ON THE MANUFACTURE OF IMPELLERS FOR TURBOCOMPRESSORS

by

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ABSTRACT

The efficiency of compressor impellers, apart from the design, depends on some features linked with their manufacture. These features are the accuracy of geometry, the surface quality obtained, and the blockages which are inevitable with covered impellers and are attributable to the joining method applied, e.g., greater blade thicknesses in the case of riveting, or narrowed cross sections, due to weld seams, in the case of welding. As a result of the ever increasing importance of efficiency, efforts have been made to further improve the manufacturing process.

The advantages and disadvantages of the various forming methods for high-quality impellers, such as milling with a relatively high accuracy, and involving high manufacturing outlay, are discussed. The various casting processes with a variety of possibilities to fulfill the requirements made with regard to the dimensional tolerances, process-dependent blade thicknesses and manual work for achieving certain specified accuracies are described.

The efficiency of impellers with closed passageways, that is, with a cover or shroud disc, is superior to that of impellers with open passageways. This means that when no cast impellers are used, suitable methods must be available for joining the blades and the cover. For maximum accuracy and minimum blockage, the high-vacuum brazing method has become more and more accepted during the past few years. However, the manufacture of impellers applying the brazing method becomes problematic for large diameters. In addition to vacuum brazing, manual and machine welding processes continue to be applied, including slot welding for two-dimensionally curved blades.

Diffusion welding and electron-beam welding have not found acceptance since high costs, unfavorable crevices, and sharp edges, along with possible deformations, have a negative influence on the behavior of such impellers during operation.

It is true that the sophisticated riveting process of some manufacturers for two-dimensionally curved blades requires great wall thicknesses; but, it is also true that high-accuracy impellers can be produced by this method. In addition, the vibratory behavior of such impellers is favorable due to system-inherent dampening. Moreover, riveted impellers will tolerate high stresses when the Bauschinger effect is taken into account.

The manufacture of highly stressed impellers for turbocompressors is based on the availability of suitable materials and adequate test methods.

INTRODUCTION

The impeller is the most essential part of a radial-flow turbocompressor. In view of the ever increasing importance of its performance, the geometrical design of an impeller is governed by the laws of aerodynamics, thermodynamics, and stress. Therefore, there is only a small choice of compromises to the effect of altering of the geometrical data with the aim of adopting a specific manufacturing process. As a consequence, special methods for the manufacture of turbocompressor impellers had to be developed or already known methods had to be adjusted to satisfy the changing demands made of a turbocompressor impeller.

These manufacturing methods, the criteria for their selection, and the resulting quality assurance measures are described herein. The emphasis, however, is put on process compressors of specific design and manufacture to meet customers' requirements. Series-manufactured compressors will not be addressed.

The field of application and the configuration of three-dimensional (3D) geometrical turbocompressor impellers with various types of the three-dimensionally curved blades is shown in Figure 1 as a function of the impeller specific flow coefficient
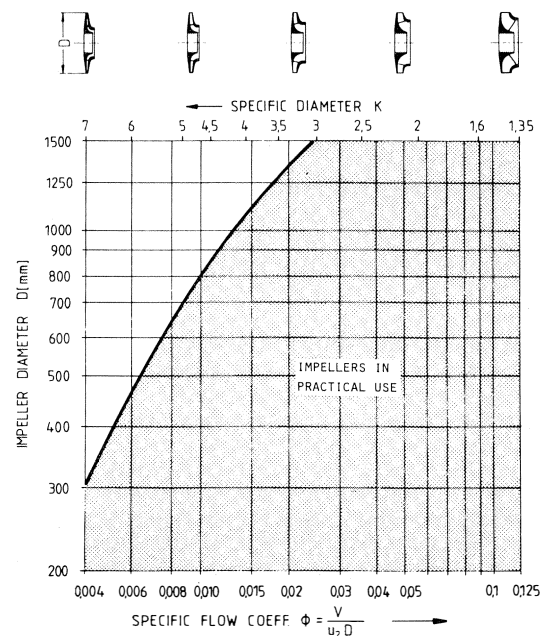

Figure 1. Field of Application of Three Dimensional Impellers in Radial Turbocompressors.

and of the impeller diameter. This diagram represents the latest impeller designs used in practice. Nevertheless, there still exists a wide range of two-dimensional impellers. Therefore, such impellers will also be discussed.

The manufacture of impellers involves complex technological problems. There are several options to systematically deal with these problems and they will be discussed as follows:

The manufacture of the hub disc with the blades will be discussed first, since manufacturing the blades and hub disc from one piece has become common. Next, special importance will be attached to the question of joining the cover to the blades. Certain criteria for the selection of materials and for the heat treatment of the blanks or of the completed impellers emerge from the variety of optional manufacturing methods. The methods and the extent of quality assurance will be governed by the manufacturing process selected and by the special requirements of materials to be satisfied.

The outlining of technical details regarding the sequence of manufacturing operations then results in the criteria to be selected for a specific case. When making this selection, one must also bear in mind that the great number of technical options is to be reduced to such an extent that the continuous application of a given manufacturing process in a workshop is ensured, taking into account the spectrum of impellers to be manufactured. Only then can the know-how and practice in working with a given process be kept on the highest standard possible.

THE MANUFACTURE OF HUB DISCS WITH BLADES

There are two principle methods of manufacturing the blank of the hub disc, i.e., casting and forging. Compared to closed impellers made from forgings, with the cover always being a separately manufactured part (except where the channels are manufactured using the electro-erosion process which is applied relatively seldom), the cover can be integrally cast when producing closed impellers by casting. This, however, implies that adjusting the impeller geometry to the requirements of thermodynamics necessitates a costly modification of the pattern. Compared to the impeller with a fixed contour of the cover that has been in use for quite some time, the principle of the impeller with a variable contour of the cover has been gaining in importance lately. In this latter case, the impeller consists of a cast hub disc with blades of maximum dimensions. By turning the blades to the required contour, it is then possible to realize with one single pattern a great number of impellers, with different flow coefficients, with and without a cover. This method will be described in more detail in the following discussion. One should, however, always bear in mind that casting of closed impellers, apart from those with extremely small blade channels, is possible over practically the entire range of dimensions up to 1500 mm diameter and more and has been practiced with great success for two decades.

Casting of Impellers

The demands made on the accuracy of cast impellers are independent of the forming or casting process applied. They are merely governed by the requirements of aerodynamics and thermodynamics. On the other hand, the question of whether a cast impeller in its as-cast condition is within the dimensional and contour tolerances, particularly regarding blade faces, or whether the specified accuracy can be achieved only by grinding, is only a matter of costs and not of quality.

Where smaller impellers with outer diameters of up to approximately 500 mm are involved, the investment casting process is able to satisfy the tolerance requirements, without necessitating any rework. For larger diameters of up to 1500 mm and larger, it is common practice to use a single ceramic core containing all the blade faces involved (monobloc). The formerly used sand core is inadequate for producting sufficiently accurate impellers.

These two methods will be briefly described in the following subsections. In the further course of discussion, the method of casting closed impellers is taken as being similar, as mentioned before, if the monobloc process is applied. Narrow passage closed impellers manufactured using the investment casting process have not been produced with convincing results. Thus, closed impellers of smaller diameter also have been produced using the conventional forming process, where this is possible under the aspect of channel size. In addition to the lack of flexibility in designing impellers, the casting of impellers with covers features another drawback: channel side faults in the cover, in the hub disc and in the blades which are difficult to find and repair, depending on their size and their accessibility.

Investment Casting Method

The basis of casting impellers following the investment casting process is a pattern of low-melting wax, as shown in Figure 2. With regard to its dimension, this wax pattern is identical to the final casting produced in that it must consider all shrinking effects during solidification of the steel casting and all changes to the contour which may occur on cooling or on heat treatment.
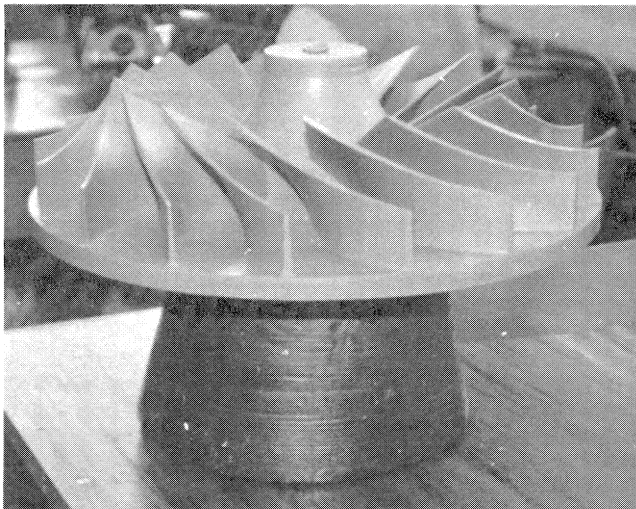

Figure 2. Wax Pattern for Investment Casting.

This wax pattern is normally made in a high precision steel mold. The surfaces of this mold, which are especially important because of the blade geometry, are made of aluminium on a five-axis milling machine. They are used for making cores of low-melting metals, which represent the channels in the mold that is shown in Figure 3. The pattern must be designed so that opening the mold and forcing out the part is possible after pressing in and solidification of the wax.

Specially selected ceramic masses of different grain sizes and composition are now applied layerwise, with the aid of manipulators which are usually computer controlled to ensure a uniform layer thickness (Figure 4). During the burning of this ceramic mass, the wax melts out, thus creating the mold for the turbocompressor impellers. Casting takes place at such high ceramic temperatures that even thin cross-sections flow out well. Allowances on the blade surfaces are, therefore, not necessary. Apart from occasional straightening operations, the
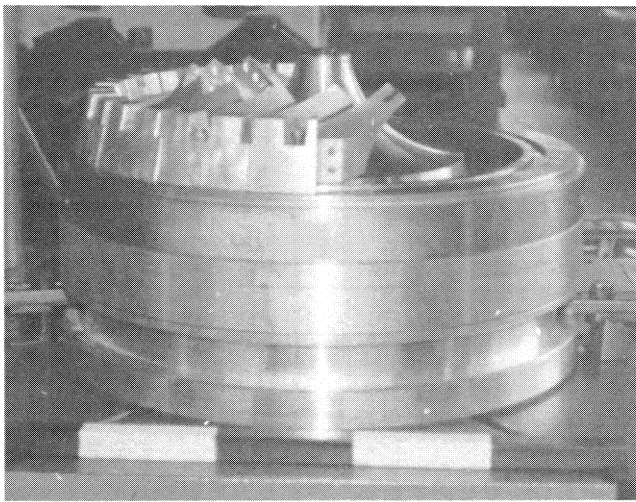
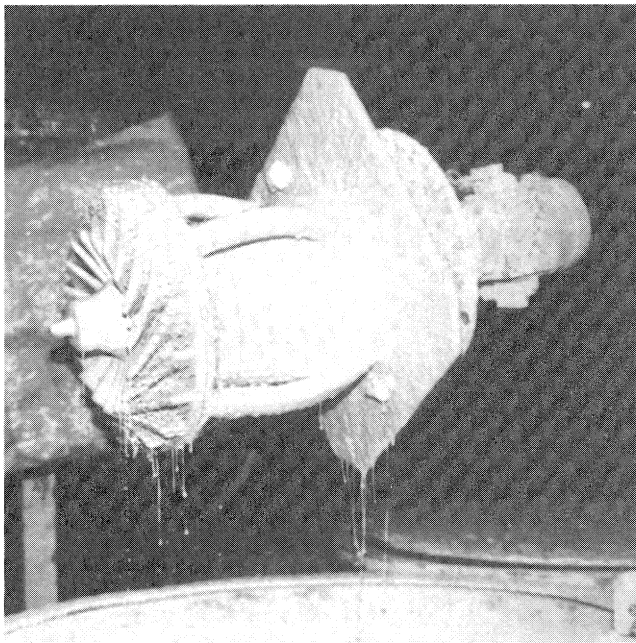*Figure 3. Die from Steel for Producing Wax Patterns.*

Figure 4. Covering of Wax Pattern with Ceramic on a Computer Controlled Manipulator.

blades and the hub disc need no furher machining in the channel area after casting.

Casting with Monobloc Cores

For larger impellers, it is no longer possible to make wax patterns of one single piece. Wax patterns assembled from individual segments or a core of solid ceramic must contain all of the impeller channel, including the blade surfaces. The method, using wax patterns from individual segments, has not been a general success, since improving of the accuracy is not possible, in contrast to the monobloc core method.

A condition for making a monobloc core is blades of a material that melts out or gasifies on burning of the ceramic material. Consequently, these blades, shown in Figure 5, must be made of wax or of plastics with a process that is very similar to the investment casting process.

The blades are inserted into a pattern of wood or of plastics, and are located in their exact position in such a manner that a

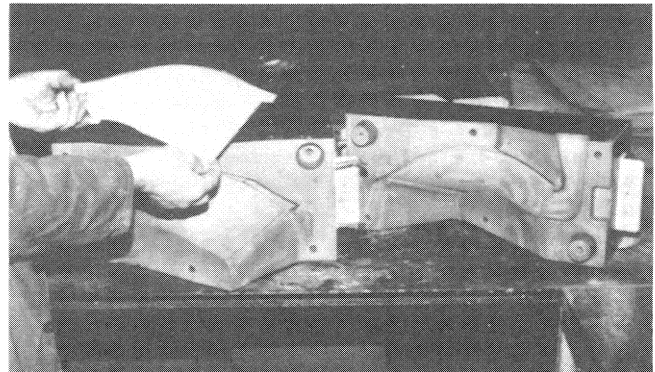highly accurate ceramic core of one single piece (monobloc) is obtained, as shown in Figure 6.

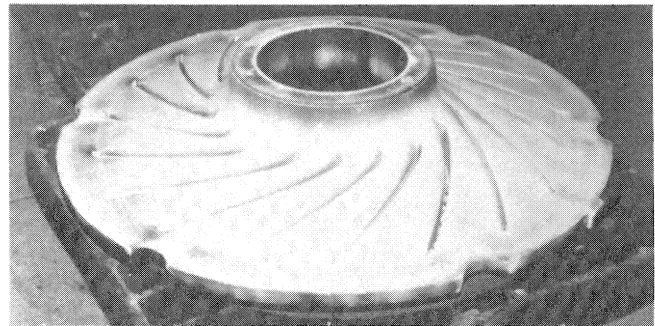*Figure 5. Blade Made from Wax and Mold Used.*

Figure 6. Monobloc Core for Two Dimensional Impeller with Outer Diameters over 500 mm.

The sequence of casting is not any different from conventional casting. Since the mold, however, is relatively cold before casting, and does not flow out so well, as in the case of the investment casting process, it is necessary to make allowance, especially on the thin blade inlet edges. In addition, the effect on the casting surface cannot be ruled out, because of the extended influence of the atmosphere and of the mold materials during solidification and cooling of large impellers. Impellers cast with a monobloc core will thus obtain their final dimensions only with 100 percent grinding of all faces not machined on the subsequent turning. The accuracy thus obtained, however, is, relative to the size of the castings, equal to that of small impellers made using the investment casting process. Some cast impellers in the as-cast condition and in the ready-for-delivery condition are shown in Figure 7.
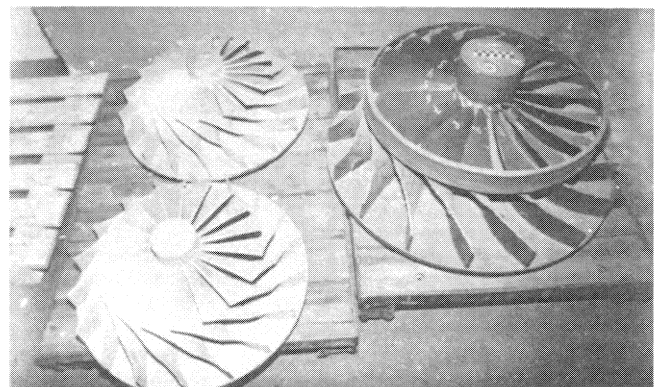

Figure 7. Three Dimensional Impellers in the As-Cast Condition and Ready for Final Machining.

Manufacture of the Hub Disc from Forgings

Thanks to the advanced steel making technology, it is nowadays not necessary to use single forgings as raw material for the fabrication of hub discs, as was common practice in the past. Rather, it is possible to take the hub disc raw meterial from a long forged rod of appropriate diameter. In addition to a cost effective production, this method offers the benefit of shorter delivery times, as stocking is possible. Depending on the material, this rod, which may have a diameter of up to 1000 mm, may already be finally heat treated, if a high-alloyed material is used. If low-alloyed steels are used, the cut or pre-turned hub disc must be subjected to final heat treatment, because of the lower hardenability.

For smaller impellers with an outer diameter of up to 600 mm to 700 mm, the blade profile is produced by milling. This is always done using the plain milling process, with the tool cutting only with its outer diameter in the circumferential direction. For this reason, the blade faces assembled from the line elements are advantageous, since as in this case the tool cutting edges are used over their entire length, as shown in Figure 8.
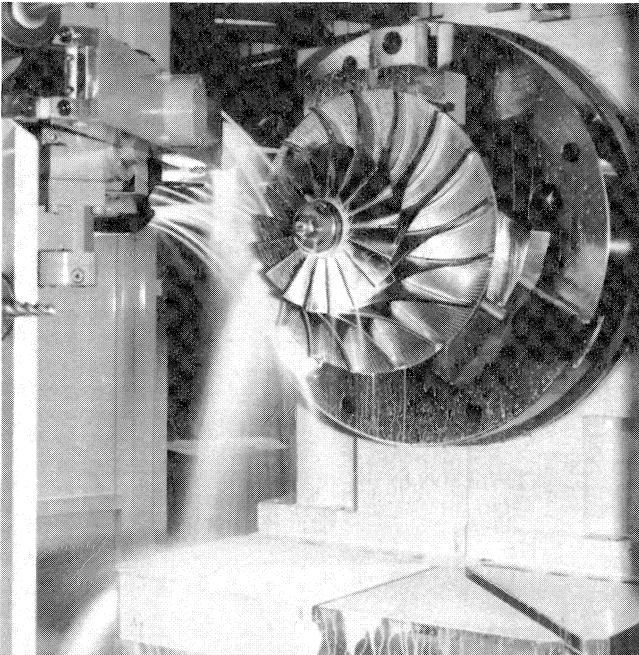

Figure 8. Milling of a Three Dimensional Impeller on a Five-Axis Milling Machine.

The milling of two and three dimensional impellers is, in principle, identical. Of course, the milling of two dimensional impellers does not make such a high demand of the degrees of freedom of the machine tools as does milling of three dimensional impellers. A schematic drawing of the procedure for generating a numerically controlled (NC) milling program appears in Figure 9. The output of a thermodynamic calculation consists of a data file which describes the blade surface in polar coordinates. These values are entered into the NC program for the selected impeller family, where they are converted into the NC program of the machine tool to be used via an electronic processor. It is possible to check the program by simulation on a monitor before starting the expensive milling process.

Hub discs with blades of the same geometry could be successfully produced this way by casting, and by forging and milling, so that the subsequent operations for mounting of the
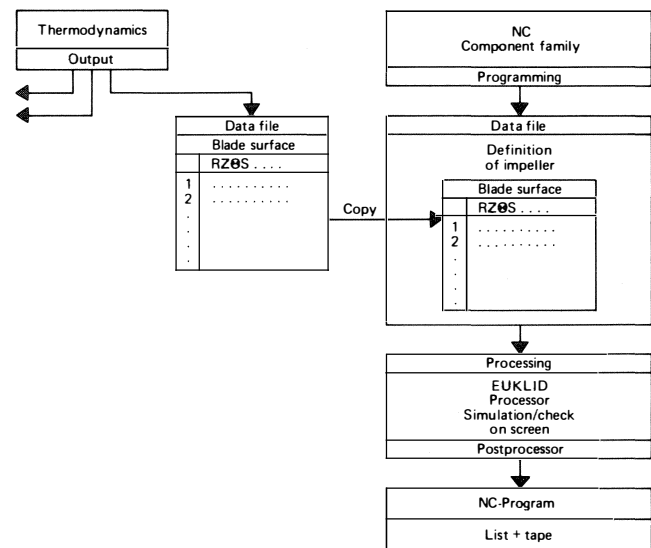

Figure 9. Steps of Programming for NC-milling of Three Dimensional Impellers.

cover are identical in both cases. Such impellers, however, may also be used as open impellers if the compressor design so permits.

There is another way to manufacture the blades which is normally used for larger impellers with an outer diameter of more than about 700 mm. In this case, the blades are made from sheets with the thickness of the final blade. Depending on the degree of complexity of the profile, simple bending tools or complicated dies are used for the hot forming process.

JOINING OF DISCS AND BLADES

There are various methods of mounting the discs to the blades. These methods can be classified without restriction into the following principle groups:

- welding method
- brazing method
- riveting method

The principles of these manufacturing processes are generally known from other sectors. However, they must be adjusted to the special requirements of the turbocompressor impeller with its poor accessibility, the high stresses to which it is subjected, and to the resulting demands made of the manufacturing quality.

Whereas the hub disc may be cast or forged, as described previously, the cover is normally made only from a forged blank. Accordingly, the manufacturing processes must be suitable to handle castings as well as forgings which, although of same chemical basic composition, may differ in their reaction to the input of heat, e.g., due to welding, brazing, and post heat treatment.

Welding

Wherever possible, it is attempted to have the actual welding process take place within the blade channel so that a solid cover is directly joined with the blades by fillet welds. Of the great number of different welding methods, the shielded metal arc welding (SMAW) and the gas tungsten arc welding-pulsed arc (GTAW-P) methods are normally applied. If the blade channel is not accessible due to its small width, it is attempted to join the cover with the blades by applying "slot welding" or 'electron-beam (EB) welding" through the cover. Diffusion welding has also been studied for its suitability for welding of narrow channels.

These five welding processes and their suitability for the manufacture of turbocompressor impellers are briefly described in the following subsections so that conclusions can be drawn on their merits and drawbacks.

Welding in the Channel

Shielded Metal Arc Welding (SMAW). SMAW is still being used where the use of automatic manipulators is not practical because of the intricate contact line between the blade and the cover. This is particularly true where three dimensional impellers are concerned.

The dimensions of the outlet area of the impeller are the main limitation of this welding process. In the author's experience, not less than about 15 mm are needed in this area, if the accessibility within the channel is relatively favorable. The length of the blades may also cause a limitation, because only electrodes of 300 mm to a maximum 450 mm length are suitable for welding in the channel.

The weld preparation consists of slight grinding of the blade in the weld area, where blades of a thickness of more than 5 mm are concerned, with not less than 60 percent of the blade thickness being maintained as the bearing face for the cover. Complete through-welding is not a goal, the reason for which is shown in Figure 10. The higher the degree of penetration, the higher the shrinkage during welding, and the scattering of this shrinkage. Accordingly, the tolerances of the channel height, which are normally in the range of one percent of this height, can only be maintained in the case of a lower degree of through-welding. Studies have shown that a lack of penetration of at least 50 percent is required for maintaining the necessary tolerances. Such welded areas of up to 90 percent of the blade thickness, however, still do not affect the quality, and are beneficial to the accuracy of the impeller.
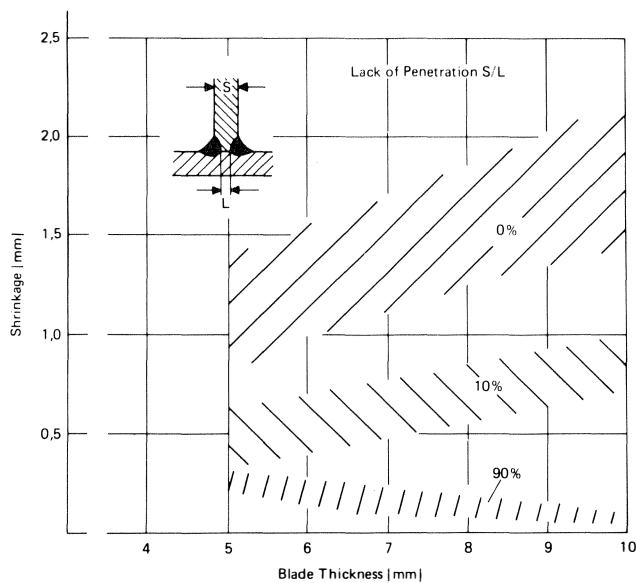

Figure 10. Influence of Weld Penetration on Shrinkage and Accuracy.

Knowledge of the welding process proper is assumed. Some aspects of the manufacture are: The impeller is mounted on a welding table, followed by heating up the former to the necessary preheating temperature, by using an induction heating system, with the temperature continuously being controlled via thermocouples (Figure 11). The electrodes must, of course, be positioned much flatter in the channel than recommended by the electrode suppliers as the favorable position. This requires a

special qualification of the welders and their continuous training to ensure a weld of perfect quality under such unfavorable conditions. The aim is to weld with one pass, or with two passes at the most, a fillet weld that already forms a fillet weld radius, and thus requires only rough irregularities in the weld surface to be ground. Undercuts in areas of high dynamic stresses must be worked out to improve the fatigue strength (Figure 12).
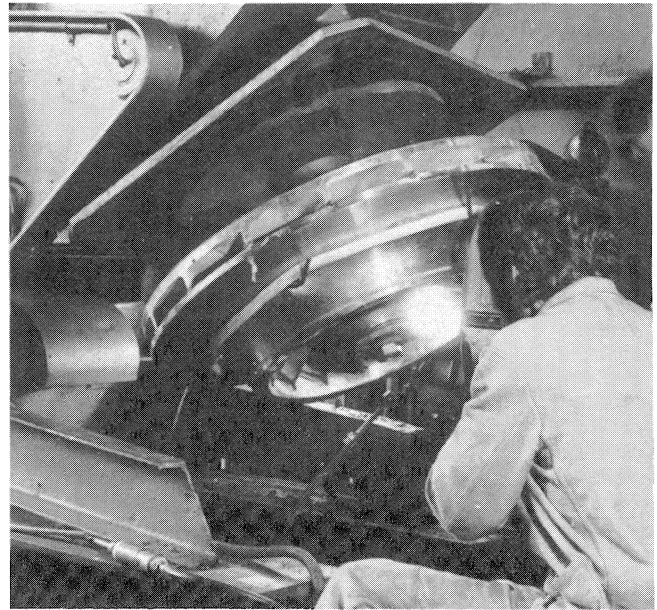

Figure 11. Welding with SMAW Process of a Cast Three Dimensional Hub Disc and Forged Cover Disc.
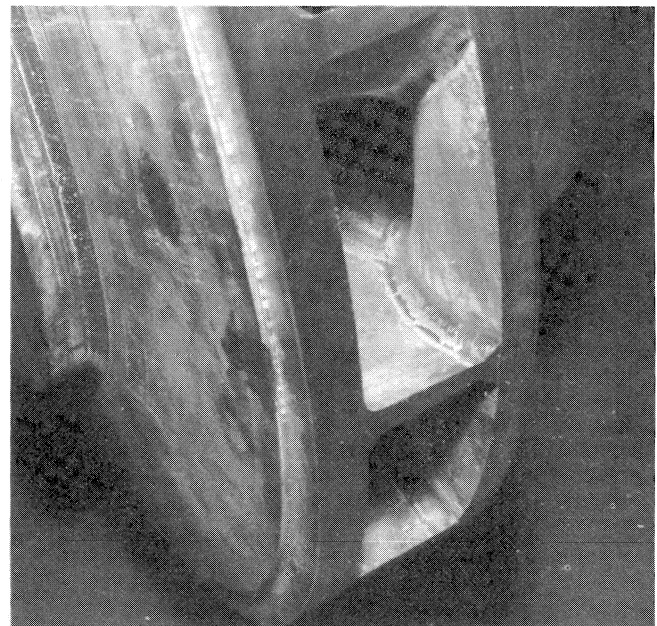

Figure 12. Three Dimensional Impeller from Cast Hub Disc and Forged Cover Disc in the As Welded Condition.

If the blades are made separately from sheets, these blades will be welded first to the cover disc, because it is evident that the accessibility to the area of welding is better in the channel on the hub disc side than on the cover side. As shown in Figure 13, the blades are held by special devices for welding on the cover disc side. After welding, grinding, eventual repair work, and

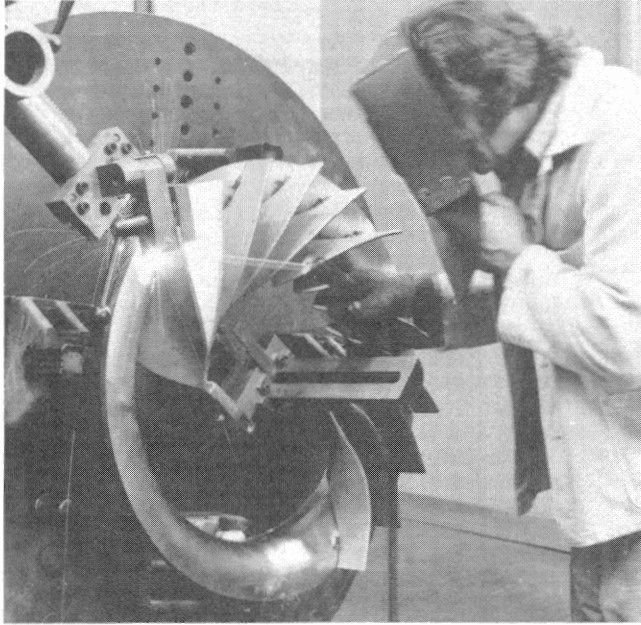heat treatment, the contour of the blades on the hub disc side is turned, and the final welding can be done.

Figure 13. Welding of Three Dimensional Blades to the Cover Disc for Fully Fabricated Impellers.

Gas Tungsten Arc Welding-Pulsed Arc (GTAW-P). Of the machine welding processes available, the GTAW-P process is characterized by a great penetration depth that can be achieved by the upper current burning only for a short time, with the heat input being relatively low. Further, it is possible to form the weld surface to a nearly ideal radius, by the appropriate control of the welding parameters, as shown in Figure 14. In addition, the weld surface shows such a fine scattering that no grinding is required (Figure 15).
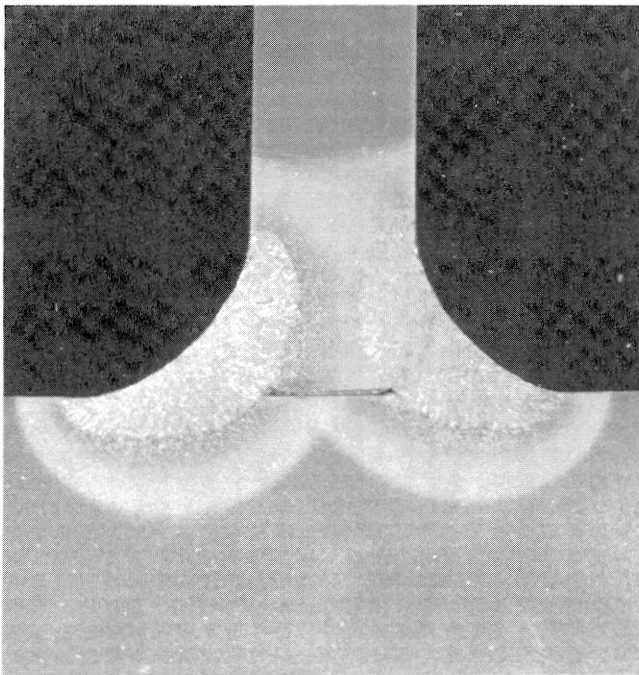

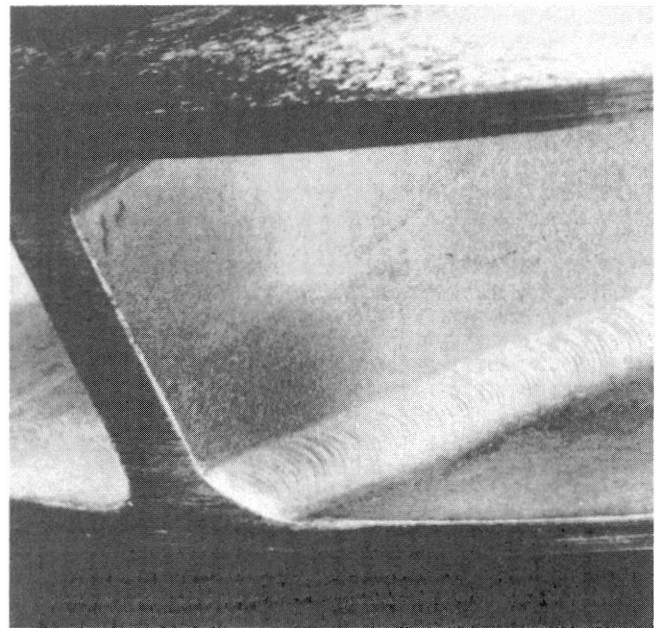*Figure 14. Weld Joint of Blade and Cover Disc after GTAW-P Welding.*

Figure 15. GTAW-P Welded Impeller.

Since no suitable torches were available on the market, special torches had to be developed for the actual process to permit welding of two dimensional impellers with an outlet width of only 16 mm. This was a particularly problematic task, because the torch tube not only carries the electric current to the tungsten electrode, but it also must accommodate passages for inert gas, for wire feeding and for the cooling water. Thanks to a useful combination of manipulators for the workpiece, and for the torch, it is now possible to realize, with the power sources being process computer controlled, even and accurate welds of high quality and toughness of the weld metal, as shown in Figure 16.
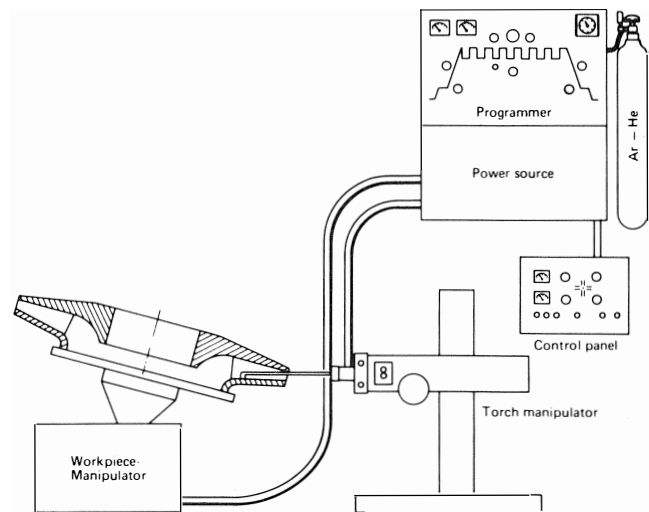
Figure 16. Equipment for GTAW-P Welding of Impellers.

Welding Through the Cover

The process described under *Welding the Channel* features the drawback that the channel must be of a certain minimum size, as otherwise there would be no access for the electrode or for the GTAW-P torch. Other methods, including welding methods, were developed to overcome this drawback and to permit joining the blade with the cover by welding through the

solid or slotted cover. "Slot welding" and "electron-beam welding" are two of these methods.

Slot Welding. For slot welding, a slot is provided in the cover, as shown in Figure 17. The blade is arranged under this slot, with appropriate overlapping. Depending on the geometry of the impeller, the weld cannot start immediately at the blade inlet edge, because of the inlet ring of the cover. It is therefore necessary to provide a fillet at some distance past the blade inlet, to avoid a sharp stress raiser. Further, the aim of welding is to achieve full penetration from the inside. The radius shown in Figure 18 is sufficient. It definitely ensures that no welded areas with lack of penetration cause a gap between the cover and the blade, which would be of great disadvantage, as far as strength and corrosion is concerned. The actual welding is carried out using the GTAW-P process, as described previously, by using a workpiece and torch manipulator, with induction heating.
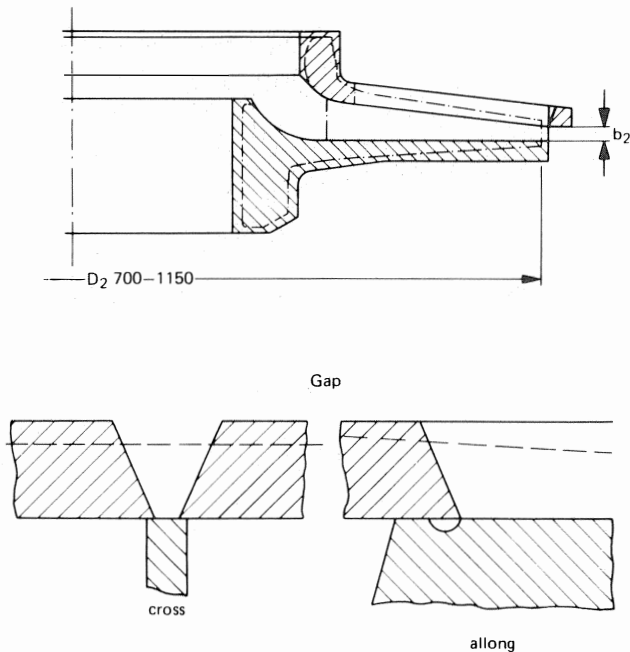

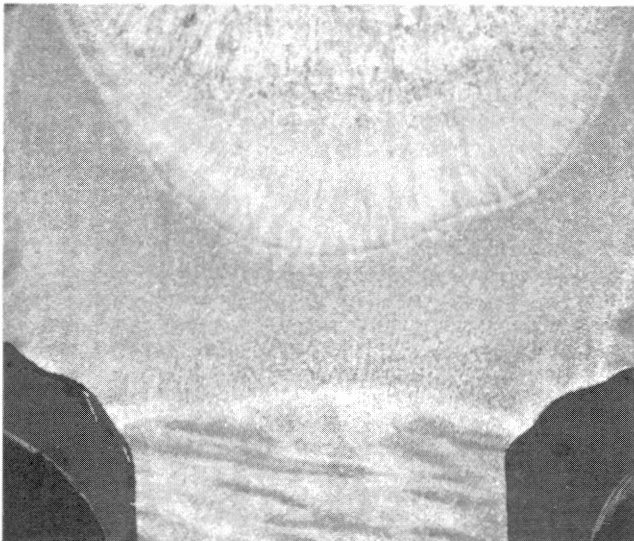*Figure 17. Preparation of Cover, Blade and Hub Disc for Slot Welding.*

Figure 18. Slot Welding Joint (Cover Disc and Blade) in the As-Welded Condition.

Electron-Beam Welding. The electron-beam process has reached a very high standard during recent years. Therefore, frequent attempts have been made to apply this method to the welding of impellers. The impeller being manufactured is shown in Figure 19. The blade was almost completely connected with the cover by three passes side by side of the electron beam (Figure 20). The gap between cover and blade, however, cannot be completely closed, let alone produce a transition radius at this point. Such joint welds feature distinct drawbacks with regard to fatigue strength and corrosion. Impellers welded to this process can, therefore, not be considered equal in quality to those manufactured to other processes such as brazing.
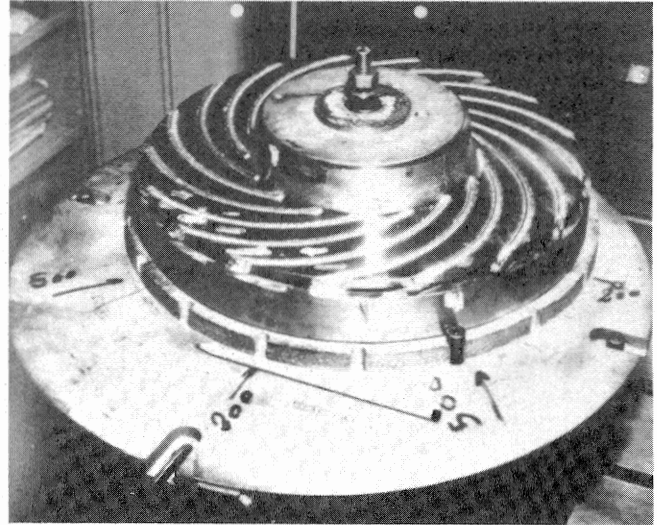
Figure 19. EB-welded Two Dimensional Impeller.
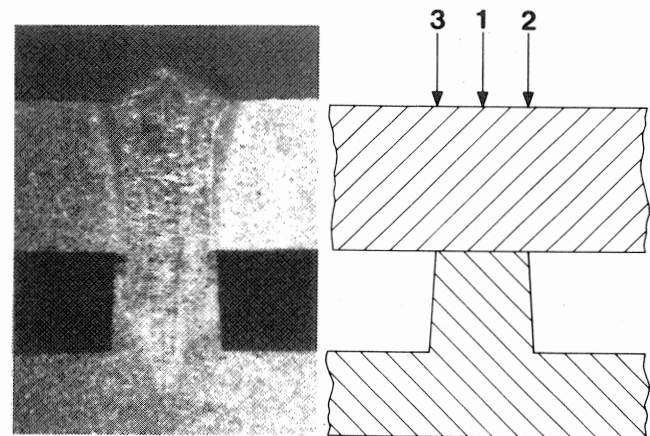
Figure 20. EB-welding of Impellers.

Diffusion Welding

Diffusion welding is another option for the manufacture of narrow impellers. The application of this process, however, requires that the faces to be joined are flat. The blades, which have to be milled from the hub disc and from the cover, as shown in Figure 21, are split approximately in the middle. The welding process takes place under a pressure of approximately $10 \, N/mm^2$ by diffusion over the contact surfaces, at temperatures of approximately 1000°C, and under low vacuum. As shown in Figure 21, the hub and cover disc have such shapes that, over the outer plane faces, which are parallel to the joints of the blades, constant pressure is achieved during welding.

Figure 21. Preparation and Welding of Impellers to the Diffusion Welding Process.

The following figures reflect the problems resulting from this process. It is extremely difficult to always make the blades on the hub disc and cover side perfectly match (Figure 22). Where thi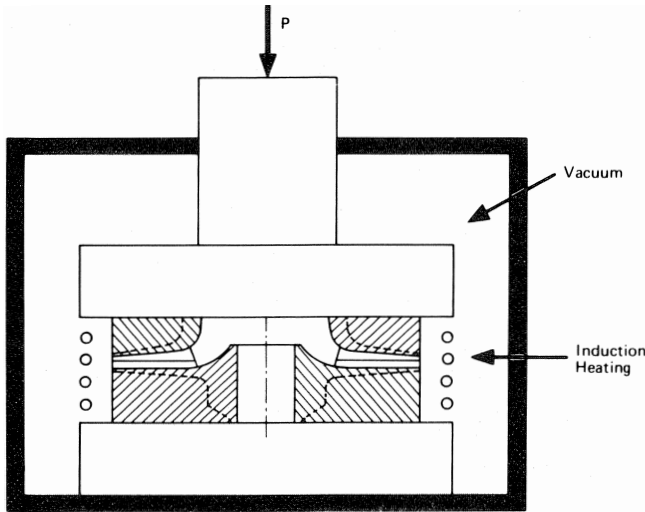s is possible, there will always be undesirable notches at the weld location. Further, it is not always achieved to coordinate pressure and temperature such that perfect welding results are obtained; however, a deformation of the blades is definitely avoided.
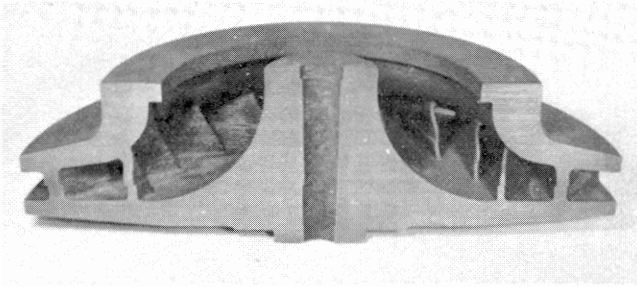

Figure 22. Diffusion Welded Two Dimensional Impeller.

Areas in the weld which have no contact due to soiling or due to surface finish problems will keep occurring, so that no diffusion welding takes place (Figure 23). Such defects can hardly be detected by non-destructive examination. They affect the fatigue strength quite considerably, the same as the previously described notches.

Brazing

A completely different type of connection between blade and cover, no matter how narrow the impellers and how difficult the shape of blades, is the brazed joint. For brazing, the cover is placed upon the blades which have been appropriately prepared for brazing, such that a gap of 50μm up to 100μm remains. The brazed alloy, a gold-nickel bases in the majority of cases, designated BAu-4 according to American Welding Society (AWS) specification A 5.8[1], is placed in the form of a mixture of metal powder and plastics material near the brazing gap or in the form of foils into the gap.

As can be seen in Figure 24, the impeller prepared for brazing is placed into a special type furnace where brazing takes place. The principle temperature and pressure patterns for this process are shown in Figure 25. In this process, the vacuum of 10^{-4}
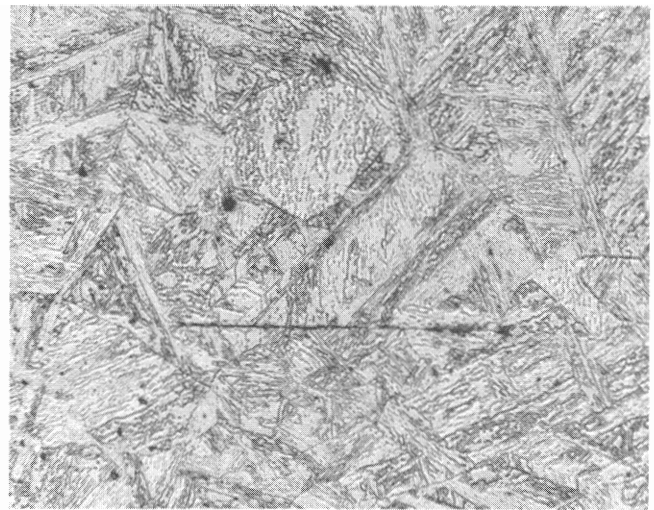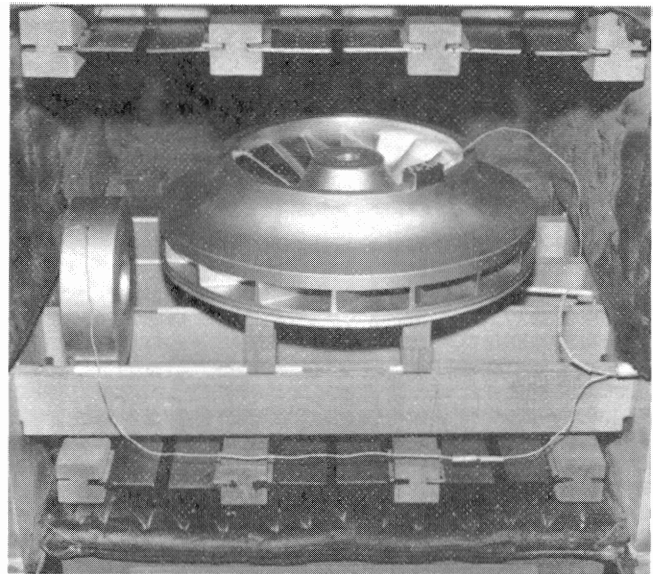

Figure 23. Defect in a Diffusion Welded Joint.

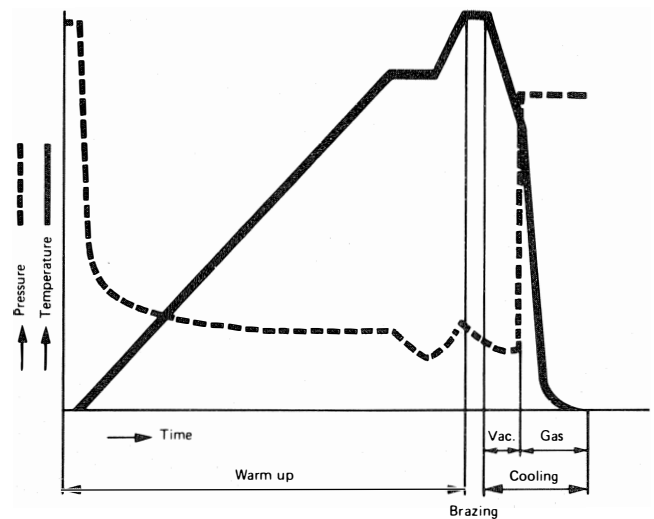*Figure 24. Three Dimensional Impeller in the Furnace Ready for Brazing.*

Figure 25. Temperature-time-curve and Pressure-time-curve for Brazing of Impellers.

mbar serves not only to avoid oxidation of the surfaces, but at the same time to clean these faces from any soiling by evaporation and to activate them for wetting by the brazing alloy.

The liquid brazing metal joins the two faces not only by bonding, but the partners "brazing alloy" and "steel" penetrate each other by diffusion and thus form a tough connection of high strength. However, this joint is tough enough only if the selected brazing alloy does not lead to brittle intermetallic phases, due to elements like boron, phosphor or silicon, which are added to the brazing alloy to lower the melting temperature. This kind of brazed joint offers adequate safety in operation for turbocompressor impellers operating at relatively low temperatures only if BAu-4 or equivalent brazing alloys are used.

Although there are no physical limits to the application of the brazing process, the maximum diameter is approximately 700 mm for two dimensional impellers, and approximately 500 mm for three dimensional impellers, according to the findings.

The quality of the brazed impeller is practically independent of the operating personnel and the percentage of defects is extremely low, because the brazing process is computer controlled. The necessity of ensuring maximum gaps of 50μm to 100μm the process calls for a pre-treatment of the material and for a process control so that no deformation can occur. This automatically leads to geometrical quality of the impellers, which satisfy the highest accuracy requirements.

Riveting

Riveting is the oldest method of connecting the cover with the blades. This method was replaced in the past by other processes, for various reasons. Riveting, however, is still in use in the manufacture of two dimensional impellers. Its merit is that high precision impellers can be manufactured without any heat input. Rivets of high accuracy are inserted into precision holes through the hub disc, blade and cover and are clinched on the cover side in a hydraulic press (Figure 26).
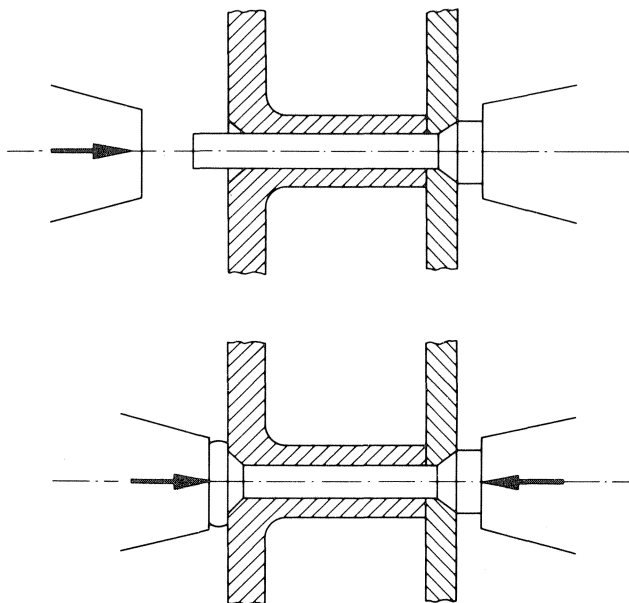
Figure 26. Riveting of Two Dimensional Impellers.

Some damages in the past were partly due to not considering the "Bauschinger effect" in the operation of such impellers. Due to the one to three percent axial plastic deformation of the rivet in the thrust direction (Figure 27), the yield strength is dramatically reduced due to residual stresses, which are the result of that deformation. The necessary strength characteristic values

can be regained only by subsequent heating to not less than 300°C. The recovery of the yield strength for a low alloyed chromium nickel steel and for an austenitic chromium nickel molybdenum steel is shown in Figure 27. This principle pattern, however, applies to all metallic materials.
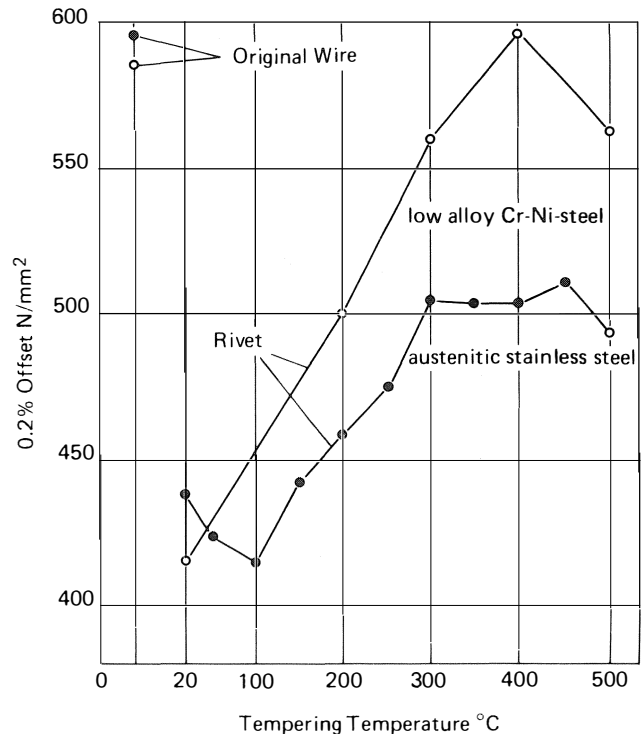
Figure 27. Influence of Small Plastic Deformation in Thrust Direction on Yield Strength in Tension (Bauschinger Effect) on Rivets.

SELECTION OF MATERIALS

The selection of materials for turbocompressor impellers must, in the first place, consider the future operating conditions. Some examples of such conditions which have an effect on the impeller are presented in Figure 28.

Figure 28. Influences on Material Selection of Impellers.

The corrosive effect of the medium to be compressed may be negligible, as in the case of nitrogen, or it may be critical, as in the case of chlorine or hydrogen cloride. In extreme cases, the presence of, for example, hydrogen sulphide may lead to disastrous fractures of an impeller within a few hours.

Service temperatures of down to − 196°C have a great impact, particularly in view of the embrittlement of ferritic steels.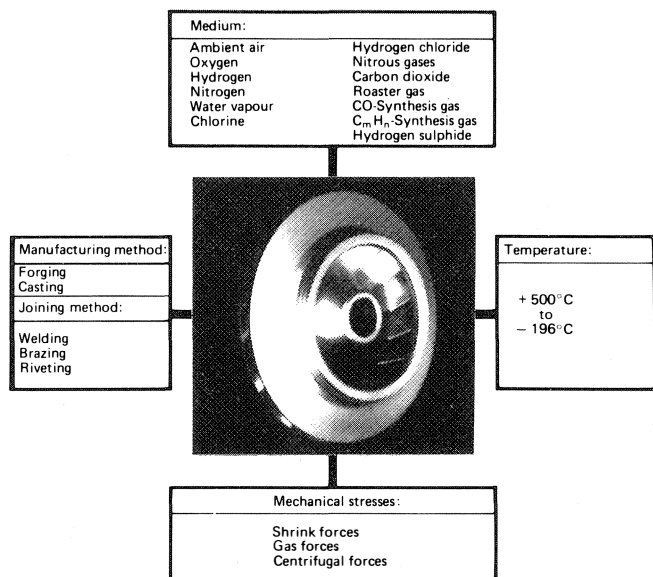 On the other hand, higher temperatures play an important part, in conjunction with the corrosion and the lowering of the strength values.

The mechanical stresses due to shrinkage forces, gas forces, and centrifugal forces in the rotating impeller can be determined with relatively high accuracy, using the "finite element method" of calculation. Local plastic deformation in small areas, however, cannot always be definitely ruled out.

The requirements of the manufacturing processes, as described in JOINING OF DISCS AND BLADES, also influence the selection of material. It is assumed in principle that in addition to an adequate corrosion resistance and strength at any service temperature, the toughness, for example, measured to the notched bar impact test method, is of exceptional importance for the safety in operation of impellers. The material selection and the performance of heat treatment which will be described later are, therefore, governed by this requirement for maximum toughness.

There are two basically different routes which can be followed in the selection of materials. The first route leads to selecting the absolute optimal material for any application. This, however, will lead to a great number of different materials used in manufacturing of impellers. As a result, only a relatively vague know-how of the workshop people in a specific case will be available, since most of the many alternatives will rarely occur. The second route, and in the author's opinion the more favorable and more direct one, is to confine oneself to relatively few materials and to create favorable conditions for as many applications as possible, by adopting appropriate treatment methods for these materials.

The selection of filler metal for welding and brazing may be more difficult. Filler metal of the same or of similar composition can be found relatively easy for "normal" service conditions. Where the service conditions are particularly adverse, such as operation in sour gas service or at low temperatures, some special criteria for selection have to be taken into consideration.

For example, when using the electrodes recommended by the suppliers for SMAW welding of the material 14 CrMoV 6 9 (similar to American Society for Testing and Materials (ASTM) A 470 Class 8) [2], the resistance to H_2S achieved will be poor, if welding is merely followed by tempering. In this case, the service life under test conditions according to National Association of Corrosion Engineers (NACE) standard TM-01-77 [3] will then only be approximately ten hours, although hardness and yield strength comply with the requirements of American Petroleum Institute (API) standard 617 [4]. An adequate service life can only be achieved by quenching and tempering of the finish welded impeller. The same applies to welding of the material X 5 CrNi 13 4, equivalent to ASTM A 182 Grade F 6NM [5] with electrodes of the same composition. As shown in Figure 29, it is much more difficult to get a hardness of maximum 23 HRC, which is the upper limit according to NACE standard MR-01-75 [6] in the weld deposit. In this case, there is only one option: to make the response of the base material and that of the weld material more alike on heat treatment, by the pin-pointed selection of batches.

However, just knowing the optimal materials and the optimal methods of their most efficient processing is not enough. Knowing the effects which any deviations from the specified manufacturing conditions may have on the quality of the
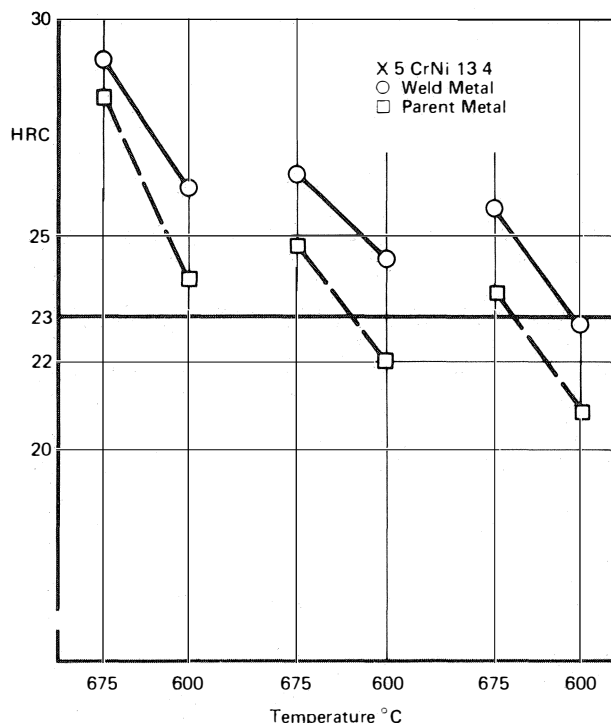
Figure 29. Comparison of Different Response of Parent Metal and Weld Metal on Heat Treatment.

finished impeller is just as important. An example of the effect which preheating before welding and of postweld heat treatment has on the lifetime of the weld joints of the impeller material 14 CrMoV 6 9 under sour gas service is shown in Figure 30. The results obtained from weld joints properly heat treated and from such joints with improper heat treatment are entered in a scattering curve which indicates the service life of the various materials in sour gas, in the presence of chlorides. The influences are so serious that the service lives differ by a factor of more than ten.
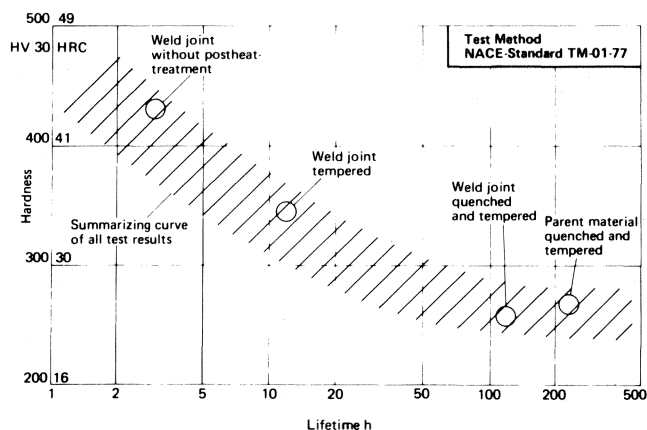
Figure 30. Influence of Heat Treatment of Welded Joints from 14 CrMoV 6 9 on Lifetime under Sour Gas Conditions 3.

HEAT TREATMENT

The heat treatment of blanks for impellers and of finished impellers is governed by the materials selected, by the manufacturing processes applied and by the service conditions. It is impossible to cover herein the complete range of influencing factors. Some examples, however, shall be dealt with in more detail.

For riveted impellers, the blanks for the hub disc and cover are subjected to final heat treatment before machining. Post-riveting heat treatment is merely required to compensate for the lowering of the yield strength of the rivets due to the "Bauschinger effect."

For welded impellers, adequate toughness characteristic values in the weld metal and in the heat affected zone can normally be achieved by one or two postweld tempering operations, when disregarding special materials, and if no special requirements are to be satisfied in respect to low temperature toughness or in respect to resistance to stress corrosion cracking.

Low temperature toughness, however, requires optimization of the heat treatment. The unaffected base material, the heat affected zone and the weld metal react differently to postweld heat treatment. The optimum energy values at −40°C, for example, are achieved for the material 14 CrMoV 6 9 only by a special postweld heating, as can be seen in Figure 31. This "intercritical" tempering treatment, at which the weld metal as well as the base material is initially tempered in the two-phase zone at approximately 760°C, is followed by a tempering treatment at 650°C. Parallel to this optimization of the notched bar impact strength, it must be investigated, of course, to what extent the yield strength, which is of equal importance to safety in operation, is affected by an intercritical heat treatment.

Figure 32. Influence of Special Heat Treatment Cycles for High Resistance under Sour Gas Conditions for X 5 CrNi 13 4.

When brazing is applied, the sequence of operations is chosen wherever possible, so that the brazing temperature and cooling after brazing coincide with the requirements for the heat treatment of the material. Brazed joints of the material X 5 CrNi 13 4 or G-X 5 CrNi 13 4 (equivalent to ASTM A 743 Grade CA-6NM [7]), thus need tempering only after brazing, to achieve the optimum toughness at the yield strength specified. This is not always possible where low-alloyed materials are involved. In this case, just tempering the material quenched from the brazing temperature produces inadequate toughness values. It is necessary to reheat the impeller to the optimum quenching temperature of the material after cooling to room temperature from the brazing temperature, to achieve optimum toughness values after subsequent tempering, as is illustrated in Figure 33.
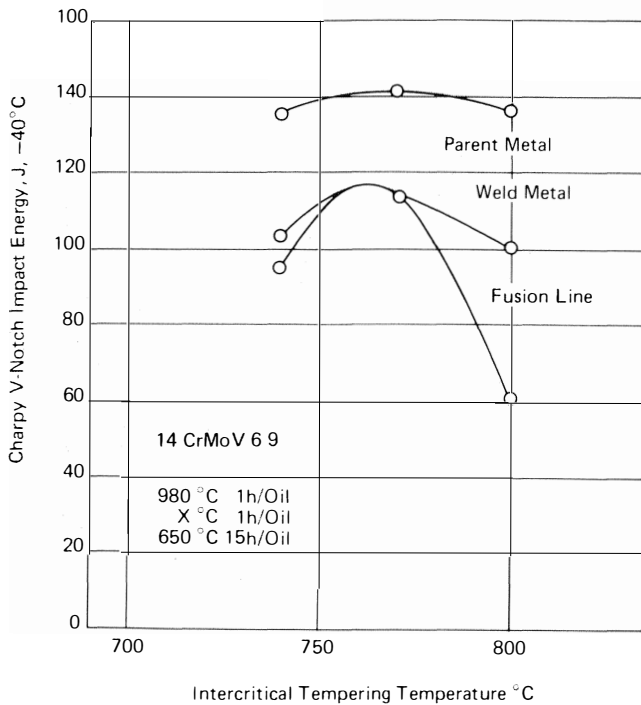

Figure 31. Heat Treatment for Optimizing Toughness of Welded Joints from 14 CrMoV 6 9.

The necessity of a complete new heat treatment after welding instead of only tempering has been covered in SELECTION OF MATERIALS, in connection with the material 14 CrMoV 6 9. The relation between the response of the base material and of the weld metal is illustrated in Figure 31.

The application of the material X 5 CrNi 13 4 in sour gas makes a particularly complicated heat treatment necessary. The changes of the tensile strength R_m, the yield strength $R_{pO,2}$, and of the hardness HRC as a function of the tempering treatments at 675°C and at 600°C in one or more cycles, and the change of the total content of austenite in the base material are illustrated in Figure 32.
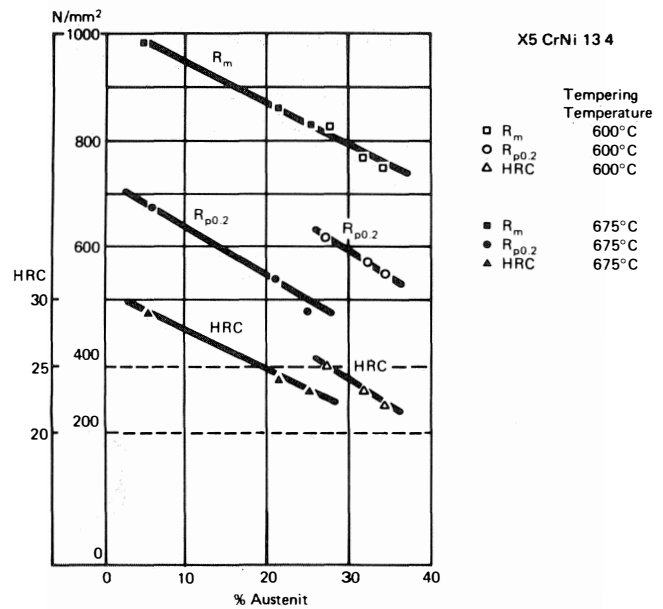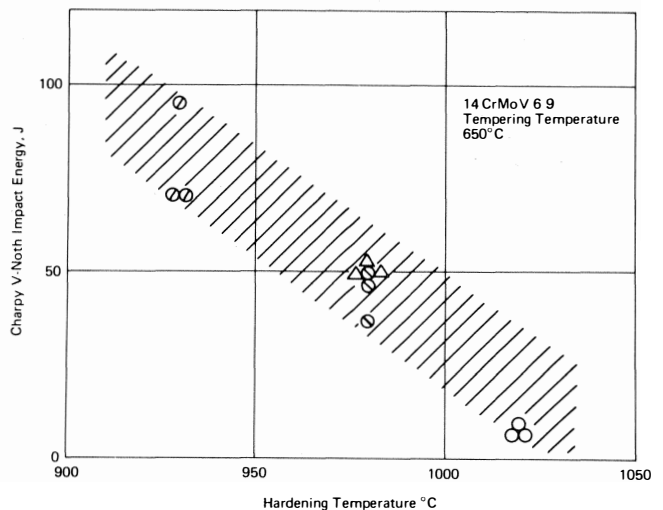

Figure 33. Influence of Hardening Temperature on Toughness of Low Alloy Steel.

QUALITY ASSURANCE

The impeller of a turbocompressor is a part that is subjected to exceptionally high stresses. A failure of this part will cause

stoppage of the complete train. For this reason, utmost importance is to be attached to quality assurance measures during design and manufacture. The most essential basic principles to be adhered to are as follows:

• Each quality assurance measure must be completely traceable. The performance of destructive tests and of non-destructive examination must be marked on the impeller or indicated in the manufacturing route sheets so that any mixing up is ruled out, and that conducting of all specified inspections and tests is ensured.

• The standards for testing procedures, indicated in Figure 34, can merely be considered as a basis for destructive and non-destructive material testing. The special demands made of the impeller must be satisfied by appropriately adjusted supply specifications for the blanks and by drawing up detailed in-process inspection/test plans.

Test Procedure	Standard	
	ASTM, ASME, API	DIN/ISO, SEP, SEL, AD
chemical analysis	ASTM E 30	Handbuch für das Eisenhüttenlaboratorium
tension test	ASTM A 370	DIN 50125/DIN 50145
notched bar impact test	ASTM E 23/A 370	DIN 50115
hardness test		
– Vickers	ASTM E 92/E 384	DIN 50133
– Brinell	ASTM E 370/E 10	DIN 50351
– Rockwell	ASTM A 370/E 18	DIN 50103 T.1
ultrasonic examination		
– procedure	ASTM E 114	DIN 54126 T.2
– of forgings	ASTM A 388	SEP 1921
– of ferritic cast steel parts	ASTM A 609	SEP 1922/DIN 1690 T.2
magnetic particle exam.		
– procedure	ASTM E 709	DIN 54130
– forgings	ASTM A 275	
– of steel castings	ASTM E 709/E 125	SEP 1935
liquid penetrant exam.		
– procedure	ASTM E 165	DIN 54152 T.1
– of steel castings	ASTM E 433	SEP 1936/DIN 1690 T.2
overspeed test	API 617	

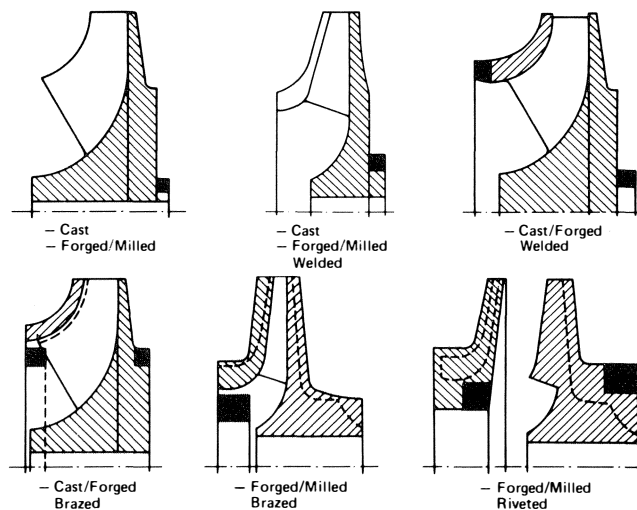Figure 34. Standards for Inspections and Tests for Impellers (U.S.-system and German System 4, 8 to 37.

• As mentioned before in the sections on SELECTION OF MATERIALS and HEAT TREATMENT, heat treatment is always governed by the requirement to ensure at any time maximum safety in operation under every service condition, by achieving maximum toughness of the impeller material.

• Each manufacturing process, including casting and forging operations, must be subjected to procedure qualification tests, before it is applied, to furnish proof that the specified quality data can be clearly verified by the proposed tests/inspections and to make sure that the manufactured impellers are up to specified operating conditions in any respect.

To ensure complete traceability, a test specimen must be taken from each impeller after its final heat treatment, which has been subjected to all in-process heat treatment operations, together with the impeller. Where welded impellers are concerned, the necessary test rings may remain on the impeller parts proper during the entire manufacturing process, as shown in Figure 35. Brazed impellers require a specimen to be taken from the cover before brazing, because of better brazeability. Its size depends on the cross section of the parts represented by the specimen. The quality assurance system must ensure that the specimen and the impeller are always subjected to the same heat treatment cycles.

In view of the special conditions which apply to the welding of impellers, the standardized procedure qualification tests, for example to ASME Section IX or to AD-code of practice,

normally cannot be used, since they have not been adjusted to the special conditions for manufacturing turbocompressor impellers. For this reason, a special test coupon was developed, for example, for repair welding on cast impellers (Figure 36). This test coupon permits the specific difficulties involved in welding in a hole to be simulated easier as compared with a standardized test coupon.

— Cast
— Forged/Milled

— Cast
— Forged/Milled
Welded

— Cast/Forged
Welded

— Cast/Forged
Brazed

— Forged/Milled
Brazed

— Forged/Milled
Riveted

Location of Specimen for Mechanical Properties

Figure 35. Specimen for Evaluation of Mechanical Properties of Impellers.

Section A–B
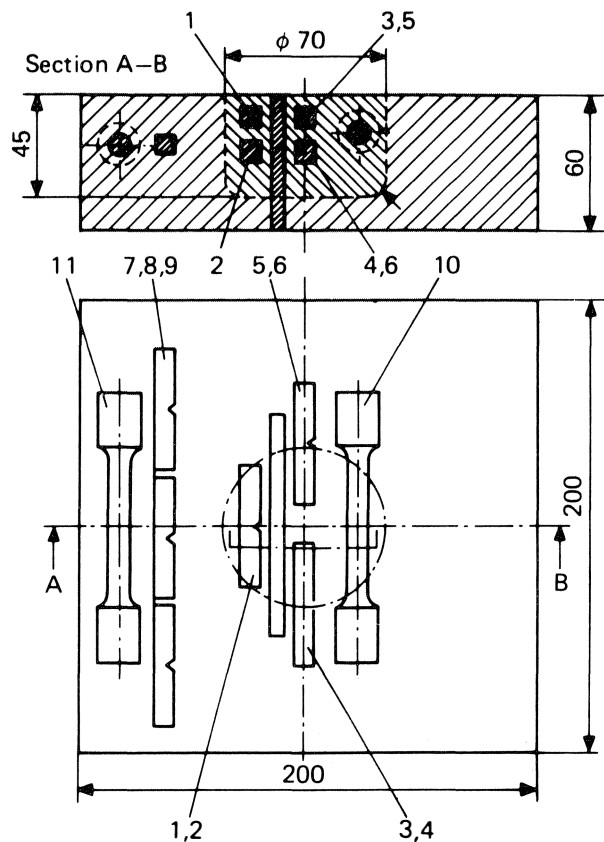
Location of notch: Specimen 1, 2   centre of weld metal
Specimen 3, 4   fusion line
Specimen 5, 6   fusion line + 2 mm

Figure 36. Welding Procedure Test Sample for Cast Impellers.

The tests and inspections currently in use for the different impeller variations are summarized in Figures 37, 38, and 39. For these examinations, it may become necessary to develop new test and inspection methods. A test facility to be used for inspecting brazed impellers is shown in Figure 40. This permits the automatic detection of defects as small as 0.8 mm diameter in the brazed joint of an impeller, and to display such defects graphically. The ultrasonic examination is affected by moving the probe over the rotating impeller so that the entire brazed surface is scanned in the shape of a spiral. The movement of the probe is controlled by a process which is connected with the central computer.

CASTINGS	FORGINGS
Dimensional check pattern	
Radiographic examination first impeller	Ultrasonic examination
Dimensional check casting	

Chemical analysis
Tension test
Impact test
Surface crack examination

Figure 37. Inspections and Test of Impeller Materials.

	BRAZED	WELDED	RIVETED
Before joining	Dimensional check Surface crack examination		
During joining process check of	Temperature		Pressure
	Vacuum	Voltage Current	
	Brazing alloy	Filler metal	Material of rivets
After joining	Ultrasonic examination		
	Dimensional check Surface crack examination		
	Tension test Impact test Hardness test		
Ready machined impeller	Balancing test Overspeed test Dimensional check Surface crack examination		

Figure 38. Inspections and Tests of Fabricated Impellers.

CAST	MILLED
Ready machined impeller	Balancing test
	Overspeed test
	Dimensional check
	Surface crack examination

Figure 39. Inspections and Tests of Unfabricated Impellers.

Figure 40. Ultrasonic Test Facility for Brazed Impellers.

Another example concerns checking for fulfillment of the high demands made of the dimensional accuracy of the blade faces. This cannot be accomplished with conventional inspection facilities, because they produce such a tremendous amount of figures that it would be impossible to follow them up and to use them for the assessment of the quality of an impeller. Only after introduction of the multi-coordinate measuring systems which permits the continuous scanning of curves, as shown in Figure 41, it has become possible to draw qualified conclusions about the useability of the impeller from the graphical display of the measured results, via the indicated deviations from shape, location and size.
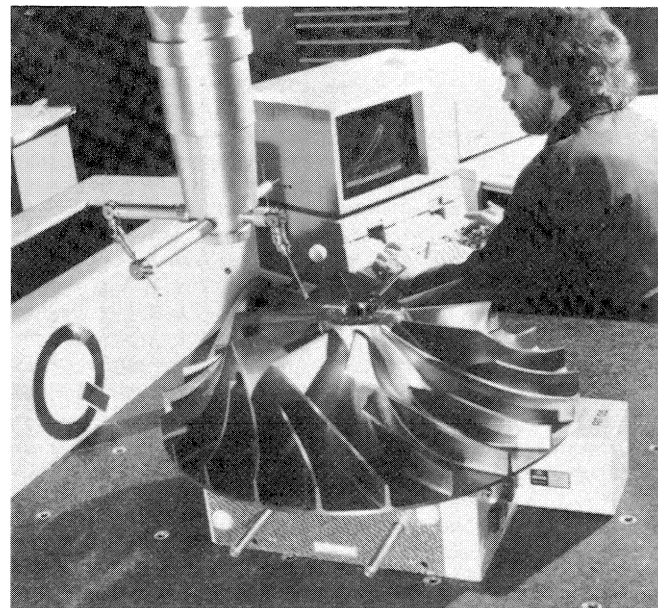

Figure 41. Measuring of Blades on a Multicoordinate Measuring Machine.

The necessary traceability of the manufacture of impellers includes the requirement for documenting the quality inspections. Such documentation is to be made out for each impeller.

CRITERIA GOVERNING THE SELECTION OF THE MANUFACTURING PROCESS

For the specific case of manufacturing a certain impeller, the optimal manufacturing process must be selected from a great variety of manufacturing processes. Of course, such a selection must particularly take into account the conditions prevailing in the specific workshop. Nevertheless, some criteria can be discussed, by which the individual processes are impartially evaluated in respect to their usability.

The most essential criteria appear to be:

• The impeller geometry, including the absolute dimensions and the accessibility in the channel.

• The choice of material, which is partly restricted by the manufacturing process to be applied.

• The mechanical properties of the impeller, including the joint between the blade and the cover under static or fatigue loading.

• The effect which design, manufacturing method, and workmanship have on corrosion in service and at standstill.

• The risk of defects during manufacture, including the possibility of carrying out any repairs, and considering the methods of checking the quality of the construction.

• The accuracy of size and surface finish which has an extraordinarily great impact on the aero-thermodynamic performance of the impeller, especially in areas exposed to the medium.

• The total costs of manufacture.

In the following subsection, the various manufacturing processes will be briefly dealt with in the light of these criteria.

Criteria for the Selection of the Disc and Blade Manufacturing Process

As outlined in THE MANUFACTURE OF HUB DISC BLADES, the selection is to be made between casting of open impellers, milling of blades out of forgings, or welding blades from sheets to forged cover disc.

The choice of materials is limited by the named criteria, especially when casting is concerned, since there are few materials available for this process. In practice, only the following two materials are used: G-X 5 CrNi 13 4, equivalent to ASTM A 743 Grade CA-6NM, and G-X 5 CrNiCuNb 17 4, equivalent to 17-4 PH cast. Other materials might also be suitable; however, the experiences with those materials are inadequate.

The accuracy of the size of cast impellers and of impellers with blades from sheets is somewhat less favorable compared with milled impellers. In every case, however, it satisfies the design requirements.

The costs of manufacture are greatly influenced by the number of pieces manufactured. An impeller cast to the investment casting process is less expensive to manufacture than the forged-milled impeller would be, if the number of pieces exceeds a certain quantity, which depends on the diameter of the impeller. For larger impellers, the minimum quantity for economic casting is even less, though the impeller with blades from sheets is not as expensive as the milled version. This is true because the manufacture of the patterns and molds for the monobloc is not as difficult as for the investment casting.

Criteria for the Cover Joining Process

Comparison of the Welding Processes

As practice has shown, it never makes sense to try to assemble the impeller by welding through the cover when welding within the channel is possible. Welds produced within the channel using the SMAW process or the GTAW-P process are under practically all aspects superior to welding through the cover, except the blocking effect of the fillet welds in the channel.

Comparison of the processes for welding within the channel. Contrary to the universally applicable SMAW which, above all, is practically independent of the impeller geometry, the mechanized GTAW-P process is still restricted to two dimensional impellers. By contrast, the blocking by the fillet weld, its surface finish and the accuracy to size of the complete impeller is superior in the case of GTAW-P. This superiority can be explained, among other things, by the fact that GTAW-P permits welding of the fillet weld over its entire length in one pass, i.e., no surface irregularities occur at the points of starting a new electrode, as is the case with SMAW.

The costs involved in these two welding processes are practically identical, but the risk of defects during manufacture is higher for the SMAW process.

Comparison of the processes of welding through the cover. In the author's opinion, EB-welding is not suitable for use in the manufacture of turbocompressor impellers, because of serious shortcomings, i.e., the low strength under fatigue stresses and the negative response to corrosion. These drawbacks have their origin in the inevitable sharp crevices between the blades and the cover.

Likewise, slot welding is not quite suitable with regard to the geometry for three dimensional impellers and with respect to its mechanical properties under fatigue loading. The most serious aspect of slot welding, however, is the high risk of manufacturing defects, as there is practically no way of repairing any defects which have possibly occurred in the first pass. Consequently, the costs involved are relatively high. Slot welding is, therefore, used only in cases where no other joining process can be used.

Criteria for judging the diffusion welding process. Not only for the manufacture of the hub disc and cover, but also for cleaning and for the welding process, diffusion welding requires exceptionally expensive facilities, which is one of the reasons that this welding process will remain restricted to impellers of smaller diameter. Besides, its use would be logical only in the manufacture of two dimensional impellers.

The strength of a diffusion welded impeller and its resistance to corrosion is restricted by the inevitable notches in the welding zone. The manuacturing safety is not really high, there is practically no way of doing repair work, and inspecting possibilities are severely restricted. As far as accuracy to size is concerned, plastic deformation may, under certain circumstances, lead to substantial deviations from size.

It can thus be concluded that diffusion welding is not a very attractive manufacturing method, either under the aspect of properties of the built impeller or under the cost aspect.

Comparison of Welding Processes with Other Joining Processes

Compared with the welded impeller, the choice of materials is limited in the case of casting closed impellers, as described previously, and the response to corrosion may be somewhat less favorable compared with forged versions. Manufacturing problems are to be expected for cast impellers of extremely small size, and the performance of repairs will be difficult, because of the poor accessibility. These threshold geometries, however, are the same for cast and for welded impellers.

Compared with these two variations, brazing and riveting offer the merit of particularly high accuracy of size. Further, the manufacturing safety is significantly higher, and the choice of materials is practically unlimited for the applications under review. In the author's opinion, these processes should thus be given preference over welding.

Brazed impellers have the additional great advantage of being practically independent of the impeller or blade geometry. With regard to their size, however, they are still restricted by their outer diameter. On the other hand, much thinner blades can be attained by brazing, which is an advantage of this process over the riveting process. Passage restrictions can thus be reduced and the number of blades can be increased, which has an exceptionally positive effect on the performance of the impeller.

The comparison of resistance to corrosion indicates that under certain circumstances some problems may occur with the brazing alloy base material combination of brazed impellers, when exposed to certain corrosive media (for example, sulfuric acid or nitrous gases). On the other hand, however, the riveted impeller is susceptible to crevice corrosion, due to the gap. The loaded element, the rivet, however, is not affected, since it has no such gap.

The statements made on the criteria for selecting manufacturing processes are summarized in Figure 42.

	Criterion / Procedure	Impeller Geometry	Material Selection	Strength Static	Strength Dynamic	Corrosion Behaviour	Production Security	Dimensional Accuracy	Cost Effectiveness
Hub disc with blades / Forging	Casting	+	−	+	O	O	+	+	O
	Milling	+	+	+	+	+	+	+	O
	Blades from plate	O	O	+	+	+	O	O	O
Joining of the shroud disc	Casting of closed impellers	O	−	+	+	O	O	O	O
Welding in the channel	SMAW	O	O	+	+	+	O	O	O
	GTAW-P	−	O	+	+	+	+	+	+
Welding from outside	Slot welding	−	O	+	−	O	−	O	−
	EB	−	O	+	−	−	O	O	−
	Diffusion welding	−	+	+	−	O	−	−	−
	Brazing	+	+	+	O	O	+	+	+
	Riveting	O	+	+	+	O	+	+	+

Legende: + Good
O Acceptable
− Not acceptable

Figure 42. Evaluation of Manufacturing Methods.

CONCLUSIONS

As the evaluation of the individual manufacturing processes made in the previous section shows, and according to the practice adopted worldwide, certain manufacturing processes are preferable for certain impeller types. The attempt is made in Figure 43 to show this in the form of a matrix. The question marks indicate where new processes may be applied in the future under certain circumstances. This graph also shows that high-quality and low-cost processes are available for the entire range of application, as indicated in Figure 1. Transformed to the representative of Figure 1, Figure 44 shows the fields of application of the manufacturing processes for the various types of impellers as a function of their outer diameter.

Summing up, it can be stated that, due to the high quality standard, casting is generally superior to forging, where greater numbers of pieces are involved. For smaller impellers, brazing will make a breakthrough, while SMAW will be given preference in the manufacture of larger impellers, with the number of impellers with three dimensional blade designs on the increase. It depends on the outer diameter, whether the blades then are milled (diameter below about 700 mm) or are made from sheet.

Whether there will ever be an automatic welding process for such impellers depends on the progress made in the develop-

	Impeller Type / Procedure	3 D without shroud disc	3 D with shroud disc	2 D with shroud disc
Hub disc with blades / Forging	Casting	+	+	
	Milling	+	+	+
	Blades from plate	+	+	+
Joining of the shroud disc	Casting of closed impellers		+	+
Welding in the channel	SMAW		+	+
	GTAW-P		?	+
Welding from outside	Slot welding		?	O
	EB			−
	Diffusion welding			−
	Brazing		+	+
	Riveting			+

Legende: + Usable without limits   − Usable with limits
O Usable   ? Not jet performed

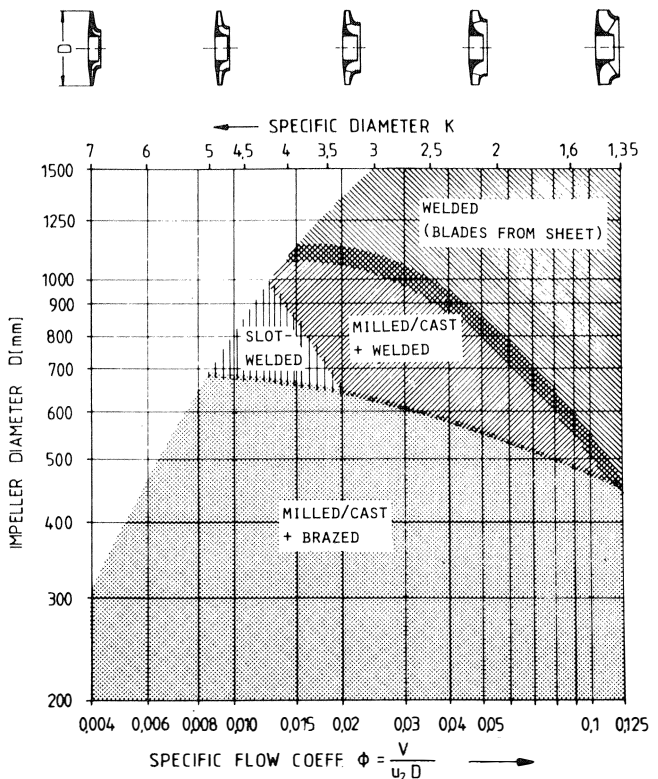*Figure 43. Fields of Use of Manufacturing Methods.*

Figure 44. Field of Application of Three Dimensional Impellers and the Optimal Manufacturing Methods.

ment of weld follow-up systems, as the precise positioning of the torch is a condition for producing high-quality welds.

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