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Application of Tolerance Charting Using Rooted Tree Graph for Allocating Manufacturing Specifications onto the Precision Machined Part: Detailed Explanation of Manufacturing a Standard Weight of Mass

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Abstract

Since objective of mechanical – process planning is achievement of the target – designed specification, a created process plan needs to be assessed prior the actual machining operations. For this respect, tolerance charting integrated with rooted tree graph is the most appropriated tool. Even through, this technique has been implemented into processes planning for many decades, but it still has been not widely used in practicality. Except its complexity by procedure and time consuming, the major reason that leads it rarely be used is closely relation between tolerance charting and machining sequences themselves. Process planner who creates a tolerance chart needs to possess the firmly backgrounds of manufacturing processes and machining operations. Unfortunately, there are many literatures reported on the successful of using tolerance chart for manufacturing, but they just give quite a few information for machining processes and sequences. Certainly, it is too hard for the readers who have less knowledge on machining operations can understand this technique completely. Therefore, this paper aims to explain how to create and work with tolerance charting in more details of machining information that has been overlooked by many literatures, and leads this technique looked too much difficult than it should be. Tolerance charting using rooted tree graph is explained and illustrated with an example of manufacturing the standard weight (of mass) by a precision manufacturer in Thailand.

Keywords: Tolerance chart; Manufacturing processes; Machining sequence; Rooted tree graph; Tolerance allocation; Standard weight.

INTRODUCTION

Production of the standard weight by manufacturers in Thailand normally has been followed the International Recommendation OIML R 111 – 1 Edition 2004 (E) [1 – 4]. In the metrological aspects, high precision acceptable weight tolerance i.e. maximum permissible error (MPE) of each weight range and accuracy class that specified by this recommendation can be satisfied with the metrological tasks and calibration completely. In the other hand, such the high precision requirement should be difficult for manufacturing actually. A study of magnetic susceptibility onto the standard weight due to manufacturing processes and machining by Sukhon et al [5] implied that dimensional tolerances of each geometrical shapes of the standard weight could not be controlled completely by using of machine tools only, and lead the variation of measured weight that related with those dimensional tolerances could not be well – fit within the acceptable range. The final weight – adjustment by manual polishing was still needed. This situation accorded with Monte Carlo simulation results from the authors' paper presented in the conference of SIMMOD 2017 [6], in which machining processes just could serve the nearly finished standard weight with the minimum safety stock weight only. To confirm the simulation results, the authors have performed the actual manufacturing for 1kg standard weight by using tolerance charting integrated with rooted tree graph to allocate dimensions and tolerances of each geometrical shape of the weight body [7].

Comparing with other techniques of tolerance allocation [8 – 10], tolerance chart is the only one that can associate with machining operations actually, and can display machining sequences clearly in practicality [11, 12]. However, by procedural itself, preparing of tolerance chart is the real time consuming and easily mistaken process due to its unclear datum hierarchy when the workpiece needs to be relocated many times during machining operations. Whybrew et al [13] first implemented rooted tree graph into tolerance chart to simplify the order of datum faces successfully. Then this graph – theory approach has been revised and developed continuously until appeared as computer – aided tolerance control (CATC) [14 – 22].

Even through, by overview, there have been reported of using

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various tolerance charting techniques for allocating manufacturing tolerances in the process planning since 1960s, but they still have been not widely used due to time consuming and its procedural complexity i.e. the closely relationship of tolerance chart and machining sequences. Process planners who created a tolerance chart needed to have strongly knowledge of manufacturing processes and machining operations. Unfortunately, those literatures overlooked the needed explanation on manufacturing processes and machining sequences that critical for providing tolerance chart. This situation leaded this technique looked too much difficult than it should be, especially for the readers who had less knowledge on machining operations. Therefore, this paper, the authors aims to explain how tolerance chart using rooted tree graph could be provided in both details of manufacturing processes and machining sequences that were crucial needed for allocating manufacturing dimensions and tolerances. To understand this technique obviously, an experiment of manufacturing 1kg standard weight which presented in SIMMOD 2017 was illustrated as followings.

METHODOLOGY

The experimental standard weight

Based on simulation and experimental results which were presented in SIMMOD 2017 conference, a cold – drawn steel JIS – SS400D was chosen for making 1kg experimental standard weight because of its density could be well – fit with minimum acceptable density for the accuracy class E_2 specified by the International Recommendation OIML R 111 – 1 Edition 2004 (E). It was available in local market with low cost as well. This experimental standard weight was provided in a simply form of one piece – solid body with lifting knob that possessed main dimensions as shown in Fig.1. All tolerances were specified as ± 0.005 mm based on the finest machine capability of conventional cylindrical grinding machine in the average cutting conditions.

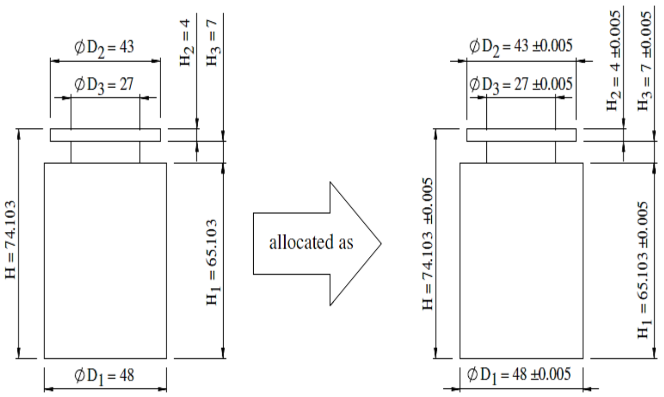

Figure 1: Designed dimensions and tolerances of the 1kg experimental standard weight [6].

Transformation of the designed tolerances into the manufacturing tolerances by using tolerance chart integrated with rooted tree graph

In the fact, designed specification that was allocated in Fig.1 was just the expected results that never be used for actual manufacturing directly because of the needs of relocating workpiece many times during machining sequences. So reference datum, working dimensions and its tolerances of each machining step needed to be changed implicitly. Unfortunately, it looked like that this situation was often overlooked by designer, and leaved technicians who operated the actual machining to allocate the working specifications by themselves. Certainly, uncertainties on both quality and process standardization could be appeared.

For the authors, tolerance chart using rooted – tree graph should be the most appropriated one to transform designed specification into manufacturing specification according with the available machining processes effectively. It should allocate and control the actual dimensional specifications into each step of machining sequences excellently, especially processes that possessed 40% probably risk to failure as was declared by the simulation results [6]. Transformation of those dimensional specifications by using tolerance charting integrated with rooted tree graph could be demonstrated via a case study of manufacturing of 1kg experimental standard weight as procedural steps then.

Select the available machine tools

The proper manufacturing processes and machine tools were selected in the boundary of the cutting conditions within maximum machine capability as a list below:

- Conventional lathe machine that was planned to operate from rough to the semi – finish cut with tolerance of 0.020mm and IT8 according with International Tolerance Grade ISO 286 – 1 [22].
- Conventional cylindrical grinding machine that was planned to operate the finishing cut for all diametral geometries with tolerance of 0.010 mm and IT8.
- Conventional surface grinding machine that was planned to operate the finishing cut for all flat surface geometries with tolerance of 0.010mm and IT8.

However, machine capability of those machine tools, were the averaged values. By using of the proper measuring instruments and skills of technicians who operated the machining, about 50% higher machine capability value i.e. 0.005mm could be reached from conventional cylindrical grinding machine manually.

Specify the machining sequence

At first, process planners or technician had to estimate the amount of stock removal on each cut face based on their experiences and capability of selected machine tools on hands. This is the real critical step to provide tolerance chart, but is usually overlooked by process planners who have no firmly experience in various machining processes. In this step, the face being cut obtained from each individual machining operation was designated by node with a capital letter as shown in Table 1. In practically, the faces before and after machining were never be the same. Hence, numerical suffix was used to designate the newly machined face i.e. D_1 was the newly face of D.

Draft rooted tree graph

By following the specified machining sequence, the rooted tree graph was drafted as shown in Fig. 2. Node from each step of machining sequence should be drafted first, and then connect them by arrow. Each arrow was designated by cut number and machining tolerances (in parentheses beside cut number). All last machined nodes (last cut faces) were enclosed by the double circles to highlight them from other nodes.

The amount of stock removal expected to be kept on each cut face, was designated in brackets beside the newly node.

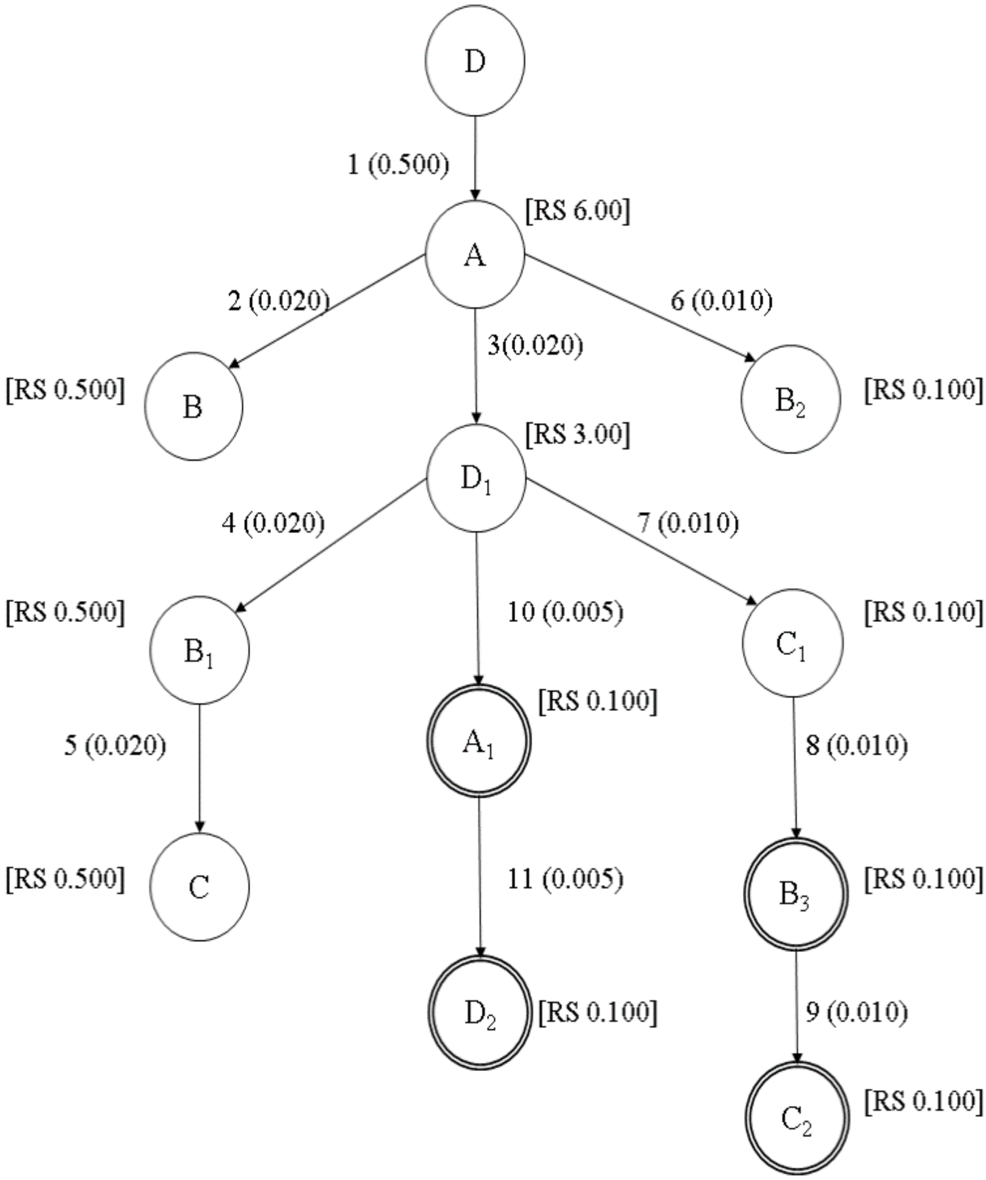

Figure 2: A rooted tree graph for manufacturing the 1kg experimental standard weight [7].

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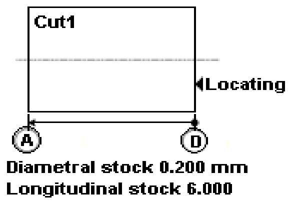
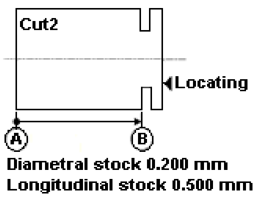
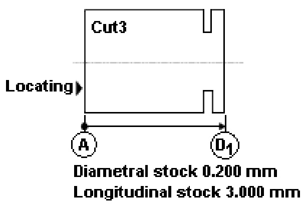
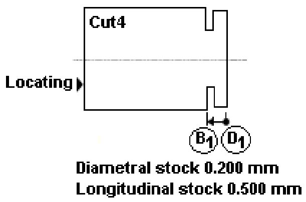
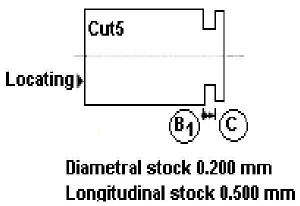
Table 1: Machining sequences operated by various machine tools and cutting conditions

Cut N0.	Machining sequence	Machine	Machine tools and cutting conditions
1		Lathe	✓ Cylindrical bar stock Ø 50.850mm x 85.000mm length will be hold on 3-jaws-chuck with depth of holding of 3.000mm, and without centering by tailstock. Alignment of bar stock is checked by mechanical dial gauge. Holding side is now declared as face D. ✓ Cutting will be operated by a carbide - insert of 87° cutting edge that possessed honed radius of 0.025mm. Even through, in case of cold drawn steel SS400D, cutting tool that made by high speed steel can be used. But it possessed a low hot hardness and is risky to wear or broken during cutting. So geometry and accuracy of the workpiece can be loosed. Also, temperature rise on the workpiece is higher with high - speed steel than with carbide. cutting as well. ✓ Refer to face D, face cutting to get a flatness end - face of workpiece; face A, and obtains the whole logitudinal dimension of 76.103mm with stock allowance of +6.000mm. ✓ Then straight turning along the whole length of workpiece by starting from face A back to face D (vicinity the depth of holding of 3.000mm), and obtains the diametral dimension of Ø 48.000mm with stock allowance of + 0.200mm. ✓ Cutting speed = 14 mm/mim.(105 rpm), feed rate = 0.5 mm/rev., depth of cut 1 mm/1.425mm.
2		Lathe	✓ External groove cutting by using 4.000mm - grooving cutter (carbide) that possessed a honed radius of 0.025mm. However, cutting will be done by cross feed without side cutting along the length. Using coolant for the cutting as well. ✓ Refer to face A, groove cutting at face B to obtains both logitudinal dimension of 65.103mm with stock allowance of + 0.500mm and dimetral dimension (groove diameter) of Ø 27.000mm with stock allowance of + 0.200mm ✓ Cutting speed = 14 mm/mim.(105 rpm), feed rate = 0.5 mm/rev., depth of cut 11.925mm.
3		Lathe	✓ Relocating the workpiece at face A by using 3-jaws-chuck (alignment is still be done by using mechanical dial gauge). To prevent any wear on the cutted workpiece due to jaws, the brass shim of a certain thickness will be used to wrap onto the holding portion of the workpiece. ✓ Refer to face A, face cutting to get a flatness end - face of workpiece; face D_1, and obtains the whole logitudinal dimension of 76.103mm with stock allowance of +3.000mm. So the holding portion of 3.000mm from beginning will be excecuted as well. ✓ Cutting will be operated by a carbide - insert of 87° cutting edge with radius of 0.025mm. ✓ Cutting speed = 14 mm/mim.(105 rpm), feed rate = 0.5 mm/rev., depth of cut 6.000mm.
4		Lathe	✓ Refer to face D1, straight turning along the longitudinal axis of workpiece by starting from face D_1 to face B_1 to obtains both logitudinal dimension of 11.000mm with stock allowance of + 0.500mm and dimetral dimension (knob diameter) of Ø 43.000mm with stock allowance of + 0.200mm. This diametral dimension will over the groove diametral dimension implecitly. ✓ Cutting will be operated by a carbide - insert of 87° cutting edge with radius of 0.025mm. ✓ Cutting speed = 14 mm/mim.(105 rpm), feed rate = 0.5 mm/rev., depth of cut 10.500mm/3.925mm.
5		Lathe	✓ Refer to face B1, groove cutting by using 4.000mm - grooving cutter (carbide) along the longitudinal axis of workpiece by starting from face B_1 to face C to obtains both logitudinal dimension of 7.000mm with stock allowance of + 0.500mm and dimetral dimension (groove diameter) of Ø 27.000mm with stock allowance of + 0.200mm. ✓ Cutting will be operated by a carbide - insert of 87° cutting edge with radius of 0.025mm. ✓ Cutting speed = 14 mm/mim.(105 rpm), feed rate = 0.5 mm/rev., depth of cut 6.500mm.

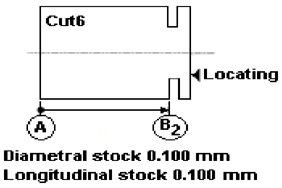
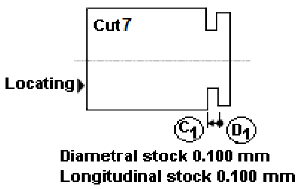
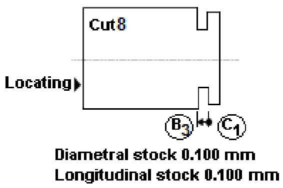
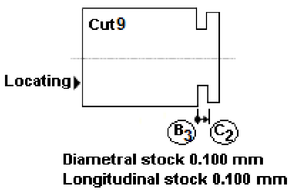
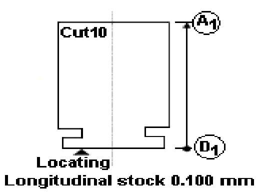
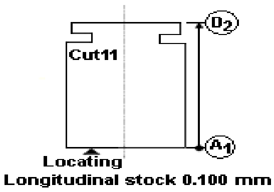
Cut N0.	Machining sequence	Machine	Machine tools and cutting conditions
6		Cylin. Grinding	✓ Installing a cylindrical grinding module onto the compound rest of lathe machine. It means grinding wheel of the module can be cross feeded onto workpiece by cross slide - mechanism of lathe machine. Relocating the workpiece at face D_1 by using 3-jaws-chuck (alignment is still be done by using dial gauge as before. To prevent any wear on the cutted workpiece due to jaws, the brass shim of a certain thickness will be used to wrap onto the holding portion of the workpiece. ✓ Using grinding wheel T1A 180X6X31.75 32A 180 KVBE as cutting tool. Removing of metal chip and cooling of workpiece is done by sweeping with a wet cloth after cutting frequently. This is for the purposes of smooth surface (without thermal deflection) and glossy appearance onto the workpiece when visually examined. ✓ Refer to face A, grinding the cylindrical surface along with the longitudinal axis of workpiece by starting from face A to face B_2 to obtain both longitudinal dimension of 65.103mm with stock allowance of + 0.100mm and dimetral dimension of 48.000mm with stock allowance of +0.100mm. ✓ Cutting speed = 15 mm/mim.(100 rpm), feed rate = 1.5 mm/rev., depth of cut 0.005mm.
7		Cylin. Grinding	✓ Relocating the workpiece at face A by using 3-jaws-chuck (alignment is still be done by using dial gauge as before. To prevent any wear on the cutted workpiece due to jaws, the brass shim of a certain thickness will be used to wrap onto the holding portion of the workpiece. ✓ Refer to face D_1, grinding the cylindrical surface along with the longitudinal axis of workpiece by starting from face D_1 to face C_1 to obtain both longitudinal dimension of 4.000mm with stock allowance of + 0.100mm and dimetral dimension of 43.000mm with stock allowance of +0.100mm. ✓ Using the same grinding wheel and cooling method. Cutting speed = 15 mm/mim.(100 rpm), feed rate = 1.5 mm/rev., depth of cut 0.005mm.
8		Cylin. Grinding	✓ Refer to face C_1, grinding the cylindrical surface along with the longitudinal axis of workpiece by starting from face C_1 to face B_3 to obtain both longitudinal dimension of 7.000mm with stock allowance of + 0.100mm and dimetral dimension of 27.000mm with stock allowance of +0.100mm. ✓ Using the same grinding wheel and cooling method. Cutting speed = 15 mm/mim.(100 rpm), feed rate = 1.5 mm/rev., depth of cut 0.005mm.
9		Cylin. Grinding	✓ Refer to face B_3, grinding the cylindrical surface along with the longitudinal axis of workpiece by starting from face B_3 to face C_2 to obtain both longitudinal dimension of 7.000mm with stock allowance of + 0.100mm and dimetral dimension of 27.000mm with stock allowance of +0.100mm. ✓ Using the same grinding wheel and cooling method. Cutting speed = 15 mm/mim.(100 rpm), feed rate = 1.5 mm/rev., depth of cut 0.005mm.
10		Surf. Grinding	✓ Relocating the workpiece by placing face D_1 onto a magnetic vise of surface grinding machine. To prevent any scratch bands on face D_1 due to effect of magnetic bands of the vise, a thin sheet of paper will be lie onto the surface of the vise to separate workpiece and vise surface first. ✓ Using grinding wheel T1A 180X6X31.75 32A 180 KVBE as cutting tool. Removing of metal chip and cooling of workpiece is done by air blowing. At the end of this stage, workpiece will be demagnitized to kill the magnetic susceptibility induced onto the workpiece. ✓ Refer to face D_1, grinding the flat surface of face A to obtain new face A_1 with the longitudinal dimension of 76.103mm with stock allowance of +0.100mm. Cutting speed = 14 mm/mim.(105 rpm) , feed rate = 1.5 mm/rev., step of cut = 1.5mm/stroke, tablefeed = 2m/min.
11		Surf. Grinding	✓ Relocating the workpiece by placing face A_1 onto a magnetic vise of surface grinding machine. To prevent any scratch bands on face D1 due to effect of magnetic bands of the vise, a thin sheet of paper will be lie onto the surface of the vise to separate workpiece and vise surface first. ✓ Using the same grinding wheel and cutting conditions as before. ✓ Refer to face A_1, grinding the flat surface of face D_1 to obtain new face D_1 with the longitudinal dimension of 76.103mm with stock allowance of +0.100mm.

Table 1. Machining sequences operated by various machine tools and cutting conditions (Cont.)

Prepare the preliminary cutting information into the blank form of tolerance chart

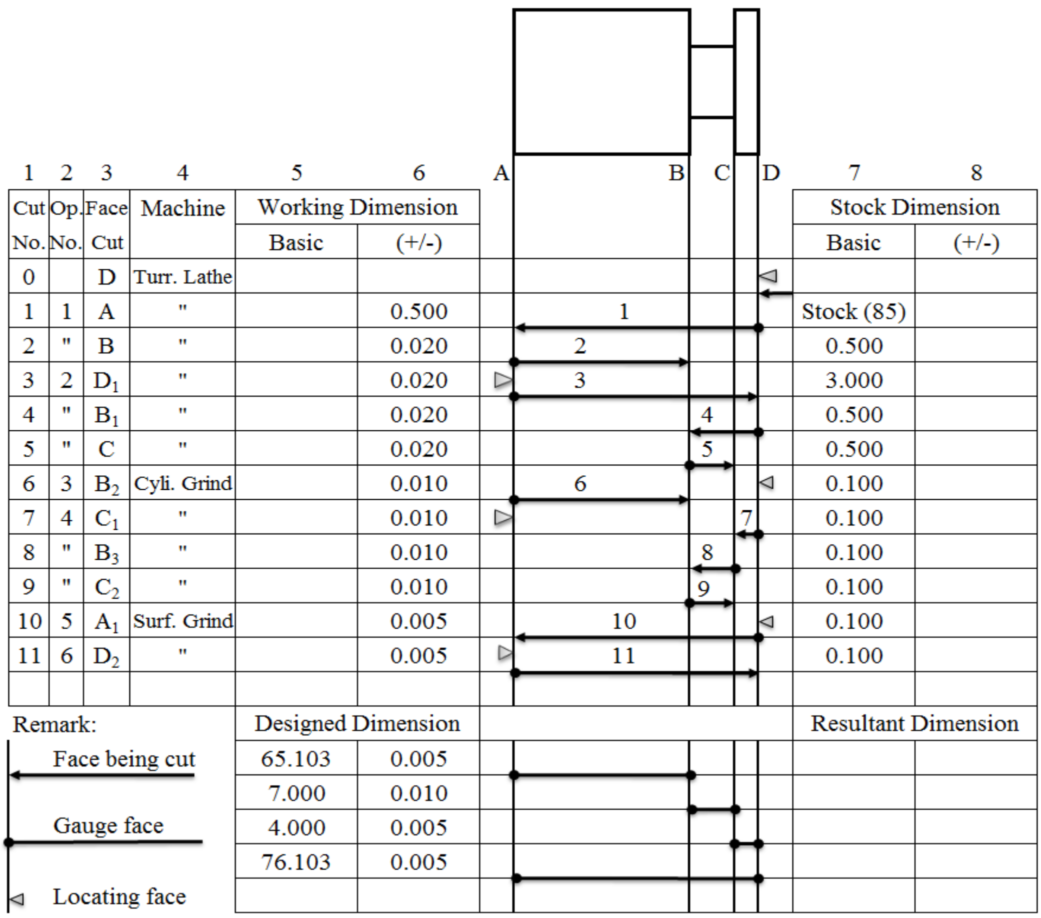
In this paper, the author used a blank form of tolerance chart as presented in the work of Sermsuti – Anuwat [16] as shown in Fig. 3 because of its simplicity for understanding. Main geometries of the experimental standard weight were sketched above tolerance chart. The orientation of this sketch must be the same as specified in machining sequences.

Because tolerance chart is concerned mainly with tolerances on the longitudinal dimensions, especially workpiece in axisymmetric form as the experimental standard weight that could be relied based on the capability of cylindrical grinding machine. Therefore, details of controlling all diametral dimensions and its tolerances could be omitted. A vertical line that was written down from each vertical face of the sketch will be represented the face being located and cut.

The preliminary cutting information that needed to be filled in the chart column included:

- Column 1st: cut number.
- Column 2nd: operation number that was implied to machining sequence.
- Column 3rd: face being cut that obtained from each operation.
- Column 4th: machine tools used for each operation.
- Column 6th: machining capability of the selected machine tools.
- Column 7th: estimated allowance of the stock removal at each cut.
- Designed dimension and tolerance of this 1kg experimental standard weight were written down at the bottom left of the chart.

Each arrow that was drafted in the rooted tree graph will be written in the tolerance chart by starting from locating or reference face (represented by triangle and dot mark respectively) and pointing out to another face being cut (represented by arrow head).



1 Cut No.	2 Op. No.	3 Face Cut	4 Machine	5 Working Dimension Basic	6 Working Dimension (+/-)	A B C D	7 Stock Dimension Basic	8 Stock Dimension (+/-)
0		D	Turr. Lathe					
1	1	A	"		0.500	1	Stock (85)	
2	"	B	"		0.020	2	0.500	
3	2	D_1	"		0.020	3	3.000	
4	"	B_1	"		0.020	4	0.500	
5	"	C	"		0.020	5	0.500	
6	3	B_2	Cyli. Grind		0.010	6	0.100	
7	4	C_1	"		0.010	7	0.100	
8	"	B_3	"		0.010	8	0.100	
9	"	C_2	"		0.010	9	0.100	
10	5	A_1	Surf. Grind		0.005	10	0.100	
11	6	D_2	"		0.005	11	0.100	
Remark:				Designed Dimension			Resultant Dimension	
Face being cut				65.103	0.005			
				7.000	0.010			
Gauge face				4.000	0.005			
Locating face				76.103	0.005			

All dimensional units are millimetres

Figure 3: A form of manual tolerance chart which filled in with preliminary information.

By considering from rooted tree graph, a path of arrow linked between any two nodes implied that machining operation contributed both dimension and tolerance between two faces (denoted by those two nodes). For example, the dimension between node A and node C_1 was the result of cut 3 and cut 7, and its tolerance was the sum of machining capability of machine tools that was used for those cut faces i.e. $0.030(A \rightarrow D_1 \rightarrow C_1) = 0.020(A \rightarrow D_1) + 0.010(D_1 \rightarrow C_1)$

Calculate the tolerance stack for stock removal of each cut face obtained by each machining sequence

This tolerance stack needs to be filled in the column 8th of tolerance chart, by summing up from the machining capability of the arrows linked paths that bounded the stock removal dimension as below.

- For face A, by considering from rooted tree graph, possessed a tolerance stack on the stock removal = 0.5000
- For face B, by considering from rooted tree graph, possessed a tolerance stack on the stock removal = 0.020
- For face D_1, by considering from rooted tree graph, tolerance stack on the stock removal along the whole path linked node D and D_1 (those nodes were both faces that bounded the stock removal dimension at Cut3): = 0.020(Cut3) + 0.500(Cut1) = 0.520
- For face B_1, by considering from rooted tree graph, tolerance stack on the stock removal along the whole path linked node B and B_1: = 0.020(Cut4) + 0.020(Cut3) + 0.020(Cut2) = 0.060
- For face C, by considering from rooted tree graph, possessed a tolerance stack on the stock removal = 0.020
- For face B_2, by considering from rooted tree graph, tolerance stack on the stock removal along the whole path linked node B and B_2: = 0.010(Cut6) + 0.020(Cut2) = 0.030
- For face C_1, by considering from rooted tree graph, tolerance stack on the stock removal along the whole path linked node C and C_1: = 0.010(Cut7) + 0.020(Cut4) + 0.020(Cut5) = 0.050
- For face B_3, by considering from rooted tree graph, tolerance stack on the stock removal along the whole path linked node B and B_3: = 0.010(Cut8) + 0.010(Cut7) + 0.020(Cut3) + 0.020(Cut2) = 0.060
- For face C_2, by considering from rooted tree graph, tolerance stack on the stock removal along the whole path linked node C and C_2: = 0.010(Cut9) + 0.010(Cut8) + 0.010(Cut7) + 0.020(Cut4) + 0.020(Cut5) = 0.070
- For face A_1, by considering from rooted tree graph, tolerance stack on the stock removal along the whole path linked node A and A_1: = 0.005(Cut10) + 0.020(Cut3) = 0.025
- For face D_2, by considering from rooted tree graph, tolerance stack on the stock removal along the whole path linked node D and D_2: = 0.005(Cut11) + 0.005(Cut10) + 0.020(Cut3) + 0.500(Cut1) = 0.530

At the end of this stage, the authors could detect an inconsistency in which tolerance stackups of 0.530 for stock removal of cut face D2 (Cut11) in column 8th was greater than corresponding estimated allowance of stock removal of 0.100 in column 7th as shown in Fig. 4. It meant there was no sufficient material left for the later machining operation (though this was the last cut face). In this case, this stock removal allowance had to be adjusted in which greater than its tolerance stackups i.e. 0.600 for at least.

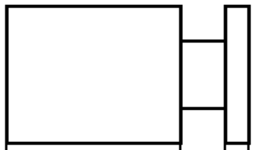
Calculate tolerance stack on the resultant dimension

This tolerance stack needs to be filled in the bottom right corner of tolerance chart as shown in Fig. 5, by summing up from machining capability of the arrows linked paths that bounded the designed dimension as below.

- For designed dimension of 65.103 (between face A and face B), by considering from the rooted tree graph, tolerance stack along the whole path linked both last node A_1 and node B_3: = 0.005(Cut10) + 0.010(Cut7) + 0.010(Cut8) = 0.025
- For designed dimension of 7.000 (between face B_3 and face C_2), by considering from the rooted tree graph, tolerance stack along the whole path linked both last node B_3 and node C_2:

  = 0.010(Cut9)
- For designed dimension of 4.000 (between face C_2 and face D_2), by considering from the rooted tree graph, tolerance stack along the whole path linked both last node C_2 and node D_2:

  = 0.010(Cut9) + 0.010(Cut8) + 0.010(Cut7) + 0.005(Cut10) + 0.005(Cut11) = 0.040
- For designed dimension of 76.103 (between face D_2 and face A_1), by considering from the rooted tree graph, tolerance stack along the whole path linked both last node D_2 and node A_1: = 0.005 mm (Cut11)



1 Cut No.	2 Op. No.	3 Face Cut	4 Machine	5 Working Dimension Basic	6 Working Dimension (+/-)	A B C D	7 Stock Dimension Basic	8 Stock Dimension (+/-)
0		D	Turr. Lathe					
1	1	A	"		0.500	1	Stock (85)	0.010
2	"	B	"		0.020	2	0.500	0.020
3	2	D_1	"		0.020	3	3.000	0.520
4	"	B_1	"		0.020	4	0.500	0.060
5	"	C	"		0.020	5	0.500	0.020
6	3	B_2	Cyli. Grind		0.010	6	0.100	0.030
7	4	C_1	"		0.010	7	0.100	0.050
8	"	B_3	"		0.010	8	0.100	0.060
9	"	C_2	"		0.010	9	0.100	0.070
10	5	A_1	Surf. Grind		0.005	10	0.100	0.025
11	6	D_2	"		0.005	11	~~0.100~~ 0.600	0.530

Remark:	Designed Dimension		Resultant Dimension	
Face being cut	65.103	0.005		
	7.000	0.010		
Gauge face	4.000	0.005		
	76.103	0.005		
Locating face				

All dimensional units are millimetres

Figure 4: A tolerance chart that was filled in with the calculated tolerance stackups on stock removal.

Cut No.	Op. No.	Face Cut	Machine	Working Dimension Basic	Working Dimension (+/-)	A B C D	Stock Dimension Basic	Stock Dimension (+/-)
11	6	D_2	"		0.005	11	0.600	0.530

Remark:	Designed Dimension		Resultant Dimension	
Face being cut	65.103	0.005	65.103	0.025
	7.000	0.010	7.000	0.010
Gauge face	4.000	0.005	4.000	0.040
	76.103	0.005	76.103	0.005
Locating face				

Figure 5: A tolerance chart that was filled in with the resultant dimensions.

In this stage, there still had a problem in which calculated tolerances of the resultant dimensions were greater than tolerances of the corresponding designed dimensions. The sum of tolerances in the path between face A_1 and B_3 (faces that bounds the final body height H_1) indicated that it was impossible to solve this problem by neither changing of the machine tools nor adjusting of the machining sequence. In this case, it may be said that designed tolerance were over the specification as it should be reached by conventional machine tools. In this case, there were two possible proposals available to solve this problem. First, the most simply, replace the existing designed tolerance by the resultant tolerances. This proposal, however, weight variation could be reached to –0.835g and maybe less than the safety stock weight value before manual polishing the experimental standard weight in the expected accuracy class E_2.

Another proposal we have chosen [7]. Instead of using machine tools, performing the manual lapping (by using wax and proper diamond powder) on lathe machinery gradually onto face B_3 (Cut8) and face C_2 (Cut9) as showed in rooted - tree graph in Fig. 6.

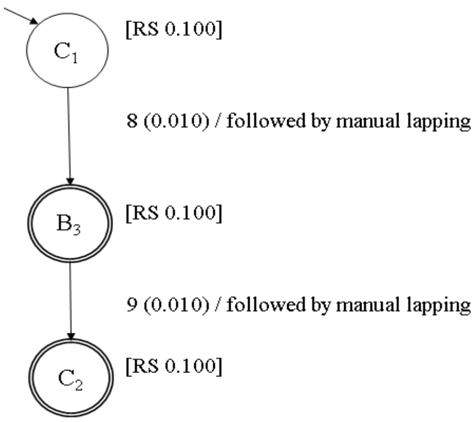


Figure 6: Manual lapping slightly onto face B_3 and face C_2 on lathe machinery [7].

In the fact, this proposal should be reasonable in practically, because the experimental standard weight was designed in very simply form without any free surface for retrenching the grinding wheel, and could lead the fillet portions on those both faces depended on the formable radius edge of the grinding wheel during operation. This lapping shall make the smallest fillets and result the better tolerances. However, this proposal needed an expertise technician and time – consume for measuring more frequently during lapping.

Calculate working dimension

This working dimension needs to be filled in column 5th of tolerance chart, by summing or subtracting the designed dimension with an amount of stock removal from each cut in which encountered those two faces that bounded the designed dimension. The conditions of summing or subtracting were based on possibility in which a particular cut is lengthen or shorten dimension between those two faces as summarized in the decision matrix as shown in Fig. 7. More details of providing and use of this matrix can be found in the reference [23]. With this matrix, working dimensions of each cut could be calculated.

Working dimension obtained from cut1

By considering from tolerance chart, face A and face D bounded the expected designed dimension of 76.103 that was represented by arrow line of cut1. Certainly, dimension from cut1 must be encountered (shorten or lengthen) from the consequence cut3, cut10 and cut11. Sign of the amount of stock removal from each cut could be considered as below.

- Encountered from the arrow line of cut3 that pointed to face D in which;
  - direction of cut face was the upper bound of workpiece (UB)
  - direction of locating face was be the left side of workpiece (Left)
  - position of locating face was below cut face (C>L)

Hence, from the matrix, sign of the cut was be +, then an amount of stock removal from cut3 = +3.000

- Encountered from the arrow line of cut10 that pointed to face A in which;
  - direction of cut face was the lower bound of workpiece (LB)
  - direction of locating face was be the right side of workpiece (Right)
  - position of locating face was above cut face (C<L)

Hence, from the matrix, sign of the cut was be +, then an amount of stock removal from cut10 = +0.100

- Encountered from the arrow line of cut11 that pointed to face D in which;
  - direction of cut face was the upper bound of workpiece (UB)
  - direction of locating face was be the left side of workpiece (Left)
  - position of locating face was below cut face (C>L)

Hence, from the matrix, sign of the cut was be +, then an amount of stock removal from cut11 = +0.600

Finally, working dimension that obtained from cut1 could be calculated as below.

= 76.103(Design dim. Cut 1) + 3.000(Cut3) + 0.100

(Cut10) + 0.600(Cut11) = 79.703

Condition stub	Condition entry							
Direction of cut face (cut at LB or UB)	LB	LB	LB	LB	UB	UB	UB	UB
Direction of locating face (related with cut face)	Left	Left	Right	Right	Left	Left	Right	Right
Position of locating face (related with cut face)	L > C	C > L	L > C	C > L	L > C	C > L	L > C	C > L
Action stub	**Action entry**							
Sign of the cut	+	–	+	–	–	+	–	+

Note: LB is lower bound of cut face, UB is upper bound of cut face, L is locating face, C is cut face

Figure 7: A decision matrix for manufacturing the 1kg experimental standard weight [7].

Working dimension obtained from cut2

By considering from tolerance chart, face A and face B bounded the expected designed dimension of 65.103 that was represented by arrow line of cut2. Certainly, dimension from this cut2 must be encountered (shorten or lengthen) from the consequence cut4, cut6, cut8 and cut10. Sign of the amount of stock removal from each cut could be considered as below.

- Encountered from the arrow line of cut4 that pointed to face B in which;
  - direction of cut face was the upper bound of workpiece (UB)
  - direction of locating face was be the left side of workpiece (Left)
  - position of locating face was below cut face (C>L)

Hence, from the matrix, sign of the cut was be +, then an amount of stock removal from cut4 = +0.500

- Encountered from the arrow line of cut6 that pointed to face B in which;
  - direction of cut face was the upper bound of workpiece (UB)
  - direction of locating face was be the right side of workpiece (Right)
  - position of locating face was above cut face (C<L)

Hence, from the matrix, sign of the cut was be +, then an amount of stock removal from cut6 = – 0.100

- Encountered from the arrow line of cut8 that pointed to face B in which;
  - direction of cut face was the upper bound of workpiece (UB)
  - direction of locating face was be the left side of workpiece (Left)
  - position of locating face was below cut face (C>L)

Hence, from the matrix, sign of the cut was be +, then an amount of stock removal from cut8 = +0.100

- Encountered from the arrow line of cut10 that pointed to face A in which;
  - direction of cut face was the lower bound of workpiece (LB)
  - direction of locating face was be the right side of workpiece (Right)
  - position of locating face was above cut face (C<L)

Hence, from the matrix, sign of the cut was be +, then an amount of stock removal from cut10 = +0.100

Finally, working dimension that obtained from cut2 could be calculated as below.

= 65.103(Design dim. Cut 2) + 0.500(Cut4) – 0.100 (Cut6) + 0.100(Cut8) + 0.100(Cut10) = 65.703

The same procedure of the calculation was applied to find other working dimensions as below:

Working dimension obtained from cut3

= 76.103(Design dim. Cut 3) + 0.100(Cut10) + 0.600

(Cut11) = 76.803

Working dimension obtained from cut4

= (7.000 + 4.000) (Design dim. Cut 4) + 0.100(Cut6) – 0.100 (Cut8) + 0.600(Cut11) = 11.600

Working dimension that obtained from cut5

= 7.000 (Design dim. Cut 5) + 0.100(Cut6) + 0.100 (Cut7) – 0.100 (Cut8) + 0.100(Cut9) = 7.200

Working dimension obtained from cut6

= 65.103 (Design dim. Cut 6) + 0.100(Cut8) + 0.100 (Cut10) = 65.303

Working dimension obtained from cut7

= 4.000 (Design dim. Cut 7) – 0.100(Cut9) + 0.600 (Cut11) = 4.500

Working dimension obtained from cut8

= 7.000 (Design dim. Cut 8) + 0.100 (Cut9) = 7.100

Working dimension obtained from cut9

= 7.000 (Design dim. Cut 8) = 7.000

Working dimension obtained from cut10

= 76.103 (Design dim. Cut 10) + 0.600 (Cut11) = 76.703

Working dimension obtained from cut11

= 76.103 (Design dim. Cut 11)

Now, the working dimensions and then complete tolerance chart could be resulted as shown in Fig. 8.

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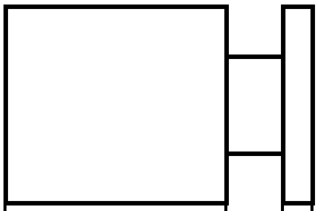

1	2	3	4	5	6	A B C D	7	8
Cut No.	Op. No.	Face Cut	Machine	Working Dimension Basic	Working Dimension (+/-)		Stock Dimension Basic	Stock Dimension (+/-)
0		D	Turr. Lathe					
1	1	A	"	79.703	0.500	1	Stock (85)	0.010
2	"	B	"	65.703	0.020	2	0.500	0.020
3	2	D_1	"	76.803	0.020	3	3.000	0.520
4	"	B_1	"	11.600	0.020	4	0.500	0.060
5	"	C	"	7.200	0.020	5	0.500	0.020
6	3	B_2	Cyli. Grind	65.303	0.010	6	0.100	0.030
7	4	C_1	"	4.500	0.010	7	0.100	0.050
8	"	B_3	"	7.100	0.010	Manual lapping 8	0.100	0.060
9	"	C_2	"	7.000	0.010	Manual lapping 9	0.100	0.070
10	5	A_1	Surf. Grind	76.703	0.005	10	0.100	0.025
11	6	D_2	"	76.103	0.005	11	0.600	0.530
Remark:				Designed Dimension			Resultant Dimension	
Face being cut				65.103	0.005		65.103	0.025
				7.000	0.010		7.000	0.010
Gauge face				4.000	0.005		4.000	0.040
				76.103	0.005		76.103	0.005
Locating face								

All dimensional units are millimetres

Figure 8: A complete tolerance chart with working dimensions and its tolerances.

Perform the actual manufacturing processes along with a created tolerance chart

With the working dimension and its tolerance which were specified in the column 5th and the column 6th respectively, technicians could use them for sequential machining operating directly as shown in Fig. 9. To verify and ensure results of using the created tolerance chart, with the same tolerance chart, four pieces of the 1kg experimental standard weight were machined by two technicians who possessed firmly experiences.

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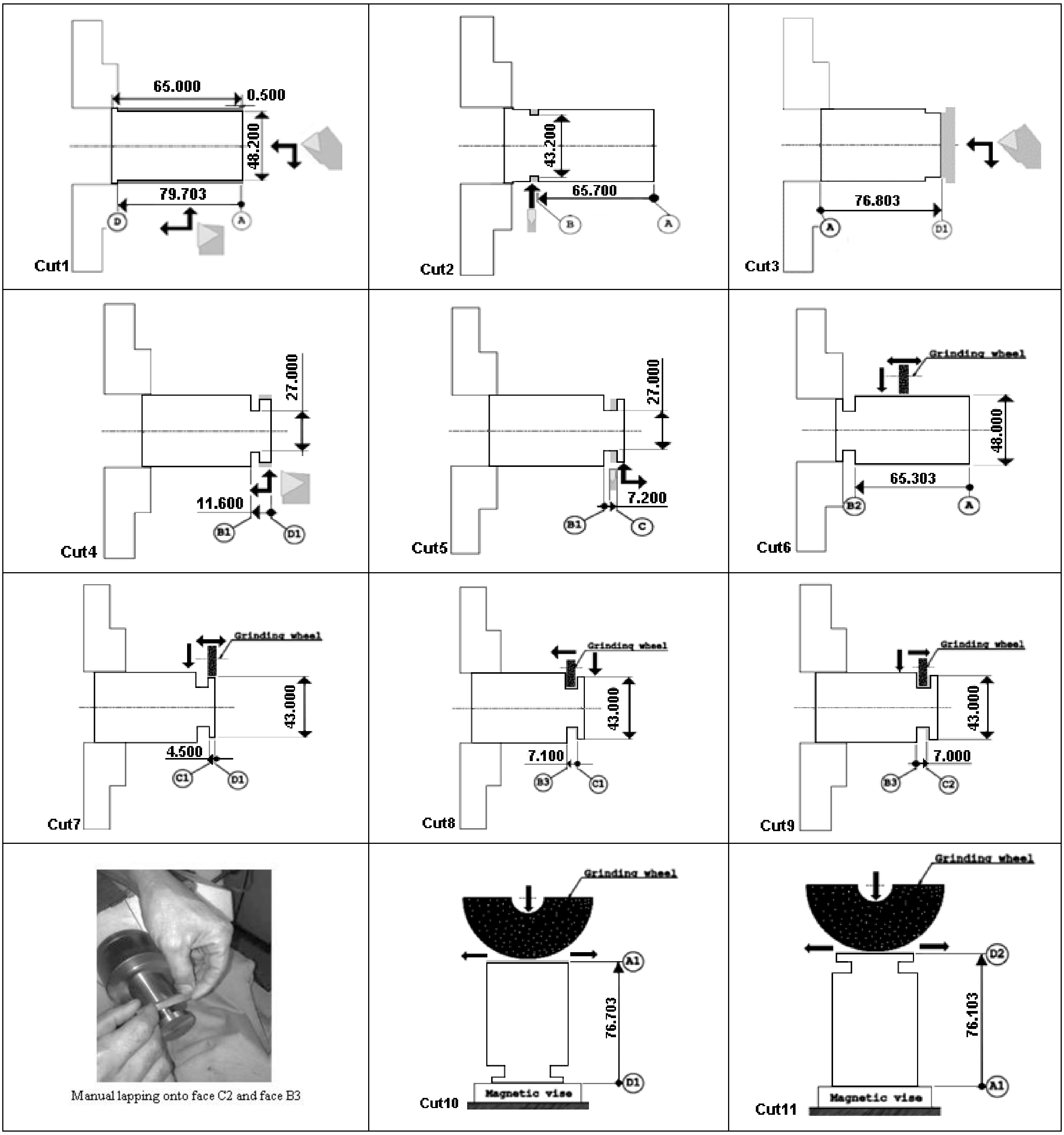

Figure 9: Actual sequential machining operation with working dimensions and tolerances specified by tolerance chart.

RESULTS

Three from four pieces of the experimental standard weights which obtained from the actual manufacturing could achieve the designed dimensional specifications excellently. By following the created tolerance chart, technicians could operate machining operations in step – by – step smoothly. A mistaken one that did not meet the requirement caused from circular running out of the whole axisymmetric shapes of the standard weight during some turning operations, and it could be not reworked. However, this deviation could be occurred normally in general machining conditions.

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Those tree pieces of the experimental standard weights were measured its weight by a precision scale Mettler Toledo® model PB 3002 – N, and could be read out its measured weight value within the range of 1001.45g – 1001.46g as shown in Fig. 10. They could be well – fit within the acceptable safety range of 1001.453g – 1001.483g before manual polishing to get the standard weight in the expected accuracy class E_2 (laboratory class). Moreover, the weight deviation of those four experimental standard weight could be passed the maximum permissible error (MPE) of the accuracy class M_1 (legal trade class) since the first time of finishing the whole machining sequences without any polishing manually.

Figure 10: A 1kg experimental standard weight could be read out its measured weight value within the expected safety - range of 1001.453 g – 1001.483g

CONCLUSION

By considering the methodology used in this paper, it exposed obviously that tolerance chart closely relate with machining sequences and capability of available machine tools.

By using tolerance chart, the designed tolerances could be transformed to the manufacturing tolerances effectively, especially processes that needed to relocate workpiece many times during the entire machining sequences. This chart could be used to calculate actual tolerance stackups of the resultant dimensions. These were compared with the designed tolerances to ensure in which workpiece could be produced within the expected – designed specifications. The chart could be also used to calculate actual tolerance stackups of the stock removal, and then could be compared with stock removal allowances to ensure that enough material is left after the existing operation for the later operations. By using the same tolerance chart, the different technicians could operate machining by following the working dimensions and its tolerances as step – by – step directly. They did not necessary to calculate and allocate the working specifications by themselves as before.

Rooted tree graph which was implemented into tolerance charting could facilitate process planners to create tolerance chart easily, and lead manufacturing dimensions and its tolerances could be calculated more accurately.

DISCUSSION

Tolerance chart relates with machining sequences and capability of the selected machine tools very closely. Any changing of machining sequences, more or less, affects to working dimensions and its tolerances, and leads tolerance chart needed to be revised. In this case, for process planners who create tolerance chart, rooted tree graph can help them to revise working dimensions and its tolerances easily. They can verify faults, and can find the proper solutions accordingly in advanced. With tolerance chart of a process plan, quality of the plan can be assessed according with production costs as proposed in a research worked by Kim and Dong [24]. However, due to machining sequences depended on both skill and experience of process planners. Therefore, the different planners maybe provide the different machining sequences and manufacturing tolerances accordingly. As well, for technicians who operate the machining, rooted tree graph can help them to cross – check working dimensions and tolerances in each step of machining sequences before running the machining actually such as adding of the manual lapping process on both face B_3 (Cut8) and face C_2 (Cut9) of the experimental standard weight. Certainly, with manual lapping specified in both tolerance chart and rooted tree graph, technicians can recognize in advanced in which they have to switch back and forth between lapping and dimensional measuring.

Because, in this paper, the finishing – machining along with the diametral dimensions of the short span workpiece such the experimental standard weight was performed by cylindrical grinding machine with the average machine capability of ±0.010 mm. By using the proper precision measuring instruments and skill of technicians, about 50% better machine capability i.e. 0.005 mm could be reached by manually. Therefore, controlling of diametral dimensions and its tolerance by using cylindrical grinding machine could be relied and tolerance chart for diametral dimensions could be neglected without any inferior effects. However, in the case of large workpiece that possessed a long span or complexity in shapes, it may be risky to face against running out problems along with the longitudinal axis of workpiece. In this case, process planners need to create more tolerance chart for diametral dimensions separately. Numbers of machining sequences, machine and cutting tools for both tolerance charts will be the same, the difference are upright orientation of the workpieces and feeding – direction of cutting tool. In the fact, a technician can use two tolerance charts for both longitudinal and diametral direction of machining according with normal working situation when they work with rotating machines as lathe and cylindrical grinding machines. This situation should be also easier when provide the cutting programs – codes for CNC machining.

By using the same tolerance chart, manufacturing of precision part such as the standard weight becomes standardized batch manufacturing i.e. all manufactured parts are still be the same within a certain acceptable range. In the other words, by using the same tolerance chart, two technicians can produce the parts within the same quality.

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