Computer Aided Tolerancing and Dimensioning in Process Planning

D. Fainguelernt, R. Weill (1), P. Bourdet (2)

SUMMARY

It is well known that future computer integrated manufacturing systems will need fast and reliable production planning programs of different types. As a contribution to this requirement, this paper tries to demonstrate the feasibility of computerized tolerancing and dimensioning on a small micro-computer system.

The algorithm which is developed takes into account all categories of tolerances relevant in manufacturing such as setting, positioning, machining tolerances and proposes a strategy to optimize tolerance ranges in relation with functional requirements and equipment capabilities.

The application of the developed software to an industrial example shows the efficiency of the method and its simplicity.

INTRODUCTION

The objective in process planning is to define the production methods for a set of mechanical parts in strict accordance with drawing requirements. The whole process of production planning consists of a high number of choices relating to selection of machining conditions, selection of jigs and fixtures, selection of machine tools, sequencing of operations and, last but not least, determination of manufacturing dimensions and tolerances.

In many instances, however, the dimensions used in manufacturing are not identical with the dimensions on the drawing defined by the designer for functional purposes. Therefore the dimensions in manufacturing must be derived by appropriate calculations performed by the process planner. In other words, it is necessary that manufactured dimensions form chains of dimensions and tolerances compatible with drawing dimensions and tolerances, i.e. a manufactured dimension must fall in the tolerance range of the corresponding design dimension.

The process of transferring dimensions is called dimensioning and tolerancing, and despite its imporance, it seems that industries are not paying enough attention to this function.(1) The reasons for this negligence are mainly due to the large quantity of computations involved, the high probability of making calculation error, due to difficulty of differentiating between dependent and independent dimensions and to a lack of information concerning tolerance limits.

In order to help in executing dimensioning and tolerancing, a special algorithm is proposed in this paper, saving for the planner the boring activity of repetitive manual computations and eliminating almost completely the risk of errors in deriving tolerance relationships.

The theory behind the algorithm in this software was developed by P. Bourdet [2][3] and in contrast to traditional tolerance chain theories, it considers tolerances of position, as well as tolerances of machining. In addition, it makes a clear distinction between dependent and independent dimensions.

The problem of tolerance transfer has also enjoyed a new interest in the recent period because of its connection with computer aided process planing. Different papers have been published on the subject without proposing comprehensive solutions.

P. HOFFMANN[4] suggests to use linear programming to solve the problem of optimum tolerance allocation in manufacturing processes.

Taking a more practical point of view, L.E. FARMER[5] has developed an algorithm for changes of data in part design.

R.S. AHLUWALIA and A.V. KAROLIN[6] have designed a classical tolerance chart which is integrated in a computer system using graphical facilities. The work of tolerancing acquires better reliability and comfort for the process planner.

The work mentioned was concerned only with one dimensional tolerancing. Chr. BECK[7] has proposed methods to incorporate geometrical tolerances in dimension chains and M.B. ANSELMETTI[8] has given setting methods for the two dimensional case of turning taking into account cones and chamfers in particular. Unidirectional dimensioning has been reconsidered in the TECHNION[9] by basing the optimisation strategy on the fundamental work of P. BOURDET[2,3] and by trying to reach a very automatic computerized tolerancing although the algorithm is implemented on a small size microcomputer.

The module takes into account the main factors influencing tolerancing, i.e. machining errors, etting errors, workpiece positioning errors, wear of tools and proposes an optimisation strateghy for the determination of setting dimensions.

The process plan has first of all to be checked with respect to its technical feasibility and the distribution of tolerances has to be optimised, as will be shown later, in order to use completely the tolerance range allowed by design and to give to the setting function on the machine the largest allowances which will guarantee the most economical manufacturing. The determination of dimensions and tolerances in manufacturing will also influence the design of fixtures and the dimension of raw material[9] which play an important role in the industrialisation process.

The program is a useful tool for the process planner, when chosing the best way to manufacture a part. Several alternative process plans can be compared quickly and easily. In addition, the results represent a starting point for the optimal design of manufacturing jigs and fixtures. Finally, it is important to mention that the technician operating the computer-aided dimensioning and tolerancing program, needs not to have extended experience in computer applications.

The software developed was implemented on a micro-computer Apple IIe, making the program flexible and accessible to small-size industries.

DEVELOPMENT OF A MODEL FOR THE OPTIMISATION OF UNIDIRECTIONAL TOLERANCE TRANSFER FROM DESIGN TO MANUFACTURING

The basic model for tolerance transfer is represented in figure 1. The machine system of reference is represented by the coordinate system (X,Y) which is considered as the absolute system for tolerance references. Dimensions L_i, $(l_{im}, \Delta l_i)$ are dimensions measured in this sytem and refer to setting dimensions of tools, setting dimensions of parts, machining dimensions during the manufacturing process, in general "machine" dimensions. They are modelised by their average value l_{im} and their range of variations Δl_i. The "Machine" error is composed of errors resulting from setting errors, machining errors due to process inaccuracies, kinematic errors and wear of tool errors which are all included in Δl_i. A special case is represented by the dimension $(l_4^3, \Delta l_4^3)$ which is a tool dimension and is independent of the machine dimensions l_i.

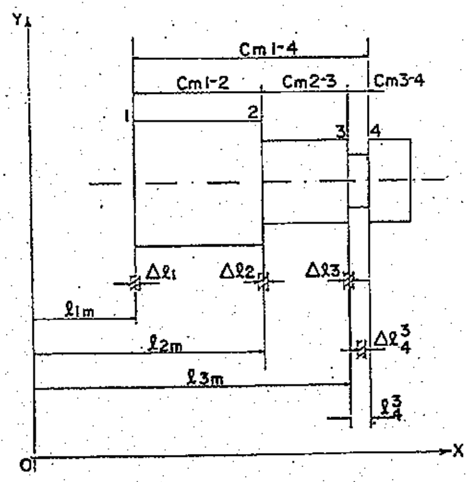

Fig. 1 Model for Tolerancing

Dimensions C_i $(C_{m\,ij})$ are measured on the manufactured part itself and represent "manufactured" dimensions. They have been defined before execution on the machine by design dimensions which represent the functional dimensions which have to be respected absolutely. The manufactured dimensions can be carried out directly or indirectly. In the latter case, the manufactured dimension is the resultant of a dimension chain consisting of independent machine dimensions as defined before. The manufactured dimensions are therefore dependent dimensions and the manipulation of their variabilities has to be carried out accordingly.

In order to simplify, it is assumed that dimensioning is carried out with the following procedure:

$C_{ijm} = D_{ijm}$ or identification of average values of design dimensions and manufactured dimensions

$\Delta C_{ij} \leq \Delta D_{ij}$ or identification of tolerance range for design and manufactured dimensions.

The optimisation of tolerance dimension transfer consists then in finding a strategy which guarantees on one hand the respect of design dimensions, and, on the other hand, takes into account the capabilities of available machinery and tries to take advantage of the maximum range of tolerance fields.

In the preceding model, chains of dimensions are composed of setting dimensions. These represent independent dimensions related to the machine-tool system of reference. The simple rules of composition of tolerances apply to these dimensions. In the future, it may be appropriate to transfer these values from the computer, where the process is being planned, directly to a computer controlled machine-tool, in order to execute the part according to these setting dimensions.

The model seeks optimal tolerances for manufacturing dimensions, considering the real conditions of manufacturing. Drawing (design) dimension tolerances are treated as constraints, and the objective is to calculate manufacturing dimensions as close as possible to the limiting design tolerances. In other words, the purpose is to manufacture a mechanical part, with the largest dimensional accuracy necessary for its correct functioning. The cost of machining is, of course, in direct relation with the accuracy required in manufacturing.

In addition, the optimization program finds minimal dimensions for the raw material blank and defines accordingly chip thicknesses which are of reasonable size.

The principle of optimisation will now be explained on the basis of a simple example.

Example of optimisation of tolerancing of a mechanical part

A mechanical part is represented in figure 2 and the corresponding process plan is the following, based on technological considerations:

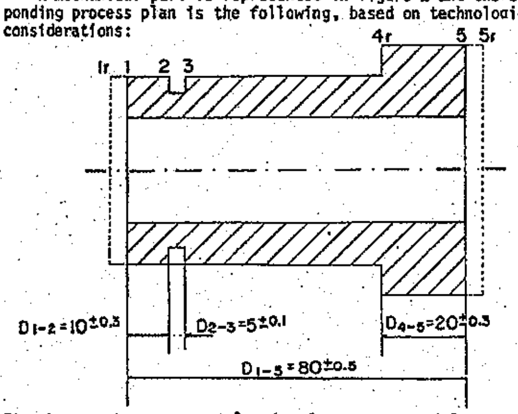

Fig. 2 Example of Part - 1r, 4r, 5r - raw material surfaces. D_{2-3} = tool dimension

Sub-phase 10- Fixture on surface 4r
- Machining of surface 5

Sub-phase 20- Fixture on surface 5
- Machining of surface 1
- Machining of surface 6

Sub-phase 30- Fixture on surface 5
- Machining of surfaces 2 and 3

The proposed process plan is just one of the many alternatives for fabricating the part. The developed program allows a comparative evaluation of various solutions in order to find the optimal one.

For the previous part, setting dimensions will be defined hereafter in the direction X for the different subphases:

Sub-phase 00- Casting

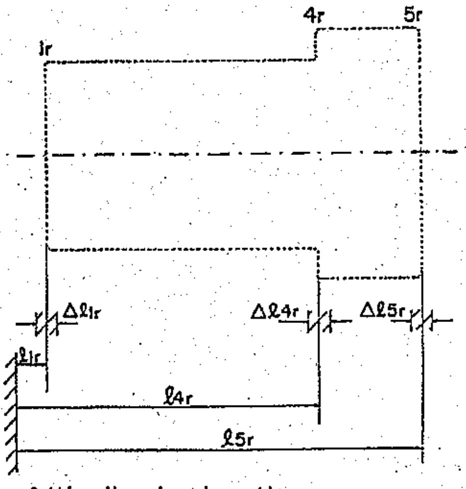

Fig. 3 Setting dimensions in casting

- Sub-phase 10

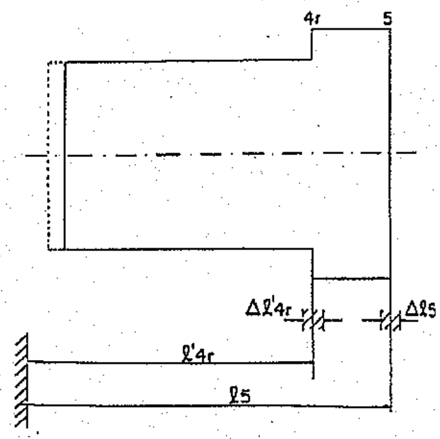

Fig. 4
Setting dimensions in Sub-phase 10.

Remark: (l'_i, $\Delta l'_i$) are positioning dimensions
(l_i, Δl_i) are machining dimensions.

- Sub-phase 20

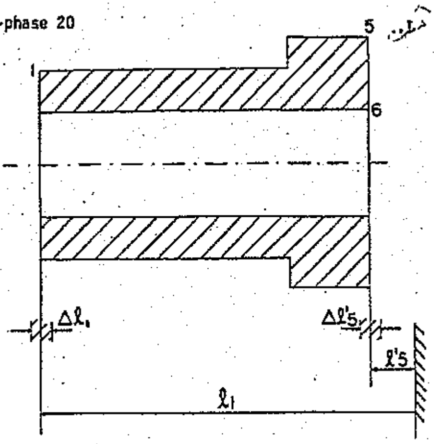

Fig. 5 Setting dimensions in sub-phase 20

- Sub-phase 30

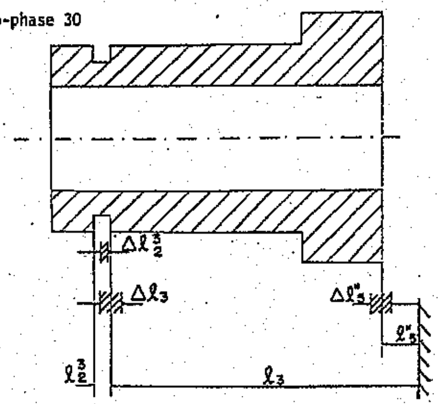

Fig. 6 Setting dimensions in sub-phase 30

A matrix (surface x sub-phase) is established (fig. 7) with initial setting tolerances Δl_i. These are chosen as the minimal tolerances feasible on the equipment used.

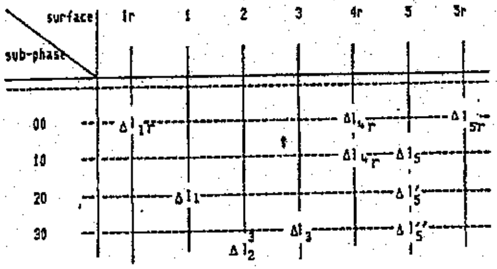

Fig. 7 Matrix sub-phase x surface

Remark: L_2^3 being a tool dimension (without any relation to other surfaces)

Δl_2^3 is located on a sub-line of the matrix.

Determination of optimal machine dimension tolerances

As mentioned before, the aim of tolerance optimization is to achieve:

$$\Delta C_{ij} = \Delta D_{ij}$$

Therefore, manufactured dimensions (C_{ij}) corresponding to one of the drawing dimensions (D_{ij}) have their tolerances C_{ij} computed according to the following rules:

a) if a constraint (ΔD_{ij}) relates to surfaces in the same sub-phase, then $\Delta C_{m\ i-j}$ is obtained by going from column i to column j along the same row.

For example: $\Delta C_{m4-5} = \Delta l'_{4r} + \Delta l_5$

b) If a constraint (ΔD_{ij}) relates to surfaces of difference phases (different diagram lines), one or more columns, relating to two or more subphases, must be used, and tolerances from these columns must be taken into account, e.g.:

$$\Delta C_{m1-2} = \Delta l_1 + \Delta l'_5 + \Delta l''_5 + \Delta l_3 + \Delta l_2^3$$

c) If a constraint (ΔD_{ij}) relates to surfaces which will be machined simultaneously (tool dimension),

$$(1) \qquad \Delta C_{m2-3} = \Delta l_2^3$$

A set of inequations is obtained as follows:

$$\Delta l_1 + \Delta l'_5 + \Delta l''_5 + \Delta l_3 + \Delta l_2^3 = \Delta C_{m1-2} \leqslant \Delta D_{1-2}$$

$$(2) \qquad \Delta l_2^3 = \Delta C_{m2-3} \leqslant \Delta D_{2-3}$$

$$\Delta l'_5 + \Delta l_1 = \Delta C_{m1-5} \leqslant \Delta D_{1-5}$$

$$\Delta l'_{4r} + \Delta l_5 = \Delta C_{m4-5} \leqslant \Delta D_{4-5}$$

The derivation can be adapted to automatic computer processing following the proposal of D. DURET[10].

If any of these inequations is not true, the process plan is not feasible and must be modified. Otherwise, the procedure of optimisation continues in order to find enlargedsetting tolerances Δl_i.

Before proceeding to this step, it is however necessary to introduce briefly the influence of tool wear.

Influence of tool wear and tolerances

A manufactured dimension will vary differently, depending on the direction of tool wear acting on the limiting surfaces of its component surfaces.

Tool wear develops differently (as a function of time), in different surfaces, according to the tool used, machining conditions, materials, etc. So, to express analytically the influence of relative tool wear, between two or more surfaces, each tool wear must be considered as a function of time, or as a function of the number of pieces the tool has cut previously, in the same batch.

For simplicity[11], we consider the maximum relative tool wear possible between machined surfaces, determining a manufactured dimension. Cases when tool wear develops in opposite directions are differentiated from cases when tool wear develops in the same direction.

A variable Δu was defined as follows:

$$\Delta u = \Sigma \Delta s_i - \underset{\text{in one direction}}{\text{Max}\,[\Delta S_i]} - \underset{\text{in the other direction}}{\text{Max}\,[\Delta S_i]}$$

where ΔS_i is the scattering due to tool wear in each setting tolerance (Δl_i) which composes a manufactured dimension tolerance (ΔC_{ij})

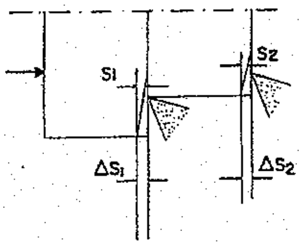

Fig. 8 Surfaces machined with identical wear direction

The explanation is given in Fig. 8 for the case of tool wear in the same direction.

In this case, relative tool wear which is equal to $|S_1 - S_2|$ can be evaluated as:

$$0 < |S_1 - S_2| < \Delta S_1 \text{ or } \Delta S_2$$

The manufactured tolerance ΔC_{12} is composed of $(\Delta l_i - \Delta S_i)$ which is the random wear and of max $|S_1 - S_2|$

$$\Delta C_{12} = (\Delta l_1 - \Delta S_1) + (\Delta l_2 - \Delta S_2) + \max(S_1 - S_2)$$

$$= \Delta l_1 + \Delta l_2 - \Sigma \Delta S_i + \max(\Delta S_1, \Delta S_2)$$

$$= \Delta l_1 + \Delta l_2 - \Delta u \text{ (as seen above)}$$

This relation is also applicable to the case of wear in opposite directions.

Optimization of setting dimensions

A tolerance matrix is constructed, taking into consideration the components of the inequations above. Each line represents one inequation only.

We start by entering the drawing dimension tolerances in the left column, and in the following columns we enter the setting dimensions tolerances (Δl_i, Δl_j), which together constitute the machined dimension tolerance ($\Delta C_{m\ i-j}$) corresponding to the drawing dimension tolerance (ΔD_{ij}) assigned in the left column. The table shows the excess of tolerances: $\varepsilon = \Delta D - \Delta C$, and

n = number of setting tolerances Δl_i multiplied by the coefficients of repartition. n defines the weight of each dimension in the distribution of the resitual tolerance. In this case, the residual tolerance will be shared equally between the Δl_i (coefficients of repartition = 1).

Coefficients of Repartition	1	1	1	1	1	1	1						
Set. Dim. Tol. / Design Dim. Tol.	Δl_1	Δl_2^3	Δl_3	$\Delta l'_{4r}$	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Sigma\Delta l$	ΔU	$\Delta C = \Sigma\Delta l - \Delta U$	$\varepsilon = \Delta D - \Delta C$	n	ε/n
$D_{1-2} = 0.65$	0.1	0.1	0.15	-	-	0.1	0.1	0.55	0.05	0.5	0.15	5	0.03
$D_{2-3} = 0.25$	-	0.1	-	-	-	-	-	0.1	0.05	0.15	0.1	1	0.1
$D_{1-5} = 1$	0.1	-	-	-	-	0.1	-	0.2	0	0.2	0.8	2	0.4
$D_{4-5} = 0.6$	-	-	-	0.15	0.15	-	-	0.3	0	0.3	0.3	2	0.15

Fig. 9: Tolerances' Matrix

The specific residual tolerance ε/n is shared among the component tolerances according to their weight.

It is assumed that $\Delta S_i = 0.05$ for $i = 1, \ldots, 5$

The purpose of the optimization procedure is to enlarge the setting dimension tolerances (Δl_i) as much as possible. Residual tolerances (ε) are redistributed among the setting tolerances. In fig. 10, the distribution is finalised and optimal.

The process follows an heuristic strategy which begins by distributing the smallest specific residual tolerance.

Then, in following steps, new residual tolerances are redistributed until no more excess is abailable (fig. 10). The tolerances assigned (Δl_i) are then considered as optimal.

A special case in the determination of the Δl_i arises in relation with the dimension of raw material l_B. An additional constraint is introduced by the minimum thickness of the first chip which is supposed to take away all the defects from casting or forging. Then, if $C_p$min is the minimum thickness required and if C_p is the tolerance of the chip thickness, resulting from the successive operations, one can write:

$$C_p \text{ average} = C_p \min + \Delta C_p/2$$

Coefficients of Repartition	-	-	-	-	-	-	-						
Set. Dim. Tol. / Design Dim. Tol.	Δl_1	Δl_2^3	Δl_3	$\Delta l_{4r}'$	Δl_5	$\Delta l_5'$	$\Delta l_5''$	$\Sigma\Delta l$	ΔU	ΔC $\Sigma\Delta l-\Delta U$	ε $\Delta D-\Delta C$	n	ε/n
$D_{1-2}=0.65$	0.13	0.13	0.18	-	-	0.13	0.13	0.7	0.05	0.65	0	0	-
$D_{2-3}=0.25$	-	0.13	-	-	-	-	-	0.13	-0.03	0.16	0.07	0	-
$D_{1-5}=1.0$	0.13	-	-	-	-	0.13	-	0.26	0	0.26	0.74	0	-
$D_{4-5}=0.6$	-	-	-	0.3	0.3	-	-	0.6	0	0.6	0	0	-

Fig. 10 Tolerance Matrix - Final distribution

The average dimension of the raw material l_B can then be determined as will be shown. It is also important to check that the variations of the chip thickness are not excessive and, eventually, to change the process plan accordingly. To this end provisions for half limited dimensions (max or min) are also included in the program (fig. 11).

Computation of Mean Values for Manufactured and Setting Dimensions

If the half-limited dimensions are reasonable, mean values of manufactured and setting dimensions may be computed.

This computation is straightforward. Based on the definition of setting dimensions, and using simple algebra only, a system of linear equations is obtained. For the previous example we obtain:

Design requirements:

$$d_{1-2} = (l_1 - l_5') - (l_3 + l_3^2 - l_5'')$$

$$d_{2-3} = l_3^2$$

$$d_{1-5} = l_1 - l_5'$$

$$d_{4r-5} = l_5 - l_{4r}'$$

Manufacturing requirements:

$$C_{1r-1_{mean}} = (l_{4r} - l_{1r}) + (l_5 - l_{4r}') - (l_1 - l_5')$$

$$C_{5-5r_{mean}} = (l_{5r} - l_{4r}) - (l_5 - l_{4r}')$$

For each sub-phase we define the position of the absolute reference system. Here we shall define the fixture positions as datum ($l_{4r} - l_{4r}' = l_5' = l_5'' = 0$). A system of six equations for six variables is obtained and average values of l_{1r}, l_{5r}, l_1, l_3, l_3^2, and l_5 are generated.

IMPLEMENTATION OF THE MODEL IN A MICRO-COMPUTER

The present model was implemented in a micro-computer composed of:

- A Computer Apple IIe with 64K bytes memory RAM
- Two Disk II disk storage systems.
- An Apple Dot matrix printer, connected to the main system by a grappler + TM interface card.

The program for process plan optimization of tolerances is carried out iteratively, following the flow-chart in fig.11:

a) Input of Workpiece data (drawing of the part and its dimensions).

b) Input of process plan data (sequence and kinds of operations, initial values for setting dimensions tolerances, etc.)

c) Optimization of Setting Dimensions Tolerances, with checking of feasibility

d) Computation of variations of the half-limited dimensions and of machine dimensions l_i

e) Computation of mean values of the setting dimensions. A special procedure(10), based on graph theory allows automatic determination of these results.

f) Output of results.

Example of Application to Dimensioning and Tolerancing of a Spindle Support

To illustrate the use of the computer program, it has been applied to a support for a machine tool spindle (fig.12).

The preceding optimisation procedure is used for manufactured dimensions and setting dimensions in three different directions independently (xx', yy', zz'). The computer output for direction yy' is shown in the following figures:

Part drawing and process plan matrices in fig.13, manufactured dimensions and setting dimensions with their tolerances in fig. 14A and 14B.

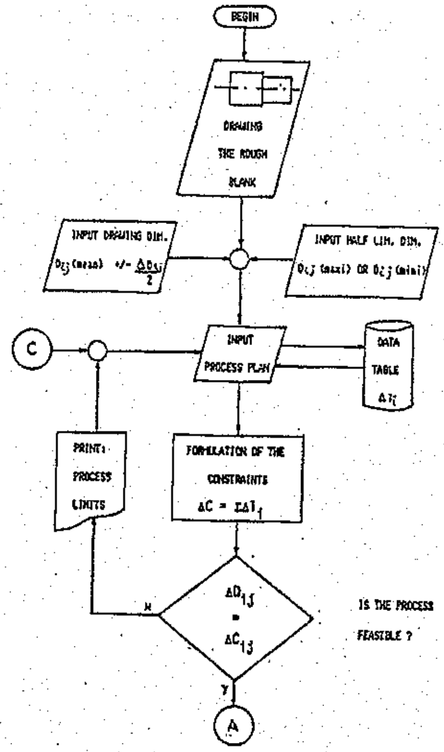

Fig. 11 Flow-chart of the computer program

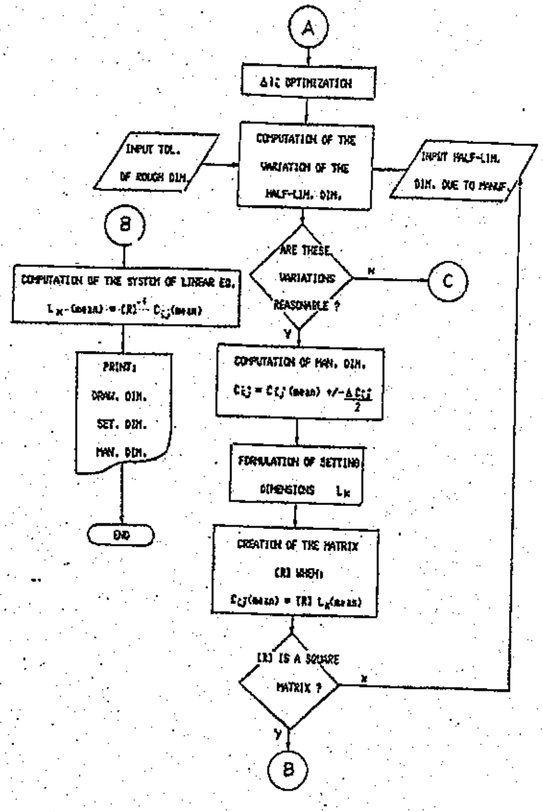

Fig. 11 Flow-chart of the computer program (contd.)

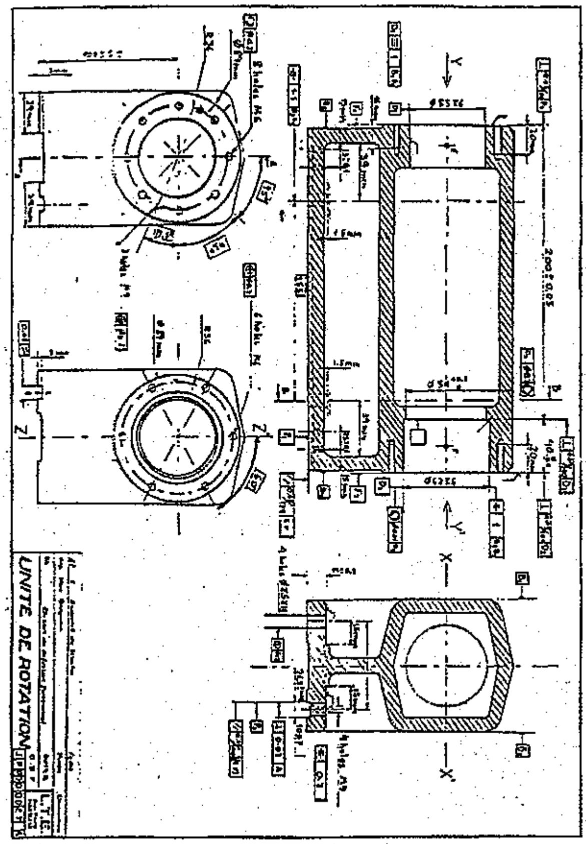

Fig. 12 Drawing of the spindle support

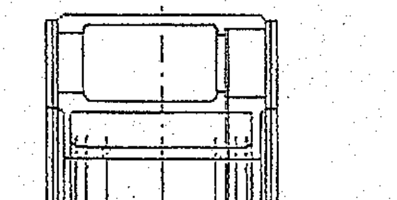

Fig. 13 Example of part drawing and dimensions (dir. yy')

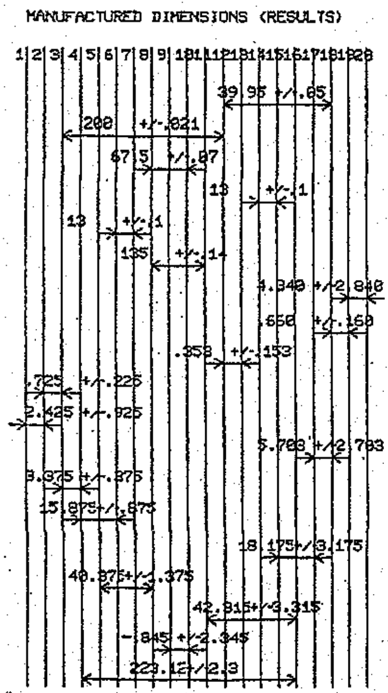

Fig. 14a. Manufactured Dimensions

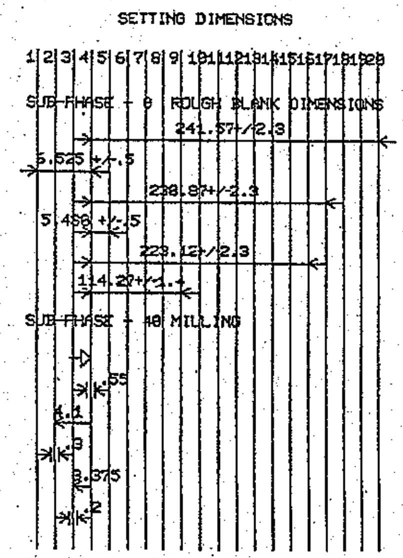

Fig. 14b Setting dimensions (partial)

CONCLUSIONS

In this paper, a computer program was developed in order to respond to the need of modern industries to implement computer aids in process planning, and, in particular, in tolerancing and dimensioning.

This program is based on a new model for dimensioning and tolerancing, developed in France by P. Bourdet (ref.2 and 3). This model takes into account tolerances of position, as well as machining tolerances, and also makes clear distinctions between dependent and independent variables. The proposed program also helps the operator to find minimal dimensions for the raw material blank and to define reasonable chip thicknesses during processing.

It was possible to implement this software on a micro-computer, making it flexible and accessible to small-size industries. A graphic unit for drafting the part on the screen, and a small data-base of recommended minimal setting dimensions tolerances, are improving the program efficiency and making it more user friendly.

The main advantage of this program lies probably in the high reliability of execution of tolerance transferring which takes a short time compared to manual processing and considers all the aspects involved. The use of the program is also straightforward, even for little trained personnel.

In the future, it is advisable to extend the model to three dimensional tolerancing, including consideration of geometrical tolerances. Such a development will need considerable efforts in the field of geometric tolerancing theory which is only in a starting stage and should be undertaken in a cooperative way by the Technical Committees of C.I.R.P.

BIBLIOGRAPHY

1. R. WEILL, Integrating Dimensioning and Tolerancing in Computer Aided Process Planning, II. International Conference on Manufacturing Science, Technology and Systems of the Future, Ljubljana, Sep.14-16,1985
2. P. BOURDET, Les Chaines de cotes de fabrication, L'Ingenieur et le Technicien de l'Enseignement Technique 11/12, 73, N-191, Mai-Juin 1975.
3. P. BOURDET, Cotation de Fabrication, Cours de l'Ecole Normale Superieure de l'Enseignement Technique, Cachan, France
4. P. HOFFMANN: Analysis of Tolerances and Process Inaccuracies in Discrete Part Manufacturing, Computer Aided Design, March 1982.
5. L.E. FARMER, Change of Datum of Dimensions on Engineering Drawings, Special Report, School of Mechanical and Industrial Engineering, The University of South Wales, Australia
6. R.S. AHLUWALIA, A.V. KAROLIN, CATC, A Computer Aided Tolerance Control System, Journal of Manufacturing Systems,Vol.3,No.2.
7. Chr. BECK, Einbeziehung von Form und Lageabweichungen in die Berechnung linearer Massketten, Feingeraetetechnik,Berlin 33 (1984)
8. M.B. ANSELMETTI, Simulation d'usinage bidimensionelle sur un exemple en tournage en commande numerique, Mecanique Materiaux Electricite, Mars, Avril 1983.
9. G. HALEVY, R. WEILL, Influence of Manufacturing Tolerances on Fixturing of Machine Parts in Process Planning Systems, 1st CIRP Working Seminar on Computer Aided Process Planning, Paris, January 22-23, 1985
10. D. DURET, Simulation de Gamme d'Usinage, L'Ingenieur et le Technicien de l'Enseignment Technique, N 220 et 230, Mars-Avril 1981
11. D. FAINGUELERNT, Development of a Computer Program for the Optimization of Tolerance Transfer from Design to Manufacturing, Master Thesis, March 1986, Technion, Israel Institute of Technology