Proceedings of the 11th International Conference on Manufacturing Research (ICMR2013), Cranfield University, UK, 19th – 20th September 2013, pp 233-238

OPTIMIZATION OF ROUGHING OPERATIONS IN CNC MACHINING FOR RAPID MANUFACTURING PROCESSES

Muhammed Nafis Osman Zahid[1,2], Keith Case[1] and Darren Watts[1]

[1]Mechanical and Manufacturing Engineering
Loughborough University
Loughborough
Leicestershire, LE11 3TU, UK
k.case@lboro.ac.uk
d.m.watts@lboro.ac.uk

[2] Faculty of Manufacturing Engineering
Universiti Malaysia Pahang
26600 Pekan, Pahang, Malaysia
m.n.osman-zahid@lboro.ac.uk

ABSTRACT

This paper presents a method for optimizing roughing operations in CNC machining particularly for parts production through a subtractive rapid manufacturing process. The roughing operation in machining is primarily used to remove the bulk of the material and to approximately shape the workpiece towards the finish form. The manufacturing process described utilizes a 3-axis CNC machine with an indexable 4th axis device that is used to hold and rotate the workpiece. The method used is derived from the multiple approaches in roughing operations that differ in the number and the angle of the orientations. Most of the machining parameters are generalized throughout the process to allow some automation in generating the machining program. Overall, 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

In recent years, the ability of rapid manufacturing(RM) in producing identical parts has been widely recognised; this technology being 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. Additive manufacturing (AM) is a method that creates parts on a layer basis by adding and stacking the material. However, this technology is still constrained by issues such as material properties, part accuracy, cost and performance (Campbell, Bourell and Gibson 2012). On the other hand, adopting Computer Numerical Control (CNC) machining as RM process seems to be a feasible approach to surmount the weaknesses of AM. CNC machines possess the highest degree of accuracy and repeatability and at the same time is capable of processing wide variety of materials. The process minimizes the staircase effect that usually found in AM and operates at minimum cost (Yang, Chen and Sze 2002). This distinct feature leads to the possibility of further enhancement of the CNC machining process to fulfil the rapid requirements of the RM process. There are some approaches that have been developed to deal with the pre-process engineering and setup planning issues in CNC machining.

One approach is the use of a 3-axis CNC milling machine with an indexable 4th axis device to hold and clamp the workpiece on the machine table. 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 and Wysk 2002). The indexable device is used to clamp the workpiece and allows it to rotates about one axis. This method employs layer-based material removal from multiple orientations until all surfaces of the part are machine without refixturing (Frank, Joshi and Wysk 2003). Dealing with a variety of machining orientations requires proper process planning to achieve reliable process efficiency. During the machining process, the surfaces contained in the part geometry must be visible in some direction. Figure 1(a) illustrates the visibility of part surface from one orientation (arrow direction). The other surfaces that not visible on this orientation require another orientations as shown on figure 1(b) and 1(c). Based on this method, visibility program is created to determine the minimum set of orientations required to completely machine the part (Frank, Wysk and Joshi 2004). Depending on part geometry and complexity, this program is able to propose orientation angles that will guide the tools to remove material until the final shape becomes visible.

Within each orientation proposed by visibility program, 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 getting the exact shape of the part. As illustrated in figure 1, 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. During roughing operations, it is important to avoid the formation of a thin layer material that could possibly wrap around the tool and cause failure. Thus, cutting through the workpiece or machining from at least three orientations are viable techniques to prevent thin layer formation. Next, the process continues with the finishing operation that will machine until the centre radius of the round workpiece. After that, the workpiece is rotated to second orientation. Then, the roughing and finishing operation is repeated again. 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.

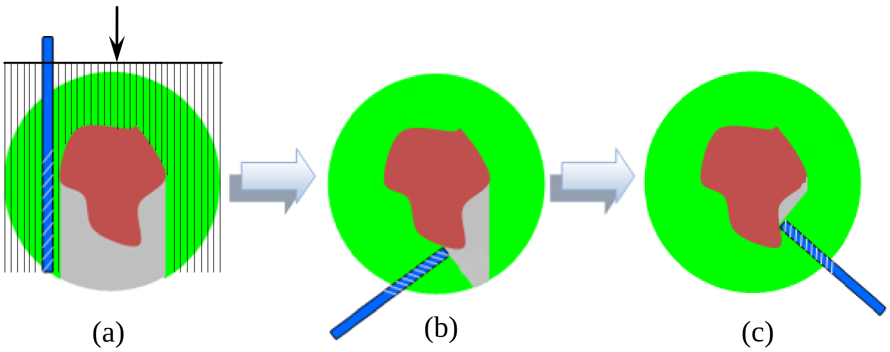

Figure 1: Roughing operation approach in CNC machining (Frank 2007)

The orientations proposed by visibility program are mainly effective during the last stage of machining (the finishing operation). In order to minimize the number of orientations required to machine the part, the visibility program incorporates the roughing operation together with the finishing operation under one same orientation. In future, further development it is proposed to use the initial angle to assist the visibility program in sequencing and optimize 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 the initial angle as first orientation, the rest of the orientations are generated to cater less uncovered surfaces. Hence, providing this angle to the visibility program minimizes the orientations set and is most likely to reduce total machining time for the process.

Referring to the current approach in adapting CNC machine for the RM application, there are two issues that should be emphasised. First, rotating the workpiece on the indexing device guarantees process continuity without any refixturing task. However, the orientations proposed constrain the roughing operation which must be performed within the finishing operation. To the contrary, instead of relying on surface visibility to decide the orientation, it is possible to execute roughing operations with a different set of orientations that aims to achieve high volume removal. In machining, time is one of the major concerns that will influence the process efficiency. The roughing operation can be considered as one of the time consuming processes especially in mould and die manufacturing that involves massive material removal (Hatna, Grieveand 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 till the furthest possible depth with the intention of avoiding thin material formation. This 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 and Lindström 1995). Based on these issues, this paper presents a methodology and approach to optimising the roughing operation in CNC machining for the RM application.

2 OVERVIEW OF METHODOOGY

Machining orientations for roughing operation are developed to accommodate the orientations proposed by the visibility program. 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 program. The second approach is based on extracting and splitting the roughing operations contained in the visibility program 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. As the process employs a feature free approach, most of the machining parameters remain constant throughout the process except for the roughing orientation angles. Simulations are run through NX7.5 software via customized coding that simulate the machining program based on the angle input. This coding generates detailed machining times for the roughing operation, finishing operation and non-cutting movement. Consequently, it also assists the simulation in running automatically given the required inputs. Overall performance was evaluated by comparing the total machining time generated from the series of simulations. Figure 2 summarizes the methodology employed to optimize the roughing operation in CNC machining.

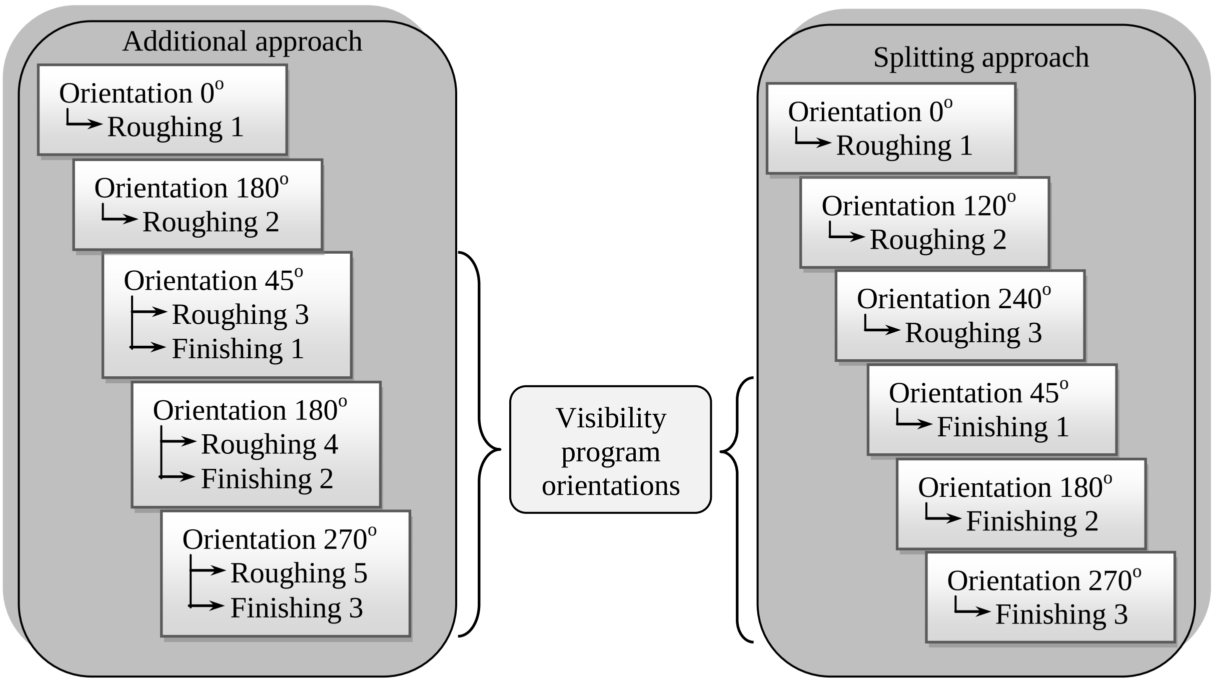

Figure 2: Two distinct approaches to find optimum roughing orientations.

2.1 Additional Roughing Orientation Approach

This approach involves introducing an extra machining orientation to the current orientation set. Two methods are proposed in this approach. The first one is adding one roughing orientation that cuts material the until the centre of the round workpiece is reached. Simulation for this method starts at angles from 0^o to 359^o. The second method deals with two additional orientations. This orientations represented at 0^o and 180^o. The angle is increased gradually in each simulation through increases of 1^o from 0^o to 179^o and from 180^o in increment of 1^o to 359^o. 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.

2.2 Splitting Roughing Orientation Approach

Instead of adding to the number of orientations, this approach modifies the visibility program output by taking out the roughing operations and incorporating them with the other orientations. A few combinations of angles 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. The set includes (0^o, 120^o, 240^o), (0^o, 135^o, 225^o), (0^o, 120^o, 225^o), (0^o, 135^o, 240^o) and (0^o, 90^o, 190^o, 270^o).

Basically, the combination of three angles is a minimum requirement to roughly machine the part without forming any thin material that is hard to remove. Therefore, (0^o, 120^o, 240^o) is the first combination set that equally divides the workpiece from one axis of rotation. The second roughing set (0^o, 135^o, 225^o) has been developed based on the coverage area of the cylindrical shape workpiece. 0^o degree covered the first half of the workpiece whereas the other two angles, 135^o and 225^o are used to cater for the other half of the workpiece (a quarter for each angle). The next two combination sets are derived from the first and second orientation sets. Two of the angle values from each orientation set are swapped to form (0^o, 120^o, 225^o) and (0^o, 135^o, 240^o) roughing combinations. Lastly, the four angle combination is used in roughing orientation to ensure extra coverage of the area and to reach all features presented on the part. The range between each angle is 90^o but on the third angle the value is increased to 190^o instead of 180^o. The reason for this incremental value is due to the possibility of thin material formation during third orientation of roughing operation. Based on this orientation, the tool is guided to start the machining from an inclined position and shapes the part effectively.

3 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. The models were selected randomly and consisted of a variety of different part features to form the object. Multiple features presented on 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 machining time (ii) maximum roughing time (iii) minimum finishing time (iv) minimum non-cutting time and (v) maximum roughing percentage. Most of the criteria are filled up with four and two orientation sets. However, minimum non-cutting time suggested two other orientation sets which consist of three orientations and orientations proposed by the visibility program. The results from the different orientation sets vary between each model because of the different features presented on the parts. Nevertheless, roughing through four orientations set is the most favourable method for almost all models.

The Additional roughing orientations approach which included the adding one or two orientations managed to increase the material removal volume. However, this approach tends to increase the number of machining operations in comparison with the operations produced by the visibility program. Additionally, the angle used can be redundant to the roughing angle from visibility program and cause inefficiencies due to repetitive work. To some extent, thin material will form if the two additional angles share the same value with angles from the visibility program.

Table 1: Example result recorded during simulation study.

Result \ Roughing orientation sets	Visibility program	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	7	7	8	6	6	6	6	7
Number of tool changing	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 program 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°

Meanwhile, 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 change that only occurred once throughout the machining. It is good practice to minimize the number of tool change even if the CNC machine is equipped with an automatic tool change system (Lim, *et al.* 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 result 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 this finding is not only limited to reducing processing time, but it also minimises the cutting depth where roughing tool only cut until the centre of 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 can be denoted as approach to optimize the roughing process in CNC machining.

4 CONCLUSION

CNC machining offers a reliable solution to rapidly manufacturing parts. The current approach using an indexable tool managed to eliminate multiple setups of the workpiece. The visibility program is an effective method to identify orientations for finishing operations. However, performing roughing operations within finishing orientations set tend to constrain the roughing task and caused 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. Future work will emphasize coding and programming that operates within the CAD system to create an automatic system to achieve the goal of rapid manufacturing.

REFERENCES

Campbell, I., Bourell, D. and I. Gibson. 2012. Additive manufacturing: rapid prototyping comes of age. *Rapid Prototyping Journal,* 18(4):255-258.

Frank, M., S. B. Joshi and R. A. Wysk. 2003. Rapid prototyping as an integrated product/process development tool an overview of issues and economics. *Journal of the Chinese Institute of Industrial Engineers,* 20(3):240-246.

Frank, M., S. B. Joshi and R. A. Wysk. 2002. CNC-RP: a technique for using CNC machining as a rapid prototyping tool in product/process development, *Proceedings of the 11th annual industrial engineering research conference, Orlando, Florida. May* 2002, Citeseer, 19-22.

Frank, M.C. 2007. Implementing rapid prototyping using CNC machining (CNC-RP) through a CAD/CAM Interface, *Proceedings of the Solid Freeform Fabrication Symposium, Austin, Texas.*

Frank, M.C., R. A. Wysk and S. B. JOSHI. 2004. Rapid planning for CNC milling-A new approach for rapid prototyping. *Journal of Manufacturing Systems,* 23(3):242-255.

Hatna, A., R. Grieve and P. BROOMHEAD. 1998. Automatic CNC milling of pockets: geometric and technological issues. *Computer Integrated Manufacturing Systems,* 11(4):309- 330.

Lim, T., J. Corney, J. Ritchie and D. Clark. 2001. Optimizing tool selection. *International Journal of Production Research,* 39(6):1239-1256.

Renner, A. 2008. Computer aided process planning for rapid prototyping using a genetic algorithm, MSc. *Iowa State University.*

Sadik, M.I. and B. Lindström. 1995. The effect of restricted contact length on tool performance. *Journal of Materials Processing Technology,* 48(1):275-282.

Yang, Z., Y. Chen and W. Sze. 2002. Layer-based machining: recent development and support structure design. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* 216(7):979-991.