CNC MACHINING OF MONOBLOCK PROPELLERS TO FINAL FORM AND FINISH

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Abstract

This paper describes the innovative way developed by Dominis Engineering Ltd. for CNC machining of monoblock propellers to final form and finish. The foundation of the system is the concept that, in order to preserve accuracy of machined surfaces and eliminate repositioning, monoblock propellers have to be CNC machined in one set-up on a 5-axis milling machine. Using this approach, Dominis has successfully machined to final form and finish a set of high skew 6 bladed monoblock propellers.

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1. Introduction

Propellers are complex rotating components which provide thrust for both forward and reverse movements of a ship. Since the latter part of the nineteenth century, when propellers were first introduced in ship propulsion, developments in marine propeller technology and propeller design have introduced vast improvements in propeller efficiency, control of cavitation, control of vibration, increase in thrust and overall performance. From the point of view of manufacturing, there are only two categories of propellers:

1) monoblock fixed pitch propellers are propellers where blades form an integral part with the hub and therefore the blades and hub have to be machined together
2) CP propellers and built up fixed pitch propellers are propellers where the blades can be detached from the hub and thus the blades and hub can be machined separately.

Depending on their application, monoblock propellers come in variety of configurations and sizes. Propellers are typically cast in Manganese bronze, Nickel Aluminum bronze or in stainless steel. All propeller castings are produced with an excess material on both hub and blade surfaces. This excess material has to be removed either manually or using machine tools before the propeller can be used for its intended purpose. There are three different approaches to machining monoblock propellers:

a) Excess material on the casting is removed by hand grinding and hand polishing with the aid of metal templates that define propeller blade sections and edges at different radial displacements from the propeller axis. This method is very labour intensive and requires highly skilled technicians to fit the templates and correctly grind and polish the propeller blade surfaces. In situations where several blades are mounted on a hub, even small variations between blades will lead to significant static and dynamic imbalance. It is difficult to produce a class I propellers and impossible to produce a class S propeller by this method. A large number of commercial use propellers are still manufactured in this way.

b) Excess material on the casting is removed by 3-axis CNC (Computer Numerically Controlled) milling of the propeller blades and hub. CNC milling on a 3-axis milling machine usually cannot remove all of the excess material especially on a monoblock propeller with overlapping blades. Therefore, 3-axis CNC milling must is followed by hand grinding and polishing of hard to reach areas. Hand grinding and polishing to fit templates introduces inaccuracies.

c) Excess material on the casting is removed by 5-axis CNC milling. Using a 5-axis simultaneous contouring milling machine to CNC mill a monoblock propeller can potentially deliver accurate results, although there are differences between various milling machine configurations and approaches which can lead to significantly different outcomes.

2. CNC Machining to Final Form and Finish

This paper describes Dominis approach to CNC milling of monoblock propellers to final form and finish using a 5-axis simultaneous contouring milling machine. Milling of monoblock propellers is an integral part of the company's IPMS (Integrated Propeller Manufacturing System). Very early in the development cycle of the DOMINIS IPMS five guiding principles were established:

1. All propeller blade surfaces, including leading and trailing edges, propeller blade tip and variable radius fillets must be defined by mathematical approximations and then CNC machined.
2. CNC machining must be done to "final form", thus completely eliminating hand finishing and manual grinding. Tool path should be created along the cylindrical sections of the propeller blades and both the leading and trailing edges should be machined integral to the pressure and suction sides of the blade.
3. All manufacturing processes and production cycles should be designed in such a way that they require minimal operator intervention – the long term objective being 100% unattended operation.
4. Optimization of cutting tool efficiency
5. Automatic identification and elimination of collisions between the cutting tool body, propeller casting and fixtures

2.1 Definition of Propeller Geometry

All propeller blade surfaces that come into contact with water are sculptured surfaces. Sculptured surfaces cannot be defined analytically and are typically described by a set of discrete points. Traditionally, propeller blade surfaces are defined by a set of 2-dimensional profile offsets. Changes in these basic profiles at specified radii are defined by camber, thickness and chord length distributions. Position and orientation of these basic profiles at specific radii are defined by pitch, rake and skew distributions. A typical monoblock propeller is defined by 9 different surfaces, namely:

- the face profiles (pressure side),
- the back profiles (suction side),
- the leading edge,
- the trailing edge,
- the pressure side fillet,
- the suction side fillet,
- the trailing edge chamfer,
- the tip profiles and
- the propeller hub.

Therefore, in order to completely machine a monoblock propeller, these 9 individual surfaces which are defined in terms of numerical approximations have to be blended into one continuous and smooth surface. Adjacent surfaces must be blended together respecting the over-riding criterion of continuous curvature at their joints. This final blended surface can then be used to define the locus of contact-points and surface normals at each contact point for a specific cutting tool to be used for machining the surface. Because of many the inherent difficulties in defining sculptured surfaces by means of mathematical approximations, blending and machining of sculptured surfaces always presents a considerable challenge.

2.2 Definition of Machining to Final Form and Finish

Machining to “final form and finish” means that the propeller, once removed from the milling machine is, except final polishing and acceptance testing, completely finished. More precisely, “final form and finish” is defined in terms of residual scallop height and average surface roughness R_a. Let us have a look at what we have been able to achieve when machining CP propeller blades on a horizontal milling machine using a 2" diameter ball nose cutter for rough machining and a 1.25" diameter ball nose cutter for finish machining (see Figure 1).

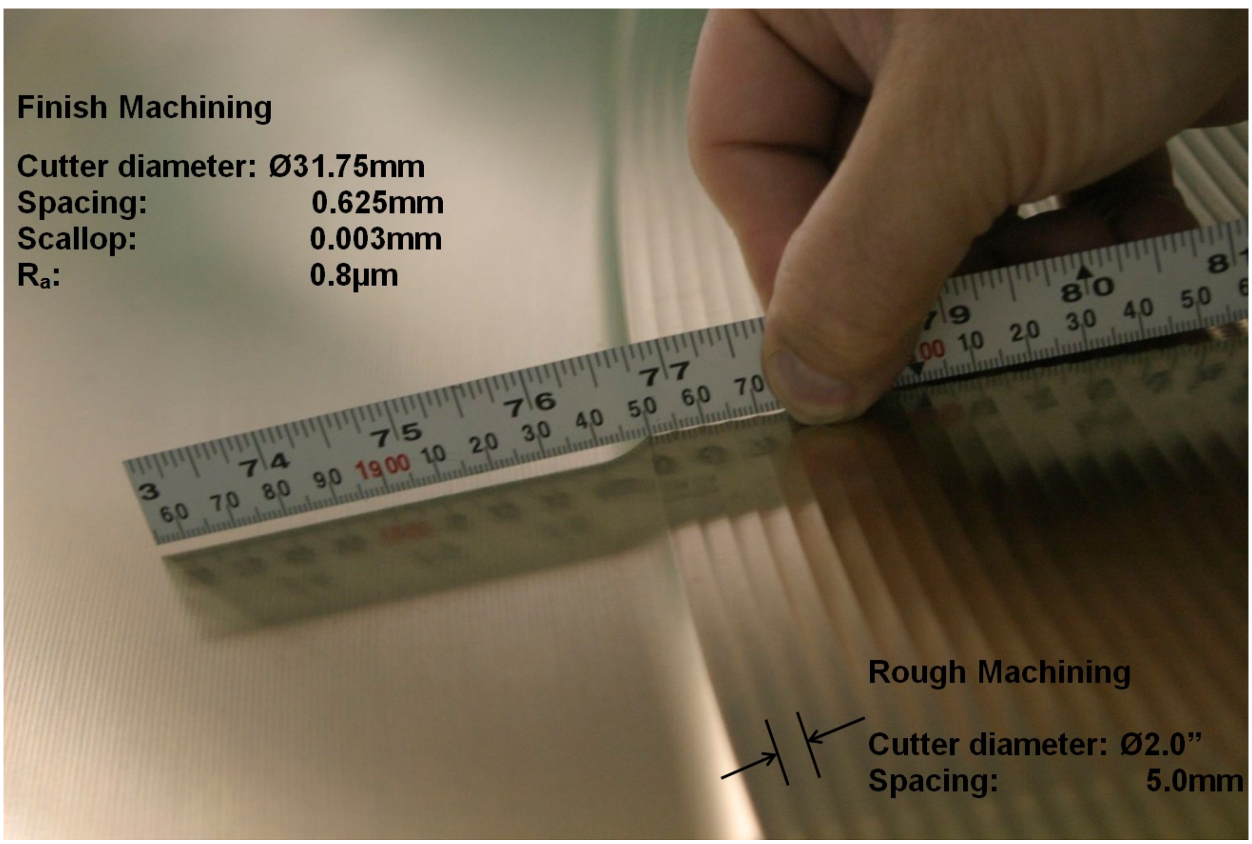

Figure 1: Finish machining with 1.25" ball nose cutter

The CP propeller blade in Figure 1 had an average chord length of 1.4 m and a span of 1.6 m for a total surface area per side of 2.2 sq. m. The required surface finish was 32 µinch (0.8 µm) and the material was Ni-Al-Bronze.

The CP propeller blade in Figure 1 was CNC machined using following protocol:

Selected cutter dia:	1.25"
Distance between cuts:	0.625 mm
Depth of cut:	2 mm
Cutter RPM:	6285
Feed rate for cutting:	6 m/min
No. of cuts per side:	2560
Length of cuts per side:	3584 m
Cutting time per side:	9.96 hours
Start/stop acc/deacc. time per side:	2.84 hours
Feed rate in air:	10 m/min
Climb milling only:	cutter return in the air
No. of return "cuts" in air per side:	2560
Length of cuts in air per side:	3584 m
Time in air per side:	5.97 hours
Start/stop acc/deacc. time per side:	2.84 hours
Grand total CNC machining time:	43.22 hours

Generating a tool path for a ball nose cutter is relatively easy. Unfortunately, ball nose cutters have a disadvantage of having only one or at most two cutting edges and additionally they have to be inclined to the surface being machined since the center of the cutter does not rotate. When using ball nose cutters, selection of the cutter diameter and depth of cut will depend on the RPM and feed rate available on the milling machine. The type of material as well as the total amount of excess material to be removed must also be taken into consideration when planning the milling process.

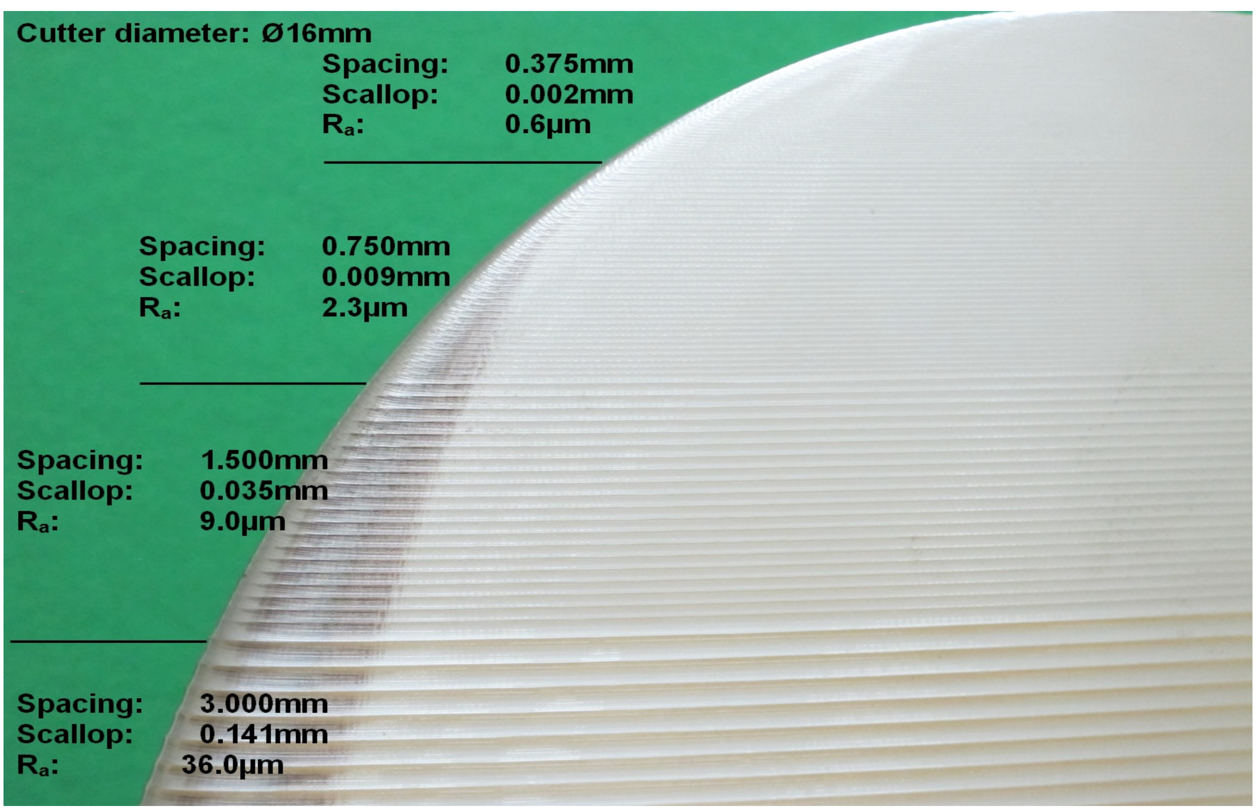

Figure 2: Finish machining with 16 mm cutter

Face mills with round inserts are more efficient in removing material. Using face mills to machine sculptured surfaces presents a programming challenge since a face mill has to be inclined in order not to gouge a propeller blade surface. Let us examine what can be achieved with regards to surface finish using a face mill with 16 mm inserts (see Figure 2). Figure 2 shows scallops created by 16 mm inserts for 4 different spacings between cuts. Note that the leading edge and trailing edge (not visible) of the blade in the picture were machined together with the pressure and suction sides. From the example presented in Figure 2, we can conclude that an exceptionally good finish can be achieved using a cutter with 16 mm inserts; spacing between cuts of 0.375 mm produces surface roughness of 0.6μm (22 μinch).

In order to achieve accurate "to final form" machining and eliminate all possible sources of distortion caused by cutting forces, material stress relieving, re-positioning of the propeller in the milling machine, Dominis has implemented the following protocols when machining monoblock propellers:

1, The propeller must be machined in one set-up.
2, Fixtures and tools must be designed to accommodate machining in one set-up
3, Blades will be machined, starting at the tip, in one complete radial section at a time, including pressure side, leading edge, suction side and trailing edge. The extra thickness of the casting is removed in two passes, a roughing pass to be followed by a finishing pass. The roughing pass must leave an equal amount of excess material on all blade surfaces for the finishing pass. Equal amount of excess material on surfaces is important for computation of an exact feed rate for the finishing pass.

2.3 Minimum Operator Intervention

The ultimate intent is that all manufacturing processes and production cycles are such that they require minimal operator intervention – the long term objective being 100% unattended operation. Once the tool life of cutter's inserts is established, the CNC machine can run without operator intervention except for insert changes. Next step would be the implementation of tool breakage detection and automatic tool replacement from the tool magazine.

2.4 Optimization of Cutting Tool Efficiency

Tool feed rates depend primarily on the type of tool being used, the material to be cut, the relative orientation of the tool to the object surface and, last but not least, the machine dynamics. Although the Dominis IPMS is uniquely capable of positioning a tool in an optimum orientation, taking advantage of the 5-axes machine controls, it is the software's ability to adapt to the dynamics of the machine that gives the Dominis IPMS its superiority in terms of efficiency.

Machine dynamics are described as follows. All NC-milling machines suffer from, what is known as a "following error". Although a machine may meet its commanded target point within the tolerances characteristic to that machine, the same cannot be said for its ability to track a path in, say, three-dimensional space, because the tool will lag the instantaneous target value. A typical time-lag for mid-size machines is about 33 msec. To overcome this problem, it is customary to specify target points very close together. As the tool follows these target points, one after the other, the control system initiates an acceleration command up to maximum speed, followed by a deceleration to zero speed. The Dominis IPMS turns off the acceleration/deceleration feature, but calculates the target point locations and the feed rate as a function of the curvature of the tool path to be cut such that the following error is always held within a specified tolerance band. In other words, the feed-rate becomes a function of the tool-path's curvature and is not interrupted by accelerations and decelerations. It implies that a tool-path with sharp bends is followed at a slower feed rate than that of a straight line.

2.5 Collision Prevention

Until recently, programming techniques to avoid tool-body collisions were based primarily on intuition and common sense. Programmed tool paths are checked and corrected though trial and error on the milling machine and by cutting test models in wood or Renshape – materials that cannot do harm to the machinery if collisions occur. These somewhat archaic and inefficient tool path verification methods have been completely replaced by running all post processed CNC programs through a true machine simulation. We make extensive use of VERICUT software for tool path verification.

3. Machining of Monoblock Propellers in one Set-up

Machining of monoblock propeller in one set-up can be achieved using a 5-axis simultaneous contouring CNC milling machine. Horizontal and vertical 5-axis milling machines come in many configurations. However, since Dominis has only horizontal milling machines only one configuration is suitable i.e. rotary on rotary set-up. A vertical rotary table (A-axis) is installed on a raiser mounted to the horizontal rotary table (B-axis). The propeller casting with custom designed adapter plates bolted on each end of the hub, is attached to the face plate of the vertical rotary table (A-axis). The other end of propeller casting is supported by a special tail stock installed on the raiser mounted to the horizontal rotary table (B-axis). Positioned in this way, a monoblock propeller casting can rotate around its horizontal center axis. The entire set-up on the horizontal rotary table including vertical rotary table, propeller casting and tail stock can rotate around the vertical axis of the milling machine table. In this set-up we have three linear axis X, Y and Z, 2 rotary axis B and A, and spindle quill W axis for a total of 6 programmable axes. The W-axis is a 200mm dia quill which, when extended from the head stock, can be used to minimize the length of tool holders when machining between blades. In this way, the propeller casting is ideally positioned so that both pressure and suction sides of each blade can be accessed. Maximum programmable feed rates for the Dominis 5-axis milling machine are as follows: X, Y and Z axes 6m/min, B-axis 2 RPM, and A-Axis 8 RPM. Loading capacity for the B-axis rotary table is 6.5 tons and the A-axis rotary table with tail stock is 4 tons. The diameter of the propeller in Figure 3 is 1.8 m.

In the configuration shown in Figure 3, the propeller blades are machined one radial section at a time starting from the blade tip. Two machining passes are required, a rough machining pass which leaves 3 mm on all blade surfaces and finish machining pass which brings all surfaces to final form and finish. Propellers machined in this set-up were laser scanned and found to be globally within +/- 0.3 mm of the design surface.

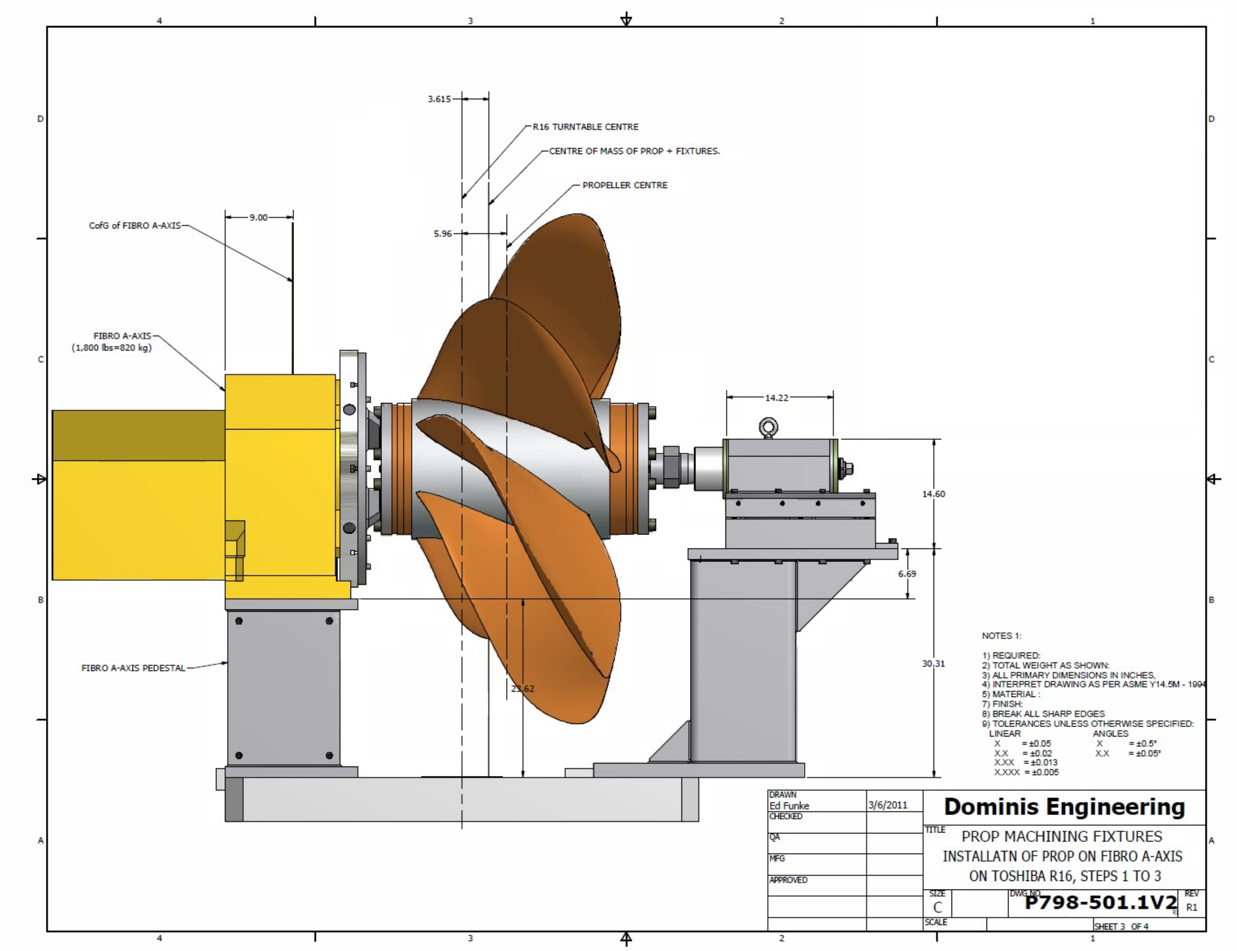

Figure 3: Set-up for 5-axis machining of monoblock propeller

4. Benefits of Machining to Final Form and FInish

The benefits of the Dominis approach to machining of monoblock propellers and other high precision rotating components, such as water jet impellers, in one set-up are as follows:

- Excellent blade to blade repeatability in form, mass and location of the centre of gravity,
- Increase in propeller and impeller efficiency,
- Effective elimination of balancing adjustments,
- Propeller designers get exactly what they specified.