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Rapid prototyping techniques for CNC machining have been developed in an effort to produce functional prototypes in appropriate materials. One of the major challenges is to develop an automatic fixturing system for the part during the milling process. The current proposed method, sacrificial support fixturing, is similar to the support structures used in existing rapid processes, such as Stereolithography. During the machining process, the sacrificial supports emerge incrementally and, at the end of the process, are the only entities connecting the part to the stock material. In this paper, we propose methodologies for the design of sacrificial support structures for a rapid machining process.

Keywords

Rapid Prototyping, Machining, Fixturing, Manufacturing

Disciplines

Industrial Engineering | Manufacturing | Operational Research

Comments

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The Use of Sacrificial Support Structures in a Rapid Machining Process

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Abstract
Rapid prototyping techniques for CNC machining have been developed in an effort to produce functional prototypes in appropriate materials. One of the major challenges is to develop an automatic fixturing system for the part during the milling process. The current proposed method, sacrificial support fixturing, is similar to the support structures used in existing rapid processes, such as Stereolithography. During the machining process, the sacrificial supports emerge incrementally and, at the end of the process, are the only entities connecting the part to the stock material. In this paper, we propose methodologies for the design of sacrificial support structures for a rapid machining process.
Keywords: Rapid Prototyping, Machining, Fixturing, Manufacturing

Introduction
Rapid prototyping (RP) is a process that automatically creates a physical prototype from a three-dimensional CAD model in a short period of time [1]. Most of the existing commercial RP processes are based on additive methods [2] and unfortunately, are limited in both accuracy and material quality. The major challenge for using a subtractive process such as machining is to develop a completely automated and flexible fixturing system. This paper presents recent work on a new methodology for fixturing that specifically addresses this problem by automatically creating support structures from the stock material. This fixturing approach is intended for a new rapid prototyping process using CNC machining [3].

The rapid machining method that sacrificial supports are intended for is similar to other layer-based RP technologies, except that layers of material are being removed rather than added. The basic concept is to machine the visible surfaces of a part from each of a plurality of orientations. In order to simplify the problem from both a process and fixture-planning standpoint, only rotations about one axis are used for orienting the stock material. From each orientation, some, but not all of the part surfaces will be visible. The goal is to machine the part from enough orientations, such that, after all toolpaths are complete, all surfaces have been fully machined from at least one orientation. One would note that if all the visible surfaces of a part from numerous orientations were machined completely, then at some point the part would simply fall from the stock material. Therefore, a fixturing approach is employed that is similar in concept to the *sacrificial supports* used in many existing additive rapid prototyping processes. However, in CNC RP the supports are not added to the physical model, rather, they are added to the CAD model prior to toolpath planning. The sacrificial supports are currently implemented as small diameter cylinders added to the solid model geometry parallel to the axis of rotation. Upon completion, the finished part is left secured to the round stock material by these supports. The setup and steps to this approach are shown in Figure 1. In this example, a component is being machined using sacrificial supports to retain the part at its ends along the axis of rotation. As an implementation example, Figure 2 shows a functional suspension component for a mountain bike that was created from a section of round stock material (Steel). In this case, four sacrificial supports were used, two on each end of the part along the axis of rotation. Upon completion of the part geometry, two of the supports were removed in a final machining operation (Figure 2a). Lastly, the part was cut from the stock by sawing the two remaining supports (Figure 2b). This relatively complex part would have been

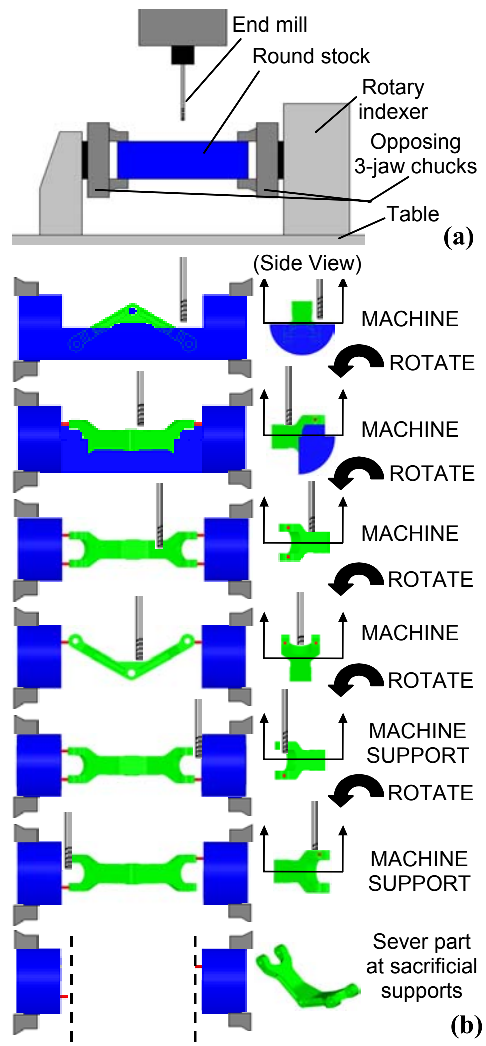


Figure 1 – Rapid machining; (a) Setup and (b) Process steps

a formidable challenge using any of the traditional methods of fixturing. To date, we have developed a visibility method that can determine if an axis of rotation is feasible, and determine the minimum set of rotations such that all surfaces are visible [4]. The next major challenge for a completely automated CNC RP process is automated fixturing.

Figure 2 – A sample part: a) in process using sacrificial supports and b) upon removal

Review of Related Work

Traditional fixturing techniques use a number of workholding elements such as vises, clamps, V-blocks, modular plates, etc. These fixturing approaches require a great deal of skill and lack the flexibility to handle arbitrary part shapes easily. Some existing methods such as dedicated, modular and phase-change fixturing are more suitable for large batches or mass production, where the investment for set up time and fixture costs can be absorbed; however, not for rapid prototyping. There has been some research dedicated to either fully subtractive or hybrid (additive/subtractive) RP systems and each has had to confront the problems related to fixturing arbitrarily shaped parts. Shape deposition manufacturing (SDM) is a hybrid approach using both additive and subtractive processes [5]. The models are constructed in a layer-based manner through sequential deposition and machining steps. Support materials are added depending on whether or not the layer contains undercut features. Sarma (1997) presents a process called Reference Free Part Encapsulation (RFPE) [6,7] that uses a low melting point material to encapsulate the stock during machining. This approach provides a rigid support structure for resisting cutting forces during the machining process and can accommodate any arbitrarily shaped workpiece; however, the process introduces thermal shrink and expansion problems. Millit [8] and DeskProto [9] are commercial software packages for generating numerical control (NC) code from STL (Stereolithography) files. In the Millit process, the software decomposes a model into several thick slabs, where each slab is called a *component*. The fixturing system consists of outer frames and bridges (thin strips) that connect the components to the frames and act as fixtures during machining. This approach is not an automated system since it requires a significant post-assembly process whereby the finished part needs to be bolted, glued, welded, or otherwise bonded to create a complete part. DeskProto uses a similar fixture approach, with bridges added to a model for fixturing during the machining process. The software uses only four available bridges (left, right, front and back) for every part. There is a more recent version for machining a part in several orientations called *N-sided milling* which uses a rotary axis and bridge supports. Unfortunately, the software does not include bridge design or analysis to determine if a feasible solution can be developed for fixturing an arbitrary part.

Sacrificial Support Structures

Sacrificial support structures serve the following purposes: 1) To secure the part during the machining process and position it for each setup orientation, 2) To minimize the deflection of the part due to bending and torsion from the cutting force and weight of the part and 3) To provide access to as much of the part surface as possible. The goal of sacrificial fixture design is not only to minimize the deflection due to bending and torsion but also to maximize the amount of machinable (accessible) surface area of the part. Sacrificial supports will be small compared to the size of the part and the deflection of the part will be the result of bending and twisting of the supports. The overarching objective of this work is to ensure that the system is flexible enough to handle any part shape and is completely automated throughout the process.

Part Shape Characterization

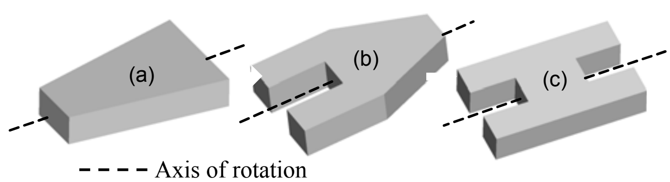


Figure 3 – Sample parts: (a) 1:1 body, (b) 2:1 body, (c) 2:2 body

The first step in the current methodology is to characterize the shape of the part. In particular, we wish to determine the number of *bodies* on each end of the part. Figure 3 illustrates examples of parts with different numbers of individual bodies on each end. A part with only one body on each end, with very small cross sectional area may be suitable for only one sacrificial support on each end. However, if the areas are large, or there is more than one body per end, then multiple supports will be employed. Multiple supports spaced far apart on each end provide a stiff system that is better able to resist bending and torsion. A part with one support on each end might undergo significant deflection (particularly in torsion) if cutting forces are applied to the unsupported body (Figure 4a). To stiffen the system, an additional support can be added to the unsupported body, as shown in Figure 4b. The current approach is to limit the number of supports on each end to two. Therefore, a part with 1:1 bodies (# on *left* end : # on *right* end), 1:*N* bodies, or *N*:*N* bodies will be designed with a sacrificial fixturing system of 1:1, 1:2, or as many as 2:2 supports.

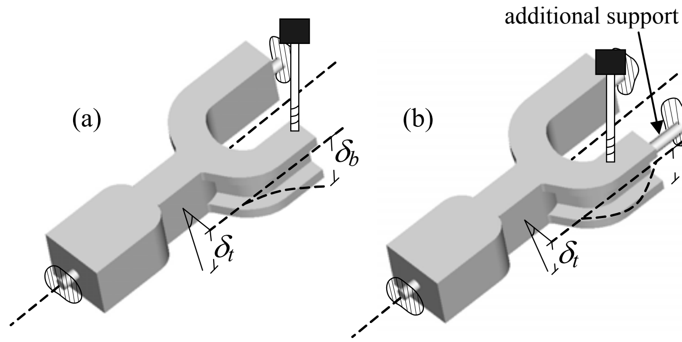


Figure 4 – Example Part (a) 1:1 supports and (b) 2:2 supports

A method that uses slice information from an STL file for determining the numbers of bodies on each of the part has been created. The method traces through the centroids of polygons from each slice, across consecutive slices, beginning from each end of the part. Tracing the centroids is more accurate than simply counting the number of polygons since a part can have different features without changing the number of polygons on a slice. An example is shown in Figure 5 where a part has two bodies adjacent to each other yet there is no change in the number of polygons on the slice. The number of bodies on the ends of the part is counted from the end to the middle of the part. If the number of polygons increases and the centroid of the new polygon is not contained by the polygon in the current slice, then a new body is detected. Detecting the number of bodies on the ends of the part provides the best attachment points for the sacrificial supports. The goal is to find locations where the supports can be attached nearest the end of the part, reducing the length of the supports and increasing accessibility.

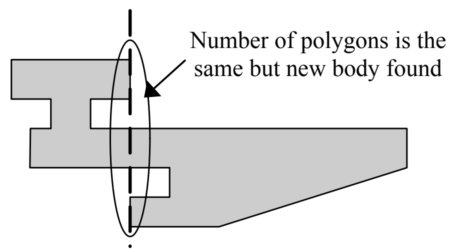


Figure 5 – Example: Tracing Centroids versus counting polygonal chains

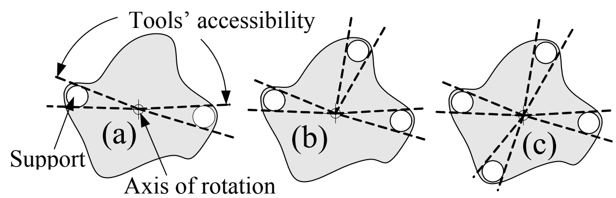


Figure 6 – Accessibility of cutting tools (end view): (a) two supports, (b) 3 supports and (c) 4 supports

Sacrificial Support Design Methodology

There are several design parameters that describe a system of sacrificial supports. This includes the number of supports on each end of the part, the size, shape, length and location of the supports. The minimum number of supports that can be used to hold the part during the machining process is one on each end. Although additional supports increase the stiffness of the system there are issues to consider: 1) The machinable surface of the part is decreased by the attached area for each support, 2) The accessibility of cutting tools is reduced, and 3) The number of machining orientations (setups required) may increase. Figure 6 illustrates tool accessibility as the number of supports increases. As mentioned previously, we currently limit the number of supports in a design to only two per end. This not only increases accessibility, but also greatly reduces the computational complexity of the layout problem.

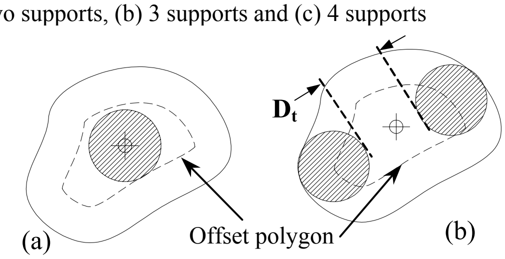


Figure 7 – Slice Polygon (a) with one support and (b) two supports

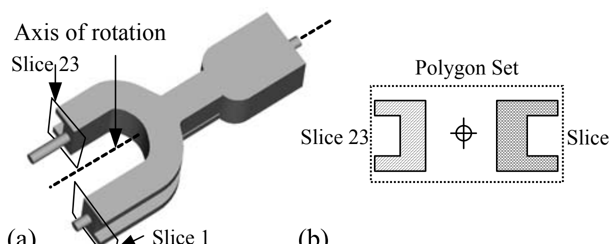


Figure 8 – Search space for placing 2 supports (a) Slice locations (b) Polygon set used in location search

The size of the support (diameter) is a design parameter that has a significant effect on deflection in both bending and torsion since the moment of inertia (I) and polar moment of inertia (J) are dependent on the support diameter. However, support diameter is a sensitive parameter since increases or decreases can significantly affect the length as well as the feasible location space for a support. Determining support size with other parameters is a complicated task and can create a circular problem (location affects size/size affects location). In the current version of the methodology, we assume a size for the support and then proceed to determine the location and thereby length of the support. We currently begin with an arbitrarily small support diameter equal to 10% of the part diameter. Once the diameter of the supports is known, the boundary of the polygon(s) on the slice files is/are offset inward equal to the radius of supports. This offset boundary represents the polygon on which the center of the support can be located (Figure 7).

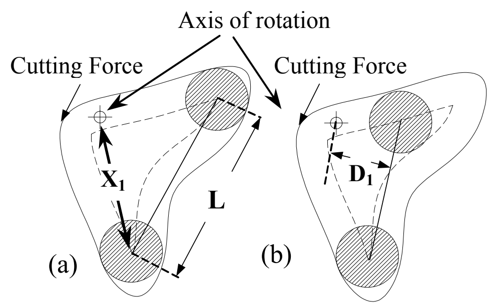
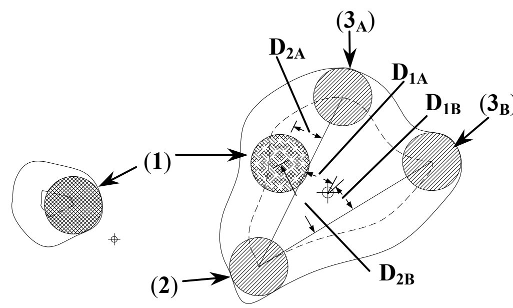


Figure 9 – Locating 2 supports: (a) maximize **L** and (b) Minimize $\mathbf{D_1}$

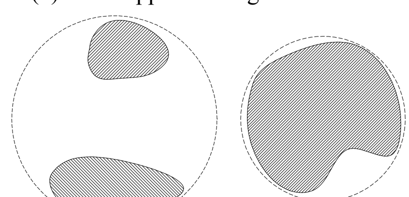
The length of a support should be minimized since the deflection of the part will be the result of the deflection of supports as the part and supports are bent and twisted by the cutting forces. Very long supports provide little rigidity and may obstruct the cutting tool's access to the part surfaces as well. In the current approach, the length of the support is dependent on the size and location. It can range from a length equal to the diameter of the cutting tool to as much as half the length of the part. The length must at least be greater than the diameter of the cutting tool since the tool will be cutting around the end of the part. The maximum length is limited to half of the part length because if it were longer then it would be better to attach a support from the other end of the part.



(a) Left end (b) Right end

Figure 10 – 1:2 supports: (a) One support on left end (b) Two supports on right end

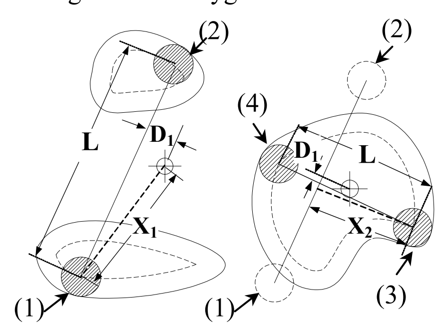
In the current method, only cylindrical shapes are employed, in an effort to reduce the complexity of the location problem. However, other support shapes may be more appropriate depending on the shape of the part. For example, slender shaped supports (e.g. ellipses) could be used to place supports on slender polygons on a part slice. This will be the subject of future work.



(a) Left end (b) Right end

Figure 11 – Polygon set diameter

The main focus of this current work in the design of a sacrificial support system is the layout (location) problem. The location of the supports is a combination of location along the axis (which cross sectional slice) and the location within the slice polygons where the cylinder will be "attached" to the part geometry. The first step (location along the axis) is simple; the support is located on the first slice (from the end of the part) where the support's cross-section is completely contained in the slice polygon. If there are two supports to be located, then two polygons from different slice locations could be treated together as the set of polygons for locating supports (Figure 8).



(a) Left end (a) Right end

Figure 12 – Placing 4 supports

Once part characterization is complete, it is known whether a part has either a 1:1, 1:*N*, or *N*:*N* shape characteristic. In the current approach, a part end with *N*-bodies will have 2 supports, however an end with 1-body could have 1 or 2 supports. For a 1-body end, the slice polygon is offset by the radius of the support. If the offset polygon can contain two supports that have at least the diameter of the tool ($\mathbf{D_t}$) separating them, then two supports will be used (Figure 7b). (If supports were placed less than a tool diameter apart, then the tool would not be able to cut between them.) In the case where only one support is used, then the location problem is simple; the support is placed nearest the axis of rotation (Figure 7a). This location is intended to generally reduce the moment arm of a cutting force applied to the part from any arbitrary orientation about the axis of rotation.

Placing multiple supports is a more complex problem and depends on the number of supports located on the opposite end of the part. First, suppose the support design will use a 1:2 layout. The single ended support is placed first, in the same manner described above. On the side with two supports, we begin by placing a support furthest from the axis of rotation ($\mathbf{X_1}$ in Figure 9). The final support is then located furthest from the first support, with the intent of maximizing the distance between supports. The goal is to create a layout that will be able to resist twisting under cutting forces. However, since we do not assume to know the set of orientations that the part will be machined, we must also consider the maximum moment arm of the cutting force. For example, two supports located far apart but also located far from the axis of rotation would have limited ability resisting a torque applied to the part (Figure 9a). Therefore, in addition to finding a large separation distance, it is also necessary to minimize the perpendicular distance from the line connecting the two supports to the rotation axis ($\mathbf{D_1}$ in Figure 9b). The objective function is:

$$MAX[\sum(\alpha L - \beta D_1) \quad (1)$$

However, the location of the first support on the opposite side of the part must be considered. Hence, the perpendicular distance between the line connecting the two supports and the single support should be maximized ($\mathbf{D_2}$ in Figure 10). The intent is to create a wide array of supports. Note in Figure 10b how we would choose location 3B for the third support, to maximize the distance $\mathbf{D_2}$. Now, the objective function becomes:

$$MAX[\sum(\alpha L - \beta D_1 + \lambda D_2) \quad (2)$$

The layout problem becomes more complex with a 2:2 support layout. First, the end with largest circumscribed diameter (about the slice polygons) is found. That is, the diameter of the polygon sets on each end is found and the end with the largest diameter is chosen first (Figure 11). On this end, the first and second supports are chosen similar to the objective function in (1) above. Next, the third support is chosen as the location that is the maximum perpendicular distance from the line connecting supports 1 and 2 ($\mathbf{X_2}$ in Figure 12). The fourth and final support is chosen by a location based on the objective function in (1) once again. This layout purposely locates the 4 supports in a wide array, providing a robust design, stiff in various orientations and cutting conditions.

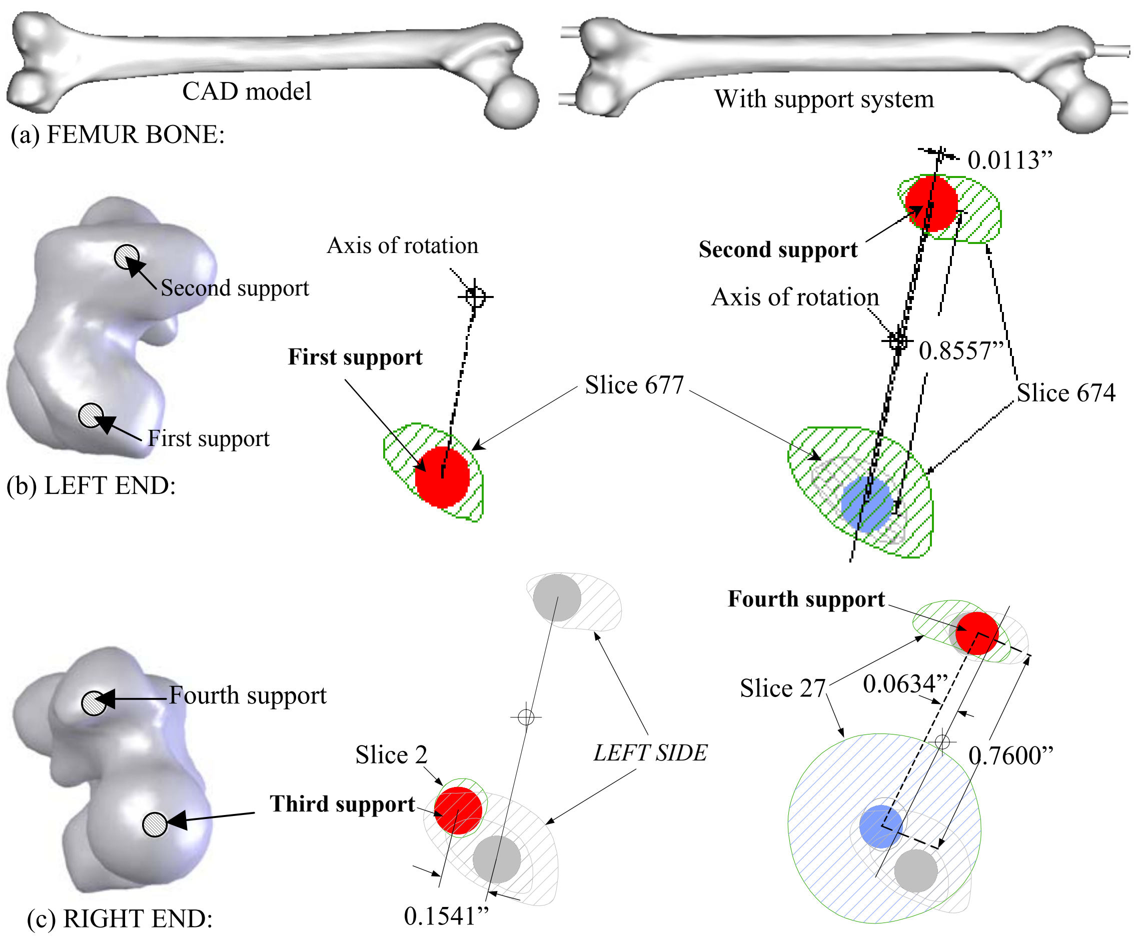


Figure 13 – Femur bone: (a) CAD model and solution, (b) Left end design steps, (c) Right end design steps

Implementation

Several sample parts have been created using CNC RP and sacrificial support fixturing. In this section a complex part is shown and the steps of the support design process is illustrated. The support design methodology was implemented in C++ and used in conjunction with the CNC RP process to create process and fixture plans for rapid machining. In this early version, objective functions are solved in a brute force manner and certainly do not represent optimal solutions, but are sufficient to test the preliminary current version of the methodology. In this paper, we present an example model of a human femur bone, which is a relatively complex part that would be very difficult or impossible to handle with typical fixturing approaches. The bone is a scale model with a length of 7 inches and width of 1.5 inches.

Figure 14 –Femur: (a) Fixtured with supports (b) Finished part

The design process began with slicing of the STL model at 0.01 inch slice spacing. Next, the slice model file was analyzed using the centroid-tracing algorithm to determine that the bone has a 2:2 part characteristic. The size of the supports is chosen to be 0.15 inch diameter (~10% of part diameter). The supports on the right and left end are placed as shown in Figure 13. The design results were used to create cylindrical features representing these supports in the CAD/CAM environment. The part was machined using the CNC-RP method on a 3-Axis Fadal mill with a 4th axis rotary indexer. Three orientations were required, based on the visibility analysis, and the total processing time was approximately 10 hours. The femur bone model, created in Delrin plastic, is illustrated in Figure 14.

Conclusion

This paper presents a method for creating sacrificial support fixtures in a rapid machining process. There are several advantages of using this approach: 1) It is completely automated, 2) It is exceedingly flexible, able to hold a vast array of complex parts and 3) The process planning for this fixturing system does not require a skilled operator. Sacrificial support fixturing is a powerful method for fixturing complex parts and could be the key to Mass Customization of machined components for replacement and service parts and for very small batch sizes where the time and skill required for a traditional fixture is not economical. The current approach to fixture design has been shown to work well for several complex parts machined in the laboratory, however, there are many opportunities for improvement. It is quite apparent that there are numerous optimization problems involved in designing the support layout and this current work did not fully address the complexity of this 3-dimensional layout problem. Future work will be focused on refining the methodology and seeking optimal solutions.

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