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Integration of CAD/CAM/CAE/RP for the development of metal forming process

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Abstract

In order to reduce lead-time and investment cost for the development of metal forming processes, the technological fusion of VP&M (virtual prototyping and manufacturing) and PP&M (physical prototyping and manufacturing) with the concept of concurrent engineering is needed. In this paper, the technology integration of CAD/CAM/CAE, as a part of the practical VP&M methods, and rapid prototyping and manufacturing (RP&M), as a part of the practical PP&M methods, in metal forming is investigated in order to improve the efficiency of development of trial products and dies for metal forming processes. The technology integration does not necessarily require fabrication of conventional trial dies and parts including drawing, machining and final treatments. The technology integration can also consider the process characteristics such as geometrical complexity, effects of the process parameters, flow pattern of workpiece, deformation induced defects, etc., so that it could reduce the trial-and-error in the design stage. Hence, the technology integration enables a remarkable shortening of the lead-time for development of metal forming processes and investment cost for the period. The integrated technology is examined by case studies such as a spider forging, preform design of a rib-web part, extrusion of a triple-connected rectangular tubular section and underframe part for a railroad vehicle, and deep drawing of a clover punch. As a result of the studies, it was verified that the technology integration could be effectively applied to various metal forming processes and reduce remarkably the lead-time and cost of the process.

Keywords: Concurrent engineering; Virtual prototyping and manufacturing; CAD/CAM/CAE; Physical prototyping and manufacturing; Rapid prototyping and manufacturing; Technology integration

1. Introduction

Recent trends of manufacturing industry can be characterized by the flexibility and complexity of products due to rapid development of manufacturing technology and various preferences of customers. The trends and increasing competition require fast and cost effective development of high quality products, and rapid changes in design and functionality to meet market demand. Especially, design and manufacturing of trial products and dies, which require a long lead-time due to so many trial-and-error during the development, holds the key to the reduction of lead-time and investment cost [1]. Metal forming is deeply related to the general framework of design and manufacturing, so that a new manufacturing technology with a concept of concurrent engineering is necessary.

A new manufacturing technology includes styling, design, analysis, prototyping, testing and manufacturing. The basic concept of concurrent engineering is that all activities related to product development procedures are to proceed simultaneously and they should be addressed from the beginning as an integrated set. Concurrent engineering makes it possible to reduce development time and investment cost, as well as to improve quality of the product. Moreover, it can be effectively connected with virtual prototyping and manufacturing (VP&M) technology including CAD/CAM/CAE and physical prototyping and manufacturing (PP&M) technology including rapid prototyping/tooling/manufacturing.

VP&M technology has advantageous features: easy understanding of products to be manufactured and a systematic investigation of the effects of the process parameters and part configuration from the design stage [2].

PP&M technology has advantageous characteristics: evaluation of the geometrical conformity and styling, ergonomic studies, manufacturability check, and other functional testing [3]. The technical connection between VP&M and PP&M is thus keenly required in metal forming.

Schreiber and Clyens [4] fabricated laminated blanking tools using the laser-cut sheet. Walczyk and Hardt [5] developed a new rapid tooling (RT) method for sheet metal forming die using a closed loop sheet metal forming system

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with finite element analysis (FEA), rapid fabrication machine, laser CMM, etc. Park and Yang [1] investigated a concurrent engineering approach to the die design for metal forming process using rapid prototyping and FEA. Park et al. [6] investigated the development of prototyping and die/mold manufacturing technology using rapid prototyping (SLA). Chua et al. [2] made a comparative study for VP and RP with respect to their relevance in product design and manufacturing. Kuzman et al. [7] developed the rapid sheet metal process development chain supported by laser sintered active tool parts. Kuzman et al. [8] investigated the integrated technology with RP and CAE in mould manufacturing. Ahn et al. [9] investigated net shape manufacturing of three-dimensional parts using a new RP and its applied technology.

In this paper, the technology integration of CAD/CAM/CAE, as practical VP&M methods, and rapid prototyping and manufacturing (RP&M), as practical PP&M methods, in metal forming is investigated in order to improve the efficiency of development for trial products and dies for metal forming processes. The technology integration is applied to both bulk and sheet metal forming. By comparing the results of CAD/CAM/CAE with those of RP&M, the number of trial-and-error has been reduced effectively. The results have been successfully reflected in the process modification procedure.

2. CAD/CAM/CAE and RP in the metal forming

2.1. CAD/CAM/CAE

CAD/CAM/CAE technology, including simulation, in metal forming is effectively used to design the process and die, to investigate the effects of process parameters, to acquire high quality products, and to reduce manufacturing cost utilizing a virtual model [10].

The design of the process and die, and effects on process parameters are examined by:

(1) checking the mechanical form, fit, interference, and assimilability [2],
(2) investigating strain/stress distributions, flow patterns and dimensions of final shape,
(3) investigating flow induced defects and temperature distributions in the final shape.

The improvement of product quality is examined by investigating microstructure and grains in the products. It is possible for the reduction of manufacturing cost to decrease tryouts, rejects and lead-time [10].

2.2. Rapid prototyping and manufacturing

RP&M technology, including RT, has advantageous characteristics that can directly fabricate a three-dimensional part from the CAD data in a CAD/CAM environment, and also the technology can rapidly manufacture plastic and metal parts indirectly or directly using RT and RM [3].

Hence, RP&M technology in metal forming is used to rapidly examine and verify the CAD/CAM/CAE results and to prove the process concept and die design utilizing a physical model. In addition, RP&M is used to fabricate rapidly the prototype tools based on the CAD/CAM/CAE results in order to perform the functional testing successfully.

The verification of CAD/CAM/CAE results and proof of the concepts are examined by:

(1) visualizing the die shape and deformed shape,
(2) checking manufacturability, including verification of tooling design, assemblability and reliability, and styling using a physical model,
(3) comparing the experimental results with the results of simulation.

RP&M technology is influenced by the complexity of shapes due to its fabrication principle, so that lead-time and cost are drastically reduced.

2.3. Integration of CAD/CAM/CAE and RP&M

CAD/CAM/CAE and RP&M technology have highly advantageous characteristics described in Sections 2.1 and 2.2, so the integration of two technologies can supply a good solution to reduction of time and cost in the stage of development. The integration procedure is shown in Fig. 1.

The key technologies are the generation of input data for a CAM system using CAD/CAE data and the fabrication of products and tools. In general, the standard input of CAM system for RP&M apparatus is .stl format with a group of triangular facets on the surface of objects. Commercial CAD software, for example, CATIA, I-DEAS, Pro-Engineer, Solidworks and so on, have their own module for data translation, so that the translation of CAD data into .stl format can be easily implemented.

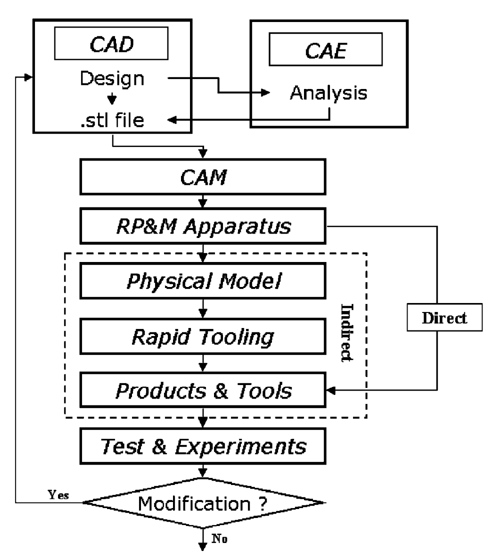


Fig. 1. Integration procedure of CAD/CAM/CAE and RP&M.

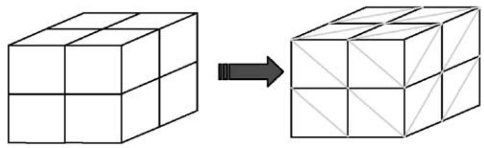


Fig. 2. Schematic representation of translation of hexahedral meshes into triangular faces.

Table 1
C (kpsi) and m values of the flow stress relation for AISI1025 (strain rate range, 3.5–30)

Strain	980 °C		1090 °C		1205 °C	
	C	m	C	m	C	m
0.25	33.7	0.004	16.2	0.075	9.3	0.077
0.50	41.4	−0.032	17.2	0.080	9.6	0.094
0.70	41.6	−0.032	17.5	0.082	8.8	0.105

The conversion of CAE results to .stl format requires special techniques. Because the intermediate shapes of a workpiece in the format of a finite element mesh data are obtained from CAE results, the conversion utilizes the mesh data in each analysis step. Firstly, the surface boundary is extracted from the solid mesh such as hexahedral or tetrahedral mesh, in order to obtain a shell mesh (Fig. 2). Then, the facets of the rectangular shell mesh are divided into triangular facets are stored in .stl format.

The die data are generally generated from CAD data except for a special purpose such as investigation of surface defects and die deformation during forming. The workpiece data are generated from CAE results except for the initial data.

Typically, the die and the workpiece are metallic, so that the experimental tools and initial billet should be also metallic so as to realistically undergo functional testing and experiments. The tools and products can be manufactured directly in the RP&M apparatus, for example SLS, and indirectly using RT technology such as lost wax casting, spray metal tooling, etc. The indirect tooling technology includes multiple steps of reversals to produce metallic parts.

In general, it is preferable to select the indirect RT due to dimensional accuracy, surface roughness and strength of parts comparing with the direct RT.

3. Applications of the technology integration in metal forming

3.1. Spider forging

In the CAE results, it is hard to check the characteristics of deformation and the defects at the corner and at a refined local region. RP&M technology may facilitate the solution by means of the physical model of the CAE results. The spider is selected to verify the deformation pattern and any existence of deformation induced defects during forging.

The spider is one of the important components of automobiles. In CAE, considering the symmetry of the spider, only one-eighth of the whole workpiece has been simulated. The workpiece material is AISI1025, and is assumed to have the isothermal condition under constant temperature of 1200 °C during the deformation process. The flow stress of the workpiece can be written as Eq. (1), and the values of C and m are listed in Table 1.

Hexahedral elements have been used in the FE analysis, and Hexagen [11], generating surface elements layers which conform the boundaries of the workpiece geometry, is adapted in the meshing and re-meshing process:

$$\bar{\sigma} = C\dot{\bar{\varepsilon}}^{m} \quad (1)$$

The simulation was carried out using Formsys 3D, which is a rigid–plastic FEA code. The results of CAE were selected in several stages such as 25, 65, and 80% height reduction and the final stage. Fig. 3 shows the deformed structure of mesh at each stage.

The deformed shapes at each stage were fabricated from laminated object manufacturing (LOM) apparatus. The input data of LOM for the deformed stages were obtained from the translation of CAE results, which is described in Section 2.3. Fig. 4 shows the fabricated shapes at each step. From the investigation of those three-dimensional physical parts, it was confirmed that no defect occurs in the forging process.

The total build time of all LOM parts was within 50 h. Considering the model test and real test, which require a long lead-time due to drawing, machining and final treatments of a metal die set and plasticine experiment, the total build time of all LOM parts is negligible.

From the results of this case study, it was considered that the integrated technology was an effective solution to solve a long lead-time and high cost in the development stage.

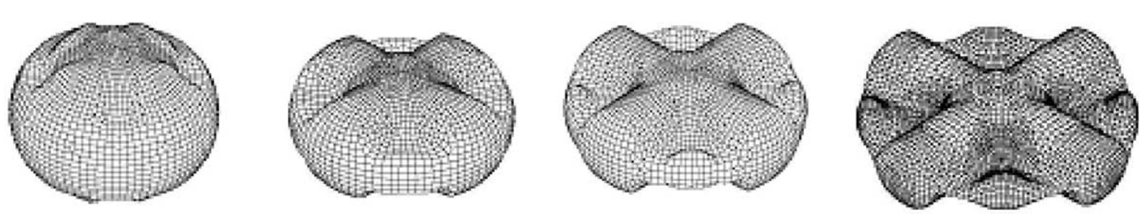
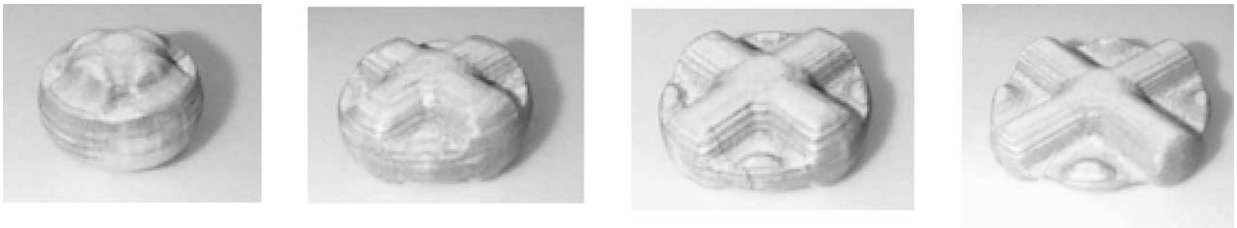


Fig. 3. Deformed shapes at each stage: (a) 25% height reduction; (b) 65% height reduction; (c) 80% height reduction; (d) final shape.



(a) 25% height reduction (b) 65% height reduction (c) 80% height reduction (d) final shape

Fig. 4. Physical models for each stage (LOM parts): (a) 25% height reduction; (b) 65% height reduction; (c) 80% height reduction; (d) final shape.

3.2. Preform design of rib-web

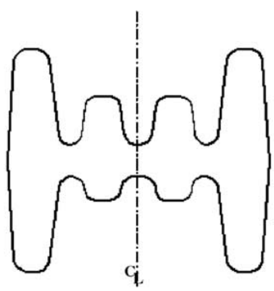
RP&M technology can be applied to preform design of forged parts. The forged part has a complicated geometry, so that it is necessary to perform the preform forming at several stages. The preforms induce better flow of metal during deformation, reduce the flash of the remainder of metal and decrease the amount of wear of dies.

Even though there has been several developments of preform design with acceptable engineering assumptions, in most companies, the preform is designed by the experience of a designer or repeated experiments. Lee et al. [12] proposed a new method using an analogy between the equipotential line at specified voltage value and the shape of the preform in a two-dimensional axisymmetric forging process.

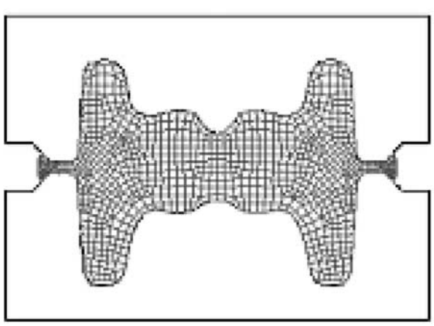
In this work, the neural network was used to find the initial volume ratio (r_V) and the potential value (Φ) of the electric field. To obtain the training data for the neural network, FEA was carried out using Formsys 3D. The workpiece material is AISI1015 and the initial temperatures of the workpiece and the die are 1300 and 250 °C, respectively. The ram speed is set at 10 mm/s.

The simulation is performed for the two-rib type product. The final shape of the forged part is shown in Fig. 5(a). Based on the results of the neural network, the preform shape was proposed (see Fig. 5(b)). The results of FEA with the preform are shown in Fig. 5(c). From the results of FEA, it was found that the dies are completely filled with workpiece material.

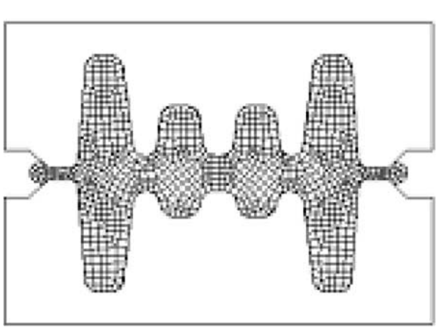
The model experiment was carried out to predict material behavior and to verify the CAE results with lower cost and time. In this experiment, plasticine was used as the model material and the dies were fabricated by LOM process. Fig. 6



(a) Final shape of forged part



(b) Result of preform stage



(c) Result of final stage

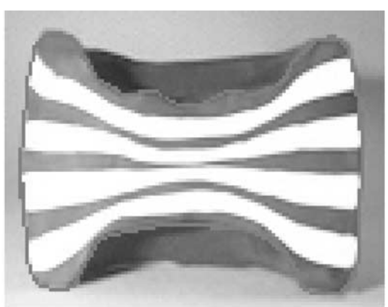
Fig. 5. Final shape and result of FE simulation: (a) final shape of forged part; (b) result of preform stage; (c) result of final stage.

Fig. 6. Experimental die (bottom part).

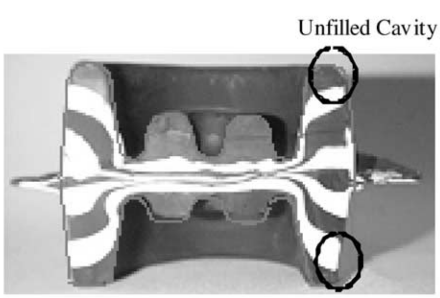
shows the fabricated die (bottom part). In general, the experiments using plasticine employ a plastic die set, which requires a long lead-time due to necessity of drawing, machining and final treatments. But, the LOM dies were used in this experiment, so that the total time of the experiment was highly reduced. The build time of the die set was 15 h and the experiments were finished within an hour.

Using the die sets, the model experiments were performed for two cases: the first without preform stage, the second with preform stage (Fig. 7(a)). The result of the first case is shown in Fig. 7(b). It was shown that incomplete filling and undesirable material flow occurred. The result of the second case is shown in Fig. 7(c). It is verified that the die cavity is filled completely to form a final shape and the material shows even and desirable material flow.

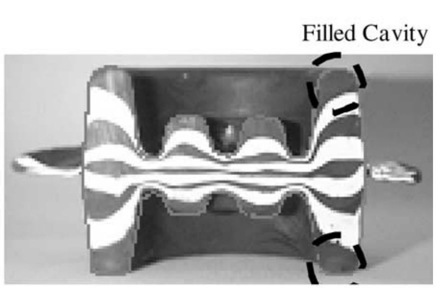
Through this study, it was confirmed that the integrated technology was effectively applicable to preform design and experiments for verification of the preform design.



(a) Preform



(b) Without preform



(c) With preform

Fig. 7. Result of model experiments: (a) preform; (b) without preform; (c) with preform.

3.3. Extrusion

The extrusion process has been applied to the manufacture of round or complicated sections and has continuously widened its area of application in the metal forming industry. In order to produce defect-free products of desirable quality in strength, surface and geometric dimension, the analysis of extrusion processes is required for proper design of the process. The importance of CAE for extrusion processes lies in the determination of forming load, flow characteristics, temperature distribution and state of stress and strain. From such information, the necessary design specifications and data are obtained for the design of dies, punches, and die setup, etc. Eventually, the material properties of products can then be controlled effectively. In recent years, owing to the development of CAD/CAM/CAE and RP&M technology, more detailed information can be obtained from the integrated method of computation and prototyping. In general, the tools of extrusion requires very long lead-time to manufacture due to large size and complicated geometry.

In the present work, various industrial extrusion problems will be simulated by Formsys 3D employing efficient numerical schemes such as arbitrary Lagrangian–Eulerian finite element method and mismatching refinement with domain decomposition. Moreover, the RP&M techniques are applied to easily understand the complex extrusion process. Selected applications are extrusion of a triply connected rectangular tubular section and the underframe part of a railroad vehicle.

3.3.1. A triple-connected rectangular tubular section

Let us consider three-dimensional extrusion of a triply connected rectangular tubular section as shown in Fig. 8. The ram speed is set as 3 mm/s and the friction factor is

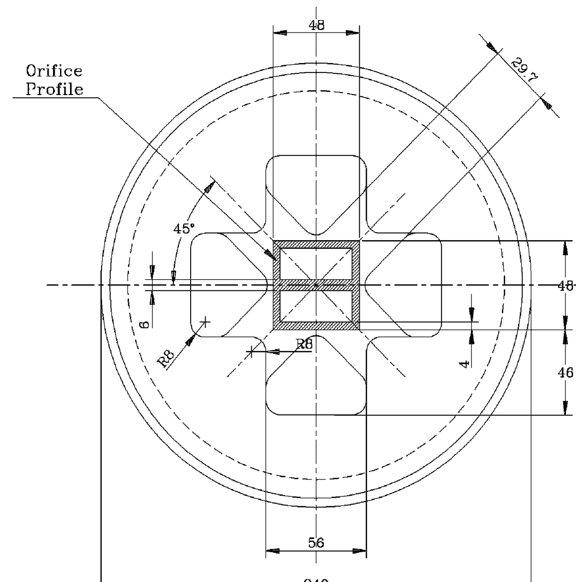
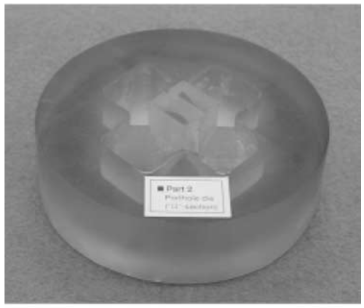
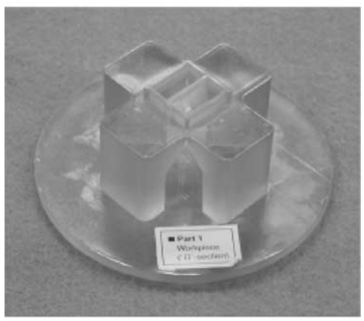


Fig. 8. Extrusion of a triply connected rectangular tubular section.



(a) Extrusion die



(b) Extruded part

Fig. 9. SLA parts of die and part for a triple-connected rectangular tubular section: (a) extrusion die; (b) extruded part.

taken to be 0.3. The workpiece material used in simulation is Al2024, and the working temperature is taken to be 400 °C.

The example has complicated geometry in CAD data, so that the physical models of the die and part are fabricated from SLA. The .stl format of the die and part is generated directly from the CAD data. Fig. 9 shows the fabricated shape of a die and a part. Using the physical model, the geometrical characteristics and flow pattern of the workpiece were investigated. Through the investigation, the concept of mesh generation and techniques of CAE analysis for the example was determined.

CAE analysis was carried out for a steady-state isothermal assumption using the Formsys 3D with mismatching domain decomposition [13]. Considering the symmetric condition of the geometry, only a quarter section of the workpiece is analyzed. Fig. 10 shows mesh configuration decomposed into two subdomains with mismatching refinement. The number of DOFs for each subdomain is 3624 for subdomain 1 and 14770 for subdomain 2, respectively.

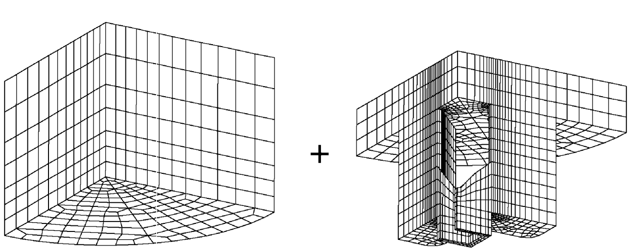


Fig. 10. Mesh configuration with mismatching refinement.

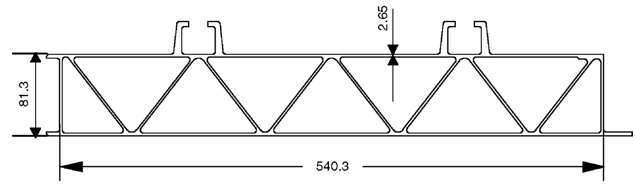


Fig. 11. Sectional view of the underframe part of a railroad vehicle.

Through this example, it was considered that the integrated technology could propose an effective solution to analysis of extrusion process with a complicated geometry.

3.3.2. Underframe part of a railroad vehicle

In this section, the industrial extrusion process for a railroad vehicle is considered. Fig. 11 shows the cross-sectional view of the underframe part of a railroad vehicle that includes nine holes. It was manufactured by the welding chamber method using porthole dies. The workpiece is divided into five subdomains as shown in Fig. 12 such as: (i) initial billet; (ii) workpiece around the porthole; (iii) workpiece in the porthole die; (iv) workpiece in the welding chamber and the feeder; and (v) extruded part through the die bearing.

In order to observe the complex process effectively, the physical models for the workpiece were fabricated from SLA and fused deposition manufacturing (FDM), respectively. Fig. 13 shows a total deformed shape from stages 1 to 5 and the extruded shape in stage 3.

Using the physical models, the geometrical characteristics and flow pattern of workpiece were considered. As a result

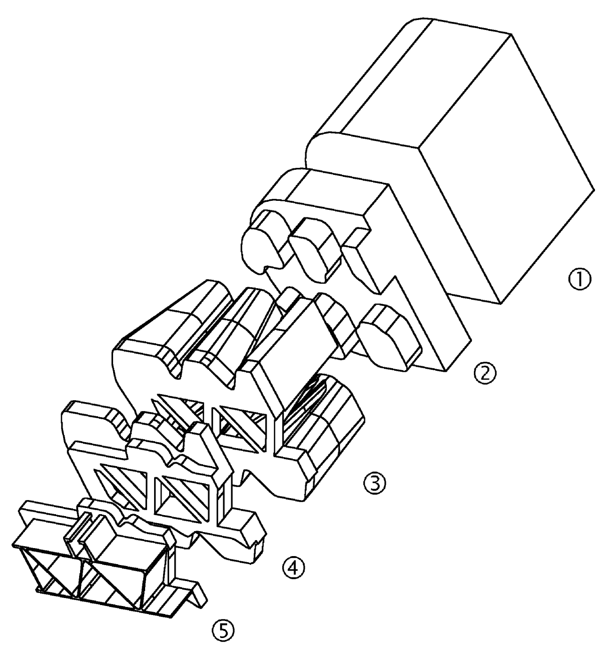
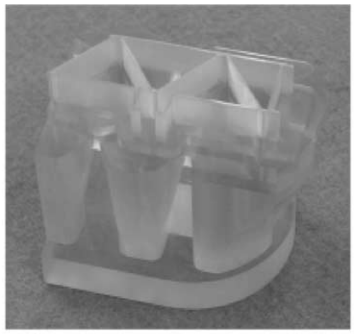
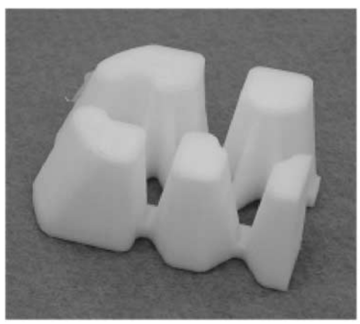


Fig. 12. CAD model of five subdomains.



(a) Deformed shape from stage 1 to stage 5 (SLA part)



(b) Deformed shape at stage 3 (FDM part)

Fig. 13. Physical models of the deformed shape at each stage: (a) deformed shape from stages 1 to 5 (SLA part); (b) deformed shape at stage 3 (FDM part).

of the consideration, it was found that it is difficult to generate three-dimensional mesh using hexahedral elements for such a complicated shape. Since all subdomains except for subdomain 3 have $2\frac{1}{2}$-dimensional characteristics of geometry, the three-dimensional meshes for the subdomains were easily constructed by the customary mesh generation scheme: (i) the two-dimensional mesh generation scheme and (ii) the three-dimensional extension of the two-dimensional mesh. Fig. 14 shows three-dimensional mesh structures for subdomains 1, 2, 4, and 5.

The discretization of subdomain 3, however, was almost impossible by the foregoing mesh generation scheme since it has a very complicated geometry. In this work, the modified grid-based approach with surface element layers and core mesh [7] was implemented. Fig. 15 represents the whole mesh structure for subdomain 3. For the analysis, the ram speed is 2 mm/s and the friction factor is taken to be 0.2. The

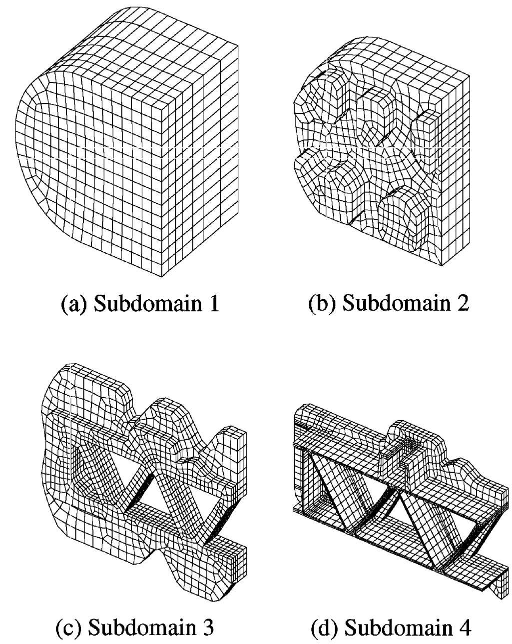


Fig. 14. Three-dimensional mesh structures: (a) subdomain 1; (b) subdomain 2; (c) subdomain 3; (d) subdomain 4.

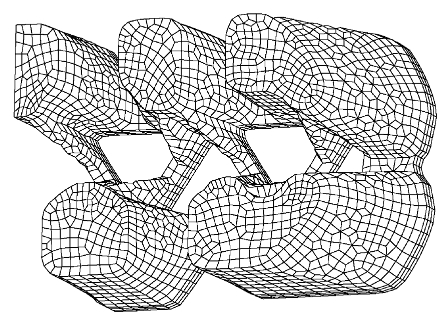
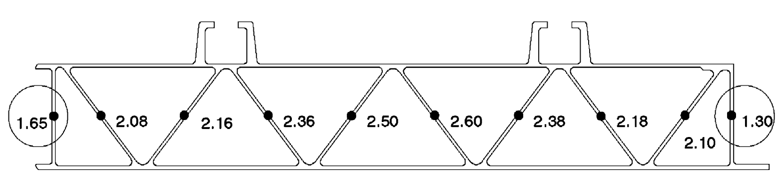
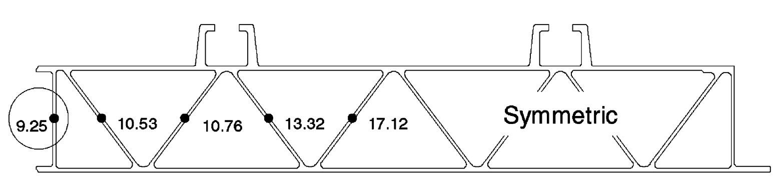


Fig. 15. Mesh structure for subdomain 3.



(a) Rib thickness (mm) (Measurement)



(b) Axial velocity components (mm/sec) (Analysis)

Fig. 16. Comparison of the measured data with the analyzed results: (a) rib thickness (mm) (measurement); (b) axial velocity components (mm/s) (analysis).

workpiece material is Al6065, and the working temperature is taken to be 500 °C.

In order to verify the results of the CAE analysis, an experiment was carried out. The extrusion process of the underframe part was carried out by using a 8000 t extrusion press. For the extruded part, the measured data of the rib thickness was compared with the axial velocity components, which were obtained from the CAE analysis, at various positions as shown in Fig. 16. It seems that the velocity distribution shows the similar tendency as that of the measured rib thickness. It was concluded that the analysis results could be reflected on the die design process by estimating the distribution of axial velocity at the outlet.

Through this example, it was considered that the integrated technology could supply an effective solution to analysis of the extrusion process with a complicated geometry.

3.4. Deep drawing

In designing the products of sheet metal, a large number of experiments and simulations are required in order to verify the process parameters. In order to design the die and punch with good formability, forming simulation is widely performed in CAE. For the sake of rapid verification of the design parameters optimized by CAE, the experiments should be done with a real die and a punch for the case using specific parameters. Because the punch load and pressure in the sheet metal forming are relatively small, the die sets do not need a high strength material. Hence, sheet metal forming is a suitable example to apply RP&M to functional testing and physical experiments.

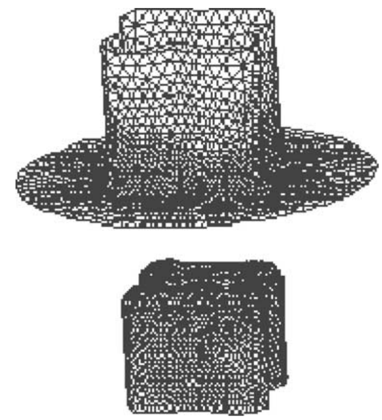


Fig. 17. FE meshes for punch and die of clover shape.

In this work, the integrated technology was applied to a deep drawing process. Fig. 17 illustrates the finite element meshes for the CAE of a clover shape. Because surfaces of the mesh were constructed by triangular elements, they could be easily transferred to the .stl format. The deep drawing process has been simulated by the implicit time integration scheme considering the planer anisotropy. The results of CAE are shown in Fig. 18. The diameter of the initial blank is 95 mm and the thickness is 0.7 mm. As a result of the CAE, the die parameters such as dimensions of major axis and minor axis, and shoulder radii of the punch and the die can be determined optimally.

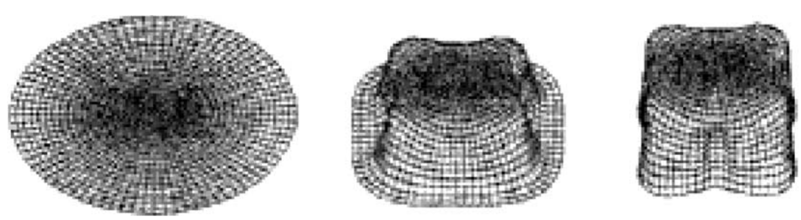


Fig. 18. CAE results (deformed shapes): (a) initial blank; (b) stroke, 20 mm; (c) stroke, 35 mm.

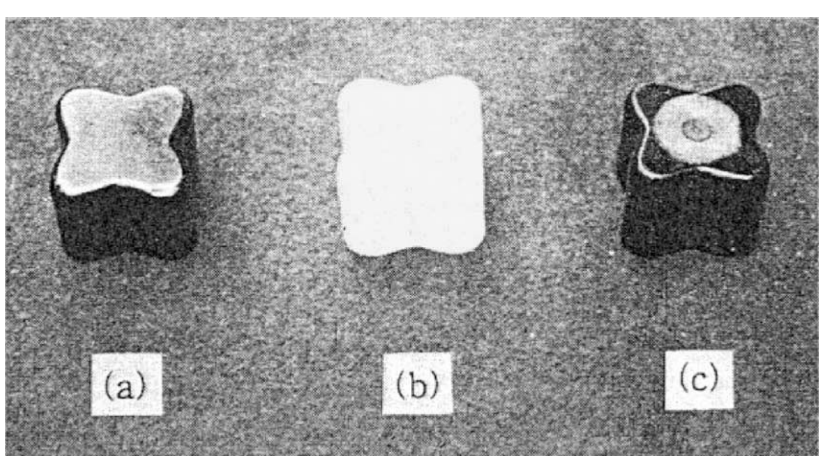


Fig. 19. Clover punch products: (a) steel punch; (b) SLA part; (c) epoxy punch.

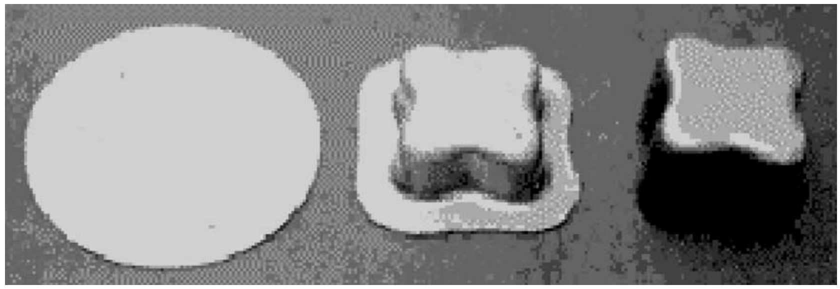


Fig. 20. Experimental results (deformed shapes): (a) initial blank; (b) stroke, 20 mm; (c) stroke, 35 mm.

Table 2
Mechanical properties of RT-432

Compressive strength (kgf/mm^2)	10–12
Tensile strength (kgf/mm^2)	6–8
Impact strength (kgf/mm^2)	4.5–5.5

In order to verify the results of CAE, experiments were carried out. The punch and the die were fabricated from SLA and RTV molding. Master patterns of the punch and the die were fabricated from SLA and the experimental punch and die are manufactured by RTV molding technique based on epoxy resin (RT-432) mixed steel powder using master patterns. The .stl data were prepared from finite element mesh data. Fig. 19 shows the punches: a steel punch (Fig. 19(a)), an SLA punch (Fig. 19(b)) and an epoxy punch (Fig. 19(c)). The resin has good mechanical properties and wear resistance as shown in Table 2. Furthermore, mixing steel powder, it was sufficient to use as a punch in some sheet metal forming processes. Fig. 20 shows the deformed shapes at each stage, which was in good accordance with the result of the CAE. It could be concluded that the deep drawing process using the punch and the die made by the aforementioned process was successful with the given conditions.

4. Conclusion

In this paper, the technology integration of CAD/CAM/CAE and RP&M for the development of metal forming process has been discussed. The technology integration does not necessarily require the fabrication of the conventional trial dies and parts including drawing, machining and final treatments. The technology integration can also consider the process characteristics such as geometrical complexity, effects of the process parameters, flow pattern of the workpiece, deformation induced defects, etc., so that the trial-and-errors can be reduced in the design stage. Hence, the technology integration shortens remarkably the lead-time for development of metal forming processes and the investment cost during development.

The integrated technology was examined by some case studies such as spider forging, preform design of a rib-web part, extrusion of a triple-connected rectangular tubular section and underframe part for a railroad vehicle, and deep drawing of a clover punch. As a result of the studies, it has been shown that the technology integration can be effectively applied to various metal forming processes and can reduce remarkably the lead-time and cost of the processes.

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