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Process Planning for 2½D Pocket Machining: A Novel Integrated Framework

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Abstract

The process planning for 2½D pocket machining generally considers the geometry of 2½D pocket as a primitive machining feature. But the non-unique mapping of the geometry of 2½D pocket to the machining steps introduces ambiguities in the design and planning phases. Process planning consists of different tasks, such as Tool Selection, Tool Path Generation and Machining Parameter Selection, with individual research issues. Most of the prior research effort treats optimization of each task as isolated research topic. Only few attempts had been made to generate the complete process plan by integrating the optimized tasks, that too in a sequential manner. It is well known that the cutting process geometry and kinematics link the different tasks together through the process parameters, like cutting tool diameter, cutting depths etc. In this paper, a "Novel Integrated Process Planning Framework" is proposed to simultaneously optimize all the process planning tasks for different elemental features. To avoid any ambiguity between the part design and process planning phase, the geometry of 2½D pocket has been separated into Elemental Machining Surfaces (EMS): Bottom, Wall and Corner. This separation allows representing the 2½D pocket machining as a well defined problem where all the planning tasks for each EMS are considered together to generate the entire process plan. The framework incorporates a bottom-up integration approach, where the planning tasks for each EMS are simultaneously optimized at the bottom level. Plans for different EMS are integrated at a higher level to obtain the optimal process plan for the entire 2½D pocket. Integrated process planning of other machining features as well as higher levels of planning can also be generated by the proposed framework. The proposed framework approach avoids the use of complex algorithms and associated high computation costs by carrying out the integration of the process plans at different levels by facilitating the optimization of a manageable number of parameters with meaningful physical basis.

1. Introduction

It is estimated that yearly millions of tonnes of chips are generated by the pocket machining operation, in aircraft industry alone. This has resulted in 2½D pocket being one of the most significant primitive features [1] for machining applications. Thus the process planning of 2½D pocket machining is of great importance for researchers [2] where the primary objective is to minimize the machining time and subsequently the machining cost. The review [3] of the literature on process planning of 2½D pocket machining suggests that considering the 2½D pocket as the primitive machining feature with non-unique mapping of the geometry to the machining steps introduces ambiguities in the design and planning phases. The study identifies different process planning tasks being Tool Selection (TS), Tool Path Generation (TPG) and Machining Parameter Selection (MPS). But in most of the prior research effort treats optimization of each task as isolated research topic with few attempts to integrate them that too in a sequential manner. It is well known that the cutting process geometry and kinematics link the different tasks together through the process parameters. This suggests the need of the integration of the planning tasks.

The word "Integration" had been loosely used in the process planning research, but can be defined as the combination of different process planning tasks to generate a complete plan. In the context of process planning, the success of the complete plan will depend on its productivity and efficiency. This brings in the need of simultaneous optimization of the different planning tasks to generate a complete optimal plan. Due to low numbers of research work in the area of integration of process planning dedicated to 2½D pocket machining, the work reviewed in this

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section addresses generic research issues and challenges in integrating the process planning for milling operation. Ostafiev et al. [4] sequentially optimized tool path, tool geometry and machining parameters to minimize the machining time and reported an improvement in the machining time of 1.5 times, even for a simple pocket geometry. Lim and Menq [5] integrated geometrical and machining parameters to reduce the machining time by 80% for turbine blade [6] and also included an approach to compensate the machining error [7]. Feng and Su [8] proposed simultaneous optimization of feedrate and tool path for 3D plane milling and found that the minimum machining time may not correspond to the shortest tool path length, as otherwise concluded by most of the sequential optimization approaches. In another work [9], the feature recognition had been combined with machining planning to obtain optimal plans. To facilitate the handling and processing of large volume of information required to integrate the process plans, researchers have proposed knowledge base [10], Artificial Intelligence [11], standardized data exchange format [12] and case-based approaches [13, 14]. Several application tools are available for a variety of machining features with different interpretations and approaches of "Integration". In Computer-Integrated Process Planning and Scheduling [15], researchers "Integrated" basic machining tasks as well as the scheduling tasks, focusing on feasibility rather than optimizing the selection of machines, tool and their sequence. In Sequential and Tool Oriented Process Planning [16], elemental features were sequentially recognized and feasible plans were generated to machine them. A feature based process planning tool has been proposed to integrate the information flow between design, planning and machining phases with the help of software agents [17] and combining individual process planning tasks [18].

Prior work in integrated process planning reveals that although several attempts have been made to integrate the planning tasks, but their optimization has been partially addressed. This may be accounted [19] due to the requirements of complex algorithms required to optimize large number of geometrical and machining parameters, the associated non-unique solutions and the required trial and error based machining experience. Thus the integrated optimization of both geometric and machining parameters will necessitate a robust [15] and complex "holistic" method [18] which can optimize large volumes of information in a systematic manner [16].

In this paper a novel Integrated Process Planning Framework has been proposed towards a systematic integration of the process planning tasks for 2½D pocket machining and their interrelated parameters. The framework incorporates the decomposition of the geometry of the 2½D pocket into elemental machining features such that each of them corresponds to unambiguous process plan. The framework facilitates the simultaneously optimization of the pertinent process parameters in a structured manner to generate an optimized process plan rather than sequential combination of locally optimized planning tasks. This is achieved b a bottom-up integration approach, where the planning tasks of each elemental features are integrated at the bottom level and plans for different elemental features are integrated at a higher level.

2. Integrated Process Planning Framework

From the above discussion, it can be concluded that any attempt to integrate the process planning for even a simple machining feature like 2½D pocket will involve a multi-variable optimization with large number of process parameters. This will not only be computationally expensive but require complex algorithm, and may not be convenient for contemporary commercial computing systems. Thus the multi-variable problem needs to be simplified such that manageable number of parameters is optimized in a systematic manner and also with a meaningful physical basis. For this purpose, a novel Integrated Process Planning Framework has been proposed and it has been discussed in details in the following sections.

2.1 Objectives

Well-defined: The correspondence of the geometry of the machining feature to the planning tasks should be unambiguous. Thus the machining of the feature can be posed as a well-defined machining problem with all the pertinent process parameters identified.

Global Plan: The plan should include all the pertinent process parameters of the planning tasks optimized under global machining constraints and objective. This would necessitate the iterative regeneration of the entire plan until no further optimization of the objective function can be done.

Multi-variable Optimization: The integration would require multivariable optimization, which may be difficult to solve due to complexities of the entire process planning and may lose the physical meaning. For this purpose, the optimization of the planning tasks is simplified such that manageable number of process parameters is optimized with a meaningful physical basis.

2.2 REQUIREMENTS

Elemental Features: To avoid discontinuities between the design and the planning phase, machining features are required to have explicit mapping to the process planning tasks. Such features should be elemental in nature, containing the basic geometric as well as machining information.

Links: Process Planning tasks of the elemental features are linked to each other by the cut geometry and cutting kinematics. Moreover if more than one elemental feature is required to represent the machining feature, the different elemental features should also be linked to each other. The parameters involved in the above links are required to be identified as well as optimized.

Structure: Integrated process planning would require the process planning tasks for the individual elemental features and the different elemental features should be optimized in a structured manner, based on valid physical basis.

3. ELEMENTAL MACHINED SURFACE

Ambiguities arising from the multiple interpretations of machining feature in terms of machining plans lead to discontinuities in the design and planning phases. Thus as mentioned earlier, the novel Integrated Process Planning Framework, should be based on primitive machining features, with one to one mapping of machining features to planning steps. As a machining feature contains both geometric and machining information, thus defining an elemental feature with the basic levels of the both the information, should be able to explicitly map the machining feature to process planning tasks. In this work, the concept of Elemental Machining Surfaces (EMS) has been proposed which is defined as the surface generated by a flat end milling tool in a single cutting movement. A surface and a single tool movement are both basic geometric and machining entities which would make EMS an extremely competent candidate for being the primitive machining feature of Integrated Process Planning as follows,

Bottom: It is the horizontal surface created by the cutting edge of flat end-mill when the tool sweeps area within a predetermined boundary. A constant axial depth is used along with a constant or consistent radial depth, as shown in Figure 1a. The tool with diameter D^B follows a certain cut pattern within the Bottom boundary, which is determined by offsetting the pocket boundary ($l \times w$) by a distance d_m^W , defined as the material to be machined during the Wall machining. It may be required to take several axial passes (n_a^B) which makes the cut pattern to be repeated at several axial depths, as shown in Figure 1a. The feedrate (f_r^B) and the path interval (δ) are selected such that the machining time is minimized as Bottom machining contributes to most of the pocket machining time.

Wall: It is the vertical surface machined by the peripheral helical cutting edge of the flat end-mill with constant axial and radial depth, without any change in the cutting direction, as shown in Figure 1b. It is the next step after Bottom machining, where the material left by Bottom machining becomes the material to be removed during Wall machining (d_m^W) is removed to generate the Wall. The tool with diameter D^W may require several axial passes (n_a^W) to machine the entire height (h) of the Wall, which needs to be optimized along with the feedrate (f_r^B) such that the resulting machining accuracy is within the tolerable limit (ε) in minimum machining time.

Corner: It is the vertical surface machined by the peripheral helical cutting edge of flat end-mill with a constant axial and constant or varying radial depth, with continuous change in the cutting direction, as shown in Figure 1c. The tool diameter, D^C can be selected based on the inside radius (r) of the pocket geometry. The material to be removed by Corner machining (d_m^C), is the function of D^W and r. The number of axial passes (n_a^C) required as well as feedrate (f_r^B) are optimized such that the variation in the cutting force is kept within a range such that the machining accuracy is under tolerable limit (ε), in minimum machining time.

As shown in Table 1, the 2½D pocket is represented as four alternating Walls (W) and Corners (C) connected to a common Bottom (B) surface. Modifying the adjacency relationship and the number of EMS, different machining features like blind step, blind slot and blind hole can also be represented. The table also justifies the selection of the 2½D pocket as the machining feature in the current work, as the other features are its subset and the proposed integration framework can also be applied to them. Thus the machining of the individual EMS can be posed as a well-defined machining problem. Given a tool diameter (D), pocket geometry ($l \times w \times h$) and tool-workpiece properties, the pertinent process parameters like path interval, cutting depths, feedrate etc. can be determined as well as optimized to achieve the objective function of minimizing the machining time or cost under the constraint of machining accuracy.

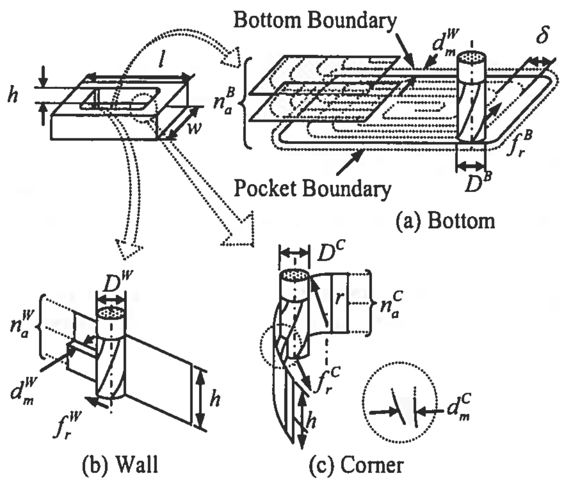
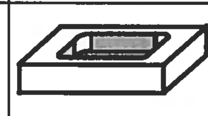
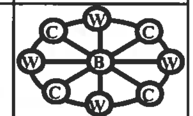
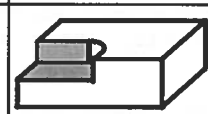
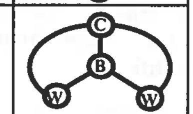
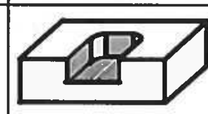
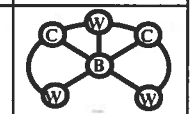
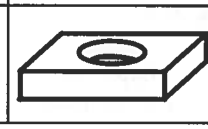
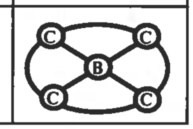


Figure 1: EMS and related Process Parameters

Table 1: Representation of machining features with EMS

Features	Diagram	EMS W	EMS B	EMS C	Adjacency Graphs
Pocket		1	1	1	
Blind STEP		1	1	1	
Blind SLOT		1	1	1	
Blind HOLE		1	1	1	

:Wall(W) :Bottom(B) :Corner(C)

4. Linking

As discussed earlier, the process planning tasks of TS, TPG and MPS for a machining feature are linked to each other through the cut geometry and the cutting kinematics. Thus for each EMS, it is important to identify the parameters linking the different tasks from the knowledge of 2½D pocket machining. The tool geometry (TS) is linked to the number of axial and radial passes (TPG) and the cutting depths and feedrate (MPS). Similarly the cut pattern and number of axial and radial passes (TPG) are linked with the cutting depths and the feedrate (MPS).

The next linking exists between the different EMS such that they can be represented as the entire 2½D pocket. This linking can be obtained by considering the order of machining the EMS. Bottom machining is the first step of pocket machining, and definition of the material to be removed is obtained by offsetting the boundary of the pocket. In the next step, the Wall is machined, where the material to be removed is defined by the material left behind by the previous step of Bottom machining. Again the material to be removed in the next step of Corner machining is defined by the material left by the Wall machining. Thus the parameter, material to be removed (MR) forms the link between the individual EMS. Although the value of the parameter may be different for the similar EMS based on the cut pattern followed, never the less the linking still holds. The above linking are incorporated at separate levels of integration in the structure of the framework, which will be discussed in details in the following section.

5. Structure

The structure of the novel Integrated Process Planning Framework, as shown in Figure 2 facilitates the multi-variable optimization of all the process parameters pertinent the process planning of 2½D pocket machining. It considers manageable number of variables at different levels with physical basis, rather than simply considering all the variables together. The structure incorporates a bottom-up integration approach by linking of the process planning tasks for a particular Elemental Machining Surface at the bottom level and then linking the plans of each EMS at a higher level to generate the process plan for the entire 2½D pocket. At first, the planning tasks of TS, TPG and MPS of individual EMS are considered, and it results in the integration at the elemental level, called the EMS Level. At this level, the TS is not performed for individual Elemental Machining Surface but performed collectively for the similar EMS. In the next level, the process plans of different EMS are considered and it results in the integration at a higher level called the Feature Level, which generated the process plan for the entire machining feature. The levels of integration for 2½D pocket machining have been discussed in more details in the following sections.

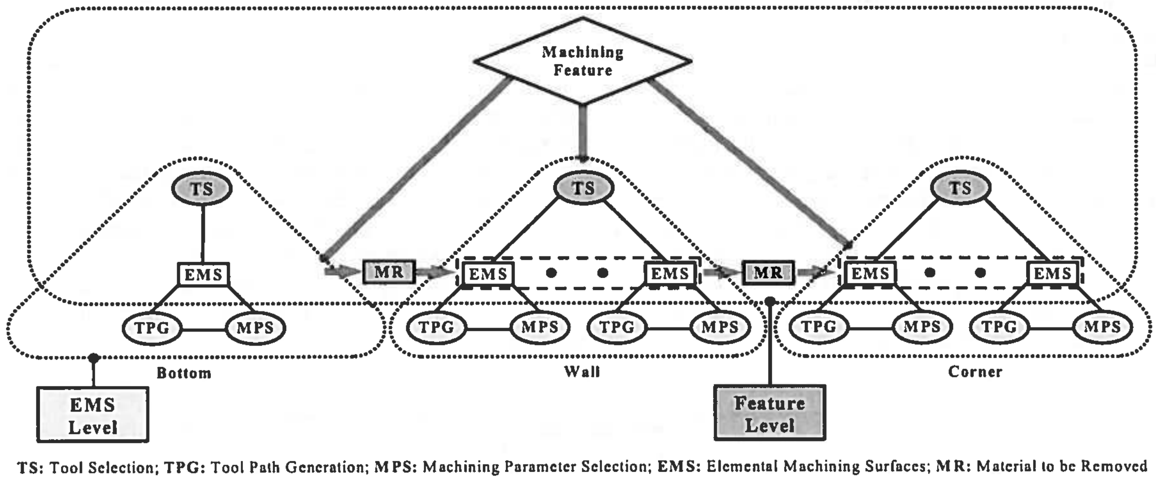


Figure 2: Structure of Novel Integrated Process Planning Framework

Although the EMS concept has been introduced in this work, but the review of the available literature on 2½D pocket machining can be used to study the research issues of the EMS. In most of the work, all the EMS has been addressed in a combined fashion, the Bottom being most frequently been addressed. The complexities of Corner machining necessitate its individual recognition but the Wall machining with rather simpler research issues is considered a part of Bottom machining. Thus the need of distinguishing each EMS and distinctly defining their research issues and machining requirements is imperative for the integrated approach.

5.1 EMS Level

This level of integration includes simultaneous optimization of TPG and MPS and for individual EMS, indicated by the shaded regions shown in Figure 3. Although, TS is considered but it is performed collectively for similar elemental features and thus optimized at a higher level. The well-defined optimization problem for each EMS is formulated at this level. For a given tool diameter (D), material to be removed (d_m) and the intrinsic properties of the pocket (geometry: $l \times w \times h$; accuracy: ε); the parameters of feedrate (f_r) and the number of axial (n_a) and radial (n_r) passes are selected and optimized. For a particular cut pattern (CP) the path interval (δ) is calculated based on the n_r and radial depth of cut, and n_a is directly related to the cutting depth and form the link between MPS and TPG.

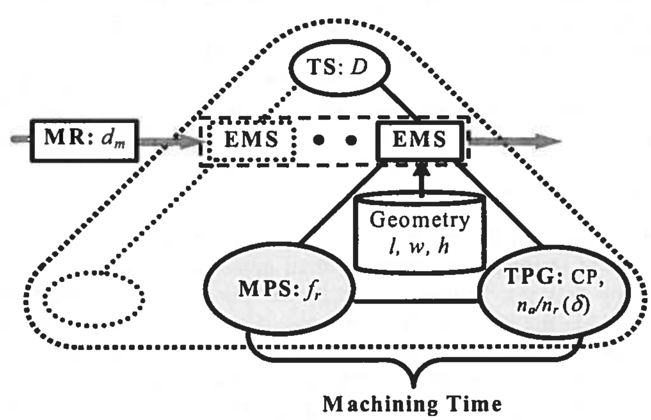


Figure 3: Integration at EMS Level

5.2 Feature Level

At Feature level, the process planning for individual EMS are integrated by linking the process parameters of TS and material to be removed (MR), indicated by shaded regions and shown in Figure 4 and subsequently optimize the associated parameters (D and d_m) to generate the process plan for the entire 2½D pocket. The tool diameter (D) selected for similar EMS and the material to be removed (d_m) links them with the machining feature and with each other respectively. As discussed earlier that the material left behind by the Bottom machining becomes the material to be removed for the Wall (d_m^W), the material left by the Wall becomes the material to be removed for machining the Corner (d_m^C). Thus the parameters optimized are material to be removed and the tool diameters. The tool diameters for Bottom and Wall may be the same as Wall machining can be considered as an extension of Bottom machining. But for Corner machining, the tool diameter is dependent only on the inside radius (r) of the pocket geometry and the tool diameter for Wall. The input information at the Feature Level is the intrinsic properties of the pocket (geometry: $l \times w \times h$; accuracy: ε) with an objective of machining the entire pocket within tolerance limit (ε) in minimum time. An optimal plan for the entire pocket is obtained by carrying out optimization in EMS and Feature levels until no further improvement of the objective function can be done. Adjustment of any parameter would require the regeneration of the optimal plans both at the EMS and the Feature level.

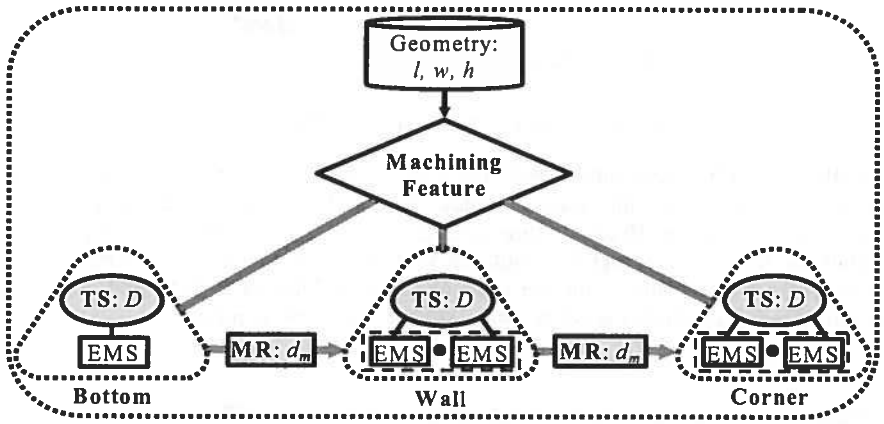


Figure 4: Integration at Feature Level

6. Discussion and Future Directions

In this paper, a novel Integrated Process Planning Framework has been proposed for 2½D pocket machining. Instead of considering the 2½D pocket as a primitive machining feature, it has been decomposed into EMS. The machining of each EMS, Bottom, Wall and Corner has been posed as a well-defined machining problem thus obtaining explicit mapping to process planning tasks. The framework incorporates a bottom-up integration approach by simultaneous optimizing the planning tasks of individual EMS at the bottom called EMS Level and optimizing the different EMS to generate the entire plan for the 2½D pocket at a higher level called Feature Level. The structure of the framework facilitates the multi-variable optimization to be performed at different levels with manageable number of variables with a physical basis.

The novel integrated framework can be extended to 3D pocket by incorporating a curved Wall and Bottom surfaces. Modifying the number of elemental features and their adjacency graph, the integrated framework can also be used for different machining features. Moreover, the framework can be extended to include higher levels of process planning integration like Set-up, Part and Product Level. The integration of process plans at the Set-up Level would include the fixturing issues of machining multiple features in a single set-up. At the Part Level, machining with different set-ups and/or machine tools would be addressed requiring tasks like scheduling, routing, etc., where as for Product level tasks like assembling could be incorporated. Business planning objectives can also be included at a higher level of integration.

Apart from the challenges reported for other integrated approaches [16, 18 and 19], the novel integrated process panning framework will require adequate process knowledge to define each process planning tasks, pertinent process parameters and their links. End-milling may be one of the simplest milling processes still its planning complexities will require significant amount of information to be handled. To obtain guarantee globally optimal plans with minimum machining time, the iterative regeneration of the process plans may be computationally expensive but will avoid sequential combination of locally optimized plans.

7. Reference

[1] *Martin Held, "On the computational geometry of pocket machining", Berlin: Springer-Verlag, 1991.*

[2] *Hatna A, Grieve RJ and Broomhead P, "Automatic CNC milling of pockets: geometric and technological issues", Computer Integrated Manufacturing Systems, Vol. 11, No. 4, pp. 309-30, 1998.*

[3] *Banerjee A, Feng HY and Bordatchev EV, "Process Planning for 2½D Pocket Machining: A Review", submitted, Flexible Automation and Intelligent Manufacturing, FAIM 2007, Philadelphia, USA.*

[4] *Ostafiev VA, Globa AV, Globa LS and Loladze TN, "Integrated end milling optimization development", Annals of CIRP, Vol. 33, No. 1, pp. 29-32, 1984.*

[5] *Lim EEM and Menq CH, "Integrated Planning for Precision Machining of Complex Surfaces. Part 1: Cutting-path and Feedrate Optimization", International Journal of Machine Tools and Manufacture, Vol. 37, No. 1, pp. 61-75, 1997.*

[6] *Lim EEM, Menq CH and Yen DW, "Integrated Planning for Precision Machining of Complex Surfaces. Part 2: Compensation of Dimensional Errors", International Journal of Machine Tools and Manufacture, Vol. 37, No. 1, pp. 77-91, 1997.*

[7] *Lim EEM, Menq CH and Yen DW, "Integrated planning for precision machining of complex surfaces - III. Compensation of dimensional errors", International Journal of Machine Tools and Manufacture, Vol. 37, No. 9, pp. 1313-1326, 1997.*

[8] *Feng HY and Su N, "Integrated tool path and feed rate optimization for the finishing machining of 3D plane surfaces", International Journal of Machine Tools and Manufacture, Vol. 40, No. 11, pp. 1557-72, 2000.*

[9] *Yang Z, Joneja A and Zhu S, "Recognizing generalized pockets for optimizing machining time in process planning - Part 2", International Journal of Production Research 2001;39, Vol. 39, No. 16, pp. 3601-21, 2001.*

[10] *Iwata K and Sugimura N, "Integrated CAD/CAPP Systems with 'Know-Hows' on Machining Accuracies of Parts. Transactions ASME", Journal of Engineering for Industry, Vol. 109, No. 2, pp. 128-33, 1987.*

[11] *Pham DT and Dimov SS, "An approach to concurrent engineering", Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture, Vol. 212, No. 1, pp. 13-27, 1998.*

[12] *Xu XW and He Q, ""Striving for a total integration of CAD, CAPP, CAM and CNC"", Robotics and Computer Integrated Manufacturing, Vol. 20, No. 2, pp. 101-9, 2004.*

[13] *Marefat M and Britanik J, "Case-based process planning using an object-oriented model representation", Robotics and Computer Integrated Manufacturing, Vol. 13, No. 3, pp. 229-51, 1997.*

[14] *Chang HC, Lu WF and Liu FX, "Machining process planning of prismatic parts using case-based reasoning and past process knowledge", Applied Artificial Intelligence, Vol. 16, No. 4, pp. 303-31, 2002.*

[15] *Aldakhilallah KA and Ramesh R, "Computer-Integrated Process Planning and Scheduling (CIPPS): intelligent support for product design process planning and control", International journal of production research, Vol. 37, No. 3, pp. 481-500, 1999.*

[16] *Choi BK and Barash MM, " STOPP: An approach to CADCAM integration", Computer Aided Design, Vol. 17, No. 4, pp. 162-68, 1985.*

[17] *Smith CS and Wright PK, " CyberCut: A world wide web based design-to-fabrication tool", . Journal of Manufacturing Systems, Vol. 15, No. pp. 432-442, 1996.*

[18] *Castelino K, Sundararajan V, D'Souza R, Kannan B and Wright PK, "AMPS-An automated modular process planning system", Transaction of ASME: Journal of Computing and Information Science in Engineering, Vol. 4, No. 3, pp. 235-41, 2004.*

[19] *Yut G and Chang TC, "Assessing the feasibility of a process plan: A study in variable interaction", Proceedings of the Symposium on Solid Modeling and Applications, Vol. No. pp. 322-335, 1997.*