MODERN MANUFACTURING OF ADVANCED IMPELLER AND DIFFUSER VANE PROFILES

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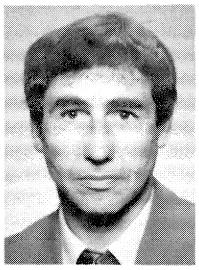

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Mr. Nicklas joined KSB's fluid dynamics research center in 1974 with responsibility for the development of improved vane profiles to reduce the risk of cavitation damage to boiler feed pumps. He has many years' experience in the hydraulic improvement of multistage pumps and fundamental research in the field of cavitation erosion.

Mr. Nicklas received a degree (Mechanical Engineering) at Darmstadt Technical University, Germany, where hydraulic machinery and plant engineering were the major fields of his studies.

ABSTRACT

Both fluid dynamics and manufacturing technology have seen rapid progress over the last few years. Vane profiles need no longer be developed in cavitation demonstration experiments, but can be optimized by computerized numeric simulation. Five-axis milling machines and four-axis electric-discharge machining tools permit manufacturing of the most complicated contours. These modern manufacturing techniques make it possible to work boiler feed pump impellers and diffusers out of a single forging block, complete with front shroud.

The manufacturing process begins with numeric simulation and profile optimization directly on the screen; the hydraulic engineer then transmits the 3D data online to the manufacturing engineer; and the vane channel is divided into several segments so that the impeller/diffuser can be manufactured from the solid blank.

The hydraulic, manufacturing and materials development steps made over the last few years are outlined herein.

INTRODUCTION

The last 20 years of boiler feed pump development have been characterized by a rise in power station block outputs. Economic reasons called for a corresponding increase in pump speed from 4700 to over 5000 1/min, which inevitably entailed a rise in the flow velocity at the impeller inlet from 66 to 72 m/s. Although booster pump heads were increased in line with the technical data then available ($NPSH_R \sim w_1^2$; w_1 = relative velocity at impeller inlet), unexpected cavitation damage occurred after just a few months of operation (Figure 1).

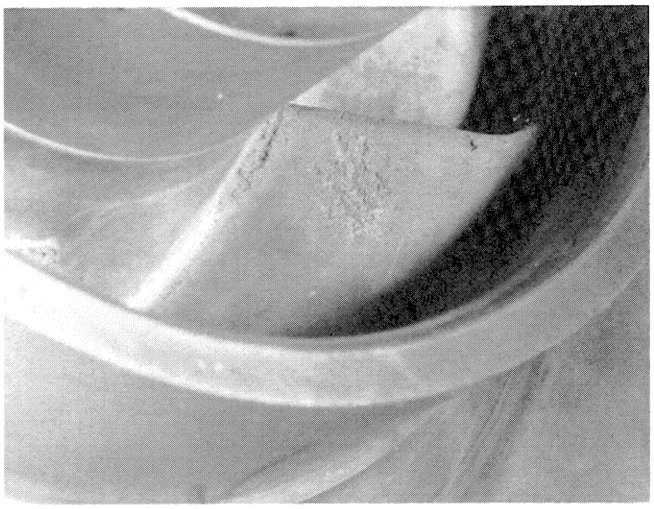

Figure 1. Cavitation Erosion on a Double-entry Impeller after a Few Hundred Operating Hours. Material: 1.4008 (CA 15), Brinell hardness 280. Geometry: inlet diameter D_1 = 266 mm; angle β_1 = 15°. Pump speed: 5200 1/min.

Two available approaches to solve this problem were:

- an increase in booster pump heads from 130 to 250 m for coal-fired power stations and to more than 400 m for nuclear power plants.
- the hydraulic improvement of the suction stage inlet geometry.

The first solution is, of course, extremely uneconomical. The second solution was deemed to be more reasonable and presented a challenge to development engineers from various specialist fields.

Issues dealt with were the improvement of the intake elbow, the use of a vaneless diffuser and, as a key focus, the development of appropriate vane profiles for the suction impeller.

For pumps without speed control, a vane profile for a larger operating range (low flow to optimum) had to be developed.

In general, the development of favorable vane profiles for these pumps covered impellers and diffusers. Efficiency and mechanical strength improvements were additional aspects under consideration. The systematic development approach resulted in exacting accuracy requirements for the production of appropriate vane profiles.

Realization of these precise profiles (± 0.1 mm ≅ 0.004 in) initially presented considerable difficulties. An improved production method combining fluid dynamics, manufacturing technology and materials know-how at a very early stage was called for. The extensive interdisciplinary development efforts to solve the given problem are outlined herein.

HYDRAULIC DEVELOPMENT STEPS

Impeller

Original-scale model pumps were used to simulate system conditions at reduced speed. The objective was to visualize and analyze the onset of cavitation and then make appropriate changes to the inlet geometry to improve the cavitation behavior.

The major results of the extensive theoretical and experimental work are summarized in Figure 2 [1]. The NPSH values for incipient cavitation ($NPSH_i$) are plotted as dimensionless parameters ($\sigma_{u_i} = 2\,g\,NPSH_i / u_i^2$) as a function of the flowrate (load point). The "incipient cavitation" state corresponds to a cavitation bubble trail length of approximately 5.0 mm.

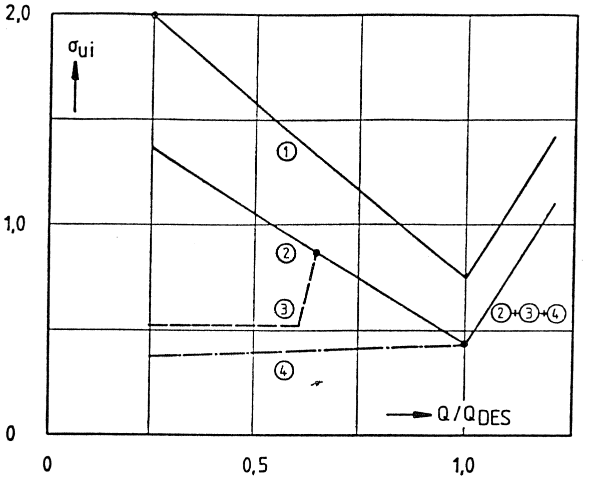

Figure 2. Dimensionless Incipient Cavitation Values Versus Relative Flow Rate. 1) Conventional profile; 2) Improved profile No. 1; 3) As (2) with diffuser; and 4) Improved profile No. 2 with diffuser.

When using a profiled vane the $NPSH_i$ values at design point can be roughly reduced by half, which permits a corresponding reduction in the booster pump head.

To the left and right of the design point ($Q_{shock\text{-}free}$) the $NPSH_i$ values rise steeply, since the angle of incidence becomes larger. Under low flow conditions, a marked minimum pressure point will appear in the suction-side vane leading edge area.

A vaneless diffuser installed directly upstream of the impeller (Figure 3) has a positive influence on the low-flow $NPSH_i$ curve (Curve 3 in Figure 2). The diffuser prevents expansion of the low-flow vortex against the inlet flow direction; the low-flow vortex cannot reach the inlet elbow's flow-straightening vanes, where it would be slowed down abruptly, causing disturbances in the impeller inlet flow.

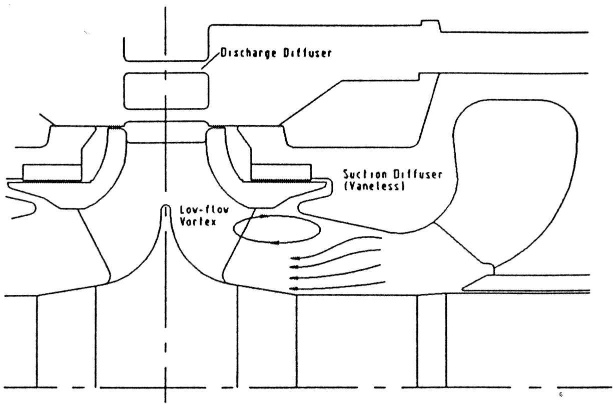

Figure 3. Double-entry Impeller with Suction Diffuser and Discharge Diffuser.

The vortex caught in the diffuser causes a displacement of the inlet flow towards the hub and a marked increase in the meridional velocity component c_m. In addition, the low-flow vortex in the direction of rotation imparts a slight preswirl (c_u component) to the hub flow. These two phenomena result in a rapid enlargement of the inlet flow angle β in the hub area accompanied by a smaller incidence angle (reduced shock component), which in turn leads to a sudden drop in the $NPSH_i$ curve.

Specific applications (for example boiler feed pumps for pressurized water reactors > 1000 MW) require bubble-free longterm operation even under low-flow conditions [2]. The stringent requirements to be met triggered the development of a special profile for duty points in the optimum and low-flow range [3]. This profile yielded an approximately horizontal $NPSH_i$ curve (Curve 4 in Figure 2). Compared with the conventional profile, the $NPSH_i$ values were reduced by a factor of three to four in the low-flow range.

It must be kept in mind that the special low-flow profile is easily affected by manufacturing inaccuracies. The first cavitation bubbles do not appear at the vane leading edge, but a bit further along the vane. Small manufacturing inaccuracies, even roughness, will promote rapid growth of the relatively thin cavitation bubbles.

Diffuser

For some years now, profiling has also been applied to diffusers. In the case of diffusers, this technique is generally not intended to prevent the formation of cavitation bubbles, since the pressure increase produced by the preceding impeller is usually sufficient under low-flow and full-load conditions. A minimum pressure point is avoided by making the distance between diffuser and impeller vanes large enough (Gap B in Makay and Barrett [4]).

Diffusers are profiled for the following reasons:

- Improvement of the diffuser vane stability, in particular for open milled diffusers, which do not have a front shroud, but abut against or are screwed to the stage casing. Profiling of the vane leading edge area will roughly double the vane's thickness. Since the square of the vane thickness is used for stress calculation at the vane base, this yields a quadruple increase in vane stability.
- The vane profile is less affected by unfavorable incidence angles. In the low-flow operating range pressure fluctuations and dynamic radial forces are reduced. A less intensive impeller/diffuser interaction results in lower instationary loading of the vanes.
- With profiled vanes, flow separation on the vane suction side will occur later at smaller flowrates. Thus H/Q curve instabilities can be eliminated or at least shifted to smaller capacities (Figure 4).
- For the preceding reasons, vane profiling increases pump efficiency in the low-flow operating range (Figure 4).

On the whole, vane profiling provides an effective additional technique of reducing the effects of impeller/diffuser interaction, supplementing the measures widely employed so far, such as the selection of appropriate diffuser vane positions and suitable combinations of impeller and diffuser vane numbers.

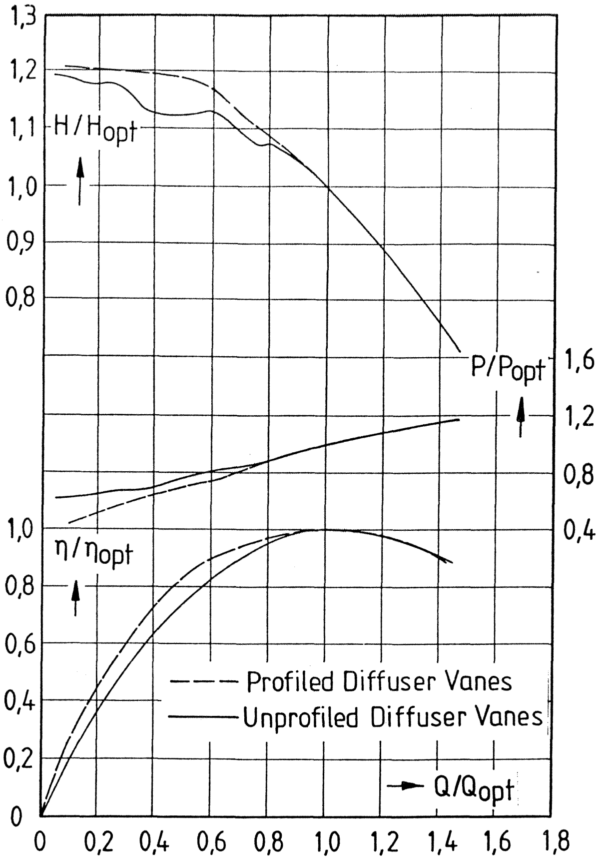

Figure 4. Influence of Diffuser Vane Profiling on H/Q Curve and Efficiency.

MANUFACTURING DEVELOPMENT STEPS

Impeller

The first vane profiles were produced by grinding sand cast impellers with meltout vanes. In a cavitation test carried out using a stroboscope on a model pump equipped with plexiglas components, the best vane profile was determined, i.e., the vane with the shortest cavitation bubble trail. A plastic mold was made of the suction-side vane surface and then transferred to electric-discharge machining electrodes by copy-milling. The system impellers machined with the aid of these electrodes rarely met the requirements of the cavitation test. Owing to the accumulation of manufacturing tolerances (vane thickness, vane pitch, leading edge level, contour deviations of the electrode caused by subsequent manual grinding, alignment inaccuracies of the electrode holders, etc.) the original cavitation behavior could not be reproduced for all vanes. Although the suction-side vane contour could be produced with relative accuracy (close shape tolerances) by using templates, the vane position (i.e., vane angle) frequently showed major deviations (large positional tolerances). This resulted in cavitation damage even on profiled vanes because of unsatisfactory manufacturing tolerances.

In a second step, the vane suction side was additionally hard-faced with a material (Stellite 6) that had shown the lowest wear in cavitation erosion tests. The complex profiling process became even more complicated. Preliminary electric-discharge machining served to remove base material for the subsequent hard-facing process. Hard-facing (surfacing by welding) resulted in vane deformations, small cracks in the transition zone between hard metal and base metal, and cracks in the transition zone between vane surface and wall. To reduce residual stress, each hard-facing process had to be followed by heat treatment.

For a double-entry impeller, for example, 36 machining steps were planned in the operations schedule. Since the final cavitation test often yielded negative results, the number of machining steps increased considerably when subsequent hard-facing operations became necessary. Some impellers had to be rejected as scrap, since due to the vane deflection towards the vane suction side, the hard-facing material was removed again by the electric-discharge machining process.

In a next step, impellers with thicker vane profiles on the vane pressure side were cast, which prevented the vane from deforming through hard-facing. Then the additional material on the difficult-to-access vane pressure side had to be removed again (by electric-discharge machining and finish-grinding).

The thicker vanes required new casting methods: precision casting or ceramic mold casting. Initially, wax residues in the surface impaired bonding between the base and hard-facing materials. Therefore, the surface had to be ground prior to surfacing by welding.

The as-cast state of an impeller is shown in Figure 5. The thicker vane profile on the pressure side (back side) cannot be seen. What is clearly visible, however, is the recess on the suction side provided for subsequent surfacing by welding (Figure 6). The finished impeller—after electric-discharge machining on the suction and pressure side and smoothing of the transition zones—can be seen in Figure 7.

The last stage in the hydraulic development of a high-precision, low-flow profile revealed the limits of the methods employed so far and necessitated a different approach (DESCRIPTION OF A NEW METHOD section).

It must be recalled at this point that radial impellers milled in open design and then equipped with a weld-on front shroud do not offer a viable solution for power engineering applications for reasons of stability, accessibility and inspection.

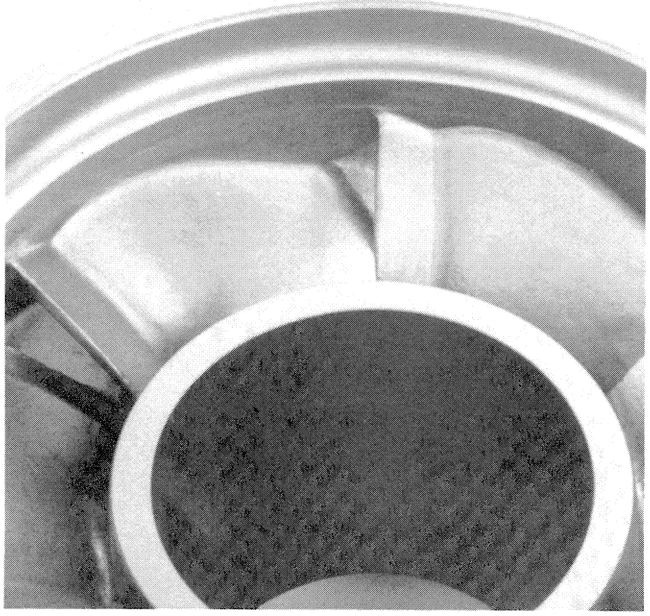

Figure 5. As-cast State of a Cast Impeller. The suction-side vane surface has already been specially shaped for subsequent surfacing by welding.

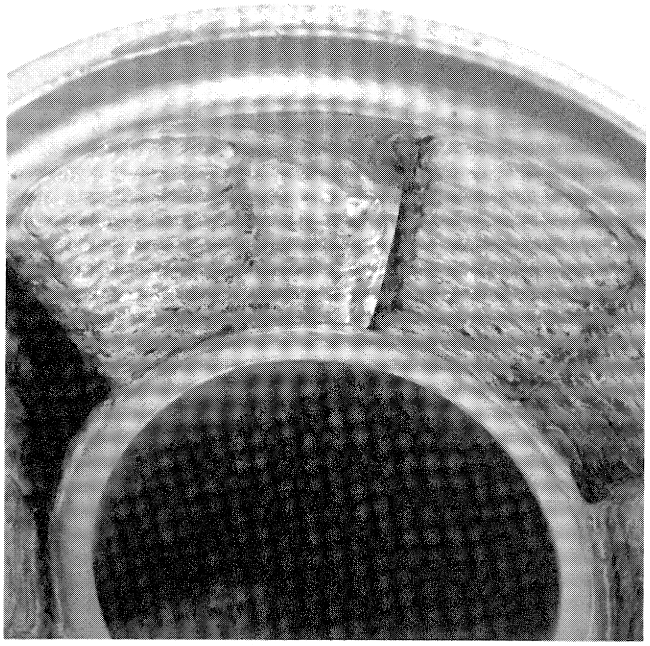

Figure 6. Impeller Vanes Immediately after Surfacing by Welding.

Diffuser

Diffusers are traditionally cast. They are either designed as open or closed (with front shroud) diffusers. For multistage pumps this also applies to the return guide vanes downstream of the 180 degree turn. Above all, an open design is used for smaller diffusers subject to low mechanical stresses. Advantages are: simpler manufacturing (free shaping) and better access to the vane passages and diffuser leading edges, that can be ground and polished after casting to improve the efficiency.

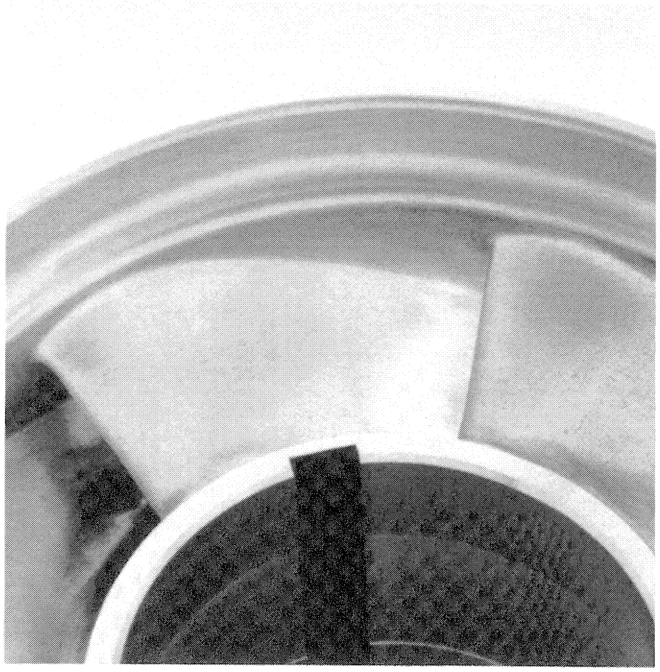

Figure 7. Impeller after Electric-Discharge Machining and Smoothing of Transition Zones.

This method is very inefficient, in particular for multistage pumps. Consequently, manufacturers began at a very early stage milling such diffusers with cylindrical vanes from a cast or forged blank. Higher costs of production are frequently offset by cutting down on pattern, machining, and test run costs.

Return guide vanes are of secondary importance for achieving the hydraulic data. Therefore, they are often cast in one piece with the diffuser blank. Then the diffuser passages or vanes are milled. This approach is of great significance for standardized modular design considerations. The pump's optimum efficiency can be shifted towards larger or smaller capacities by appropriate impeller and diffuser designs. The cast return guide vanes remain unchanged or are just turned down laterally (reduction of vane height).

Diffusers subject to higher loads are equipped with a front shroud that is usually brazed on. A more complicated technique is guidance in grooves and welding. Screwed joints are not possible because conventional vanes are too thin at the maximum-load point (vane leading edge area).

The hydraulic design progress (reinforcement of the vane leading edge area by profiling) has, in many cases, eliminated the need for brazing on a front shroud. All the same, a front shroud is often retained for safety reasons.

Diffusers subject to maximum loads (stage heads of 600 to 800 m) are as a rule provided with a cast-on shroud, or a diffuser worked out of a forged block is used. The latter represents the most sophisticated manufacturing stage. In analogy to impeller production, the passageways are milled and electric-discharge machined from the forged material. This method allows achievement of hitherto unachieved accuracy and stability levels. Vane profiles for the low-flow operating range as described under the *Diffuser* section can be produced without difficulty.

MATERIALS DEVELOPMENT STEPS

The hydraulic and manufacturing technology development in pump engineering has always gone hand in hand with continuous materials improvement aimed at fighting corrosion, cavitation, and abrasion damage and improving static and dynamic stability.

Cast Materials

For boiler feed pumps in power engineering and numerous other applications, the G-X5CrNi134 cast steel (DIN material No. 1.4313 = ASTM A 487, CA-6NM) has been generally accepted in Germany. A reduction of the carbon content to approximately 0.05 percent and the addition of 3.5 to 5 percent nickel improved the material's weldability, increased its toughness and reduced its susceptibility to cracking. In addition, this steel grade has much better corrosion properties than traditional chromium steels (e.g., G-X20Cr14). Owing to the low carbon content, the material's chromium content becomes almost fully effective for passivation, which results in good resistance in boiler feedwater. After hardening and annealing, the cast 1.4313 steel has a microstructure of an annealed martensite (Figure 8) and a nontransformable austenite, which, however, is not visible under the microscope.

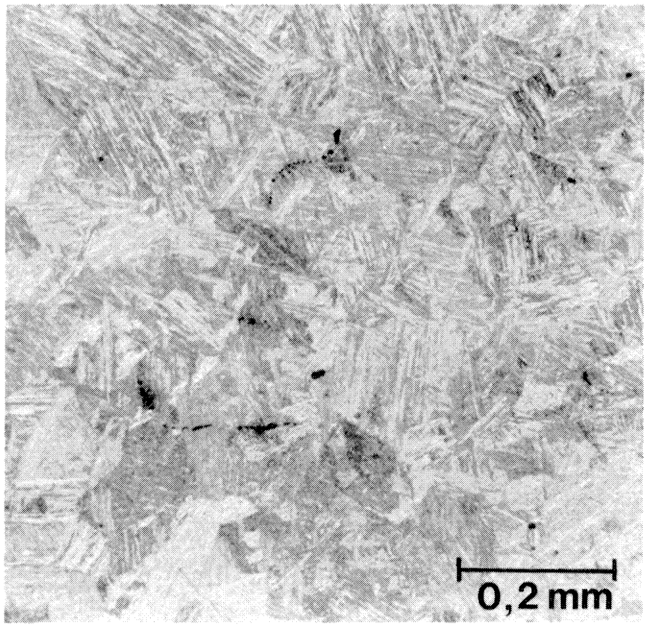

Figure 8. Microstructure of Cast G-X5CrNi134 Steel with Inclusions and Blowholes.

Complicated single and double entry pump impellers with curved vanes that have to meet high technical requirements have traditionally been cast. Although the casting quality meets the ASTM-E 71 specifications, class I, it is substantially influenced by the casting method used.

- The probability of casting defects, pores, and blowholes when manufacturing the complicated three-dimensional impellers is very high. Dye penetrant tests must be carried out to verify the absence of fissures or cracks.

- The casting tolerances are relatively large. Depending on the absolute impeller dimensions, a vane thickness tolerance of ± 2.0 mm (for a vane thickness above 15 mm) and ± 1.0 mm (for a vane thickness of 6.0 mm) must be taken into account. The tolerances for the other vane dimensions range at ± 3.0 mm compared with the nominal dimensions. The modern, hydraulically improved profiled vanes require tolerances (± 0.1 mm) that are difficult to achieve with traditional methods. Subsequent treatment by grinding or electric-discharge machining is indispensable.

- The cast structure shows relatively coarse grains. The mean grain size is 0.2 mm, which has so far been accepted by the pump industry in consideration of the production method.

- Scale residues in the impeller vane passages and chromium depletion on the casting surface are additional, metallurgical reasons for subsequent machining of the impellers. The surface texture of the casting requires expensive and time-consuming grinding.

The microstructure of a cast impeller made of 1.4313 with blowholes and casting defects is shown in Figure 8. In spite of the weaknesses of the manufacturing method, the casting of complex, three-dimensional shapes (impellers, casings, etc.) was a significant technical achievement. It was in fact an indispensable prerequisite for manufacturing large pumps and compressors with improved hydraulic properties. The process benefits and the improvements developed in foundries have a long tradition of being applied by pump engineers to enhance their own products.

Weldability Allows Production of Composite Impellers

The low carbon content of 1.4313 cast steel ensures the material's good weldability. This positive characteristic is taken advantage of both by foundries and the pump industry. The pump manufacturer can produce pump components by welding; for example, by separately manufacturing an open impeller and a front shroud and then welding them together, or by breaking down a double-entry impeller design into several simpler parts. In short, the material's weldability allows composite impeller manufacturing.

In addition, operational damage can be remedied by repair welding.

Production welding is often an integral part of the manufacturing process in foundries and serves to eliminate casting or manufacturing defects. It is used to ensure the specified external and internal casting quality. The production weld should have the same mechanical properties as the base metal. The casting's residual stresses should not jeopardize its intended use and are relieved by annealing.

All welding processes are subject to stringent welding procedure codes. In the pump industry, procedure qualification tests are carried out in close cooperation with the relevant authorities and the operators. Even production welding in the foundry is subject to the general approval of the power station operator.

Hard-facing of Impellers

The described cavitation damage on pump impellers called for material-based solutions, for example hard-facing 1.4313 cast steel (base metal) with cavitation-resistant materials like Stellite 6. In Figure 9, the superior cavitation characteristics of Stellite 6 as hard-facing material on 1.4313 cast steel are depicted. The erosion behavior of Stellite 6 is shown as a function of cavitation intensity on a test rig specially set up for cavitation wear testing [8]. For comparison, SiC, a Noridur duplex steel and the 1.4313 steel used were tested under the same conditions. The processing stages of surfacing impeller vanes made of 1.4313 with Stellite 6 and subsequent electric-discharge machining to achieve the required tolerances and improve the surface quality are illustrated in Figures 5 through 7.

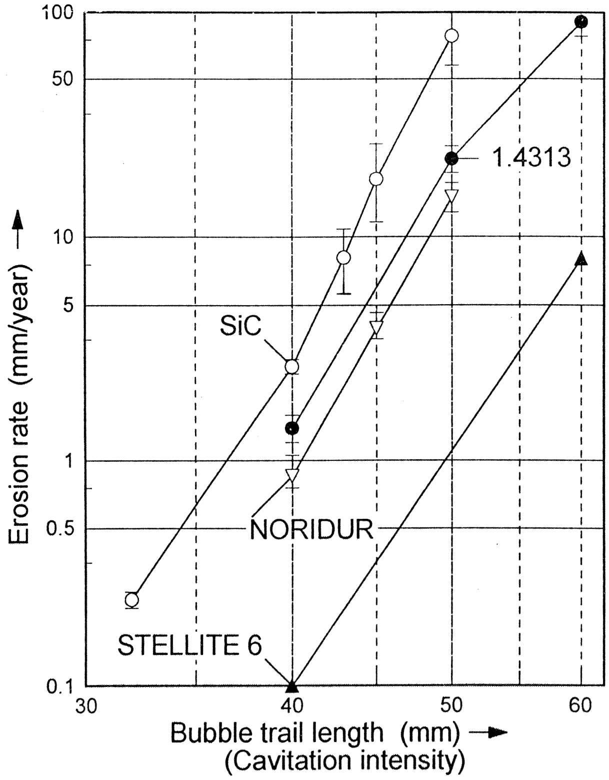

Figure 9. Loss of Material by Cavitation Erosion as a Function of the Cavitation Intensity for Stellite 6, SiC, Noridur, and 1.4313.

Forged Materials

Forged parts of martensitic materials have been available for pump engineering applications for quite some time now and are typically used for shafts, casings and casing components [9]. The new manufacturing techniques have opened up new possibilities of producing impellers and diffusers from a *single forging block.* The microstructure of forged 1.4313 steel, which is superior to the cast structure, is shown in Figure 10.

- The microstructure is characterized by fine-grained martensite with a mean grain size of 0.05 mm; the martensite is homogenous and without flaws.

- Heat treatment of the fine-grained forged material at 400°C yields the following mechanical properties: tensile strength 1280 MPa, yield point 1020 MPa, elongation at failure 15 percent. The cast material annealed at 400°C to 530°C does not achieve these mechanical values: tensile strength 900 to 1050 MPa, yield point 850 MPa, elongation at failure 12 percent.

- A forged and machined part does not suffer from chromium depletion on the surface; no scale residues are found in the impeller vane passages after manufacturing.

- An impeller manufactured from a forged block does not need metallurgical surface inspection. Dye penetrant tests to detect cracks and ultrasonic testing to detect blowholes and defects are not required. In addition, there is no need for production welds, since machining will not uncover blowholes or porous areas.

The obvious metallurgical advantages offered by forged components, manufacturing benefits like narrow tolerances and hydraulic improvements (profiled vanes) all add up to a new advanced manufacturing approach.

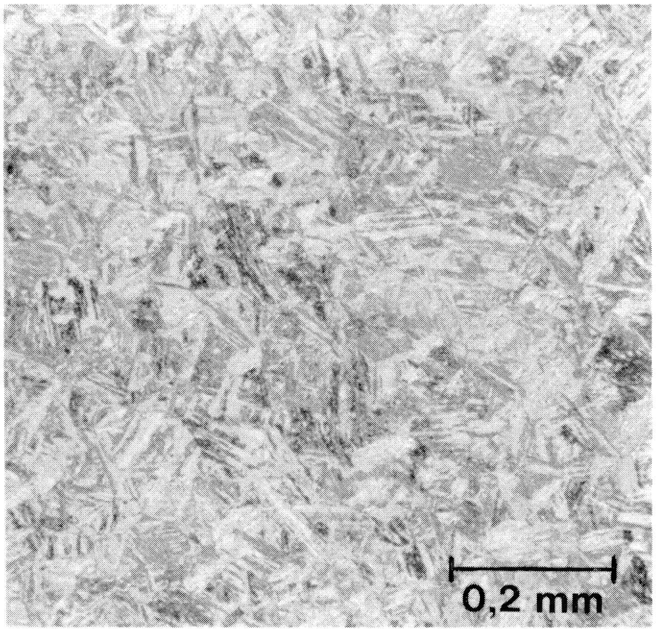

Figure 10. Microstructure of Forged X5CrNi134 Steel.

DESCRIPTION OF THE NEW METHOD

Numerical Flow Simulation and 3D Surface Modelling

At first, the main dimensions of the impeller (or diffuser) must be determined for the given hydraulic data (Q, H, η, NPSH, slope of the characteristic curve). The computerized definition of the meridional section is either based on a model hydraulic design, possibly modified, or done from scratch based on the available know-how.

The next steps include the calculation of the meridional velocity, determination of partial flow paths and correction based on the radial balance. Then the number of vanes, the estimated vane thickness, the vane angle variations, and the position of the vane leading and trailing edges are defined.

The most important step is the interactive optimization of the vane shape along a streamline (flow path section) and assessment on the basis of the pressure distribution. The pressure distribution is computed using a singularity flow method [5], which simulates the pressure distribution around the vanes very well in spite of the frictionless calculation. An exemplary computation for a profiled and an unprofiled vane is presented in Figure 11. The required meridional velocity is calculated by a Q3D method. These flow calculation techniques are not as effective as computer codes based on Navier Stokes differential equations (application examples in Cooper, et al. [6]), since they cannot be used to localize recirculations. In spite of their limitations, they are well-suited for the task to be solved, i.e., predicting the pressure distribution, which in turn will help pinpoint the onset of cavitation. This has been confirmed by the fact that the theoretical and experimental results agree very well [3].

The vane profile is designed using up to 100 computation points both on the vane suction and pressure side (Figure 12). In the vane leading edge area, these points lie very close to each other to define the critical area for minimum pressure points as accurately as possible.

The point sequence is mathematically described by cubic polynomials or B-splines. B-splines permit local adaptation of the curve. For a presentation of the 3D surfaces (suction and

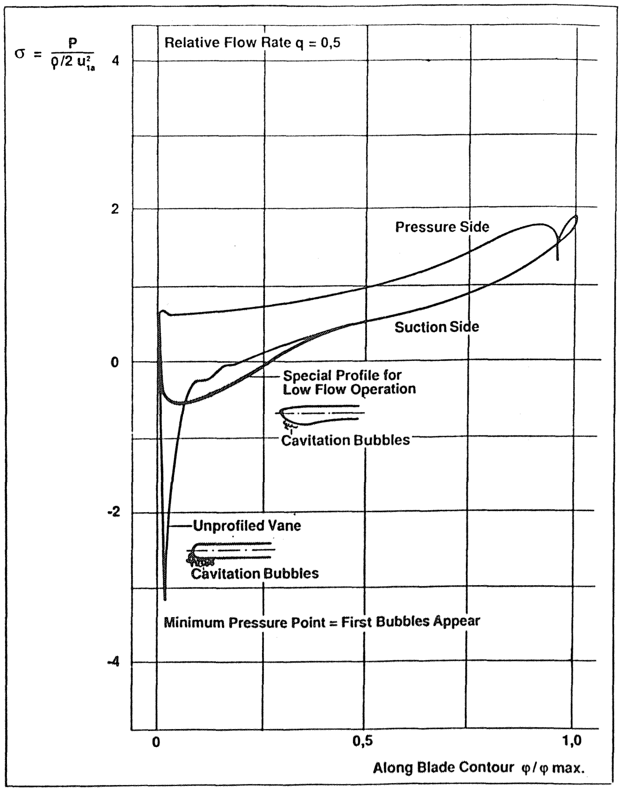

Figure 11. Pressure Distribution of Profiled and Unprofiled Vane.

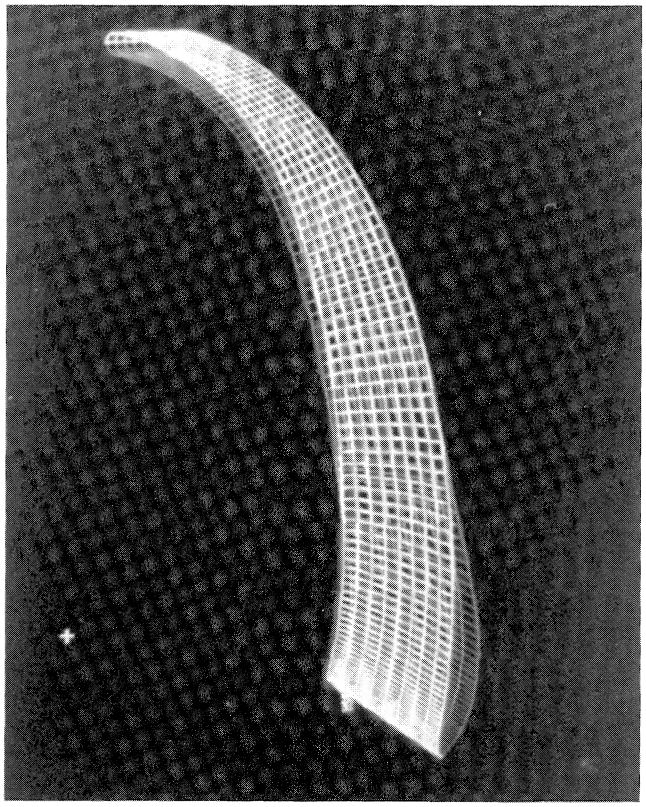

Figure 12. Computation Points for Defining the Pressure and Suction Side Vane Contour of a Profiled Vane.

pressure side of the vane) the spline lines (approximately nine) are transformed into a spline surface.

Modern CAD workstations speed up the hydraulic development process considerably. Within minutes, complete impellers can be assembled on the screen from individual components (vanes, hub, rear shroud, or front shroud). A wire model of a double-entry impeller vane made up of two individual vanes is illustrated in Figure 13. The vane is divided into various profiling zones. By pressing a function key, the wire model is turned into a shaded view, usually presenting individual elements in different colors. In Figure 14, the hub (internal contour) and the two shrouds (external contour) can be seen. In Figure 15, two vanes have been added; for clarity, one of the shrouds has been omitted. Another perspective of the same model is presented in Figure 16. The convergence of two individual vanes into a double-entry impeller vane is clearly visible.

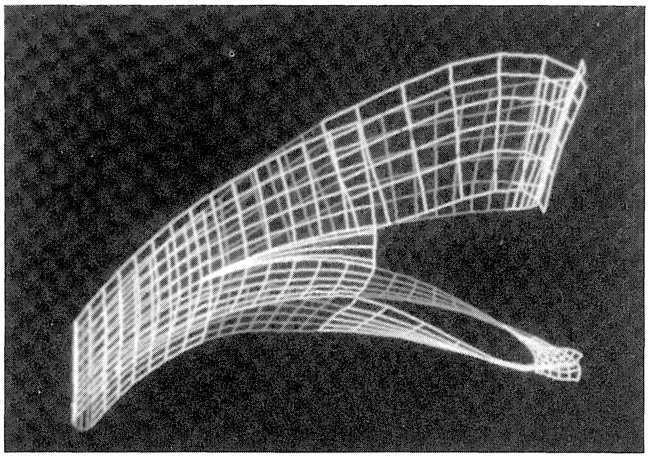

Figure 13. Wire Model of a Double-Entry Impeller Vane with Different Profiling Zones.

The last hydraulic design step consists of defining the transition radii between vane contour and wall (hub and front shroud). The vanes and the transition zones towards the hub modelled by splines are depicted in Figure 17. In Figure 18, the transition zones towards the front shroud have been added, and the complete double-entry impeller modelled by splines is shown in Figure 19.

Thus, the complete impeller or diffuser geometry has been defined, and the designer can pass on the 3D data to the manufacturing department without running the risk of transmission errors.

Manufacturing a Radial Impeller (or Diffuser) With 3D Blading from a Forged Blank

The source material is a forged block. The first machining step consists in generating the rotating component's (impeller or diffuser) external contour by preturning. The subsequent milling and electric-discharge machining operations produce the vane passages by material removal. What remains after these processing steps are in fact the components that are usually cast: the hub, vanes, and front shroud. Contrary to conventional practice, the impeller is not milled in open design and provided with a front shroud later.

Of paramount importance for the NC programmer is the decision of how to divide the passage geometry into appropriate machining zones. For sophisticated geometries, simulation of the machine tool movements on the screen does not suffice; a

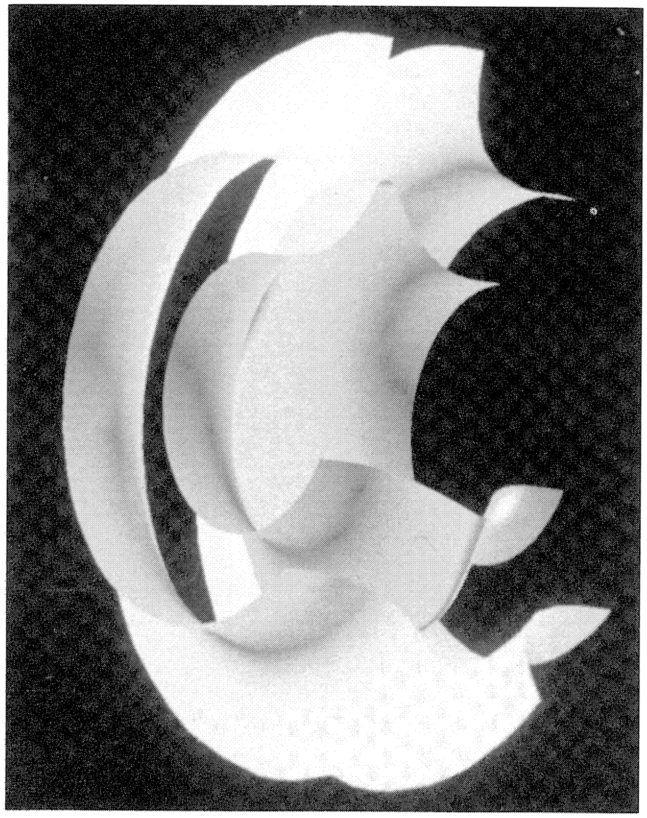

Figure 14. Hub and Front Shrouds of a Double-Entry Impeller.

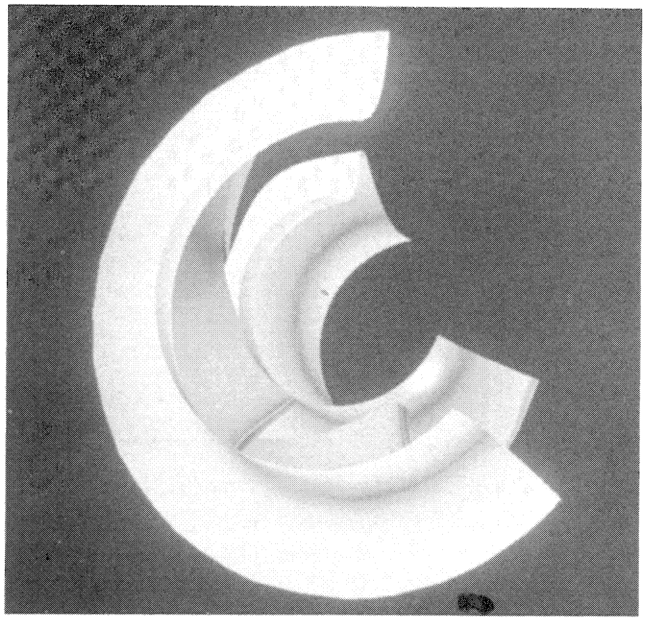

Figure 15. Hub, Front Shroud, and Vane of a Double-Entry Impeller.

pattern must be made. For this purpose, either a previously cast impeller or a model made of turned components and individually milled vanes can be used.

As far as the passageway can be accessed from the outside, it is milled. The main section of the passage is electric-discharge machined with the aid of partly overlapping graphite-electrode segments. Four-axis electric-discharge machining programs are used to define the electrode travel path and the final position. Designing this process calls for special manufacturing know-how.

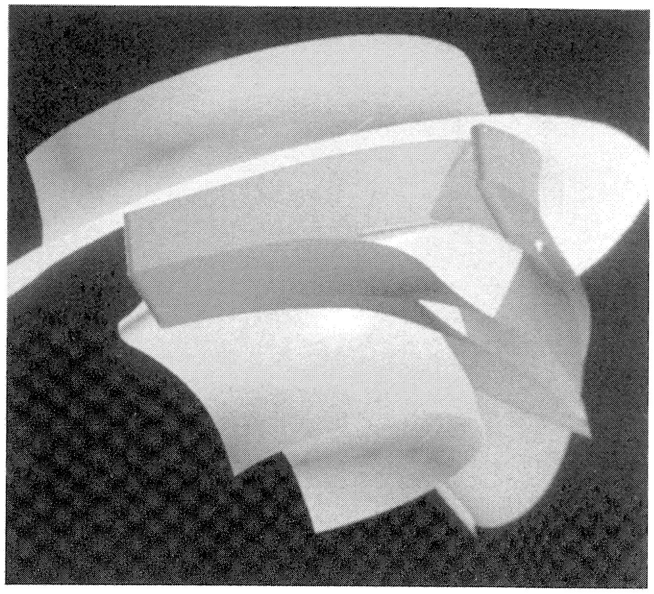

Figure 16. Figure 14 from a Different Perspective.

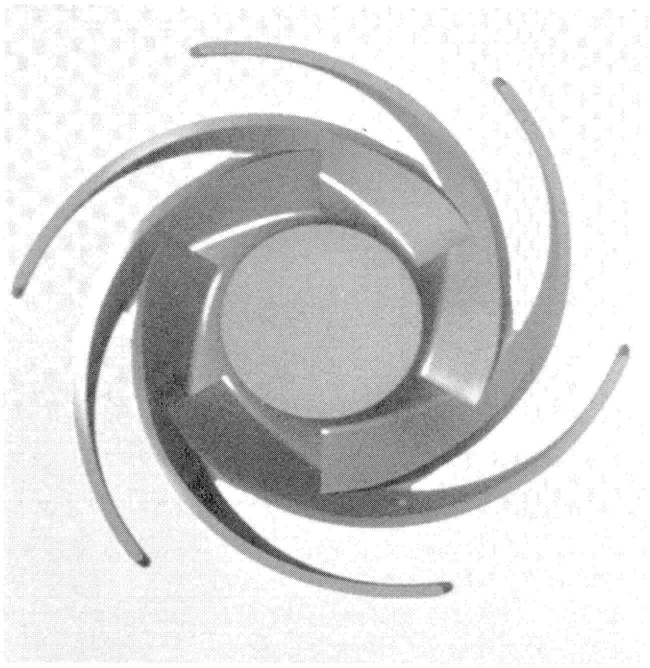

Figure 17. Vanes and Transition Zones towards the Hub Modelled by Splines; Lateral View of a Double-Entry Impeller without Front Shroud.

For a double-entry impeller, up to 60 electrodes are required, including roughing and smoothing electrodes. After that, the impellers are usually polished to avoid excessive electric-discharge machining times. Geometrical verification and control are the last steps of the manufacturing cycle as such.

Finally, the finished impeller (Figure 20) is subjected to a cavitation test in a model pump. The complete production cycle,

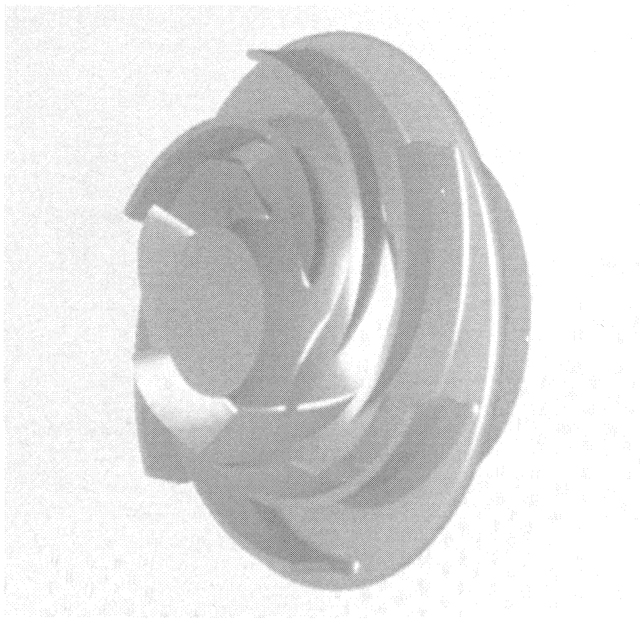

Figure 18. Vanes and Transition Zones towards the Hub and Front Shroud Modelled by Splines. For a better presentation of the vane curvature of the profiled vanes, one of the front shrouds has been omitted.

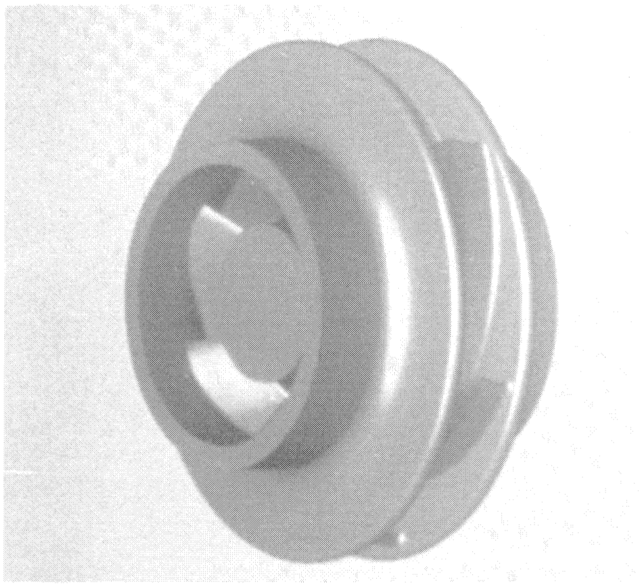

Figure 19. Complete Double-Entry Impeller Modelled by Splines.

from hydraulic design through to the final cavitation test, takes about four months. Cast impellers of the same type usually require twice this time. However, the costs of production of the improved impeller exceed those of the conventionally cast impeller by approximately 40 percent.

Benefits

In principle, the new method can be applied to all types of pumps. Its benefits are obvious:

- The new method reduces impeller manufacturing times, also in research and development. The fact that patterns are used for the conventional manufacturing method does not result in significant advantages, since the production time and cost required are only reduced by 20 percent. Comparable savings can be made with the new technique when previously designed, available calculated geometries (3D data), milling and electric-discharge machining programs can be used.
- The new method generates superior accuracy when manufacturing complicated three-dimensional contours.
- The new method ensures reproducibility of all impeller vanes (all vanes are identical).
- Computerized processing yields better documentation of the individual vane geometries.
- Hydraulic testing is reduced to a minimum.
- The extremely precise profile made possible by hydraulic development (HYDRAULIC DEVELOPMENT STEPS) can only be manufactured economically when using the new method. Usually, no changes in the contour are required after the final hydraulic test. The cavitation results are presented in Figure 2, Curve 4. They show the superior NPSH behavior over the complete operating range.
- The impeller's metallographic structure is substantially improved compared with cast variants.
- Surface quality checks are not required.

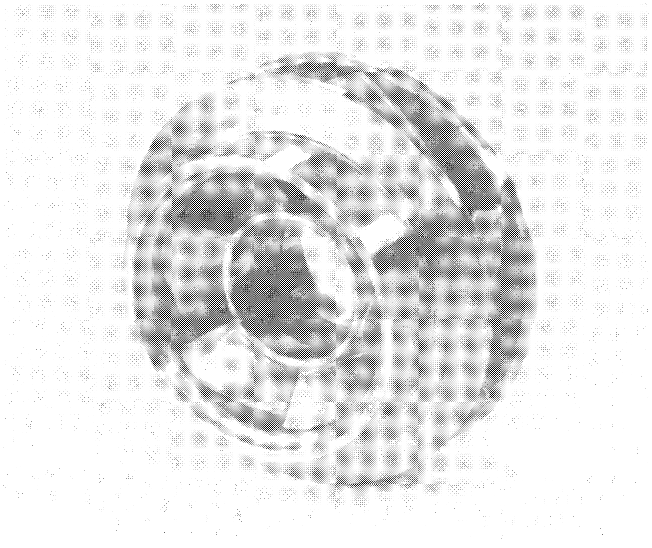

Figure 20. Finished Double-Entry Impeller Manufactured from a Forged Blank.

CONCLUSION

Major hydraulic developments and improvements on pumps have been fostered by modern fluid flow calculation techniques and computer codes. For some time, this hydraulic progress could not be readily implemented in production for technical reasons (manufacturing precise profiles). Time-consuming production cycles were the result: impellers and diffusers had to manufactured by welding and brazing and then had to be surfaced to improve their resistance to cavitation damage. The improvements made were based on advanced materials technology employed by the design engineer.

Compared with this situation, the new method described here represents a significant step forward. The tremendous progress in manufacturing technology (systematic application of multi-axis milling and electric-discharge machining) helped translate the hydraulic improvements (profiled impeller and diffuser vanes) into practical applications with satisfactory results.

The new method is not limited to the production of vane profiles, and allows vane manufacturing from special materials, where wear resistance is improved by a special design (determination of transition radii), or volute tongues.

In fact, all complicated, difficult-to-access pump components can be economically produced with the new method.

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