

Tolerance Planning and Control

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Introduction

Tolerance planning and tolerance control are important techniques used during manufacturing to ensure parts meet design specifications. The goal of tolerance planning is to produce a cost effective and valid process plan. A valid process plan is one that **can** produce parts within design specification. The goal of tolerance control is to ensure parts **are** manufactured within design specification.

Virtually no tolerance planning is needed for simple parts for which it is possible to directly machine most or all of the design dimensions. Direct machining uses one of the defining surfaces of a dimension as a reference (datum) to machine the other surface. In this case, the tolerance of the dimension is equal to the tolerance of the manufacturing process and there is no accumulation of tolerances due to datum changes. Tolerance planning simply involves selecting processes and machines that can economically produce parts with tolerances within the design specification.

However, tolerance planning is very difficult when parts are complex, design tolerances are tight, datum changes are frequent, and the number of operations needed to make the parts is large. Under these conditions operation tolerances will accumulate and there will be a *stackup* on design dimensions. The major problem for tolerance planning is to identify the operations that contribute to stackups and calculate their values. A formal technique, called *tolerance charting*, has been developed to solve this problem. Tolerance charting is widely used in the aerospace and automotive industries for parts produced by machining processes, such as turning, milling and grinding. In these industries charting is usually performed manually or by using in-house computer programs. Tolerance charting is notorious for its difficulty and, despite the enormous benefits that tolerance charting can bring, the technique has not enjoyed much popularity outside of the automotive and aerospace industries.

This part of the course is based on a new tolerance charting technique developed by the course lecturer and his colleagues. This new technique makes use of graph theory and rooted tree directed graphs. Our technique is easy to use and because of this we believe tolerance charting has much wider application than in the past. The technique is in regular use by industry in Singapore and is taught to engineering students at the University of Canterbury, New Zealand. It has been implemented in an industrial software program called CATCH.

These notes begin by explaining how process tolerances and tolerance stackups are controlled. Next the rooted tree tolerance charting technique is described.

Tolerance Control

Parts produced by a manufacturing process vary in size. Virtually every aspect of the process may contribute to the variation. In metal cutting the sources of this variation can be the machine tool, the cutting tool, the fixture that locates the workpiece, deflection of the workpiece, the lubricant or coolant used during the process, and the operator. Tolerance control of parts is achieved two ways. *Process control* controls the sources of variation directly or indirectly, by measurement and compensation. *Product control* relies on inspection, which filters out (rejects) parts whose dimensions fall outside the design specification limits. Because product control is very costly it should only be used as a last resort. It will not be discussed further.

Process control is the basis for tolerance planning. No planning is possible unless the performances of the processes are predictable (stable). Process stability is ensured through statistical process control. Once control has been achieved, then and only then, is it possible to obtain reliable measures of process performance. Such measures are referred to as process capability measures. These measures are the basis for

the process tolerance values used during tolerance planning; for further details refer to your notes on “process capability”.

Tolerance Planning

The major feature of tolerance planning is identifying and calculating *tolerance stackups*. Tolerance stackup is inevitable when a surface not directly referred to by a dimension is used for location. Two types of tolerance stackups must be considered: tolerance stackups on the *resultant dimensions* and tolerance stackups on the *stock removal*. The occurrence and calculation of both types of tolerance stack up are illustrated in Figure 1. The part in Figure 1 is produced on a vertical spindle milling machine by four operations with process tolerances of $\pm 0,05\text{mm}$. Two set-ups are used, locating first on surface labelled 0100 and secondly on surface labelled 0401. (The labelling convention is explained in full in the section on the rooted tree technique.) The figure shows the process sketches for the four machining operations and calculation of tolerances on stock removal and on the resultant dimensions. It can be seen from the calculations that the planned sequence of operations does not result in dimensions that satisfy the design dimensions. The tolerance on dimension 0101-0201 is $\pm 0,10\text{mm}$ and is a stackup of two other dimensions. The tolerance on dimension 0201-0301 is $\pm 0,15\text{mm}$ and is a stackup of three other dimensions.

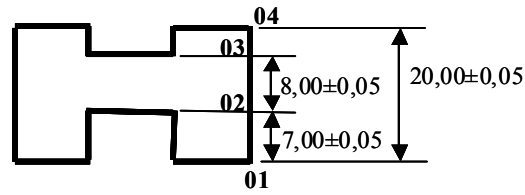
In Figure 1 distinction is made between different types of dimension relating to the manufacturing process. This distinction is important in tolerance planning therefore the different dimensions are defined below.

Design dimensions

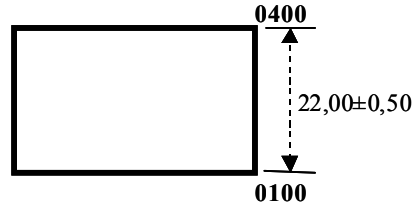
Design dimensions are the workpiece dimensions specified in the design drawing or CAD model. They are sometimes called *blueprint dimensions*. They have two components, a *nominal dimension* and a *tolerance* that is the permissible deviation from the nominal dimension. To facilitate calculation it is convenient to convert dimensions so that the tolerances are in equally disposed bilateral form, e.g., a dimension such as $25,0_{-0,10}^{+0}$ must be converted to $24,95\pm 0,05$. In this form the tolerances are always added when a dimension is added or subtracted with another.

Working dimensions

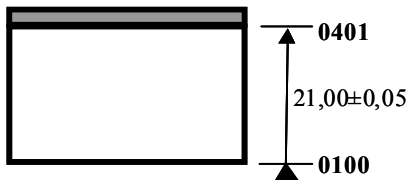
Each operation has an associated working dimension (WD). A working dimension also consists of a nominal dimension and a tolerance on the nominal dimension. The tolerance in this case is the process tolerance; it is an instruction to the machinist or machine setter of the allowable deviation from the nominal dimension. As such it has a profound influence on the choice and cost of the operation. Working dimensions are vectors and have direction as well as size. The direction is from a reference or location surface to the surface being cut. The working dimensions in Figure 1 are indicated using the convention that will be used in the tolerance chart in the next section: the cut surface is identified by an arrowhead and the location surface is identified by a triangle.



Design Dimensions

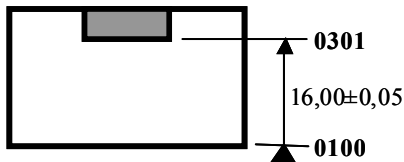


Pre-form Dimensions



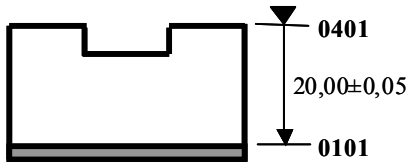
Operation 1

Cut surface is 0401, locating surface is 0100
 Working dimension 1 (WD1) = $21,00 \pm 0,05$
 Stock removal = $22,00 \pm 0,50 - 21,00 \pm 0,05$
 = $1,0 \pm 0,55$



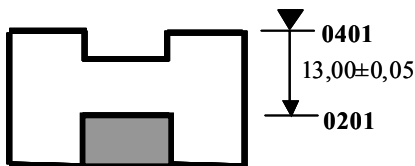
Operation 2

Cut surface is 0301, locating surface is 0100
 Working dimension 2 = $16,00 \pm 0,05$



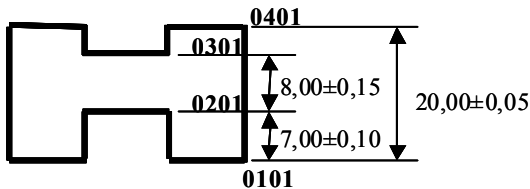
Operation 3

Cut surface is 0101, locating surface is 0401
 Working dimension 3 = $20,00 \pm 0,05$
 Stock removal = $WD1 - WD3$
 = $21,00 \pm 0,50 - 20,00 \pm 0,05$
 = $1,0 \pm 0,10$



Operation 4

Cut surface is 0201, locating surface is 0401
 Working dimension 4 = $13,00 \pm 0,05$



Resultant Dimensions

Resultant Dimension 0101_0201
 = $WD3 - WD4$
 = $20,00 \pm 0,05 - 13,00 \pm 0,05$
 = $7,00 \pm 0,10$

Resultant Dimension 0201_0301
 = $WD4 - (WD1 - WD2)$
 = $12,00 \pm 0,05 - (21,00 \pm 0,05 - 16,00 \pm 0,05)$
 = $8,00 \pm 0,15$

Figure 1.: Illustration of tolerance stackups

Working dimensions have a different meaning in automatic and manual machining operations. In automatic machining, such as CNC machining, the nominal component of the working dimension is equivalent to the programmed dimension using absolute measurement co-ordinates. It is the dimension from some specified machine zero to the surface being processed. If the workpiece is accurately located in a fixture the origin for the dimension can be considered to be the location surface. In manually controlled machining the nominal component of the working dimension is the distance measured from an existing reference surface to the surface being processed. (The existing surface is not necessarily a surface used for location.)

Pre-form dimensions

Pre-form dimensions are the dimensions of the blank or raw material, i.e., sawn bar, forging or casting dimensions. They also have nominal and tolerance components. Pre-form dimensions can be treated as special cases of working dimensions.

Balance dimensions

Balance dimensions are dimensions between workpiece surfaces, which can be calculated from working dimensions. If further processing is to be done on either of the two surfaces defining the dimension, the balance dimension is an *intermediate resultant dimension*. Because they are calculated from working dimensions, balance dimensions also have nominal and tolerance components. It is usual practice to simply add tolerances when calculating balance dimensions, this gives worst case tolerances and is a very conservative approach. An alternative is to use statistical methods to add the tolerances and maintain the three standard deviation tolerance band. The worst case approach is followed here.

Resultant dimensions

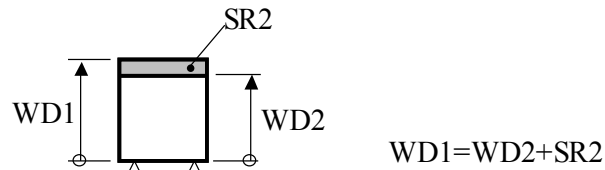
A resultant dimension is a special case of a balance dimension when no further processing is done on either surface defining the dimension. For the sequence of operations to be acceptable the upper and lower limits of the resultant dimension must be equal to the upper and lower limits of the design dimension or lie in the range between the upper and lower limits of the design dimension. In most cases this will mean that the nominal component of the resultant dimension must be equal to the nominal component of the equivalent design dimension, and the tolerance component must be less than or equal to the tolerance component of the design dimension. However, in some cases it may be necessary to offset the nominal value and reduce the tolerance on the resultant dimension to keep it within the bounds of the design dimension.

Tolerance stackups on the resultant dimensions are the result of the cumulative tolerances of the working dimensions of the processes that produce the resultant dimensions. These must be checked to confirm that the tolerances on the design dimensions can be achieved. Ideally the operations contributing to a resultant dimension should only be finishing operations because these have the smallest tolerances. In practice, however, this is usually technically impossible and some roughing or semi-roughing operations will contribute also.

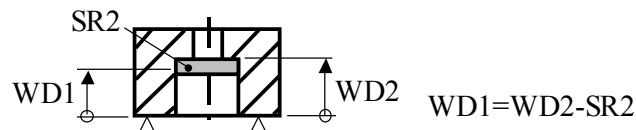
Stock Removal Allowance

Machining removes material from a surface of the workpiece. The change in dimension before and after machining is the stock removal allowance. It is the amount of material that was left on a surface for the next machining operation on that surface. The minimum allowance is both a technological property of the current machining process and a function of the surface roughness, defective layer, and distortions from previous operations. It cannot be arbitrarily determined. Some alternative stock removals are shown in Figure 2. The stock removal is a nominal dimension with no explicit tolerance. The actual stock removed is subject to a

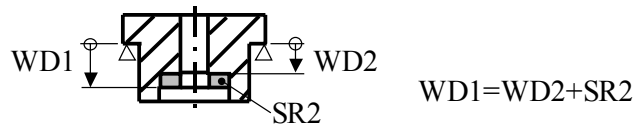
tolerance that is a tolerance stack of the working dimensions contributing to the stock removal. For the process to be viable, the stock removal allowance must be greater than half the tolerance on the stock removal (otherwise the actual stock removal may be negative and this is clearly impossible). If the stock removal is insufficient and the surface is not cut, then the balance dimension will be incorrect. The actual stock removal must be checked to ensure that the minimum stock removal allowance for proper function of the cutting process is satisfied otherwise the finish on the surface as well as dimensions may be incorrect.



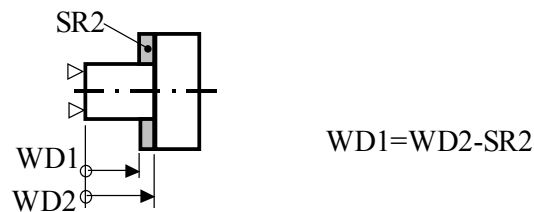
Example 1 Face Milling



Example 2 Back Boring



Example 3 Back Boring



Example 4 Right-hand Lathe Turning

N.B. WD = working dimension
SR = stock removal

Figure 2.: Some alternative stock removals

Stock removal tolerance stackup is illustrated in Figure 3. The example is taken from an industrial part. The figure has been simplified by only showing the key surfaces and relevant operations.

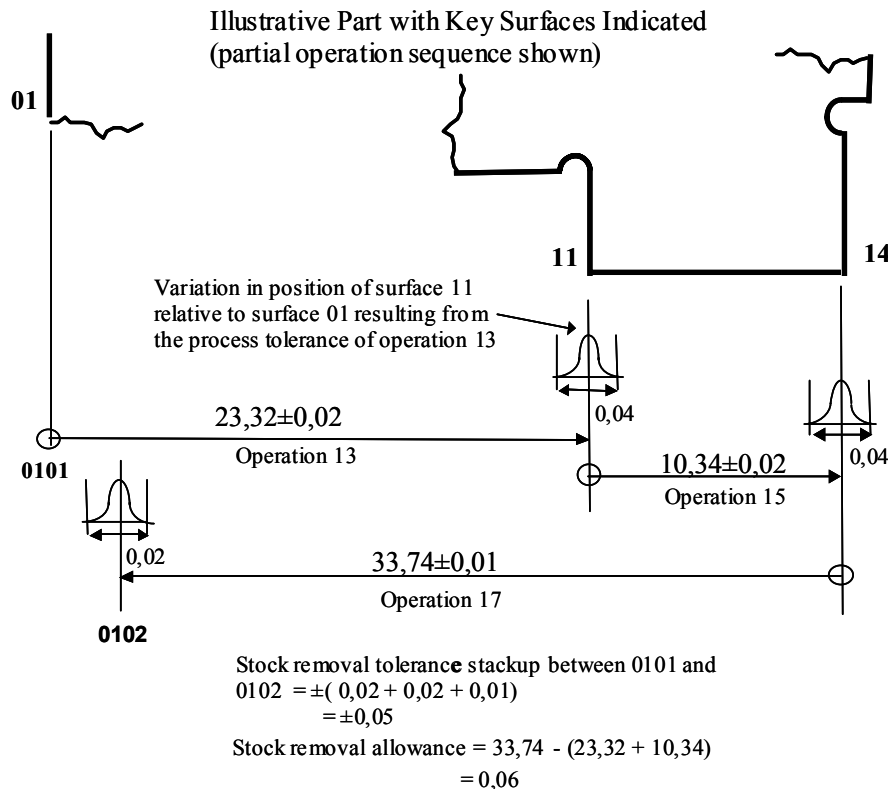


Figure 3.: Stock removal tolerance stackup

Working dimensions are calculated by working backward from the resultant dimensions and adding or subtracting the appropriate stock removal allowances. Choice of sign, that is, whether to add or subtract, depends on the direction of tool movement with respect to the relevant dimension, as illustrated in Figure 2.

The task sequence for tolerance planning is:

1. Specify a manufacturing sequence.
2. Assign tolerances to operations and check that the tolerances on resultant dimensions are within the design specifications.
3. Assign stock removal allowances to operations and check that the tolerance stackups on stock removal are within the stock removal allowances.
4. Calculate the working dimensions for all operations.

A tolerance chart is a graphical technique for accomplishing and recording these tasks.

Figure 4 shows the main features of a tolerance chart. A sketch of the part is drawn at top centre. Leader lines (facelines) are drawn to indicate the surfaces, points and centrelines on the part that will be used to define the datum and machined surfaces. These lines are numbered from left to right, with two digit numbers. They act as endpoints for the operation and design dimension symbols. These symbols are defined in Figure 5. The design nominal dimensions, tolerances and dimension symbols are entered at the bottom of the chart, as are the resultant nominal dimensions and tolerances. Operation data, working dimensions,

operation symbols and stock removal tolerance stackups are entered in the middle of the chart. The order of the operations, from top to bottom, indicates the manufacturing sequence. The first operation is at the top and the last one at the bottom.

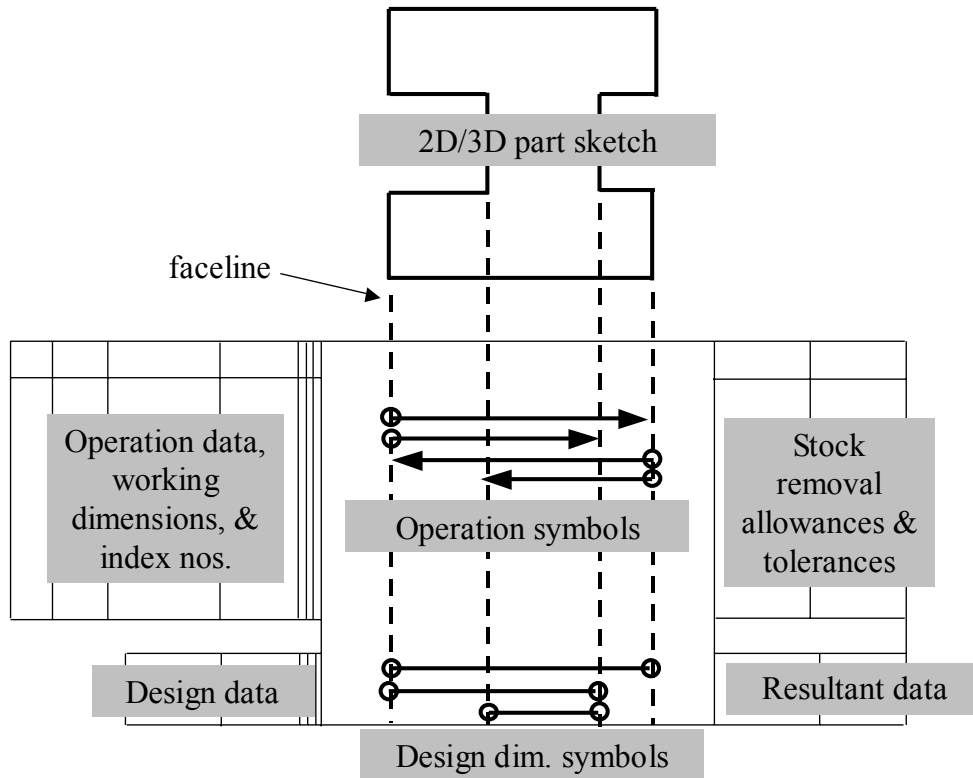


Figure 4.: Basic Features of a Tolerance Chart

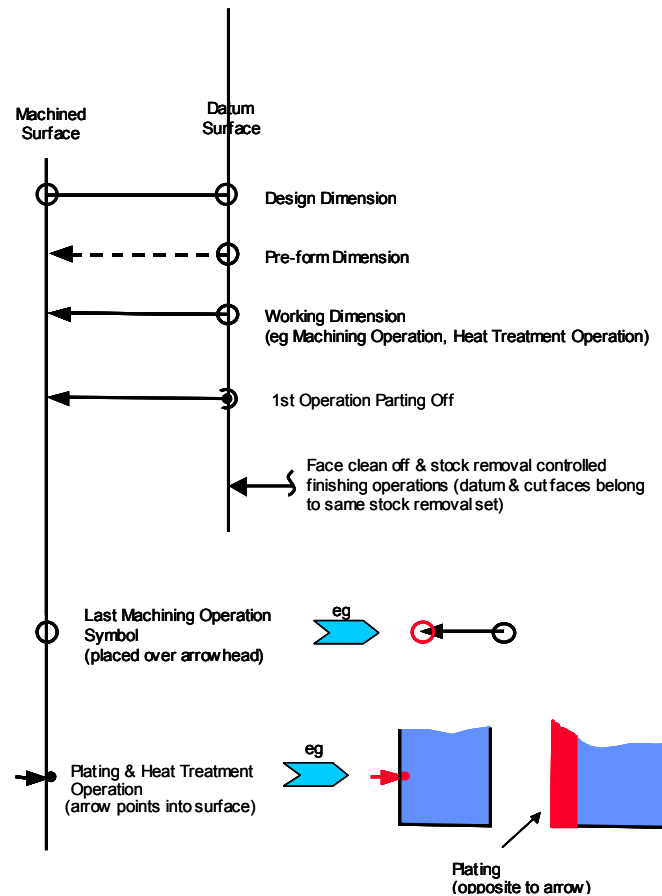


Figure 5.: Tolerance Chart Symbols

The Rooted Tree Tolerance Charting Technique

This section illustrates and explains how to manually construct a tolerance chart using the rooted (datum hierarchy) tree technique. The chart is for the example shown in Figure 1. The completed chart and rooted tree are shown in Figures 6 and 7 respectively. The chart represents the manufacturing sequence and relates the operations to the part features. The tree represents the datum hierarchy for the manufacturing sequence. Both the tree and chart representations are necessary for efficient and effective process planning.

The technique for tolerance charting depends on uniquely identifying each occurrence of every surface. Surfaces before and after a machining operation that are related to each other by the stock removal are part of a *stock removal set*. A four-digit number is used to identify each surface. The first two digits represent the stock removal set. The number of the set is the same as the number of the surface on the design specification associated with the set. In Figure 3 there are four surfaces and hence four stock removal sets, numbered 01, 02, 03, and 04 as shown in Table 1. The second pair of digits of the number indicates the number of cuts on a surface. Newly created surfaces are assigned the digits 00. Thus 0200 indicates the creation of surface 02, and 0101 indicates the first cut on surface 01 (previous existed from prior operation). For pre-form dimensions, such as casting and forging dimensions, the last two digits are zeros, e.g., 0100 and 0400.

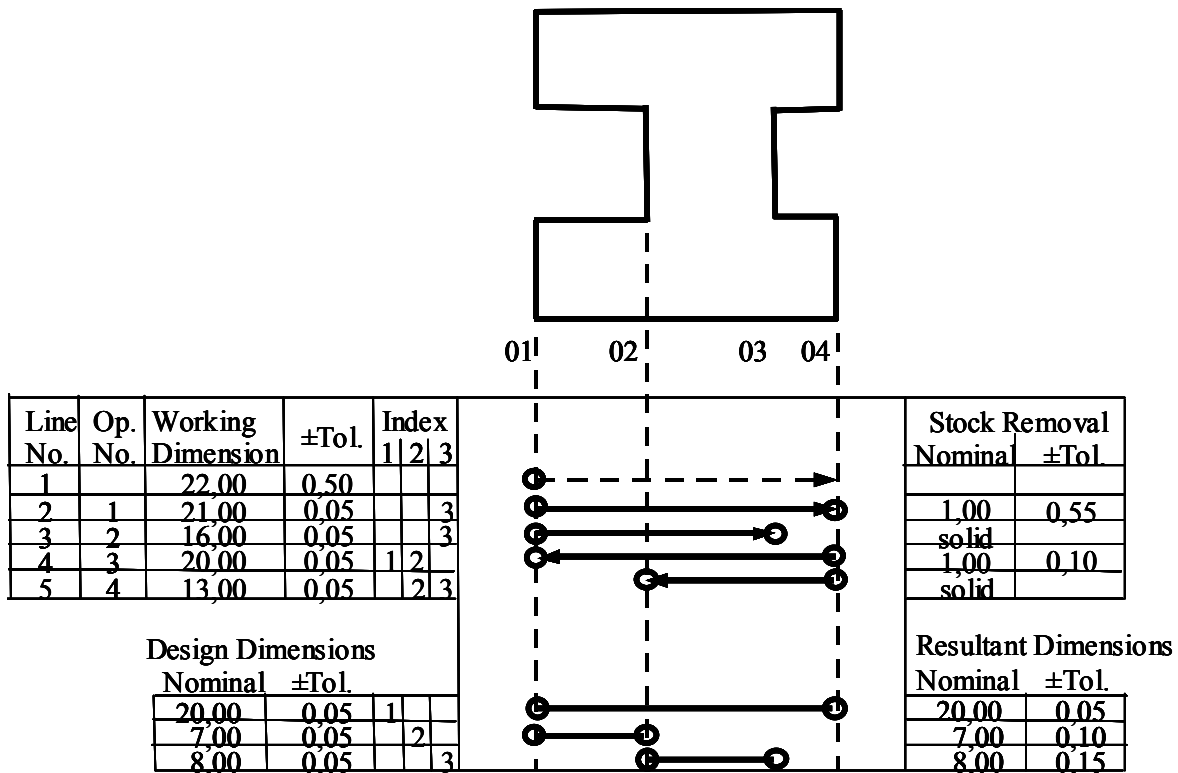


Figure 6.: Tolerance Chart for Example

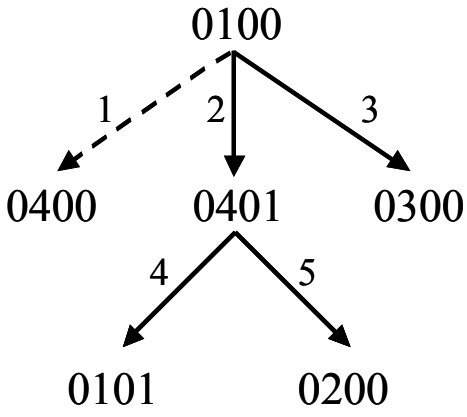


Figure 7.: Tree for Example

Referring to the tree in Figure 7, each node on the tree represents a machined and/or datum surface. Some nodes are both machined surfaces and datum surfaces. The datum surface is either a location or reference surface. A link between a pair of nodes on the graph represents a machining operation; the arrowhead points to the surface being machined with the tail end of the link originating at the datum surface. The corresponding line number from the tolerance chart is attached to the link. The tree can be constructed from top to bottom or left to right. Here the top-down convention is used. The path from one node to another represents the operations that contribute to the distance between the two surfaces represented by the nodes. This path must

be used to calculate the dimension between two surfaces. For instance the resultant dimension between 0200 and 0300 is the path 0200-0401-0100-0300 and the contributing operations are the links on this path, that is operations with line numbers 5, 2 and 3. The tolerance on the resultant dimension 0200-0300 is $\pm (0,05 + 0,05 + 0,05) = \pm 0,15$.

Table 1.: Stock removal sets

Set 01	Set 02	Set 03	Set 04
0100	0200	0300	0400
0101			0401

Stock removal is the distance between two consecutive surfaces in a stock removal set. For example, the stock removal for operation 3 (line 4 in the tolerance chart) is the distance 0100-0101. This is calculated from the operations on the path 0101-0401-0100. The contributing operations are line numbers 4 and 2. The tolerance on stock removal is $\pm (0,05 + 0,05) = \pm 0,10$.

Initial Chart Preparation and Tree Creation

The starting point for constructing the chart and tree is a blank template chart. (A blank chart is provided as a template for student use.) The profile of the finished part is drawn or copied to the chart and the facelines drawn in. If a CAD system has been used to model the part, then the 2D profile can be generated as a hardcopy output (to the correct scale), cut out and pasted on the chart. For manual charting it is essential to ensure that all surfaces and machined features are identified and that the corresponding facelines are drawn in at this stage because it is very difficult and time consuming to add in extra lines later. The facelines are numbered from left to right using the stock removal set numbers.

Next the design nominal dimensions and tolerances are obtained from the part drawing or CAD model and entered at the bottom of the chart with the corresponding chart symbols. The resultant nominal dimensions are also entered. They are set to the same values as the design nominal dimensions.

The chart can now be used to plan the sequence of operations. The first operation is entered at the top of the chart (line 1). In this example it is a pre-form dimension (0100-0400). The pre-form symbol is drawn on the chart and the tolerance for the dimension entered (no other information is required for pre-form dimensions). This is represented on the tree as a dashed arrow from 0100 to 0400 at the top of the graph. 0100 is the first surface in the graph and is called the tree root. Surface 0100 has been arbitrarily chosen as the datum. Either end could have been chosen as datum for the symbol, the tolerance calculations will give the same answer for both cases.

The machining operations are entered in the chart and tree in a similar manner, working from top to bottom, and including the operation numbers, the process tolerances and the stock removal allowances. The process tolerance is obtained from company data for the particular machine and process. The stock removal allowance is set to "solid" for a first cut that produces a surface that does not appear on the pre-form. For second and higher cuts a stock removal amount must be entered. The stock removal allowance is a technological property of the operation and the surface condition from the previous machining operation, and is obtained from the planner's knowledge or company data on the process being used.

The symbols for the datum surfaces are defined in Figure 5. In this example all the datum surfaces are locating surfaces and therefore they are represented by triangles. Circles are used to represent datum surfaces that are not locating surfaces.

In this example a top-down approach to planning has been used, starting with the pre form dimensions and working down the chart to the final finishing cuts. In practice a combination of top-down and bottom-up approaches is used to plan a sequence. Planning starts in a bottom-up manner, with the finishing operations being planned first. Then a top-down approach is used to plan the roughing and semi-roughing operations. Irrespective of the approach used to generate a manufacturing sequence, the end result must be a rooted tree. That is, the operations must start at one and only one node, and all nodes must be connected to each other by operations.

When all of the operations have been entered and the sequence has been completed, last cuts on surfaces are marked by drawing circles on the arrowheads of the symbols for the operations making these cuts. Every faceline must have one and only one last cut symbol on it. For small charts, these symbols may not be necessary. However, for large charts the symbols help the planner to quickly identify the finished surfaces and the operations producing them. At this stage the rooted tree diagram as it appears in Figure 7 is complete and all known data concerning the sequence have been entered in the tolerance chart. What remains to be done is to check that the tolerances on the resultant dimensions are within the design specification tolerances on design dimensions, to check that the stock removal allowances are sufficient, and to calculate the nominal values of the working dimensions.

Tolerances on Resultant Dimensions

Tolerance stackups for the resultant dimensions are calculated using the following procedure:

1. Start with the first resultant dimension.
2. Identify the last cuts on the surfaces defining the dimension, ie the nodes with the highest values in the second two digits.
3. Find the path between these surfaces on the rooted tree.
4. Calculate the tolerance stacks for the resultant dimension by adding the tolerances of the operations on the path.
5. Repeat steps 2-4 for the remaining resultant dimensions.
6. Finally check that all resultants tolerances are equal to or smaller than the associated design tolerances. If any tolerances are outside the design limits then the sequence must be modified.

Applying this procedure to the example:

The first resultant dimension is defined by surfaces 0101 and 0401. The path on the tree is 0101-0401. The only contributing operation is in line number 4. There is no tolerance stackup and so tolerance on the resultant dimension is obtained directly from the working dimension. This value is entered on the chart.

The second dimension is defined by surfaces 0101 and 0200. The path is 0101-0401-0200. The tolerance is a stack of operations in lines 4 and 5. The tolerance stackup is $\pm(0,05 + 0,05) = \pm 0,10$. This value is entered in the chart. It can be seen immediately that the design specification has not been satisfied. For practical purposes the chart development would stop at this stage and the sequence re-planned, but development of the chart is continued to illustrate the method.

The last dimension is defined by surfaces 0200 and 0300. The line numbers of the operations in the path between these nodes on the tree are 5, 2, and 3. The resultant tolerance is given by adding tolerances for lines 2, 3, and 5, i.e., $\pm (0,05 + 0,05 + 0,05) = \pm 0,15$. This value is entered in the chart and again, when it is compared with the tolerance of the design dimension, it can be seen that it does not satisfy the specification.

The technique described above is the simplest way to calculate and compare the resultant dimension limits against the design dimension limits. However, a more general technique involves calculating the upper and lower resultant dimension limits separately and comparing these to the upper and lower design specification limits respectively. The advantage of the more general technique is that resultant dimensions do not need to be set at the middle of the design tolerance intervals. Offset resultant dimensions may be required for two reasons. First a design dimension may have been specified in unilateral form. In order to optimise a design, the designer may require the target value for the process-making-the-part to be offset towards one of the design limits, e.g., the lower limit. In order to facilitate process and tolerance planning, the unilateral design limits would be converted to bilateral form. However, during tolerance planning the designer's intent can be met by offsetting the relevant resultant nominal dimension towards the lower limit. Second, it may be necessary to offset a working dimension for ease of manufacture or to round off calculated values. If this occurs then the relevant resultant dimension(s) may need offsetting also.

Tolerances on Stock Removal

The tolerances on stock removal must be calculated for all operations that have a stock removal allowance specified. The method of calculating the tolerances is similar to the method for calculating tolerance stack ups for resultant dimensions. The calculations are listed below:

Stock removal set 01

Stackup for operation producing 0101: The consecutive pair of surfaces are 0100 and 0101 and the path is 0100-0401-0101. The contributing operations are in lines 2 and 4. Tolerance stackup is $\pm (0,05+0,05) = \pm 0,10$. This value is entered in the \pm tol column for stock removal on line 4.

Stock removal set 04

Stackup for operation producing 0401: The consecutive pair of surfaces are 0400 and 0401 and the path is 0400-0100-0401. The contributing operations are in lines 1 and 2. Note in this case that one of the operations is a pre-form dimension, with a tolerance value from a prior manufacturing process. The tolerance stackup is $\pm (0,5+0,05) = \pm 0,55$. This value is entered in the \pm tol column for stock removal on line 2.

Sets 02 and 03 contain one member and therefore a stock removal check is not required.

Half the tolerance stackup values (ie the \pm tolerances) are compared with the stock removal allowances. In both cases the allowances are greater than the stackups, therefore the stock removal check is satisfactory.

Working Dimensions

When a satisfactory sequence that satisfies both the design specification and stock removal has been planned, the nominal values of the working dimensions can be calculated. Calculation of the working dimensions has been considered to be the most difficult of the tolerance chart calculations. Previous methods have involved a tedious procedure working through the chart from the final operation back to the raw material and calculating the working dimensions at each line by adding or subtracting the stock removal allowance for each operation. A simple tabular method is presented here. The method is applied to the

example in Figures 1, 6 and 7 using Table 2. The columns of the matrix indicate the stock removal sets and the rows the cut number (positions) in the sets. The centre of the table indicates the position of each surface (or stock removal set) at the completion of each operation relative to the final position of the left hand surface. To calculate a working dimension for any line number on the chart, identify the two surfaces involved. Extract their surfaces positions from Table 2 and take the absolute difference between them: this is the working dimension.

Table 2.: Stock Removal Matrix

Cut number or position	Stock Removal Sets			
	01	02	03	04
00	-1,00	7,00	15,00	21,00
01	0,00			20,00

A few simple rules are needed to construct the table.

The table is filled in working from the bottom upwards. Find the last cut number for each stock removal set. At the relevant row/column intersection enter the position of the last surface in the set with respect to the left hand end of the part, using the design dimensions. For column 01 the last position is always set at 0,00mm because this is always the left-hand end of the finished part. This is entered at row 01. The finished dimension between stock removal sets 01 and 02 is 7,00mm, which is entered in row 00 because 0200 is the last surface in the set. For 03 enter 15,00mm at row 00 and for 04 enter 20,00mm at row 01.

Now each column can be completed in turn working upwards from the last surface position. Columns 2 and 3 need no further calculation. For column 1, the position of surface 0100 is calculated by subtracting the stock removal allowance allowed for surface 0101, which is 1,00mm, giving $-1,00$. The allowance for surface 0401 is also 1mm. Thus the position of 0400 is $20,00 + 1,00 = 21,00$. The allowance is added as surface 0400 is further from the left hand end than 0401.

The working dimensions can now be calculated very easily. For each line number on the chart, identify the two surfaces that defined the ends of the dimension (using the rooted tree). Get the surface positions from the stock removal matrix and take the absolute difference. For example, consider line 1. The surfaces defining the working dimension are 0100 and 0400. The working dimension is $21,00 - (-1,00) = 22,00$. Enter this value into the tolerance chart. For line 5, the surfaces involved are 0200 and 0401. The working dimension is $20,00 - 7,00 = 13,00$.

The chart is now complete. If properly completed it is a complete record of the operations to produce a part within the specified tolerances.

Off-Set Dimensions

Thus far the calculations of working dimensions has been based on nominal values of the resultant dimensions. These are set the same as the nominal values of the design specification dimensions. In practice, it may be desirable to offset working and resultant dimensions. Working dimensions may be offset to allow for tool wear. However more commonly they are offset to provide achievable values. For example, when grinding is performed after a turning operation, the stock removal allowance for the grinding operation can result in a working dimension for the turning operation that requires a higher accuracy than the lathe is capable of producing. In these cases, it is usual to round the working dimension to an appropriate value by applying an offset. Resultant dimensions may be offset to bias the resultant dimension towards one design specification limit in order to improve performance or to allow for drift in the manufacturing processes.

For the purposes of illustration of off-sets, a different example will be used (it is the example shown in the powerpoint slides). The tolerance chart, design dimension graph and the rooted tree for the example are shown in the Figures 8-10 below. The stock removal matrix is shown in Table 3.

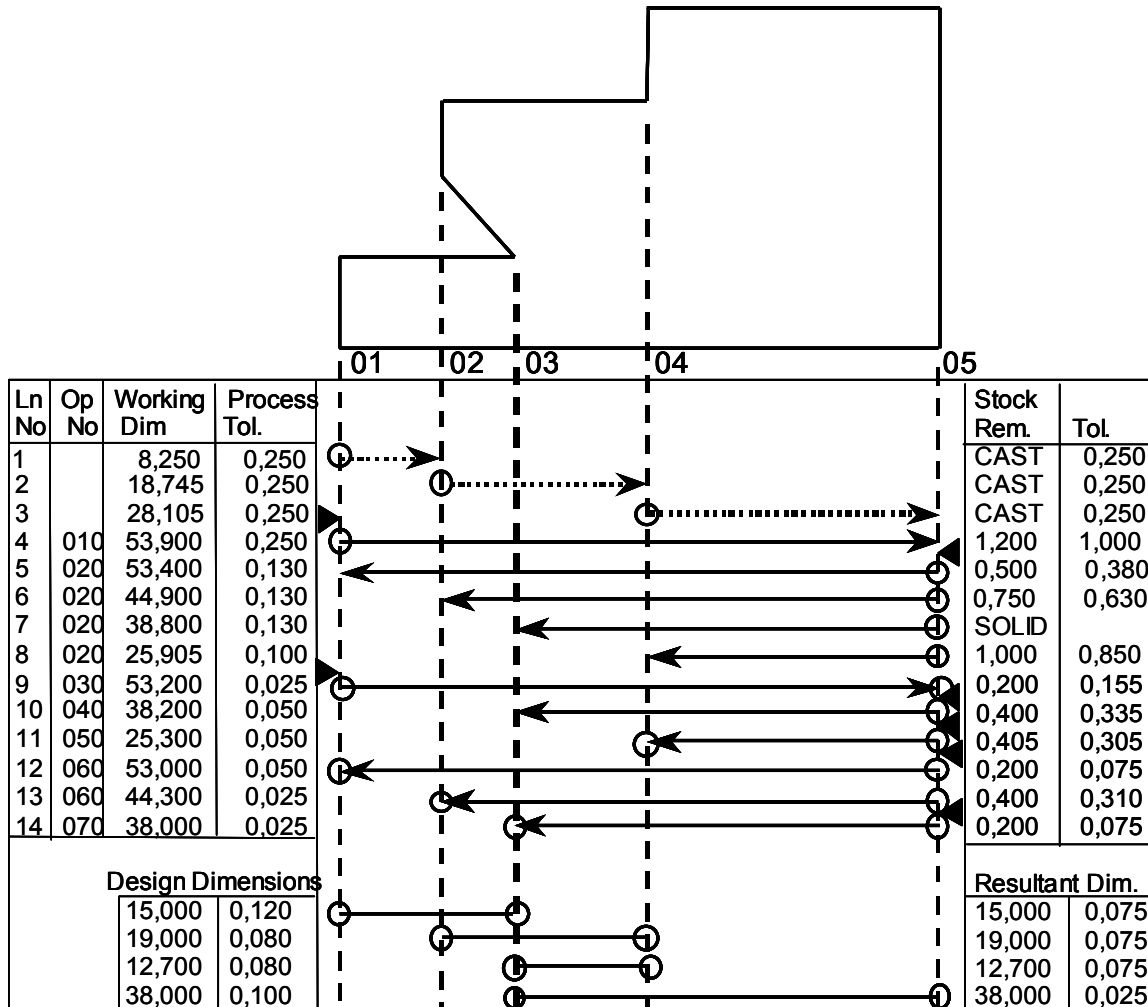


Figure 8.: Tolerance Chart for Example

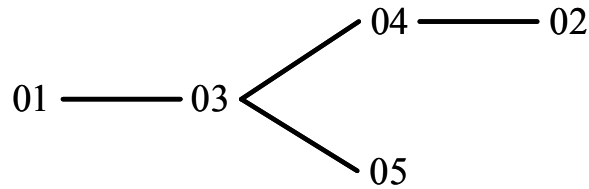


Figure 9.: Design Dimension Graph

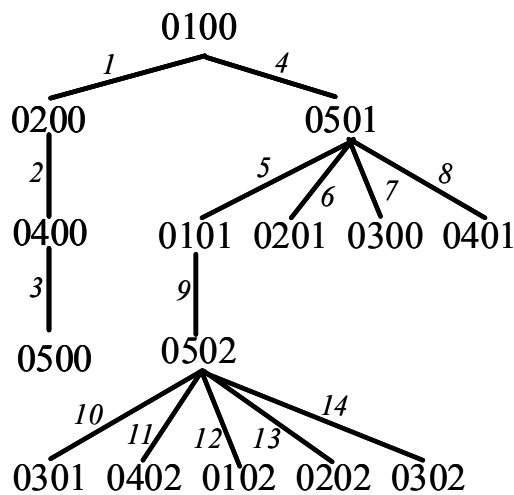


Figure 10.: Rooted Tree

Table 3.: Stock Removal Matrix

Set No.>> Position	01	02	03	04	05
00	-0,700	7,550	14,400	26,295	54,400
01	-0,200	8,300	14,800	27,295	53,200
02	0,000	8,700	15,000	27,700	53,000

Working dimension offsets

Working dimension offsets can be applied two ways:

1. Offset the machined surface and adjust the positions of ALL other surfaces in the stock removal set and the working dimensions defined by these surfaces. One or more resultant dimensions will be affected by this approach, and so the tolerance stackups need to be re-calculated for the affected resultant dimensions, and checked against the design specification limits. This kind of offset is normally applied when biasing a working dimension for tool wear, etc.

2. Offset the relevant surface and absorb the offset in the stock removal allowance of the following surface. In this case, the positions of the surfaces in the stock removal set preceding the offset surface and the working dimensions defined by these will be changed. On the other hand, the positions of the surfaces following the offset surface will not be affected, nor will the resultant dimensions. This kind of offset is normally applied when adjusting a working dimension to give a more easily achievable machining target.

As an illustration of the second approach, assume working dimension 0401 (line 8, Figure 8) is offset 0,005mm, to round it to 25,900 (instead of 25,905). The offset will be absorbed by the stock removal allowance of 0402 (line 11, Figure 8), by reducing it from 0,405 to 0,400. First it is essential to check the tolerance stackup on the stock removal to ensure that sufficient stock remains. In this case, the stackup is 0,305mm. As $0,305 < 0,400$ the new allowance is acceptable.

The revised matrix is shown in Table 4. The changes are highlighted in bold. The revised tolerance chart is shown in Figure 11; changes are highlighted in bold and by shading.

Table 4.: Revised Stock Removal Matrix
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Set No.>> Position	01	02	03	04	05
00	-0,700	7,550	14,400	26,300	54,400
01	-0,200	8,300	14,800	27,300	53,200
02	0,000	8,700	15,000	27,700	53,000

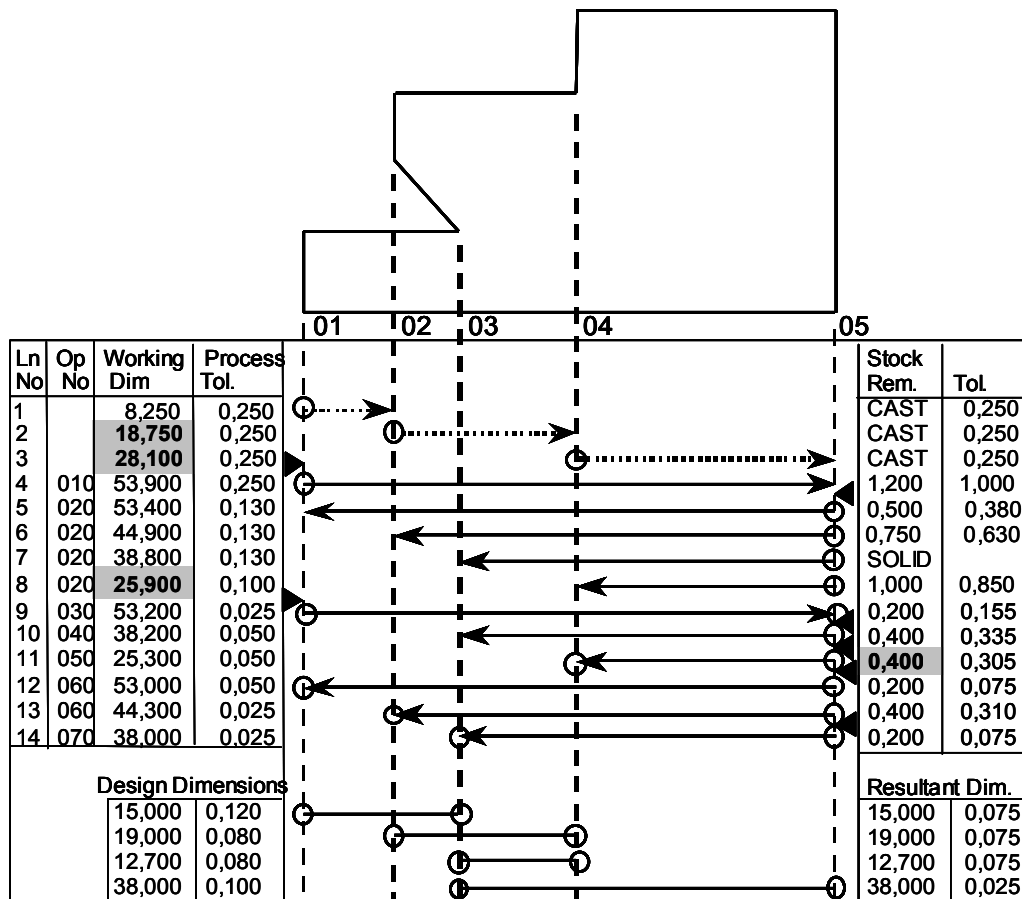


Figure 11.: Tolerance Chart with 0401 offset 0,005mm.

Resultant dimension offsets

There are three ways to offset a resultant dimension:

1. offset the left hand surface defining the dimension,
2. offset the right hand surface defining the dimension,
3. offset both surfaces defining the dimension, proportioning the total offset amount between the two surfaces.

Whichever method is chosen, it is necessary to check whether other resultant dimensions are affected by offsetting the surface(s). The design dimension graph is used for this purpose. For example, assume that resultant dimension 03-05 (last resultant dimension) is to be offset. If the offset is applied to surface 05 (0502) then it can be seen from Figure 9 that no other resultant dimension is affected. If the offset is applied to surface 03 (0302) then two other dimensions are affected, 03-01 and 03-04. The rule is simple. If the offset is applied to a leaf node then no other dimension is affected. If the offset is applied to a branch node then at least one other dimension is affected.

The maximum amount of offset that can be applied without exceeding design specification limits is the minimum tolerance slack for the affected dimensions, where:

Tolerance slack = design tolerance – resultant tolerance.

For example, consider an offset applied to surface 0302. The maximum offset is the minimum tolerance slack for dimensions 03-01 and 03-04 and 03-05:

Tolerance slack 03-01 = $0,120 - 0,075 = 0,045$

Tolerance slack 03-04 = $0,080 - 0,075 = 0,005$

Tolerance slack 03-05 = $0,100 - 0,025 = 0,075$

Minimum tolerance slack = $\text{Min} [0,045; 0,005; 0,075] = 0,005$

Thus the limiting dimension is 03-04. Table 5 shows the working dimension matrix when surface 0302 is offset 0,005; changes are highlighted in bold. Figure 12 shows the tolerance chart; changes are highlighted in bold and shaded.

Table 5.: Revised Stock Removal Matrix

Set No.>> Position	01	02	03	04	05
00	-0,700	7,550	14,375	26,295	54,400
01	-0,200	8,300	14,775	27,295	53,200
02	0,000	8,700	15,975	27,700	53,000

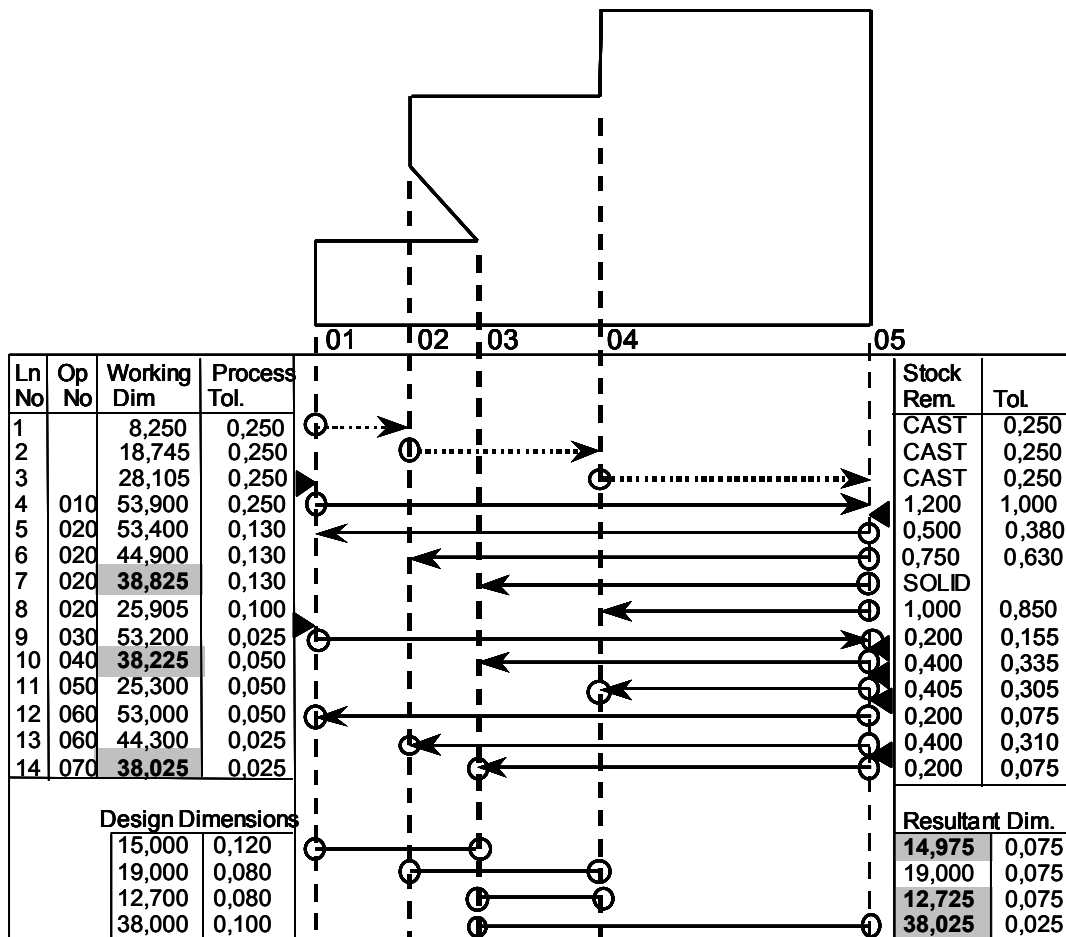


Figure 12.: Tolerance Chart with 0302 offset 0,005mm.

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