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12th CIRP Conference on Computer Aided Tolerancing

Process plans and manufacturing dimensions for the steering of machining: The Copilot-Pro® methodology

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Abstract
To set the machining, the technique commonly used is to measure dimensions between each machined surface and the one which locates the workpiece into the workpiece holder. This technique leads to dimensions with much smaller tolerances than the ones specified on the design drawing and to long time setting. On an example of a screw machining process we present the first stage of the Copilot-Pro® methodology. It consists in identifying the groups of manufacturing operations which must be done before extracting the workpiece from the machine-tool to measure the surfaces achieved. Thus, the number of workpieces extracted from the machine-tool is minimized which reduces the setting times, the number of unfinished and rejected workpieces and which permit to select manufacturing dimensions with higher tolerances.

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Keywords: Automatic lathe, Screw machining, Process plan, Manufacturing dimensions, tool correction, Copilot-Pro®

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1. Introduction

One of the daily issues of the setters of machining is to correct the shape and location of the cutting tools in order that workpieces meet the tolerances specified by the designers. The technique commonly used is to machine a first workpiece, then to extract it from the machine tool in order to measure it and finally to compute the corrections to the tools.

The dimensions which are measured on the workpiece do not correspond to the dimensions specified by the designer of the part. For instance, in order to adjust the final location of the tool 1 (see figure 1), the setter will measure the manufacturing dimension *CF1* instead of the dimensions *CE1* and *CE2* specified by the designer. Indeed it is easier to calculate the correction of tool 1 by measuring *CF1* than by measuring *CE1* and *CE2* which also depend on the location of tool 2. However, this method has several disadvantages:

- The setter will tend to measure *CF1* before making the surface 2. He will therefore mount and unmount the workpiece twice: Once for *CF1* and a second time for *CF2*, which lengthens the setting times.
- The tolerances of these manufacturing dimensions should be much smaller than the ones of the design dimensions *CEi*. On this example, *CF1* and *CF2* must have a tolerance about 0.1mm (±*0.05*mm) in order that the tolerance about 0.2mm (±0.1mm) of the *CE2* is guarantied, which is a division by two of the tolerances on this example.
- The conformity of the workpieces cannot be declared from these manufacturing dimensions because one would take the risk to reject workpieces which meet the design dimensions. For instance, *CF1* and *CF2* may have a deviation of *0.07*mm and therefore be out of the tolerance of ±*0.05*mm, whereas neither *CE1* nor *CE2* are out of their tolerances. Indeed, in this case, *CE1* has got a deviation of *0.07*mm and *CE2* none.

Nevertheless this method, historically attributed to Wade [1], [2], has largely been developed [3-13].

The main objective of the Copilot-Pro® methodology [14], presented in this paper, is to minimize the number of extracted workpieces from the machine. In this example, the workpiece, to be measured, will be extracted from the machine only once the two machining operations are performed. This objective has several advantages:

- The setting time, which include measuring time, is minimized.
- The number of setting workpieces is greatly reduced especially when the extracted workpiece can no longer be re-introduced in the machine. This is particularly the case in screw machining that requires the sawing of the workpiece from the bar in which it is machined (see figure 5).

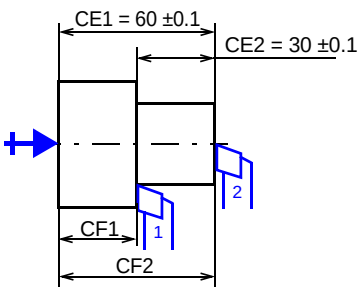

Fig. 1. Design dimensions specified by the designer, *CEi*, and manufacturing dimensions used by the setter, *CFi*.

- The manufacturing dimensions to measure, have got tolerances wider than those of the Wade's dimensions. They may even correspond, in some cases, to the tolerances of the design dimensions which permit, in this case, to verify the conformity of the workpieces without the risk of rejecting good parts [15].

In this example, the workpiece will be extracted after the machining of surfaces 1 and 2. The setter will be able to directly measure the design dimensions *CE1* and *CE2* which will allow to decide of the conformity of the workpiece and to calculate the corrections, c_i, to do on the tools through the following relationships, in which e_{CEi} are the deviation of the dimension *CEi* :

$$c_2 = -e_{CE1} \quad (1)$$

$$c_1 = e_{CE2} - e_{CE1} \quad (2)$$

These relationships are difficult to determine mentally in front of the machine, but it can be done in advance and provided to the setter who has then only to use them. We do not detail, in this paper, this aspect of the Copilot-Pro® methodology which has already been presented [16], but the technique used to group the machining operations before the extraction of a workpiece to measure the manufacturing dimensions and to correct the tools.

The conditions that permit to group the manufacturing operations, before the exit of a workpiece from the machine to measure its dimensions and to correct the tools, are not trivial. They are related to the work-in-progress of workpieces in the production flow and to the time constraints between operations especially when there are roughed surfaces to measure before the finishing operations are performed. We study these different conditions in the following sections before the presentation of the manual method for determining these groupings of manufacturing operations and the manufacturing dimensions for the correction of the tools.

2. Manufacturing phases and stages of the setting and monitoring plans Copilot-Pro®

We consider that the general case of a **manufacturing process** consists of **manufacturing stations**, after which the workpieces are stored or carried, and within which there are one or more **workpiece holders** enabling the achievement of one or more **manufacturing operations** (see figure 2)[1].

To set the manufacturing tools, it is necessary to measure at the start of production, and periodically during it, a workpiece just being machined (or multiple workpieces to reduce the random deviations by averaging the measured deviations). The least expensive is to measure and set the tools accordingly, just before it enters in a stock in order to do so in hidden time respected to production. However if the measured workpiece has a geometrical deviation greater than a defined acceptance limit, all the work-in-progress workpieces, from the manufacturing operation on responsible for this deviation and that probably also have the same geometrical deviation, will have to be scrapped. This is the first, of the two reasons, why it is not possible, in general, to wait until the end of the manufacturing process, to measure a workpiece and to set its tools accordingly. The second reason is that at the end of the process, the setter of the last manufacturing operations, may not have the control of the setting of the first operations, either because they are performed by another person, or because they have already been made on all workpieces.

So we have to divide chronologically the manufacturing process into manufacturing phases, at the end of which the measuring of workpieces will allows to set the manufacturing operations that they contain.

1. The description of the process according to the hierarchical model "Process / Station / Workpiece holding / Manufacturing Operation" is the formatted input data of the Copilot-Pro® method. Stocks and carriers systems are associated with stations that they precede.

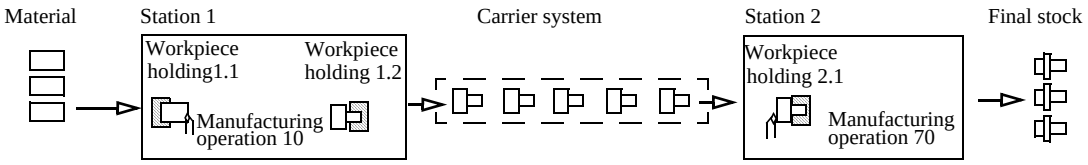

Fig. 2. General diagram of a manufacturing process according to the hierarchical model "Station / Workpiece-holders / Operations" of Copilot Pro®.

We define the **manufacturing phase** as the grouping of a set of manufacturing operations, performed on one or more workpiece holders, and which can be jointly set. The addition of a workpiece holding, and the manufacturing operations performed in this workpiece holder, in a phase already containing the previous workpiece holders, should be done taking into account the following two criteria:

- Can we jointly control the setting of the new operations with the operations already in the phase?
- Can we accept the work-in-progress increasing of workpieces that would result[1]?

In fact, even if all the manufacturing operations of a phase can be set, this will require measurement stages before the end of the phase because some surfaces will then disappear. This is especially true for rough surfaces of which the setting is nevertheless important because it determines the quality of the finished surface and the lifetime of the finishing tool.

However the introduction of intermediate measuring stages leads to, in most cases, increased cycle time of the measured workpiece. In order for this to not be the case, the intermediate measurement should be done at the storage or the carrying of the workpiece between workpiece-holders. However, the grouping in a single phase of two workpiece-holders, separated by a carrying or stock, is rarely possible. It is therefore in the just-in-time flow of the manufacturing operations that these measuring stages should be introduced to measure the surfaces that disappear. The increase in cycle time that would result is often not acceptable in industry. This has therefore led to define two Copilot-Pro® manufacturing plans for any manufacturing process:

- The **monitoring plan** for which a single measuring stage is defined at the end of each manufacturing stage and therefore can not set the tools of surfaces that disappear during the phase. This plan will be used with high frequency when the production is in progress.
- The **setting plan** in which intermediate measuring stages are defined in order to be also able to set the tools of which the surfaces disappear, including roughed surfaces. These intermediate measuring stages leading, in general, to an increase in cycle time, the setting plan will be used with a lower frequency than the monitoring plan and mostly requires a production stop in order to have time to extract the workpiece out of the machine and to measure it. It will also be used for initial setting of all tools before starting production.

To limit the number and duration of the intermediate measuring stages of the setting plan, we are going to seek to achieve the most manufacturing operations possible before having to do a measuring stage.

1. In classical productions, which are push flows, the Copilot-Pro® manufacturing phases correspond to manufacturing stations because those last end with stocks. We find here the commonly accepted sense of the term of the manufacturing phase. But the Copilot-Pro® definition, more general and more precise, allows to consider more important grouping of operations, especially in just-in-time flows.

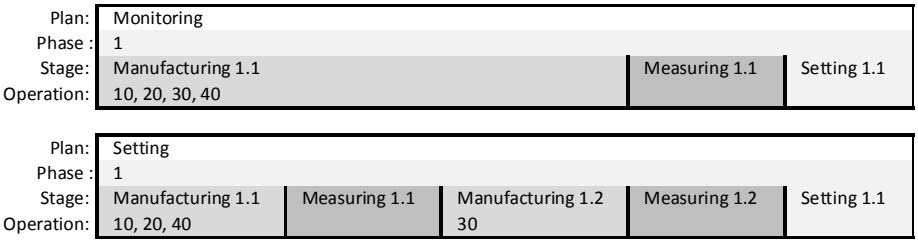

Fig. 3. Hierarchical organization of the Copilot-Pro® plans and typical chronological process of phases, stages and operations.

These groupings of operations before the measuring stages, are called the **manufacturing stages**. In the case of the monitoring plan, there is only one single manufacturing stage, followed by a single measuring stage and a single setting stage in a manufacturing phase, while for the setting plan, there may be several manufacturing stages, each followed by a measuring stage, and completed at the end of the phase, by a setting stage. The figure 3 illustrates this hierarchical organization of a plan in phases, stages and manufacturing operations, and their chronological sequences.

3. Manufacturing process taken in example

We consider the example of a part, of which the design drawing is given in figure 4, machined from a free-cutting bar on a automatic lathe, also called screw machine, according to the manufacturing process shown in figure 5.

The design dimensions of the workpiece are named *CE1*, *CE2* and *CE3* (see figure 5. The diameter dimensions are not indicated in order to simplify the presentation). These dimensions have got tolerances even if they are not indicated here. At any time, the location of the second workpiece holding (operation 50 on figure 5), which is performed by the secondary spindle of the machine, is well known relatively to the location of first workpiece holding, which is performed by the main spindle. This is why the workpiece is not laid on its plate surface in the second workpiece holder. The secondary spindle pinches the workpiece before the sawing off (operation 40), then moves back (operation 50) to permit the achievement of the operations 60 and 70.

4. Setting plan of the example process

On the manufacturing process presented in the previous section, the setter can simultaneously control all settings of the tools. In addition the work-in-progress of workpieces is acceptable.

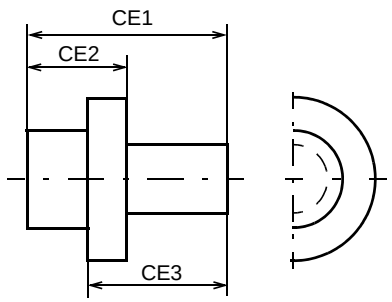

Fig. 4. Design drawing of the part.

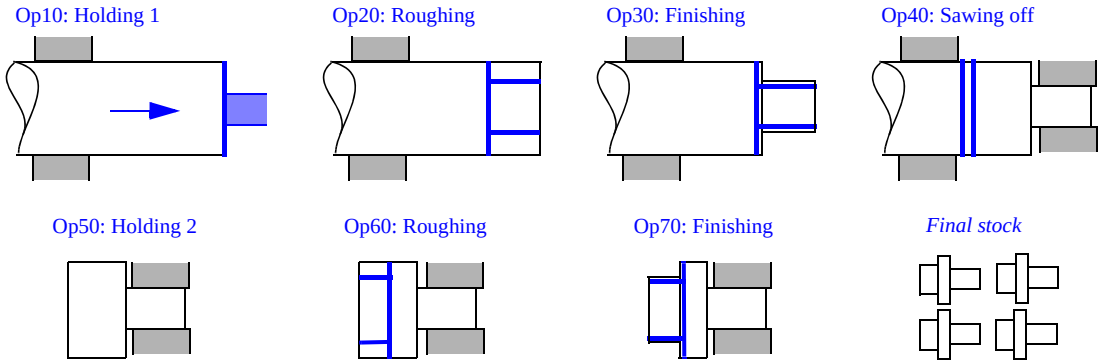

Fig. 5. Manufacturing process: A unique manufacturing station which is an automatic lathe with a secondary spindle.

If it is a single spindle lathe, it is about of two workpieces: One on the main spindle, the other on the secondary spindle. The two workpieces holders, and the manufacturing operations they allow to perform, can be placed in the same phase.

However, at the end of the manufacturing phase, the rough surfaces will be gone (operations 20 and 60). The monitoring plan does not allow us to adjust the location of these surfaces. We are therefore going to determine the manufacturing stages and the measuring stages of the setting plan necessary to set all the manufacturing operations.

To group the largest number of manufacturing operations before performing a measuring stage, we are going to discuss the constraints between operations, in relation with their grouping into a single manufacturing stage.

The most obvious constraint is that no operation of a stage in the setting plan, should remove a surface already done in the stage otherwise the operation which has machined this last surface could not be set. In particular, a roughing operation should be performed in a manufacturing stage **anterior** to the one containing the finishing operation. This constraint is the first in table 1. As the manufacturing stages are not yet established, this constraint will be introduced between the two operations. Graphically, we represent by an arc in thick line, oriented from the roughing operation towards the finishing operation (see arcs between operations 20 and 30 on the one hand, and 60 and 70 on the second hand, in figure 6).

On the other hand, there are technological constraints that impose a chronological order between operations (some operations can only be achieved if others have been before). These constraints, three in number, are explained in table 1, numbered 2, 3 and 4. They require that the first operation, in chronological order, is in an **anterior or identical** stage to the one containing the second operation. These constraints are represented graphically by a dashed arc oriented from the first operation to the second operation in the chronological order (see arcs in dashed lines on figure 6).

A last constraint is related to the Copilot-Pro® method of determining the manufacturing dimensions presented below. If, in a phase, a workpiece holding, uses a surface not manufactured or laid on in the phase, then it should open a new manufacturing stage. This is obviously the case of the first workpiece holding of the phase but it can also be the case for further workpiece holders in the phase even if it is uncommon.

In order that this workpiece holding opens a new stage, we should introduce constraints between the last manufacturing operations of the previous workpiece holders and this workpiece holder, in the aim to indicate that those operations should be placed in stages **anterior** to the one containing this new workpiece holding. This constraint is number 5 in the table. It occurs only very rarely and is not present

on the process presented in this article. The table below lists the five constraints that seem necessary and sufficient, until now, for the grouping of operations in manufacturing stages[1].

Table 1: Constraints between operations for their grouping in manufacturing stages.

#	Constraints	Representations on the graph of constraints
1	If an operation (like a finishing) removes the surface achieved by another (like a roughing), this last one must be in an anterior stage to the one containing the first[a].	Thick arc from the roughing operation towards the finishing operation.
2	Any workpiece holding must be made in an anterior or identical stage to those containing the manufacturing operations performed in this workpiece holding[b].	Dashed arc from the workpiece holding towards the manufacturing operations performed in this workpiece holding.
3	A surface must be machined in an anterior or identical stage to those containing a workpiece holding using this surface[c].	Dashed arc from the machining operation of the surface towards the workpiece holders using this surface.
4	The sawing off must be machined in an anterior or identical stage to the one containing the next workpiece holding if it exists[d].	Dashed arc from the sawing off operation towards the following workpiece holding.
5	The latest manufacturing operations, performed in the first workpiece holders of a manufacturing phase, must be performed in the anterior stages to the one containing a workpiece holder using a surface neither machined nor laid on in this phase[e].	Thick arcs from the latest manufacturing operations performed in the first workpiece holders of a manufacturing phase towards the workpiece holder using a surface neither performed nor laid on in this phase.

a. This constraint has been highlighted by Ephraïm Goldschmidt [14]. We have generalized it for every operation removing a surface made by another operation.
b. This constraint has been also highlighted by Ephraïm Goldschmidt [14].
c. This constraint has been expressed by B. Vayre [17].
d. This constraint had not been introduced into any work before this article. If it is not respected, there is a risk of getting a stage containing machining operations performed before and after a sawing off, while this last one is in a subsequent stage, which is not technically possible.
e. This constraint has been highlighted by B. Vayre [17]. If this constraint is not respected, there is a risk of placing the new workpiece holding in the stage containing the previous workpiece holders and then to introduce manufacturing dimensions between, on the one hand, surfaces made by the manufacturing operations of the previous holders and, on the other hand, the surface used by the new workpiece holding. But the location of this last surface is unknown and uncontrolled in the previous workpiece holders.

By systematically applying these constraints to the operations of the manufacturing process used as an example, we obtain the graph of figure 6, which then determines the grouping of operations in manufacturing stages. Indeed, one finds that the operation 40 can be performed without having achieved the operation 30 (since there is no arc between them). The first stage will be made up of the operations 10, 20 and 40 which are connected by a constraint of kind "anterior or identical stage". The machined part will have the form shown on the first drawing of the figure 9.

1. These constraints are said automatic. Other constraints, which can not be determined automatically from the description of the process, can be introduced. For example to indicate that it is not possible to perform a groove in a bore as the bore has not been achieved. These constraints are of type "anterior or identical". Indeed the groove may be machined in the same stage as the bore.

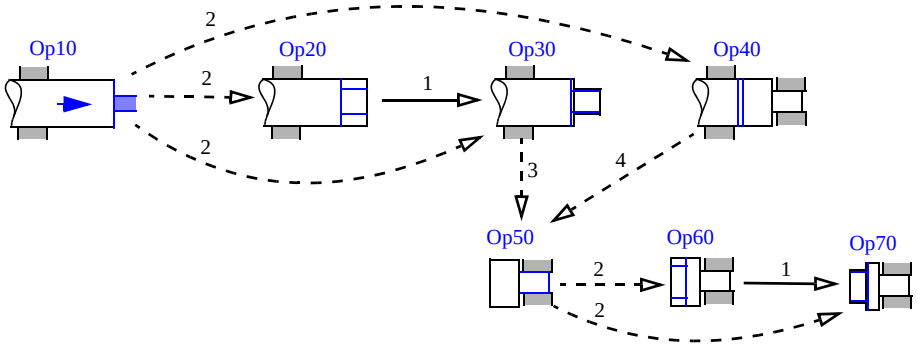

Fig. 6. Graph of constraints between manufacturing operations.

The operation 30 should be performed in a second stage with the operations 50 and 60 which are connected by constraints of kind "anterior or identical stage". The workpiece after the first stage can not be reused for the second stage. It will be necessary to make a second workpiece with the operations 10, 20, 30, 40, 50 et 60. In other words the new manufacturing stage adds operations to those made in previous stages. Finally a third stage will be needed to perform the operation 70.

The workpieces coming from the three manufacturing stages are represented in figure 9[1].

5. Manufacturing dimensions of the setting plan

Next, we need to identify each surface. The identifier of a surface begins with a capital letter, corresponding to the direction of the dimension which locates it, followed by a serial number and a lowercase letter if it is a rough surface (see figure 7).

To determine the manufacturing dimensions, we create a table in which, for each stage in line, we place the X character for each machined surface and the O character for each holding surface (or both if the surface is first machined then placed on a workpiece holder. See figure 8).

Since for each new stage, the setter will have made the operations of the previous stage, the surfaces of these operations remain after the new stage (unless it was the roughed surface of the finished surface machined in the stage). This information is indicated by the I character. For example, Z1 is made in stage 1.1 and is not removed by any following operations. So this surface is present on the workpiece in stages 1.2 and 1.3. This is indicated by the I character in these stages (see figure 8).

The manufacturing dimensions that can be measured and controlled by the setting of tools, are those which link two surfaces present in the same stage, that is to say surfaces identified by the X, O or I characters. Thus, at the end of stage 1.1, any dimension between Z1, Z3a and Z4 can be measured and controlled by the setter. In contrast, the dimension between Z2 and Z2a, for example, is never measurable (in none of the lines, the two surfaces are present simultaneously).

To search for all the manufacturing dimensions that need to be measured at the end of each stage, we build a second table, under the first, to represent the surface linked by design dimensions and stock removal dimensions (see figure 8). The stock removal dimensions correspond to the thickness given for finishing operations. They are also toleranced.

1. Although this is not useful for determining the manufacturing stages, we have identified the number of the constraint of each arc.

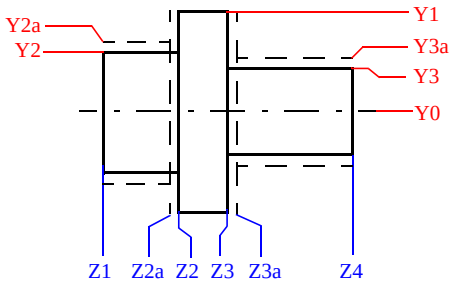

Fig. 7. Identification of the machined surfaces.

For each design dimension and stock removal dimension, we are looking, in the first table, for the shortest path between the surfaces which the dimensions connect. Thus, for the design dimension *CE1*, *CE2* and *CE3*, are obtained manufacturing dimensions CF_{Z1Z4}, CF_{Z1Z3} and CF_{Z2Z4} measurable at the end of stage 1.3 (or even earlier for CF_{Z1Z4}, CF_{Z1Z3}).

For the stock removal dimensions *CM1* and *CM2*, the surfaces they connect are never simultaneously present in the stages. They should therefore be measured indirectly by a chain of at least two manufacturing dimensions. We can use, for instance, the previous manufacturing dimensions, CF_{Z2Z4} and CF_{Z1Z3}:

$$CM1 = -CF_{Z2Z4} + CF_{Z4Z2a} \quad (3)$$

$$CM2 = -CF_{Z1Z3} + CF_{Z1Z3a} \quad (4)$$

This choice can result in reduced tolerances of the dimensions CF_{Z2Z4} and CF_{Z1Z3}, especially if the tolerances of the stock removal dimensions, are of the same order of magnitude as those of the design dimensions. Other chains would be possible to prevent this decrease, however, they would introduce additional manufacturing dimensions. So, by choosing this solution, we can specify the state of the workpiece after each manufacturing stage and the manufacturing dimensions to be measured, on three manufacturing designs (figure 9).

The measurement of the deviation of these manufacturing dimensions will permit to set all the tools [16]. One of the tools should be fixed, that is to say, considered without deviation, to calculate the deviations of others. Otherwise an infinite number of solutions are possible. In general, in screw machining, it is the sawing off tool which is fixed because it is very close to the spindle.

	Z1	Z2a	Z2	Z3	Z3a	Z4	Y0	Y1	Y2a	Y2	Y3a	Y3	Operations
Stage 1.1	X				X	O	I	O			X		Op10, 20, 40
Stage 1.2	I	X		X		I	I	I	X			XO	Op30, 50, 60
Stage 1.3	I		X	I		I	I	I		X		I	Op70

CE1	<					>
CE2	<			>		
CE3			<			>
CM1		<	>			
CM2				<	>	

Fig. 8. Manufacturing stages of the setting plan and table of the design dimensions and stock removal dimensions.

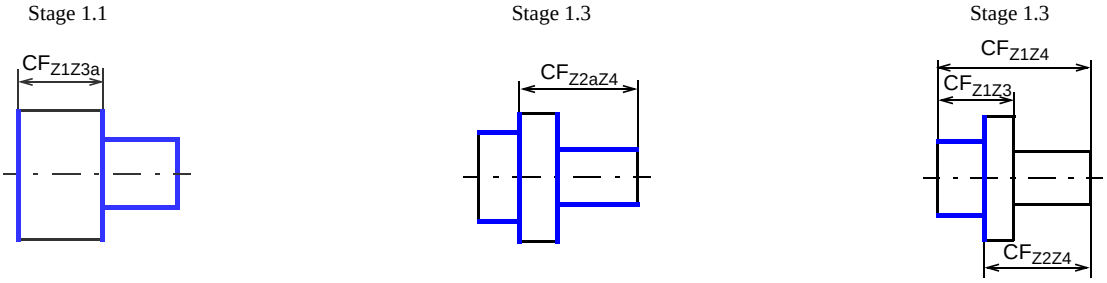

Fig. 9. Manufacturing drawings for the setting plan, with the manufacturing dimensions to measure (the machined surfaces are highlighted with blue thick lines).

6. Monitoring plan of the example process

The monitoring plan is used during the production. The measurement of the workpiece is done only at the end of each manufacturing phase. As some rough surfaces have then disappeared, some manufacturing dimensions of the setting plan are no longer measurable. In our example, these are the manufacturing dimensions CF_{Z1Z3a} and CF_{Z2aZ4}. Only the manufacturing dimensions, of the surfaces remaining at the end of the manufacturing phases, remain, that is to say, for the example, the dimensions CF_{Z1Z4}, CF_{Z1Z3} and CF_{Z2Z4} which correspond, in this example, to the design dimensions (it is not always the case). However, their tolerances must be re-calculated because they are no longer used to control the stock removal dimensions *CM1* and *CM2*. They will have, in this example, directly the tolerances of the design dimensions. The manufacturing dimensions to measure in this monitoring plan are only a part of the manufacturing dimensions of the setting plan. This has the advantage of being able to use the same process of measurement at the end of the manufacturing phases for the setting plan as for the monitoring plan.

7. Influence of intermediate stocks on the plans and on the manufacturing dimensions

By way of comparison, and of explanation of the Copilot-Pro® methodology, we will now determine the setting plan and the manufacturing dimensions of a variant of the previous manufacturing process. This variant consists in producing the part in two times: First operations from 10 to 40 are performed and, after an intermediate stock, operations from 50 to 70 are performed (see figure 10). For this variant, the holding 2 is different. The workpiece must be located on the flat surface Z2 (see figure 10).

Due to the intermediate stock, we consider that it is not possible to wait for the end of the process to set the tools. The work-in-progress, which may be put off, is too big. The setting and monitoring plans will therefore consist of two manufacturing phases.

By performing the constraint graph, it is possible to determine that each phase will consist of two manufacturing stages. We have therefore, for this variant, two manufacturing phases and consequently two setting stages, instead of a unique, and four manufacturing stages, each one followed by a measuring stage, instead of three. Moreover, by representing the design dimensions and the stock removal dimensions in a table under the setting stages, we observe that, for this variant of the process, the design dimension *CE3* can no longer be measured directly because the surfaces that it connects do not exist simultaneously in any manufacturing stage (see figure 11).

Several sets of manufacturing dimensions are possible. When seeking for a set with a minimum number of manufacturing dimensions, we can obtain those ones given from equation 5 to equation 9. For the most part of them, they use the Z3 surface, common to the two manufacturing phases.

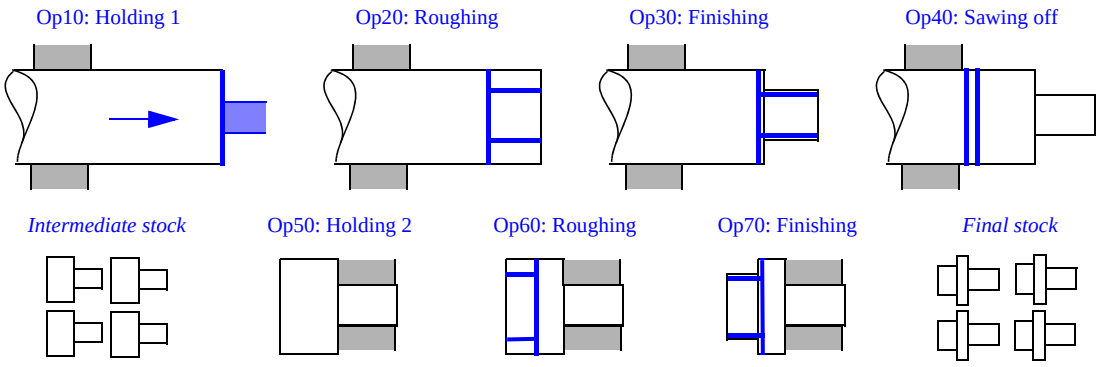

Fig. 10. Manufacturing process with an intermediate stock

$$CE1 = CF_{Z1Z3} + CF_{Z3Z4} \quad (5)$$

$$CE2 = CF_{Z1Z3} \quad (6)$$

$$CE3 = CF_{Z2Z3} + CF_{Z3Z4} \quad (7)$$

$$CM1 = CF_{Z2aZ3} - CF_{Z2Z3} \quad (8)$$

$$CM2 = CF_{Z3Z4} - CF_{Z3aZ4} \quad (9)$$

Those manufacturing dimension can be indicated on the manufacturing drawings (see figure 12). Compared with the initial process, we see that it is better to have a single manufacturing phase rather than two. Indeed, the design dimension *CE3* can no longer be measured even in the monitoring plan. The tolerances on the two manufacturing dimensions which replace *CE3* should have smaller tolerances, especially if the stock removal dimensions have tolerances of the same order of magnitude as the design dimensions.

	Z1	Z2a	Z2	Z3	Z3a	Z4	0	Y1	Y2a	Y2	Y3a	Y3	Operations
Stage 1.1	X				X	O	I	O			X		Op10, 20, 40
Stage 1.2	I			X		I	I	I				X	Op30
Stage 2.1		X		O			I		X			O	Op50, 60
Stage 2.2			X	I			I			X		I	Op70

CE1	<					>
CE2	<			>		
CE3			<			>
CM1		<	>			
CM2				<	>	

Fig. 11. Setting plan for the variant manufacturing process: Two manufacturing phases of two setting stages each one.

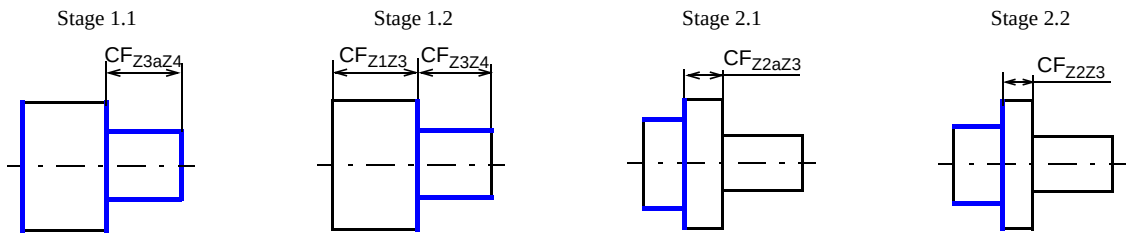

Fig. 12. Manufacturing drawings of the setting plan for the process with an intermediate stock (the machined surfaces are highlighted with blue thick lines).

8. Conclusion

We have presented a method to arrange the manufacturing operations in order to minimize the number of measuring stages necessary to set the cutting tools during the manufacturing of a part. This method is part of a comprehensive methodology, called Copilot-Pro®, for the preparation of the manufacturing and the setting of the tools in production or in a production halt. It streamlines the operations of measuring workpieces and setting tools that are too often left up the setters in industry, leading to many scrapped workpieces, long times of production halt and lower quality for the batches of workpieces.

If the manual preparation, as presented in this paper, can be engaged on workpieces with few machined surfaces, the use of software for more complex workpieces is essential. We are currently developing a software implementing this innovative method.

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