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RECONFIGURABLE MACHINE TOOL: METHODOLOGY OF RMT DESIGN

Reconfigurable Machine Tool (RMT) is the active issue to realize both the flexibility and productivity of manufacturing systems and satisfy the mass-customization production. The purpose of this paper is to present a RMT design methodology. Specifically, the part analysis and the RMT architectural modelling. The method of RMT design is focused on a simultaneous machining process using multi-spindle in a single RMT. Based on the concept of machining features, the process data, retrieved as a starting point in identifying various functions necessary to carry out a given part family, are displayed. Moreover, geometrical and kinematical architectures of RMT are defined as a result of the specification of all manufacturing processes of features to be machined. Where, all architectural solutions and the criterions related to select the suited solution are presented. Our methodology presents all activities allowing to pass from machining features of part to be machined to the structure of RMT.

1. INTRODUCTION

Since paradigm was proposed. Reconfigurable Manufacturing System (RMS) has received increasing attention as a means for realizing both the flexibility and productivity. In particular, RMT formed the key part of RMS, is a structural creation to produce shaping motion between the tool and workpiece, designed to produce a given part family as well as the volume responsiveness (e.g. cylinder head, engine block).

To design a RMT, it is necessary to define process data generated by analyze the part to machining features and create a geometric, technologic and machining descriptions of features, specify the geometric and kinematic architectures, model the basic functionality of the machine that is described by a structural and kinematical modeling between the tool and the part, and select suited modules then structure the RMT.

The concept of changeable systems has been treated in 1993 by Garro and Martin [4] presenting a model of machine tool with higher performance in terms of productivity

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and flexibility, defined a methodology of design for this type of machines based on the use of manufacturing features. Then, Koren, Moriwaki (1999) [5] and Mehrabi (2000) [6] defined the ideology and the key characteristicsof RMS. Moreover, to establish the process data, [7-11] presented a set-up planning module as part of a feature-based process planning system. [12] proposed a procedure for design of a production system, using production features. With a view to design RMT [13] applied the dual vector in order to present the machining task and the mathematical framework of RMT with one only spindle.

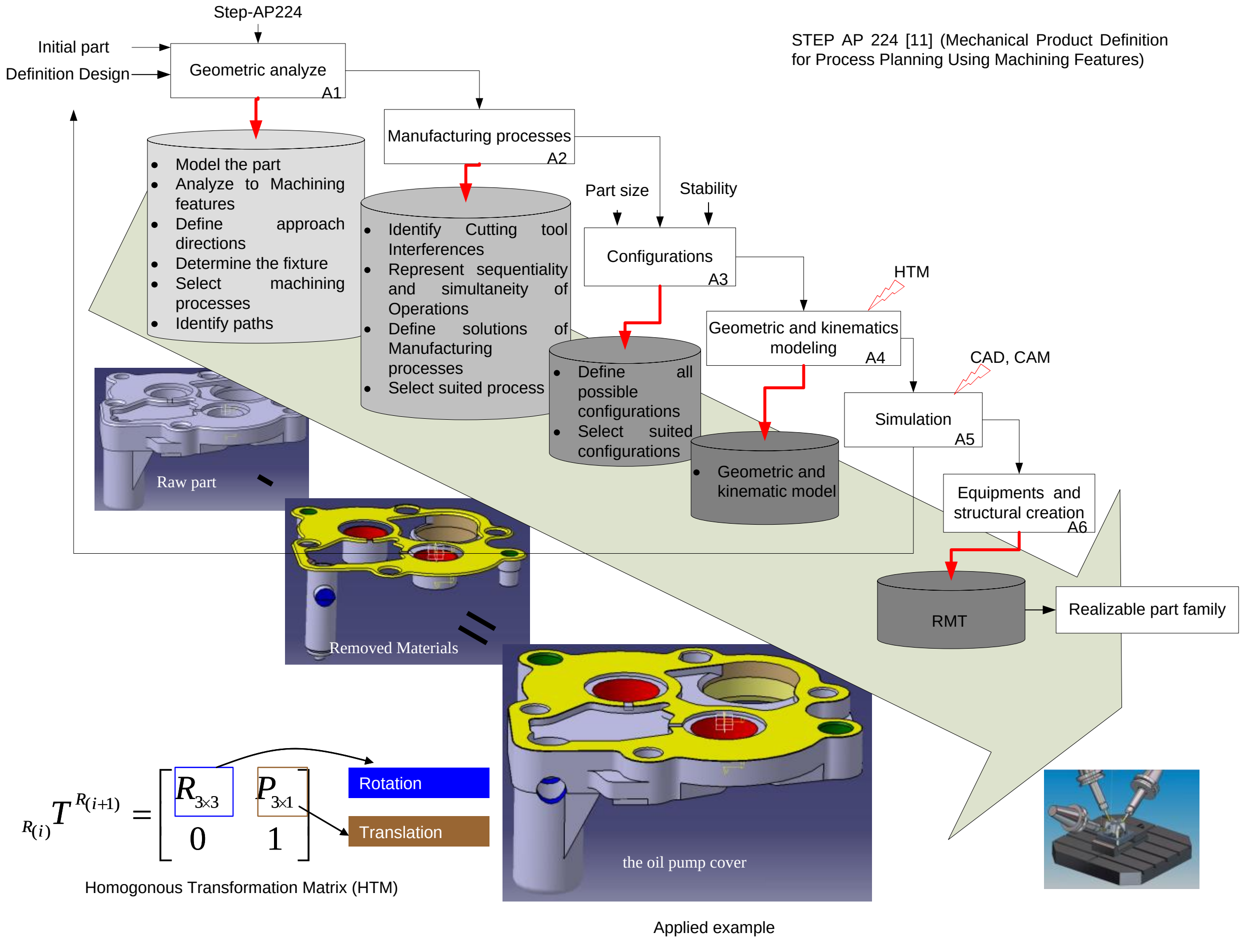


Fig. 1. RMT design methodology

On the other hand, as a result of the increasing attention of multi-spindle machine tool from manufacturing industry, [14,15] introduced prototypes of multi-spindle machining centres. Most researches are focused on the structural configuration synthesis and structure modelling of a one spindle machine tool such as [16-20]. So, it is apparent that previous researches based on the specification of process data and structural configurations concerning one spindle of machining centres. However, the simultaneous machining process using multi-spindle has not been fully treated, in spite of its responding to the mass-customization as well as the multi-spindle RMT design provides a range of benefits in productivity and increase the accuracy by reduce the required degree of freedom.

This research is to present a methodology of RMT design that is focused on a simultaneous machining process using multi-spindle in a single machine. We apply Homogonous Transformation Matrix (HTM) as a means to model the structure of a multi-spindle RMT by tacking into account that, we treat only the prismatic machining and just one positioning for the part to be machine.

To illustrate our methodology, we present the oil pump cover (Fig. 1) as the applied example. This part is produced at 6000 units per month. Actually, this part is machined by four axe machine tool with machining time is more than 1.5 minutes.

2. METHODOLOGY OF RECONFIGURABLE MACHINE TOOL DESIGN

We introduce a methodology based on the concept of manufacturing features that already used in the generation of the manufacturing process. The methodology process presents all activities enabling to pass from machining features of the part to be machined (Fig. 1.A1) to the structural creation of RMT (Fig. 1.A6) forming the desired objective of the method. Moreover, it presents all architectural manufacturing solutions and structural configurations enabling to realize the machining task related to the part. Our methodology articulated about following key points begins with A1 and finishing by A6 (Fig. 1):

- Present and analyze the part to be machined (A1);
- Specify all manufacturing processes and select the suited solution (A2);
- Specify all possible configurations and select the appropriate configuration (A3);
- Model geometric and kinematic structure of RMT (A4);
- Simulate with CAD, CAM (CATIA, DELMIA) (A5);
- Select modules and create the RMT structure (A6).
- In this article, we represent particularly the first and the second key points of the methodology.

2.1. PRESENTATION AND ANALYSIS OF PART

The geometric analyze activity (A1) is decomposed into three subactivities (Fig. 2) A11 to A13.

The activity A11 able to ensure data related to the geometrical, technological and economical representation of the part to be machined. Where, in order to design the RMT, it is necessary to make out process data concerning the part shape to be machined and its production requirements. Moreover, the RMT design process has to take into account likely changes in part characteristics that may be appeared in the future and which would require to change in the configuration of RMT. We can distinguish three data types related to the part.

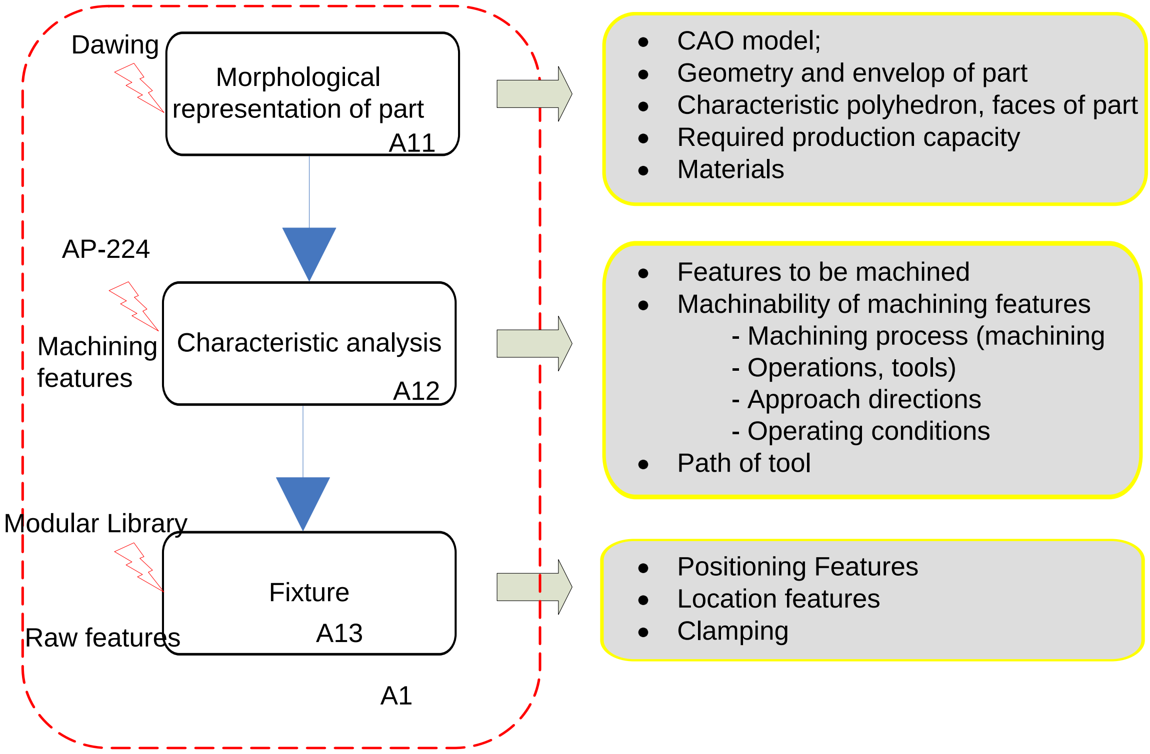


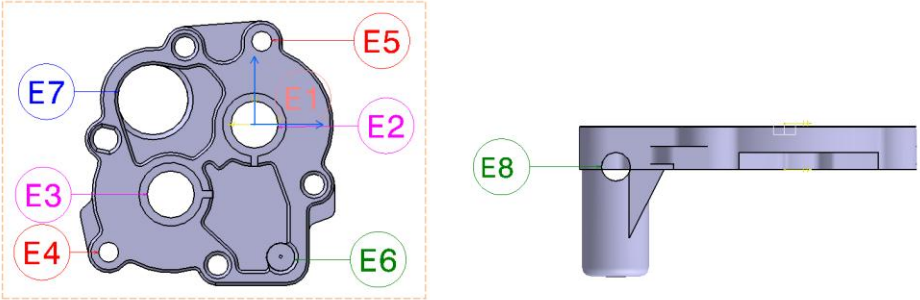
Fig. 2. Subactivities of geometric analysis A1

2.1.1. PRESENTATION OF PART

- Geometrical data of the part, which are defined on the drawing of the part or in a CAD and CAM file: envelop, dimensions, characteristic polyhedron, directions of its faces, dimensional and geometrical tolerances, etc.
- Technological data concerns the features to be machined, machining features classification such as STEP AP224 (hole, plane…), features specifying positioning, location and clamping of the part. Furthermore, tolerances and roughness required to realize the part are defined for each features (machine and positioning). It also deals with the material and the mass of the part.
- Economic and logistic data. These data describes the required production capacity, the production type (mass production, unitary production…), the repetitiveness of the production, the allowed time, the number of daily working hours, the allowed budget

2.1.2. CHARACTERISTIC ANALYSIS

The second activity A12, characteristic analysis of the part, is focused on a set of describing functions associated to the following steps:



E1, E2, E3, E4, E5 ,E6, E7 and E8 Features to be machined

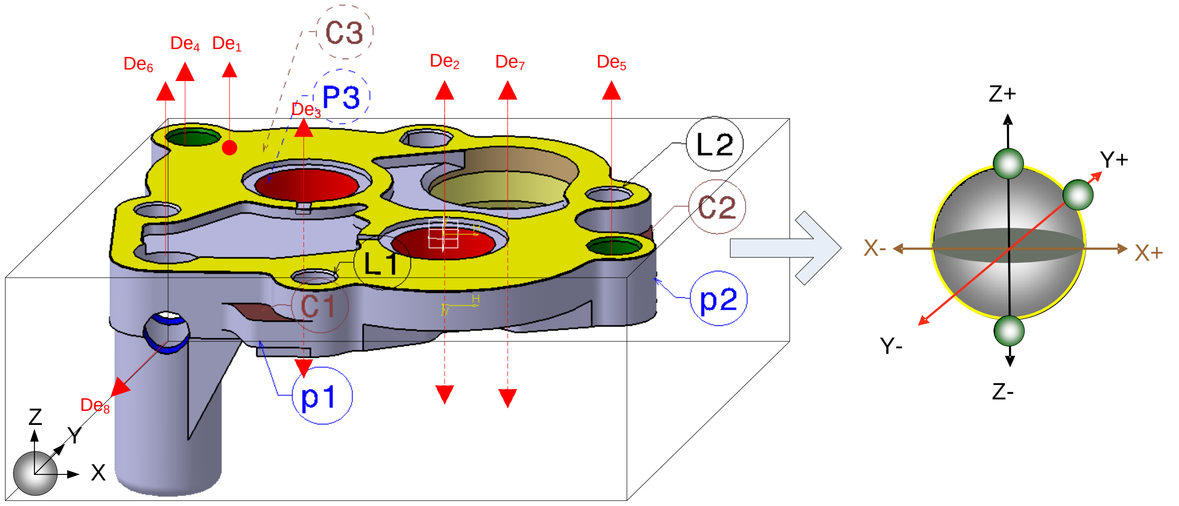
Fig. 3. Features to be machined concerning the oil pump cover

Step 1: geometric identification

In order to specify the manufacturing process, it is necessary to identify the geometric structure of the part to be machined. We introduce the concept of a characteristic polyhedron as means to make out part faces and its directions. In the case of oil pump cover, the polyhedron has six faces expressing all faces directions of the pump cover (Fig. 4).

Step 2: identification of features to be machined

To specify the manufacturing process of the part, it is essential to define the features to be executed that forming the machining task required to realize by the RMT. The part analysis to machining features is performed according to STEP AP-224 [21] (Mechanical Product Definition for Process Planning Using Machining Features) largely presenting a parametric library of machining features (such as boss, chamfer, counterbore-hole, countersink-hole…). The analysis of the oil pump cover presented E1, E2, E3, E4, E5, E6, E7 and E8 as features to be machined (Fig. 3).



P_1, P_2 and P_3 Positioning features
L_1 and L_3 Location Features

C_1, C_2 and C_3 Clamping features
De approach direction of features

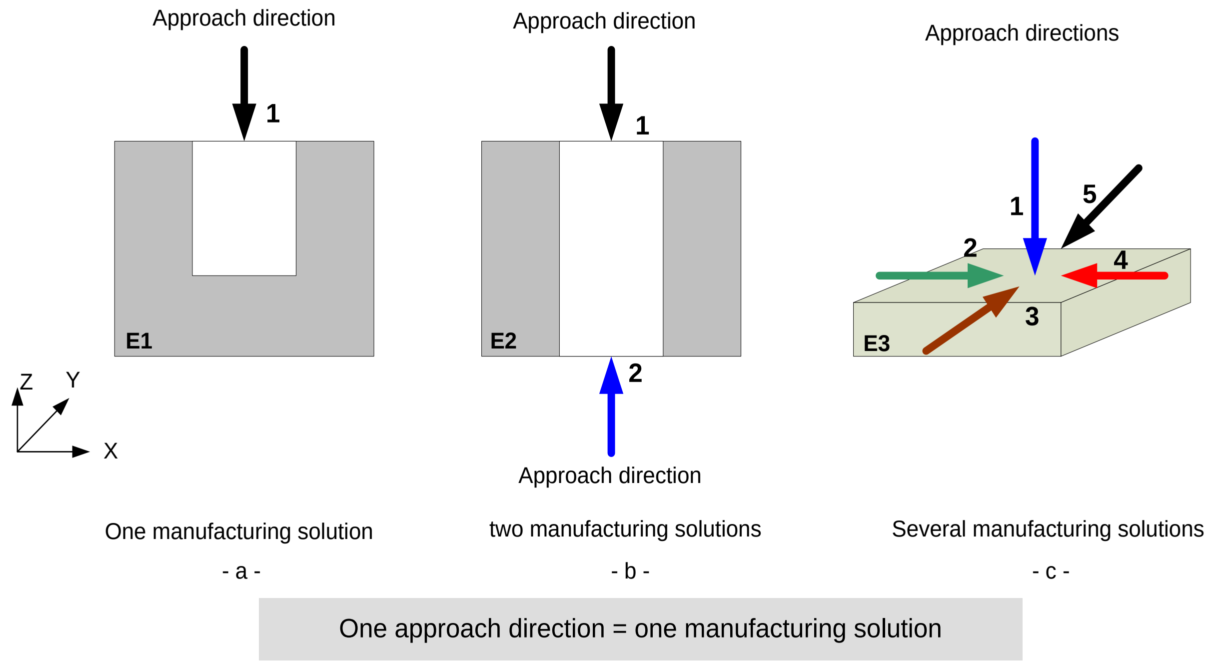
Approach directions required to realize the oil pump cover

Fig. 4. Characteristic polyhedron, positioning, locating and clamping features, approach directions

Where, the machining features have attributes enable to sufficiently describe the morphology, geometric and topologic relations according to technical data present parameters articulating to (a) intrinsic data presenting internal parameters of the feature description such as dimensions, dimensional tolerances, locating, roughness…, and (b) extrinsic data pointing to external parameters of description specifying data between features such as geometrical and topological relations.

Step 3: define the machinability of machining features

The machinability is defined by a set of process data related to the machining process, approach directions and operative conditions of the feature.



One manufacturing solution
- a -

two manufacturing solutions
- b -

Several manufacturing solutions
- c -

Fig. 5. Approach directions of feature types, manufacturing solutions

The machining process consist of define all machining operations having the possibility to realize accurately the feature, its appropriate cutting tool and tool holder. Then the Tool Approach Direction (TAD) is determined for every feature. Where, the TAD determination based on the feature type and the accessibility that is necessary to eliminate the collision between the tool and the part morphology. We specify two feature types according to the approach direction, the first feature with one tool approach direction such as hole (Fig. 5a) with one approach direction, and the other feature with several tool approach directions such as through hole and opening face (Fig. 5b and c).

Moreover, in order to machine the feature it is necessary to specify the cutting tool path required to perform its and the swept volume resulted of tool motions. In other hand, the definition of machinability is complete with set of operative conditions have to specify such as cutting time, cutting force etc.

2.1.3. SPECIFICATION OF POSITIONING AND CLAMPING

Based on the polyhedron, all faces of the part are defined. The select of positioning, locating and clamping faces, has a critical influence on the geometrical structure of RMT, are defined with the activity A13 (Fig. 2).

For the oil pump cover has been included, positioning and clamping faces are specified previously by the designer of the part. Where, the positioning is performed according to three faces P_1, P_2 and P_3 (Fig. 4) circulated homogeneously around the part enabling to eliminate three degrees of freedom. Whereas, the clamping is carry out by three faces C_1, C_2 and C_3 (Fig. 4) are located inversely of positioning faces. Furthermore, the part present as well two holes L_1 and L_2 (Fig. 4) in the interests of defined locating of the part that is essential function to realize the required quality. Thus, three remaining degrees of freedom are eliminated. For more information about process data of machining features, look up our article [2].

2.2. SPECIFICATION OF MANUFACTURING PROCESSES

Based on manufacturing processes, all machining solutions able to realize the part are completely presented. Activities of the manufacturing processes specification are specified with the following steps (Fig. 6):

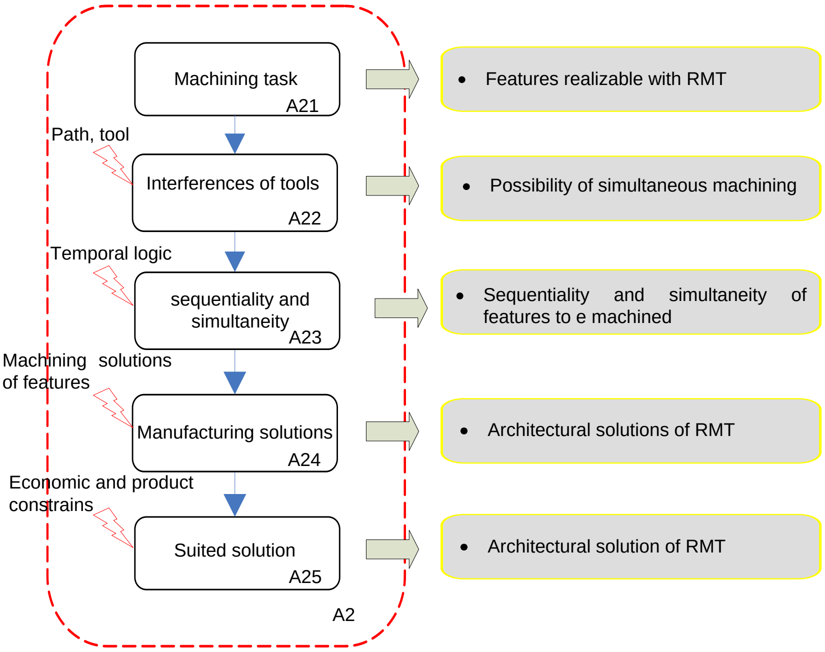


Fig. 6. Subactivities of the manufacturing processes specification

Definition of the machining task (A21)

The activity (A21), specifying the machining task, express all machining features have to be machined by RMT with the aim of realizes the required part, define with the following formalism:

$$Q_m = \bigcup (E_i) \text{ for } i = (1 \rightarrow n) \tag{1}$$

Where, Q_m *and* E_i present the machining task and features to be machined successively. Where, RMT has to realize all features that are constituted in Q_m. It must to verify the next relation:

$$E_1 \wedge E_2 \wedge \cdots \wedge E_i \tag{2}$$

Where, $E_i \wedge E_j$ express features Ei and Ej have to machine in order to perform the required part. Thus, by apply Equ.1 and 2 the machining task Q_m of RMT in order to carry out the oil pump cover is:

$$Q_m = \{E_1 \wedge E_2 \wedge E_3 \wedge E_4 \wedge E_5 \wedge E_6 \wedge E_7 \wedge E_8\} \tag{3}$$

Interferences of cutting tools (A22)

The detection of cutting tools interference concerning multi-spindles RMT is realized using the swept volume approach. The detection of interferences is implemented considering the following four steps:

- Define geometric data of cutting tools;
- Specify trajectories (paths) of tools;
- Simulate the swept volume of tools along the trajectories required to realize the features;
- Detect interferences.

Geometric data of cutting tools and trajectories are specified with the machinability of machining features. The task of generating swept volume based on tool motions. Hence, given the motion at every cutter location, the cutter swept volume is created through extruding or revolving the tool outline along the cutter trajectory. The swept volume of linear motion is accomplished through extruding operation (drilling) while the circular motion is through the revolving operation (milling). Fig. 7 illustrates swept volumes as result of cutting tools motions for realizes the features E_2 and E_3. The simulation of the swept volume can be performed trough 3D modelling software (CATIA…) by storing the cutter swept volume as a feature of the part [22]. The tools interferences are implied by the existence of a common space between the first tool swept volume and other tool swept volume. The static interference detection between tools swept volumes is performed in a manner of the interference analysis (Fig. 7a, b, c), the interference is confirmed in the case a and c of Fig. 7 while in the case c the interference is zero. Thus the machining simultaneity of features is realizable on only the case c of Fig. 7. For our example based on the swept volumes of features to be machined, les interferences are existed in case of (E_6 with E_8) and the case of (E_1 with E_4, E_5, and E_6). Moreover, in case of E_2, E_3 and E_7 are realizable with the access direction (Z-), the interference is confirmed with E_1.

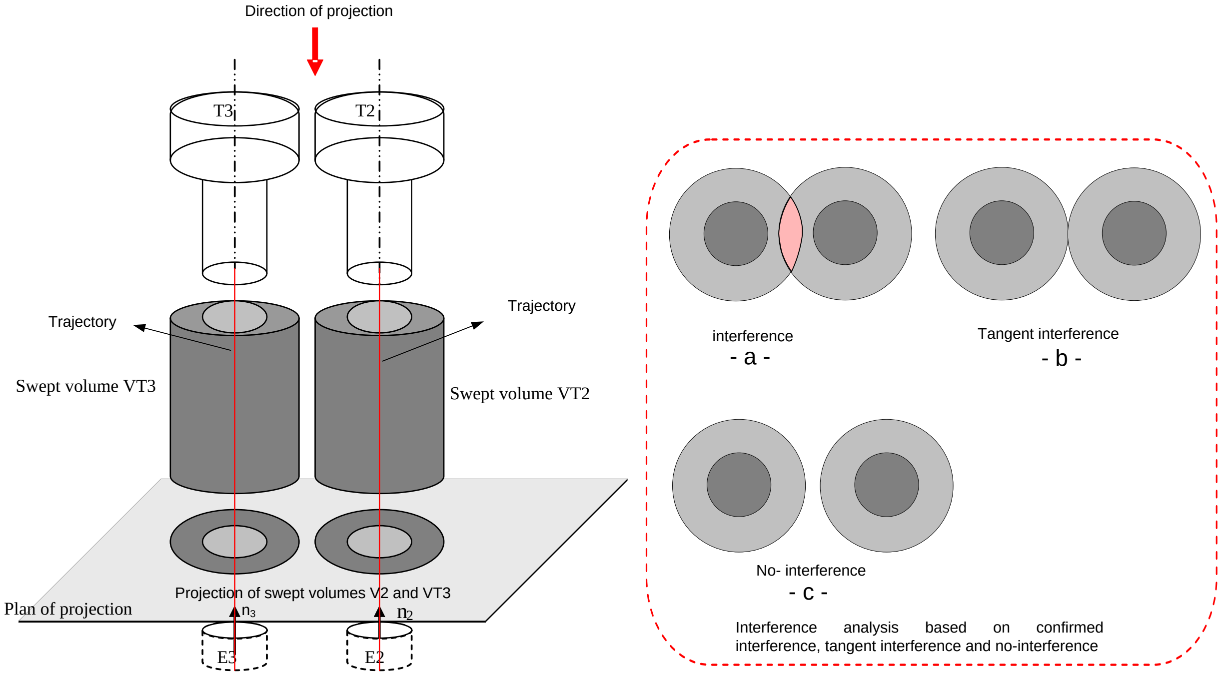


Fig. 7. Swept volume, interferences of cutting tools

Sequentiality and simultaneity of machining features (A23)

To realize features to be machined establishing the machining task of multi-spindle RMT, it is essential to define machining sequences according to a set of geometric, technologic and topologic relations concerning the positioning of the part (in order to wanted quality of the part, we defined only one positioning for our example), and the possibility of the machining simultaneity of features contingent on tool interference specifications.

Where, the manufacturing of features E_i and E_j have two machining solutions, either features E_i and E_j can be produced simultaneously at the same time, or features E_i and E_j are produced sequentially. In order to translate these notions of simultaneity and sequentiallity, we use a mathematical tool based on temporal logic [4].

The first case, if E_i is machined simultaneously with E_j is denoted by:

$$S(E_i \wedge E_j) \tag{4}$$

The second case, If E_i is realized sequentially with E_j is represented by:

$$(E_i \wedge ME_j)\, W\, (E_j \wedge ME_i) \tag{5}$$

Where, (W=or), $E_i \wedge M(E_j)$ present E_i is machined before E_j, whereas $E_j \wedge M(E_i)$ present E_i is machined after E_j. So, the application of the simultaneity and sequentiallty concepts on our example, we can write that:

$$\begin{aligned} &E_1 \wedge M(E_2 \wedge E_3 \wedge E_4 \wedge E_5 \wedge E_6 \wedge E_7) \\ &S(E_1 \wedge E_8) \\ &E_1 \wedge M(E_8) \end{aligned} \qquad (6)$$

Where:

$$(E_i \wedge E_j) = (E_i \wedge ME_j)\, W\, (E_j \wedge ME_i)\, W\, S(E_i \wedge E_j) \qquad (7)$$

For more information of the temporal logic looks up our work [1].

Specification of architectural manufacturing solutions (A24)

The multi spindle RMT consist of a set of independent spindles (F_n) which the n number to be defined. We can write in mathematic method the following expression:

$$RMT = \bigcup_{K=1}^{k=n} (F_n) \ \ for\ k = (1 \to n) \qquad (8)$$

$$\forall E_i \in Q_m,\ E_i\ machinable\ with\ (F_1 \vee F_1 \vee \cdots \vee F_n) \qquad (9)$$

Architectural manufacturing solutions are specified according to the definition of manufacturing solutions of every feature to be machined and regrouping these features.

$$\forall E_i \in Q_m, E_i\ machinable\ with \begin{Bmatrix} F_1 \to first\ solution \to architecture\ 1 \\ W \\ F_2 \to \text{sec}ond\ solution \to architecture\ 2 \\ W \\ \vdots \\ W \\ F_n \to n\ solution \qquad \to architecture\ n \end{Bmatrix}$$

We define manufacturing solutions of the feature with the following rule:

Rule (1):A machining approach direction of a feature = a manufacturing solution of the feature

Based on rule (1), we can identify all manufacturing solutions of features to be machined. Fig. 5 illustrates three types of features (hole, through hole and face). The hole has one too approach direction thus one manufacturing solution corresponding to its approach direction such as drilling. Whereas, the face has five manufacturing solutions as a result of five approach directions of the feature. Where, four solutions are corresponded to the slab ng and one to the face milling.

The regrouping of features is performed according to next rules:

Rule (2): Manufacturing solutions having the same approach direction = a spindle
Rule (3): An approach direction = a spindle

$$
\mathit{manufacturing\ solutions}\left\{\begin{array}{l}
S\begin{bmatrix} F_1(E_1\wedge M(E_2\wedge E_3\wedge E_4\wedge E_5\wedge E_6\wedge E_7)\wedge \\ F_2(E_8) \end{bmatrix} \rightarrow \mathit{first\ architecture} \\
W \\
S\begin{bmatrix} F_1(E_1\wedge M(E_3\wedge E_4\wedge E_5\wedge E_6\wedge E_7)\wedge \\ F_2(E_8)\wedge \\ F_3(E_2) \end{bmatrix} \rightarrow \mathit{second\ architecture} \\
W \\
S\begin{bmatrix} F_1(E_1\wedge M(E_4\wedge E_5\wedge E_6\wedge E_7)\wedge \\ F_2(E_8)\wedge \\ F_3(E_2\wedge E_3) \end{bmatrix} \rightarrow \mathit{third\ architecture} \\
W \\
S\begin{bmatrix} F_1(E_1\wedge M(E_4\wedge E_5\wedge E_6)\wedge \\ F_2(E_8)\wedge \\ F_3(E_2\wedge E_3\wedge E_7) \end{bmatrix} \rightarrow \mathit{fourth\ architecture} \\
W \\
S\begin{bmatrix} F_1(E_1\wedge M(E_2\wedge E_4\wedge E_5\wedge E_6\wedge E_7)\wedge \\ F_2(E_8)\wedge \\ F_3(E_3) \end{bmatrix} \rightarrow \mathit{fifth\ architecture} \\
W \\
S\begin{bmatrix} F_1(E_1\wedge M(E_2\wedge E_3\wedge E_4\wedge E_5\wedge E_6)\wedge \\ F_2(E_8)\wedge \\ F_3(E_7) \end{bmatrix} \rightarrow \mathit{sixth\ architecture} \\
W \\
S\begin{bmatrix} F_1(E_1\wedge M(E_3\wedge E_4\wedge E_5\wedge E_6)\wedge \\ F_2(E_8)\wedge \\ F_3(E_2\wedge E_7) \end{bmatrix} \rightarrow \mathit{seventh\ architecture} \\
W \\
S\begin{bmatrix} F_1(E_1\wedge M(E_2\wedge E_4\wedge E_5\wedge E_6)\wedge \\ F_2(E_8)\wedge \\ F_3(E_3\wedge E_7) \end{bmatrix} \rightarrow \mathit{eighth\ architecture}
\end{array}\right\}
$$

So, from rules (2 and 3), the possibility of features regrouping and the number of spindles are defined successively. Based on approach directions of each feature to be machined, that are defined with the characteristic polyhedron (Fig. 4), and by taking into account the rule 1, Table 1 present manufacturing solutions of each feature to be machined of the pump cover according to directions of the characteristic polyhedron.

Table 1. Types, machining process, manufacturing possibility of features to be machined of the oil pump cover

Features	Type	Machining process	X-	X+	Y-	Y+	Z-	Z+
E1	Face	finish milling	0	0	0	0	1	0
E2	Hole	rough and finish reaming	0	0	0	0	1	1
E3	Hole	rough and finish reaming	0	0	0	0	1	1
E4	Hole	finish reaming	0	0	0	0	1	0
E5	Hole	finish reaming	0	0	0	0	1	0
E6	Hole	finish reaming	0	0	0	0	1	0
E7	Hole	finish reaming	0	0	0	0	1	1
E8	Hole	finish reaming	0	0	0	1	0	0

In relation to data of tab. 1and with take into account the rules 2 and 3, we can specify eight architectural manufacturing solutions of RMT, reply to realize the oil pump cover, are represented in the following expression:

Selection of the suited architecture manufacturing solution (A25)

The selection of the architecture manufacturing solution of RMT is performed by systematic method is supported by a set of characters articulate to economic and product constraints.

- Product constraints is defined with:
  - the required production of the part that is defined by the company or by the customer corresponding to the required marketing;
  - the number of parts realize by each solution in time.
- Economic constraints are supported on the reduction of the RMT spindle number having a response to carry out of the part. Thus, the reduction of RMT cost.

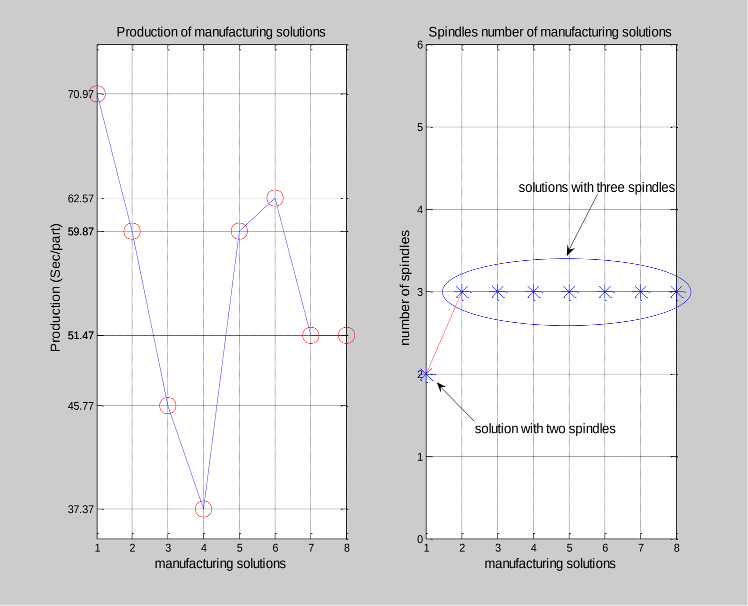


Fig. 8. Production and spindles number of architectural manufacturing solutions of RMT concerning the oil pump cover

The following diagram present the time required to machine the oil pump cover and the spindles number concerning each manufacturing solutions.

From the diagram (Fig. 8) we note that in terms of the production, the fourth solution has the advantage with reference to the time required to realize the part is 37.37 (sec/part),

Whereas the first solution is the weakness with the required time is 70.97 (sec/part).

On other hand, in terms of the spindles number, we note that just the first solution has two spindles, while the other solutions have three spindles. Thus, solutions 2, 3, 4, 5, 6, 7 and 8 are corresponded in terms of the number of spindles (tree spindles) so these solutions have identical economic parameters. Whereas, the fourth solution has the advantage in terms of the production. On the other hand, the first solution has the advantage in terms of the number of spindles (two spindles) but in terms of the productions is the weakness.

Consequently, the decision of selection between the first and the fourth solutions is defined by the customer in line with its economic and product requirements satisfying the actual and the future goals of its company.

3. CONCLUSION

In this paper, we introduced a method concerning the design of RMT that is focused on a simultaneous machining process using multi-spindles RMT. Our method based on the concept of machining features, the process data retrieved as a starting point in identifying various functions necessary to carry out a given part family are displayed. Moreover, architectural structure of RMT is defined as a result of the specification of all manufacturing processes of features to be machined. We presented the all possible architectural manufacturing solutions of RMT and the selection criterions of the suited solution satisfying the mass-customization production.

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