MASS CUSTOMIZED DESIGN AND MANUFACTURING SYSTEM OF ADVANCED HYDRAULIC PARTS

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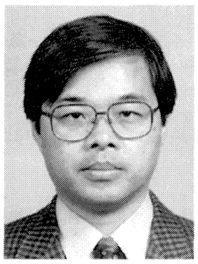

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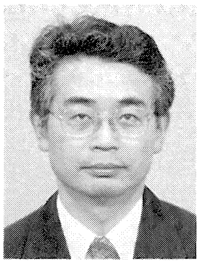

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ABSTRACT

This paper describes a production system for hydraulic parts. The system allows the rapid development and fabrication of hydraulic parts for custom-made pumps through the integration of innovative means and the positive use of three-dimensional digital design information. This unique production system is called "mass-customized production system of hydraulic parts."

The key technologies of this system are:

- Inverse solution design procedure,
- Rapid prototyping of hydraulic models for performance tests,
- Investment precision casting method utilizing rapid prototyping pattern,
- Flexible manufacturing system, and
- Concurrent production control system.

INTRODUCTION

In the past, rapid design of high performance hydraulic parts needed a large volume of background test data of hydrodynamic models and extensive experience for effectively utilizing these accumulated data. Thus, manufacturers of custom-made pumps had to prepare a full line of hydraulic designs for favorable performance and wooden casting patterns for every pump size. Since, however, custom-made pumps require a wide variety of designs and fabrication specifications, the prepared wooden patterns often fail to match the required performance. In that case, the shape of an existing wooden pattern should be modified if possible, or new hydraulic designs should be developed. Then the performance of this modified or newly designed pattern should be subjected to a model test before fabricating the hydraulic parts of the production pump. The manufacturers are requested to complete that process within a short period. With the limitation of time and cost, the design and production of hydraulic parts of custom-made pumps, which should be done under optimum conditions, face many technological compromises.

Owing to the recent developments in CFD technology, however, accurate prediction of pump performance under the conditions at and around the design point has become reality. Furthermore, a design procedure using the inverse solution method (hereinafter referred to as the "inverse solution design procedure"), has been introduced as an innovative design method, which establishes a procedure to automatically design hydraulic parts giving specified performance. Along with the rapid progress of impeller design technology, the *rapid prototyping technology* has made possible the direct production of hydraulic parts having complex 3-D shapes from the respective CAD data within a short time. Since the inverse solution design directly acquires 3-D digital design data, the direct application of the data to the rapid prototyping system provides hydraulic models used for model performance tests within a very short time. The effectiveness of the rapid prototyping system enhanced the shift from 2-D CAD to 3-D CAD, and the 3-D CAD data have also been used positively in precision casting, in numerically controlled (NC) machining, and in automatic measurement of 3-D blade surface profiles. Therefore, conventional thinking relating to experience, cost, and time requested for the development and fabrication of hydraulic parts for custom pumps has gradually changed. *Thus the pump user can obtain made-to-order hydraulic parts for custom pumps quite easily—like those for mass production pumps—and that can decrease cost and delivery time for custom pump users.* The technology innovations relating to the above-described design and fabrication of hydraulic parts have been unified and have been prepared to establish a system for application in the production activities of industrial level hydraulic parts for custom-made pumps. Recently, the whole system has successfully been brought into practical use at an author's factory, and it is now shipping more than a hundred custom-made hydraulic parts every month. The following is the description of the system.

OVERVIEW OF THE MASS-CUSTOMIZED PRODUCTION SYSTEM OF HYDRAULIC PARTS

The whole process of the design and fabrication system for *hydraulic parts* to be used for production pumps is illustrated in Figure 1. The hydraulic design and model test stage includes:

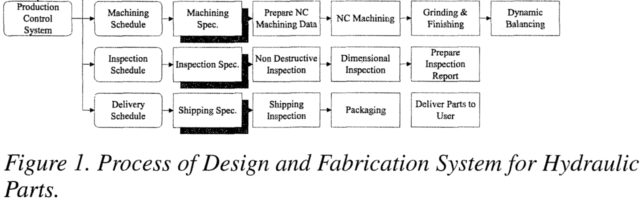

Figure 1. Process of Design and Fabrication System for Hydraulic Parts.

- Inverse solution design.
- Fabrication of 3-D hydraulic parts by rapid prototyping system.
- Performance test using the rapid prototyping model.
- Establish final design.
- Release of drawing to production engineering.

The starting material casting stage includes:

- Design of casting procedure by solidification analysis.
- Fabrication of casting pattern using the rapid prototyping system.
- Investment precision casting of hydraulic parts.
- Starting materials inspection and shipment.

The machining stage of hydraulic parts includes:

- Preparation of NC machining data.
- NC machining.
- Finish grinding.
- Correction of dynamic unbalance.

The inspection stage of hydraulic parts includes:

- Nondestructive inspection.
- Dimensional inspection.
- Formulation of inspection report.

The shipment stage of hydraulic parts includes:

- Inspection before shipment.
- Packaging and shipment for pump assembly.

At the point that the design and fabrication specification of hydraulic parts is established for a production pump, the total development of the design and production sequence begins. Conventionally, the information transmission between design, starting material casting, machining, inspection, and shipment is given in a sequential path. Accordingly, there appears a waiting time after the arrival of information and product from the preceding stage. Owing to the implementation of the inverse solution design, however, the hydraulic design stage has significantly been automated. Further automation is obtained with the rapid prototyping system, the NC machining, and the determination of blade surface profiles using the 3-D modeling data that are the output of the inverse solution design. Thus, along with the release of design data, the works necessary for each individual stage are able to begin at the same time. That is, by adopting the production system using the 3-D modeling data, the information transmission shifts from the series pattern to the parallel pattern. Thus the retention time of information and semifinished components between stages is drastically shortened and each stage work time is also shortened because of the automatization.

In the past, the production of custom-made hydraulic parts, which include the model test and fabrication of the impeller for a production pump of nominal nozzle size of 350 mm (13.78 inches), for example, took about four months at the least. However, the adoption of the parallel mode production system that uses 3-D modeling data shortens the production period to about one and a half months, which is expected to further shorten to one month in the near future. These short delivery characteristics will contribute to the minimization of plant shutdown time due to the lack of hydraulic parts or save the cost of storing spare parts for all pump users.

Table 1 shows the characteristic summary of the present design and manufacturing system in compare with the conventional system.

Table 1. Characteristic Summary Comparing Present System with Conventional System.

	Conventional System	Present System
Design	By experineced engineer utilizing the large volume of back ground	By young engineer utilizing the inverse design method and CFD
Model Test	By NC machined or casting hydraulic parts which takes more than one month for preparation	By rapid prototyping hydraulic parts which takes only one week for preparation
Casting of production parts material	By sand casting utilizing wooden pattern	By investment precision casting utilizing rapid prototyping (RP) pattern
Machining of production parts	By manned machining utilizing general purpose machines.	By unmanned flexible manufacturing system
Quality	Sand casting material level	Precision casting material level
Delivery Time	Typically 4 month	Typicaly 1.5 month
Cost	Typically, one wooden pattern corresponds to 10 pieces of RP patterns	

FUNCTIONS AND ADVANTAGES OF THE HYDRAULIC PARTS PRODUCTION SYSTEM

Inverse Solution CFD Design System

In general, the hydraulic designer first determines the complete geometry of flow passage, including both impeller and casing, based on former experience. Then the flow pattern is calculated by CFD to check whether the pressure and velocity vector distribution along and between the blades is acceptable or not. Whereas, in the *inverse solution design procedure*, the hydraulic designer first specifies the preferable blade loading distribution along the vane surface, and then obtains 3D-blade geometry inversely by the computation.

Regarding the 3-D inverse solution technology for hydraulic geometry, Zangeneh (1991, 1996) and Zangeneh, et al. (1996), provided the basics, and Goto (1995), Goto, et al. (1995), Ashihara and Goto (1999), and Sakurai, et al. (1999), conducted detailed study on the relation between the blade surface loading distribution on the impeller and the performance. According to the theory of Zangeneh (1991, 1996) and Zangeneh, et al. (1996), the flow within the impeller area is assumed as nonviscous and nonrotational. The following procedure is applied to generate the blade profile (Figure 2).

1. The vortex distribution around the complete blade camber surface ($drV_\theta/d\xi$) is specified.

2. The initial profile of the blade camber surface is specified.

3. The velocity vector induced by the vortex layer on the camber surface is computed. Here, the blade thickness is considered as blockage effect.

4. The blade camber profile is modified for the induced velocity vector, not to penetrate the blade surface plane.

5. Steps 3 and 4 are repeated until the modified quantity of the profile becomes less than the preliminarily determined convergence limit.

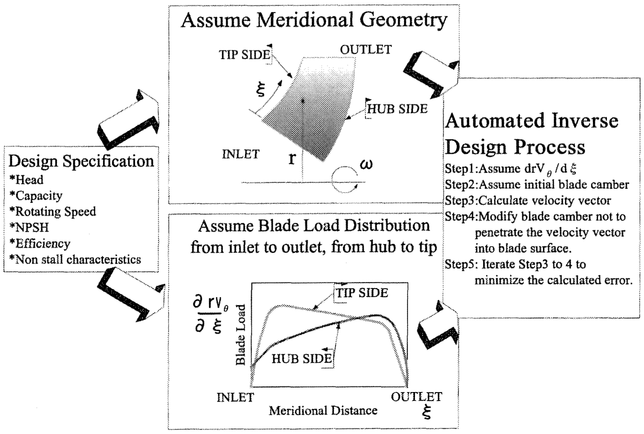

Figure 2. Inverse Solution Design Procedure.

Inverse solution design for various blade-loading distributions has been carried out to give the CFD performance evaluation. The confirmation of the evaluation was given for several design examples through the model tests. The tests revealed that all the performance of hydraulic characteristics, like flow rate versus head, efficiency, $NPSH_R$, can be controlled basically by the impeller and diffuser blade loading distribution profiles for given meridional geometry. Figure 3 shows an example of model test results for a bowl type diffuser pump having a specific speed of Ns 3723 (US gpm, ft, rpm = 560 m, m^3/min, rpm) with the design of four impellers based on the result of the above-described CFD parametric survey.

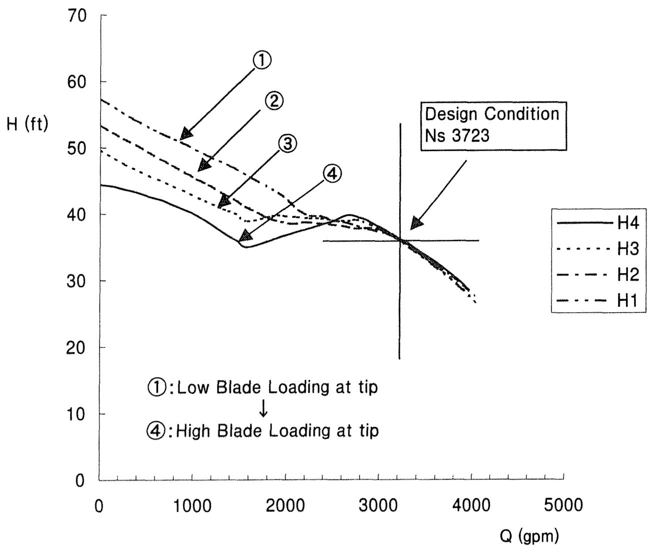

Figure 3. Variation of Performance Curve by Blade Load Control.

The variations of performance curves including higher shutoff head case (Figure 3, item 1) to lower shutoff head case (Figure 3, item 4) appeared successively by moving the location of the blade load peak point at the tip side from the outlet toward the inlet section, while the peak point of blade load for the hub side is fixed at the rear side. The phenomenon, conforming to the expression of conventional design method, corresponds to the pump characteristics that are obtained by varying the exit angle of the blade from small to large. According to the conventional design method, at the time that the blade angle is varied, the blade angle distribution should also be finely adjusted in manual mode to assure smooth curvature of the total blade surface. Since the inverse solution design determines the variations of the blade camber from the inlet to the outlet and from tip to hub in an analytical manner to satisfy the preliminarily specified blade loading distribution, there is no need of specifying the actual blade angle distribution.

When a similar parametric survey is made at several specific speeds, and when the results are displayed in 3-D graphs in terms of specific speed, flow rate, and head, or efficiency and suction performance, the performance curves shown in Figure 4, for example, are drawn. That is, the two kinds of curves that intersect at the 100 percent flow rate line express the upper limit and the lower limit, respectively, of performance obtained from the parametric survey. Therefore, if meridional shapes and blade loading distributions are expressed by numeric continuous functions against pump specific speeds, the shape of the impeller and the shape of the diffuser blade surface within an area enclosed by the curves in Figure 4 are directly determined by the inverse solution analysis.

The inverse solution design is effective not only for control of the head performance curves as described above but also for control of efficiency, suction performance, and compactness. To

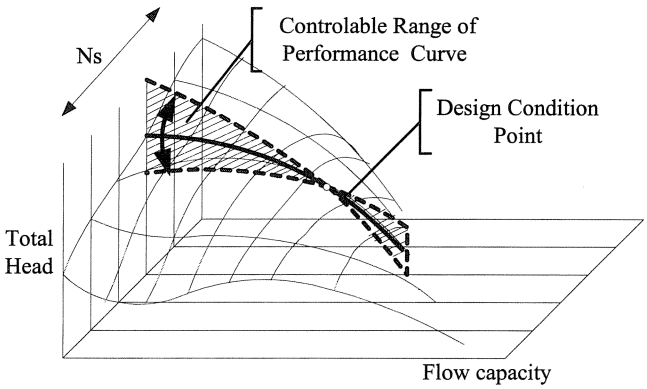

Figure 4. Concept of Continuous Characteristics of Pump Performance Curve by Inverse Solution Design.

obtain a favorable result on these varieties of conditions, however, it is necessary to know how to choose the blade loading distribution. At the beginning of application of the inverse solution design approach, even an experienced designer took about one week in the trial and error computations over several tens of cycles. An automatic design system was established using optimized algorithms, so that the nearly optimized solution is derived within about three days without human interface.

Figure 5 shows the result of manual calculations and the automatic computations for attaining the optimum solution of suction performance for a mixed flow type impeller having a specific speed of 9000 (US gpm, ft, rpm = 1350 m^3/m, m, rpm). Here, a simulated annealing (SA) algorithm was adopted for the optimization method. The optimization computation took about 70 hours.

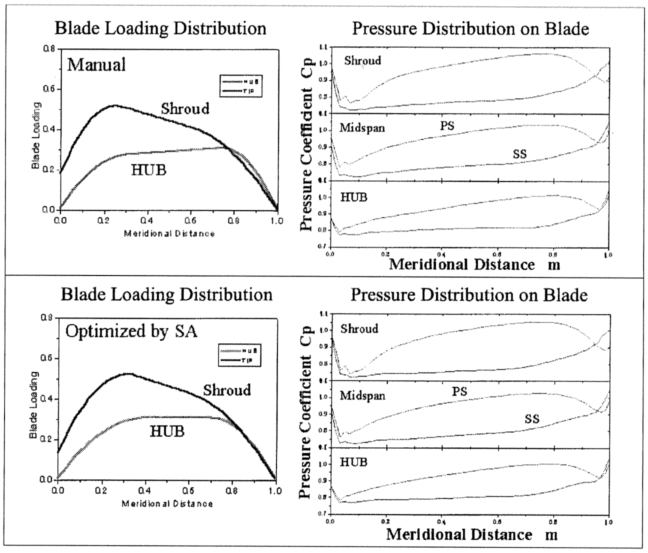

Figure 5. Comparison of Blade Loading and Pressure Distribution for Mixed Flow Pump Obtained by Manual and Automatic Optimization Method.

The inverse solution design procedure has been applied to develop various types of pumps such as bowl type diffuser pumps, volute pumps, multistage pumps, sewage pumps, etc. For these types of pumps, optimum design parameters have been established realizing highest efficiency, highest suction performance, smallest size, nonstall characteristics, limit load characteristics, etc., in a wide range of specific speeds.

3-D Modeling System

The blade surface shape that was determined by the inverse solution design procedure is analytically established to satisfy the target blade loading distribution. Consequently, there may occur a complex wavy pattern of the blade surface that would not be intentionally adopted in conventional manual design. If the 3-D blade surface profile is converted into a 2-D developed drawing that expresses the profile only by a typical cross section, the analytically obtained fine curved surface profile may not be accurately reflected. Therefore, a 3-D CAD system for hydraulic parts has been developed, as shown in Figure 6, by customizing commercially available CAD software. According to the system, the blade surface profile obtained by the inverse solution design can be combined with the preliminarily optimized shroud and hub meridional shape. The system also automatically gives the fillets between blade and shroud or hub. With such a system, solid model data of the complete impeller are prepared in about 30 minutes from the file of the blade surface.

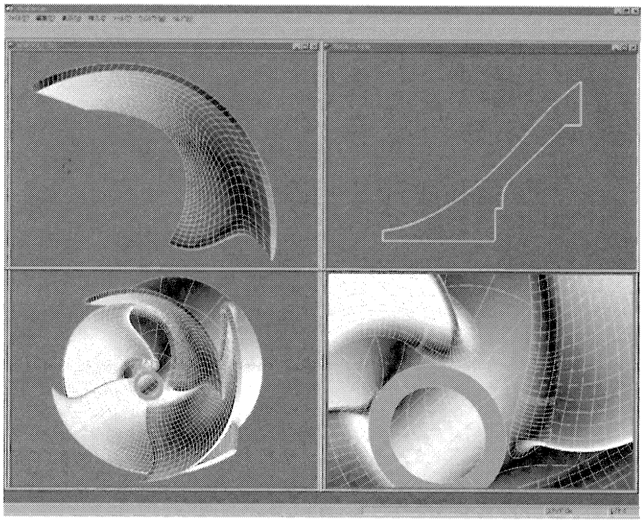

Figure 6. 3-D CAD System Customized for Hydraulic Parts Modeling.

Rapid Prototype Fabrication of Hydraulic Model

Owing to the improvement in performance estimation accuracy applying the inverse solution CFD design, the necessity of a model test for validation of various hydraulic designs significantly reduces. However, because of the inadequate accuracy under the current CFD technology, such as, for example, performance at off-design condition or cavitation behavior, a conventional model test should be conducted to verify detailed performance.

To reflect the blade surface profile determined by the inverse solution design accurately into the actual impeller and diffuser blade surfaces, NC machining may be applied to aluminum or bronze blocks using 3-D blade geometry data. The NC method, however, requires both a long time and high cost for fabrication, so it cannot be readily applicable. To this point, the rapid prototype (RP) fabrication technology was applied successfully, and significantly reduced the cost and time of the model test. That is, as for the fabrication of impellers, a selective laser sintering system (SLS) apparatus was used to form a high-strength glass nylon resin model of up to 360 mm (14.17 inches) in diameter (Figure 7). Instead a laser stereotype lithography (LSL) apparatus was used for the casing or diffuser model, as it permits production of a large size epoxy resin model of up to 800 mm (34.5 inches) (width) × 1200 mm (47.24 inches) (length) × 1000 mm (39.37 inches) (heighth) in mono block size (Figure 8).

In the case of the inverse solution design, 3-D modeling of the blade surface has already been established at the point of the completion of design. Therefore, once the solid model data are applied to the RP system by adding the thickness for the shroud and hub, the succeeding configuration-forming actions are

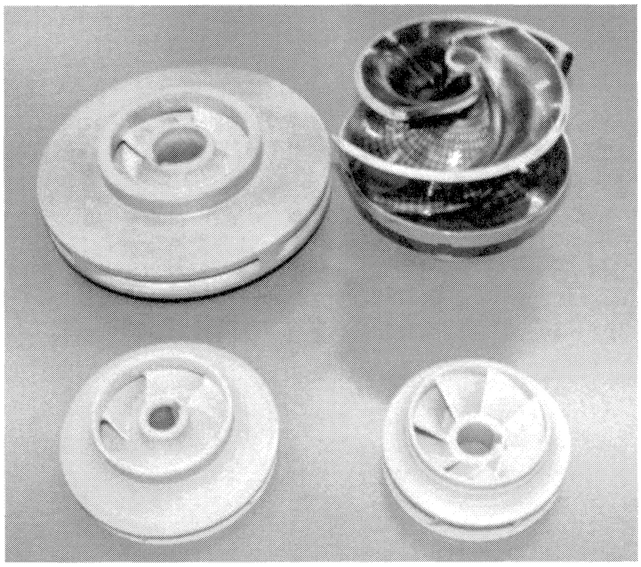

Figure 7. Glass Nylon Resin Impeller for Model Test.

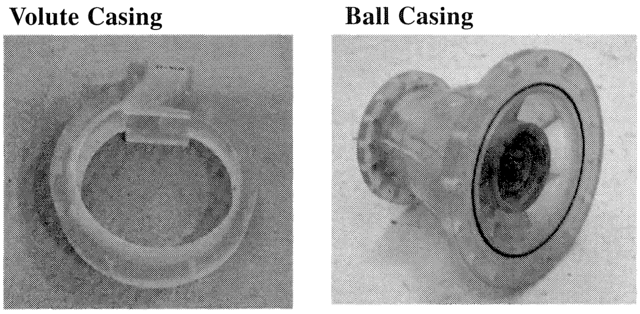

Figure 8. Epoxy Resin Casing for Model Test.

conducted without human interface. In the case of typical hydraulic model tests, the time necessary for fabricating a complete set of impeller and bowl diffuser casing models is a total of about one week. In the case of NC machining, the time is at least about one month for one complete set of hydraulic parts because of the sequence of the following steps needed: ordering starting material, rough machining of outer profile, computation of NC cutter paths, NC machining, and parts assembly. In the case of the rapid prototyping system, the starting materials are resin powder or liquid, which are filled in the apparatus so there is no need for preparation of material ordering and other preliminary actions. In the case of the RP model, a lamination step of around 0.1 mm (.0039 inch) has to be used, which results in generation of a fine stripe pattern on the blade surface. Thus, an emery paper finish is applied after impregnation with urethane resin and then a coating using a surfacer on the urethane resin surface is applied. Therefore the completed hydraulic models are set on a 3-D measurement system (coordinate measurement machine (CMM)) and the blade profiles are accurately checked (Figure 9). Typically a dimensional error exists around 0.2 mm (.0079 inch), which is satisfactory for a normal 300 mm (11.81 inches) diameter impeller used for the model test.

The RP model-based hydraulic model test system is quite effective not only for the development of new hydraulic design, but also for the design of retrofitting parts that are often necessary to improve the efficiency or change the operating condition of an existing pump.

Hydraulic Model Test System

The hydraulic model is placed in an exclusive-use performance testing apparatus, which allows a general performance test and

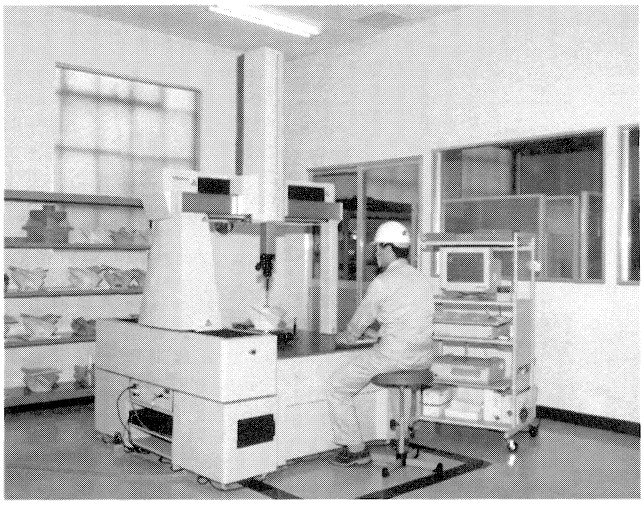

Figure 9. 3-D Dimensional Measurement System for Hydraulic Parts.

reversing flow characteristic tests in full-automated mode. The apparatus is fitted with an audio/video system, thus enabling a simultaneous investigation of various kinds of measured parameters like pressure pulsation, vibration, and, with motion pictures of flow patterns, acoustic signals, etc. (Figure 10).

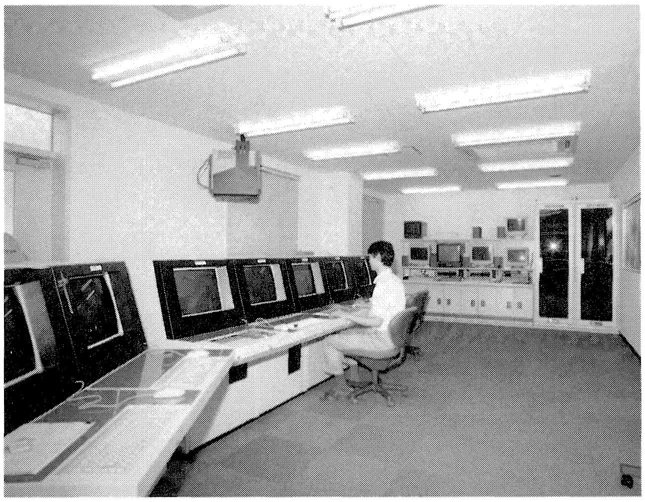

Figure 10. Pump Model Test Facility Utilizing Multimedia System.

FABRICATION OF HYDRAULIC PARTS FOR PRODUCTION PUMPS

Investment Casting Using RP Pattern

For the same reason as the test model components, the investment precision casting process using the RP technology was also adopted for the fabrication of hydraulic parts for production pumps. The RP system fabricates directly a lost form pattern for casting, or indirectly a wax model via a master model, which is then applied to the investment precision casting process to produce the metallic hydraulic parts. The SLS system produces polystyrene resin models up to about 360 mm (14.17 inches) in diameter. The LSL system produces epoxy models with honeycomb structure up to about 800 mm (34.5 inches) in diameter. The time for forming 300 mm (11.81 inches) diameter impellers for SLS is about 10 hours, and 800 mm (34.5 inches) diameter impellers for LSL is about 90 hours. The nominal dimensional accuracy is 0.2 mm (.0079 inch) for the former, and 0.4 mm (.0158 inch) for the latter.

Investment casting is a known method of lost wax precision casting. According to the investment casting process, a wax model prepared by an injection molding die is applied by multiple layers of slurry and sand to form a mold shell. Then the wax inside the shell is melted off by heating the shell to about 160ºC (320ºF) in an autoclave. The shell is further fired at high temperatures, and then the liquid metal is poured into the shell to obtain the precision cast. Instead of the wax model, an RP model made of polystyrene or epoxy resin may be used. In that case, the firing temperature should be as high as about 1000ºC (1832ºF) to remove the resin from the shell. To prevent crack generation on the mold caused from releasing gas during the high temperature firing, the thickness of the casting shell must be about double that of the lost wax process, which is a major difference from the lost wax process (Figures 11 and 12).

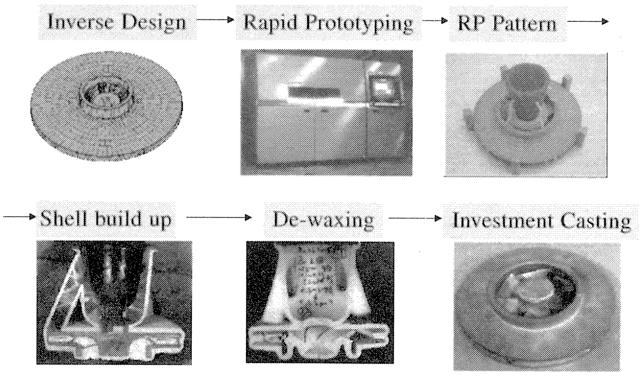

Figure 11. Investment Precision Casting Process Utilizing RP Pattern.

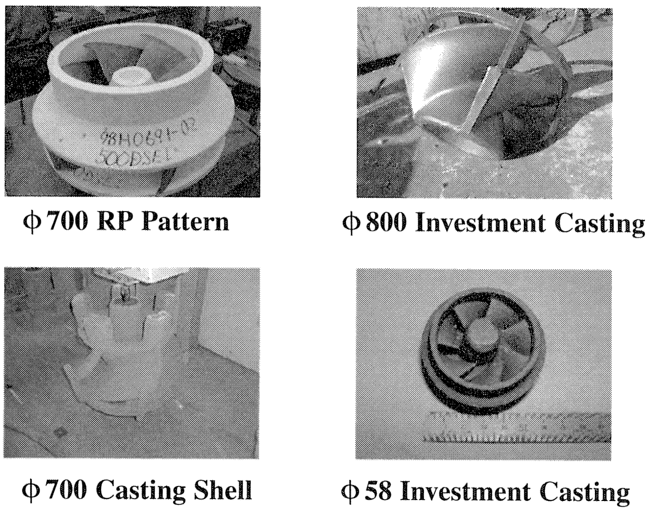

Figure 12. Examples of Investment Precision Casting Impellers and RP Pattern.

Investment casting using the RP model needs no injection-molding die, and needs only a 3-D model for production without human interface. However, polystyrene powder or epoxy resins as the starting material of the RP model are more expensive than ordinary wax, and requires several days for forming. Accordingly, the production number of the RP models is around 10 casts. For more than 10 casts, the RP model is used as the master model. The master model is transferred to a silicon rubber inverse mold, from which further models are obtained (Figure 13). In the case of a rubber mold, the wax models can be used to form up to around 100 casts. Compared with metallic die, however, the process for cooling and solidifying the wax model requires a lot of time, so that the model forming time is about four hours per cast. For producing a plurality of large casts exceeding 600 mm (23.62 inches) in diameter, combined models are also applied, in which only the blades are produced by the RP model for cost reduction, while the axisymmetrical parts, such as shroud and hub, are made of polystyrene resin.

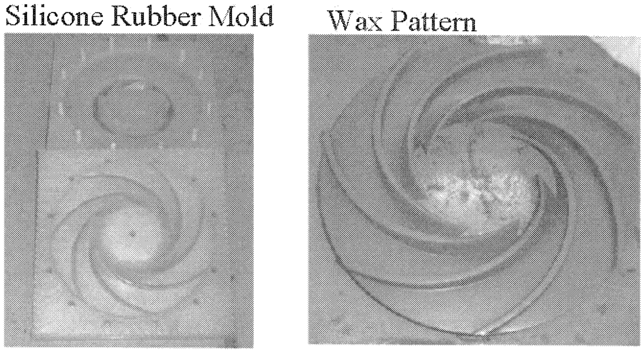

Figure 13. Silicone Rubber Mold Made from RP Master Model.

In the case of investment casting, after pouring the molten metal into the casting shell, the known methods to control the solidification process are limited, so the casting procedure is particularly important. To this point, the most advanced technology for casting and solidification analysis has been implemented to predict the generation of strain and voids for optimization of casting the procedure (Figure 14).

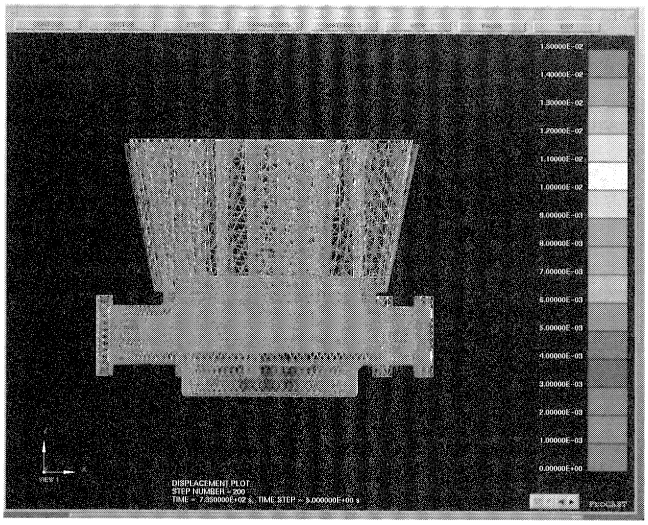

Figure 14. Solidification Analysis for Investment Casting Process.

Investment casting using the RP model of the 300 mm (11.81 inches) diameter impeller takes a total of 10 days, i.e., two days for the RP model fabrication and jigs assembling, three days for shell formation, one day for mold disjoining and shell firing, one day for pouring melted metal and shell disjoining, and three days for post-treatment such as heat treatment, etc. In the case of the pattern lost wax method, however, the pattern preparation alone takes about two months. Therefore, the throughput times for small lots of custom-made products is shortened to about one sixth or less. That may introduce a great benefit for custom pump users requesting short delivery time.

Unmanned Machining by Flexible Manufacturing System

The hydraulic parts are machined by a flexible manufacturing system (FMS) comprising a five-shaft machining center, a turning machining center, an optical alignment unit, an automated transfer machine, an automated warehouse, and a computer numerically controlled (CNC) machine (Figure 15).