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Cutting orientations for non-complex parts in 4th axis machining

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Abstract. The application of Computer Numerically Controlled (CNC) machining for Rapid Manufacturing processes (CNC-RM) exploits the innate potential of 4th axis machining. The use of an indexer allows the workpiece to be rotated to various orientations which directly increased the region accessible to the cutting tool. However, in order to avoid thin webs and preserve tool life, cutting must be executed with a minimum of three orientations even for geometrically simple parts. Recent findings have suggested the separation of cutting orientations into roughing and finishing operations. Thus, the selection of orientations in finishing processes becomes more flexible and independent. This study was conducted to identify the effects of using a minimum of two cutting orientations in finishing operations for CNC-RM applications. This method is only applicable for non-complex parts where all the features can be machined from two directions. The results of the study illustrate the positive effects of minimizing the number of orientations. Despite improvement in machining operations, the complexity in defining the cutting orientations was also reduced.

1. Introduction

Computer Numerically Controlled (CNC) machines are one of the most important elements in current manufacturing industries. This technology has been used in many areas of production such as moulds and tooling, biomedical parts and customized products. Accordingly, the way of this technology being implemented has evolved and is not only restricted to conventional machining operations. Over the past decade, a distinct machining method has been introduced by integrating 3-axis CNC milling machines with indexable rotating devices [1]. The integration allows cutting processes to take place in 4 axes which expands the workpiece cutting area. Additionally, machining can be executed continuously without the need for any re-fixturing. This realizes the implementation of CNC machines in rapid manufacturing processes (CNC-RM). Figure 1 illustrates the mechanism of clamping the workpiece in an indexable rotational device. This process allows cutting operations to be performed in various rotations of one axis and is capable of producing complex shapes and features [2].

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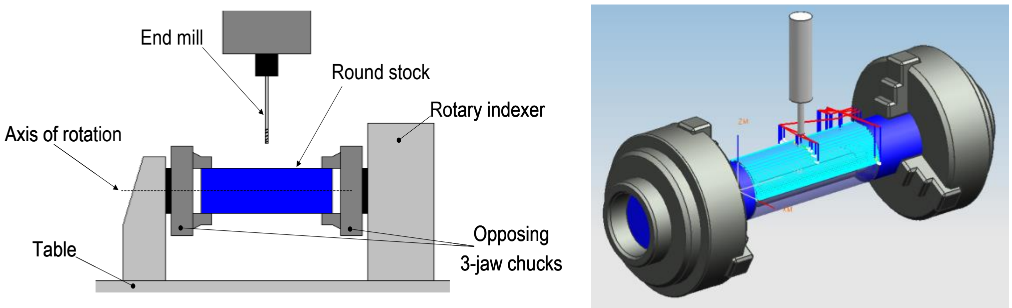

Figure 1. 4th axes cutting mechanism in CNC-RM processes.

Cutting orientations are considered as one of the crucial parameters to ensure all machined surfaces are visible (i.e. accessible to the tool) during the machining process. While determining the orientations, several rules need to be followed to ensure a correct distribution of cutting angles. The issue of thin web formation has received considerable attention during this stage. Thin webs are thin layers of material that form during cutting operations due to the process sequence and opposing cutting directions [3]. It is an undesirable situation in machining because the thin materials can wrap around the cutting tool and collide with the workpiece. In the worst circumstances, the machining process is disrupted and this leads to poor surface finish on the part. So far, however, the only way to prevent this is by using a minimum of three cutting orientations within certain angle ranges. This rule is applied to all kinds of shapes including non-complex parts, and most of the time machining from two opposite directions is prevented. This research studied the implications of machining from two opposite directions while at the same time eliminating the formation of thin webs during the process.

This paper has been divided into four parts. The first part briefly describes the background of the research area. The second section highlights the methodology adopted to employ two cutting orientations. The next section deals with the results and discussion, and the last section consists of the conclusions.

Tool orientation is recognized as an important parameter in four- and five-axis machining. A study highlighted the influence of cutting orientation in 4-axis plunge milling operations and the residual material after machining [4]. Another study related the tool orientation errors with the quality achieved in the fabrication of miniature lenses [5]. Meanwhile, in 5-axis machining, research has attempted to formulate an optimal tool orientation to mill impeller blades [6]. All the studies indicated the influence of cutting orientations on the efficiency of machining operations. Similarly with the method adopted in this study, integrating a 3-axis milling machine with an indexable device allows the workpiece to be rotated so that several orientations are used in machining the part surfaces. Visibility algorithms to identify the minimum number of orientations needed to completely machine the parts have been proposed [7]. Within each orientation, roughing and finishing operations are executed one after the other with different cutting tools and parameters. Further screening is required to evaluate the distribution of orientations and prevent thin webs. As illustrated in Figure 2, the formation of thin webs can be seen when there are opposite cutting directions employed in the process. The first machining operations will remove the material until a predetermined cutting level. Next, the workpiece is rotated by 180^{o} providing a new orientation for the second machining operation. As cutting proceeds to a certain depth, a thin layer of material will be formed and this compromises the operation.

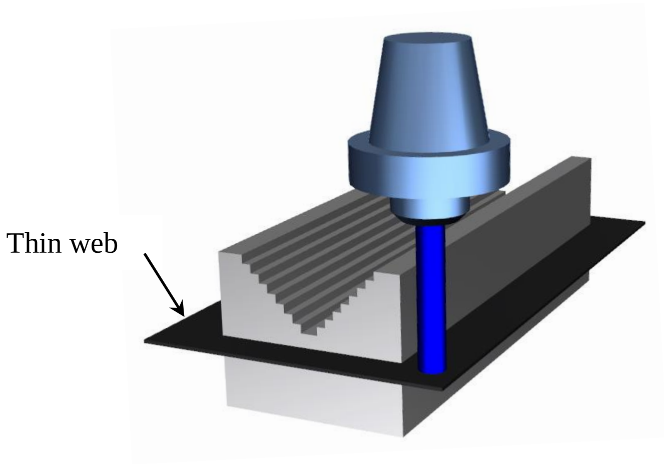

Figure 2. Formation of thin webs when cutting from opposite directions.

Because of this problem, machining from 0°, 135° and 225° to avoid thin webs and to remove the bulk of material from the workpiece has been proposed [8]. Therefore, machining from a minimum of three orientations is most likely to be adopted to comply with the thin web avoidance requirement. In the case of machining complex parts, the numbers of orientations are likely to be increased beyond three orientations. It is normal for the minimum three cutting orientations rule to be applied to all kinds of parts including non-complex parts. In order to get an optimum set of cutting orientations, the part will undergo visibility analysis. Certainly, this is essential for parts containing complex shapes where the features are only visible in specific orientation ranges. However, for non-complex parts, the orientations can be easily interpreted as there is no restricted access for cutting tools.

In this study, the definition of complex and non-complex parts can be related to the number of orientations required to achieve the final geometry. If there are many closed regions that are only accessible from specific orientations, the part has complex shapes and requires more than two cutting orientations. On the other hand, if all the geometries can be machined within two cutting orientations, the part is considered as non-complex. Recent developments have proposed the splitting approach between roughing and finishing operations [9]. Whilst the key contributions of the study is the elimination of thin material formation, the method also imparts some flexibility in finishing operations where cutting directions can be widely selected and it may be possible to machine from two orientations. Therefore, the research reported in this paper is mainly concerned with the implications of machining with only two finishing orientations. The results produced act as an indicator to decide whether it is an alternative method to perform finishing operations in rapid machining processes.

2. Methodology

The machining method employed in CNC-RM has made the process capable of dealing with a wide range of components and materials. Since the workpiece can be rotated about one axis, cutting orientations have become crucial parameters in the machining plan. Determining cutting orientations based on part visibility is definitely a reliable method to ensure all surfaces are machined. However, the thin web avoidance rule must be complied with, and thus a minimum three cutting orientations are typically adopted to create parts. This approach is expected to minimize the tendency of thin web formation but further assessments are still required. If any two from the three proposed orientations are in opposite directions, there is the possibility for thin material to be formed during machining. Taking an example from the orientation set (0°, 130°, 180°), cutting tends to form thin material during the third orientation as illustrated in Figure 3. Hence, as well as generating the orientations from visibility analysis, it is important to revise the distribution before employ the cutting orientations in real machining.

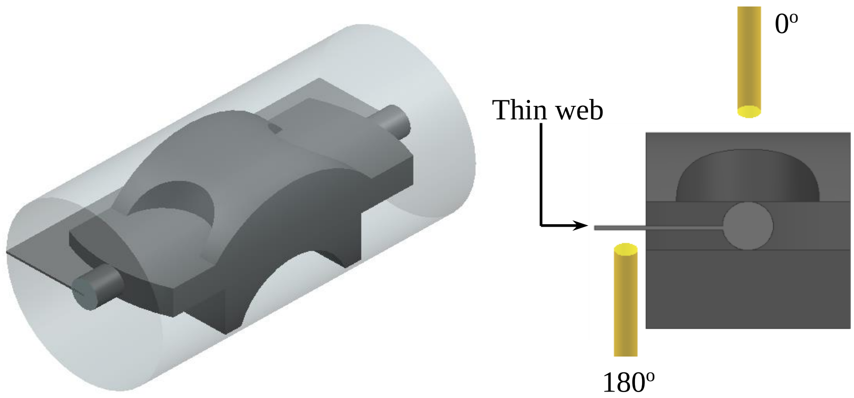

Figure 3. Thin web formed during the third cutting orientation.

An approach that groups and performs all roughing operations at the beginning of the process seems to be a viable method to eliminate thin webs. At the same time it also conserves some flexibility in selecting the roughing and finishing orientations. Both operations can be carried out independently with different orientation sets. Roughing operations are performed through four standard cutting directions (0^o, 90^o, 190^o, 270^o). Then, finishing operations would be based on the orientations suggested by visibility analysis and the minimum two orientations proposed in this study. Initially, roughing operations will form the profile of the part and leave residual materials based on a predetermined thickness. The thickness depends on program settings and in this study a 1mm layer of stock was left on the part. Figure 4 visualizes the profile of the part after a series of roughing operations and it will be machined to the final profile through finishing operations. As a result, this method has made the selection of finishing orientations more flexible. Since there is no requirement for thin web avoidance, two opposites cutting orientations can be employed. However, this is only applicable for non-complex parts. If complex features are present, then more orientations are required and these need to be defined based on the visibility analysis.

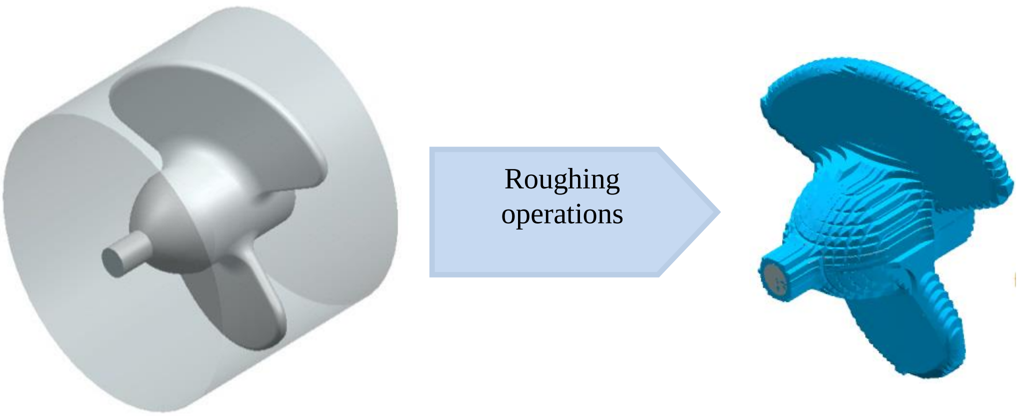

Figure 4. Remaining material left after roughing operations.

In order to illustrate the implementation the methodology, three different parts have been selected that have different shapes and sizes (drive shaft, salt bottle and knob). All these are considered to be non-complex parts since only two orientations are sufficient to completely machine the parts. In this study, the two finishing cut orientations were selected based on opposite directions and were required to cover all part surfaces. However, there is another option for selecting the orientations set. For example, orientations of 45° and 225° are capable of providing wide coverage on the salt bottle model. Similarly, this model also can be machined from 0° and 180° as these orientations allow cutting on all surfaces. The aim of this study was not to find optimum orientations but rather to evaluate the implications of using two cutting orientations in finishing processes. Therefore, the orientations set is selected randomly from possible cutting directions based on part features. It is justified to select any two finishing orientations that are capable of machining the parts completely. Later, the selection will influence the type of cutters used depending on the classifications of the surfaces. Figure 5 visualizes finishing orientations used on the selected models. Machining simulations were carried out using NX 7.5 CAD/CAM software which generated the estimated cutting time to produce the parts. Then the analysis was extended further by using CGTech VERICUT® 7.2.3 to calculate the excess volume left on the parts once machining had been completed.

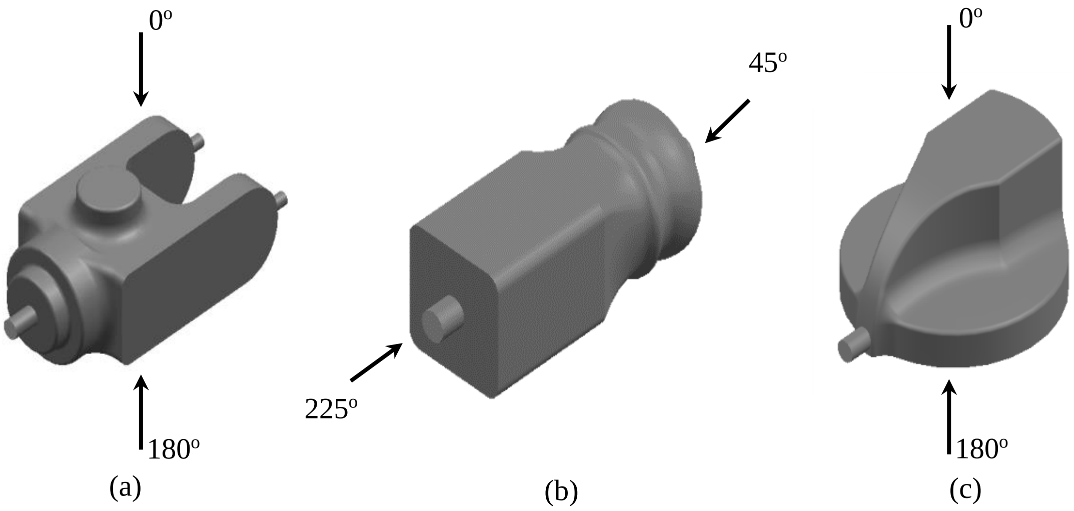

Figure 5. Two finishing orientations proposed for (a) drive shaft, (b) salt bottle and (c) knob models.

3. Results and Discussion

In order to validate the approach, a machining program for each model was developed. The roughing operations were performed through a set of four optimum orientations while the finishing operations were based on the two opposite orientations proposed. Two parameters were identified based on machining time and excess volume left on the part. The results were compared to the previous analysis that executed machining by using three cutting orientations [9]. Table 1 summarizes the simulation results for the selected models. For each model, the first column represents the three finishing orientations approach which was based on part visibility and fulfilled the thin web avoidance requirement. The second column represents the approach adopted in this study where the results were obtained after simplifying the orientations into only two cutting directions.

Table 1. Comparison between three and two finishing orientations

Model		Drive shaft		Salt bottle		Knob	
		3 orientations	2 orientations	3 orientations	2 orientations	3 orientations	2 orientations
Number of finishing orientations		32°-180°-0°	180°-0°	45°-180°-270°	45°-225°	180°-45°-315°	180°-0°
Machining time	hours:minutes:seconds	04:02:35	03:36:08	04:23:26	04:10:07	03:52:40	03:21:24
Finishing time	hours:minutes:seconds	02:28:39	02:05:21	02:29:33	02:19:18	02:27:16	01:59:17
Non-cutting time	hours:minutes:seconds	00:16:08	00:13:00	00:12:28	00:09:23	00:10:20	00:07:02
Roughing time	hours:minutes:seconds	01:17:48	01:17:48	01:41:26	01:41:26	01:15:04	01:15:04
Number of operations		9	8	9	6	7	7
Number of tool changes		5	4	5	1	2	2
Part volume	mm^3	52729.23		34081.83		21132.64	
Stock volume	mm^3	203517.28		111176.19		134607.50	
Machined volume	mm^3	150432.83	150436.58	76845.85	76897.50	113203.71	113222.73
Current part volume	mm^3	53084.45	53080.71	34330.33	34278.70	21403.79	21384.77
Excess volume	mm^3	355.22	351.48	248.5	196.87	271.15	252.13

Comparisons were made between both approaches that differ in term of number of finishing orientations. The performance and efficiency was evaluated based on machining time and excess volume. It is apparent from Table 1 that finish cuts using two orientations produce a significant result in terms of machining time. All models consistently showed a similar trend in terms of time consumed in machining processes. Total machining time decreased when two finishing orientations were used. Most of the saving is contributed by the reduction of finishing cutting time. Hence, reducing the number of orientations in the finishing process will influence the cutting time. The number of operations is highly dependent on the type of surfaces presented on the part. As an example, the numbers of operations for the salt bottle model decreased as only non-flat surfaces were present in both cutting directions. This required only one type of cutter, a ball nose end mill to finish cut the part. On the other hand, the number of operations on the knob model remains constant even though the finishing orientations are reduced from three to two. This is because of the different types of surface presented in one of the cutting orientations. Thus, two operations were performed; a flat end mill was used to machine the flat surfaces and a ball nose end mill catered for non-flat surfaces.

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The study also revealed some correlation between finishing orientations and remaining uncut material. The excess volume decreased when two finishing orientations were used. However, the differences are not really significant as both approaches have already adopted different cutting tools in finishing operations. The excess volume was only reduced by $4mm^3$ in the drive shaft model and the highest reduction is only about $50mm^3$ recorded in the salt bottle model. Sufficient cutting levels must be provided while cutting from two opposite directions. If a ball nose tool is used in the operations, there is a high tendency for excess material to be left if cutting down only to the centre of the workpiece. To overcome this, cutting levels must be extended further so that there is an overlap distance between the orientations. If there are only flat surfaces present in both directions this problem can be ignored as only flat end mills would be used.

4. Conclusions

This study has proposed an alternative method of determining the finishing orientations for non-complex parts. Returning to the question posed at the beginning of this study, it is now possible to state that using two finishing orientations influences the process in certain aspects. The findings suggest that, in general, reducing the number of finishing orientations manages to minimize the cutting time but does not produce a notable effect on excess material. Executing roughing operations in different orientations sets made the orientations for finishing operations more flexible. Therefore, non-complex parts can be directly machined from two opposite directions. The orientations can be directly proposed based on user interpretation. Thus, the visibility analysis can be excluded while developing the machining operations. However, the visibility analysis is still required in the case of complex parts, where the cutting tools are not able to cover all surfaces within two directions.

An issue that was not addressed in this study is a definite classification of complex and non-complex parts. Based on common interpretation, it is possible to implement this approach on any parts where all surfaces are exposed only to two cutting directions. A further study could possibly focus on establishing the guidelines to select an optimum two finishing orientations set. This is important as the combination of the two orientations is proven to influence the efficiency of the cutting operations.

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