3D Manufacturing Tolerancing with Analysis Line Method Taking into Account Joining Operations During Manufacturing Process

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Procedia CIRP
14th CIRP CAT 2016 - CIRP Conference on Computer Aided Tolerancing
Volume 43, 2016, pp 88-93

Abstract

In the aeronautic field, parts need many phases of machining and joining. The presentation proposes to apply analysis line method on manufacturing transfer. This method realizes both specification synthesis and tolerance analysis. The major contribution is a set of rules which make possible to calculate a three-dimensional transfer in the case of braze welding operations. For each functional requirement, the conditions are expressed as sets of linear relations on production deviations, from blank parts to finished part. These relations allow specification of blank parts, machining phases and braze welding phases. The method is applied on a part from Snecma.

Keywords: 3D ISO manufacturing tolerancing, joining process, braze welding, tolerance analysis, analysis line method.

1 The context

1.1 The tolerancing process

Classically, the engineering department decides the geometry and functional specifications of the part. The manufacturing engineer must choose a manufacturing process which is capable of meeting the functional requirements. The manufacturing transfer consists in choosing the specifications which must be met in each phase and allocating the tolerances.
Snecma wants a new approach to the tolerancing process (Fig.1), introduced in [10], which consists in expressing the production specifications directly with respect to the datum systems of the phases. This approach enables one to identify the mother specifications for tracking and adjusting each tool.

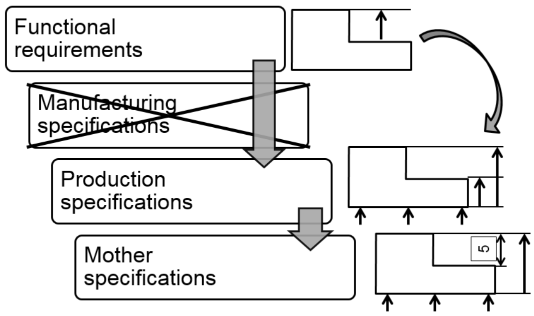

Figure 1: The new approach to the tolerancing process [10]

1.2 Braze welding

For some complex parts, the manufacturing process consists in machining a set of components which are then assembled by braze welding prior to carrying out the finishing machining operations.
In order to braze two weld components together, each one is set-up isostatically (as shown by arrows in Fig.2) on a part holder. A sheet of filler metal is inserted between the components (Fig.2). Metal beads are spot welded in order to maintain the components in position (Fig.2). Then the whole set is removed and introduced into a furnace to complete the braze welding process.
The relative positions of the components become frozen; the relative deviations of the surfaces of the two components are due to:

- the defects in the surfaces of the components before brazing,
- the defects induced by the braze welding operation itself. These defects are due mainly to the defects in the part holder for the brazing.

The main difficulty in the manufacturing transfer is controlling the relative positions of the two components, which requires manufacturing specifications for the braze welding operation.

1.3 State of the art

There are two preferred approaches to the analysis of manufacturing tolerances.
The first approach consists in carrying out operations in domains which model manufacturing deviations. The resultant of these domains gives an image of the actual finished part. This resultant must meet the functional requirements. Thus, the Model of Manufactured Parts (MMP)

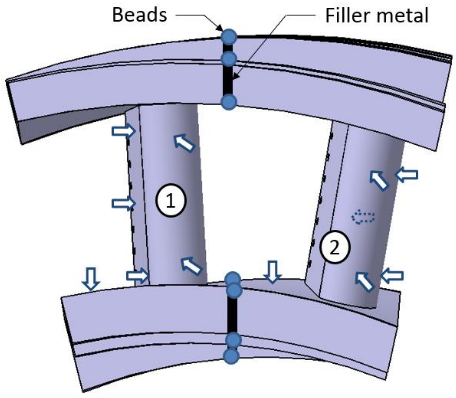

Figure 2: Braze welding of a high pressure turbine nozzle.

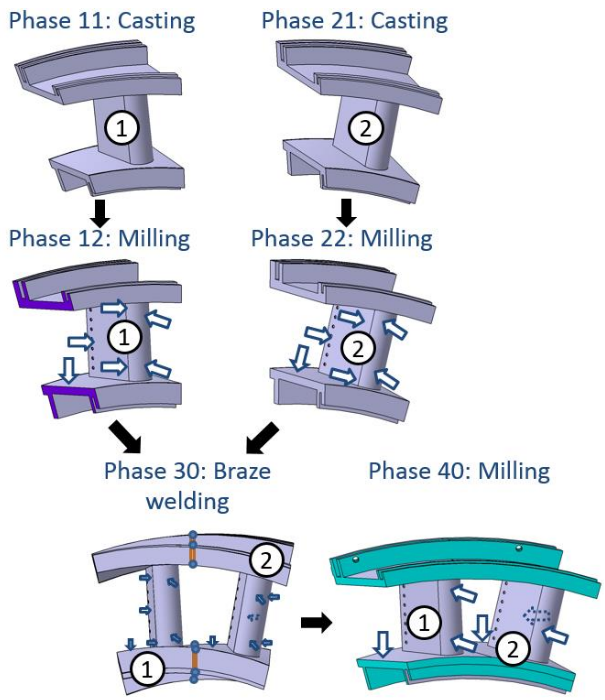

Figure 3: Process plan.

proposed by Villeneuve and Vignat is the resultant of the deviations due to machining and to positioning dispersions [14, 12]. These deviations are expressed through the small-displacement torsor (SDT) [5]. More recently, Haghighi defined M-Maps, which model the resultant of the manufacturing defects determined by simulation [8].

The second approach consists in propagating the manufacturing deviations induced by each phase by means of calculations. This is the type of approach which is used in the Δl method. This method, which was developed by Bourdet [4], enables one to express the functional or manufacturing requirements as an accumulation of manufacturing specifications through a one-dimensional calculation. This method was extended to 2D and 3D problems by Anselmetti [1]. 3D calculation methods based on SDT have been proposed by Ballot [3], Laifa [9] and Ayadi [2].

Here, the analysis line method proposed by Anselmetti [1] is extended to braze welded assemblies. The methods proposed in the literature are used mainly for machining operations. Nevertheless, Vignat takes into account the specificities of blanks obtaining through casting or forging in the definition of MMP models [13]. In addition, Dahlström and Söderberg study the

geometric quality of welded assemblies, particularly in the case of spot welding in the automotive industry [7, 6, 11].
The contribution of this article is a three-dimensional manufacturing tolerance analysis method which can be used when rough or machined components are assembled by braze welding prior to further machining operations on the braze welded assembly.

2 Analysis of the requirement

2.1 The industrial application

The approach can be illustrated with a very simplified high pressure turbine nozzle taken from the Snecma product range. The process plan for this part is shown in Fig.3.
The blanks of the two components are obtained by casting. These components are then machined before being joined together by braze welding. The assembly of the two components forms a new part on which additional machining operations are carried out.

2.2 Coordinate systems R, R_1, R_2, R'_1 and R'_2 on the parts

For a machining process, the analysis line method requires that all the deviations of the machined surfaces due to manufacturing dispersions be expressed in the same coordinate system R. This system is set in the CAD model of the finished part. The model is supplemented with all the nominal rough and blank surfaces. This model is positioned with respect to the actual part using the datum system of the first machining phase.
In the case of a braze welded assembly, five coordinate systems are necessary for a good understanding of the phenomena induced by the assembly process. The coordinate system R_1 is positioned on the actual part using the partial datum system of the first machining phase of component 1: F_1, F_2, F_3, F_4, F_5, H_1 (Fig.7). Likewise, the coordinate system R_2 is defined in reference to component 2.
The coordinate system R'_1 is positioned on the actual part using the setting-up system of component 1 during the braze welding operation: F_1, F_2, F_3, F_4, F_5, H_1. For this example, $R'_1 = R_1$. The same applies to R'_2 on component 2.
The coordinate system R is positioned on the actual part using the datum system of the braze welding phase. It is recommended to take R equal to R'_1 or R'_2. In the example considered, R is positioned on the braze welding setting-up system of component 2: E_1, E_2, E_3, E_4, E_5, G_1. Thus, $R = R'_2$.
In order to simplify the calculations, the positions of the 5 coordinate systems are identified nominally with the CAD coordinate system of the finished part.

2.3 Analysis of the requirement

The functional requirement to be studied is the location of the axis of a hole S on the blade of component 1 with respect to the datum reference frame (see Fig.4). The transfer consists in studying the deviations of the two ends M and M' of hole S with respect to the datum reference frame in all the directions $\mathbf{n_i}$ normal to the axis (Fig.4). This calculation is carried out along an analysis line going through point $M\begin{pmatrix}30 & -9.3 & 44\end{pmatrix}$ in the direction $\mathbf{n}\begin{pmatrix}-0.049 & 0 & -0.99\end{pmatrix}$. For the functional requirement to be met, the deviation must be less than or equal to 0.1 mm.

The nominal positions of surfaces A, B, C, D and of the axis of S in the coordinate system R are represented in Fig.5 by dotted lines. In practice, each surface was manufactured with a deviation with respect to this coordinate system R. The actual surfaces are shown in Fig.5 as

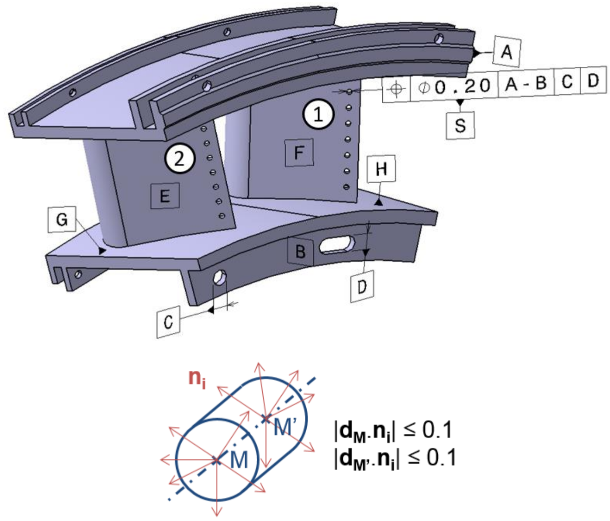

Figure 4: Functional requirement and naming of surfaces; Analysis if the requirement (top to bottom).

continuous lines. The objective is to determine the position of the actual axis of hole S with respect to the datum reference frame of the requirement based on the actual surfaces. The requirement is decomposed according to the following relation:

$$d_S\left(M,\mathbf{n}\right)_{/ABCD} = d_S\left(M,\mathbf{n}\right)_{/R} - d_{ABCD}\left(M,\mathbf{n}\right)_{/R} \tag{1}$$

where $d_S\left(M,\mathbf{n}\right)_{/ABCD}$ is the deviation being sought, *i.e.* the distance between the point M belonging to the actual axis of S and the nominal point M based on the datum reference frame $A-B|C|D$ in direction $\mathbf{n}$;
$d_S\left(M,\mathbf{n}\right)_{/R}$ is the displacement of the point M belonging to the actual axis of S with respect to R in direction $\mathbf{n}$;
$d_{ABCD}\left(M,\mathbf{n}\right)_{/R}$ is the displacement of the nominal point M based on the datum reference frame $A-B|C|D$ with respect to R in direction $\mathbf{n}$.

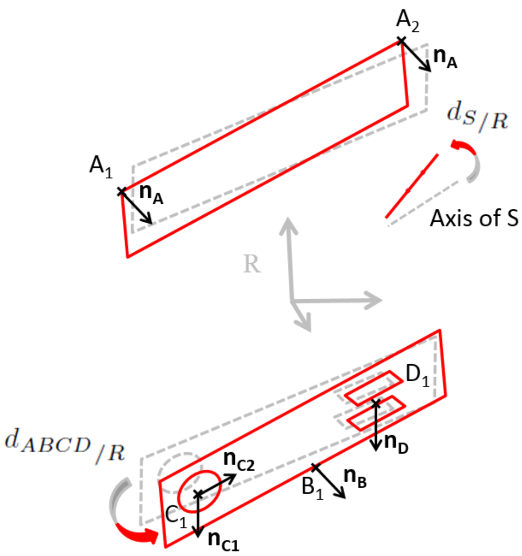

Figure 5: Decomposition of the requirement.

2.4 Decomposition of the requirement

In order to calculate the displacement $d_{ABCD}\left(M,\mathbf{n}\right)_{/R}$, one has to model datum reference frame $A-B|C|D$ using an isostatic system. Points A_1, A_2, B_1, C_1, D_1 and the associated normals are shown in Fig.5. The nominal position of the point M belonging to the axis of S is defined with respect to the datum reference frame which goes through these 6 points. This nominal model behaves like a solid. Its displacement, which is due to the deviations of the points of the isostatism with respect to R, can be modeled using a SDT characterized by a translation at the origin $\begin{pmatrix} u & v & w \end{pmatrix}$ and by a rotation $\begin{pmatrix} \alpha & \beta & \gamma \end{pmatrix}$ (Eq.2).

$$\begin{pmatrix} u \\ v \\ w \\ \alpha \\ \beta \\ \gamma \end{pmatrix} = \begin{pmatrix} 0.15 & -0.17 & 0.02 & 0.32 & 0.99 & -0.19 \\ 0.19 & 0.01 & 0.80 & 0 & 0 & 0 \\ -0.16 & -0.14 & 0.30 & 0.49 & -0.14 & 0.50 \\ -0.01 & -0.01 & 0.01 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.02 & 0 & -0.02 \\ -0.01 & 0.01 & -0.01 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} d_A\left(A_1,\mathbf{n_A}\right)_{/R} \\ d_A\left(A_2,\mathbf{n_A}\right)_{/R} \\ d_B\left(B_1,\mathbf{n_B}\right)_{/R} \\ d_C\left(C_1,\mathbf{n_{C_1}}\right)_{/R} \\ d_C\left(C_1,\mathbf{n_{C_2}}\right)_{/R} \\ d_D\left(D_1,\mathbf{n_D}\right)_{/R} \end{pmatrix} \tag{2}$$

Thus, the displacement $d_{ABCD}\left(M,\mathbf{n}\right)_{/R}$ of point M can be expressed as a function of the displacements of points A_1, A_2, B_1, C_1, D_1 (Eq.3). This relation shows that it is possible to express the deviation of a point of a solid as a function of the deviations of the isostatism points of this solid.

$$\begin{aligned} & d_{ABCD}\left(M,\mathbf{n}\right)_{/R} \\ & = \begin{pmatrix} -0.05 & 0 & -1.00 & 9.28 & 28.04 & -0.46 \end{pmatrix} \\ & \quad \begin{pmatrix} u & v & w & \alpha & \beta & \gamma \end{pmatrix}^T \\ & = \begin{pmatrix} 0.08 \\ 0.09 \\ -0.17 \\ 0.04 \\ 0.09 \\ -1.04 \end{pmatrix}^T \begin{pmatrix} d_A\left(A_1,\mathbf{n_A}\right)_{/R} \\ d_A\left(A_2,\mathbf{n_A}\right)_{/R} \\ d_B\left(B_1,\mathbf{n_B}\right)_{/R} \\ d_C\left(C_1,\mathbf{n_{C_1}}\right)_{/R} \\ d_C\left(C_1,\mathbf{n_{C_2}}\right)_{/R} \\ d_D\left(D_1,\mathbf{n_D}\right)_{/R} \end{pmatrix} \end{aligned} \tag{3}$$

Thus, the requirement is decomposed as a linear combination of the displacements of points M, A_1, A_2, B_1, C_1, D_1 (Eq.4):

$$\begin{aligned} d_S\left(M,\mathbf{n}\right)_{/ABCD} = & \; d_S\left(M,\mathbf{n}\right)_{/R} \\ & - \begin{pmatrix} 0.08 \\ 0.09 \\ -0.17 \\ 0.04 \\ 0.09 \\ -1.04 \end{pmatrix}^T \begin{pmatrix} d_A\left(A_1,\mathbf{n_A}\right)_{/R} \\ d_A\left(A_2,\mathbf{n_A}\right)_{/R} \\ d_B\left(B_1,\mathbf{n_B}\right)_{/R} \\ d_C\left(C_1,\mathbf{n_{C_1}}\right)_{/R} \\ d_C\left(C_1,\mathbf{n_{C_2}}\right)_{/R} \\ d_D\left(D_1,\mathbf{n_D}\right)_{/R} \end{pmatrix} \end{aligned} \tag{4}$$

3 The manufacturing transfer

3.1 Principle of the transfer

The objective is to express the transfer relation as a sum of displacements of surfaces with respect to their respective datum systems. These displacements shall be expressed using production tolerances during the synthesis of the production specifications. Each point which appears in the transfer relation (4) belongs to a surface which is created in a phase (S in phase 12 and A, B, C, D in phase 40). The transfer is carried out sequentially one phase at a time, beginning with the most recently created surface of those which appear in the transfer relation. The first surfaces which must be studied are surfaces A, B, C and D, which are manufactured in phase 40.

3.2 Study of phase 40

Surfaces A, B, C, D are manufactured with some defects with respect to the datum reference frame of phase 40, defined from the contact points of the part on the set-up. In addition, the contact surfaces of the part themselves were manufactured with defects in the previous phases. Thus, in order to determine the displacement of surfaces A, B, C, D with respect to R, one must calculate, on the one hand, the displacements of surfaces A, B, C, D with respect to the coordinate system R_{40} of phase 40 and, on the other hand, the displacement of R_{40} with respect to R. For example, the relation for point A_1 is:

$$d_A\left(A_1,\mathbf{n_A}\right)_{/R} = d_A\left(A_1,\mathbf{n_A}\right)_{/R_{40}} + d_{R_{40}}\left(A_1,\mathbf{n_A}\right)_{/R} \tag{5}$$

Since surface A is created in phase 40, the displacement $d_A\left(A_1,\mathbf{n_A}\right)_{/R_{40}}$ of A_1 belonging to A with respect to R_{40} shall be controlled using a production specification of surface A in phase 40. One still has to calculate the displacement $d_{R_{40}}\left(A_1,\mathbf{n_A}\right)_{/R}$ of R_{40} with respect to R at point A_1. The deviations of contact points E_6, E_7, E_8, F_6, G_1, H_1 (whose positions are described in Fig.6) result in a rigid displacement of R_{40} with respect to R which can be expressed through a SDT. Thus, the displacements of points A_1, A_2, B_1, C_1 et D_1 are expressed as linear combinations of the displacements of points E_6, E_7, E_8, F_6, G_1, H_1. This leads to the transfer relation after phase 40, which contains the terms related to R_{40}, and to the production specifications in phase 40 (Eq.6):

$$\begin{aligned} d_S\left(M,\mathbf{n}\right)_{/ABCD} = {} & d_S\left(M,\mathbf{n}\right)_{/R} \\ & + \begin{pmatrix} -0.19 \\ 0.34 \\ 0.10 \\ -0.13 \\ 0.01 \\ 1.02 \end{pmatrix}^T \begin{pmatrix} d_E\left(E_6,\mathbf{n_{E_6}}\right)_{/R} \\ d_E\left(E_7,\mathbf{n_{E_7}}\right)_{/R} \\ d_E\left(E_8,\mathbf{n_{E_8}}\right)_{/R} \\ d_F\left(F_6,\mathbf{n_{F_6}}\right)_{/R} \\ d_G\left(G_1,\mathbf{n_{G_1}}\right)_{/R} \\ d_H\left(H_1,\mathbf{n_{H_1}}\right)_{/R} \end{pmatrix} \\ & + \begin{pmatrix} -0.08 \\ -0.09 \\ 0.17 \\ -0.04 \\ -0.09 \\ 1.04 \end{pmatrix}^T \begin{pmatrix} d_A\left(A_1,\mathbf{n_A}\right)_{/R_{40}} \\ d_A\left(A_2,\mathbf{n_A}\right)_{/R_{40}} \\ d_B\left(B_1,\mathbf{n_B}\right)_{/R_{40}} \\ d_C\left(C_1,\mathbf{n_{C_1}}\right)_{/R_{40}} \\ d_C\left(C_1,\mathbf{n_{C_2}}\right)_{/R_{40}} \\ d_D\left(D_1,\mathbf{n_D}\right)_{/R_{40}} \end{pmatrix} \end{aligned} \tag{6}$$

Surface S is manufactured in phase 12 on component 1. The displacement $d_S\left(M,\mathbf{n}\right)_{/R}$ depends on the braze welding operation and on the manufacturing deviation $d_S\left(M,\mathbf{n}\right)_{/R_1}$ of component 1 prior to braze welding.

3.3 Change of coordinate system

In order to express displacement $d_S(M,\mathbf{n})_{/R}$ as a function of $d_S(M,\mathbf{n})_{/R_1}$, one carries out a change of coordinate system using Eq.7.

$$\begin{aligned} d_S(M,\mathbf{n})_{/R} &= d_S(M,\mathbf{n})_{/R_1} \\ &\quad - d_{R'_1}(M,\mathbf{n})_{/R_1} + d_{R'_1}(M,\mathbf{n})_{/R} \end{aligned} \tag{7}$$

This relation involves the displacement $d_S(M,\mathbf{n})_{/R_1}$ which is to be calculated from the manufacturing transfer associated with the process plan of component 1.
The displacements $d_{R'_1}(M,\mathbf{n})_{/R}$ and $d_{R'_1}(M,\mathbf{n})_{/R_1}$ model the deviation between R_1 of component 1 and R of the braze welded assembly. In addition, we chose $R_1 = R'_1$, which makes the term $d_{R'_1}(M,\mathbf{n})_{/R_1}$ equal to zero and simplifies the transfer.

3.4 Calculation of $d_{R'_1}(M,\mathbf{n})_{/R}$

The displacement of R'_1 with respect to R is viewed as a rigid displacement and is expressed by means of a SDT. The components of the SDT depend linearly on the displacements of the isostatism points of R'_1 : F_1, F_2, F_3, F_4, F_5 and H_1. Thus, the displacement along $\mathbf{n}$ of the point M belonging to R'_1 can be expressed as a linear combination of the displacements of points F_1, F_2, F_3, F_4, F_5 and H_1 (Eq.8).

$$\begin{aligned} & d_{R'_1}(M,\mathbf{n})_{/R} \\ &= \begin{pmatrix} -0.05 & 0 & 1.00 & 9.28 & 28.04 & -0.46 \end{pmatrix} \\ &\quad \begin{pmatrix} u & v & w & \alpha & \beta & \gamma \end{pmatrix}^T \\ &= \begin{pmatrix} -0.05 & 0 & 1.00 & 9.28 & 28.04 & -0.46 \end{pmatrix} \\ &\quad \begin{pmatrix} -0.61 & 0.19 & 0.10 & 0.23 & -1.10 & 0.05 \\ -0.64 & 1.48 & -1.81 & -0.17 & 0.69 & 0 \\ -0.31 & 0.49 & -0.11 & -0.98 & 1.07 & 1.00 \\ -0.04 & 0.04 & 0 & -0.01 & 0.01 & 0 \\ 0.01 & -0.01 & 0 & -0.03 & 0.03 & 0 \\ -0.02 & -0.03 & 0.05 & 0 & 0 & 0 \end{pmatrix} \\ &\quad \begin{pmatrix} d_F(F_1,\mathbf{n_{F_1}})_{/R} \\ d_F(F_2,\mathbf{n_{F_2}})_{/R} \\ d_F(F_3,\mathbf{n_{F_3}})_{/R} \\ d_F(F_4,\mathbf{n_{F_4}})_{/R} \\ d_F(F_5,\mathbf{n_{F_5}})_{/R} \\ d_H(H_1,\mathbf{n_{H_1}})_{/R} \end{pmatrix} = \begin{pmatrix} 0.35 \\ -0.51 \\ 0.10 \\ 0.12 \\ -0.18 \\ -1.00 \end{pmatrix}^T \begin{pmatrix} d_F(F_1,\mathbf{n_{F_1}})_{/R} \\ d_F(F_2,\mathbf{n_{F_2}})_{/R} \\ d_F(F_3,\mathbf{n_{F_3}})_{/R} \\ d_F(F_4,\mathbf{n_{F_4}})_{/R} \\ d_F(F_5,\mathbf{n_{F_5}})_{/R} \\ d_H(H_1,\mathbf{n_{H_1}})_{/R} \end{pmatrix} \end{aligned} \tag{8}$$

Finally, the transfer relation becomes Eq.9.

$$
\begin{aligned}
d_S(M,\mathbf{n})_{/ABCD} &= d_S(M,\mathbf{n})_{/R_1} \\
&+ \begin{pmatrix} 0.35 \\ -0.51 \\ 0.10 \\ 0.12 \\ -0.18 \\ -1 \\ -0.19 \\ 0.34 \\ 0.10 \\ -0.13 \\ 0.01 \\ 1.02 \end{pmatrix}^T
\begin{pmatrix} d_F(F_1,\mathbf{n_{F_1}})_{/R} \\ d_F(F_2,\mathbf{n_{F_2}})_{/R} \\ d_F(F_3,\mathbf{n_{F_3}})_{/R} \\ d_F(F_4,\mathbf{n_{F_4}})_{/R} \\ d_F(F_5,\mathbf{n_{F_5}})_{/R} \\ d_H(H_1,\mathbf{n_{H_1}})_{/R} \\ d_E(E_6,\mathbf{n_{E_6}})_{/R} \\ d_E(E_7,\mathbf{n_{E_7}})_{/R} \\ d_E(E_8,\mathbf{n_{E_8}})_{/R} \\ d_F(F_6,\mathbf{n_{F_6}})_{/R} \\ d_G(G_1,\mathbf{n_{G_1}})_{/R} \\ d_H(H_1,\mathbf{n_{H_1}})_{/R} \end{pmatrix} \\
&+ \begin{pmatrix} -0.08 \\ -0.09 \\ 0.17 \\ -0.04 \\ -0.09 \\ 1.04 \end{pmatrix}^T
\begin{pmatrix} d_A(A_1,\mathbf{n_A})_{/R_{40}} \\ d_A(A_2,\mathbf{n_A})_{/R_{40}} \\ d_B(B_1,\mathbf{n_B})_{/R_{40}} \\ d_C(C_1,\mathbf{n_{C_1}})_{/R_{40}} \\ d_C(C_1,\mathbf{n_{C_2}})_{/R_{40}} \\ d_D(D_1,\mathbf{n_D})_{/R_{40}} \end{pmatrix}
\end{aligned}
\tag{9}
$$

This relation involves the displacement of S with respect to R_1. Before carrying out the transfer of $d_S(M,\mathbf{n})_{/R_1}$ in component 1, one must study the braze welding phase.

3.5 Study of the braze welding phase

The coordinate system R is based on the braze welding setting-up surfaces of component 2. Therefore, the displacements of these setting-up surfaces (E, G) with respect to R are equal to zero. The transfer relation simplifies to (10). The displacements of the points of F and H, which are the braze welding setting-up surfaces of component 1, are to be expressed using production specifications. Since surface S is manufactured in phase 12, this phase must be studied in order to complete the transfer.

$$
\begin{aligned}
d_S(M,\mathbf{n})_{/ABCD} &= d_S(M,\mathbf{n})_{/R_1} \\
&+ \begin{pmatrix} 0.35 \\ -0.51 \\ 0.10 \\ 0.12 \\ -0.18 \\ -1 \\ -0.13 \\ 1.02 \end{pmatrix}^T
\begin{pmatrix} d_F(F_1,\mathbf{n_{F_1}})_{/R_{30}} \\ d_F(F_2,\mathbf{n_{F_2}})_{/R_{30}} \\ d_F(F_3,\mathbf{n_{F_3}})_{/R_{30}} \\ d_F(F_4,\mathbf{n_{F_4}})_{/R_{30}} \\ d_F(F_5,\mathbf{n_{F_5}})_{/R_{30}} \\ d_H(H_1,\mathbf{n_H})_{/R_{30}} \\ d_F(F_6,\mathbf{n_{F_6}})_{/R_{30}} \\ d_H(H_1,\mathbf{n_{H_1}})_{/R_{30}} \end{pmatrix} \\
&+ \begin{pmatrix} -0.08 \\ -0.09 \\ 0.17 \\ -0.04 \\ -0.09 \\ 1.04 \end{pmatrix}^T
\begin{pmatrix} d_A(A_1,\mathbf{n_A})_{/R_{40}} \\ d_A(A_2,\mathbf{n_A})_{/R_{40}} \\ d_B(B_1,\mathbf{n_B})_{/R_{40}} \\ d_C(C_1,\mathbf{n_{C_1}})_{/R_{40}} \\ d_C(C_1,\mathbf{n_{C_2}})_{/R_{40}} \\ d_D(D_1,\mathbf{n_D})_{/R_{40}} \end{pmatrix}
\end{aligned}
\tag{10}
$$

3.6 Study of phase 12

R_1 was defined on the datum system of the first machining phase of component 1, *i.e.* $R_1 = R_{12}$. Thus, $d_S\left(M, \mathbf{n}\right)_{/R_1} = d_S\left(M, \mathbf{n}\right)_{/R_{12}}$ and the transfer relation becomes:

$$d_S\left(M,\mathbf{n}\right)_{/ABCD} = \begin{pmatrix} 1 \\ 0.35 \\ -0.51 \\ 0.10 \\ 0.12 \\ -0.18 \\ -1 \\ -0.13 \\ 1.02 \\ -0.08 \\ -0.09 \\ 0.17 \\ -0.04 \\ -0.09 \\ 1.04 \end{pmatrix}^T \begin{pmatrix} d_S\left(M,\mathbf{n}\right)_{/R_{12}} \\ d_F\left(F_1,\mathbf{n_{F_1}}\right)_{/R_{30}} \\ d_F\left(F_2,\mathbf{n_{F_2}}\right)_{/R_{30}} \\ d_F\left(F_3,\mathbf{n_{F_3}}\right)_{/R_{30}} \\ d_F\left(F_4,\mathbf{n_{F_4}}\right)_{/R_{30}} \\ d_F\left(F_5,\mathbf{n_{F_5}}\right)_{/R_{30}} \\ d_H\left(H_1,\mathbf{n_{H}}\right)_{/R_{30}} \\ d_F\left(F_6,\mathbf{n_{F_6}}\right)_{/R_{30}} \\ d_H\left(H_1,\mathbf{n_{H_1}}\right)_{/R_{30}} \\ d_A\left(A_1,\mathbf{n_{A}}\right)_{/R_{40}} \\ d_A\left(A_2,\mathbf{n_{A}}\right)_{/R_{40}} \\ d_B\left(B_1,\mathbf{n_{B}}\right)_{/R_{40}} \\ d_C\left(C_1,\mathbf{n_{C_1}}\right)_{/R_{40}} \\ d_C\left(C_1,\mathbf{n_{C_2}}\right)_{/R_{40}} \\ d_D\left(D_1,\mathbf{n_{D}}\right)_{/R_{40}} \end{pmatrix} \quad (11)$$

This linear relation yields the deviation of point M of S related to the nominal axis created in the datum reference frame, as a function of the manufacturing deviations in phases 12, 30 (braze welding) and 40.
Similar relations can be determined for the two ends of the axis of hole S and for the various analysis directions $\mathbf{n_i}$. All these relations contain the same points because these are the isostatism points of the phases. Only the coefficients differ.

4 Production specification synthesis

Now the transfer relation involves only surface displacements with respect to the datum systems of the phases. These displacements are controlled by the production specifications. These specifications are chosen using a method described in [10]. The production specifications are indicated on the phase drawings (Fig.6).
The displacements are expressed as functions of the production tolerances (see [10]): at most, they are equal to half the position tolerance. The final transfer relation for direction $\mathbf{n}$ at point M is:

$$\begin{aligned} d_S\left(M,\mathbf{n}\right)_{/ABCD} &= 0.09\ t_{A,loc,40} \ + \ 0.09\ t_{B,loc,40} \\ &+ 0.06\ t_{C,loc,40} \ + \ 0.52\ t_{D,loc,40} \ + \ 0.50\ t_{S,loc,12} \\ &+ \ 0.70\ t_{F,loc,30} \ + \ 1.01\ t_{H,loc,30} \leq 0.1 \end{aligned} \quad (12)$$

where $t_{Surf,pos,N}$ is a location tolerance of surface Surf with respect to the datum reference frame of phase N.
With a discretization in 8 directions $\mathbf{n_i}$ at each end of the axis, there are 16 such conditions which must be satisfied.

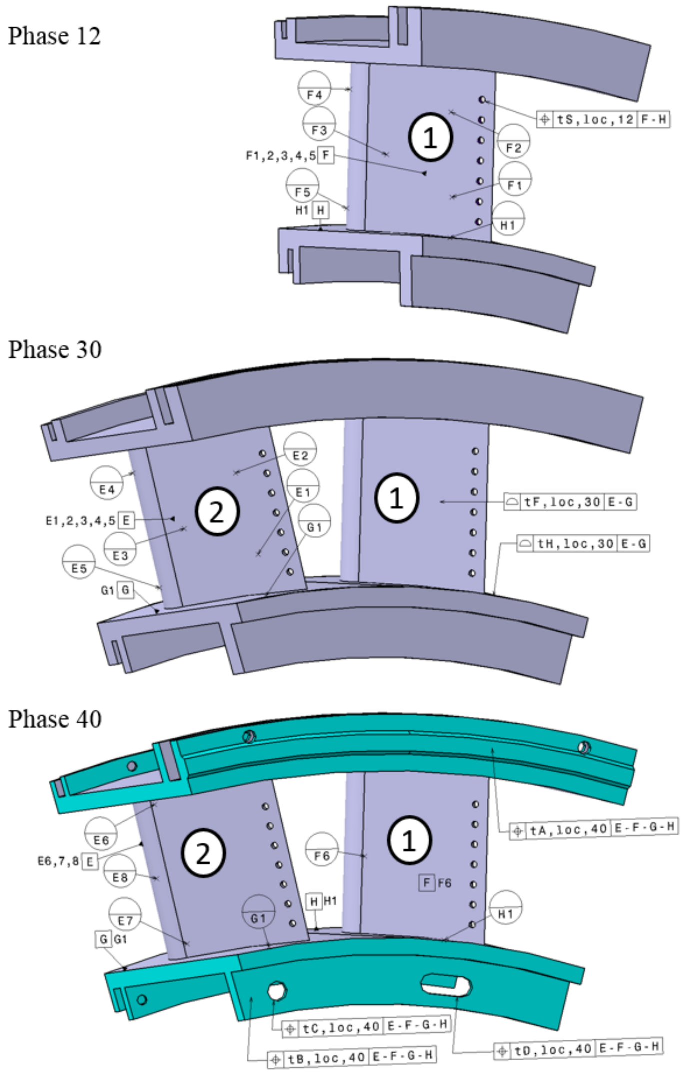

Figure 6: The phase drawings.

5 Conclusion

This paper shows that a 3D manufacturing transfer can be carried out using the analysis line method when braze welding operations are performed in the course of a machining plan. With this method, it is no longer necessary to consider that the braze welded assembly is a new blank; the transfer binds all the phases together, from the blanks of the components to the finished part. The method enables one to carry out both the production specification synthesis and the tolerance analysis. The resulting linear relations enable one to choose the production tolerances based on either a worst-case calculation or a statistical calculation.
This method also lends itself to other joining processes. The rules to be applied are the same as those discussed here provided that the relative positions of the components after assembly are given by a part holder. A possible extension of this work would be to carry out an inventory of industrial cases in order to propose appropriate rules for each assembly process.
Another development would be the implementation of this method into a Computer-Aided Tolerancing program in order to make it available in an industrial context.

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