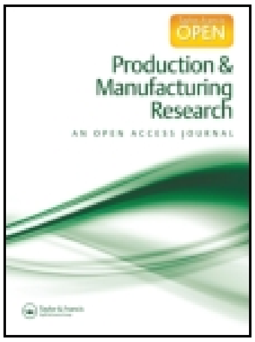

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Optimization of roughing operations in CNC machining for rapid manufacturing processes

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This paper presents a method for optimizing roughing operations in CNC machining, particularly for parts production through a subtractive rapid manufacturing process. The overall objective is to utilize the characteristics of CNC machining (rapid removal rates, suitability for a wide range of materials and precision) whilst obtaining some of the benefits of additive manufacturing (shape flexibility and reduction in process planning effort). The roughing operation in machining is primarily used to remove the bulk material and to approximately shape the workpiece towards the finished form. The manufacturing process described, utilizes a three-axis CNC machine with an indexable fourth axis device that is used to hold and rotate the workpiece. The method uses multiple approaches in roughing operations that differ in the number of orientations and the angles of the orientations. Most of the machining parameters are generalized throughout the process to allow some automation in generating the machining programme. The performance of each of the approaches is evaluated based on the lowest machining time to produce the part.

Keywords: roughing operation; CNC machining; rapid manufacturing

1. Introduction

Rapid manufacturing (RM) has for some years been used in many areas of production such as moulds and tooling, biomedical parts and customized products. Various tools and methods have been developed to cater for parts production in RM and frequently these are based on additive manufacturing (AM) which is a method that creates parts on a layer basis by adding and stacking the material together. However, this technology is still constrained by issues such as material properties (Karunakaran, Bernard, Surykumar, Dembinski, & Taillandier, 2012), part accuracy (Paul & Anand, 2011), cost and performance (Campbell, Bourell, & Gibson, 2012). On the other hand, adopting computer numerical control (CNC) machining as a RM process seems to be a feasible approach to surmount the weaknesses of AM. CNC machines possess the highest degree of precision and repeatability and at the same time are capable of processing a wide variety of materials. The process minimizes the staircase effect that is usually found in AM and operates at minimum cost (Yang, Chen, & Sze, 2002). Generally, the main characteristics of rapid processes are that they need to be operated quickly, be highly automated and flexible (Noorani, 2006). This reflects the performance of CNC machining but process planning tasks are carried out manually and are therefore highly

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dependent on human inputs. Process planning time and effort is a major consideration in conventional CNC machining and makes a very significant contribution to costs, particularly when manufacturing small batches. Process planning also becomes a major restriction that prevents CNC processes from being adopted in RM applications. However, several approaches that have been developed recently manage to handle the preprocess engineering and set-up planning issues which enhance the process abilities and performance (Petrzelka & Frank, 2010).

One approach is the use of a three-axis CNC milling machine with an indexable fourth axis device to hold and clamp the workpiece. This approach allows the slicing process to take place at various rotations of one axis and is able to produce complex shapes and features (Frank, Joshi, & Wysk, 2002). The fixturing method uses the indexable device to clamp and rotate the workpiece about one axis, and allows layer-based material removal from multiple orientations until all surfaces of the part are machined without re-fixturing (Frank, Joshi, & Wysk, 2003). Dealing with a variety of machining orientations requires proper process planning to achieve reliable process efficiency. Therefore, visibility analysis is executed to determine the cutting orientations required for a particular part (Frank, Wysk, & Joshi, 2004). During the machining process, the surfaces contained in the part geometry must be visible from some direction. Figure 1(a) illustrates the visibility of a part surface from one orientation (the direction of the arrow). The other surfaces that are not visible in this orientation require other orientations as shown in Figure 1(b) and (c). Depending on part geometry and complexity, this method is able to propose orientation angles that will guide the tools to remove material until the final shape becomes visible. The analysis is also capable of suggesting other process parameters, including minimum size of workpiece and the maximum and minimum cutting levels for each orientation (Frank, 2003).

Within each orientation proposed by the visibility programme, roughing and finishing operations are performed one after the other, the operations being different in terms of tool usage and machining parameters. The roughing operation aims to remove large amounts of material whereas the finishing is concerned with achieving the precise shape of the part. As illustrated in Figure 1(a), during the first roughing operation, the material removal process occurs until the furthest possible surface is reached or the workpiece is fully cut (Frank, 2007). Consequently, the roughing tool selected must be of adequate length to cut through the workpiece. The main reason to machine to maximum cutting levels is to avoid the formation of a thin layer material that could possibly wrap around the tool and cause failure. Machining from at least three orientations is another viable

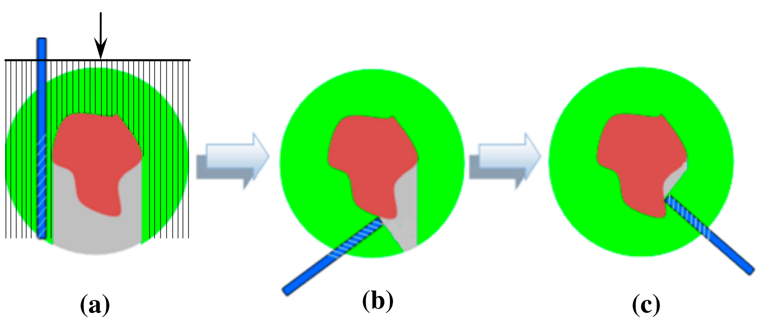

Figure 1. Roughing operation approach in CNC machining (Frank, 2007).

technique to prevent thin layer formation. Next, the process continues with the finishing operation that machines until the centre radius of the round workpiece. The workpiece is then rotated to a second orientation, and the roughing and finishing operations are repeated. At the end of the process, small diameter cylinders are left to connect the finished part and the workpiece. These cylinders act as sacrificial supports that will be removed later on as part of post processing.

The orientations proposed by the visibility programme are mainly effective during the final stage of machining (the finishing operation). In order to minimize the number of orientations required to machine the part, the visibility programme incorporates the roughing operation together with the finishing operation within the same orientation. In future, further developments are proposed to use the initial angle to assist the visibility programme in sequencing and optimizing the orientations (Renner, 2008). The initial angle is determined based on the angle at which most of the surfaces of the part are visible to machining. Starting with the initial angle as the first orientation, the rest of the orientations are generated to cater for less uncovered surfaces. Hence, providing this angle to the visibility programme minimizes the orientations set and is most likely to reduce total machining time for the process.

In relation to the current approach of adapting CNC machining for the RM application, there are two issues that should be emphasized. First, rotating the workpiece on the indexing device guarantees process continuity without any re-fixturing task. However, the orientations proposed constrain the roughing operation which must be performed within the finishing operation. Common approaches are to optimize the machining operation by manipulating the cutting parameters of the processes. However, this is not applicable in CNC-RM applications as it tends to complicate the planning tasks. As a result, the optimization is carried out through the roughing orientations employed by the process. Instead of relying on surface visibility to decide on the orientation, it is possible to execute roughing operations with a different set of orientations that aim to achieve high volume removal. In machining, time is one of the major concerns that influences process efficiency. The roughing operation can be considered as one of the time-consuming processes especially in mould and die manufacture that involves massive material removal (Hatna, Grieve, & Broomhead, 1998). Thus, it is important to maintain proper control and sustain the process efficiency in roughing operations. The second issue relates to the cutting tool penetration at the beginning of the process. Roughing tools need to cut the material to the furthest possible depth with the intention of avoiding thin material formation. Increased depths of cut might increase the risk of tool failure because the tool can easily deflect due to the cutting forces generated. Increasing the contact length will influence the tool performance as it tends to effect the tool temperature and causes flank wear (Sadik & Lindström, 1995). Based on these issues, this paper presents a methodology and approach to optimizing the roughing operation in CNC machining for the RM application.

2. Overview of CNC-RP

CNC-RP is a method that is derived from the simple set of layer-based tool paths that are used in additive RP technology. The basic concept involves machining all visible surfaces of a part from a particular orientation using a three-axis vertical machining centre. Visible surfaces are those surfaces that can be ‘seen’ when looking down the axis of the cutting tool – the z-axis. Not all surfaces will be visible in a particular orientation and therefore a number of orientations are normally needed in order to machine all part surfaces but without re-fixturing. This re-orientation is achieved by the use of two opposing fourth axis indexers. This removal of visible cross-sections of the part using simple 2.5 D layer-based tool paths is similar to a roughing process in traditional machining operations (Balasubramaniam, 1999). The 'staircase' effect evident in additive RP are also found in this subtractive process, but this is not a problem as very shallow depths of cut down to approximately 20 microns (0.02 mm) or less can be achieved.

This process is feature free and successfully eliminates feature recognition and feature-based process planning (Frank, 2006), as there is no need to plan the manufacture of each feature independently. Since only 2.5 dimensional tool paths are machined and no feature information is required, a generic approach using a small diameter flat-end mill cutter is feasible. However, there are some drawbacks in using a small diameter tool. Avoiding tool deflection or breakage requires relatively low feed rates and depths of cut are limited by the required precision of machined surfaces and so material removal rates are low and machining times are consequently high. The objective is, however, that overall efficiency is improved through the removal or very significant reduction of process planning and set-up efforts (Frank et al., 2004). Fixturing methods are made generic by the use of sacrificial supports of small diameter cylinders that are added to each end of the CAD model geometry parallel to the axis of rotation so as to retain the part upon completion of the machining process (Frank, 2006). This does create a need for some post processing in the removal of the supports. Figure 2 shows the basic set-up for the CNC-RP approach using a round stock material between two indexing heads.

Figure 3 illustrates the process steps and the finished part in using CNC-RP to machine a mountain bike suspension component. Five orientations are needed to complete the entire machining operation which uses four sacrificial supports. Two supports are removed as the last machining operation and the remaining two are removed by post-processing. Producing the same complex part using traditional fixturing would have been a substantial problem especially in re-clamping and resetting the machine coordinate system for each orientation.

Manufacture planning is not entirely eliminated (as indeed it is not in conventional additive rapid prototyping). The need to add sacrificial supports to the model has already been mentioned and some limited set-up planning is required. There is a need to determine the number of orientations required to machine the entire part surface, and algorithms using 2D visibility maps are used to minimize the number of set-ups. Tool paths for each orientation can be generated using a conventional CAM system together with simple algorithms that can determine the required depths of layers to the farthest

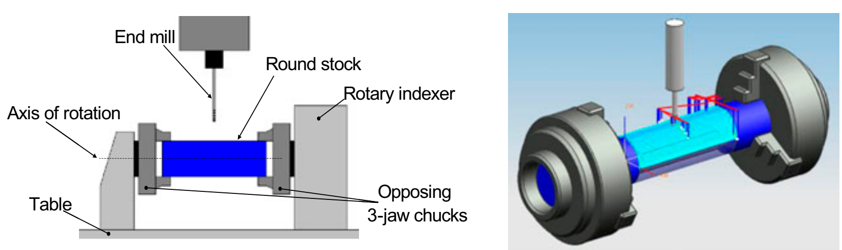

Figure 2. Setup for CNC-RP (Wysk, 2008).

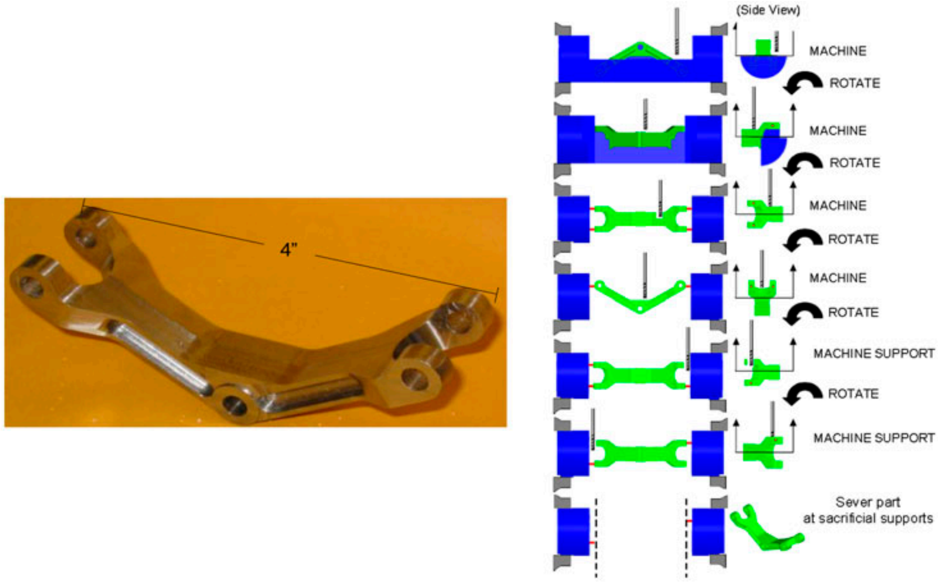

Figure 3. Process steps for CNC-RP (Wysk, 2008).

visible surface from each orientation. Tool selection is very important to avoid collisions. The tool length must be greater than the distance to the furthest visible surface for each orientation (Frank, 2006) so that the tool holder does not collide with the stock material. The tool diameter is defined by the need to manufacture the smallest features of the part.

3. Roughing operations methodology

Machining orientations for roughing operations are developed to accommodate the orientations proposed by the visibility programme. Two approaches are used. The first approach proposes additional orientations for the roughing operation instead of just relying on the orientations provided by the visibility programme (Li & Frank, 2012). The second approach is based on extracting and splitting the roughing operations contained in the visibility programme and assigning them to other independent orientations that are not bound with the visibility orientations. Machining simulation has been conducted to evaluate the practicality of both approaches and to discover the optimum roughing orientation angles. Cutting parameters are determined based on the workpiece materials and cutting tool sizes. In this simulation study, cylindrical aluminium stock was defined as the workpiece and carbide flat end mills of different sizes were used for roughing and finishing operations. As the process employs a feature-free approach, the cutting parameters remain constant and the only parameters that change are the roughing orientation values.

Simulations use Siemen's NX7.5 software via customized coding that simulates the machining programme based on the angle input. This coding generates detailed machining times for the roughing operations, finishing operations and non-cutting movements and runs automatically once provided with the required inputs. Overall performance was evaluated by comparing the total machining time generated from the series of simulations. Figure 4 summarizes the methodology employed to optimize the roughing operation in CNC machining.

3.1. Additional roughing orientation approach

This approach involves introducing an extra machining orientation to the current orientation set. Two methods are proposed. The first one adds one roughing orientation that permits cutting of material until the centre of the round workpiece is reached. Simulation for this method starts at angles from 0° to 359°. The second method deals with two additional orientations of 0° and 180°. The angle is increased gradually in each simulation through increments of 1° from 0° to 179° and from 180° in increments of 1° to 359°. To avoid the formation of thin material, the cutting only proceeds until the circumference of the sacrificial support cylinder is reached. The thick material left will be removed later by other roughing operations. The idea of having these additional roughing orientations is mainly because it is possible to remove more material and shorten the roughing process in visibility orientations.

3.2. Splitting roughing orientation approach

Instead of adding to the number of orientations, this approach modifies the visibility programme output by taking out the roughing orientations and incorporating them with the other orientations. A number of angle combinations are identified to work on the roughing process. The combinations are built up from three and four angles that together generate five sets of roughing orientations; (0°, 120°, 240°), (0°, 135°, 225°), (0°, 120°, 225°), (0°, 135°, 240°) and (0°, 90°, 190°, 270°).

The combination of three angles is a minimum requirement for roughing operations without forming any difficulty in removing thin sections. The first orientation set (0°, 120°, 240°) equally divides the workpiece in one axis of rotation. The second orientation set (0°, 135°, 225°) has been developed based on the coverage area of the cylindrical shape workpiece. The 0° angle covers the first half of the workpiece, whereas the

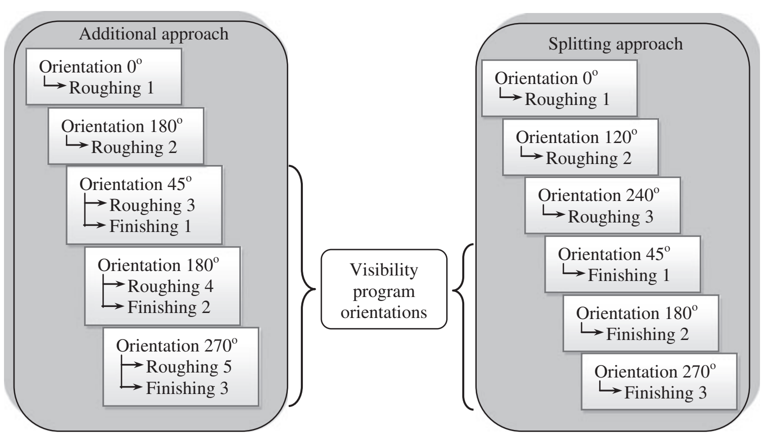

Figure 4. Two distinct approaches to find optimum roughing orientations.

other two angles, 135° and 225° are used to cater to the other half of the workpiece (a quarter for each angle). The next two orientation sets are derived from the first and second orientation sets. Two of the angle values from each orientation set are swapped to form (0°, 120°, 225°) and (0°, 135°, 240°) roughing orientations. Lastly, the four-angle roughing orientation set is used to ensure extra coverage of the area and to reach all features on the part. The range between each angle is 90° but on the third angle, the value is increased to 190° instead of 180°. The reason for this incremental value is due to the possibility of thin material formation during the third orientation of the roughing operation. Based on this orientation, the tool is guided to start the machining from an inclined position and shapes the part effectively.

4. Implementation

Using the method described above, experimental results were obtained by conducting a series of simulation studies using four-part models; drive shaft (flange yoke), knob, salt bottle and toy jack (Figure 5). The models were selected randomly and consisted of a variety of different part features to form the object. The presence of multiple features on the part was important to test the effectiveness of the orientation sets that had been developed. Table 1 shows one of the results produced for the knob model. Based on this result, each of the orientation sets were compared by evaluating the machining time and efficiency.

In this work, an objective was to establish a methodology to identify a roughing orientation set that suits the rapid manufacturing process using CNC machining. Referring to the set of orientations proposed, the performance was analysed based on distinctive criteria as indicated in Table 2. The criteria were (i) minimum total

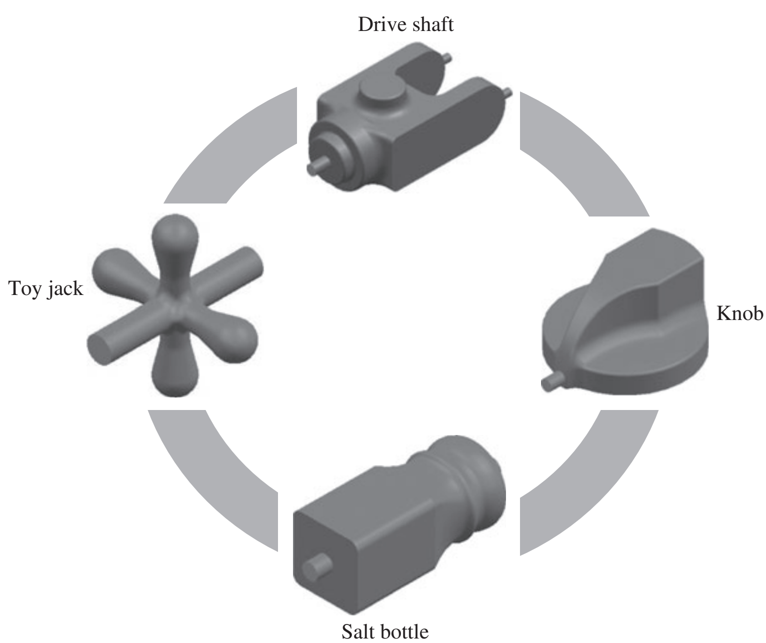

Figure 5. Test components.

Table 1. Example result recorded during simulation study.

Result	Roughing orientation sets							
	Visibility programme	1 Orientation	2 Orientations (0°/180°)	3 Orientations (0°/120°/240°)	3 Orientations (0°/135°/225°)	3 Orientations (0°/120°/225°)	3 Orientations (0°/135°/240°)	4 Orientations (0°/90°/190°/270°)
Machining time (hour:min:sec)	04:25:00	04:08:49	04:00:43	04:26:13	04:22:32	04:21:10	04:28:35	04:04:17
Finishing time (hour:min:sec)	03:03:47	02:49:53	02:39:28	03:00:51	03:03:49	03:03:39	03:04:50	02:38:50
Non-cutting time (hour:min:sec)	00:12:14	00:12:10	00:12:21	00:11:52	00:11:55	00:11:12	00:11:58	00:10:23
Roughing time (hour:min:sec)	01:09:00	01:06:46	01:08:55	01:13:30	01:06:47	01:06:18	01:11:47	01:15:04
Percentage of roughing time	26.0	26.8	28.6	27.6	25.4	25.4	26.7	30.7
Number of operations	6	7	8	6	6	6	6	7
Number of tool changes	5	5	5	1	1	1	1	1
Orientation set	180° 45° 315°	40° 180° 45° 315°	0° 180° 180° 45° 315°	0° 120° 240° 180° 45° 315°	181° 316° 46° 180° 45° 315°	181° 301° 46° 180° 45° 315°	0° 135° 240° 180° 45° 315°	90° 180° 280° 0° 180° 45° 315°

Table 2. Overall performance of orientation sets.

Criteria	Model			
	Drive shaft	Knob	Salt bottle	Toy jack
Minimum machining time	4 orientations 0°/90°/190°/270°	2 orientations 0°/180°	4 orientations 0°/90°/190°/270°	2 orientations 35°/215°
Maximum roughing time	2 orientations 91°/271°	4 orientations 90°/180°/280°/0°	4 orientations 0°/90°/190°/270°	2 orientations 35°/215°
Minimum finishing time	4 orientations 0°/90°/190°/270°	4 orientations 90°/180°/280°/0°	4 orientations 0°/90°/190°/270°	2 orientations 35°/215°
Minimum non-cutting time	4 orientations 0°/90°/190°/270°	4 orientations 90°/180°/280°/0°	3 orientations 45°/180°/275°	Visibility programme 49°/140°/228°/320°
Maximum roughing percentage	4 orientations 0°/90°/190°/270°	4 orientations 90°/180°/280°/0°	4 orientations 0°/90°/190°/270°	2 orientations 35°/215°

machining time, (ii) maximum roughing time, (iii) minimum finishing time, (iv) minimum non-cutting time and (v) maximum roughing percentage. The times spent on the roughing and finishing operations are directly related. Since the roughing operation is executed to remove large volumes of material, increasing the time spent for this operation would be expected to minimize the finishing operation time. Due to the nature of the process that operates from many cutting angles, the volume removed during roughing operations is variable. Consequently, leaving less material will reduce the finishing operation time and ultimately minimizes the total machining time. Therefore, the assessment criteria are formulated based on the relationship between the cutting operations involved in CNC-RM.

5. Results and discussion

Generally, most of the assessment criteria are met by four or two orientation sets. However, minimum non-cutting time suggested two other orientation sets which consist of three orientations and orientations proposed by the visibility programme. The results from the different orientation sets vary between each model because of the different features present on the parts. Nevertheless, roughing through a set of four orientations is the most favourable method for almost all models.

The additional roughing orientations approach, which included the adding of one or two orientations, managed to increase the material removal volume. In some models that have been analysed, this approach met the assessment criteria. However, there are several drawbacks found that prohibit this method being used to formulate optimum roughing orientations. First, it increases the number of machining operations in comparison with the operations produced by the visibility programme. Additionally, the angle used can be redundant when considered alongside the roughing angle from the visibility programme and this will cause inefficiencies due to repetitive cutting areas. Another problem is related to the thin material that may be formed if the two additional angles share the same value with angles from the visibility programme. This is an unfavourable condition in cutting as it can cause wrapping of material around the tool and leading to defects on the machined part. Since the roughing and finishing operations are preserved in visibility orientations, tool changes are performed between the operations and for each orientation.

The split roughing orientation approach seems to be a feasible method to optimize the roughing operations. It allows the roughing task to be carried out independently without any reference to the other operations. At the same time, this approach reduced the number of tool changes that only occurred once throughout the machining. It is good practice to minimize the number of tool changes even if the CNC machine is equipped with an automatic tool change system (Lim, Corney, Ritchie, & Clark, 2001). Machining simulation through three roughing orientations demonstrates consistency in performance but does not generate a significant result. A notable weakness is identified when dealing with complicated parts as some regions are not well covered and results in a large volume being left for finishing operations.

Apparently, an attempt to use four roughing orientations seems to be a viable solution in optimizing the roughing process. The method effectively removes the bulk volume of material leaving a reasonable amount for finishing operations. Moreover, this method achieved the highest roughing operation percentage in almost all of the tested models. The implications of these findings are that the method not only reduces processing time, but also minimizes the cutting depth where the roughing tool only cuts until the centre of the cylindrical workpiece. This is a practical solution to prevent the tool travelling to the furthest possible surface that will increase the risk of failure. Considering all these capabilities, the use of four roughing orientations is identified as the approach to optimize the roughing process in subtractive CNC machining.

6. Conclusion

CNC machining offers a reliable solution for rapidly manufacturing the parts. The current approach, using an indexable tool, managed to eliminate multiple set-ups of the workpiece. The visibility programme is an effective method to identify orientations for finishing operations. However, performing roughing operations within a finishing orientations sets tends to constrain the roughing task and causes several inefficiencies. This study overcomes this constraint by formulating an alternative method to find optimum orientations for roughing operations. Implementing four roughing orientations reduced machining time and tool contact length. This approach is considered as a feasible solution to optimize the process. The present study makes several noteworthy contributions in the rapid production of end-user products. Particularly, in low volume productions, the roughing processes can be improved using the optimum cutting orientations proposed from this research. Minimizing the fabrication time will increase production rates. Moreover, the roughing strategy is also capable of controlling the tool contact length which results in longer cutting tool life. Ultimately, all these will drive the production cost lower and make CNC machining a viable process for RM. Future work will emphasize coding and programming that operates within the CAD system to create an automatic system and achieve the goal of rapid manufacturing.

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