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Method of determining the process applied for feature machining: experimental validation of a slot

Patrick Martin · Alain D’Acunto

Abstract In this paper, we evaluate the “manufacturability” levels for several machining processes of “slot” feature. Using the STEP standard, we identify the slot feature characteristics and then, using the ascendant generation of process method, we define the associated milling process. The expertise is based on a methodology relative to the experience plans carried out during the formalization and systematic evaluation of the machining process associated with the feature.

Keywords Process planning · Machining · Slot · Cutting conditions · Taguchi method

1 Introduction

In general, the machining process illustrates a method of manufacturing a mechanical part by defining the processes, procedures, and the means applied (tooling, machines, assembly), as well as the sequence of operations that takes into consideration the economical and technological factors. The design of process planning can be therefore defined at two levels (i) type of industry (automotive, aerospace, suppliers..) and (ii) professional. At a “type of industry” level, the procedure consists of processing the process plan according to the activity sector. At this stage, this approach leads to the definition of a skeleton plan or type based on the machining features composed of successive phases (processes and machines) and sub-phases (set-up). This level of decomposition provides access to characteristics which are sufficiently explicit (parts, part family, phases, machines, assembly, series, batches) that enables management and organization of production (alternative to the process).

The “professional” level provides a greater degree of detail. Based on machining features (e.g. hole or bore, pocket, slot), the process plan defines a list of machining operations, the choice of tools and parameters, cutting conditions for each of the sub-phases and the machining assembly. At this stage, the operator defines the characteristics of the part and its features (machining, blank part, set-up and clamping, etc). An understanding of the processes and resources (tools, tooling, and machine) in terms of operating constrains is essential for determining valid technical and economical solutions.

For each level, the dominant strategies are expressed in the form of constraints in order to define the production means or simulate and optimise the manufacturing process. In the “type of industry” approach, the optimisation methods are based on the propagation of constraints or the alternative choice (various technologies). As for the “professional” approach, the tools and methods provide a management compromise with preferences and alternatives (creation and destruction of operations, use of resources) based on rules and experience. Therefore the operator adjusts variable data during the process planning creation phase, which is sometimes incomplete with regard to time, space, and form (i.e. modification of part geometry, quantities, or resources).

In this context, it is essential to provide pertinent data relative to the “manufacturability” of a part in a coherent format to ensure that the process generation activity may be incorporated into the engineering process. Our work is carried out at the “professional” level for which we propose formalization procedures for sequence generation know-how and machining processes in order to evaluate the “manu-

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facturability" in an explicit way by providing alternative processes.

In this paper, we evaluate the "manufacturability" levels during the machining process of creating a "slot" feature. Using the STEP standard, we identify the slot feature characteristics and then, using the ascendant generation of process method [1], we define the associated milling process. The expertise is based on a methodology relative to the experience plans carried out during the formalization and systematic evaluation of the machining process associated with the feature.

2 Part and process modeling

2.1 Modelling per feature

The part machined is modelled by using feature, feature concept is commonly used is CAD software with only geometrical information, for process planning technical information are needed. The machining feature is defined as a geometric form with a set of specifications for which a machining process is known. This process is practically independent of the processes of other features [2–4]. The feature concept enables semantic expression of all characteristics used to describe an object that depends on the specific point of view and activity required (design or manufacture for example). Modelling per feature provides, at the design phase, all information required for manufacture based on the defined functional constraints. Furthermore, this modelling contributes towards formulizing the expertise and capitalizing the knowledge.

2.2 Ascendant generation machining process

The machining process generation is a method that uses the knowledge available and it is based on the feature machining concept that may be either ascending or descending. The advantages offered by the ascendant method are as follows:

- Extreme flexibility enabling diversification of parts on small production runs;
- Independence of the user system and the production environment;
- Compactness and flexibility of sequences and features;
- Reliability and precision of results.

The ascendant approach is applied to hole and slot [1] features using a "calling-card sequence" (CCS). This modelling method requires the know-how of an expert in order to carry out automation of the machining range. The properties of this approach are as follows:

> All intermediary states between the blank state and the finished state of a machining feature result from application of a sequence.
>
> The values of attributes of an intermediate state result from the sequence which generates it and the attributes of the states immediately before it (in the normal order from blank to finish).

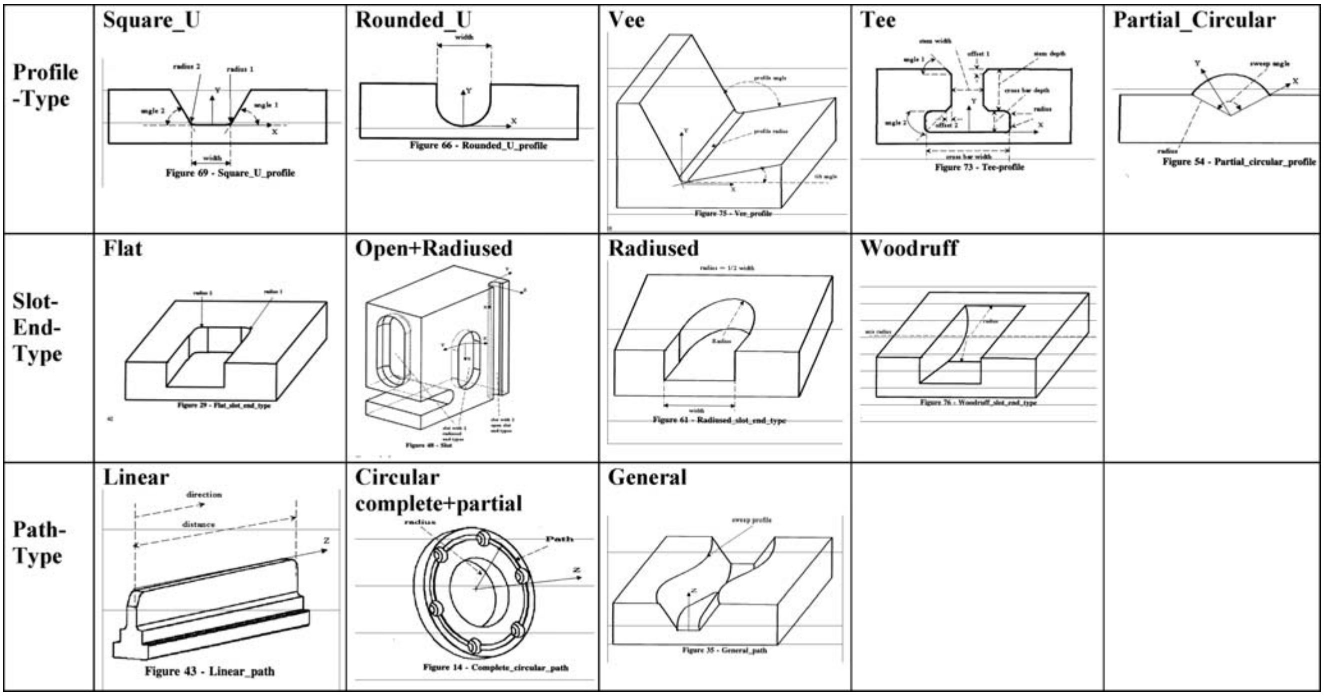
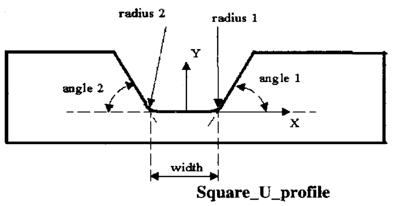


Fig. 1 STEP (STEP AP214) slot definition

Fig. 2 Topological and geometrical definition of the feature “slot - square-U profile”

ID	*Rep. item*	**Name**
1	**Edge**	**Edge external surface – plane surface side1**
2	**Face**	**Plane surface side1**
3	**Face**	**Cylindrical surface 1**
4	**Edge**	**Edge plane surface side1 – plane surface bottom**
5	**Face**	**Plane surface bottom**
6	**Face**	**Face median**
7	**Face**	**Cylindrical surface 2**
8	**Edge**	**Edge plane surface bottom – plane surface side2**
9	**Face**	**Plane surface side2**
10	**Edge**	**Edge plane surface side2 – external surface**



All intermediary states between the blank state and the finished state of a machining feature are also machining features.

This ascendant generation process is used to compare and evaluate the slot machining process.

3 Description of the feature tested

3.1 Slot

We adapt the geometric model proposed by STEP [5] for the slot which renders the geometric formalization easier. According to STEP, the slot is defined as follows (Fig. 1):

- Profile type (U, V, T, circular, ...);
- Path, circuit within the slot (linear, circular, ...);
- End type (flat, open, fanning...).

This purely geometric information is used to introduce technological constraints and dimensions. The associated topological attributes (sides, edges,....) are provided for each geometrically defined profile. These representations are referred to as “Representation_items”.

Figure 2 represents an example of the topological modelling of a slot of the type Square-U-profile. In practice,

Fig. 3 Drawing of the machined part

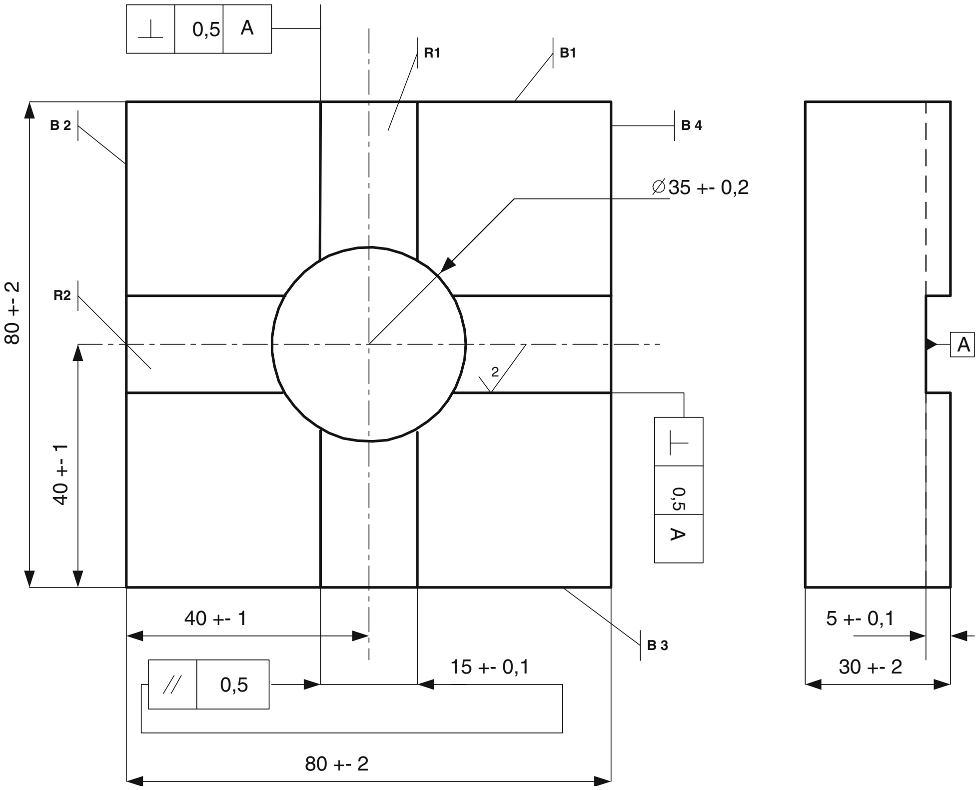


Table 1 Geometric and topological data on the test part

Item	Feature	Access direction	Geometric relations	Topological relations
B1, B2, B3, B4, B5, B6	Rough surfaces	/		
T1	Open bore ∅35±2, L =30 mm	Z-		Begin at B6, End at B5
R1, R2	Slot L=80, l=15, h=5, Ra=2 µm	Z−X+, X−,Y−, Y+	⊥ 0.5 A // 0.5	Begin at B1/B2 End at B3/B4 Cross T1

numbering takes place from left to right and starts at the edge of the intersection between the outer surface of the part and the left vertical surface. There are three types of requirements for machined parts:

- Dimensional tolerance limits (adjustment);
- Geometric tolerance limits (form, orientation, position, overlap);
- Technological tolerance limits (surface).

The constraints may be classified according to the topological aspects of representation features. In our application, we only take into account of the characteristics and defects of the slot feature.

3.2 Description of the test part

In this study we focus on the slot in a part containing a hole and two slots while excluding all external topological relationships (Fig. 3). The geometric and topological data (Table 1) are defined to enable selection of the best available adapted processes.

4 Experimental procedure

4.1 Robust experimental plan

Our test procedure is based on the experimental plan (Taguchi method) [6–8]. These techniques enable definition of the nominal and *extreme*. The advantage of this method is the capacity of progressive acquisition of results, the choice of factors to be studied, as well as analysis of results. To facilitate interpretation and exploitation, we have chosen to present the results in the form of a matrix. The theoretical responses are noted $\widetilde{Y}$, the factors are represented by vectors which are noted [A] [B], [C]. The authors of this notation propose calling this vector a level indicator. The general form of this notation is:

$$\widetilde{Y} = M + [E_{A1} \quad E_{A2}][A] + [E_{B1} \quad E_{B2} \quad E_{B3}][B] + [E_{C1} \quad E_{C2}][C] + \ldots$$

$$\ldots +^{t}[A]\begin{bmatrix} I_{A1B1} & I_{A1B2} & I_{A1B3} \\ I_{A2B1} & I_{A2B2} & I_{A2B3} \end{bmatrix}[B] +^{t}[A]\begin{bmatrix} I_{A1C1} & I_{A1C2} \\ I_{A2C1} & I_{A2C2} \end{bmatrix}[C] +^{t}[B]\begin{bmatrix} I_{B1C1} & I_{B1C2} \\ I_{B2C1} & I_{B2C2} \\ I_{B3C1} & I_{B3C2} \end{bmatrix}[C]$$

Whereby ${}^{t}[A]$ is the transposed vector, and M is the general average and [I] interaction matrix.

The reliability of the test plan is defined by the “signal/noise (S/N)” function. Analysis of the influence of the factors studied and the estimation of the test error margin provides a significant evaluation of the measurement precision of each effect.

4.2 Choice of factors and responses

The parameters used in planning the tests are defined by the input data as well as the action and evaluation parameters. In summary, the data is composed of the test part, geometric conditions, the blank state, the machines used, the tools and tool holders. The action parameters are then expressed according to the cutting conditions relative to the “Tool/Material” pair, as well as the machining modes and procedures. Finally, the evaluation parameters apply to the part (surface, geometry, respect of conditions and external relations, etc), the techniques and technologies (forces, wear, power, chip state, burr, vibrations during machining, etc) and economic aspects (time, cost) (Table 2).

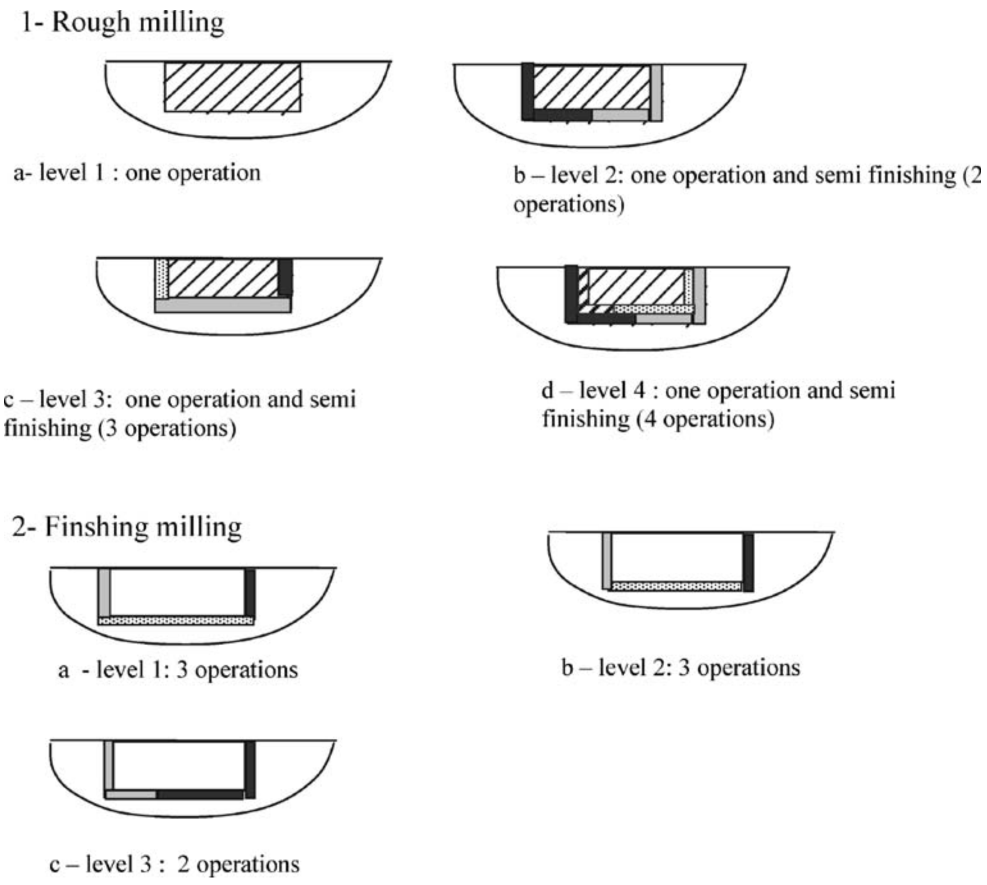
The responses attained are primarily nominal and qualitative, which accounts for the high factor level number. To simplify our approach, the three factors examined are:

- Material (factor A);
- Rough milling strategy (factor B);
- Finished milling strategy (factor C).

Table 2 List of factors and responses

PARAMETERS		RESPONSES		
Factors checked	Noise	Nominal	Extremum	Qualitative
Blank and finishing strategy	Tool wear	Ra (roughness of sides and bottom of slot)	Min. cost	Burr
Vc, fz, ap, ar	Temperature	Parallelism (geometry)		State of chips
Tool geometry	Vibration	Perpendicularity (geometry)		Integrity of surface
Chip rate		Slot dimensions		

Fig. 4 Rough and finishing methods respecting the ascendant generation groove machining principle (blank: 4 levels, finishing: 3 levels)



As for the influence of materials, we selected the following alloys: XC38, 42CD4 and Z30C13. We limited our test to four rough and three finishes milling strategies. The proposals relative to the ascendant slot machining process (Fig. 4) are defined to minimize the number of operations and the tooling cost.

For rough milling the four strategies are:

1 Slot made with one tool in a single operation;
2 One rough operation then two semi finishing operations with a tool for which the diameter is lower that the slot width;
3 One rough operation then three semi finishing operations, two with a tool for which the diameter is lower that the slot width for the sides and one with a tool for which the diameter is equal to the slot width for the bottom;

Table 3 Orthogonality table

Orthogonality condition			
A (3 levels)	+		
B (4 levels)	3*4=12	+	
C (3 levels)	3*3=9	3*4=12	+
	A (3)	B (4)	C (3)

Table 4 Non-standard plan comprising 18 tests

Exp nº	A	B	C
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	2	2	1
8	2	2	2
9	2	2	3
10	2	3	1
11	2	3	2
12	2	3	3
13	3	3	1
14	3	3	2
15	3	3	3
16	3	4	1
17	3	4	2
18	3	4	3

- factor A: material : three levels;
- factor B Rough milling strategy four levels
- factor C: Finished milling three levels

Table 5 Test results chart

Test	Height (mm)		Width (mm)		Parallelism		Perpendicularity				Burrs	Roughness	
	R1	R2	R1	R2	R1	R2	R1 2/4	R2 2/4	R1 2/3	R2 2/3	(1,2,3)	Ra fd	Ra fn
1	5.618	5.623	14.973	14.978	1.430	1.349	0.835	0.608	0.583	0.721	1	0.96	0.75
2	5.498	5.503	14.966	14.970	1.699	1.329	1.075	0.012	0.435	1.281	1	1.03	0.93
3	5.702	5.701	14.888	14.888	3.382	2.344	2.463	0.287	0.585	2.025	1	1.82	1.59
4	5.662	5.664	14.949	14.933	1.880	1.904	0.797	0.897	0.898	0.981	1	1.7	1.56
5	5.593	5.598	14.940	14.949	1.100	2.096	0.996	0.770	0.093	1.316	3	1.69	1.21
6	5.666	5.675	14.871	14.876	3.215	2.273	1.552	0.591	1.346	1.651	2	1.89	1.65
7	5.500	5.505	14.940	14.923	2.752	3.566	1.182	0.847	1.300	1.671	2	1.15	1.38
8	5.367	5.360	14.937	14.900	2.904	4.964	1.037	2.271	1.582	2.628	3	1.3	1.43
9	5.818	5.822	14.824	14.823	3.551	1.084	2.320	0.385	0.882	1.454	2	3.98	1.92
10	5.616	5.619	14.941	14.934	1.074	4.002	0.893	2.501	1.860	1.448	3	4.24	2.22
11	5.679	5.679	14.960	14.926	5.642	5.040	2.953	1.763	2.136	3.210	2	3.77	2.07
12	5.704	5.702	14.776	14.823	6.140	3.921	3.447	0.679	2.092	3.189	3	4.38	2.09
13	5.748	5.747	14.953	14.938	2.599	3.886	1.182	2.141	1.161	1.694	3	3.44	2.15
14	5.780	5.786	14.937	14.941	4.328	4.589	1.834	1.143	2.304	3.127	4	3.96	1.9
15	5.771	5.778	14.816	14.831	4.065	2.862	2.381	0.277	1.284	3.098	4	4.27	2.97
16	5.747	5.750	14.931	14.929	2.824	3.356	0.729	2.025	1.817	1.286	2	3.77	2.5
17	5.645	5.654	14.859	14.893	5.546	4.364	2.525	0.753	2.478	3.552	5	3.53	2.45
18	5.772	5.778	14.714	14.766	6.219	1.370	4.169	0.001	1.441	1.350	3	3.78	2.86

4 One rough operation then two semi finishing operations with a tool for which the diameter is lower that the slot width and then two more semi finishing operation.

For finished milling the four strategies are:

1 Three finishing operations, two with a tool for which the diameter is lower that the slot width for the sides and then for the whole bottom with a tool for which the diameter is equal to the slot width;
2 Three finishing operations, two with a tool for which the diameter is lower that the slot width for the whole sides and one for the bottom with a tool for which the diameter is lower to the slot width;
3 Two semi finishing operations with a tool for which the diameter is lower that the slot width and which realise the side and a part of the bottom.

4.3 Test planning conditions and constraints

The test conditions are defined in order to minimise configuration changes. Furthermore, we respect the orthogonality conditions and minimum number of tests in the compiled fractioning plan.

The orthogonality condition is written as follows in Table 3.

The lowest common denominator (LCD) is 12 (3*4). According to the model, the conditions concerning the degree of freedom are written as follows:

$$\begin{aligned}\widetilde{Y} = M &+ [\,E_{A1} \quad E_{A2} \quad E_{A3}\,][A] \\ &+ [\,E_{B1} \quad E_{B2} \quad E_{B3} \quad E_{B4}\,][B] + [\,E_{C1} \quad E_{C2} \quad E_{C3}\,][C]\end{aligned}$$

The levels are 3, 4, 3 and C, respectively, for A, B, and C.

Table 6 Response Model

For the height:	For the width:
a: The response model	
$\begin{aligned}\widetilde{Y} = 5,66 &+ [\,-0,04 \quad -0,05 \quad -0,08\,][A] \\ &+ [\,-0,05 \quad -0,06 \quad 0,06 \quad 0,06\,][B] \\ &+ [\,-0,01 \quad -0,07 \quad -0,08\,][C]\end{aligned}$	$\begin{aligned}\widetilde{Y} = 14,9 &+ [\,-0,03 \quad -0,01 \quad 0,02\,][A] \\ &+ [\,-0,04 \quad -0,01 \quad 0 \quad 0,05\,][B] \\ &+ [\,-0,04 \quad -0,03 \quad 0,08\,][C]\end{aligned}$
b: Response of the system to noise after optimisation:	
$\begin{aligned}\widetilde{Y} = 67,95 &+ [\,-1,13 \quad 3,91 \quad 2,78\,][A] \\ &+ [\,-0,51 \quad -3,30 \quad 5,76 \quad -4,41\,][B] \\ &+ [\,2,33 \quad 0,22 \quad 2,11\,][C]\end{aligned}$	$\begin{aligned}\widetilde{Y} = 67,89 &+ [\,6,13 \quad -3,23 \quad -2,89\,][A] \\ &+ [\,12,91 \quad 0,66 \quad -4,91 \quad -4,41\,][B] \\ &+ [\,0,76 \quad -4,49 \quad 3,73\,][C]\end{aligned}$

Table 7 Adjusted tolerance limits

	A	B	C
a			
For the height	2	2	2
For the width	3	4	3
b			
For the height	2	3	1
For the width	1	1	3

The degree of liberty condition imposes a minimum of 8 (1+2+3+2) tests.

The test plan must therefore comprise at least 12 tests which satisfies both criteria. However, the fractioning plan we intended to carry out does not exist as a standard Taguchi plan. We therefore compiled a non-standard plan corresponding to our expectation. The test plan comprises 18 tests (Table 4). Consequently, there are sufficient tests (greater than 12) to carry out this plan.

4.4 Machining and inspection procedures

The tests are carried out on an FH45 machining centre (max power: 11 kW, max. spindle speed: 6,000 rpm). A carbide-tipped drill bit was used for drilling (reference: SANDVIK R416.2-0350 L40-31), for rough and finish milling, and a two-size, four-tooth milling head with a diameter of 10 mm (reference: Leclerc ELCO ϕ 10 CNC 54 36/C) is used under cutting conditions adapted to the different types of machined steel (XC38, 42CD4, Z30C13).

Dimensional, parallelism and perpendicularity measurements are carried out using a specific programme on the WENZEL LH87 3D measuring machine. Roughness measurements are carried out with a TAYLOR-HOBSON Surtonic 3+ roughness tester with associated data processing software.

5 Study of experimental results

The table of responses is given by Table 5.

5.1 Slot dimensions (height and width)

As shown in Table 5, the average height value is 5.66 mm. The difference between the required values and the true values may be due to incorrect adjustment of the measuring instruments. Furthermore, when machining stainless steel (tests 1 to 6), high level forces are applied. A difference of 13% can be observed.

Table 8 Adjusted tolerance limits

	A	B	C
a			
Parallelism	1	1	1
b			
Parallelism	1	1	2

Table 9 Adjusted factor levels of the signal/noise ratio

	A	B	C
a			
Perpendicularity	1	1	1
B			
Perpendicularity	2	4	1

In the same way as the height measurements, the two slots are practically identical. We attained an average value of 14.89 mm, which is outside the imposed tolerance limit of 15 (+ 0.1) mm. None of the parts meet this tolerance limit. It can be concluded bearing in mind the tool radius reading error.

The response model is as follows (Table 6): $\widetilde{Y} = M + A + B + C$.

In the case of 3D measuring instruments, the response error is $\Delta\widetilde{Y} = 4\mu\text{m}$. We may therefore deduct that the effects are significant as the subsequent ratio is low, i.e. $\Delta E = 0.004/\sqrt{18} = 0.0009$ and $E > 10 \times \Delta E$ for 18 tests.

Confirmation of these trends by repeating the tests has enabled optimisation of the response model. In order to come as close as possible to the geometric tolerance limits, the level of these factors must be adjusted as shown in Table 7 section “a”.

Optimisation of the system response model to noise is defined by determining the maximum signal/noise (S/N) ratio. These factor levels must be adjusted as shown Table 7, in section “b”.

5.2 Parallelism

The parallelism was measured between two sides. The results obtained are slightly higher or even under the tolerance limit (0.22 and 0.19 mm). This discrepancy may be explained by flexion of the tool on which forces are applied in different ways between rough and finished parts.

The response model is as follows: $\widetilde{Y} = M + A + B + C$

$$\begin{aligned}\widetilde{Y} = 0,21 &+ [-0,08 \quad 0,12 \quad -0,04][A] \\ &+ [-0,07 \quad -0,02 \quad 0,01 \quad 0][B] \\ &+ [-0,03 \quad 0,11 \quad -0,08][C]\end{aligned}$$

Table 10 Adjusted factor levels

	A	B	C
Burr	1	1	1

Table 11 Response model

At the bottom of the slot:	On the sides :
a: The response model	
$\widetilde{Y}=2,81+[-1,3 \quad 0,32 \quad 0,98][A]$ $+[-1,54 \quad -0,86 \quad 1,2 \quad 0,88][B]$ $+[-0,27 \quad -0,27 \quad -0,54][C]$	$\widetilde{Y}=1,87+[-0,59 \quad -0,02 \quad 0,6][A]$ $+[-0,78 \quad -0,01 \quad 0,36 \quad 0,74][B]$ $+[-0,11 \quad -0,2 \quad 0,31][C]$
b: Response of the system to noise after optimisation	
$\widetilde{Y}=22,25+[-1,9 \quad 1,75 \quad 0,15][A]$ $+[-7,74 \quad 3,78 \quad -0,72 \quad 1,63][B]$ $+[-1,34 \quad 0,18 \quad 1,17][C]$	$\widetilde{Y}=22,94+[0,44 \quad 0,84 \quad -1,27][A]$ $+[-1,85 \quad 1,7 \quad -0,58 \quad -0,4][B]$ $+[-1,97 \quad -1,17 \quad 3,14][C]$

The system response to noise is:

$$
\begin{aligned}
\widetilde{Y}=2,46&+[6,96 \quad -0,74 \quad -6,22][A]\\
&+[13,51 \quad -0,08 \quad -3,13 \quad -7,09][B]\\
&+[-0,38 \quad 1,19 \quad -0,81][C]
\end{aligned}
$$

The error does not exceed ΔE=0.0009 and $E > 10 \times \Delta E$ for the 18 tests. Consequently, we can conclude that the effects are significant.

In order to be between the parallelism tolerance limits, the level of these factors must be adjusted following Table 8, section “a”.

Optimisation of the system response model to noise is defined by determining the maximum signal/noise (S/N). These factor levels must be adjusted following Table 8, section “b”.

5.3 Perpendicularity

We noted that the tolerance limits were not satisfied. Indeed, measurements on all parts provided an average value of 1.53 mm, whereas a value of 0.5 mm is specified. This is not particularly surprising considering the results noted on the parallelism test. These discrepancies are generally due to the surface quality of reference A.

The response model is as follows: $\widetilde{Y}=M+A+B+C$

$$
\begin{aligned}
\widetilde{Y}=1,53&+[-0,58 \quad 0,29 \quad 0,29][A]\\
&+[-0,62 \quad -0,3 \quad 0,46 \quad 0,31][B]\\
&+[-0,28 \quad 0,19 \quad -0,09][C]
\end{aligned}
$$

The system response to noise is:

$$
\begin{aligned}
\widetilde{Y}=14,41&+[-0,03 \quad 0,47 \quad -0,44][A]\\
&+[-0,23 \quad 0,01 \quad -0,34 \quad 0,89][B]\\
&+[7,19 \quad -5,35 \quad -1,84][C]
\end{aligned}
$$

Similar to the aforementioned responses, the error does not exceed ΔE=0.0009 and $E > 10 \times \Delta E$ for 18 tests and we may therefore deduct that the effects are significant.

In order to be between the perpendicularity tolerance limits, the level of these factors must also be adjusted as well as the factor levels of the signal/noise ratio, which defines the optimisation of the system response model to noise. These factor adjustments are shown in Table 9, in sections a and b, respectively.

5.4 Burr

A point system is used to evaluate burr level where the points range from 0 to 5; with 5 representing the worst case. Since the grading system takes into account the general aspect of the part, it is not possible to have several evaluations for the same part and it is therefore impossible to calculate variations, i.e. evaluate the signal/noise ratio.

For the parts themselves, we noted that the burr level is directly related to the material machined. Therefore, the material with the lowest level of burrs is stainless steel.

The response model is as follows: $\widetilde{Y}=M+A+B+C$

$$
\begin{aligned}
\widetilde{Y}=2,5&+[-1 \quad 0 \quad 1][A]\\
&+[-1,5 \quad -0,33 \quad 0,67 \quad 0,83][B]\\
&+[-0,5 \quad 0,5 \quad 0][C]
\end{aligned}
$$

Table 12 Adjusted levels to be under the geometric tolerance limits

	A	B	C
For the bottom	1	1	1/2
On the sides	1	1	2

Table 13 Adjusted factor levels

	A	B	C
For the bottom	2	2	3
On the sides	2	2	3

Table 14 Final results

	A	B	C
For the height	2	2	2
For the width	3	4	3
Parallelism	1	1	1
Perpendicularity	1	1	1
Burr	1	1	1
For the bottom	1	1	1/2
On the sides	1	1	2
Balance	1	1	1

In this case, it is not possible to evaluate the measurement error as this is a qualitative evaluation. Furthermore, analysis of the variance is impossible, since no measurements are available.

However the effects are greater than those found previously and we estimate that these factors have an influence on this. In order to have as little burr as possible, it would be wise to adjust the level of these, which is shown in Table 10.

5.5 Roughness

Calculations of the effects of the factors take into account the average per part on the two slots. We do however make a difference between the roughness at the bottom and on the sides of the slot as we noted a better surface state on the side walls than at the bottom of the slot. Indeed, these results confirm the finish conditions when privileging the surface state. Furthermore, the sides done by periphical milling provide a better surface state. The average roughness measured on the slot side walls is 1.87 µm, which complies with the definition drawing requirements (Ra=2 µm). It must not be forgotten that this is an average value and some parts exceed the tolerance limits. The material machined also plays a major role in surface quality. For instance, the best Ra can be obtained with stainless steel.

The response model is as follows (Table 11): $\widetilde{Y} = M + A + B + C$

For the roughness test, the response error is $\Delta\widetilde{Y} = 0.01\mu m$. We may therefore deduce that the effects are significant as the subsequent ratio is low, i.e. $\Delta E = 0.01/\sqrt{18} = 0.0023$ and $E > 100 \times \Delta E$ for the 18 tests. We can therefore deduce that the effects are significant.

The trends can be confirmed with new tests enabled from the optimisation of the response model. In order to be under the geometric tolerance limits, the level of these factors must be adjusted following Table 12.

Optimisation of the system response model to noise is defined by determining the maximum signal/noise (S/N) ratio. The factor levels must be adjusted following Table 13.

5.6 Summary

The results are summarized in Table 14.

Optimisation of the system model response to noise is given Table 15.

In summary, according the critical parameter analysed and to the response which is to be rendered insensitive to noise, tests will be chosen in Table 15.

For confirmation tests the choice will be:

- 1, 1, 1: this test appears to be the best configuration.
- 2, 2, 3: this test is better from a system reliability viewpoint by limited roughness noise.
- 2, 4, 3: point out perpendicularity and parallelism limited noise.
- 2, 1, 3: point out dimension limited noise.

The theoretic responses are calculated according to the choices that are detailed in Table 16.

6 Conclusions

The results comply with our expectations. Test 1 1 1, i.e. using stainless steel with a single-pass rough strategy and a 1 finish strategy, provided the best part when following the specifications imposed in the definition drawing. However, test 2 1 3 provided the best results when considering roughness and global system quality. Furthermore, this test is quicker (4.45 min as opposed to 34.58 min for test 1 1 1).

The tester must therefore choose the most suitable test in terms of quality and execution time with respect to conditions imposed. We have not detailed specifications of the test part to enable us to make a reasonable choice between these two tests. We do not know whether we have to give priority to serial production costs, dimensional quality, robustness, etc.

The study of residues enables validation of the model. For each response and for each test, the residue (difference between the test response and the theoretic response calculated with a mathematical model) is close to 0. We are therefore able to validate the model.

Table 15 Optimisation of the system model response to noise

	A	B	C
For the height	2	3	1
For the width	1	1	3
Parallelism	1	1	2
Perpendicularity	2	4	1
For the bottom	2	2	3
On the sides	2	2	3
Balance	2	2/3/4	3

Table 16 Theoretical responses

	Height	Width	Parallelism	Perpendicularity	Burr	Ra bottom	Ra sides
1, 1, 1	5.56	15.01	0.03	0.05	0	0	0.39
2, 2, 3	5.63	14.89	0.27	1.61	2	3.81	1.82
2, 4, 3	5.75	14.76	0.25	2.22	3	5.05	2.9
2, 1, 3	5.64	14.89	0.18	1.29	1	2.13	1.32

With this work, we are able to illustrate that it is possible to formalise and evaluate the machining process in order to make the best choice. However, the test plan approach is complex and requires considerable time and means. Nevertheless, the results enable selection of the most suitable slot machining process.

Furthermore, our approach should be compared with digital simulations such as that of Engin [9, 10].

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