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A BRIEF REVIEW ON FEED RATE OPTIMIZATION AND DIFFERENT TYPE OF TOOLPATH USE IN POCKET MACHINING

BAVARAMANANDI SWETANGKUMAR K[1], Dr. DIVYANG D PATEL[2], HARDIK R. DODIYA[3]

[1]Department of mechanical engineering at SVIT vasad,
[2]Department of mechanical engineering at SRICT ankleshwar,
[3]Department of mechanical engineering at SVIT vasad,

***Abstract*— the implementation and selection of cutter path and process parameter are most important in aerospace and mould and die industries. Proper selection of this parameter save machining time, improve workpiece surface quality and improve tool life. This lead to overall cost reduction and higher productivity. This paper identifies and review the different type of cutter path (tool path) and compare them based on tool path length, cutting time and cutter life. Also review the different feed rate selection strategies for pocket milling.**

***Keywords*— Pocket Machining, High Speed Machining (HSM), Feed Rate, Toolpath, Computer Aided Manufacturing (CAM), Offset Curve, Voronoi Diagram, Force-based Feed Rate Scheduling (FFS), Feed Rate Scheduling Strategy (FSS), Adaptive Control (AC)**

I. INTRODUCTION

The invention of the computer is the backbone of humankind development. This revolution makes human life easier. This revolution also beneficial in manufacturing industries because due to the use of a computer, the better control over the manufacturing process. At present, industrial necessity is to handle complicated processes, and speedy production in order to compete in the market. But still computer does not attain desired results, and human interference is likable. Nowadays, in manufacturing industries, computers are used to tackle all the activities like; tool path generation, surface modelling, machining monitoring, and process planning. Pocket machining is an important manufacturing operation in aerospace, mould, and die manufacturing industries. It is the operation in which material is removed layer by layer from the flat surface to defined depth. According to one approximation, 80% of milling operations are done by pocket machining [1]. The pocket machining operation is shown in fig.1.

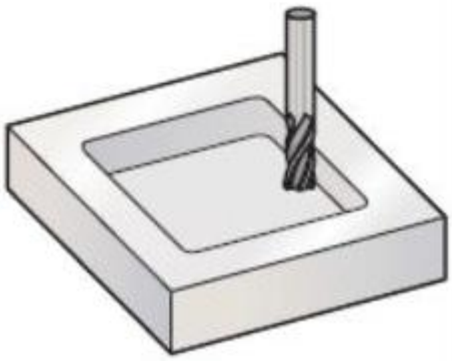


Figure 1 Pocket machining [2]

High speed machining (HSM) plays an important role in modern machine shops, particularly in aerospace machining, mould manufacturing and dies manufacturing. In the last few years, the aerospace industries had made use of high speed machining. High speed machining process offers to mill complicated structure that was difficult to machine earlier. High speed machining replaces many complicated assemblies into a single machining part. This reduces lead time and increases productivity. High speed machining process combines high feed rate with high spindle speed. It uses very high spindle speed (greater than 10,000 rpm) compared to the conventional machining. As it gives the same rewards but it has some restriction. When performing HSM, one should always avoid sharp turn and higher curvature in tool path. Cutter engagement angle is the angle formed between a cutter and the workpiece when both are in contact during machining and it tends to change as the machining operation preceded. It continuously influences cutting force and tool deflections which results in an increase in tool wear and poor surface quality. Toolpath generated by CAM software has some limitation, it only considers geometrical data. It ignores physical condition like cutting force and vibration.

Research on tool path generation method has been favourite in past decay. But the execution of the tool path technique has been strictly restricted to easy to machine workpiece material. Appropriate selection of tool path strategies is critical for achieving the desired result (good surface finish, higher tool life etc.). Machining strictly depends on cutting force, vibration, tool life, cutting temperature and workpiece surface integrity. If the proper machining condition was not select then it leads to catastrophic cutter failure which is followed by unnecessary waste of time and money, poor surface quality as well.

In this paper, the thorough review of the different toolpath used for the pocket machining, the methods to generate the same, its limitations and the various methods to remove these limitations are discussed. The paper also covers the different Feed Rate Scheduling Strategy (FSS) which is used in machining. The article first explain the different type of toolpath used for pocket machining and its related research and then discussed the different type of feed rate optimization techniques, its advantages, and limitations.

II. LITERATURE REVIEW

1. Toolpath generation Basically, there are mainly two type of pocket machining strategies used for the generation of toolpath Held, et al. [3].
1. Contour parallel machining or boundary offset machining.
2. Direction parallel machining.

1. Boundary offset Machining Strategy

This method is also called as offset machining. In this strategy boundary of the region is offset inward to the same distance and generate contour. This distance is limited to the step over distance. These contours are smoothing out and generate a toolpath for machining. Numerous kinds of literature was found that used this approach. [3]

2. Direction Parallel Machining Strategy

In this approach, the tool is moved along the line segment which is parallel to some reference line which was created initially. By connecting this parallel segment, the tool path is generated Held, et al. [3]. This approach is also called as Zig-Zag machining.

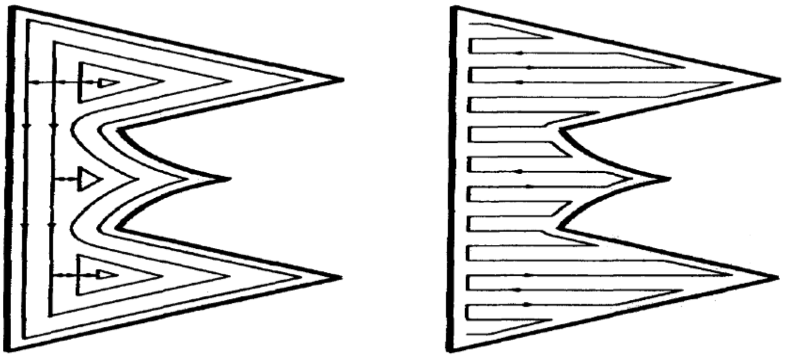


Figure 2 machining strategyHeld, et al. [3]

Direction parallel tool path is further categorized into the following type:
1. One-way direction –parallel toolpath
2. Zig-Zag direction –parallel toolpath

One-way direction –parallel toolpath is also called as uni-directional toolpath which is shown in the fig.3 (a). In this toolpath, chip removal can be maintained during up-cut or down-cut. However, there is high non-productive time involved in rapid travel from end to a starting position of next pass at the end of each cutting path [1].

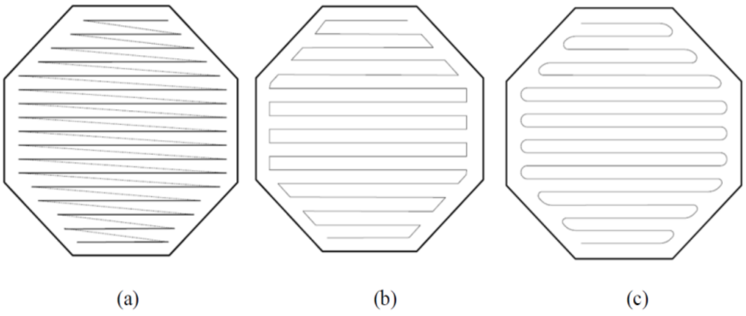
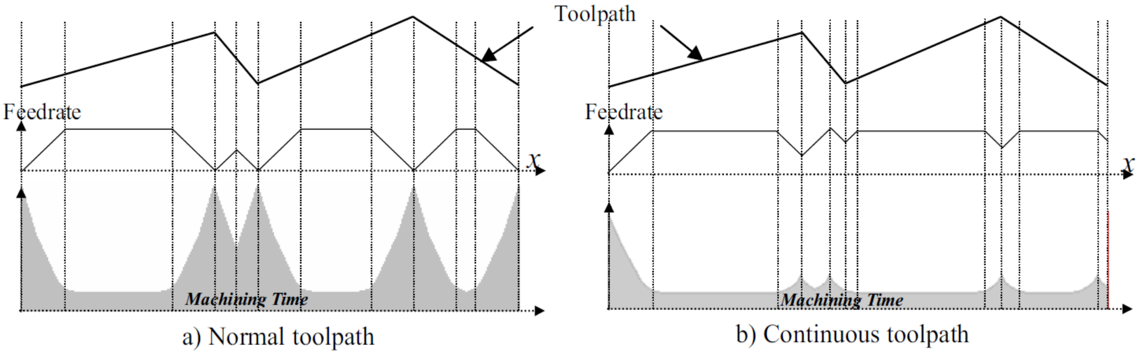


Figure 3 (a) One-way tool-path. (b) Zigzag tool-path. (c) Smooth zigzag tool-path.

Limitation of this tool path is solved by zig-zag toolpath. Zig-Zag toolpath is bi-direction toolpath, in which material removal is possible in forward as well as in a backward motion of the tool. Limitation of this toolpath is that during a machining operation, the up milling and down milling is alternatively applied, which leads to machine chatter and shorter the tool life.

Direction parallel toolpath has one drawback, sharp turn at corner region. As already deliberated above, in HSM sharp turn must be avoided because as the curvature of toolpath increases, the tool load changes rapidly which result in an increment of tool wear. This limitation is cracked with a contour parallel tool path.

El-Midany et al [4] compares different type of toolpath on the basis of machining time. They found from the experiment that the minimum stops and go motion toolpath has less machine time, as shown in figure 4. Shajari, et al. [5] Also conducted a comparative study for different toolpath based on surface texture and cutting force. They found in the experiment that the radial toolpath has a lower cutting force and a more uniform texture, but a higher machining time. Similarly, a spiral toolpath has a higher cutting force and worst surface texture. Therefore, the spiral tool path is not appropriate for the lower curvature convex surface.



a) Normal toolpath   b) Continuous toolpath

Figure 4 the normal and continuous toolpath [4]

The various tactics to achieving boundary parallel toolpath can be divided as follows Pamali [1]:

1. Pair-wise intersection .Hansen and Arbab [6]
2. Voronoi diagram. Persson [7]
3. Pixel-based method .Choi and Kim [8]

In pair-wise intersection approach, the boundary of pocket is offset inward by step over distance. Held, et al. [3] Explains the steps to generate the offset of curves.

Step 1: An elementary offset segment is generated for every boundary element.

Step 2: Gaps between consecutive offset segments are closed by trimming arcs. The result of this step is a set of closed curves which most probably have (self) intersections.

Step 3: Intersecting offset segment of the concave corner need to be trimmed to form the resultant contour profile. At convex corner, the offset segment needs to extend and connect to produce the resultant contour profile.

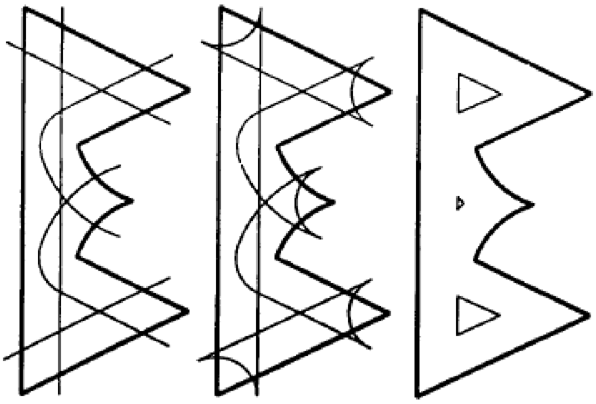


Figure 5 Conventional offsetting procedure [3]

Eliminating self-intersecting segment is time consuming and that may lead to numerical errors. The offsetting, trimming and extending process is carried out repeatedly on each layer of the offset segments until sufficient layers of contour profiles are created to cover the entire machining volume.

The second approach is based on a Voronoi diagram, in which offset segment is trimmed to their intersection using a Voronoi diagram of original pocket. The benefit of this approach is to handle topological change during the offset of the pocket profile. The Voronoi diagram method which is mentioned in references [9-11] are more efficient and robust for offset computation. Lee et al [12] use split-and-merge technique to generate an efficient algorithm to calculate Voronoi diagram. However, Choi et al [13] point out that when Voronoi diagram method is applied to the boundary of point sequence curve (PS-curve), it leads to incurring numerical instability near the circular portion.

The third approach is the pixel-based method which requires a large amount of memory and a long time for a calculation to achieve a desired level of precision because it depends on the Z- map resolution.Park et al [14] proposed a new pair-wise offset algorithm based on the pair-wise interference detection test to remove local invalid loops from the input PS curve before constructing a raw offset curve. It can side out circular singularity condition that exists in the traditional pair-wise approach. Kim et al [15] have anticipated geometric algorithms for the zigzag toolpath and a pixel-based simulation technique in order to maintain constant material removal rate (MRR) at all times, while considering cutting forces and machining stability. Bieterman et al [16] used Laplacian boundary condition to generate a curvilinear toolpath, but this toolpath approach has some limitation. This approach is not suitable for a pocket machining that has a too concave shape.

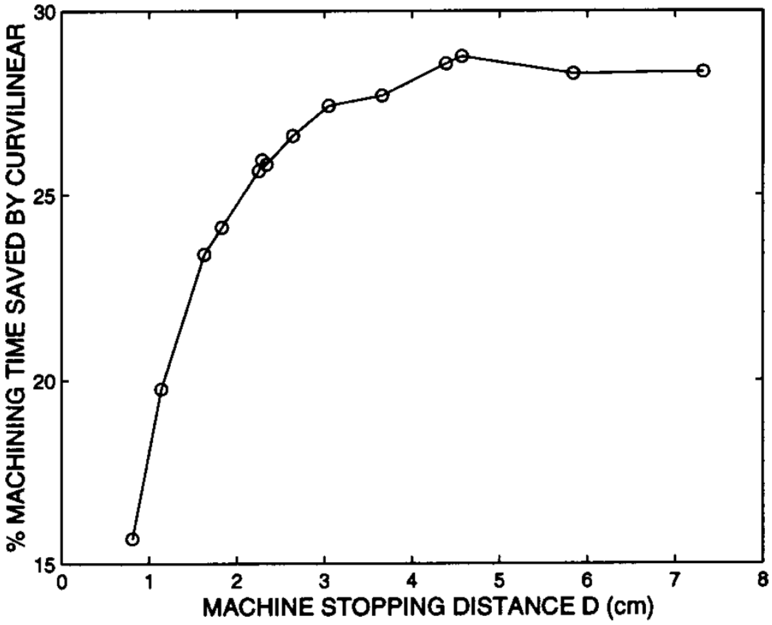


Figure 5 Results for computational experiment [16]

They found from experiment that morphing leads to reduced tool wear when machining harder metals and also reduces machining time up to 30%.

Pamali [1] have tried to use clothoidal curves for the generation of the toolpath. A former member of the Pamali's group tried to use the clothoidal curves for the generation of toolpath and the toolpath can take a higher feed rate, which reduces machining time. The results of her work involved some uncut regions in the pocket between the contour parallel offsets curve. The step distance of the contour offsets has been reduced in order to avoid such uncut regions. This leads to a longer toolpath which effects efficiency. Pamali solve this problem with the use of an iterative method to determined suitable Bi-clothoids to make no uncut region during machining.

Dharmendra [17] have used the elliptical partial differential equation to generate a spiral tool path for pockets with a varying aspect ratio (aspect ratio is the ratio of minor axis to major axis) as 1.0, 0.8, 0.6, 0.4 and 0.2. They observed that as the ratio of the minor axis to the major axis of the elliptical pocket decreases, the length of the toolpath increases significantly for the same pocket area. The reason behind this is as the aspect ratio decreases, the length of major axis increases. Due to the increase of major axis, the number of passes to cover the entire pocket also increases.

2. Feed rate optimization

In traditional contour toolpath, when cutter moves into corner region then the contact of the cutter and material is change. This leads to a change in cutting load, which produces undesired effects such as reducing tool life, machine chatter, and even a cutter breakage. Many researchers performed research to regulate the cutting load. Method of tool load regulating are classified into:

1. Online monitoring and control.
2. Offline monitoring and control or prediction of cutting load by cutting load model.

Online monitoring and control is the hardware-based method in which different sensor is used to reach the optimal and safe cutting environment. Optimum and safe machining condition can be achieved by monitoring the machining parameter (tool deflection, vibrations, cutting force/torque, chatter, spindle power, temperature, etc.). Feed and speed of the machining can be select based on the change of this parameter measured during machining. Online adaptive controller (AC) directly connect with CNC milling controller. Large investment required in online AC controller due to following reasons [18].

1. A costly sensor is required.
2. Fixing a sensor close to the cutting zone is required, which is very difficult.

3. Each CNC required one AC.
4. Changing the parameter with the third party is difficult.

Offline monitoring and control are one type of simulation-based control system. This method is flexible and versatile compared to the online AC method. In this method, the machining parameter is selected on the basis of the simulation result and feed and speed are pre-selected with the help of this result. Offline AC is economical and can create output acceptable to any CNC milling center. This method reduces the time of NC programming and machining of a part produced in the die and aerospace industries [18]

The most commonly used FSS method is divided into two stages: in the first stage finding optimum feed rate based on mark value. For example, setting a specific value of cutting force, MRR, chip thickness, chip volume to some value and then finding feed rate. And the second stage is a modification of the NC code. Mostly one constraint is used for FSS for all machining segment and other constraints are kept fixed. Various FSS can be integrated to get a better result based on machining time and cost [19, 20].

Researchers ' attention has recently been attracted by feed rate optimization related studies. Qian et al [19]combine feed rate rescheduling strategies, which use constant chip thickness and MRR to maintain cutting force below certain limits. When producing a tool path (CL file), the present CAM package considers a geometric aspect of the part, but cannot help selecting the correct or optimal operating condition[21, 22]. FSS also called as feed rate optimization. It is a process that modified the NC code of the given part in order to cut at varying feed rate values in place of fixed feed rate value. The feed rate scheduling model used in the offline method is classified in the following categories [20].

MRR model or volumetric model, the feed rate is directly proportional to average or on the spot MRR.

1. Force-based model (FFS), the feed rate is selected to maintain an average or instantaneous force at a certain value.
2. Rule-based model, which applied the principle of AI techniques, genetic algorithm, RSM (response surface methodology) etc.

Erdim, et al. [23] found that FFS model is more precise and efficient. But FFS model has some difficulty, in FFS model we need to track changing process parameter which depends on geometry [24, 25]. Yazar et al [26]develop force based feed rate optimization approach. In this approach, force is calculated using Kienzle 's lattice geometry modeler and empirical force modeler[27]. One limitation of this approach is the high computer storage and computing power required to prepare the lattice surface. Also in this approach, only Z-value is store for each lattice point, so the geometry model is not capable of representing undercuts and vertical walls. Kaymakci, et al. [28] also used the FFS feed rate optimization method, from which they found that the cycle time for sculpted surface machining reduced to 38.1 % with this strategy. They also validated experimentally and result shown in fig. 6.

During rough and semi-finishing processing time, the feed rate is an important factor. Therefore, during rough or semi-finishing milling, the feed rate must be selected to maximize the cutting time. However, high feed rate increases the cutting load. Rising the cutting load produce new problems such as machining chatter, tool wear, deflection, and breakage.

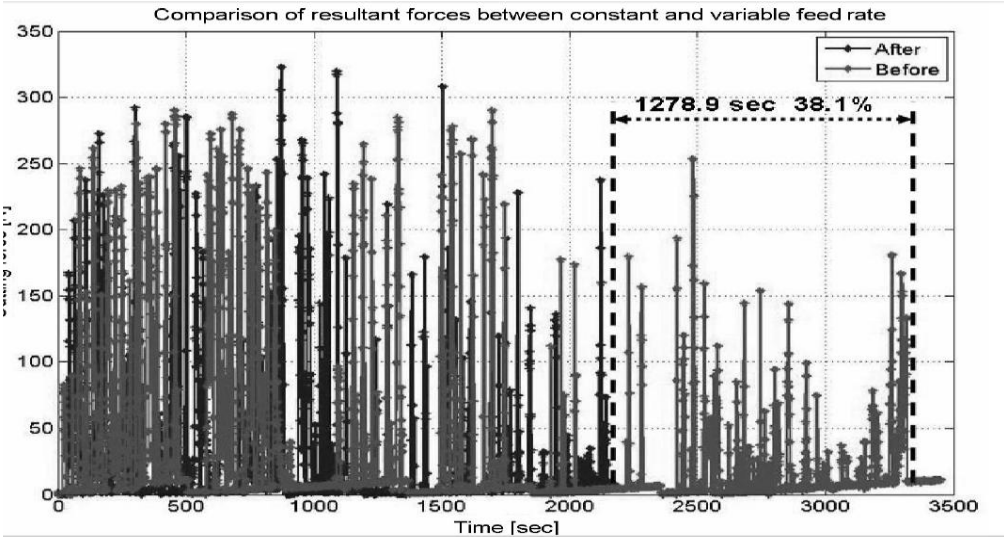


Figure 6 Comparison of the feed rate scheduling strategy with a constant feed rate [28]

The traditional FSS is most widely used based on MRR. In this model, the feed rate is directly proportional to the average or instantaneous MRR. This approach is based on a volumetric analysis which is widely used by the researchers. In MRR, the feed rate is optimized using geometric data such as chip section and chip volume. The MRR model is easier to use but is not precise and rigorous than the FFS. In the volumetric strategy, the assumption is kept that the power required to cut the material is proportional to the volumetric material removal rate[21, 29]. Wang develops an algorithm for feed rate adjusting using MRR with the help of z-map description of the workpiece volumetric analysis. Fussell et al [30]suggest an algorithm which is very reasonable then Wang. He uses computer-based automatic re/generation feed rate for enhancing the performance of milling. Jang [22]used vox-based model and confirmation system for feed rate scheduling using MRR. Lan et al [31]suggest a mathematical model in order to improve optimal MRR. For feed rate scheduling, Bailey et al [32]used a solid modeler to maximize the cutting force constraint in rough machining. For that, they find Volumatic meeting of cutting tool and workpiece. Feed and speed can be selected on the basis of cutting force. Chen, et al. [33] select the feed rate under the control surface roughness.Kloypayan and Lee [34] they develop one algorithm in which first they find cutting cross-section area for volumetric analysis, fixing this cutting cross-section area they select optimum feed rate.Lim and Menq [35] take force and geometry restriction into account whilst simultaneously adaptive regulating feed rate for a free-form surface. It was found that cutting time could be decreased for high curvature surface. However, they not validate this result with experimentally. Desai et al [36] develop mathamaatical model for finding cutter enagament angl for circular cut, on the basis of cutter engagment they maintain cutting forc by use of optimum feed rate. Gupta et al.[37] geometric algorithms described for computing piece-wise stable closed-form cutter engagement functions for 2.5D milling operations to determine and improve efficient cutter path. Further results are compared with discrete simulations showing that cutter engagement angle increases in circular cuts and linear half-spaces of the same.

Ip [38] consider tool life, wear and surface gradient for maintaining a cutting force for feed rate scheduling. Ip, et al. [39] proposed Fuzzy based MRR approach with consideration of spindle power and specific energy. Erdim, et al. [23] compared (FFS) and MRR-based feed rate scheduling using analytical cutter engagement model for sculptured surfaces. From this they conclude that force amplitudes can be controlled using feed rate control, FSS more reliable than the MRR technique. MRR based feed rate values can cause greater forces that can damage the cutter, workpiece, and CNC machine tool.

Kurt and Bagci [40] give detail review of the different type of feed rate optimization algorithm used in now a day. They suggest that FSS must consider some factor such as computational efficiency and requirement, precision, easy to use.

TABLE 1
FEED RATE OPTIMIZATION MODEL

Author	**Method of FSS**	**Remark**
Zhang, et al. [41]	force prediction and federate scheduling of geometric and mechanistic milling models	Decrease the machining time significantly along the toolpath, improve machining efficiency. However, in these methods, some kinematic parameter constraints are ignored, including acceleration and jerk. If acceleration and jerk exceed their limits, it will generate a huge dynamic load and cause vibration for machine tools.
Sencer, et al. [42]	MRR based Feed rate optimization technique	Introduced a feed scheduling algorithm for CNC systems to minimize the machining time for five-axis contour machining of a sculptured surface. The time-optimal feed motion is obtained by iteratively modulating the feed control points of the B-spline. And this is conducive to maximize the feed along the toolpath without violating the programmed feed and the drives' physical limits.
Liang, et al. [43]	MRR based Feed rate optimization technique	Reduced cutting time.
Fan, et al. [44]	force based Feed rate optimization technique	They presented a time-optimal federate planning method with complex constraints, including the motor torque constraint and the friction error constraint
Bharathi and Dong [45]	Force based feed rate optimization technique	Authors proposed a federate optimization method under velocity and acceleration constraints
Sun, et al. [46]	adaptive feed rate optimization	They consider velocity and acceleration constraints for precision five-axis machining to reduce machining time.
Lu and Chen [47]	genetic algorithm based on S-curve acceleration/ deceleration scheme	They presented a genetic algorithm based on S-curve acceleration/ deceleration scheme to increase processing efficiency
[Li, et al. [48]]	BFSA-Bidirectional feed rate scheduling algorithm	The proposed algorithm is used for minimizing machining time and voided this algorithm with simulation and experimental results.

III. CONCLUSIONS

From the literature, we have seen that the traditional offset contour used directly as the tool path has some limitation, which increases the cutting load, produces chatter and reduces the life of the tool. Whatever contour offset tool path generation strategies we use, we need to optimize it with FSS.

Offline feed rate adjusting methodology new in industries now a day. This automatically decide optimum feed rat for CL file modification. However, commercially used FSS have some limitation. Because they used MRR or cutting force module which depend on operating condition. Some CAM software package used MRR based feed rate optimization to reduced lead time in rough milling operation. However, when precision/accuracy is required then we suggest to use FFS approach. When we required both (reducing lead time and precision/accuracy) at a time then we need to integrate MRR and FFS approach together. Selection of proper approach of tool path generation and FFS depend on operator choice.

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