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ORIGINAL ARTICLE

3D ISO manufacturing specifications with vectorial representation of tolerance zones

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Abstract In order to respect the functional drawing of a part, the process planer first has to choose the manufacturing process and then establish the manufacturing specifications to fulfill on the part after each phase. This paper introduces the tolerance zone transfer method, which is based on a vectorial representation of tolerance zones. For each functional requirement, it consists in analyzing the tolerance zone mobilities and the datum function. The transfer determines by iteration manufacturing specifications for each phase. Operations on degrees of freedom allow us to specify the right need using the ISO standards of tolerancing.

Keywords Manufacturing tolerancing · ISO standard · Three-dimensional model dimension chain

1 Manufacturing tolerancing

1.1 Introduction

Functional definition drawing describes all functional specifications necessary for a good functioning of a mechanism. With this drawing, process planner chooses a manufacturing process and composes a manufacturing plan and a phase contract for each manufacturing phase. Each phase drawing incorporates manufacturing specifications to respect on each workpiece after the phase.

1.2 State of the art

Manufacturing tolerancing models used in industry are generally unidirectional, like the Δl method [6], developed by P. Bourdet, which determines manufacturing specification of one workpiece in one direction. B. Anselmetti adds rules to specify with ISO standards the datum reference frame for each phase [2]. However, unidirectional approach does not consider form and orientation error of surfaces.

Bourdet and Ballot [7] developed the ΔTol method with small displacement torsor's concept, to describe gap between a manufactured surface and a surface of nominal part. This approach is usable in functional tolerancing and in manufacturing tolerancing [5]. This approach is used by Villeneuve and Vignat [12] to predict defaults of a part which are caused by manufacturing. Legoff et al. [13] also used this concept of small displacement torsor, to analyze a manufacturing phase to quantify defaults induced by setting up and manufacturing operations. Laperrière et al. [9] used small displacement torsor too, with Jacobian operators, to determine the contribution of dispersion on the tolerance zone. Tichadou et al. [11] formalized the behavior of manufacturing geometrical defects on the entire workstation with a torsor chain. Louati et al. [10] used this method to optimize the positioning of an angle bracket.

In the ΔTol method, the nominal model of a part is in an indifferent position inside the matter. This choice imposes to define datum reference frame of the requirement relating to deviation of each datum

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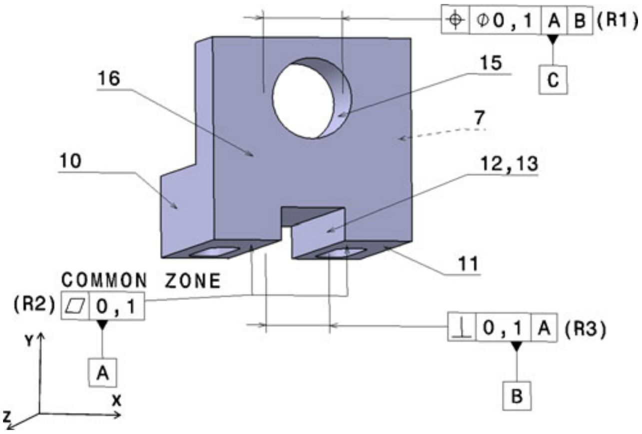


Fig. 1 Functional specifications

surface. The equations obtained are very complex, and finding the most unfavorable situation and optimizing manufacturing tolerances are difficult. So, Ayadi et al. [4] propose to place the nominal model directly on the datum. Usually, these methods allow us to do the tolerances analyzed but do not allow us to determine the type of specifications, datums, and modifiers.

1.3 Purpose

Tolerance zone transfer (TZT) method [2] allows us to generate manufacturing requirements corresponding to each functional requirements of the functional drawing. This method uses a vector representation of tolerance zone. This article formalizes this method and presents the computing approach. The aims of this work is to extend the concept of vectorial representation of tolerance zones proposed by Anselmetti [1] and Anselmetti and Louati [3] for functional tolerancing to study manufacturing transfer.

2 Part studied

In this paper, the method is expounded on a simple part machined in four phases (Fig. 1). The functional specification studied is the specification of location `R1` of the bore `C(15)`. The datum reference frame is made up of a primary plan `A(11)` parallel to the toleranced surface and a groove made up of two planes `B(12,13)`, perpendicular to the primary datum `A`.

Fig. 2 Setting up in phase 10

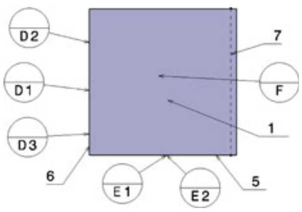
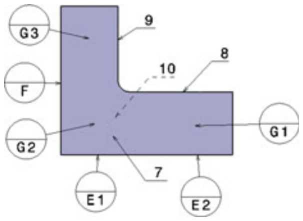


Fig. 3 Setting up in phase 20



In phase 10 (Fig. 2), the part holder comprises six jigs, simulated by the datum target frame `DEF`. These jigs are defined on the planes `D(6)`, `E(5)`, and `F(1)`. The plane (`7`) is machined in this phase 10.

In phase 20 (Fig. 3), the part holder comprises six jigs too, simulated this time by the datum target frame `GEF` on the planes `G(7)`, `E(5)`, and `F(1)`. In this phase, surfaces 8–10 are realized.

For phases 30 and 40 (Fig. 4), the same datum target frame `HIJ` comprises three jigs on the plan `H(8)` to realize the primary datum, two jigs on the plane `I(9)` to realize the secondary datum, and one last jig to realize the third datum on the plane `J(10)`. In phase 30, bore `15` and plane `16` are manufactured. In phase 40, the plane `11`, the slot made up of surfaces 12–14, and the two others slots are manufactured.

3 Requirement analysis

3.1 Three-dimensional representation of the requirement

The transfer method is really three-dimensional; that is why we need to clearly identify useful directions and to distinguish translations from rotations. So the requirement is analyzed in a transfer table which contains all useful characteristics.

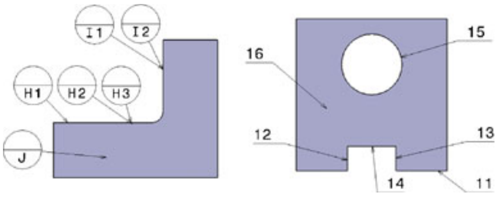


Fig. 4 Setting up in phases 30 and 40

Table 1 Initialization of the table for the set E0

	Toleranced surfaces	Datum surfaces	
Set E0			
Surface	`C(15)`	`A(11)`	`B(12,13)`
Phase	30	40	40
Indication			

3.2 Surfaces initialization

The initial transfer table contains the set E0 of toleranced surfaces, datum surfaces, and phase number in which they are manufactured. Table 1 describes requirement `R1` presented (Fig. 1).

3.3 Degrees of freedom of surfaces

3.3.1 Aims

Surfaces listed in the table E0 are manufactured in several phases. Surfaces `A(11)` and `B(12,13)` are machined in phase 40, after the surface `C(15)` realized in phase 30.

Accuracy of surfaces `A(11)` and `B(12,13)` positioning regarding `C(15)` requires manufacturing specifications on phase 40, which can be locations or orientations. This choice impose to determine degrees of freedom to master on surfaces `A(11)` and `B(12,13)` to respect the requirement `R1`.

3.3.2 Vectorial representation of tolerance zones

The Fig. 5 proposed by B. Anselmetti [2] describes the vectorial representation and its degrees of freedom for a tolerance zone. A vectorial representation contains two information. Firstly, a letter describes the form of the tolerance zone. Secondarily, a vector gives the direction of the tolerance zone. For example, indication $p\mathbf{u}$ represents a planar zone, in direction $\mathbf{u}$. Any rotation around $\mathbf{u}$ and any translation perpendicular to $\mathbf{u}$ do not change the tolerance zone.

This representation does not need choice of vectors in the plane perpendicular to $\mathbf{u}$, in opposition to a traditional representation of degrees of freedom, with translations in $\mathbf{X}$ and $\mathbf{Y}$ in the plane for example. Vectorial representation can represent location, orientation, or form specifications and are listed in Fig. 5. Degrees of freedom are represented by arrows.

This vectorial representation is used for transfer of functional requirements but is difficultly usable for manufacturing transfer because of linear and pinpoint jigs. A new vectorial representation is proposed in Table 2, separating rotations and translations.

Table 2 represents the mobilities of tolerance zone, in translation or rotation, parallel or perpendicular to a direction. They can be written like before, for example, $m\mathbf{X}$ for a translation mobility parallel to $\mathbf{X}$, or $(1, 0, 0, 0)\mathbf{X}$.

3.3.3 Operations on vectorial representations

Several operations can be realized on these vectorial representations. Let three vectors $\mathbf{U}$, $\mathbf{V}$, and $\mathbf{W}$ be perpendicular to $\mathbf{U}$ and $\mathbf{V}$.

- Union, written "+," represents the accumulation of several mobilities. For example, $m\mathbf{U} + m\mathbf{V}$ will give $b\mathbf{W}$ if $\mathbf{U} \neq \pm\mathbf{V}$. All translations perpendicular to $\mathbf{W}$

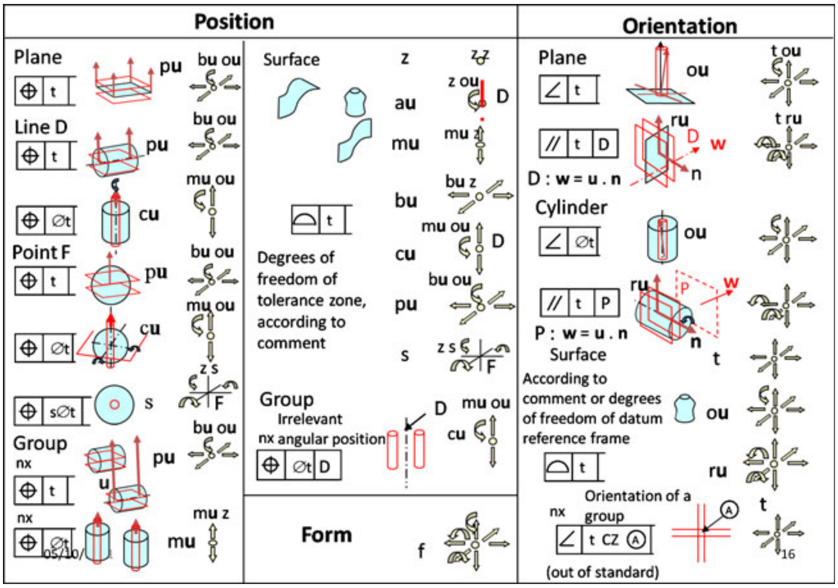


Fig. 5 Vectorial representation of tolerance zones

Table 2 Vectorial representation of mobilities

	Translations		Rotations	
	//**X**	⊥**X**	//**X**	⊥**X**
e	0	0	0	0
m**X**	1	0	0	0
b**X**	0	1	0	0
t	1	1	0	0
r**X**	0	0	1	0
o**X**	0	0	0	1
s	0	0	1	1
f	1	1	1	1
c**X**	1	0	1	0
p**X**	0	1	1	0
$\overline{m}\mathbf{X}$	0	1	1	1
$\overline{b}\mathbf{X}$	1	0	1	1
$\overline{r}\mathbf{X}$	1	1	0	1
$\overline{o}\mathbf{X}$	1	1	1	0

are possible. If **U** is perpendicular to **V**, then $m\mathbf{U} + b\,\mathbf{V} = b\,\mathbf{V}$, else $m\mathbf{U} + b\,\mathbf{V} = t$.

- Intersection, written "·," represents the intersection of several mobilities. $b\,\mathbf{U} \cdot b\,\mathbf{V}$ will give $m\mathbf{W}$. Indeed, the single mobility included in all translations perpendicular to **U** and in all translations perpendicular to **V** is the translation in **W**. If **U** is perpendicular to **V**, then $m\mathbf{U} \cdot b\,\mathbf{V} = m\mathbf{U}$, else $m\mathbf{U} \cdot b\,\mathbf{V} = e$. Intersection between translation mobilities and rotation mobilities will be empty.
- Complementary, represented by an overline, defines which mobilities are not in a representation. $m\mathbf{X}$ represents a **X** translation mobility. $\overline{m}\mathbf{X}$ will represent all mobilities, except that translation mobility in **X**; this translation will be blocked.

3.3.4 Analysis of requirement `R1`

The functional requirement `R1` (Fig. 1) is a location of the bore `C(15)`, with a datum reference frame `AB`. The tolerance zone is a cylindrical zone of direction **Z**. Any rotation of the tolerance zone around the axis of the bore **Z** and any translation of this zone in **Z** will not have consequences. Vectorial representation of the tolerance zone is $c\mathbf{Z}$, which is carry forward the fourth line of table E0 (Table 3).

Table 3 Vectorial representation of `R1`

Set E0			
Surface	`C(15)`	`A(11)`	`B(12,13)`
Phase	30	40	40
Indication	c**Z**		

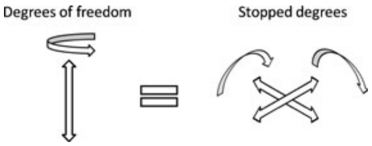


Fig. 6 Link between degrees of freedom and imposed degrees

In general case, calculation is more complex, and calculation of vectorial representation will be developed in Section 5.

3.3.5 Vectorial representation for primary datum

The tolerance zone of the requirement R1 has two degrees of freedom. So four degrees must be controlled to respect the requirement. The aim is now to know which datum of the reference frame will stop these imposed degrees (Fig. 6).

Vectorial representation $c\mathbf{Z}$ imposes $\overline{m}\mathbf{X} \cdot \overline{m}\mathbf{Y} \cdot \overline{r}\mathbf{X} \cdot \overline{r}\mathbf{Y}$. Primary datum is a plan with normal **Y**, so its mobilities are $p\mathbf{Y}$.

All degrees stopped by `A` are not useful. Degrees stopped by `A` which are mobilities for the requirement `R1` are not necessary. It is necessary to add to the mobilities p**Y** of datum `A` and the mobilities $c\mathbf{Z}$ of tolerance zone which are in the complementary of datum `A` mobility's (Fig. 7).

Mobilities of primary datum `A` are written $\mathscr{R}_A$ and are calculated with the following relation:

$$\mathscr{R}_A = \mathscr{M}_A + \overline{\mathscr{M}_A} \cdot \mathscr{M}_{R1}$$

with: $\mathscr{M}_A = p\mathbf{Y} = b\,\mathbf{Y} + r\mathbf{Y}$: mobilities of datum `A`, $\mathscr{M}_{R1} = c\mathbf{Z} = m\mathbf{Z} + r\mathbf{Z}$: mobilities of requirement `R1`, and $\overline{\mathscr{M}_A} = \overline{p}\mathbf{Y} = m\mathbf{Y} + o\mathbf{Y}$: complementary of surface `A` mobility's

$$\mathscr{R}_A = p\mathbf{Y} + \overline{p}\mathbf{Y} \cdot c\mathbf{Z}$$

$$\mathscr{R}_A = b\,\mathbf{Y} + r\mathbf{Y} + m\mathbf{Y} \cdot m\mathbf{Z} + o\mathbf{Y} \cdot r\mathbf{Z}$$

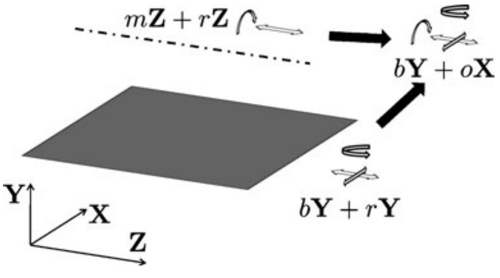


Fig. 7 Addition of mobilities of requirement and datum `A`

Table 4 Primary datum's role

Set E0			
Surface	`C(15)`	`A(11)`	`B(12,13)`
Phase	30	40	40
Indication	$p\mathbf{X}$	$\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$	

$$\mathscr{R}_A = b\mathbf{Y} + r\mathbf{Y} + r\mathbf{Z}$$

$$\mathscr{R}_A = b\mathbf{Y} + o\mathbf{X} = \overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$$

The result of this calculation is all mobilities, except $m\mathbf{Y}$ and $r\mathbf{X}$. The primary datum role is $\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$. It is now possible to carry forward this in the table E0 (Table 4; Fig. 8).

It is now necessary to verify if primary datum is enough for the requirement. Datum is enough if starting from requirement's mobilities, and adding mobilities stopped by datum, the result is all mobilities. $\mathscr{V}$ is the result of this calculation and needs to be equal to f for having sufficient datum. This method is similar to the work of Dominique Gaunet about technologically and topologically associated surfaces [8].

$$\mathscr{V} = \mathscr{M}_{R1} + \overline{\mathscr{R}_A}$$

$$\mathscr{V} = c\mathbf{Z} + \overline{\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}}$$

$$\mathscr{V} = m\mathbf{Z} + r\mathbf{Z} + m\mathbf{Y} + r\mathbf{X}$$

$$\mathscr{V} = b\mathbf{X} + o\mathbf{Y}$$

Mobilities in translation on $\mathbf{X}$ and in rotation around $\mathbf{Y}$ are not blocked, so the datum `A` is not enough.

Datum's role is to locate or orientate toleranced surface. This role can change if there is another datum. In Fig. 9a, analysis of datum's roles concludes that primary datum stops $\mathbf{Y}$ translation and secondary datum stops $\mathbf{X}$ translation, although a translation of primary datum in $\mathbf{Y}$ produces an equal translation of the tolerance zone.

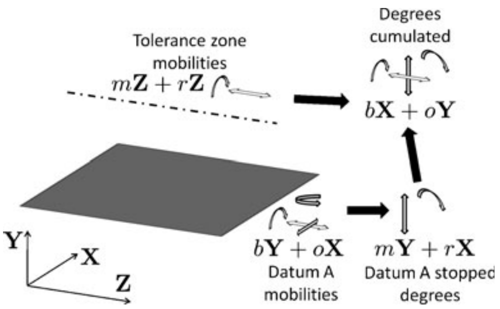


Fig. 8 Addition of mobilities of the requirement and block of datum `A`

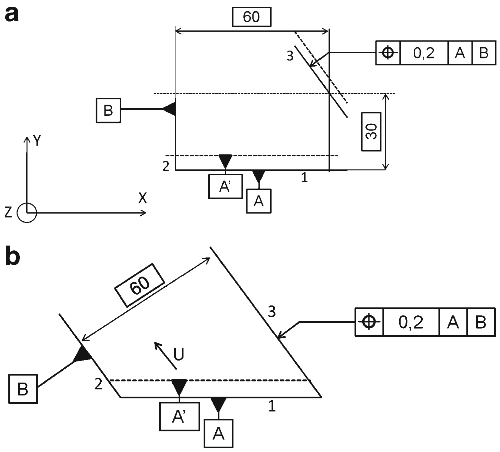


Fig. 9 Specification with not perpendicular directions

However, in Fig. 9b, the same translation of primary datum has not any influence on the tolerance zone because the displacement is parallel to `B` in $\mathbf{u}$ direction. On the other hand, the only location specification is between secondary datum and tolerance zone. The complete rule will not develop here.

3.3.6 Vectorial representation for secondary datum

Datum `B` (Fig. 1) is equivalent to a plane normal to $\mathbf{X}$ characterized by $\mathscr{M}_B = p\mathbf{X}$. $\mathscr{R}_B$ is the secondary datum's role.

Secondary datum does not stop the mobilities of tolerance zone, neither degrees already stopped by other datum.

$$\mathscr{R}_B = \mathscr{M}_B + \overline{\mathscr{M}_B}\cdot\mathscr{M}_{R1} + \overline{\mathscr{M}_B}\cdot\overline{\mathscr{R}_A}$$

with $\mathscr{M}_B = p\mathbf{X} = b\mathbf{X} + r\mathbf{X}$: mobilities of surface `B`, $\overline{\mathscr{M}_B} = \overline{p}\mathbf{X} = m\mathbf{X} + o\mathbf{X}$: degrees which can be stopped by `B`, $\mathscr{M}_{R1} = c\mathbf{Z} = m\mathbf{Z} + r\mathbf{Z}$: mobilities of requirement `R1`, and $\overline{\mathscr{R}_A} = \overline{\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}} = m\mathbf{Y} + r\mathbf{X}$: complementary of primary datum's role

$$\mathscr{R}_B = p\mathbf{X} + \overline{p}\mathbf{X}\cdot c\mathbf{Z} + \overline{p}\mathbf{X}\cdot(m\mathbf{Y} + r\mathbf{X})$$

$$\mathscr{R}_B = p\mathbf{X} + (m\mathbf{X} + o\mathbf{X}).(m\mathbf{Z} + r\mathbf{Z})$$

$$+(m\mathbf{X} + o\mathbf{X}).(m\mathbf{Y} + r\mathbf{X})$$

$$\mathscr{R}_B = p\mathbf{X} + r\mathbf{Z}$$

$$\mathscr{R}_B = b\mathbf{X} + o\mathbf{Y} = \overline{m}\mathbf{X}\cdot\overline{r}\mathbf{Y}$$

Mobilities of secondary datum define degrees stopped by this datum, which are $\overline{m}\mathbf{X}$ and $\overline{r}\mathbf{Y}$, carrying forward in Table 5.

Table 5 Secondary datum's role

Ensemble E0			
Surface	`C(15)`	`A(11)`	`B(12,13)`
Phase	30	40	40
Indication	$c\mathbf{Z}$	$\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$	$\overline{m}\mathbf{X}\cdot\overline{r}\mathbf{Y}$

It is now necessary to control if the datum reference frame AB is enough.

$$\mathscr{V} = \mathscr{M}_{R1} + \overline{\mathscr{R}_A \cdot \mathscr{R}_B}$$

$$\mathscr{V} = c\mathbf{Z} + \overline{\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}\cdot\overline{m}\mathbf{X}\cdot\overline{r}\mathbf{Y}}$$

$$\mathscr{V} = c\mathbf{Z} + \overline{m\mathbf{Z} + r\mathbf{Z}}$$

$$\mathscr{V} = m\mathbf{Z} + r\mathbf{Z} + b\,\mathbf{Z} + o\mathbf{Z}$$

$$\mathscr{V} = f$$

All degrees of freedom are stopped, so datum reference frame is enough.

4 Transfer

4.1 Direct requirement

Surfaces are active in a phase if they are manufactured in this phase, or if they are used as setting up in this phase. However, it is important to distinguish datum surfaces and datum target frame, but a datum on a plane and a datum plane on three datum targets on this plane are identical, neglecting the flatness default of the plane.

If all surfaces of set E0 (toleranced or datum) are active in the same phase, then requirement is direct and functional requirement can be copied on the phase drawing, as manufacturing specification. Else, transfer is necessary.

In Table 5, surfaces are not active in the same phase 40. Surfaces that are manufactured lastly in phase 40 are datu `A(11)` and `B(12,13)`. The surface `15` is not used as setting up in this phase. Transfer is necessary.

4.2 Transfer process

Algorithm described in Fig. 10 is carried out for every requirement of functional drawing.

4.3 Choice of surfaces to transfer

Surfaces that need to be transferred are surfaces that are manufactured lastly. In our example, they are surfaces `A(11)` and `B(12,13)`, which are datum surfaces of the requirement.

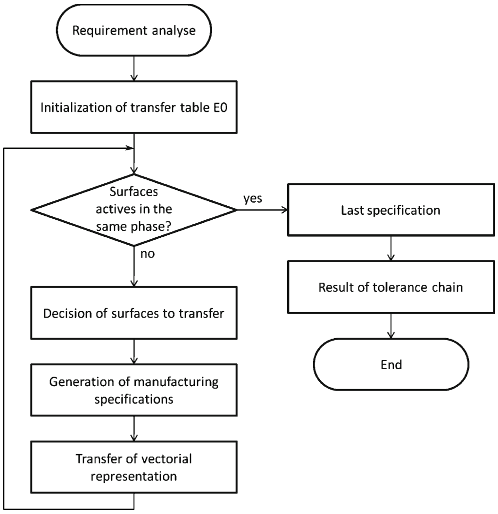


Fig. 10 Transfer algorithm

Transfer will bring manufacturing specifications for phase 40 to locate and/or orientate surfaces `A` and `B`, compared to the positioning system `HIJ` of this phase. Set `E0` will be carried forward in set `E1` (Table 6), replacing surfaces `A` and `B` by `HIJ`, surfaces which are manufactured in phase 20.

The aim is to transfer vectorial representation of surfaces `A` and `B` to the setting up frame of phase 40. `H`, `I`, and `J` make up setting up system of phase 40. `H` is made up of three jig points on surface `8` and stops **Y** translation and rotations around **X** and **Z**. `I` is made up of two jig points on surface `9` and stops **Z** translation and rotation around **Y**. Finally, last jig point `J` is on surface `10` and stops **X** translation.

4.4 Surface `A` study

4.4.1 Manufacturing requirement for `A`

Vectorial representation of transfer in Table 5 and Fig. 5 produces manufacturing requirement for phase 40. In E0 (Table 5) for plan `A(11)` with a normal **Y**, manufactured on phase 40, vectorial representation is

Table 6 Carry forward setting up frame of phase 40

Set E1				
Surface	`C(15)`	`H(8)`	`I(9)`	`J(10)`
Phase	30	20	20	20
Indication	$c\mathbf{Z}$			

$\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$. There are two degrees to stop, $\overline{m}\mathbf{Y}$ and $\overline{r}\mathbf{X}$. These degrees will be studied independently, and each one will generate a manufacturing requirement.

For a vectorial representation $\overline{m}\mathbf{Y}$ for a plane, Fig. 5 imposes to create a $\mathbf{Y}$ location `S1` for this plane.

For $\overline{r}\mathbf{X}$ for a plane with $\mathbf{Y}$ normal, Fig. 5 imposes to create a parallelism `S2` of this plane, regarding a line with direction $\mathbf{Z}$, perpendicular to $\mathbf{X}$ and $\mathbf{Y}$. This line `K` is the intersection between plane `H(8)` and plane `J(10)` (Fig. 11).

4.4.2 Vectorial representation transfer

In the requirement, role of datum `A` is $\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$. Plane `H` has mobilities $p\mathbf{Y}$, line `I` has mobilities $b\mathbf{Z}+o\mathbf{Y}$, and jig `J` has mobilities $b\mathbf{X}+s$. The aim is now to determinate role of each jig for the manufacturing requirement.

- `H` role:

$$\mathscr{R}_H = \mathscr{M}_H + \overline{\mathscr{M}_H}\cdot\mathscr{R}_A$$

$$\mathscr{R}_H = p\mathbf{Y} + \overline{p}\mathbf{Y}\cdot\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$$

$$\mathscr{R}_H = b\mathbf{Y} + r\mathbf{Y} + (m\mathbf{Y}+o\mathbf{Y}).(b\mathbf{Y}+o\mathbf{X})$$

$$\mathscr{R}_H = b\mathbf{Y} + r\mathbf{Y} + r\mathbf{Z}$$

$$\mathscr{R}_H = b\mathbf{Y} + o\mathbf{X}$$

$$\mathscr{R}_H = \overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X} = \mathscr{R}_A$$

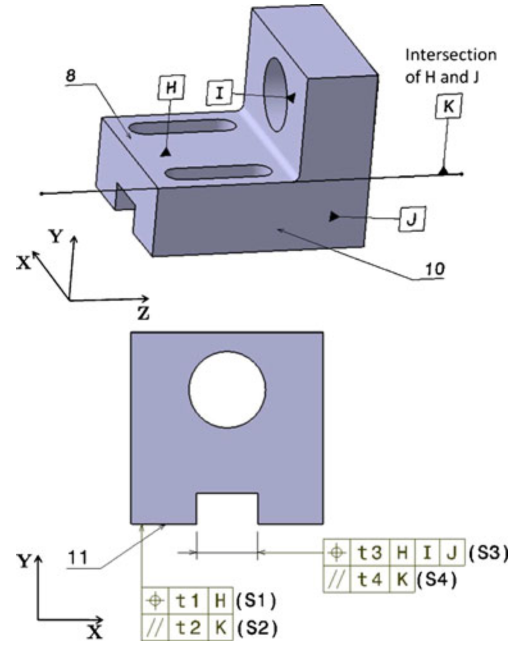


Fig. 11 Phase 40 drawing

Table 7 Carry forward `A` mobilities in table E1

Set E1				
Surface	`C(15)`	`H(8)`	`I(9)`	`J(10)`
Phase	30	20	20	20
Indication	c$\mathbf{Z}$	$\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$		

Location and orientation of `A` regarding datum reference frame `HIJ` are only carried out by `H`. Table 6 is completed and become Table 7, with $\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$ in column `H`.

4.5 Surface `B` study

4.5.1 Manufacturing requirement for surface `B`

In E0 (Table 5), datum `B` has two degrees to stop again, $\overline{m}\mathbf{X}$ and $\overline{r}\mathbf{Y}$. These degrees will be studied independently too.

$\overline{m}\mathbf{X}$ ensures $\mathbf{X}$ location of median plane of the groove. Mobilities in translation $b\mathbf{X}$ are allowed. Using Fig. 5, to ensure location $b\mathbf{X}$ of a plane, requirement to create is a location `(S3)`. Datum reference frame for this location will be `HIJ`.

In E0 (Table 5), `B` stops $\overline{r}\mathbf{Y}$ too. `B` is a plane with $\mathbf{X}$ normal. Table 5 imposes to create a parallelism `S4` regarding $\mathbf{Z}$, that is to say a parallelism `S4` (Fig. 11) regarding line `K`.

4.5.2 Vectorial representation transfer

The same method that in Section 4.4.2 generates datum's role for mobilities of surface `B`, as

$$\mathscr{R}_H = \mathscr{M}_H + \overline{\mathscr{M}_H}\cdot\mathscr{R}_B = f$$

$$\mathscr{R}_I = \mathscr{M}_I + \overline{\mathscr{M}_I}\cdot\mathscr{R}_B + \overline{\mathscr{M}_I}\cdot\overline{\mathscr{R}_H} = \overline{r}\mathbf{Y}$$

$$\mathscr{R}_J = \mathscr{M}_J + \overline{\mathscr{M}_J}\cdot\mathscr{R}_B + \overline{\mathscr{M}_J}\cdot\overline{\mathscr{R}_H} + \overline{\mathscr{M}_J}\cdot\overline{\mathscr{R}_I} = \overline{m}\mathbf{X}$$

4.6 Study of new transfer

In Table 8, surfaces `H(8)`, `I(9)`, and `J(10)` are manufactured in phase 20 and are positioning frame of phase 30, in which surface `C(15)` is manufactured.

Table 8 Transfer of `B` in table E1

Set E1				
Surface	`C(15)`	`H(8)`	`I(9)`	`J(10)`
Phase	30	20	20	20
Indication	c$\mathbf{Z}$	$\overline{m}\mathbf{Y}\cdot\overline{r}\mathbf{X}$	$\overline{r}\mathbf{Y}$	$\overline{m}\mathbf{X}$

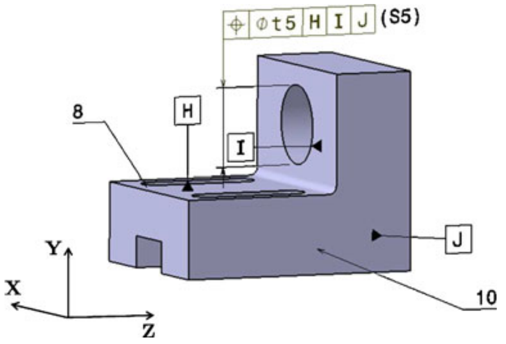


Fig. 12 Phase 30 drawing

These surfaces are active in phase 30 and transfer is not useful.

Vectorial representation of `C(15)` is $c\mathbf{Z}$. It must be a location of surface `C(15)`, regarding the datum reference frame `HIJ` (Fig. 12).

5 Generalization of end surface analyze

5.1 Principle

Degrees of freedom to control on toleranced surface are a combination of invariance degrees of nominal toleranced surface, of tolerance zone, and of datum reference frame.

5.2 Mobilities of toleranced surface

5.2.1 Rotation axis

Degrees of freedom of toleranced surface are displacements that do not change this surface. A plane surface is invariant for any rotation around its normal, for any position of the rotation axis.

A cylinder surface (cylinder, cone, torus...) is invariant for a rotation around its own axis only. The vectorial representation must give direction of the axis and a point of this axis too.

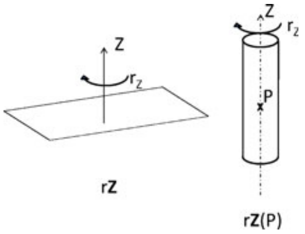


Fig. 13 Rotation invariance of a plane and a cylinder

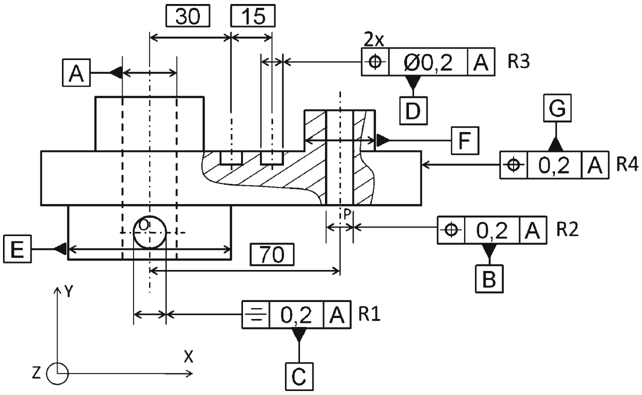


Fig. 14 Definition drawing

In Fig. 13, rotation degree of freedom of plane is $r\mathbf{Z}$, while degree of freedom of cylinder is $r\mathbf{Z}(P)$.

In definition drawing of Fig. 14, degrees of freedom for toleranced surfaces are:

- $c\mathbf{Z}(O)$ for requirement `R1`
- $c\mathbf{Y}(P)$ for requirement `R2`

5.2.2 Low extent surfaces

In the case of low extent toleranced surface, like a cylinder with a low height compared to its diameter, or a plane with a breadth very lower compared to its length, some rotations will have few influences on the requirement respect (Fig. 15).

For an orientation tolerance t_0 on a planar surface, the equation to fulfill is $\alpha l + \beta L \leq t_0$. If l is low, then α has few influence. So it is not necessary to impose an orientation requirement for the plane around $\mathbf{X}$; that is to say, α will be limited by general tolerancing of the part.

For requirement `R3` (Fig. 14), two-hole group `D` is a prismatic feature with direction $\mathbf{Y}$. So the only degree of freedom is $\mathbf{Y}$ translation and the vectorial representation is $m\mathbf{Y}$. However, cylinders are shorts, so a little

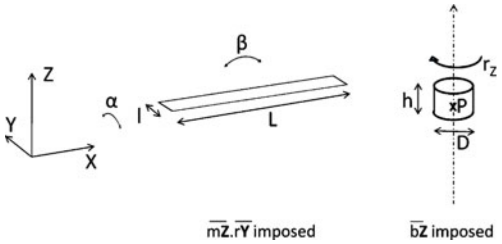


Fig. 15 Narrow plane and short cylinder

rotation around $\mathbf{X}$ or $\mathbf{Z}$ will have few influence. It is possible to add $r\mathbf{X}$ and $r\mathbf{Z}$ to the degree of freedom of the group. For `D`, degrees of freedom are $m\mathbf{Y} + o\mathbf{Y}$.

5.3 Tolerance zone mobilities

Figure 5 gives mobilities to tolerance zone $\mathscr{M}_Z$:

- For `R1`: planar zone of normal $\mathbf{X} \Rightarrow p\mathbf{X}$
- For `R2`: planar zone of normal $\mathbf{X} \Rightarrow p\mathbf{X}$
- For `R3`: prismatic zone of direction $\mathbf{Y} \Rightarrow m\mathbf{Y}$

5.4 Datum reference frame mobilities

Datum reference frame mobilities $\mathscr{M}_F$ are equal to the mobilities of the equivalent link of the entire datum reference frame. For part (Fig. 14), datum reference frame is realized by cylindrical surface `A` for the three requirements. The equivalent link is a cylinder link, with mobility $c\mathbf{Y}(O) = m\mathbf{Y} + r\mathbf{Y}(O)$.

5.5 Combination of degrees of freedom

5.5.1 Without point transfer

The toleranced surface will have all mobilities. For requirement `R1` (Fig. 14), mobilities of toleranced surface, tolerance zone, and datum reference frame are all in the same point. Mobilities can be directly added.

$$\mathscr{M}_{R1} = \mathscr{M}_C + \mathscr{M}_{Z1} + \mathscr{M}_{F1}$$

with $\mathscr{M}_C$: mobilities of surface `C`, $\mathscr{M}_{Z1}$: mobilities of requirement `R1` tolerance zone, and $\mathscr{M}_{F1}$: mobilities requirement `R1` datum reference frame

$$\mathscr{M}_{R1} = c\mathbf{Z}(O) + p\mathbf{X} + c\mathbf{Y}(O)$$

$$\mathscr{M}_{R1} = m\mathbf{Z} + r\mathbf{Z}(O) + b\mathbf{X} + r\mathbf{X} + m\mathbf{Y} + r\mathbf{Y}(O)$$

$$\mathscr{M}_{R1} = b\mathbf{X} + r\mathbf{X} + o\mathbf{X}(O).$$

5.5.2 With point transfer

For requirement `R2`, mobilities of toleranced surface and datum reference frame are not expressed in the same point. It is necessary to express everything in the characteristic point of toleranced surface, which is `P`.

Translation mobilities do not change whatever is the application point. $\mathbf{Y}$ translation of datum reference frame stays in point `P`. However, it is necessary to express mobility $c\mathbf{Y}(O)$ in point `P`.

If points O and P are aligned in direction $\mathbf{Y}$, then vectorial representation does not change; it is possible to replace O by P. Else, a rotation around $(O, \mathbf{Y})$ axis allows a translation of P in direction $\mathbf{Y} \times \mathbf{OP} = \mathbf{Z}$. In the case of requirement `R2`, $r\mathbf{Y}(O)$ becomes $m\mathbf{Z}$ in point P.

The combination of degrees of freedom in O is

$$\mathscr{M}_{R2} = \mathscr{M}_B + \mathscr{M}_{Z2} + \mathscr{M}_{F2}$$

$$\mathscr{M}_{R2} = c\mathbf{Y}(P) + p\mathbf{X} + m\mathbf{Y} + m\mathbf{Z}$$

$$\mathscr{M}_{R2} = m\mathbf{Y} + r\mathbf{Y}(P) + b\mathbf{X} + r\mathbf{X} + m\mathbf{Z}$$

$$\mathscr{M}_{R2} = b\mathbf{X} + r\mathbf{X} + r\mathbf{Y}(P).$$

5.5.3 Group of surfaces

Requirement `R3` specifies a group of short holes. There are two different possible solutions. If all holes are manufactured in the same phase, then there will be a requirement of the group in this phase.

$$\mathscr{M}_{R3} = \mathscr{M}_D + \mathscr{M}_{Z3} + \mathscr{M}_{F3}$$

$$\mathscr{M}_{R3} = m\mathbf{Y} + o\mathbf{Y} + m\mathbf{Y} + c\mathbf{Y}(O)$$

$$\mathscr{M}_{R3} = m\mathbf{Y} + o\mathbf{Y} + m\mathbf{Y} + m\mathbf{Y} + r\mathbf{Y}(O)$$

$$\mathscr{M}_{R3} = m\mathbf{Y} + o\mathbf{Y} + r\mathbf{Y}(O).$$

For a setting up with `JEB`, `J` is not enough, but `JE` has for only mobility $r\mathbf{Y}(O)$. `JE` is enough for the manufacturing requirement. However, to orientate the part

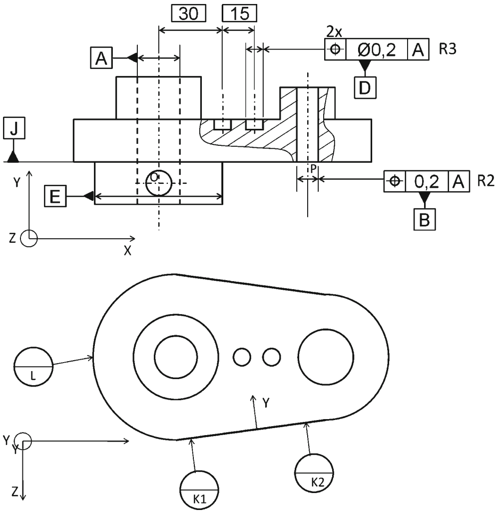


Fig. 16 Setting up for the realization of the group of holes

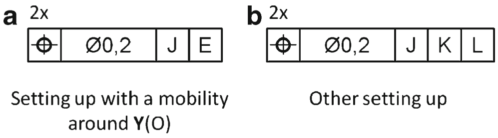


Fig. 17 Group manufacturing specification

Rang	Nom	Nb BReps	BReps
0	Planéité.1	1	Selection_RSur:(Face:(Brp:(Pad.1;0:(Brp:(Sketch.1;3))))
1	Référence simple.1	1	Selection_RSur:(Face:(Brp:(Pad.1;0:(Brp:(Sketch.1;3))))
2	Tolérance linéaire.20	4	Selection_RSur:(Face:(Brp:(Hole.6;0:(Brp:(Sketch.14;3))))
			Selection_RSur:(Face:(Brp:(Hole.6;0:(Brp:(Sketch.14;3))))
			Selection_RSur:(Face:(Brp:(Hole.5;0:(Brp:(Sketch.12;3))))
			Selection_RSur:(Face:(Brp:(Hole.5;0:(Brp:(Sketch.12;3))))

Fig. 19 Export of FTA information

for manufacturing, it is necessary to keep a centering B. Manufacturing requirement of holes D is given in Fig. 17a.

If setting up for the manufacturing of the group of holes is realized by JKL (Fig. 16), J stops $\overline{m}\mathbf{Y} \cdot \overline{o}\mathbf{Y}$ and is not enough for the requirement. JK stops $\overline{m}\mathbf{Y} \cdot \overline{m}\mathbf{V} \cdot \overline{s}$. It is not yet possible to stop the mobility in $\mathbf{W} = \mathbf{V} \times \mathbf{Y}$. JKL stops all degrees, so this system is sufficient to realize the setting up. Manufacturing requirement of holes D is given in Fig. 17b. It is not possible to keep mobility $r\mathbf{Y}(O)$.

If the two holes are realized in different phases, then it should study the first hole like for requirement R2, and the second will be located regarding A for primary datum and the first hole for secondary datum.

6 Software

6.1 Aims

TZT method was initialized by B. Anselmetti in 2007 reported the digital factory project of the competitiveness pole System@tic. Procedure has been developed in VBA in CATIA, with a processing in Excel. The finished part is described by the CAD model, and requirements are defined in functional tolerancing annotation (FTA) workbench. The aim is to allow a process planer to test quickly several manufacture plannings. For each manufacture planning, software must give manufacturing tolerancing, with an optimization of tolerance repartition. In 2007, the software works in a single dimension.

6.2 Initialization

6.2.1 *Export of the part geometry on excel*

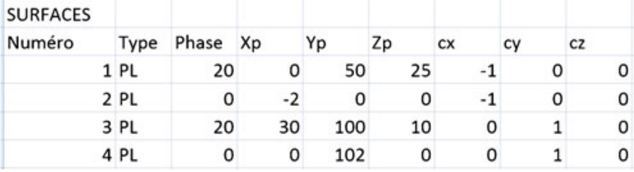
The method will proceed in Excel, with macro developed in VBA. So it is necessary to get geometry of the part somewhere in Excel. That is why a sheet is created to realize a link between Excel and Catia. This sheet will be the base of any calculation. A macro will automatically produce a table, with any surfaces of the part, and for each part type of the surface, coordinate, name of this surface on Catia, and any information regarding this surface and useful for calculation (Fig. 18).

6.2.2 *Export of FTA information*

After the geometry, it is necessary to know the functional specifications to determine the manufacturing specifications. So there are two steps to obtain the functional specifications in Excel. Firstly, a macro identifies all specifications in a new sheet, with its name, the number of surfaces concerned with this specification, and the name in Catia of each surface (Fig. 19).

Secondly, the program will fill the first sheet, with a new table describing annotations, adding to previous information values of specifications, modifier, type of tolerance zone, and any useful information. It also links annotations and surfaces listed in the previous step (Fig. 20).

With these information, it will be possible now to describe process planning and next to obtain manufacturing specifications. Particularly, with Fig. 3, it is possible to obtain vectorial representation of each tolerance zone and datum.



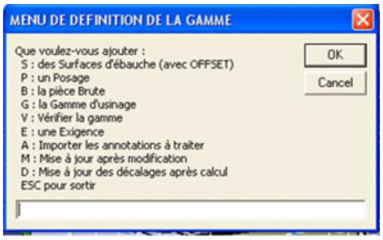
SURFACES

Numéro	Type	Phase	Xp	Yp	Zp	cx	cy	cz
1	PL	20	0	50	25	-1	0	0
2	PL	0	-2	0	0	-1	0	0
3	PL	20	30	100	10	0	1	0
4	PL	0	0	102	0	0	1	0

Fig. 18 Export of the part geometry

N°spécif.	Symbole	Type surface	Surf.spécifiée	zone	Tolérance
1	Planéité.1	PL	5	p	0,01
2	Référence simple.1	PL	5		
3	Tolérance linéaire.20	CYG	'27,28		0,02
4	Référence simple.7	CYG	'27,28		

Fig. 20 Link between geometry and FTA information



MENU DE DEFINITION DE LA GAMME

Que voulez-vous ajouter :
S : des Surfaces d'ébauche (avec OFFSET)
P : un Posage
B : la pièce Brute
G : la Gamme d'usinage
V : Vérifier la gamme
E : une Exigence
A : Importer les annotations à traiter
M : Mise à jour après modification
D : Mise à jour des décalages après calcul
ESC pour sortir

Fig. 21 Main dialog box

6.3 Process planning description

6.3.1 Creation of intermediary surfaces

A dialog box allows us to realize all operations described thereafter (Fig. 21).

Intermediary surfaces are offset surfaces created from finished part to raw part, adding material. The model presented in Fig. 22 includes finished surfaces, intermediate surfaces, and raw surfaces.

These surfaces are described on the three construction of Catia, without notion of manufacturing order. It will be possible to test quickly several manufacturing planning with these surfaces.

6.3.2 Setting up description

Each setting up is described by the selection of primary, secondary, and tertiary surface. In the actual state of the software, isostatism points are not defined (Fig. 23).

6.3.3 Manufacturing process

The manufacturing process is described in the three constructions of Catia. This description is composed by a list of manufacturing phases. For each phase, there is a setting up and a list of operations. Each operation uses a tool to create one or several surfaces (Fig. 24).

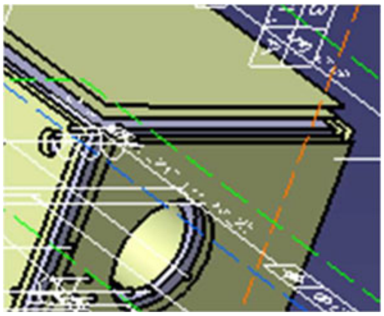
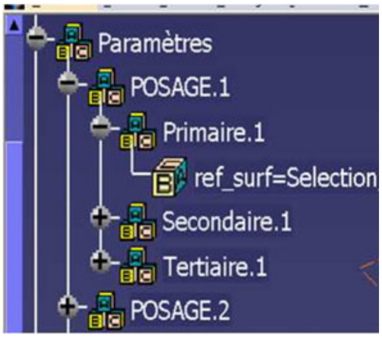


Fig. 22 Creation of offset surfaces



Paramètres
POSAGE.1
Primaire.1
ref_surf=Selection
Secondaire.1
Tertiaire.1
POSAGE.2

Fig. 23 Setting up description

An offset surface disappears when it is selected. When the manufacturing planning is over, all offset surfaces must have been selected and must not be on screen.

6.4 Generation of manufacturing specifications

When the manufacturing planning is described, a procedure on Catia will export data in Excel sheets.

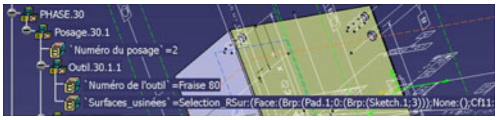
Exported data are:

- Used surfaces (final or intermediaries)
- Functional requirements (from CAD model)
- Manufacturing requirements (minimal cutting thickness…)
- Setting up
- Manufacturing planning

All elements are stored in a table, like for the manufacturing planning in Fig. 25.

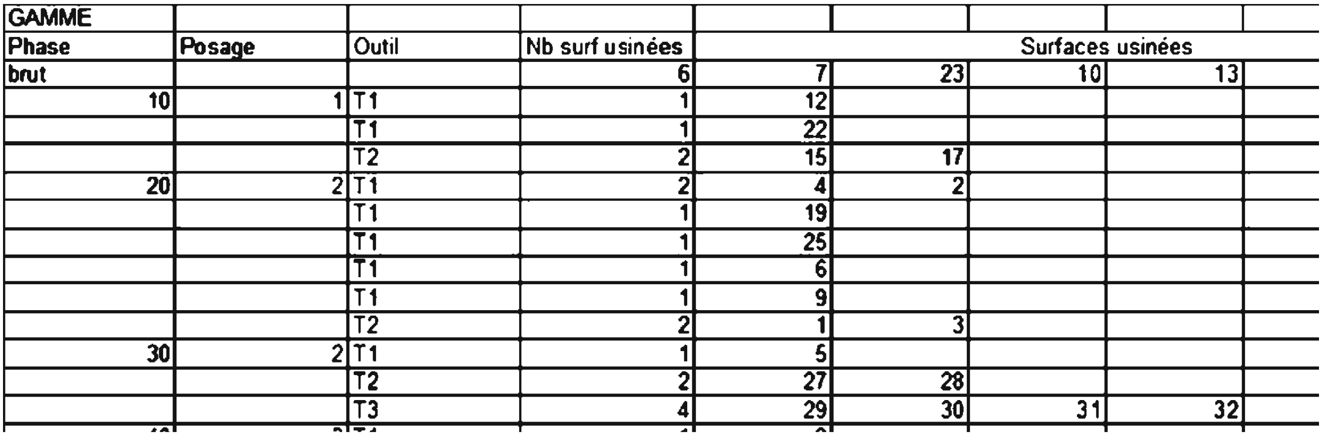
From these elements, transfer will progress automatically, in the same way than in Section 3 and 4. The software can actually determine manufacturing specifications to write on phase drawing, but it cannot yet optimize tolerance and generate phase drawing in CAD system.

Methods presented in this paper are in integration in order to introduce three-dimensional approach.



PHASE.30
Posage.30.1
`Numéro du posage` =2
Outil.30.1.1
`Numéro de l'outil` =Fraise 80
`Surfaces_usinées` =Selection_RSur:(Face:(Brp:(Pad.1;0:(Brp:(Sketch.1;3)));None:();Cf11:

Fig. 24 Phase description



GAMME							
Phase	Posage	Outil	Nb surf usinées	Surfaces usinées			
brut			6	7	23	10	13
10	1	T1	1	12			
		T1	1	22			
		T2	2	15	17		
20	2	T1	2	4	2		
		T1	1	19			
		T1	1	25			
		T1	1	6			
		T1	1	9			
		T2	2	1	3		
30	2	T1	1	5			
		T2	2	27	28		
		T3	4	29	30	31	32

Fig. 25 Manufacturing planning in Excel

7 Conclusion and outlooks

Method presented makes it possible to choose manufacturing specifications to write on phase drawing. However, it is not possible yet to determine tolerances. The aim is now to use line analysis, developed by B. Anselmetti at the LURPA, to determine inequations to respect functional tolerancing, and to optimize values of manufacturing specifications [2]. Finally, the aims will be to use manufacturing specifications determined to generate automatically each phase drawing.

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