Dec. 6, 1960 W. J. STEIN ET AL 2,962,941

APPARATUS FOR PRODUCING A CENTRIFUGAL COMPRESSOR ROTOR

Filed Aug. 3, 1955 3 Sheets-Sheet 1

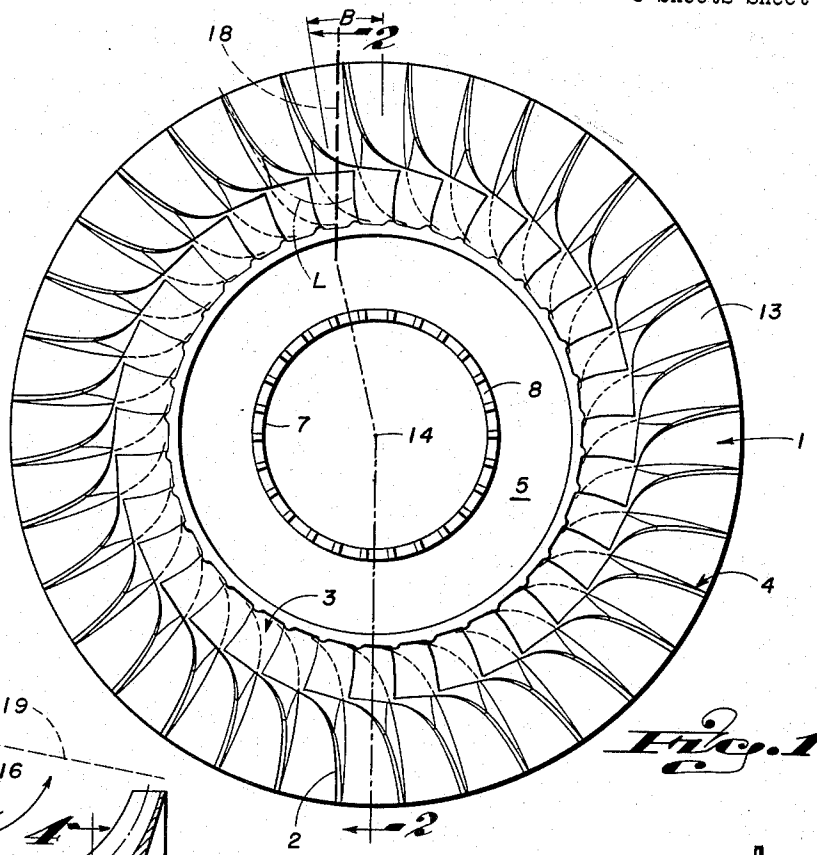


Fig. 1

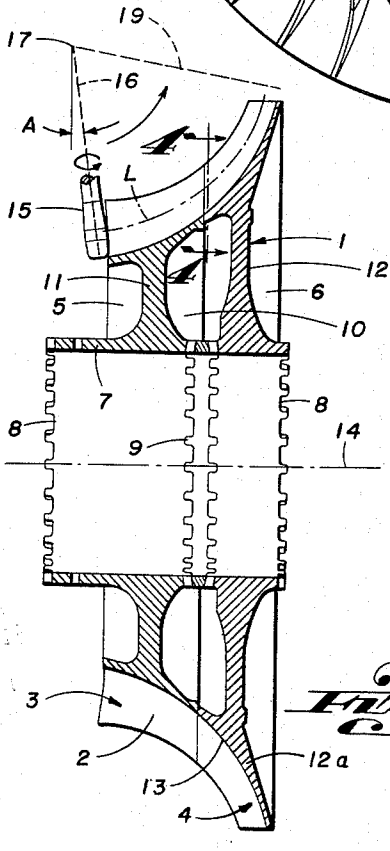


Fig. 2

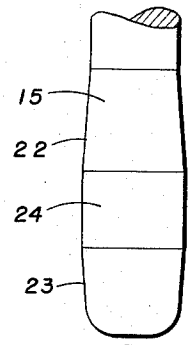


Fig. 3

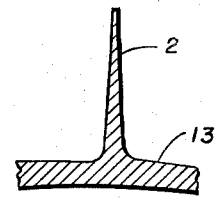


Fig. 4

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APPARATUS FOR PRODUCING A CENTRIFUGAL COMPRESSOR ROTOR

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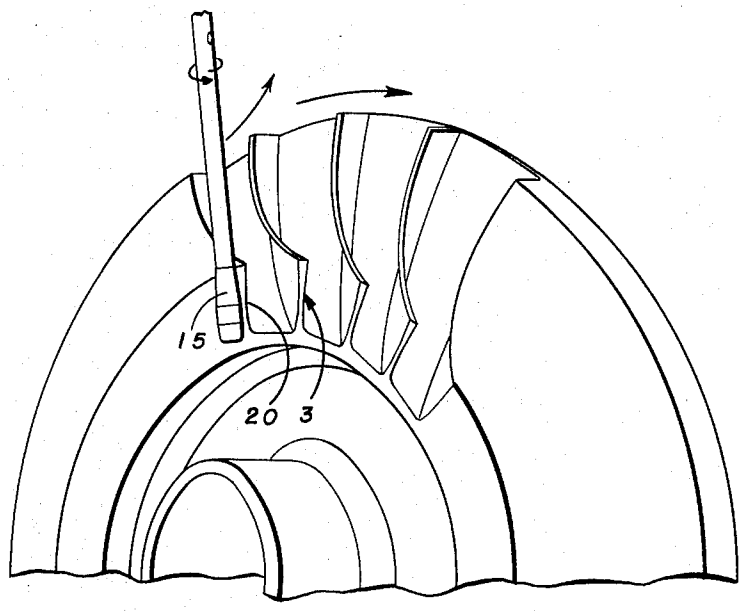


Fig. 5

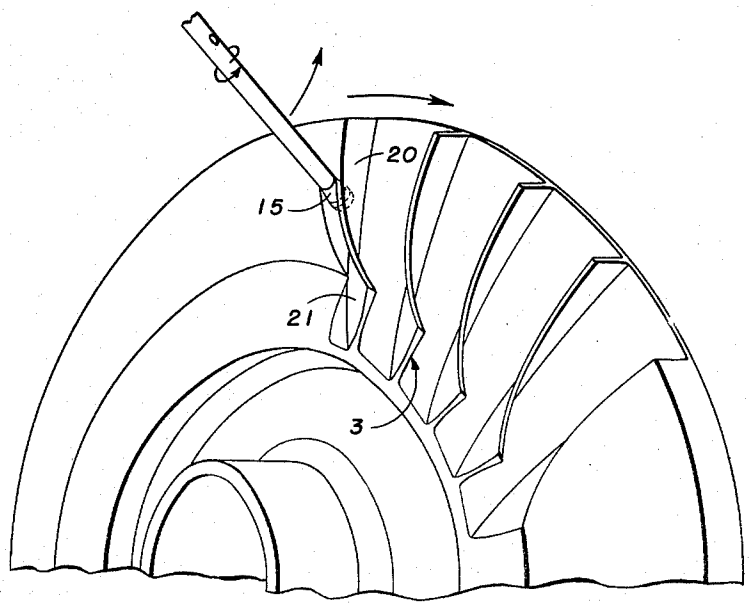


Fig. 6

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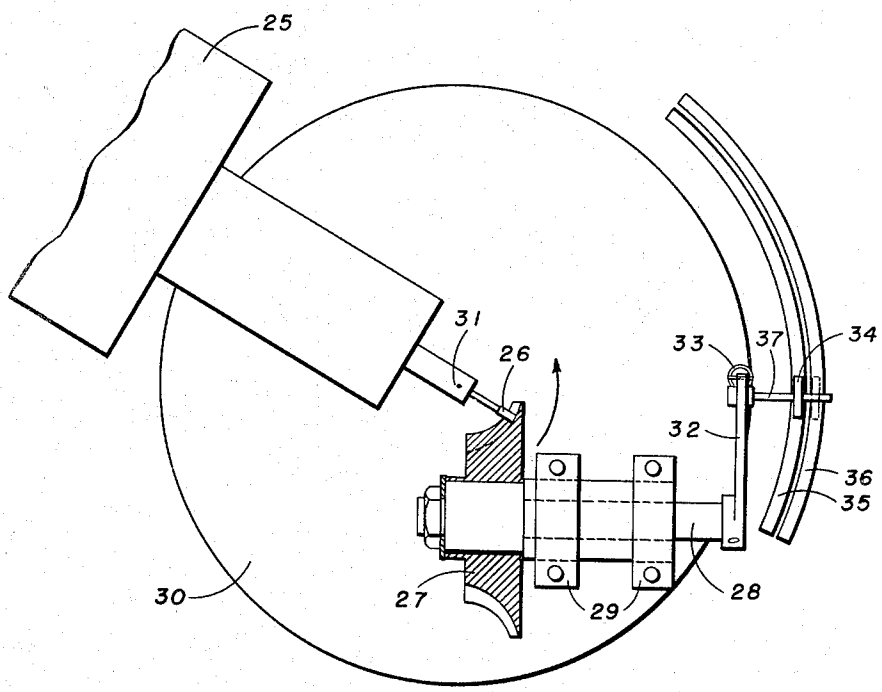


Fig. 7

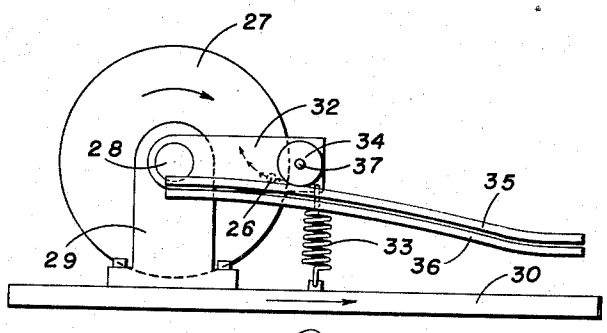


Fig. 8

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APPARATUS FOR PRODUCING A CENTRIFUGAL COMPRESSOR ROTOR

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1 Claim. (Cl. 90—13.9)

The present invention relates to an improved centrifugal compressor rotor particularly adapted for use in the compressor section of a turbine engine, although it has wider application, as in superchargers of internal combustion engines and other high speed centrifugal compressors.

The invention also concerns a method of producing the novel rotor. The method does not require expensive or unusual machining operations and can be carried out with machine tools which are well-known in the aircraft engine industry today. As a result, the novel method makes it possible to produce at moderate cost improved rotors having high strength and increased efficiency.

The present invention relates to that broad class of centrifugal compressors in which the air, or other gas to be compressed, is introduced axially to the rotor. The air is accelerated by the rotor and delivered radially at high speed.

Such rotors usually have a plurality of equally spaced vanes formed integrally with a central hub which is attached to a high speed shaft. The vanes have curved leading edges at the inlet end of the hub, which has a relatively small diameter. The curvature of the leading edges minimizes air turbulence and attendant losses which reduce efficiency. The vanes desirably curve uniformly towards the discharge end of the hub which is larger in diameter than the inlet end. Here, the ends of the vanes extend substantially radially and are designed to deliver air at high speed to a collector or diffuser where its speed is reduced and pressure head increased according to well-known laws of aerodynamics.

It is desirable from a strength standpoint that the vanes extend radially from the hub. That is to say, the cross sections of the vanes in any plane normal to the axis of rotation should be substantially radial. In this way, bending moments resulting from centrifugal forces incidental to high speed rotation, are avoided. This vane form may be conveniently termed "radial fairing."

As a practical matter, an efficient rotor with radial fairing is difficult to produce by conventional machining methods. As a practical solution, compromise designs have been followed resulting in inefficient rotors giving barely satisfactory performance.

To illustrate, it is common in the radial engine field to manufacture rotors by first milling a plurality of planar, radially-extending vanes from a rotor blank. Thereafter, the inlet ends of the vanes are bent slightly to form an inducer. Although the machining operations are relatively simple and radial fairing is attained, the resulting rotor is very crude from an aerodynamic standpoint.

The present invention represents a substantial advance in the art. Briefly described, the novel rotor of this invention comprises a hub having integral vanes which closely approach radial fairing over a majority of their length. Such departures as do exist occur at the small radius inlet ends of the vanes where the substantial vane curvature and relatively small centrifugal forces make

acceptable minor deviations from optimum design conditions.

Over much of their length, the vanes of this novel impeller also have a uniform rate of change of curvature excellently adapted to gradually accelerate the air and change its direction of flow from substantially axial to substantially radial. The vane form is such that a large portion thereof contributes to air acceleration, assuring more uniform vane loading and improved efficiency. Vane loading may be defined as the differential static pressure acting on a small increment of area of vane surface at any point along the path of airflow through the rotor. From an aerodynamic standpoint, the improved rotor is characterized by better velocity distribution, better boundary layer control, and more uniform vane loading.

The novel method of producing the rotor comprises rotation of the rotor blank about its principal axis simultaneously with rotational movement of the blank relative to a milling center. Although the important consideration is the overall relative movement between the cutter and the rotor blank, the process is most easily visualized as comprising simple rotation of the rotor blank about its principal axis during simultaneous pivotal movement of the rotating cutter about a point lying on its axis of rotation. During this pivotal movement, the axis of the cutter generates a plane offset slightly from but parallel to the principal axis of the rotor. The reasons for so positioning the axes will be fully understood from the description of the invention which follows.

The "principal" axis about which the rotor blank is indexed during the machining operation is the same axis about which the finished rotor revolves when used in a compressor.

It is important to recognize that the rotor of the present invention can be produced through two simple pivotal movements of the blank relative to the cutter. This is in distinct contrast to other prior art machining methods where relatively complex movements had to be imparted to either cutter or blank or both, if a complex vane form was to be produced. The new method, in which a sizable length of cutting tool edge acts constantly during machining of the vanes, also represents a singular advance over contour milling. In this tedious prior art method, a pantograph milling installation generates the surface of the vanes by a point by point process.

An important object of the present invention is, therefore the provision of an improved rotor and the method of making it.

Another important object of the invention is the provision of a machining method which may be utilized to produce the rotor, the vanes of which have radial cross sections in planes normal to the axis of rotation, i.e., radial fairing.

A further object of the invention is the provision of a method of producing rotors with radial fairing regardless of the curvature of the vanes. The method is very flexible and may be readily used to produce a wide variety of rotors and vane forms.

It is also an object of the invention to provide a method of producing a rotor which involves only two simple rotary movements of the cutter and blank relative to each other.

An obvious advantage of the novel method is that it yields a strong rotor having excellent aerodynamic characteristics. No longer need strength be attained through sacrifice of performance.

The novel features that are considered characteristic of our invention are set forth in the appended claim; the invention itself, however, both as to its organization

and method of operation together with additional objects and advantages thereof will best be understood from the following description of specific embodiments when read in conjunction with the accompanying drawings, in which:

Figure 1 is a front elevational view of the novel rotor made by the improved method set forth in this specification;

Figure 2 is a cross sectional view of the rotor taken on line 2—2 of Figure 1;

Figure 3 is an enlarged view showing the contour of a typical milling cutter used in machining a rotor of the type shown in Figure 1;

Figure 4 is a cross sectional view of a rotor vane taken on plane 4—4 of Figure 2, the view illustrating the significance of radial fairing;

Figure 5 is a perspective view of a rotor blank showing diagrammatically the relative movement of cutter and blank during the formation of one surface of a vane;

Figure 6 is a view similar to Figure 5 showing the cutter advanced from the position shown in Figure 5;

Figure 7 is a top plan view of a milling machine set up for carrying out the method of the present invention; and

Figure 8 is a side elevational view of the setup shown in Figure 7.

The novel rotor can best be described by reference to Figures 1 and 2 which show a rotor hub, generally designated **1**, on which is integrally formed a plurality of projecting vanes **2**. As illustrated in Figure 1, each rotor vane is curved from an inlet end, generally designated **3**, to a discharge end, generally designated **4**. Each vane is substantially radial and planar in the region of the discharge end.

The specific curvature and form of the vane is not critical in the present invention since the method set forth is quite flexible and may be readily used to produce rotors having a wide variety of vane forms.

The specific rotor illustrated comprises two sections joined on a radial plane. For convenience, the first section is termed "the inducer section" and is indicated at **5**. The second section **6** may be termed "the impeller section." Each section includes cylindrical hollow shaft portions **7** provided at each end **8** with a "curvic" coupling or face spline used for joining the rotor to a high speed driving shaft.

It will be noted that an annular ring **9**, each end of which also defines a curvic coupling, is positioned between sections **5** and **6**. The space occupied by the ring is only provided to simplify machining operations during which material is removed from region **10** for weight reduction purposes. Removal of material from region **10** is also made possible by the split construction of the rotor.

Sections **5** and **6** of the rotor include disk-like members **11** and **12**, respectively, which extend from shaft portions **7** to rim **12***a* bounded on its periphery by ground surface **13** from which the vanes extend radially.

It should be recognized that the structural details such as the curvic coupling, ring **9**, and split rotor sections, do not constitute limitations of the invention. These are typical design features of an aircraft gas turbine type rotor.

As mentioned earlier in the specification, it is desirable that each cross section of the vanes in planes normal to the principal axis, indicated at **14**, extend substantially radially, i.e., the vanes should be characterized by radial fairing. The significance of radial fairing can be gained by reference to Figure 4 which shows the cross section of a vane as it appears close to the parting plane of the rotor sections. It will be noted that the vane **2** extends substantially radially and is substantially perpendicular with a transverse tangent to the adjacent ground surface **13**.

Radial fairing is important in a rotor of the type illustrated which, during normal operation, is subjected to high speed rotation in the order of 20,000 r.p.m. At such high speeds, centrifugal force generates very high stresses throughout the rotor. It is undersirable that the vanes be formed in such a manner that bending moments result from the centrifugal forces present. With radial fairing, as illustrated in Figure 4, no bending moments are present since the vane section is symmetrical relative to a central radial line, and is not overhung with respect to its point of restraint.

Radial fairing is by no means new in the art. Its desirability in a high speed rotor has long been recognized; however, up to the advent of the present invention, no aceptable machining process was known for producing complicated vane forms having radial fairing.

As a result, machining processes have been used in the past which necessitated a compromise of strength and aerodynamic characteristics of the resulting rotor. A typical prior art process is disclosed in the Meisser Patent 2,429,324. Processes of this type may be satisfactory for many purposes but can only be used to make a small number of vane forms. Further, where the vane height at the discharge end of the rotor is substantial, radial fairing is difficult, if not impossible, to attain since the process inherently imparts the contour of the cutter to the cross section of the discharge ends of the vanes.

The principles involved in the present method can be easily understood by reference to Figure 2. There is shown a milling cutter **15** rotating about its longitudinal axis indicated in one position at **16**. During movement of the cutter whereby it generates one face of a vane, the axis **16** pivots about a point **17** lying on the axis. During this pivotal movement, the axis generates a plane indicated at **18** in Figure 1.

Plane **18** is offset laterally with respect to rotor axis **14**, as indicated in Figure 1. It should also be noted that plane **18** is parallel to the axis of the rotor. The purpose for offsetting the cutter in this manner will be more fully discussed shortly.

During movement of the cutter generating one surface of a vane, the cutter axis moves between the extreme positions indicated at **16** and **19**. It should be observed that every point on the cutter axis generates a circular arc about point **17** during the cutting operation. In other words, simple rotation of the cutter axis is all that is involved.

Simultaneously, with movement of the cuter axis, simple rotation is imparted to the rotor blank about principal axis **14**. Blank rotation is coordinated with the angular movement of the cutter axis and in this way a predetermined vane surface is generated.

Thus, by simple rotation of the cutter axis and the rotor blank, a relatively complex vane form can readily be created.

The relative movements of the cutter and rotor blank are illustrated in Figures 5 and 6. These figures are diagrammatic and intended more to illustrate the basic principles of the method than to show any particular rotor.

With reference to Figure 5, there is shown cutter **15** positioned momentarily at inlet **3** of a rotor vane, one face **20** of which has already been formed. As the cutter moves between the positions shown in Figure 5 and Figure 6, the second face **21** of the vane is generated. By comparing the figures, it will be noted that clockwise movement is imparted to the rotor blank as the cutter is gradually raised towards a horizontal position. Coordination of these movements generates the curvature of the finished vane.

In carrying out the foregoing method, it has been found from actual experience that the cross sectional shape of the vanes is a function of the cutter proportions and the position of plane **18** with relation to axis **14**. By offsetting the axis of the cutter as indicated, and choosing a cutter having dimensions proportionate to the height of the vanes to be formed, a vane can be produced having substantial radial fairing throughout its length.

One cutter form which has been found to be quite acceptable is shown in Figure 3. As illustrated in this figure, it will be noted that the cutter has conical end portions **22** and **23** between which is provided a cylindrical portion **24**. Because of differences of vane height, all portions of the cutter are not effective at all times; however, a substantial length of the cutter is always active and a complete side of a vane is formed in one pass of the cutter.

The particular curvature of the vanes illustrated constitutes no limitation of the invention. In fact, a highly desirable feature of the invention is that a wide variety of rotors can be produced having radial fairing simply by coordinating, as may be desired, the rotation of the cutter axis and the rotor blank. In this way, it is possible to produce rotors having ideal strength and aerodynamic characteristics, and it is no longer necessary to sacrifice performance in order to simplify machining operations and meet strength requirements.

The particular vane illustrated in Figures 1 and 2 is best defined by the angular positions of the blank and the cutter axis which define an imaginary curved center line L lying between the actual boundary surfaces of the vane at a radium of 3.47 inches from point **17** (see Fig. 2). Once this information is known, it is a relatively simple matter for a tool maker to design tools for machining the vane surfaces lying at any specified distance from the imaginary center line.

For convenience, the angular positions of the blank and cutter axis are measured from initial reference positions. The angular position of the cuter axis is measured from a plane through point **17** normal to axis **14**. Rotation of the rotor is measured from a vertical plane coincident with axis **14**.

To illustrate, for a blank having a discharge diameter of 13.08 inches and an inlet diameter over the vanes of 9.42 inches, point **17** would lie at a radius of 7.48 inches from axis **14** at a distance of .40 inch from the face of the adjacent curvic coupling. In a rotor of these proportions, plane **18** is offset from axis **14** by .75 inch. The imaginary curved center line of the vane illustrated is then defined as follows:

A=Cutter Axis Rotation From Vertical Reference Plane	B=Rotor Rotation From Vertical Reference Plane Coincident With Axis 14
20°	20°53′
30°	15°23′
40°	11°50′
50°	9°34′
60°	8°05′
70°	6°57′
80°	6°03′

By actual use of the method set forth, it has been found that the blades conform closely to radial fairing throughout their length. Such minor departures as may exist fall within the inducer section. Here such minor departures are not serious since the centrifugal forces acting on the vanes in this region are relatively small and the curvature of the vanes inherently results in a strong shape resisting any bending moments that may be present.

The vanes conform closely to radial fairing at the parting plane between the rotor sections and throughout the impeller section. This is particularly desirable since the vanes in the impeller section are subjected to the highest centrifugal stresses. Since forces cannot be transferred across the parting plane, it is also desirable that both sections of the vanes adjacent the parting plane conform to radial fairing so that no relative movement will result under centrifugal loading. Thus, the vane shape remains smooth and no step, which might present an impediment to airflow, is present at the parting plane.

With reference to Figure 2, it will be noted that a longitudinal section through the ground surface inherently has a circular configuration by virtue of the pivotal movement of the cutter axis. Although not necessary from an aerodynamic standpoint, this is entirely acceptable and desirable in simplifying the machining process.

The ground surface closely resembles a portion of a toroid although it tends to be flattened slightly by the end of the cutter. Further, the offset of plane **18** results in a slight difference in the levels of the ground surface on opposite sides of a given vane, as suggested in Figure 4. These minor deviations are in no way material.

Attention may now be directed to Figures 7 and 8 which illustrate diagrammatically a milling machine setup for manufacture of rotors in accordance with the principles of this invention. A portion of a milling machine is indicated at **25**. A milling cutter of the type indicated in Figure 3 is provided at **26** and rotates about its longitudinal axis which is stationary. Here movement of the cutter relative to the blank is accomplished by moving the blank rather than the cutter as in the previous illustrations.

The rotor blank is indicated at **27**. It is attached for conjoint rotation to a shaft **28** supported in bearings **29** which are attached to a face plate **30**. The face plate rotates about center **31** which corresponds to center **17** illustrated in Figure 2.

Attached to shaft **28** is a projecting arm **32** connected by spring **33** to the face plate. A cam follower roller **34** is rotatably attached to the projecting end of arm **32** and is designed for alternate cooperation with cam tracks **35** and **36**.

These cam tracks extend circumferentially about the periphery of the face plate. As indicated in Figure 7, cam follower **34** may be shifted axially on supporting shaft **37** which projects laterally from arm **32**. In one position, the follower cooperates with cam **35**, as indicated in full lines; in the other position, the follower cooperates with cam **36** as indicated by dash lines.

Rotation of the face plate rotates and in effect tilts the blank about center **31** simultaneously with limited rotation about its principal axis imparted by the contour of cam **35**. Through simultaneous rotation of cutter **26**, one surface of one vane is machined. Thereafter, the cam follower **34** is shifted into engagement with cam **36** and rotation of the face plate is repeated to generate the opposite face of the vane. Through use of suitable contours for cams **35** and **36**, a major portion of the leading edge of each vane can be machined simultaneously with the faces of the vanes.

Thereafter, the impeller blank may be indexed on shaft **28** by a preselected number of degrees and the process may be repeated. In this way, a plurality of vanes is produced at equal angular intervals around the rotor.

It is important to emphasize that the shape of the vane may readily be controlled simply through the contour of cams **35** and **36**. It also should be recognized that the vanes are generated through two simple relative movements of cutter and blank.

Other machine setups may occur to those skilled in the art. The important considerations are the movements of the cutter with relation to the impeller blank. Any movement of a cutting tool relative to the blank conforming to the principles of this invention will yield the novel rotor and involve the principles of this method.

The various features and advantages of the construction and method disclosed are thought to be clear from the foregoing description. Various other features and advantages not specifically enumerated will undoubtedly occur to those versed in the art, as likewise will many variations and modifications of the preferred embodiment of the invention illustrated, all of which may be achieved without departing from the spirit and scope of the invention.

Having described a preferred embodiment of our invention, we claim:

In an apparatus for forming radially faired centrifugal rotor vanes in a rotor blank, the combination of: means for mounting said blank for limited rotation about its principal axis, a cutting tool mounted above and to one side of said principal axis of said blank in an offset position relative to a plane passing through the principal axis, and means for imparting simultaneous rotation of said blank about its principal axis and relative movement between said blank and cutter in a plane offset from but parallel to the plane of the principal axis of said blank to create an arcuate cut about a fixed center which is also offset from but parallel to the plane of the principal axis of said blank, said cut being modified by the rotation of said blank.

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