OAK RIDGE NATIONAL LABORATORY

LOCKHEED MARTIN

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CRADA Final Report for CRADA Number C/ORNL96-0457

Demonstration of BEPLATE Electroforming Simulation Code In General Production Conditions and Geometries

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Oak Ridge National Laboratory

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Also Final Report for the
Technology Partnership Program Project:
"Electroforming Cell Design Tool Development"

Prepared by the
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Under contract DE-AC05-960R22464

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ABSTRACT

The ORNL/Y-12/Cemcom team has developed an electroforming advisor, CellSim. CellSim is an easy-to-use design and computational problem-solving environment for electroforming. A primary goal of this project was to enable electroformers to optimally design a process that would make a part right the first time and with minimum cost. The computer simulations can be carried out much faster than experimentation, and without hazardous waste production. Electroforming (EF) Advisor CellSim integrates and uses the Computer Aided Design (CAD) and the Computer Aided Engineering (CAE) capabilities of the UniGraphics and Patran commercial systems coupled with the simulation capabilities of a locally developed three-dimensional boundary element code, BEPLATE.

INTRODUCTION

The purpose of this project was to develop a tool for the design of optimum geometries and electrochemical parameters for the electroforming process as used at the Y-12 plant and at Cemcom, Inc. Electroforming is an electrochemical process to manufacture freestanding parts by cathodically depositing metal on a mandrel. Electroforming can produce complex-shaped parts, with constant or varying wall thicknesses as needed, the manufacture of which would not be feasible using other methods. One surface of the electroform exactly copies the mandrel surface. Even fine, microscopic details of the mandrel surface can be replicated on the electroformed part. Precise control of the location (wall thickness) and surface morphology (roughness) of the opposite or growth surface is more difficult.

Development of the electroforming process design and control is currently a laborious cut-and-try method involving multiple iterations of tooling design and fabrication, experimental tests and evaluation of the product. For complex parts, several months may be required before production can begin. A highly experienced expert is required to do this efficiently. Considerable waste can be produced during this pre-production experimentation.

The goal of this project is to provide the designer with a "Virtual EF Cell" which will allow much more effective EF cell design and optimization. The Advisor, CellSim, uses the power of a commercial system of codes that when integrated provides a seamless CAD/CAE and GUI development environment. This Advisor incorporates a locally developed simulator, and expert systems developed on captured human knowledge to assist the design in developing an optimum electroforming cell for the desired part. The UniGraphics system is a collection of layered products that are integrated into a smooth easy-to-use Graphical User Interface (GUI) for engineering design work. This integrated system allows the user to rapidly describe a cell design. We have developed several customized windows and tools to allow the user to quickly develop cells for the designs that are in use at Y-12 and Cemcom. We have coupled the locally developed EF simulation code, BEPLATE,[1] with this powerful CAD/CAE environment and developed specialized modifications to this environment in order to provide a complete cycle of design, analysis, and evaluation to the user.

CELLSIM - ELECTROFORMING ADVISOR

At the start of this project we envisioned an Electroforming Advisor to be an advanced design tool that combines the traditional Computer Aided Design (CAD) with the Computer Aided Engineering (CAE) and analysis functions in a seamless environment. The CellSim advisor enables the design of an EF cell in an easy-to-use CAD environment that can be easily transferred to a CAE system. A CAE system contains: an analytical model generation system (traditionally called a pre-processor, and in this application is the Patran code); an analytical simulation system; and a results viewing system (post-processor, Patran). Combining the CAD and CAE functions into one system allows the easy generation and modification of the model by CAD operations, transparent generation of an analytical model from this CAD representation, analytical simulation of the process, and viewing of the results in the same environment. The first, most obvious benefit of this technique comes from the easy modification of the design and the rapid generation of a new model to be analyzed. The user controls the whole process from one environment, never leaving the Advisor system. The CellSim advisor is built on top of a commercial CAD program (Unigraphics) with sufficient GUI development and software integration capability.

Creating CellSim in a seamless CAD/CAE environment allowed the development of the tool into a true advisor system incorporating expert system rules and logic to provide the user with a guide to designing the part. We have used such a system to capture knowledge from existing experts. Electroforming is an area ripe for this knowledge-capture effort, since so much of the electroforming cell design process involves experiential-guided guessing. This guessing is shaped by many years of electroforming experiments based on trial-and-error. These experiments involve considerable time and effort to perform, and produce a significant volume of hazardous waste. Thus the capture of this knowledge from experts before retirement represents a recouping of the investment of many years of professional development and costly experiments.

CONCLUSIONS

The first version of the CellSim advisor level 1.0 was completed. The simulator component, BEPLATE, has been used extensively at Y-12 and Cemcom and has proven to be a significant aid to productive electroforming. The team will install CellSim on several Y-12 user workstations in the next few weeks and provide limited training and support. This will enable the application of the CellSim tool to real Y-12 production problems. This limited amount of work is being funded by Y-12 but will allow Y-12 to apply the fruits of this CRADA to production needs.

Due to the nature of software developments, no patents were applied for and no patentable inventions were generated. The initial code was copyrighted and the new version will be copyrighted this year. We are awaiting the outcome of the attempt by our partner to sell the Cemcom process but are also looking for other potential partners to commercialize the software. Language in this report referring to a continuing relationship with Cemcom is contingent on the continuing existence of Cemcom in some form.

DESCRIPTION OF TECHNICAL WORK

The following sections describe the work that has been accomplished on the CellSim advisor. The sections describe the work done on the electroforming simulator, BEPLATE, the GUI, knowledge capture, integration of the CAD, CAE, and analysis components of the advisor.

SIMULATOR-BEPLATE

BEPLATE Level 1a (BE1a) - Automatic User Aids

The basic numerical simulation package for the electroforming process was significantly improved and named Level 1a. The original version of BEPLATE required that the model developer perform various operations to make sure that the model was correctly defined for the BEPLATE 1.0 code. Failure to perform these operations correctly would result in aborted computations or incorrect but seemingly reasonable results.

Automatic model modification and various modeling aids were developed. These improvements included automated techniques to make sure that the model is acceptable for analysis such as node equivalencing, reorientation of elements to provide proper normal direction, checking the model for correctness prior to analysis, and improved surface evolution techniques. It also included improved overrelaxation techniques to reduce the iterations and computational time necessary to converge the polarization iterative technique. Improvements to the robustness of the polarization iterative technique were also accomplished by the modified overrelaxation techniques. Many minor coding modifications throughout the program were made that improve the overall robustness of the code and further reduce the possibility of input errors. This version was delivered to Cemcom for stress testing on August 8, 1998. These improvements make it easier and more reliable to develop and analyze a model.

BEPLATE Level 1b (BE1b)– Improved Polarization Technique

For typical electroforming situations, determining the proper description of the polarization effects can take a significant portion of the computational time. For some exotic cases (e.g., Electrospray simulation described below) more than 99% of the simulation time (several days to weeks) is spent in the polarization iterative technique. The polarization portion of the code was rewritten to provide an even more effective technique. A Two-level Gauss-Siedel (TLGS) technique that independently solves each row of the matrix in the inner loop has proven to be up to 50 times faster than the highly modified Picard iteration that was used in the previous version of BEPLATE (BE1a). The TLGS technique was delivered to Cemcom on March 29, 1999. Cemcom reported that the new technique substantially improved their computational throughput. The description of this technique is to be published in a journal article.

STRESS TESTING

Stress testing of a computer code is a vital step in the development process. The object of stress testing is to identify coding faults or flaws that prevent the code from operating as intended in all cases. In the first stage of stress testing, the developers test the code on problems that span the range of options and parameters for which the code was intended. (However, for completeness, two other steps in the stress testing process must be performed before the code can be accepted as reliable.)

Second, the developers must be challenged to use the code on problems that are outside of the range of problems that they have used previously or in unique combinations of parameters that have not been tested. The developers have performed this level by simulating several processes that were new to the project and developers. These include various Cemcom-generated part shapes, the SRET instrument, a LANL electroformed part, electroformed diamond cutting wheels of complex shape (Wendt-Dunningham), microtrenches in electronic manufacturing (SEMATECH and TVJ), an electrospray ion source (ORNL), an electropainting process (Ford), a small electroformed electronic package (LMMS), and an electroformed X-Ray mirror (NASA). The electrospray, SRET, and microtrench processes involved micrometer scaled problems with closely spaced surfaces and small sized elements. This scale of problem, element sizes, and proximity of surfaces were much smaller than any previous simulations using the BEPLATE code. The application of the numerical techniques to these problems taught us how to improve the accuracy and robustness of the larger scale problems. A few of these problems have associated experimental data: two of the Cemcom generated parts, the SRET instrument, diamond-cutting wheel part and electronic package part. These data and the comparison with calculations are discussed in the section on validation.

Third, other non-developer users must use the code in real applications to find the faults and logic flaws. Our CRADA partner, Cemcom, accomplished the third stage of stress testing. They applied the code to many quite complex shapes that are typical of forms for injection molding of plastic materials. During this process, the partner developed a technique of using secondary anodes in close proximity to the cathode surfaces to improve plating into deep recesses. The BEPLATE code was not developed for this condition and it was found that the two versions produced somewhat different results in these regions. These results were more accurate for the BE1b version. The reasons for the increased accuracy indicate that the BEPLATE 2.0 numerics will be even more effective for these cases. Thus, the partner's stress testing added impetus to the development of the newer technique as well as improving the BE1b code.

BE2.0 CODE STATUS

This version incorporates direct treatment of both potential (included in the BE1 codes) and flux (new in the BE2 code). Flux equations, based on the "Hypersingular" algorithm, are required to allow shield design capability; the BE2 code also incorporates the "Galerkin" approximation, which makes handling both the potential and flux equations more computationally efficient. It also uses quadratic instead of linear elements to define surfaces, which allows greater fidelity in some cases with a reduced number of nodes. Unfortunately, the code development has taken longer than planned and the withdrawal of Cemcom from the project has reduced the funding intended for this development. Continued code development work using the new algorithms is beginning to achieve results as good as or superior to the original algorithm set, with respect to both speed and robustness. This is true both for cases with and without polarization boundary conditions. There are some continuing issues related to the more stringent meshing requirements of the new code, which will have to be solved before certain complex geometries can be routinely handled. Significant progress has been made, but the goal of superior performance of the new code for all situations has yet to be achieved.

The new Y-12 96-processor ASCI Manhattan computer was very effective in assisting in the code development and testing.

VALIDATION

Validation is the process of assuring that a code produces results that are consistent with reality. Comparing the code results with experimental data typically does this. The validation cases for the simulator include: Y-12 experiments, Cemcom Kodak and egg parts, the LMMS electronic package, and limited data from the SRET instrument. Each of these cases will be discussed in this section.

Of these cases, the Y-12 lead electroform tests are the best validation cases for rotating axisymmetric parts. Although the details of the bath are known, the electrochemical parameters of that specified bath were not measured – we used polarization data from a closely related bath, measured by CWRU researchers. This lead electroforming bath is no longer active at Y-12. As an aside, lead electroforming is a commercial process. The electrochemical parameters for the lead bath are quite different from a more common bath such as nickel. The cathode was a short cylinder joined with a hemisphere at its equator. The part was rotated around the centerline of the cylinder. The comparison of the results from BEPLATE 1b is shown with experimental data in Fig. 1 for cases with and without a semi-conformal solid cathode shield around a hemispherical cathode with a short cylindrical base. Generally the no-shield simulation achieved agreement with 2% of the local thickness. With a shield in place, using the same electrochemical parameters, the agreement was generally within 5% of the local thickness. A more complete description of the experiment and earlier validations are contained in ref. 1.

The Cemcom Kodak part is the best validation case for complex shapes due to the richness of the thickness data. However, the exact details of the electrolyte and the plating history were not recorded. The lessons learned in using this case to validate the code were reflected in the validation plan developed with Cemcom (discussed below). Unfortunately, the demise of Cemcom prevented the completion of the plan and the complete validation of the simulator and Advisor.

The Cemcom Kodak part consisted of two flat plates; one with a protrusion and one with a depression (Fig. 2). Both of these plates were electroformed at the same time in a manner so as to maintain the exact relative position of the plates (indexing). Cemcom's manufacturing goal was to electroform both sides at the same time, maintaining indexing and producing an acceptable pair of electroformed parts for the two halves of an injection molding setup. The primary measure for acceptability was the maximum and minimum thickness on both sides and the ratio of these values. Since the two sides have completely different surface topology, achieving thickness uniformity was a challenging task and could require several pre-production iterations to achieve an acceptable electroform. For the validation, the local thickness of the electroformed plates was measured by an ultrasound probe, and by micrometer on the sectioned part. The precise location of the ultrasound probe was not measured so these measurements were less useful than the micrometer measurements.

Since exact details on the electrolyte were not available, the limited Cemcom electrochemical data was used with literature values for the unmeasured values. These values produce reasonable matches with the experimental data. However, measurements made on similar baths by Darrel Engelhaupt of the University of Alabama at NASA Marshall Space Flight Center were also made available.[2] Engelhaupt's measurements were made on different instruments and under a range of conditions. The values thus produced spanned a range that, unfortunately, did not include the data assumed for the initial validation (a combination of Cemcom and literature values). Some of Engelhaupt's measured electrochemical values when used in the BEPLATE code produced thickness results that compare closer to the Cemcom thickness data. A limited optimization study was made to find an optimum set of parameters. These parameters were in-between the Cemcom/literature and Engelhaupt's values, and produce much better agreement when measured by the difference between the final experimental surface (calculated from the measured thicknesses and the original mandrel shape) and the calculated surface. Figure 3 presents the calculated final surface for one side of the model. Figures 4–6 present the comparison of the thicknesses generated and measured for three different sections of the part. Overall the agreement was 3.8 mils RMS while the RMS of the local error divided by the local thickness was 20%. The RMS errors for the bottom of the cavity were 0.6 mils and the top of the cathode surface was 5.8 mils. The general shape of the simulated electroform agrees well with the experimental data. This initial validation study indicated that BEPLATE is able to produce reasonable comparisons with experimental thickness data using limited measurements in combination with literature data. However, for the more accurate level of precision required for some applications (e.g. NASA) an appropriate method of measurement of the electrochemical data for a specific bath used must be determined. Our CRADA partner deemed this level of agreement acceptable.

The Cemcom Egg part was a test set of plates, one with an egg-shaped depression and the other with an egg-shaped protrusion, Fig. 7. Cemcom performed validations for both nickel and copper electroforming and shows good agreement as shown in Figs. 8–9. Cemcom also performed other validations for which the data have not been received.

The Lockheed Martin Missiles and Space electronic package electroform, Fig. 10, consisted of a rectangular shell that contained several components that were held in place by the electroformed shell. Proper performance of the package required precise control of the flatness of the front surface. This precision was achieved by LMMS by mounting the cathodes on a rotating table, with a complex shielding and fluid jet arrangement that required many design/experimental iterations. The BEPLATE code was able to produce reasonable comparison with the electroformed thickness with initial basic experiments without jets and shielding. When electroforming with the complex shield in place, the thickness data didn't agree as well. This was attributed to the complicated fluid flow pattern set up by the jets and rotational table arrangement used by LMMS. The BEPLATE simulations were done assuming no rotation and no concentration polarization (no flow). The results from this validation indicate that reasonable validation is possible but fluid dynamics must be considered for some processes. This prompted the addition of a CFD task to the proposed extension of the CRADA.

The SRET instrument consists of an electroactive coupon (a flat disk of material to be tested) placed beneath a small scanning probe, which maps the electrical field directly above the coupon while it is immersed in an electrolyte solution. A remote electrode induces the electrical field. This system is used to profile spatial inhomogeneities in the electrochemical reaction distribution of surfaces. The average potential change produced in the calculational experiment was 14.47 mV, and the Full-Width-at-Half-Maximum was 750 μm, for an electrical conductivity of 1.5×10^{-4} S/cm and an assumed probe height of 150 μm. Since there was a significant potential gradient from the top to the bottom of the probe tip electrode, the average is reported. This compares very well with the experimental values of 15.7 mV and 870 μm.

Also, we have for the first time demonstrated the ability to change the electrochemical parameter values locally, instead of being confined to only a choice of insulating and electroactive surfaces. These results, together with the electrospray simulations, were reported in the paper "Numerical Simulations of Anodic Reactions," presented at the 1999 Joint International Meeting of the Electrochemical Society, in Honolulu, HI, October 19, 1999. In addition to stress testing and expanding the capabilities of the code, this model was used to determine the expected sensitivity to the size and reactivity of these features for another Y-12 Development project, which paid for this portion of the work.

The electrospray investigation applied the basic technique to micrometer scaled features and also helped to improve the polarization iterative technique. This investigation required the development of the simulation of multiple reactions, which produced reasonable results. Unfortunately exact electrochemical parameters and detailed experimental results were not available to allow full validation of this technique. These may become available in the future. The multiple reaction capability will be useful in simulating the electroforming of alloys or the deposition of materials with parasitic side reactions, and thus the technique will be useful to electroforming processes.

VALIDATION PLAN

A draft of a proposed generic geometry for experimental validation of BEPLATE was prepared and reviewed by Cemcom. The plan is based on a simple geometry cathode that is used in electroforming experiments under different conditions. The thickness data and measurements of the electrochemical parameters within the experimental bath will allow much more accurate validations across a wide range of the Cemcom/Y-12 operating parameters. This simple geometry has dimensions that can be varied in order to allow statistically valid fits of BEPLATE results to experimental data. This will permit optimization of the electrochemical parameter input to BEPLATE and checking against parameter values obtained by other methods. Unfortunately, the plan was developed right before the demise of Cemcom and no experiments were performed.

ADVISOR

The project first had to identify the appropriate hardware and software environments that would best serve the development and operation of the CellSim advisor. Platform decisions were made in light of the

Partner's commercial interests and Y-12's needs, as well as the dynamics of the hardware/software market. There were somewhat contradictory aspects involved. The UniGraphics CAD/GUI system was chosen as the best available at the time. UniGraphics can provide the GUI capabilities that we need, serve as a good CAD platform, and allow the complete integration of the simulator and CAE package.

The CellSim GUI, built in C++ and UG Styler, creates a plating-tank-generation user interface module for Unigraphics. Object-oriented C++ code was used. Additional modules were created, using the UG Styler capability, to handle file control matters as well as part of the plating tank system generation. Such internal functionality is used when available and supplemented with C++ as required.

The electrochemical parameter input/library menu has been completed. The library has been populated with data for some common metals and baths. The data files for the library are in ASCII, so they can be easily edited as needed. We did not receive all of the expected data from the partner to populate the library.

A library of CAD templates for the various EF cell elements has been developed. The user is able to click-select types of elements (such as anodes of a particular shape or shields of a particular type), easily define their number and location, and supply a small number of parameters to define their size. This is a much more efficient way of assembling a geometric cell model than the basic "from scratch" method. The GUI will allow the user to select a predefined square or cylindrical tank or modify the size of the tank. He can then select a predefined rectangular or round anode size and the number and placement in the tank. If he wishes he can specify the location of each anode. The predefined anode arrangements include: two Y-12 arrangements, one similar to Cemcom's arrangement, one arrangement with rectangular anodes in the corners, anodes at the middle of the sides, combination of anodes in the corners and at the midsides, combination of 4 types, and evenly distribute the maximum number of anodes of the selected size at a selected distance apart and from the tank wall - a forest of anodes.

The automatic meshing using UniGraphics and Patran has been accomplished. Some additional work is needed to reduce the user interactions to a minimum as preparation for the development of the automatic CAD variable optimization technique.

The information obtained in the knowledge capture interviews with Ray Waldrop (described below) was used to develop an automated shield tool as part of the CellSim advisor. This technique reduces the amount of work necessary for the definition of a porous or solid shield and will be the first step in the automatic porous shield optimization technique. From the basic technique required to implement the automatic shield design, various shield definition tools were developed. The definition for an essentially solid shield will be based on analysis of the thickness profile calculated for an unshielded case. The definition for a shield with significant porosity will be based on a uniform standoff from the mandrel surface. Also, a tool that will de-feature (simplify surfaces by removing small features) mandrel surfaces to desired levels of scale and complexity is being developed. All of these tools require common algorithm development techniques. They will be callable either from BE1b or from CellSim. The more modern numerics of BE2 will be required to implement true general porosity capability.

KNOWLEDGE CAPTURE

Comprehensive electroforming procedures developed from eight knowledge capture (KC) sessions with Ray Waldrop (senior Development electroforming expert) have been transcribed. These interviews are yielding important specific facts about processes, as well as clues on general strategies that can be used for process design and optimization. These interviews are recovering very important information both for the CellSim project and electroforming at the Y-12 plant. The interviews have led to the creation of the first of several draft comprehensive electroforming procedures. A comprehensive literature search was performed on both the electroforming subject area and the expert systems area. A bibliography has been prepared. Initial results indicate in particular the complexity of surface preparation issues, which will require judicious focusing of effort to stay within realistic boundaries.

The Rules-of-Thumb for shield design revealed in the interviews was converted into a set of automatic shield generation codes. These codes will automatically generate solid partial shields, such as shown in Fig. 11 and a complete semi-conformal porous shield form as shown in Fig. 12. The porous shield form would be further modified by a variable porosity distribution determined by the BEPLATE code. This first guess for a porous shield would be used as a start for a shield optimization process.

A KC interview was performed using in an interactive manner the developmental version of the CellSim Advisor. CellSim was not complete and the minor editing of the geometry and the computational time required for the analysis resulted in response times that were too long for a natural, intuitive interaction in an interview format. Even so, the ability to have an electroforming expert provide input into a cell design through the CellSim Advisor hinted at the power of this tool. Using the Manhattan computer and the completed advisor would make the process much smoother and more effective.

MISCELLANEOUS

CEMCOM IN-KIND CONTRIBUTIONS

Some data on nickel and copper solution properties were received from Cemcom for input to simulations for their problems. Computational trials by our CRADA partner using the latest version of BEPLATE (BE1b) have demonstrated a sensitivity of the results to cell design features having unusually small anode-to-cathode spacings. The BE1b version handles this situation better than the previous versions, but to get full understanding an experiment will have to be done for validation.

REVIEWS AND TRIPS

During the course of the project two Peer Reviews (1998 and 1999) and a DOE (1998) yearly review were successfully completed.

One team member participated in a trip to the semi-annual meeting of the other ASCI Principal Investigators, January 1999. It was instructive to see where the rest of the complex was going, and several code projects should provide improved capabilities that would help the future development of CellSim.

Team members made two separate trips to our commercial partner's location (Cemcom, Inc., Baltimore, MD) for maintenance of communications and exchange of information. Discussions were held on the subjects of speed and RAM requirements for the code, problems with CAD geometry files, and geometry limitations and efforts to correct them. We were each given tours of the Cemcom plating facility, which was valuable in visualizing the real physical problems as opposed to only working with calculational constructs. Cemcom representatives made two trips to Oak Ridge.

J. S. Bullock and G. E. Giles traveled to NASA-MSFC in Huntsville, AL for discussions with members of the X-ray Optics team, regarding our assistance to their development of processes to make components for their X-ray Telescope program.

PAPERS PRODUCED BY THIS PROJECT

"Electroforming Cell Design Tool Development" presented at the 1997 American Electroplaters and Surface Finishers (AESF) Electroforming Symposium and Conference in Las Vegas, NV.

"Validation of the BEPLATE code" presented at the 1999 (AESF) Electroforming Symposium and Conference in San Diego, CA.

"Numerical Simulation of Anodic Reactions" presented at the 1999 Fall Meeting of the Electrochemical Society in Honolulu, HI.

" Efficient numerical treatment of Electrochemical boundary conditions" in preparation.

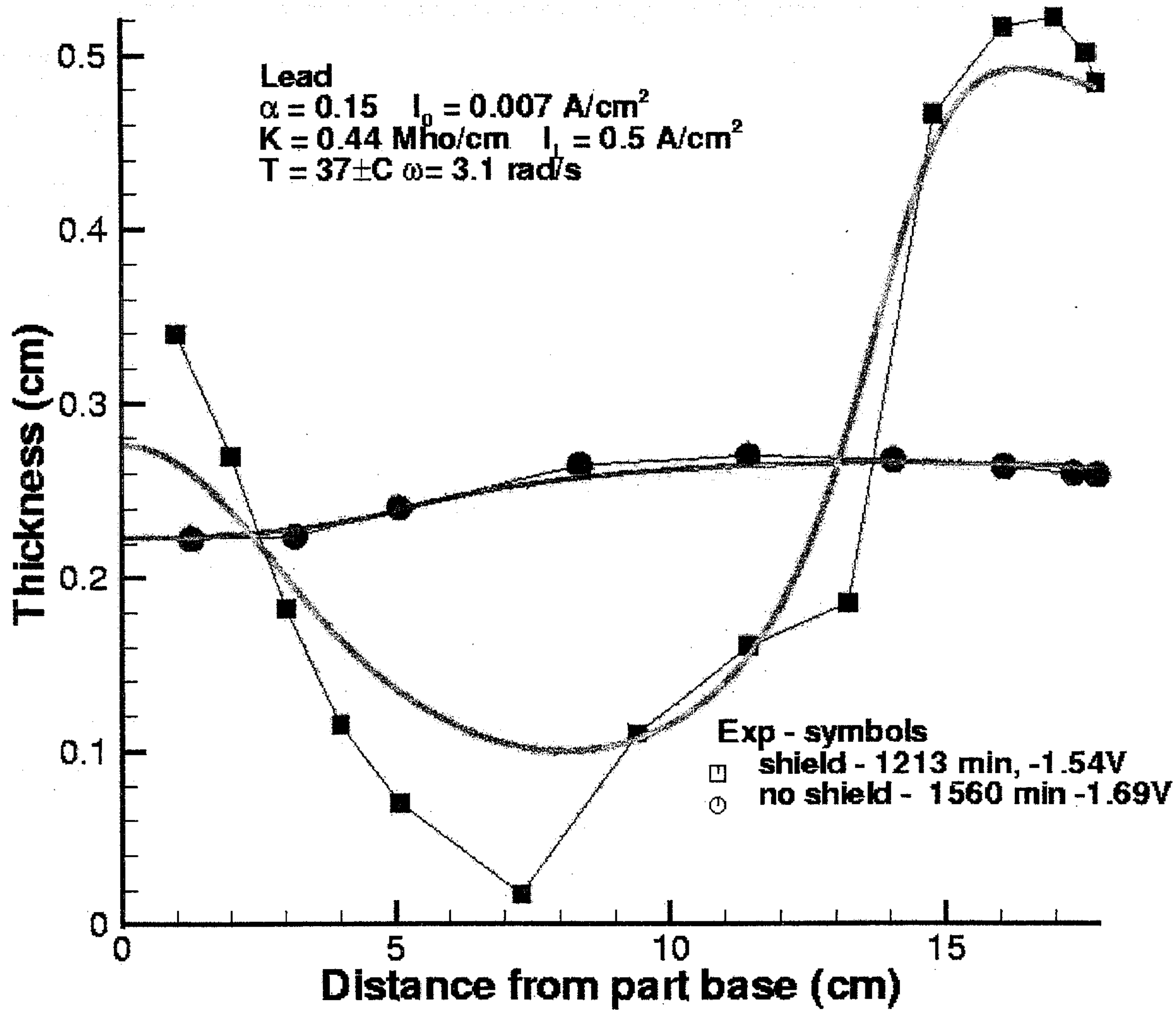


Fig. 1 Comparison of calculated thicknesses with experiments for the hemisphere/cylinder test part.

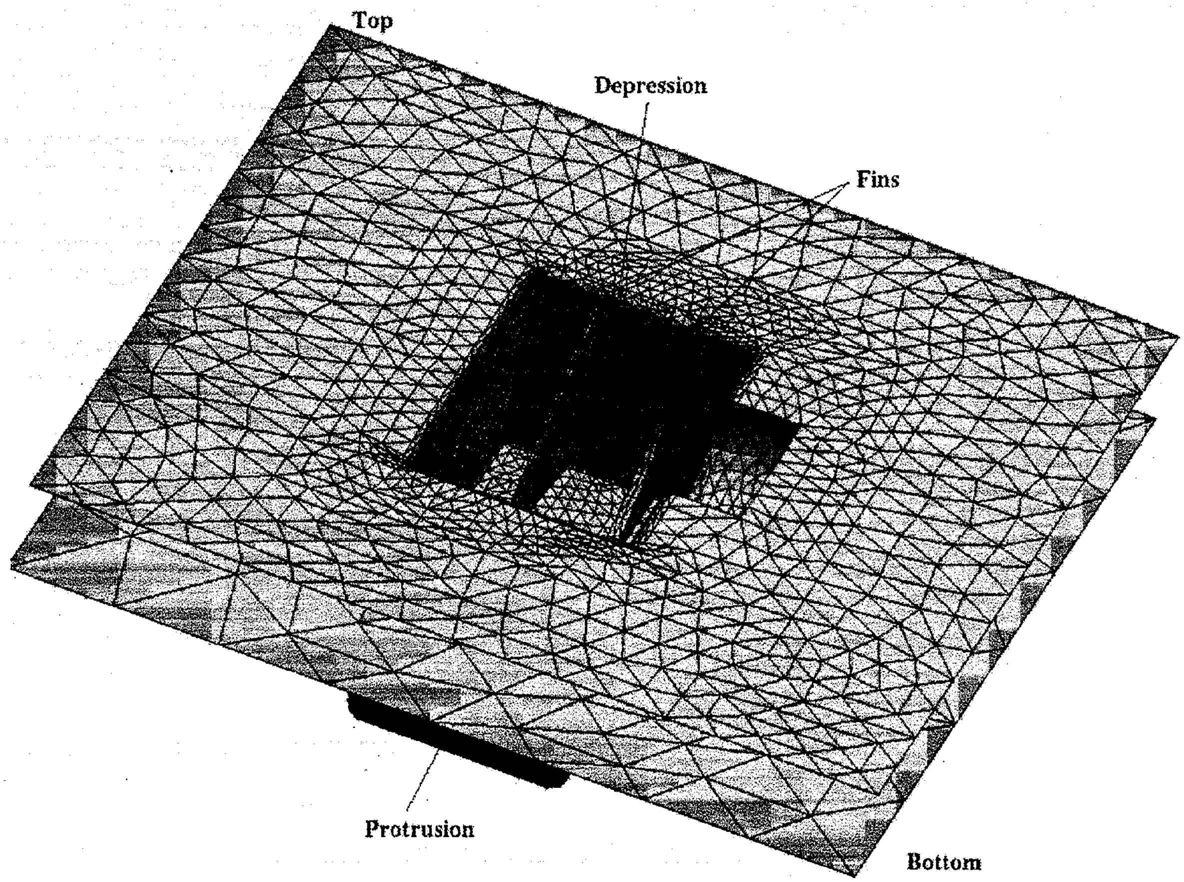


Fig. 2 BEPLATE model of the Cemcom Kodak part electroform.

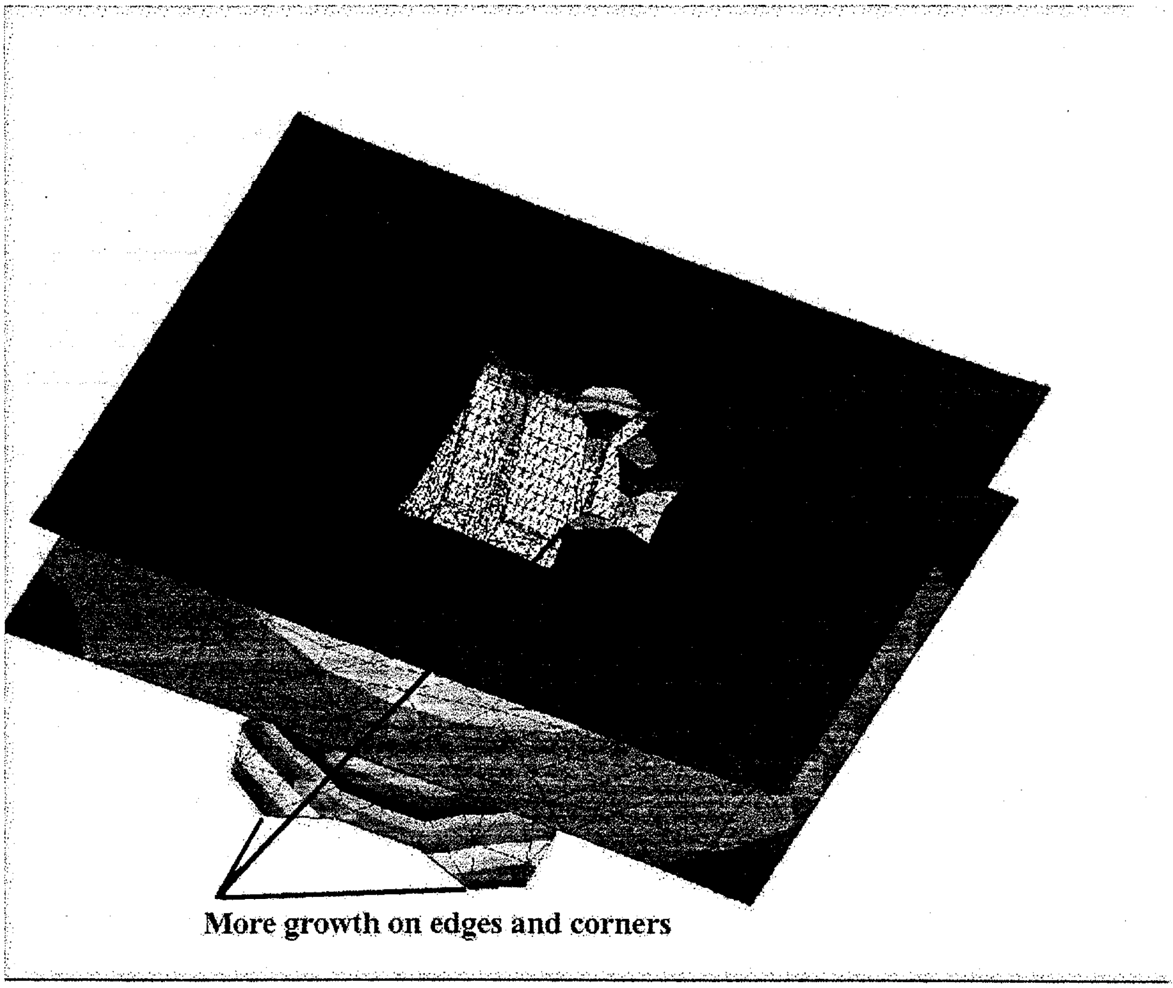


Fig. 3 Final calculated growth surface for the Cemcom/Kodak part mandrel surface with depression.

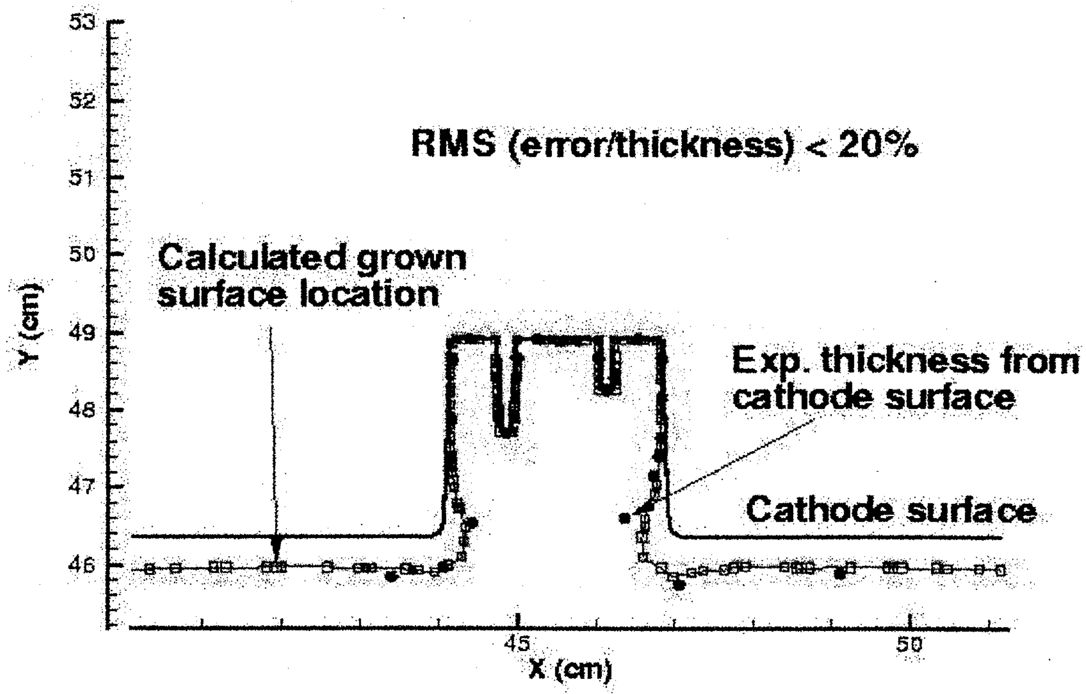


Fig. 4 Comparison of calculated with experimental thickness for the Cemcom Kodak part. Section C-C showing fins and depression. Full span view.

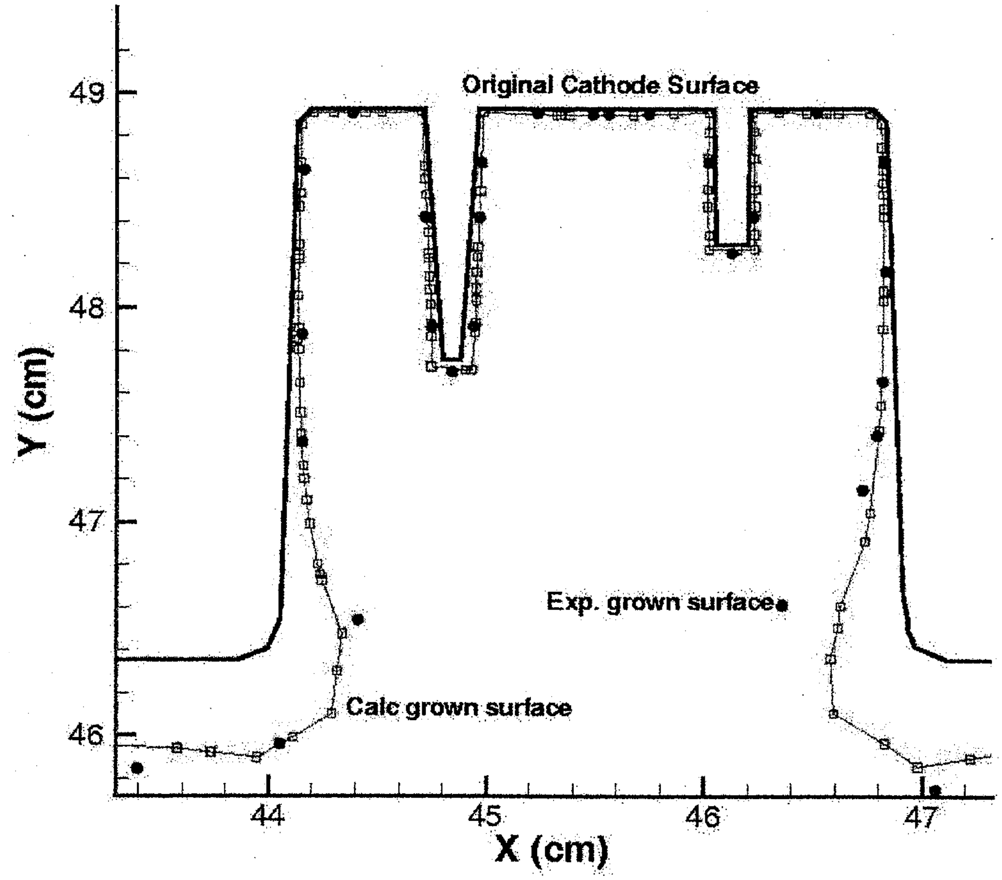


Fig. 5 Detail view of comparison showing depression.

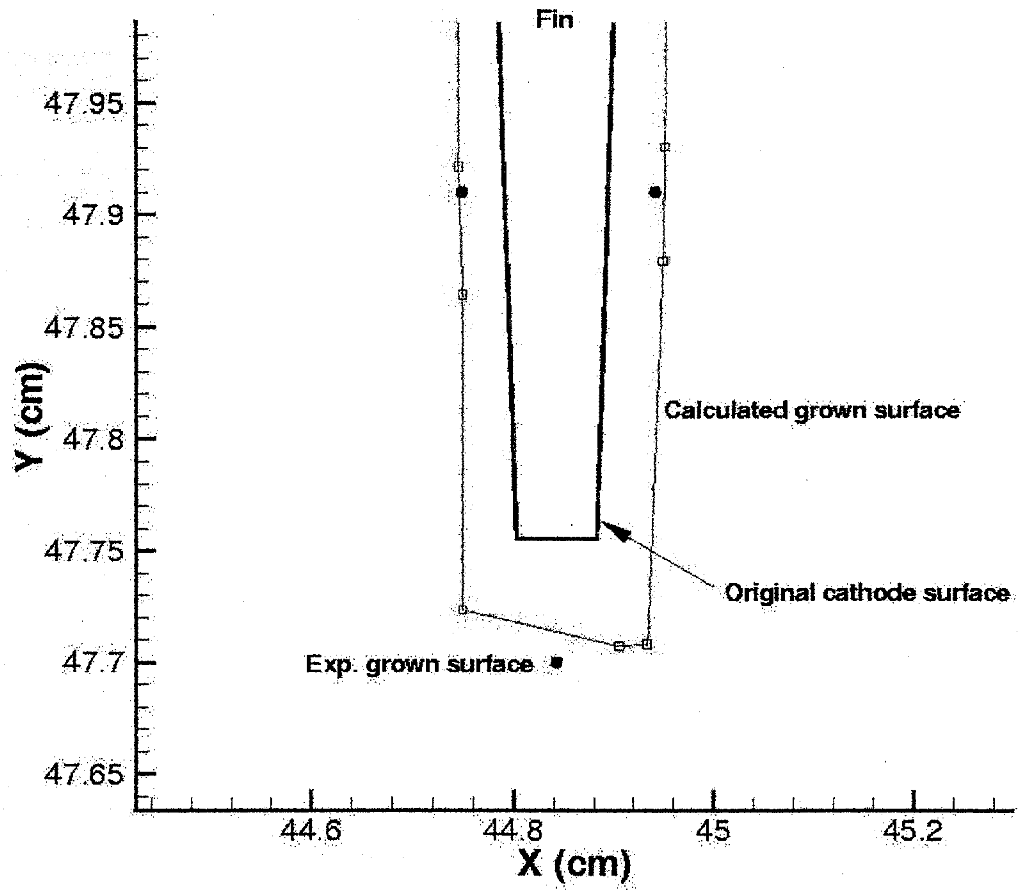


Fig. 6 Detail view of comparison showing fin.

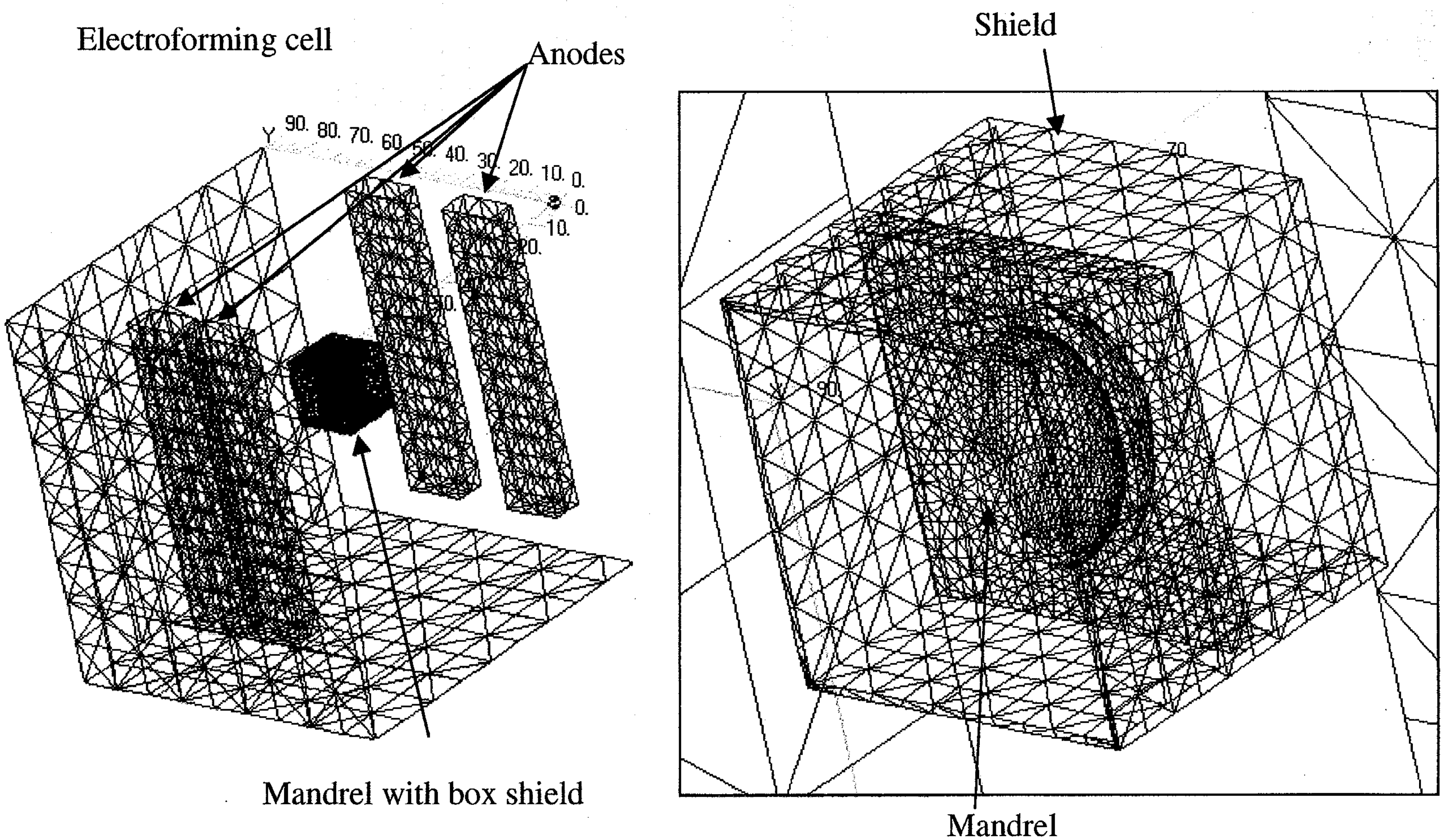
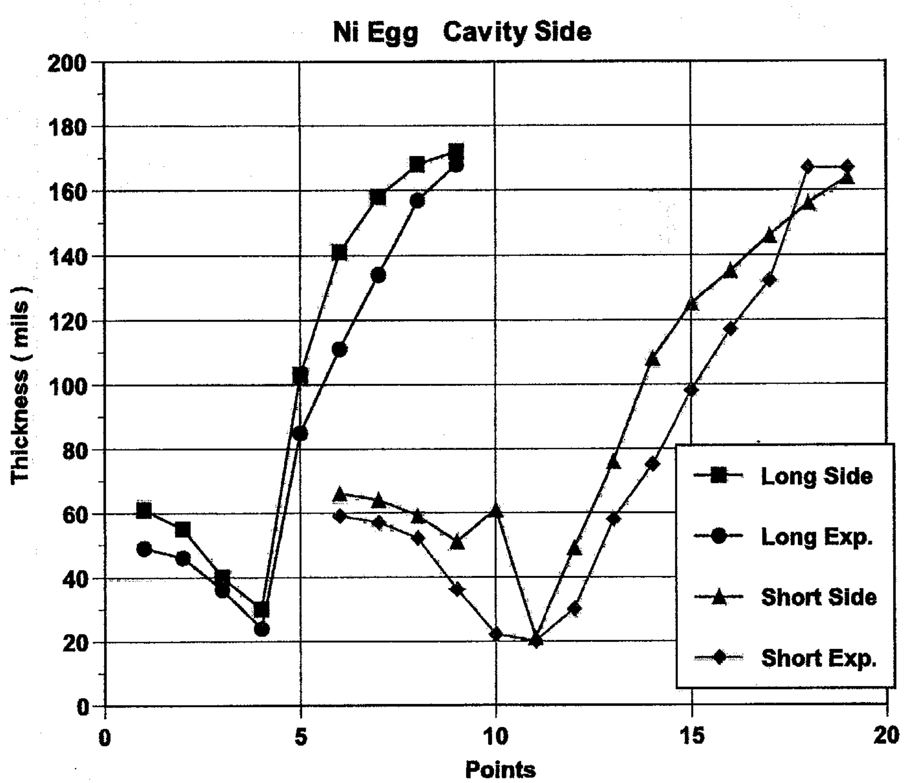


Fig. 7 Cemcom egg model



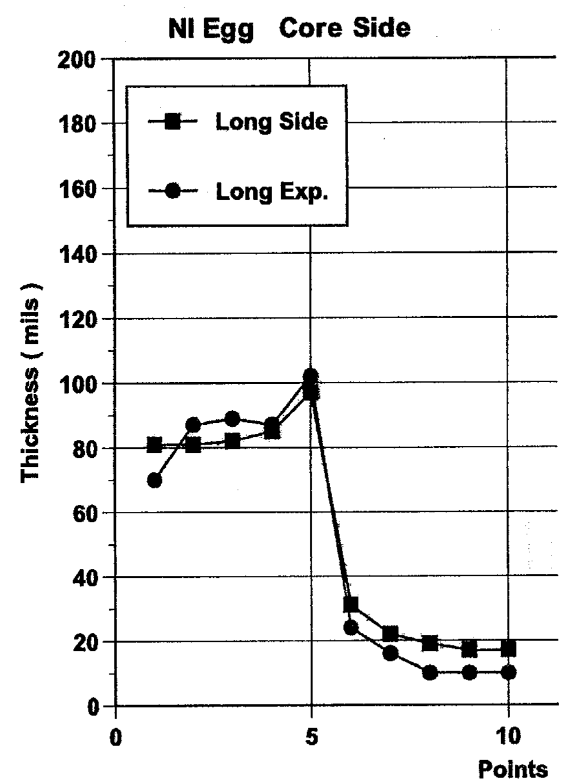


Fig. 8 Comparison of Cemcom application of BEPLATE 1a to egg model with experimental thicknesses for the nickel electroform.

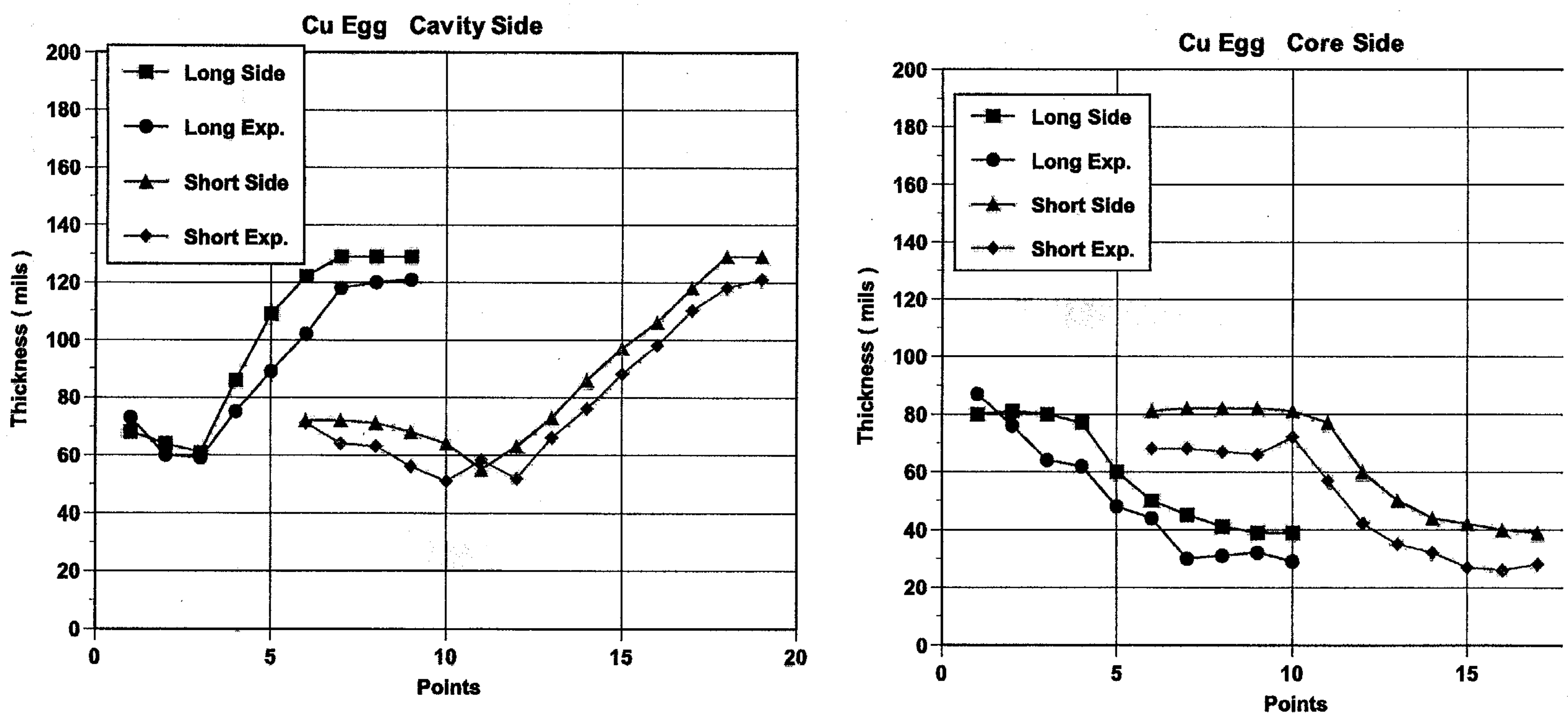


Fig. 9 Comparison of Cemcom application of BEPLATE 1a to egg model with experimental thicknesses for the copper electroform.

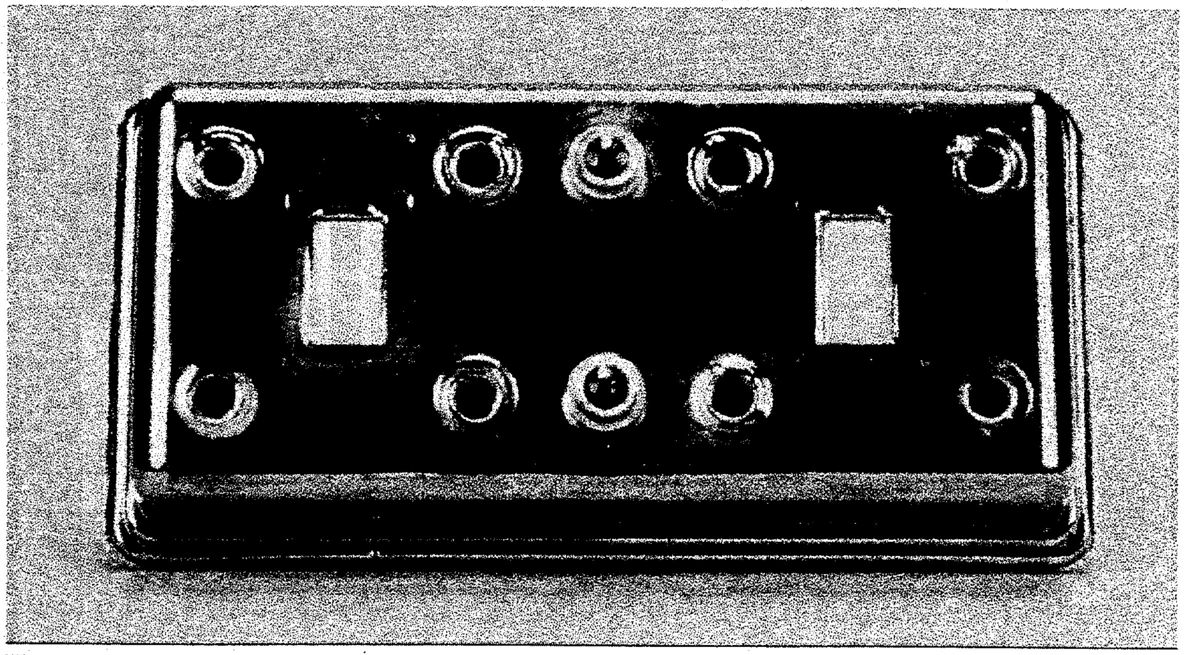


Fig. 10 LMMS Electronic Package electroform

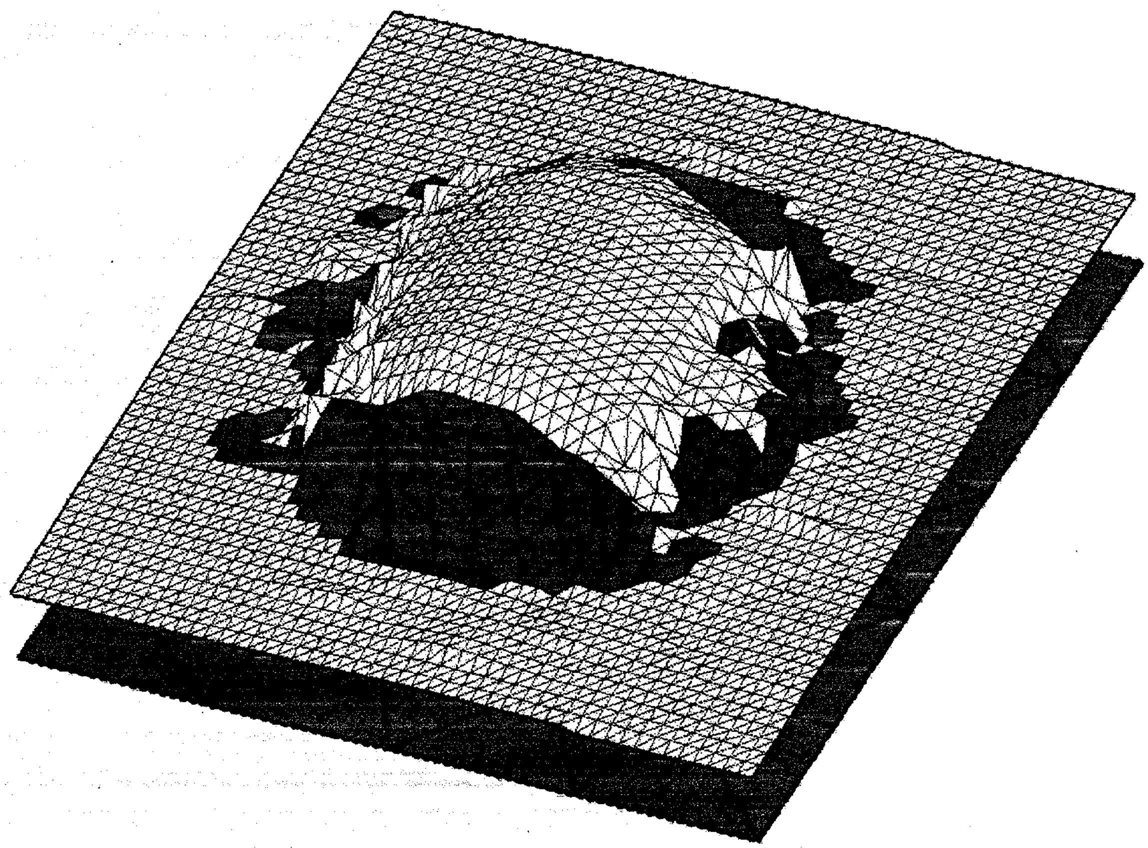


Fig. 11 Sample solid shield generated by KC1 program.

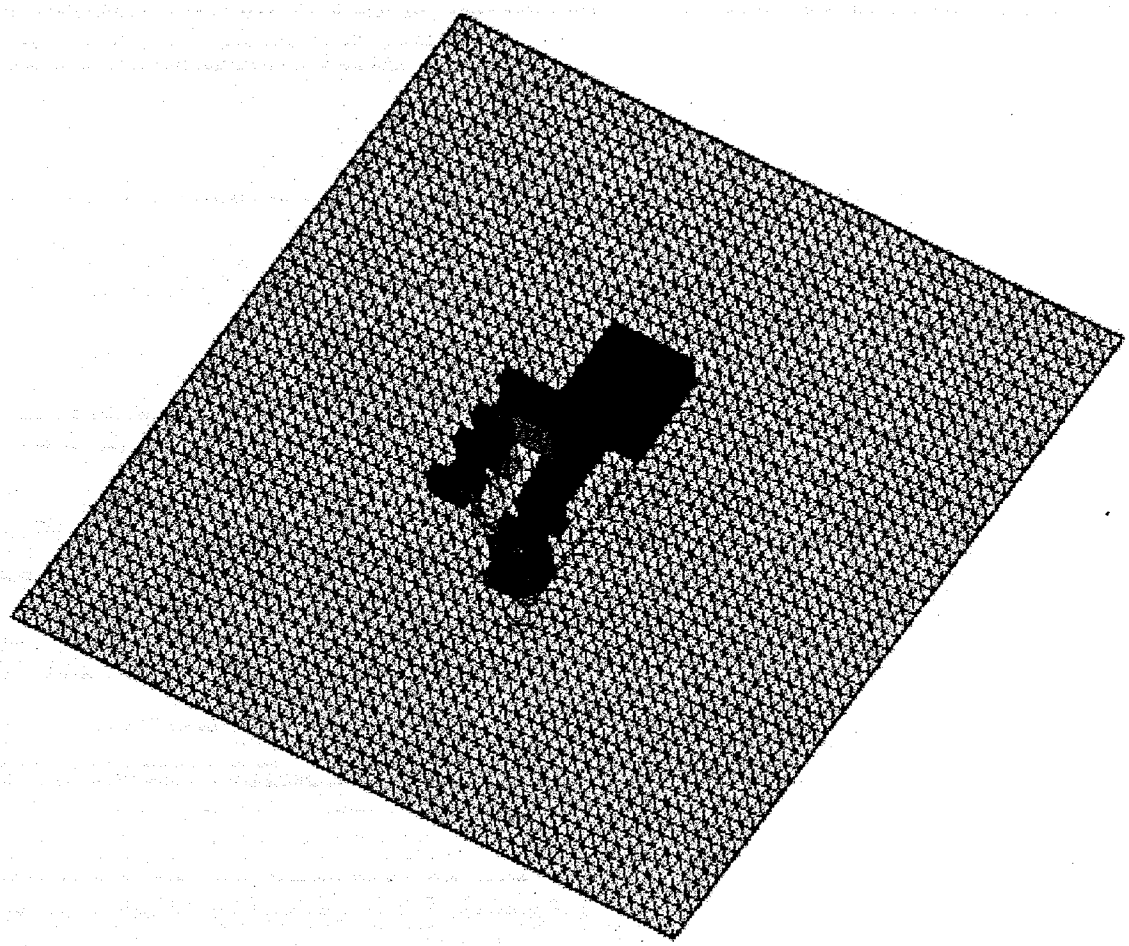


Fig. 12 Sample porous shield template generated by KC1 program. This is a porous shield form before the holes are distributed.

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REFERENCES

1. G. E. Giles, L. J. Gray, J. S. Bullock, IV, *BEPLATE - Simulation of Electrochemical Plating*, K/CSD/TM-89, Martin Marietta Energy Systems, Inc., September 1990.

2. Personal Communication, Darrel Englehaupt, University of Alabama at NASA Marshall Space Flight Center, to Jon S. Bullock, Lockheed Martin Energy Systems, Y-12 plant, May 20, 1997.

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