kuczynski, *Int. J. Mech. Sci.*, 9 (1967) 609–620.
[3] R. Arrieux and M. Boivin, Ann. *CIRP*, 31(1) (1987) 195–198.
[4] B.R. Deis, SAE paper 900279 (1990).
[5] S.P. Keeler and W.A. Backofen, *Trans. ASM*, 56 (1963) 25–49.
[6] W.G. Brazier and R.W. Thompson, SAE paper 850274 (1985).