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THE ART of SHEET FORMING SIMULATION TECHNOLOGY in JAPAN

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Japan.

Recently the sheet forming simulation technology revealed great progress in the sense of practical application in the automotive, electric/electronics and aviation/space industries. The goal of sheet forming simulation is to embedded in the design engineering system which is consisted by the analysis and synthesis modules. This design simulation system predicts the slackness of sheet and estimate the formability, and search the optimum material/forming/structure conditions. This OVER-ALL OPTIMUM DESIGN can be classified as follow;

1.ANALYZING PROCEDURE: Numerical simulation based on nonlinear theories -geometry, material and friction nonlinearities-
2. OPTIMIZATION PROCEDURE: Optimum design based on mathematical programing and AI technologies, those are implemented in CAD/CAM/CAE System - Concurrent Engineering System-.

In this paper, four subjects will be discussed; (1) State of arts of computer simulation technologies in Japan. (2)History of sheet forming simulation. (3) Benchmark problems. (4) Future technology in the sheet forming simulation.

1. State of arts of computer simulation technologies in Japan.

In this ten years, the metal forming process simulation, in the material / manufacture/structure design, reveals the great progress based on the computer hardware and software technology development. Especially computer and network engineering contributes this progress very much. Table 1 shows how the simulation technology developed in the past and future. In the future, the requirement will be more complex and high demanding, therefore the simulation paradigm should shift from high efficiency mass production engineering to the simultaneous engineering system by integrating independent/diverge and integrated/harmonized technologies. As shown in Fig. 1, automotive industries implemented these computer simulation modules conjunction with COMPUTER GRAPHICS technology in VIRTUAL REALITY world, which is created in computer space. The forming simulation is combined with car body designing, die designing and NC machining, before the real forming process as shown under half of Fig.1. Fig. 2 shows VIRTUAL MANUFACTURING in VIRTUAL FACTORY generated by the computer simulation technology. Before the real forming, the forming process assessment was completed. Trials were performed by introducing the process design factor and modifying the tool shape and die setting in the computer CAD/CAE system. Fig. 3 shows the integrated design system for MATERIAL-PROCESS/FORMING-PROCESS/STRUCTURE-STRENGTH optimization. This simultaneous design engineering will be completed by the rigorous mathematical modeling and mathematical programing scheme - ANALYSIS and SYNTHESIS - as shown in Table 2. The paradigm shift in the ANALYSIS and SYNTHESIS technology will be realized by switching from the interpolate simulation by using data-base, say expert system, to the extrapolate simulation based on the correct physical and information science modeling technologies.

Table 1

DEVELOPMENT of COMPUTER SIMULATION TECHNOLOGY

SEEDS

1. Computer Technology
2. Network Technology
3. Scientific Visualization Technology
4. Numerical Analysis Technology
5. Physics and Information Science Modeling Technology

NEEDS

1. Cover the Lack of Information obtained by Experiment
2. Reduce the Lead Time for Material/Forming/Structure Design
3. Quantitative Estimation of Manufacturing System
4. Establish the Economical Strategy for the Management
5. Harmonize the Technology with the Environment

COMPUTER SIMULATION in the FUTURE

Requirement will be more complex, high demandable, and diverged. To response this requirement, the computer technology should offer the harmonized system between independent control/diverged system and integrated control/unified system, rather than the efficient system based on the unification/standarzation, homogenization and mass treatment.

PARADIGM SHIFT

The high quality micro-processor and down-sizing of computer promise the paradigm-shift From the interpolate simulation -LEARNING SIMULATION- such like expert system based on the data-base searching, to the extrapolate simulation -CREATIVE SIMULATION- by employing the physical and information science modeling technologies

Table 2

COMPUTER SIMULATION for METAL FORMING

ANALYSIS

1. NONLINEAR FEM

- 1-1.Numerical Method
  - (a) explicit integration
    - static, dynamic
  - (b) implicit integration
    - static, dynamic
- 1-2. Formulation
  - updated Lagrange
  - total Lagrange
  - Euler
  - Arbitrary E-L
- 1-3. FE Model
  - (a) 3-D model
    - solid, shell
    - membrane
  - (b) 2-D model
    - plane strain
    - plane stress
  - (c) 1-D model
    - truss, line
    - beam
- 1-4. Numerical Integration
  - (a)full integration
  - (b)reduced integ.
  - (c)selective reduced integration

2.PHYSICAL MODEL

- 2-1. Material Model
  - (a) strain rate sensitivity
    - rigid/elastoplastic
    - rigid/elastoviscoplastic
  - (b)thermal effect
  - (c)yield function
    - isotopic
    - anisotropic
    - (Hill, Barlat....)
  - (d)hardening law
    - isotropic
    - anisotropy
  - (e)constitutive equation
    - associate flow law
    - non-associate flow law
    - crystalline plasticity
- 2-2. Contact Model
  - (a)friction law
    - Coulomb law
    - constant shear
  - (b)contact evaluation
    - tool featuring
    - (rigid, deformable)
    - contact force
    - (penalty method, ,kinematical descript.)

SYNTHESIS

3. INTELLIGENT CAD/CAM/CAE

- 3-1. Expert System
  - neural network
  - fuzzy control
  - GA algorithm
  - neuro-chaos
- 3-2. CAD/CAE System
  - surface model
  - solid model
  - standard CAD data
  - (IGES NURBS, STEP)
- 3-3. Data Base
  - material
  - (blank, tool)
  - lubricant
  - surface treatment
  - forming process
  - FLD criteria
  - Formability criteria
- 3-4. Networking
  - Information transfer
  - parallel strategy
  - data control
- 3-5. AI
  - numerical algorithm
  - adaptive control

4. MATHEMATICAL PROGRAMING

- 4-1. Design Parameter
  - (A) Physical Parameter
    - (a) material properties
      - elasticity(E, ν)
      - plasticity
      - (yield condition, anisotropy)
    - (b) friction properties
      - friction coefficient
      - external parameter
      - internal parameter
  - (B)Boundary Condition
    - (a) mechanical cond.
      - load, pressure
      - heat,draw-bead
    - (b) geometrical cond.
      - tool shape
- 4-2. Constraint Condition
  - (a) instability limit
    - necking, wrinkling
  - (b)formability requirement
    - spring-back
- 4-3.Objective Function
  - forming energy minimum
  - uniform deformation
  - absorbed energy max.

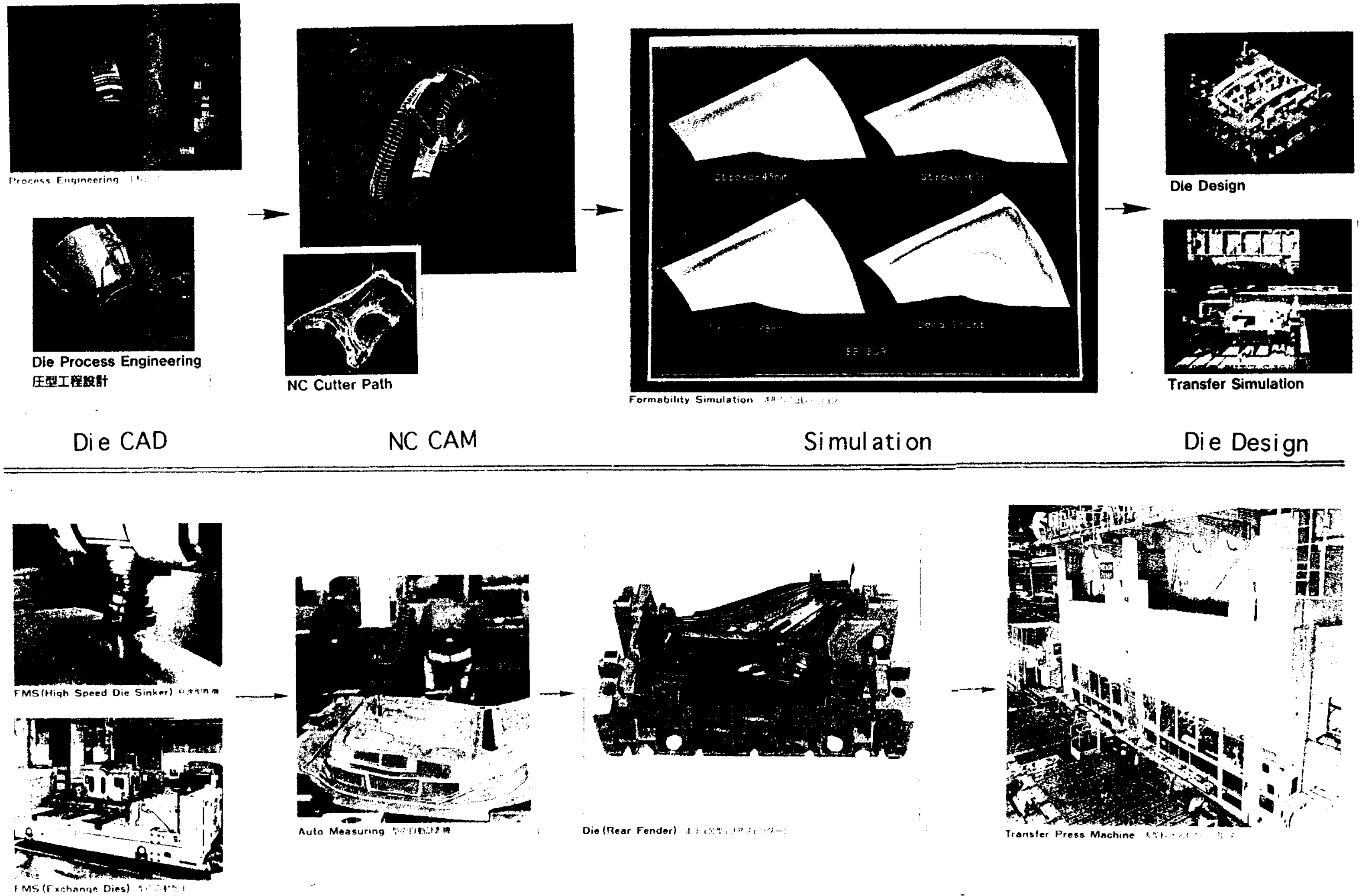


Fig.1 Computer Simulation and Real manufacturing

Nakamachi, E. (NISSAN MOTOR Co.)

Fig.2(a) The first simulation by ROBUST.
Deformed shape with thickness strain distribution.

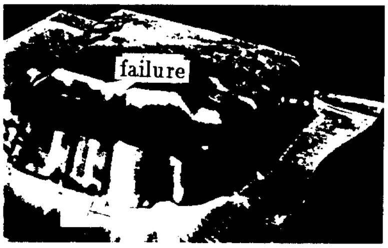


Fig.2(d) The first experimental verification.
Real stamping by using SOFT TOOL.

Fig.2(b) The second simulation by ROBUST.
Wrinkling shape by using CG.

Fig.2(e) The second experimental verification.
Open draw forming.

Fig.2(c) The third simulation by ROBUST.
Deformed shape with thickness strain distribution.

Fig.2(f) The real production result in the stamping line of MITSUBISHI MOTOR Co..

Fig. 2(g) Simulation result by OPTRIS(Dynamic Software Co.).
Before the final stage.

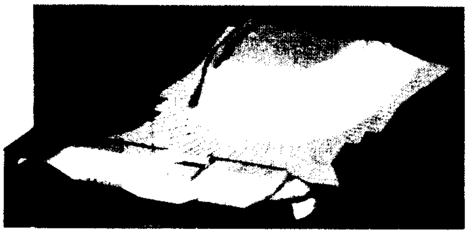
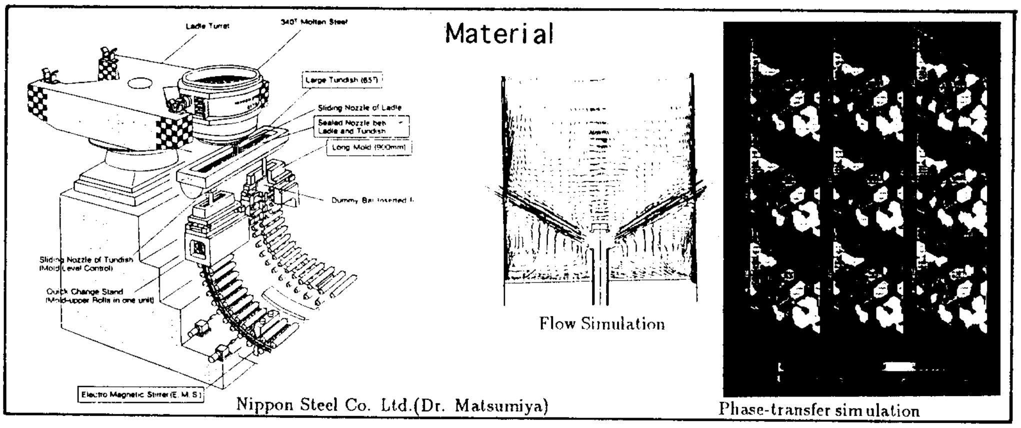


Fig. 2(h) Simulation result by OPTRIS(Dynamic Software Co.).
The final stage.

Fig. 2. Virtual Manufacturing of PAN REAR FLOOR and its experimental verification.
- The comparison with simulation results and experiments, performed in the stamping line of MITSUBISHI MOTOR Co.(H. Aoh) -.

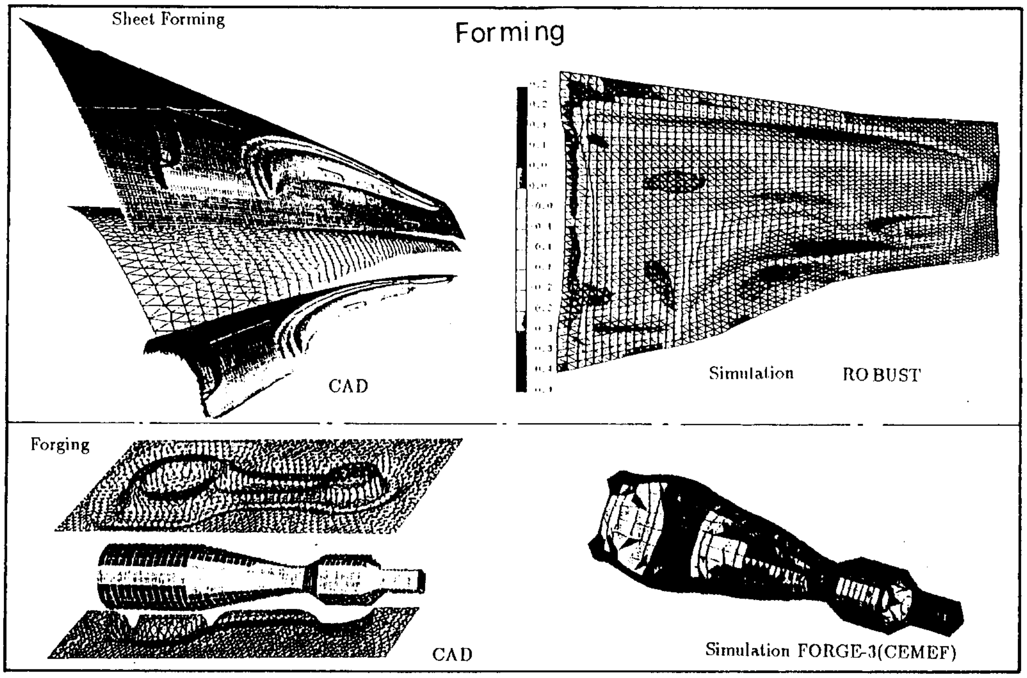


Material

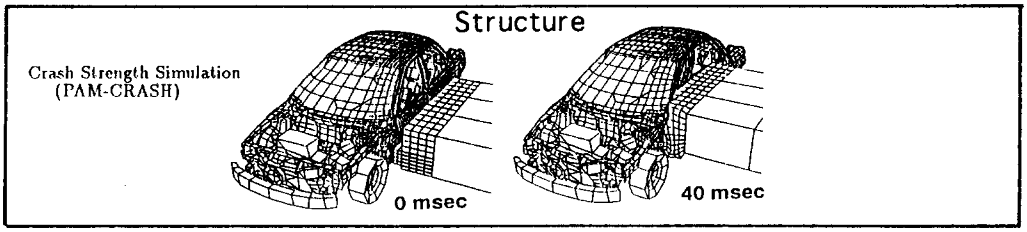
Nippon Steel Co. Ltd.(Dr. Matsumiya)

Flow Simulation

Phase-transfer simulation



Forming



Structure

Crash Strength Simulation (PAM-CRASH)

Fig.3 Integrated Design

2. History of sheet forming simulation.

In this chapter, rough sketch of the history of finite element sheet forming analyses appears. In 1978, Wang, N.M. and Budiansky, B. have analyzed the hemi-spherical punch stretch of disks by nonlinear elastic-plastic finite element method as shown in Fig. 4. After eight years blank of progress, in 1985 Toh, C. H. and Kobayashi, S analyzed the square-cup deep drawing by rigid-plastic finite element method, and also proposed the optimum design, which can be categorized the optimum design by using the inverse analysis. Until the end of 1980' s, finite element simulation has been recognized as the research tool to solve the academic problems, even there have been already the commercial base software packages, such like nonlinear finite element codes, say MARC, ABAQUS and NIKE. And also the trial to solve the real automotive panel stamping process by Stoughton in GM in USA. But still the simulation has been done independently, there was no interface between CAD data and no pass the simulation results to NC tooling in CAM system. In 1988, the big change started in the practical application for the industrial forming process simulation. Nakamachi and engineers in HONDA Co. analyzed the single action stamping process by using the CAD surface data for the tool and elastic-plastic membrane element for the blank. Fig. 6 shows the simulation results. Simultaneously, Tang, S.C. of FORD MOTOR Co. has shown the FE results of rear fender stamping by employing elastic-plastic shell element as shown in Fig. 7. Further in NUMIFORM89 conference in 1989, Honecker,A. and Mattiasson, K. presented the oil-pan forming results, which has given a shock for the automotive engineers, because of the detailed wrinkling prediction during the drawing process was appeared as shown in Fig. 8. The dynamic-explicit type finite element appeared in this conference. This DYNA-3D analysis promoted the researchers and engineers of the FE simulation to develop own or commercial base program to the actual forming process simulations. In 1990 and 1991, Tang, S.C.(Fig.9) and Aoh, H and Nakamachi, E. (Fig.10,11)applied their own FE codes to simulate the automotive panel stamping processes. From 1991, DYNA-3D, PAM-STAMP, ABAQUS-explicit, OPTRIS, RADIOSS started to apply their explicit code to the panel stamping process in automotive industries. But it started to publish after 1991 VDI FE simulation conference - 1st NUMISHEET conference-. In 1992, the more reliable and comprehensive FE program based on elastic-plastic shell element and nonlinear contact algorithm have been developed and applied to the real forming process. Makinouchi shows more accurate results of wrinkling of square cup drawing as shown in Fig.12. PAM-STAMP has shown more practical results of MAZDA panel stamping as shown in Fig. 13, which has shown the possibility to adopt FE simulation for the die designing. In 1993, NUMISHEET93 conference in Tokyo gave a chance for FE developers to meet, discuss and recognize the now situation of sheet metal forming simulation technology. Fig. 14 shows the CG output of front-fender die and also the simulation results obtained by ROBUST, Nakamachi has developed. Detailed results will appears in the following chapter.

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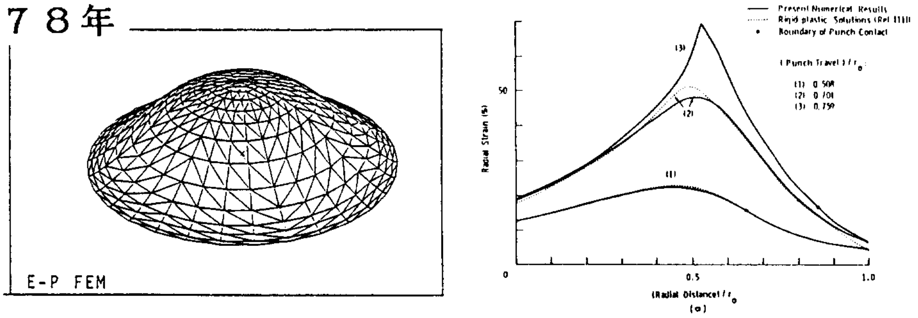


Fig.4 Wang, N.M. and Budiansky, B.

1 9 8 5 年

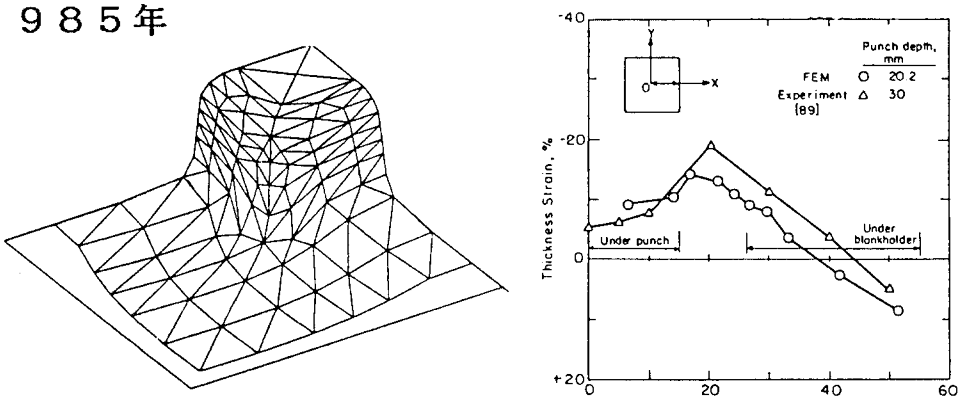


Fig.5 C.H.Toh and S.Kobayashi

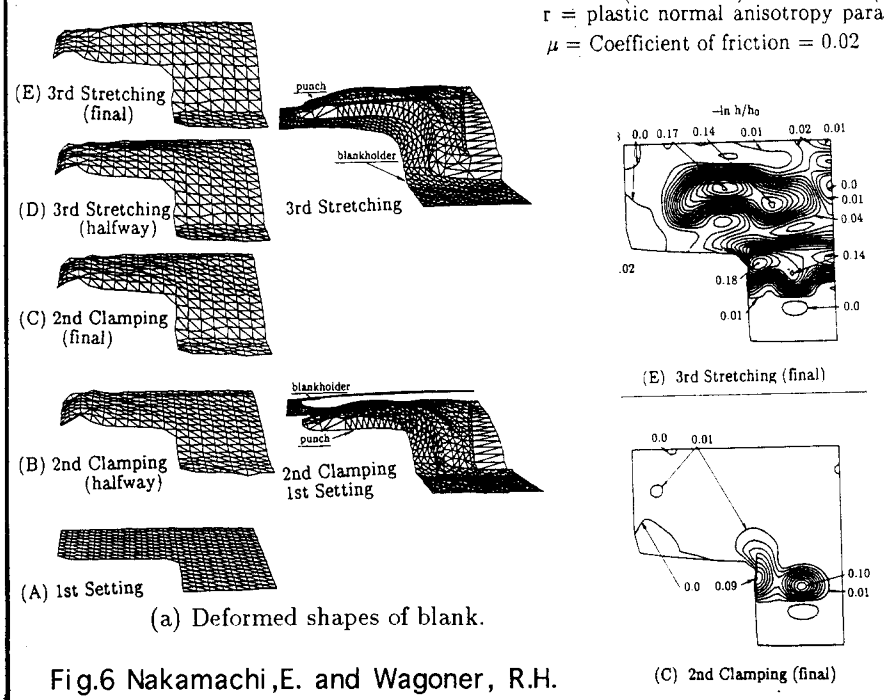
1 9 8 8 年

– Material :

$\bar{\sigma} = 425(0.0245+\bar{\epsilon}^{P})^{0.234}$ MPa (flow curve)

r = plastic normal anisotropy parameter = 1.57

μ = Coefficient of friction = 0.02



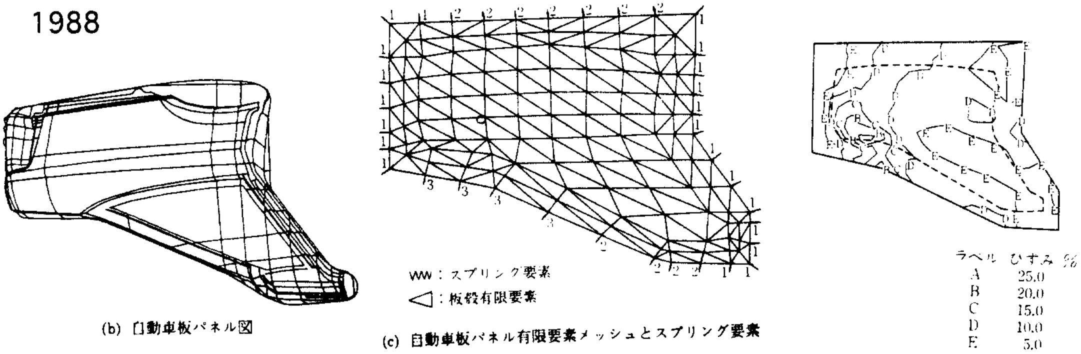
(a) Deformed shapes of blank.

(E) 3rd Stretching (final)

(C) 2nd Clamping (final)

Fig.6 Nakamachi,E. and Wagoner, R.H.

1988

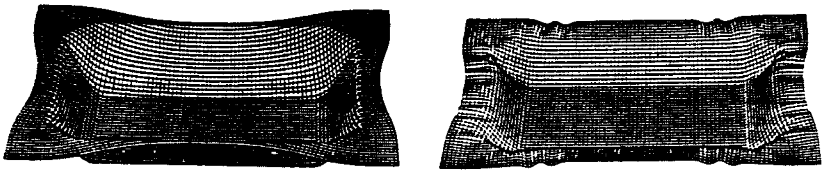


(b) 自動車板パネル図

(c) 自動車板パネル有限要素メッシュとスプリング要素

Fig.7 Tang, S.C.

１９８９年



（ i ）押圧大　　（ ii ）押圧小

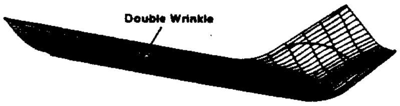
図5　オイルパンの絞りにおけるブランクホルダー部の押圧による変形の相違

Fig.8 A.Honecker and K.Mattiasson

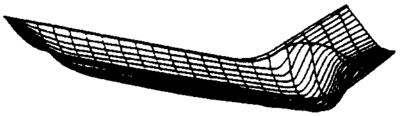
1990

(a) Binder-Wrap

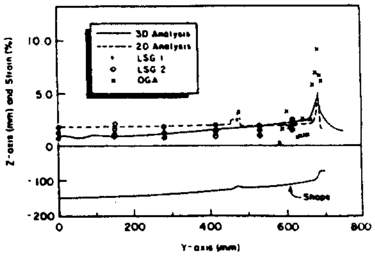
(b) 15% (38 mm) Punch Travel



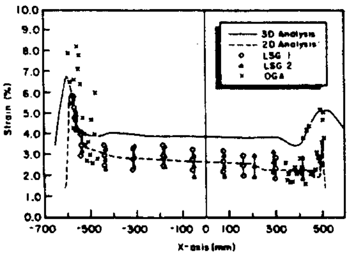
(c) 20% (51 mm) Punch Travel



(d) 85% (216 mm) Punch Travel



(a) Strains at section x = 0



(b) Strains at section y = 0

Fig.9 S.C.Tang

Comparison of strains at two sections.

1991 Nakamachi, E. and Aoh, H.

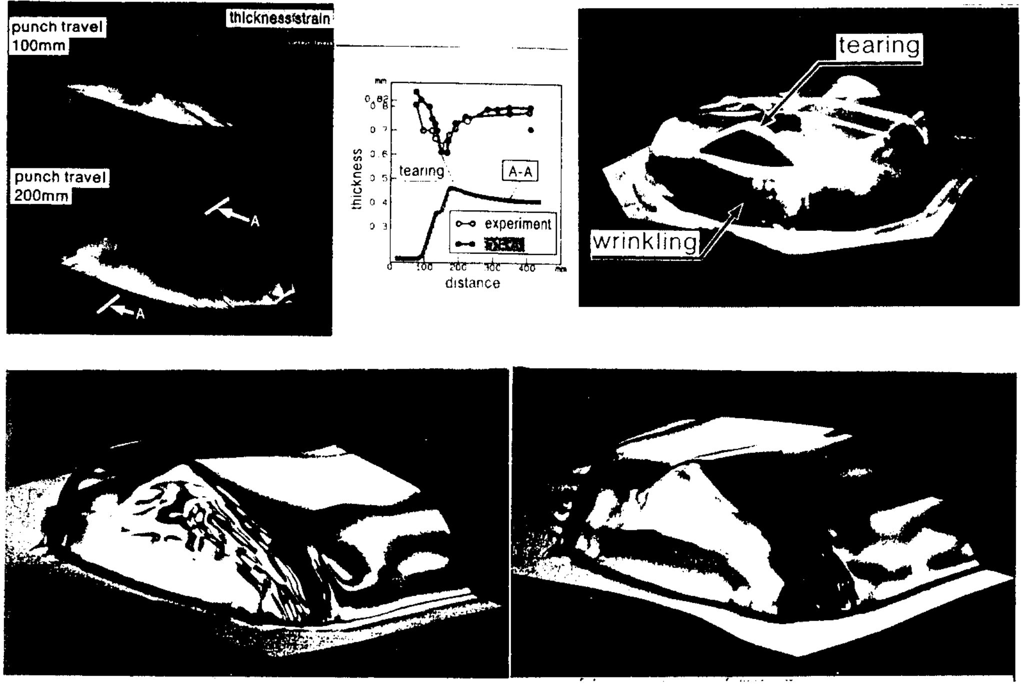


Fig.10 Nakamachi, E. and Aoh, H.

1991

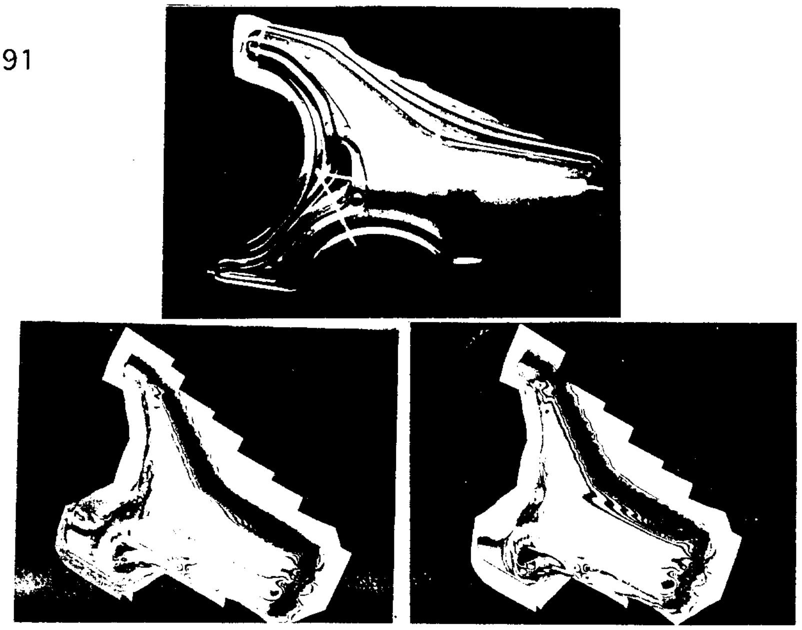


Fig.11 Nakamachi, E. and Aoh, H.

1 9 9 2

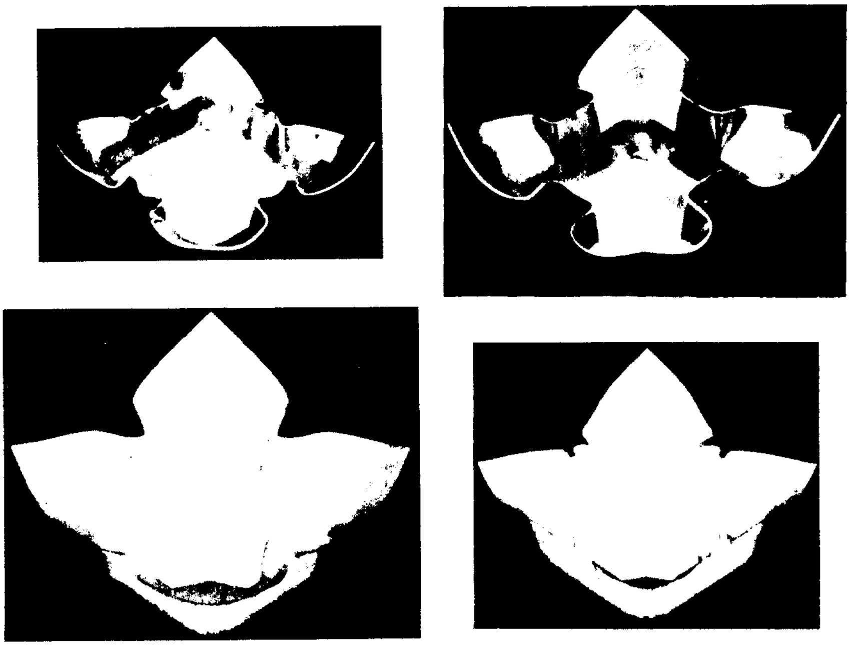


Fig.12 Makinouchi, A. and Kawka, M.

1 9 9 2

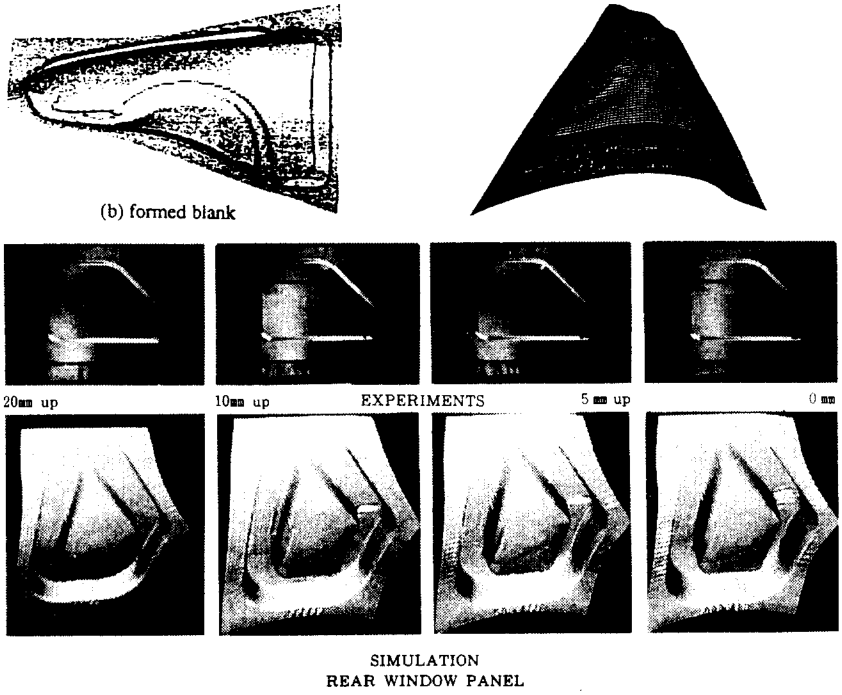


Fig.13 PAM-STAMP El Khaldi, F.

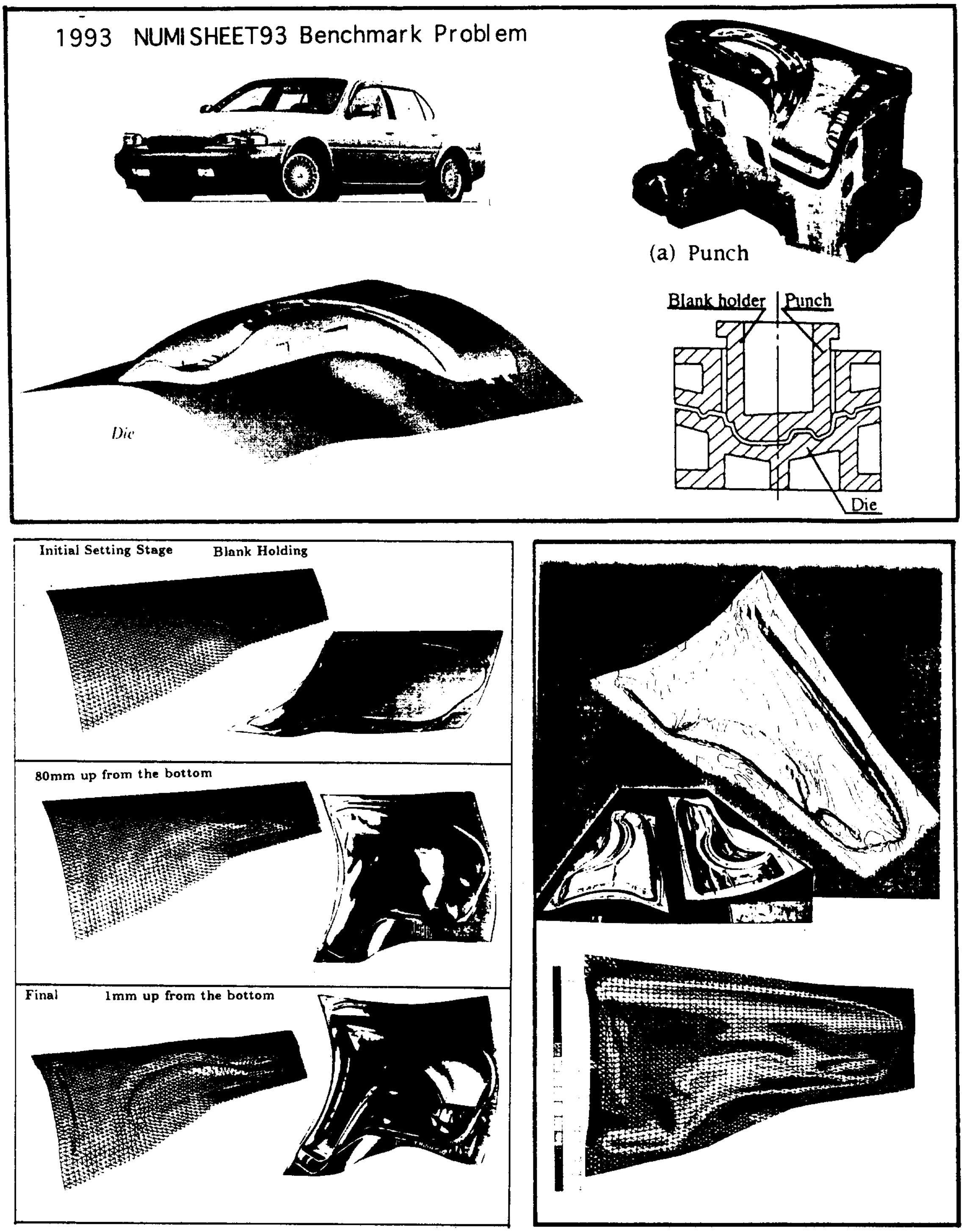


Fig.14 NUMISHEET93 Benchmark Problem

3. Benchmark problems.

Every three years, we have NUMIFORM conference, started from SWANSEA conference in 1982. In these conference we could see how the progress of the numerical simulation technology for the industrial forming process analyses and syntheses. Historical review of simulation technology relating to benchmark problems can be found as follow.

Actually, the state of numerical simulation for the sheet forming in 1975-1980 was the baby age. The subject is definitely simple, such like hemispherical punch stretching and drawing or square cup stretching and drawing. The material model is also rigid-plastic or elastic-plastic. Most of the people employed membrane finite element based on finite deformation theory of continua. Basically, simple boundary condition and simple friction condition - the constant shear force resistance or Coulomb friction law -. The contact algorithm is not enough to overcome the difficulty of convergence to satisfied the equilibrium condition by solving the highly nonlinear problem.

In 1980-1985, there are no evident progress, just the improvement of material model - so many material model for elastic-plastic, say J2F, J2D, Corner theory, and Void nucleation theory based on the plastic potential theory, and Crystalline-Plasticity based on the micro structure dislocation. The rate sensitive model, say rigid-viscoplastic and elastic-viscoplastic model. But there were not so many model for friction. Still Coulomb's friction law is mainly used. The updated Lagrange formulation, the elastic-plastic material model, Coulomb friction model, the membrane finite element and the simple functional description of tool were commonly used.

In 1985-1990, the modification of shell element and contact algorithm conjunction with CAD tool data. The convergence problem was attacked by the numerical analysis experts and improved very much. The practical application for the industrial sheet forming process simulation appeared. Dynamic-explicit FE program was started to apply to predict the wrinkling problems. Those problems are very important in the industry but very difficult to solve because of including the instability, bifurcation and singularity. Especially for the implicit-static FE program , like NIKE, MARC and ABAQUS, the buckling initiation and post-buckling problem gives the serious problem of equilibrium satisfaction. Therefore, the beginning of 1990's the explicit type FE simulation codes have shown the great progress of simulation in the sense of practical application.

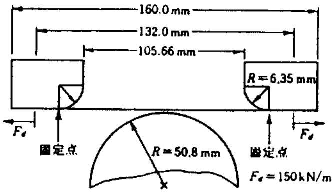
From 1989 NUMIFORM conference, first benchmark problems of sheet forming has been proposed. Fig. 15 shows OSU benchmark test results. Wagoner, R.H., Lee, J.K. and Nakamachi, E. are the organizers. As already mentioned, in this time those were simple problems, such like the hemispherical punch stretching and drawing, and plane strain stretching and drawing -like 1-D problem-. Most participants were the static-implicit FE membrane codes and a few static-explicit one. Most of them adopted the elastic-plastic material model, because of the requirement of rigorous stress prediction. The organizer recognized that the stretch problem is basically stable deformation process, therefore most analyses show reasonable results, without geometrical model and total strain analysis. But the drawing problem made clear the difficulty of convergence, because of unstable deformation process -loading, unloading and the possibility of buckling-. The results are terribly scattered.

Fig. 16 shows 2nd benchmark problem results in 1st NUMSIHEET conference in Zurich in 1991. The CAD data of tool was delivered by the organizer, Reissner, J. and Hora. In spite of rather complicated shape of tool as shown in Fig. 16, the numerical results are not so spread. It seems that the great progress of FE simulation technique has been achieved by static-implicit, static-explicit and dynamic-explicit FE programs. But still problem of unclearness of material and friction modeling was pointed out. The best fitting result from ETH(now they named AUTOFORM) was obtained by the model of isotropic plasticity and zero-friction resistant force. Still there remained the problem of modeling technique, especially concerning with CAD data transfer.

In 1993, NUMISHEET93 conference, those organizer is Makinouchi, A., Nakamachi, E., Onate, E. and Wagoner, R.H., offered three benchmark problems, square-cup deep drawing, front fender stamping, and 2-D draw bending.

1st problem can be featured as the simple shape tool and stretch dominant stable deformation. Therefore we could see the accuracy and verify the material and friction model availability. The strain distribution results obtained by static-implicit(SI), static-explicit(SE) and dynamic-explicit(DE) showed good agreement with the experiment. The nonlinear FE analyses can predict this kind of stable deformation with enough accuracy. We concluded that the material model can not predict the forming limit, if there is no experimental data of FLD. There are so big different between the experimental results of Aluminum alloy (Mg contents) failer. If we have FLD from experiment, we can predict rather good accuracy. But this is not mean the material model for failer prediction is correct. This will be a future problem for the material modeling. There remains also the friction model. No new model than Coulomb friction law was proposed.

2nd benchmark problem results are shown in Fig.17(a) and (b). The participants are also shown in Table 3. We compared three types of FE codes, say SI,SE and DE. We can featured as follow; SI gives good accuracy, but still difficulty of convergence - improved very much-,
larger CPU time and the less finite element number. SE shows robustness, without difficulty of convergence, but not so good accuracy and large CPU time. The less finite element number means not enough to predict the detail wrinkling mode and strain distributions. This caused by the limitation of CPU memory and computation time restricted by the number of freedom to solve the finite element simultaneous equation as same as SI FE code. DE shows good prediction of wrinkling because of huge number of finite element and less CPU time compared with SI and SE FE codes, but not so good accuracy of strain distributions. DE's advantage is no necessary to solve the simultaneous equation. But the problem is how to decide the parameter concerning the numerical damping and analogy between the quasi-static phenomena and dynamic-impact one. three figures of Fig. 17(b) show the comparison of thickness strain distribution. SI shows better accuracy than SE and DE FE analyses results.



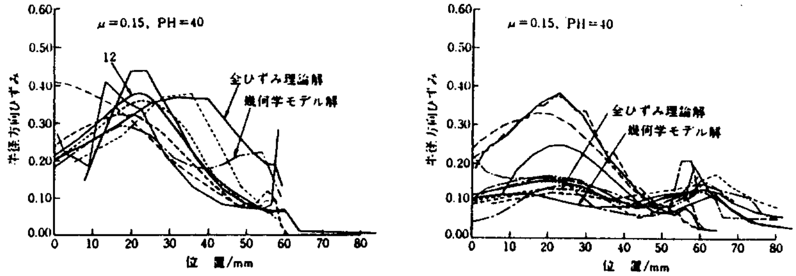
Benchmark Problems

Material Properties

1. 等方硬化材料, フォンミーゼス降伏条件
2. 応力-ひずみ関係
   $\bar{\sigma}=589(10^{-4}+\bar{\varepsilon}^{p})^{0.216}$
3. 縦弾性係数　$E=68$ GPa
4. ポアソン比　$\nu=0.3$

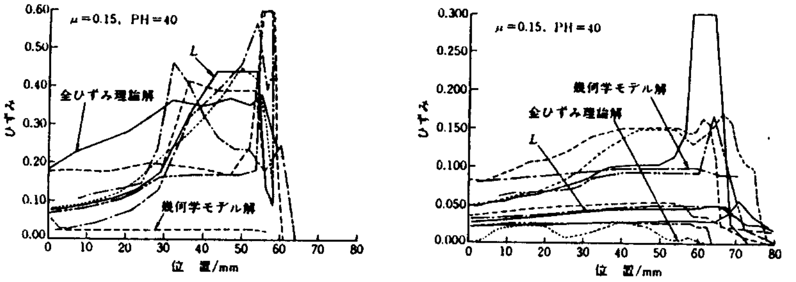
Table of Participants

A	1	BESDO/U. Hannover	FEMSY, TLFEM, Solid, EP, LM
B	2	SITARAMAN/OSU	SHEET-FORM, EXPL, FDM, RP
C	3	LEE/RPI	SUPER, CST, EP
D	4	DOEGE/U. Hannover	ABAQUS 4-6-171
E	5	HEIMERDINGER/D-B	ABAQUS
F	6	MAKINOUCHI/Riken	SOLID, CQ4, EP
G	7	NAGTEGAAL/Hibbitt	ABAQUS 4.7-17, EP, SAX1
H	8	LOGAN/Lawr. Liv.	SQUIRREL, 1D, RVP
I	9	GERDEEN/Mich. Tech.	AXIFORM-Mapping, Def. Pl.
J	10	REBELO/MARC	MARC-ISO (4), EP
K	11	KEUM-WANG/OSU	SHEET3, RVP, CST
L	12	WENNER/GMR	LINEFORM, Memb. line, EP
M	13	NAKAMACHI/YATSU	Memb (CST), EP
N	14	YANG/KAIST	Memb (CST), RP
O	15	LEE/OSU	SBEND, E-RVP
P	16	MASSONI/CEMEF	Memb (CST)
Q	17	GUERRA/Los Alamos	NIKE2D, QA, Solid, EP, Penalty
R	18	BATOZ/Compiegne	FORMEF 9.1, Memb (CST), EP
S	19	TANG/VW-Gedas	TIEFSIM, Memb (CST, CQ4), EP, AEL
T	20	FLOWER/L. Livermore	NIKE2D
U	21	AMODIO/U. Rome	ABAQUS (U), MARC (V)
W	22	MATTIASSON/Volvo	ABAQUS, CAX (W), SAX (X)



(a)　円板の球頭ポンチ張出し解析（軸対称）

(b)　円板の球頭ポンチ絞り解析(軸対称)

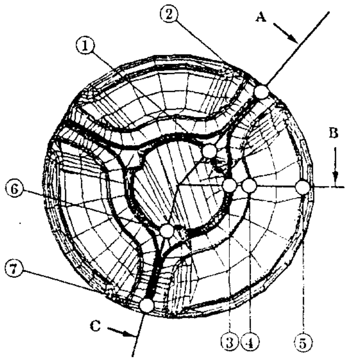


(c)　二次元板張出し解析（平面ひずみ）

(d)　二次元板絞り解析（平面ひずみ）

Fig.15 1989 OSV Bench mark problem

CG output (High-light Simulation)



Deformed Shapes in Experiments

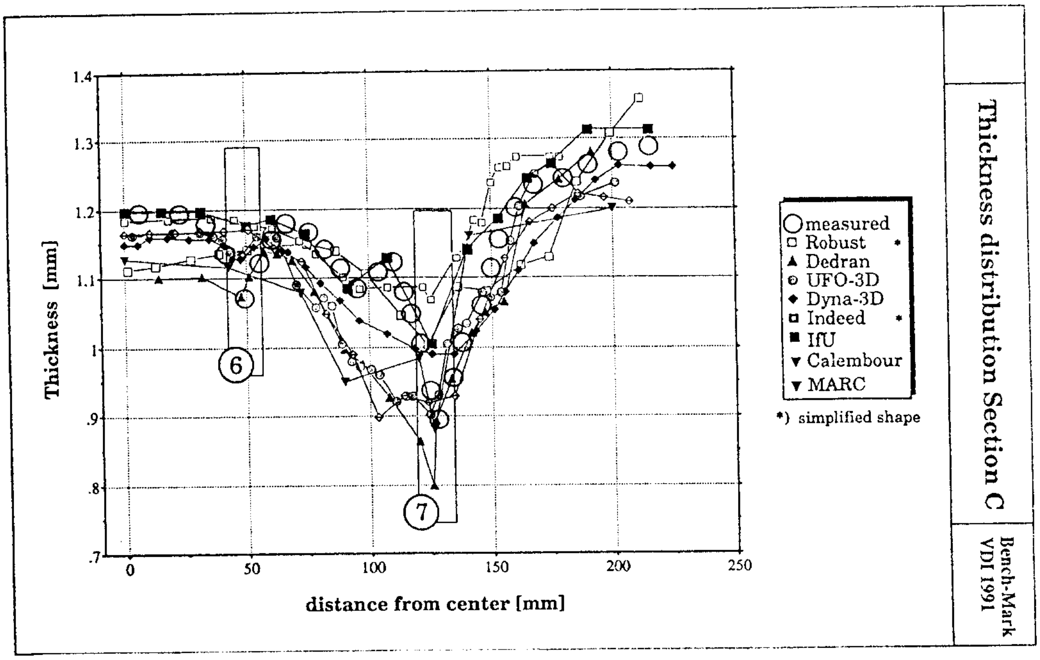
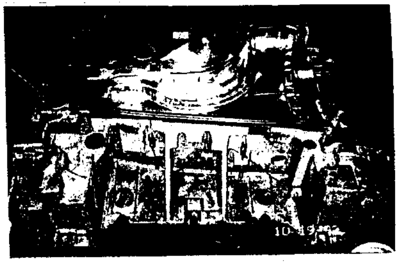


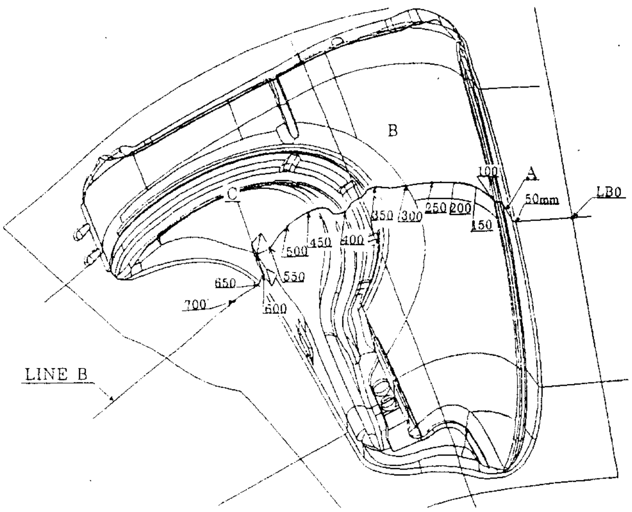
Fig.16 1991 VDI Bench mark problem

(b－1) プレス成形工具 (現実)　パンチ



(b－2) プレス成形工具 (現実)　ダイ

Numbers in figure indicate the initial distances from the point LB0 in flat blank sheet.



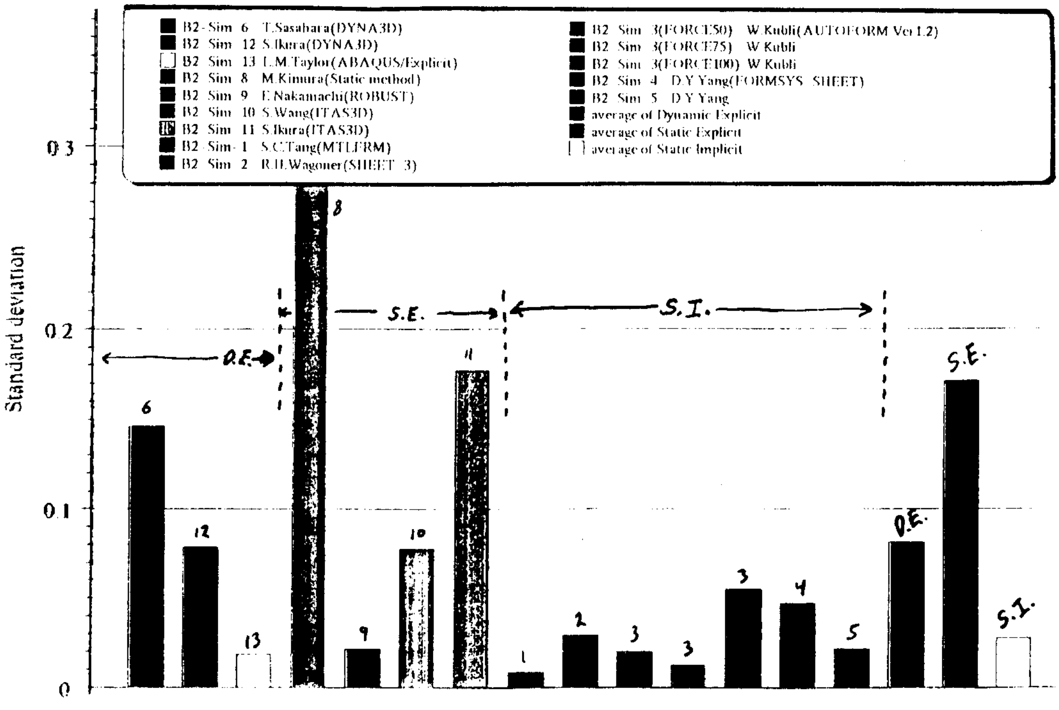


Fig Standard deviation of thickness strain for experiment on the Line B

Fig.17(a) 1993 NUMISHEET Bench mark problem

Table 3 List of Participants to the Front Fender Simulation

No.	B2 - Sim - 1
Name	S.C.Tang / W. Jiang* / P.R. MacNeille
Affiliation	Ford Motor Co. *Automated Analysis Corporation
FEM code	MTLFRM
No.	B2 - Sim - 2
Name	D. Zhou
Affiliation	Department of Materials Sci. & Eng. The Ohio State University
FEM code	
No.	B2 - Sim - 3
Name	W. Kubli
Affiliation	Institute of forming technology, Swiss Federal Institute of Technology
FEM code	AUTOFORM
No.	B2 - Sim - 4
Name	D. Y. Yang
Affiliation	Dept. of Precision Eng. & Mechatronics, KAIST
FEM code	FORMSYS - SHEET
No.	B2 - Sim - 5
Name	D. Y. Yang
Affiliation	Dept. of Precision Eng. & Mechatronics, KAIST
FEM code	FORMSYS - SHEET
No.	B2 - Sim - 6
Name	T.Sasahara / R.Mizuno /Y.Araki / Y.Ohsumi
Affiliation	Suzuki Motor Corporation
FEM code	DYNA - 3D
No.	B2 - Sim - 7
Name	H.Tai*/T.Sugimoto*/K.Igaki*/F.Arnaudeau**/G.Winkelmuller** et al.
Affiliation	*Recruit Co., Ltd. **Mecalog
FEM code	RADIOSS
No.	B2 - Sim - 8
Name	M. Kimura
Affiliation	Fuji Heavy Industries Ltd.
FEM code	ITAS - 3D
No.	B2 - Sim - 9
Name	E. Nakamachi
Affiliation	Osaka University
FEM code	ROBUST
No.	B2 - Sim - 10
Name	S.Wang / A.Makinouchi /M.Kawka / A.Santos
Affiliation	The Institute of Physical and Chemical Research (RIKEN)
FEM code	

No.	B2 - Sim - 11
Name	S. Ikura / K. Serizawa / H. Tsutamori
Affiliation	Toyota Motor Corporation
Name of FEM code	ITAS－3D
No.	B2 - Sim - 12
Name	S. Ikura / K. Serizawa / H. Tsutamori
Affiliation	Toyota Motor Corp.
Name of FEM code	LS - DYNA3D
No.	B2 - Sim - 13
Name	L. M. Taylor
Affiliation	Hibbitt, Karlsson, & Sorensen, Inc.
Name of FEM code	ABAQUS
No.	B2 - Sim - 14
Name	M. P. Sklad
Affiliation	McMaster University
Name of FEM code	
No.	B2 - Sim - 15
Name	E. Onate / J. Rojek / F. Flores / O. Fruitos
Affiliation	International Center for Num. Meth. and Eng.
Name of FEM code	
No.	B2 - Sim - 16
Name	K. Mattiasson
Affiliation	Volvo Data Co.
Name of FEM code	

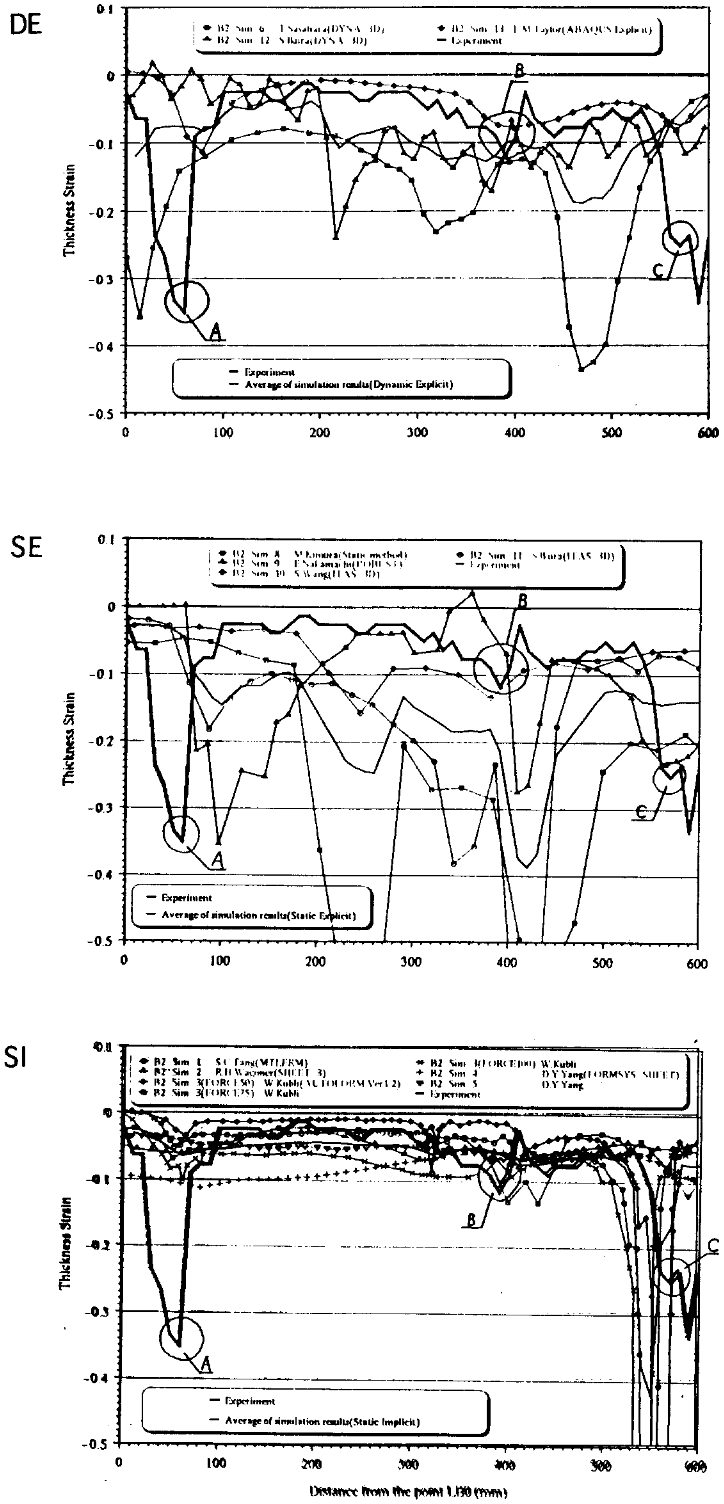


Fig.17(b) NUMISHEET 93 Bench mark results

4. Future technology in the sheet forming simulation.

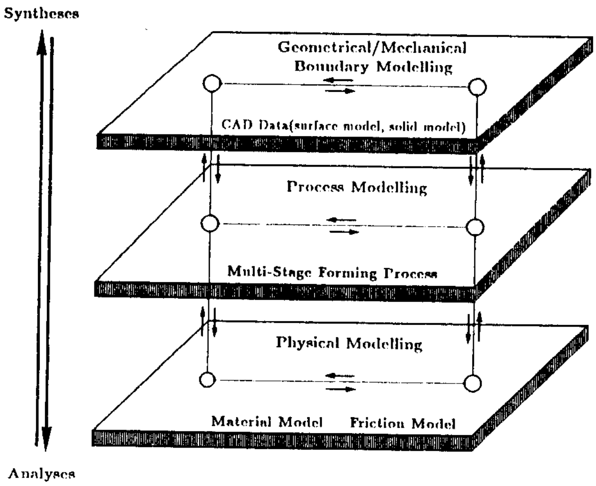
The progress of computer simulation and mathematical programing technologies leads the new paradigm of material/forming/structure design technology. Fig.18(a) and (b) show the Integrated Design Engineering in CAD/CAE/CAM system of industrial manufacturing system. Optimum design, named Over-all optimization, can be realized by employing the numerical analyses and syntheses technology. As shown in Fig. 18(a), In this optimization process has hierarchical featuring. As example, three layers can be considered, as the physical modeling (material and friction), forming process modeling, and boundary condition (tool description by using CAD data, force boundaries - pressure and draw beads-.) Fig. 18(b) shows FE computer simulation flow in conjunction with CAD, CG, pre- and post-process modules. The actual problem of thermal plastic sheet forming design was performed by using FE analyses (ROBUST) and the mathematical programing (nonlinear programing - direct lattice methods, most simple one-). In two stage forming process as shown in Fig. 19(a). The stress-strain curve is also shown. Two design parameter were employed, such like the radius of 1st stage punch and the punch travel of first stage stretch-drawing. Totally 45 cases simulation results gave the objective function surfaces as shown in Fig. 19(b). The objective functions employed are, (1)the deviation norm from the uniform thickness, (2)total forming energy, (3) the displacement norm summation of each finite element node, deformed by internal pressure after the final forming stage. (1) and (2) show the optimum forming design and (3) shows the structure strength design. The constraint conditions are the limits of the radius and height of first stage punch. This over-all optimization will be a big subject of the computer simulation of sheet forming design in the industrial manufacturing system - CAD/CAM/CAE, CIM, Concurrent Engineering, Simultaneous Engineering and VIRTUAL MANUFACTURING in VIRTUAL FACTORY -.

Fig.20 and 21 show the material modeling technology in the future. The anisotropy predicted by using the plastic potential theory(Barlat model in Fig. 20) or more micro structure base prediction, such like the crystalline-plasticity model as shown in Fig. 21(Dawson). The molecular mechanics simulation is now available for solid mechanics motion prediction. But still not enough to predict the failer and instability phenomena of sheet metal forming process. The combination of micro- mezzo- and macro structure material modeling technique should be developed by the precise phenomenological observation. The experimental observation technology development will help the numerical modeling technique very much in the future.

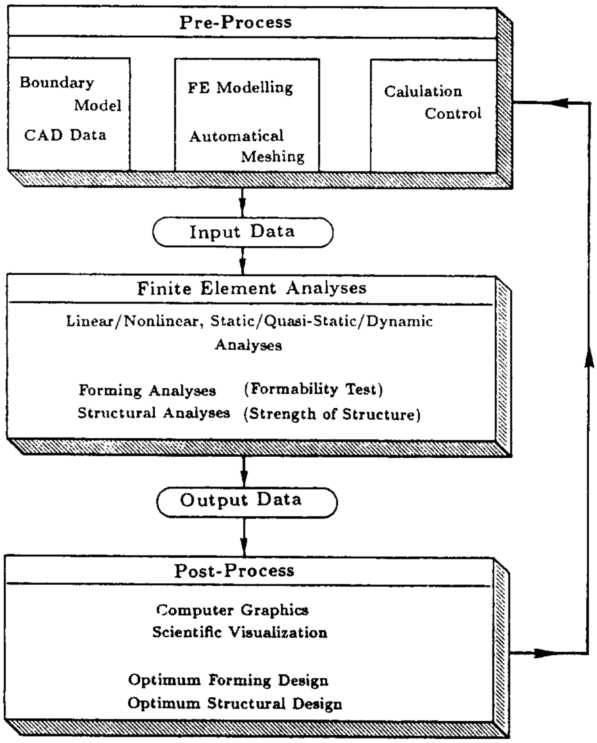
Fig. 21 shows the friction model for the galvanized steel sheet, GA, GI and EG. The features of cracking and delamination are quite different and therefore the macro mechanical modeling should be different. In this case we proposed the functional description for the friction coefficient by employing the parameters, such like strain and contact sliding length.

Fig. 22 shows the different failer points and punch travel in case of square-cup deep drawing. More precise experimental observation and functional description - the external function and also internal function formulations are available - should be developed in the future.

These physical modeling technique - material and friction - can be established by bridging the science and engineering approach.

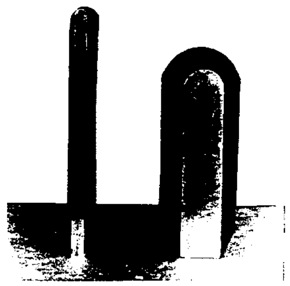


Computer Simulation

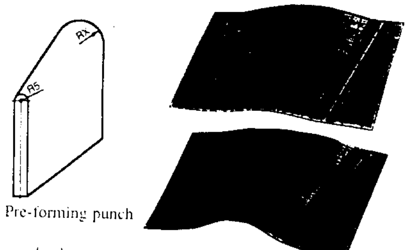


FE Analyses for Optimum Design

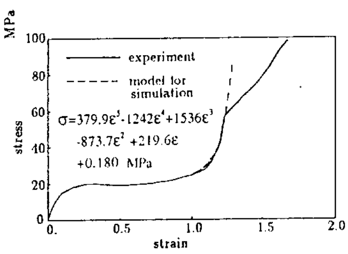
Fig.18 Integrated Design -Overall Optimization-



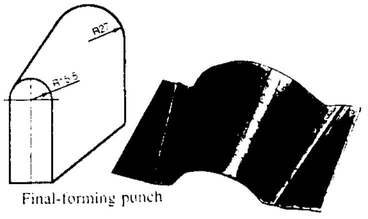
(a) 金型工具



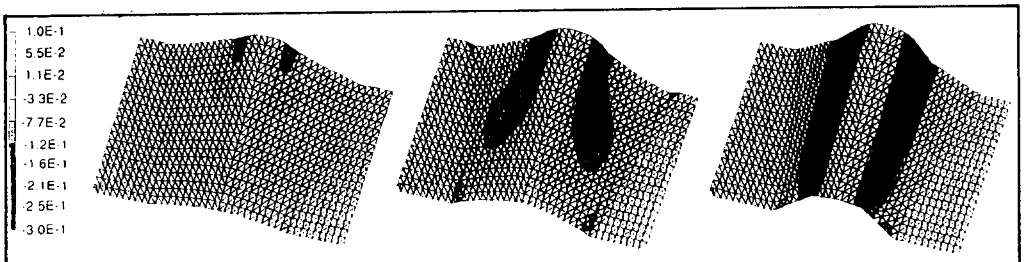
(c) 1st stage(pre-forming process)



(b) 熱可塑プラスティック材料の 応力ーひずみ関係

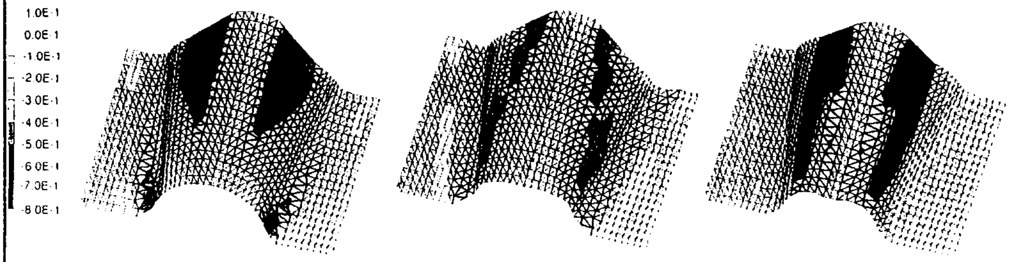


(d) 2nd stage(final-forming process)



punch stroke 15mm punch stroke 20mm punch stroke 25mm

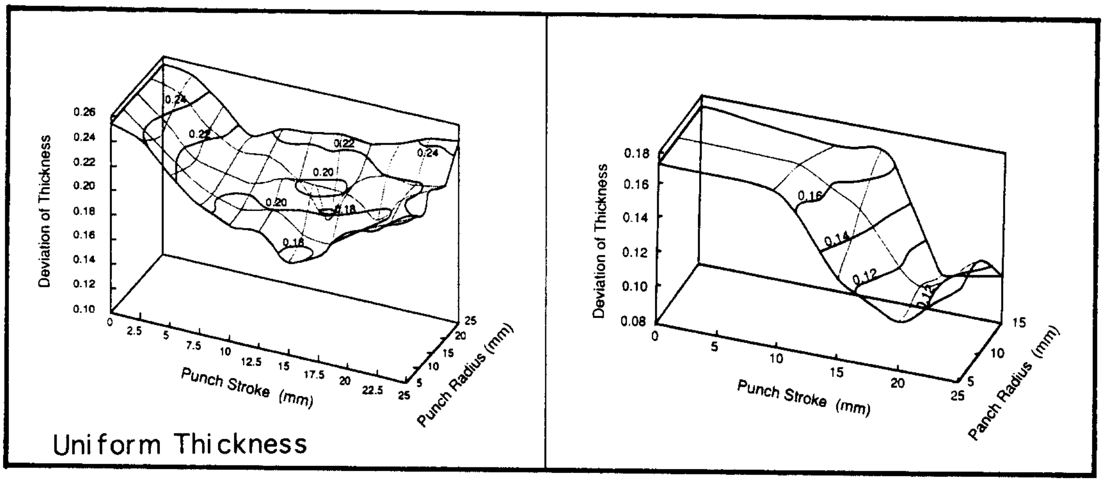
(a) Thickness strain distribution of pre-forming products. (Analysis)



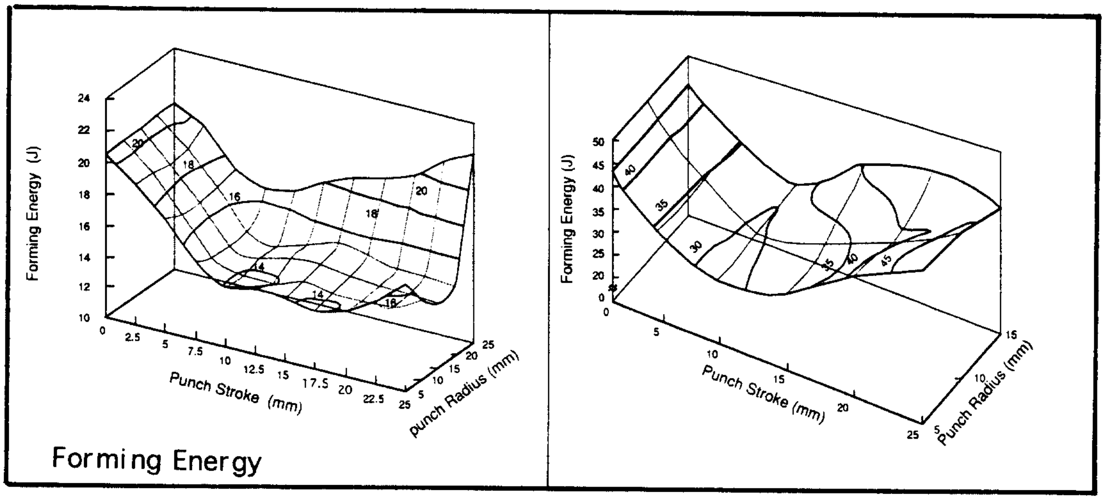
punch stroke 15mm punch stroke 20mm punch stroke 25mm

(b) Thickness strain distribution of final-forming products. (Analysis)

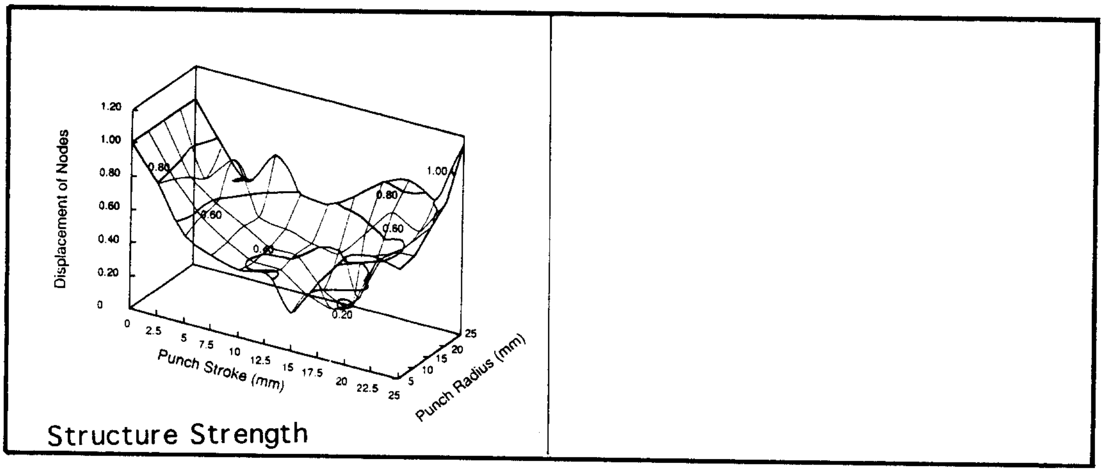
Fig.19(a) The Optimization of Thermoplastic Sheet Forming Process



Uniform Thickness



Forming Energy



Structure Strength

Fig.19(b) Objective Function Surfaces
Direct Methods of Nonlinear Programing

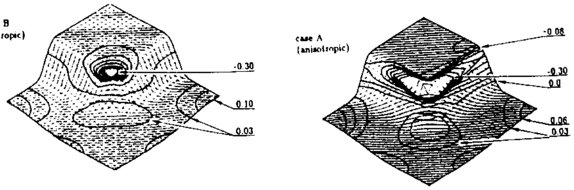
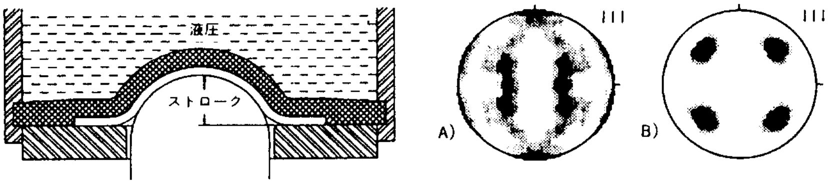
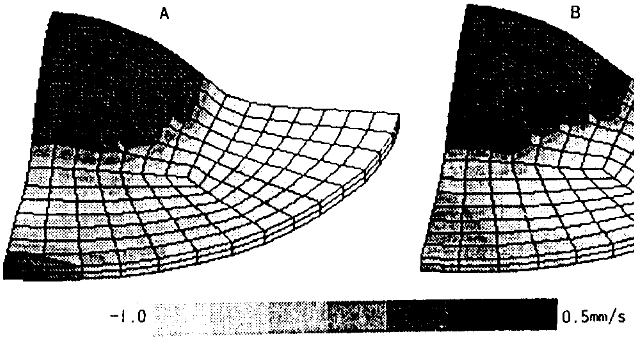


Fig.20 Barlat Anisotropic Model



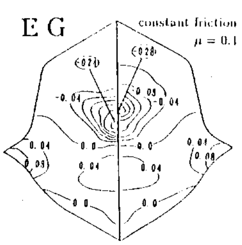
シミュレーションに用いた初期組織の{111}極点図　-A)圧延組織 B)立方組織

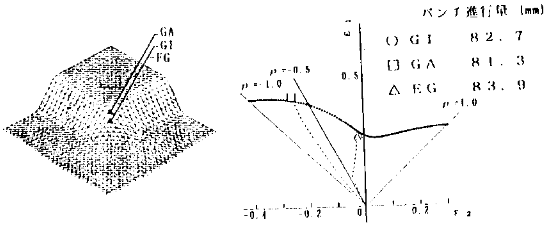


半径方向速度(3秒後)-A)圧延組織-B)立方組織

Fig.21 Dawson crystalline Plasticity

20%引張りひずみでの表面処理層の割れ状態のSEM観察結果





板厚ひずみ分布の比較　　表面処理板材のS-R理論による割れ予測結果

（ＥＧおよび摩擦係数μ=0.1の場合の比較）

Fig.22 garvanized steel sheet -square cup deep drawing

5. Conclusion

The sheet forming simulation technology shows great progress in this ten years, promoted mainly by the computer technology software and hardware development. The trial of forming design in computer space - VIRTUAL MANUFACTURING in VIRTUAL FACTORY- starts in the automotive, electric/electronics and aviation/space industries. The forming process optimization should develop in conjunction with material process and structural optimization. The Virtual Reality and Networking technologies and the super-parallel computing are also important to generate this integrated design engineering in CAD/CAE/CAM and CIM systems.

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