Real Time Compensation of Machining Errors for Machine Tools NC based on Systematic Dispersion

M. Rahou, A. Cheikh, and F. Sebaa

Abstract—Manufacturing tolerancing is intended to determine the intermediate geometrical and dimensional states of the part during its manufacturing process. These manufacturing dimensions also serve to satisfy not only the functional requirements given in the definition drawing, but also the manufacturing constraints, for example geometrical defects of the machine, vibration and the wear of the cutting tool. In this paper, an experimental study on the influence of the wear of the cutting tool (systematic dispersions) is explored. This study was carried out on three stages. The first stage allows machining without elimination of dispersions (random, systematic) so the tolerances of manufacture according to total dispersions. In the second stage, the results of the first stage are filtered in such a way to obtain the tolerances according to random dispersions. Finally, from the two previous stages, the systematic dispersions are generated. The objective of this study is to model by the least squares method the error of manufacture based on systematic dispersion. Finally, an approach of optimization of the manufacturing tolerances was developed for machining on a CNC machine tool.

Keywords—Dispensations, Compensation, modeling, manufacturing Tolerance, machine tool.

I. INTRODUCTION

MANUFACTURING tolerancing is intended to determine the intermediate geometrical and dimensional states of the part during its manufacturing process. These manufacturing dimensions also serve to satisfy not only the functional requirements given in the definition drawing, but also the manufacturing constraints, for example geometrical defects of the machine, vibration and the wear of the cutting tool…

II. SOURCE OF ERROR

Before we look at how the task of error compensation can be achieved, we need to clearly understand what we mean by accuracy and error. Accuracy could be defined as the degree of agreement or conformance of a finished part with the required dimensional and geometrical accuracy [13]. Error, on the other hand, can be understood as any deviation in the position of the cutting edge from the theoretically required value to produce a workpiece of the specified tolerance. The extent of error in a machine gives a measure of its accuracy; that is the maximum translation error between any two points in the work volume of the machine. This of course depends on the resolution of the system. Positioning can never be more accurate than this as there will be no further feedback to improve the positioning within this range. However, more important than system resolution, are the errors that occur between the measurement point and the feedback point [14]. The best way to keep track of the errors is to formulate an error budget. An error budget allocates resources among the different components of a machine. It is a system analysis tool used for the prediction and control of the total error of a system. An error budget basically addresses two fundamental issues. One involves obtaining the influence of different sources of error (the individual members of the kinematic chain of the machine tool) on the accuracy of the machine. The other involves taking a set of specifications and determining the permissible level of each source so that some criterion like cost etc., is optimised [15]. Errors can be classified into two categories namely quasi-static errors and dynamic errors. Quasi-static errors are those between the tool and the workpiece that are slowly varying with time and related to the structure of the machine tool itself. These sources include the geometric/kinematic errors, errors due to dead weight of the machine’s components and those due to thermally induced strains in the machine tool structure. Dynamic errors on the other hand are caused by sources such as spindle error motion, vibrations of the machine…

control collision free tool path and post processing for NC-data.

In the work of [8], the authors present an experimental semi study of the vibratory behavior of the cutting tool golds of the operation of slide-lathing, is the object to show that it is possible to consider the roughness average of the part machined starting from displacement resulting from the nozzle of the tool. In the work of [9] a study was presented on the influence of the position of the cutting tool on dynamic behavior in milling of thin walls, and in work of [10,11,12], authors thus illustrate the influence of the trajectory of the cutting tool on the surface quality tolerances of manufacture for machining on the machine tool has numerical control.
Geometric errors are those errors that are extant in a machine on account of its basic design, the inaccuracies built-in during assembly and as a result of the components have been identified, the next step in the problem of error budgeting is to determine the optimal level of these errors so that the cost factor is minimised [15].

In general, a machining centre consists of a bed, column, spindle and its slide and the various linear and/or rotary axes. Each of these elements contributes to the total error of the system that is represented by the error budget. Errors can broadly be classified as:

a) Geometric errors of machine components and structures
b) Kinematic errors
c) Errors induced by thermal distortions
d) Errors caused by cutting forces including
   (i) by gravity loads
   (ii) by accelerating axes, and
   (iii) by the cutting action itself
e) Material instability errors
f) Machine assembly-induced errors
g) Instrumentation errors
h) Tool wear
i) Fixturing errors and
j) Other sources of errors like servo errors of the machine (following errors and interpolation algorithmic errors) [16,17,18].

A. Geometric and Kinematic Errors

Geometric errors are those errors that are extant in a machine on account of its basic design, the inaccuracies built-in during assembly and as a result of the components used on the machine.

As such, they form one of the biggest sources of inaccuracy. These errors are concerned with the quasi-static accuracy of surfaces moving relative to one another. Geometric errors can be smooth and continuous or they could exhibit hysteresis or random behaviour. These errors are affected by factors like surface straightness, surface roughness, bearing pre-loads etc. Geometric errors have various components like linear displacement error (positioning accuracy), straightness and flatness of movement of the axis, spindle inclination angle, squareness error, backlash error etc [17]. Kinematic errors are concerned with the relative motion errors of several moving machine components that need to move in accordance with precise functional requirements. These errors are particularly significant during the combined motion of different axes as in the case of gear hobbing or profile machining where co-ordination of rotary with respect to linear axes or linear with respect to linear axes is of prime importance. Such errors occur during the execution of linear, circular or other types of interpolation algorithms and are more pronounced during actual machining.

B. Thermal Errors

Another principal cause for inaccurate workpieces is error due to improper tool positioning on account of thermal deformation. It is well understood that errors due to thermal factors account for 40–70% of the total dimensional and shape errors of a workpiece in precision engineering [19].
The wear of the tool leads us to make an experimental study which makes it possible to show the influence of systematic dispersion on the manufacturing tolerances.

IV. PROCEDURE OF THE TESTS

It is difficult, if not impossible; to obtain manufacturing tolerances while being limited only to systematic dispersions. For this reason, it is necessary to take into account all dispersions. In order to achieve this goal, there are three stages:

1st stage:
The machining of the parts is done without the elimination of dispersions (random, systematic) so that one finds the manufacturing tolerances according to total dispersions.

2nd stage:
The results of the first stage were filtered in such way that one only finds the tolerances of manufacture according to random dispersions.

3rd stage:
From the two previous stages, we compute the systematic dispersions.

V. CONDITIONS OF THE TESTS

We have machined 40 parts, C35 matter, on lathe with numerical control using a facing tool with standard brought back pastille “J11ER”

We place the test in the following conditions:
- The wear of the tool is a linear function;
- Thermal balance is reached;
- Geometrical dispersion is immersed in random dispersion;
- The machining of surface 1 is carried out under phase with the same tool;

VI. STAGES OF MANUFACTURE

After having presented the procedure, let us detail the three stages of the study:

A. First Stage

Starting from a crude, we carried out 5 surfaces on a lathe white numerical control, (Fig. 3), by respecting the following parameters of the cut:

- Cutting speed: $C_s = 80 \text{ m/mn}$;
- Speed in advance: $F = 0.05 \text{ mm/tr}$;
- machining without lubrication;
- Depth of cut = 2 mm;

A program of machining was developed under a language FANUC (Fig. 3), for the realization of these tests:

On each part of the series, we measures dimensions $d_{12}$, $d_{13}$, $d_{14}$, $d_{15}$ and we calculates $d_{23}$.

From the equations (1), (2) and (3), we gives the statistical results (the average $X$, the standard deviations $\sigma_{ij}$ and $\Delta CF_{ij}$) illustrated in Table I.

### TABLE I

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{12}$</td>
<td>13.0052</td>
<td>3.489 10-2</td>
</tr>
<tr>
<td>$d_{13}$</td>
<td>22.0074</td>
<td>2.860 10-2</td>
</tr>
<tr>
<td>$d_{14}$</td>
<td>26.0076</td>
<td>3.199 10-2</td>
</tr>
<tr>
<td>$d_{15}$</td>
<td>31.0141</td>
<td>2.685 10-2</td>
</tr>
<tr>
<td>$d_{23}$</td>
<td>9.0020</td>
<td>3.369 10-2</td>
</tr>
</tbody>
</table>
\[ \sum_{i=1}^{N} n_i x_i \]
\[ v(x) = \sum_{i=1}^{N} \frac{n_i}{N} (x_i - \bar{x})^2 \]
\[ \sigma = \sqrt{v(x)} \]

The system (5) is deduced by the equation (4)

\[ \Delta CF_{ij} = \Delta l_i + \Delta l_j \]

\[ \begin{align*}
\Delta CF_{12} &= \Delta l_1 + \Delta l_2 \\
\Delta CF_{13} &= \Delta l_1 + \Delta l_3 \\
\Delta CF_{14} &= \Delta l_1 + \Delta l_4 \\
\Delta CF_{23} &= \Delta l_2 + \Delta l_3 \\
\Delta CF_{24} &= \Delta l_2 + \Delta l_4 \\
\end{align*} \]

The resolution of the system (5) leads to the solutions (6):

\[ \begin{align*}
\Delta l_1 &= 8.949 \times 10^{-2} \text{ mm} \\
\Delta l_2 &= 1.200 \times 10^{-1} \text{ mm} \\
\Delta l_3 &= 8.221 \times 10^{-2} \text{ mm} \\
\Delta l_4 &= 1.029 \times 10^{-1} \text{ mm} \\
\Delta l_5 &= 7.199 \times 10^{-2} \text{ mm} \\
\end{align*} \]

The results (6) represent total dispersions.

**B. Second Phase**

In this stage, formula (7) was used to filter dimensions of the first stage.

\[ d_{ij} = d_{ij} - \frac{\Delta CF_{ij}}{N} \]

\[ \Delta CF_{ij} : \text{The variation of the dimensions manufactured with systematic dispersion;} \]
\[ d_{ij} : \text{Filtered dimensions;} \]
\[ d_{ij} : \text{Dimensions according to total dispersion;} \]
\[ i : \text{Number of test;} \]

To calculate \( \Delta e_{ij} \), we trace for each \( d_{ij} \) the graphs (dij (N)) and average lines, Figs. 4, 5, 6, 7, 8.

\[ \Delta e_{ij} = \Delta l_{ij} \cdot N \]

The resolution of the system (8) gives the results of \( \Delta CF_{ij} \) represented by (9).

\[ \begin{align*}
\Delta CF_{12} &= 2.656 \times 10^{-2} \text{ mm} \\
\Delta CF_{13} &= 2.508 \times 10^{-2} \text{ mm} \\
\Delta CF_{14} &= 3.428 \times 10^{-2} \text{ mm} \\
\Delta CF_{23} &= 3.816 \times 10^{-2} \text{ mm} \\
\Delta CF_{24} &= 0.169 \times 10^{-2} \text{ mm} \\
\end{align*} \]

From the equation (7) and the system (9), calculation gives new dimensions (\( d_{ij} \)).
Table II represents the statistical results calculated starting from the equations (1), (2) and (3).

**TABLE II**

<table>
<thead>
<tr>
<th>X (mm)</th>
<th>δ (mm)</th>
<th>ΔCFaij (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>da12</td>
<td>12.992</td>
<td>3.403 10^-2</td>
</tr>
<tr>
<td>da13</td>
<td>21.995</td>
<td>2.767 10^-2</td>
</tr>
<tr>
<td>da14</td>
<td>25.991</td>
<td>3.042 10^-2</td>
</tr>
<tr>
<td>da15</td>
<td>30.995</td>
<td>2.448 10^-2</td>
</tr>
<tr>
<td>da23</td>
<td>9.003</td>
<td>3.369 10^-2</td>
</tr>
</tbody>
</table>

According to the equation (10), there is the system of expressions (11):

\[ \Delta CF_{ij} = \Delta a_i + \Delta a_j \] (10)

\[ \begin{align*}
\Delta CF_{a12} &= \Delta a_1 + \Delta a_2 \\
\Delta CF_{a13} &= \Delta a_1 + \Delta a_3 \\
\Delta CF_{a14} &= \Delta a_1 + \Delta a_4 \\
\Delta CF_{a25} &= \Delta a_2 + \Delta a_5 \\
\Delta CF_{a23} &= \Delta a_2 + \Delta a_3
\end{align*} \] (11)

The resolution of the system (11) leads to the solutions (12):

\[ \begin{align*}
\Delta a_1 &= 8.379 \times 10^{-2} \text{ mm} \\
\Delta a_2 &= 1.199 \times 10^{-1} \text{ mm} \\
\Delta a_3 &= 8.200 \times 10^{-2} \text{ mm} \\
\Delta a_4 &= 9.824 \times 10^{-2} \text{ mm} \\
\Delta a_5 &= 6.279 \times 10^{-2} \text{ mm}
\end{align*} \] (12)

The results of system (12) represent random dispersions.

**C. Third Stage**

In this stage we trace the graphs of the dimensions filtered (daij) according to many tests (N).

According to Figs. 9, 10, 11, 12, 13, we notice that the tangents are equal to zero. Therefore filtering is made completely. The replacement of the equation (13) in the system (14), leads to the system (15):

\[ \Delta CF_{sij} = \Delta s_i + \Delta s_j \] (13)

\[ \begin{align*}
\Delta CF_{s12} &= 2.656 \times 10^{-2} \text{ mm} \\
\Delta CF_{s13} &= 2.508 \times 10^{-2} \text{ mm} \\
\Delta CF_{s14} &= 3.428 \times 10^{-2} \text{ mm} \\
\Delta CF_{s15} &= 3.816 \times 10^{-2} \text{ mm} \\
\Delta CF_{s23} &= 0.169 \times 10^{-2} \text{ mm}
\end{align*} \] (14)

\[ \begin{align*}
\Delta s_1 &= 2.497 \times 10^{-2} \text{ mm} \\
\Delta s_2 &= 0.158 \times 10^{-2} \text{ mm} \\
\Delta s_3 &= 0.00105 \times 10^{-2} \text{ mm} \\
\Delta s_4 &= 0.931 \times 10^{-2} \text{ mm} \\
\Delta s_5 &= 1.319 \times 10^{-2} \text{ mm}
\end{align*} \] (15)

The results of system (15) represent systematic dispersion.

**VII. INTERPRETATION OF THE RESULTS**

Table III presents a recapitulation of the results of the dispersions calculated in the three stages.
TABLE III
RESULTS OF CALCULATED DISPERSIONS

<table>
<thead>
<tr>
<th>Surface</th>
<th>Total Dispersion (mm)</th>
<th>Random Dispersion (mm)</th>
<th>Systematic Dispersion (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface 1</td>
<td>$0.895 \times 10^{-1}$</td>
<td>$0.837 \times 10^{-1}$</td>
<td>$2.497 \times 10^{-2}$</td>
</tr>
<tr>
<td>Surface 2</td>
<td>$1.200 \times 10^{-1}$</td>
<td>$1.199 \times 10^{-1}$</td>
<td>$0.158 \times 10^{-2}$</td>
</tr>
<tr>
<td>Surface 3</td>
<td>$0.822 \times 10^{-1}$</td>
<td>$0.819 \times 10^{-1}$</td>
<td>$0.105 \times 10^{-2}$</td>
</tr>
<tr>
<td>Surface 4</td>
<td>$1.029 \times 10^{-1}$</td>
<td>$0.982 \times 10^{-1}$</td>
<td>$0.158 \times 10^{-2}$</td>
</tr>
<tr>
<td>Surface 5</td>
<td>$0.719 \times 10^{-1}$</td>
<td>$0.627 \times 10^{-1}$</td>
<td>$1.319 \times 10^{-2}$</td>
</tr>
<tr>
<td>Summon</td>
<td>$4.667 \times 10^{-1}$</td>
<td>$4.462 \times 10^{-1}$</td>
<td>$0.490 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

In Fig. 17 the graph of total dispersion is almost confused with the graph of random dispersion. The influence of systematic dispersions on the tolerances of manufacture is minimal compared to random dispersions.

The greatest value of systematic dispersions (Fig. 14) is on surface 1 used as reference surfaces, due to the influence of the machined surfaces 2, 3, 4, and 5, and the grinding problem of the tool.

On the other hand, the greatest value of random dispersions (Fig. 15) is on surface 2, then surface 4. The order of surfaces is not imperative; it has a relationship to the setting in position of the part in the chuck, the quality of tightening (manual or pneumatic) or the stop materializing the fifth point of isostatism. The smallest value is at the level of surface 3, since the latter is between two machined surfaces characterized by a small machining length.

The values of systematic dispersions are very small relative with total dispersion. The sum of the values of systematic dispersions is about 10% of the sum of total dispersions. Therefore random dispersion accounts for 90% of total dispersion.

Fig. 14 illustrates the percentage between the sum of the values of systematic dispersions and the sum of the values of total dispersions.

In this part, a modeling of the errors of dispersions was worked out by the method of Lagrange to develop two models of correction of the tolerances. In the first model, equation 16, we can calculate tolerances of manufacture due to systematic dispersion according to the machined length. In the second model, equation 17, we can calculate tolerances of manufacture according to the machined length.

$$IT = 6.5 \times 10^{-4} + 3\sqrt[3]{D} + 1.3 \times 10^{-5}D + 1.2 \times 10^{-5}$$  (16)
After the integration of tolerancing models in the numerical command control program, the new statistical results are given by the Table VI.

According to the results, the variations of manufacture (tolerance of manufacture) were decrease by 55%.

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>STATISTICAL RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (mm)</td>
<td>δ (mm)</td>
</tr>
<tr>
<td>d12</td>
<td>13.0022</td>
</tr>
<tr>
<td>d13</td>
<td>22.0024</td>
</tr>
<tr>
<td>d14</td>
<td>26.0016</td>
</tr>
<tr>
<td>d15</td>
<td>31.0031</td>
</tr>
<tr>
<td>d23</td>
<td>9.0002</td>
</tr>
</tbody>
</table>

IX. CONCLUSION

In this work, a step centered on three stages, was presented to calculate dispersions of machining and their influence on the intervals of tolerances. The influence of systematic dispersion accounts for 10% of the total discrepancies under the conditions normal and between 25% and 35%, if the parameters of cut or the cutting tool are badly selected.

The relative value of 10% of the tolerance is very important especially in work in series; because the wear of the tool influences the dimensions of adjustment. An error about the micron influences the overall costs of the end product and risk to guarantee the competitiveness of the product on the market.

Two models of compensation the error in the tool machine numerical control were developed, the first models it is the calculation of systematic dispersion according to the machined length; for the second it is the calculation of the tolerances of manufacture (total dispersions) according to the machined length. These models allowed us optimize the manufacturing dimensions, that is to say by integration in the command balls or in the machining programming.

REFERENCES


Mohamed Rahou was born in Tlemcen Province, Algeria, in 1979. He received his Eng, 2003 and Magister ,2006, in mechanical engineering from Abou Bakr Belkaid University, Algeria . Dr RAHOU is currently a lecturer in the Department of Sciences and technical Abou Bakr Belkaid University,Tlemcen, Algeria. His areas of interest are: Tolerancing and Numerical Command.