Surface finish

The process of cutting requires the determination of the speed, feed, and depth of cut. These factors affect the tool life and surface finish – and therefore play important roles in the economics of the machining process. In reality, several other factors also affect surface finish, including vibrations of the machine tool, inaccuracies in the machine table motion, workpiece material effects, surface damage due to scratching by the chips, etc.

Tool Life,

In early 1900's, F. W. Taylor performed a series of experiments which showed that the single most important factor in determination of tool life was the cutting speed, ***V****; his experiments resulted in the famous tool-life formula:*

His simple and easy-to-use analytical expression which gives the relationship between the cutting speed and the tool life is given below. This expression is called **Taylor's Equation**.

Frederick W. Taylor
(1856 -1915)

$$V\,T\,n = C$$

V - Cutting speed in m/min

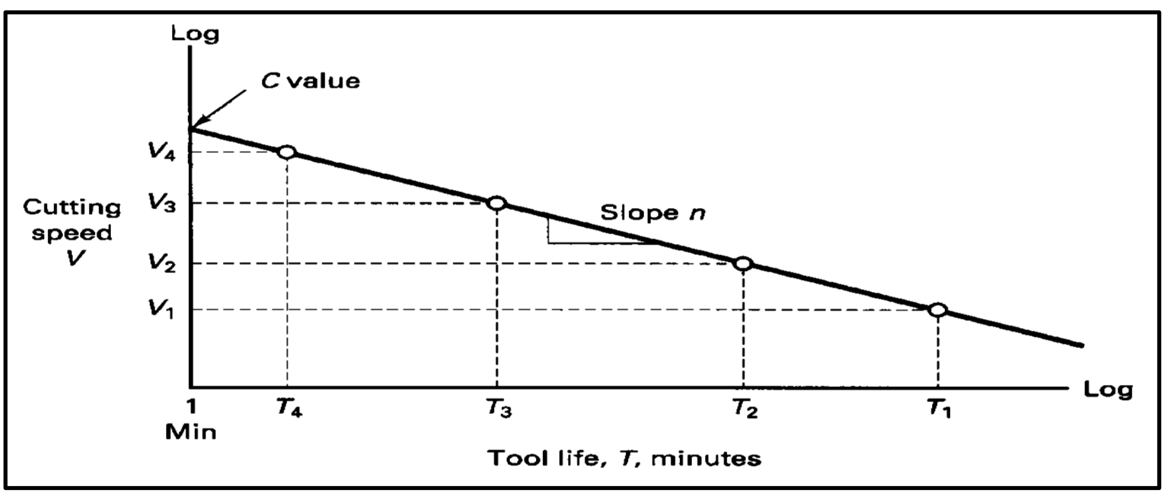
T - Tool life in minutes

C - Cutting speed for 1 minute tool life

n - Exponent (Slope of the cutting speed versus tool life plot)

C and n are found by conducting experiments at different cutting speeds and recording the tool life.

When plotted on log-log scale, cutting speed versus tool life relationship becomes a straight line, so that values of C and n can be determined easily.



V T n = C

C - Cutting speed for 1 minute tool life

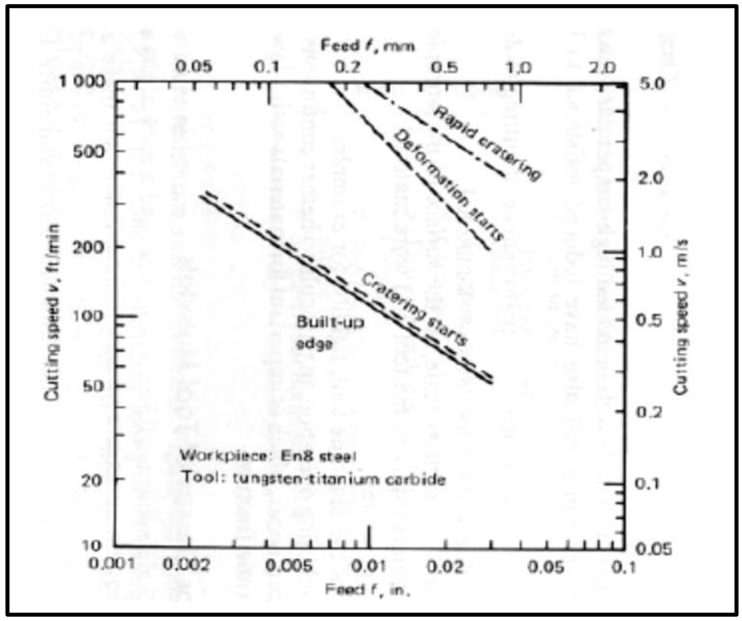
Depends on all input parameters, including feed.

n - Exponent (Slope of the cutting speed versus tool life plot)

Depends mostly on cutting tool material, but is effected by work material, cutting conditions, and environment.

- *0.14 to 0.16 for HSS*
- *0.25 for uncoated carbides,*
- *0.30 for TiC-coated insert*
- *0.40 for ceramic coated inserts.*

= > n increases with increasing tool material quality



Typical experimental chart showing relation of tool wear with *f* and *V*.

Machining Economics

We develop a simple model of the economics of machining. For any production facility, it is important to use their machines at an optimum level. Here, optimality is defined in terms of an objective to minimize either time (i.e. maximize production rate), or costs (i.e. minimize production costs). Our analysis has several stages.

(i) ***Stock***: Before cutting, we must determine the ideal starting stock to produce a given part. If the starting stock is already of a shape similar to that of the final part (this is called ***near net shape*** stock) then only a small amount of machining is required and can be done faster. On the other hand, producing near net shaped stocks may be more expensive than starting from rectangular stock.

(ii) ***Operations planning and tool selection***: The amount of material removed in unit time, or material removal rate (MRR) is an important determinant for the production rate.

(iii) ***Feed***: A higher feed will provide higher MRR; however, as we saw above, it leads to lower surface quality. Hence the best feed is determined as the highest feed allowed by the surface finish required.

Given the feed rate and other parameters, how do we determine the optimum cutting speed? Consider that we are producing a large number of identical parts in one batch, replacing the tool by a new one whenever it is worn. Our model has three components:

Non-productive time:

Let t_l = time to load the stock, set the tool at the start position, and the time to unload the part after it is machined. Let N_b be the total number of parts in the batch.

Total non-productive time = $N_b t_l$

Machining time:

Let t_m = time to machine the part;

Total machining time = $N_b t_m$

Tool change time:

Let t_c = time to replace the worn tool with a new one; let N_t be the total number tools used to machine the entire batch.

Total tool change time = $N_t t_c$

Let the cost of each tool = C_t, and the cost per unit time for machine and operator = M. thus the average cost to produce each item in the batch, C_{pr}, is given by:

$$C_{pr} = Mt_l + Mt_m + M\frac{N_t}{N_b}t_c + \frac{N_t}{N_b}C_t \qquad (2)$$

The first term is constant for each batch;

Note that once the depth of cut and feed are determined, the motion of the tool with respect to the workpiece is determined purely by the geometry of the part and the stock, and therefore the total length of the tool-path is fixed. Let the total length of the cutter path = L.

$t_m = \frac{L}{V}$; therefore the second term can be written as: $M\frac{L}{V} = MLV^{-1}$

The last three terms are the tool costs, which increase with increasing V. To minimize the cost per item, we differentiate this expression with respect to V; however, note that the number of tool changes is a function of the cutting velocity. To find its relationship,

we shall use Taylor's simple model: $Vt^n = C'$; where C' is a constant; t = tool life and V is the cutting speed. Thus, $Nt = (N_b\, t_m)/t$. Rewriting,

$$\frac{N_t}{N_b} = \frac{t_m}{t} = \frac{L}{V}\frac{V^{1/n}}{C} = \frac{LV^{(1-n)/n}}{C}$$

, where $C = C'^{1/n}$.

Substituting, we can now write the cost per unit as:

$$C_{pr} = Mt_l + MLV^{-1} + \frac{L}{C}(Mt_c + C_t)V^{(1-n)/n} \qquad (3)$$

$$\frac{dC_{pr}}{dV} = 0 = -MLV^{-2} + \frac{L}{C}(Mt_c + C_t)\frac{(1-n)}{n}V^{(1-2n)/n}$$

and solving this, we get the optimum speed for minimum total cost as:

$$V = \left(\frac{MC}{(Mt_c + C_t)}\frac{n}{(1-n)}\right)^n \qquad (4)$$

Similarly, it is possible to write the average time to produce a part as:

$$t_{pr} = t_l + t_m + \frac{N_t}{N_b}t_c \qquad (5)$$

Writing the expression for t_m and N_t in terms of the cutting velocity, V, we can get the average time to produce each part as a function of V. By minimizing this expression, we get the value of V that is optimal for maximizing the production rate. It is not surprising that the optimum velocities for the two criteria are not the same.

Process Planning

The ***process plan*** specifies:

- *operations*
- *tools*, *path plan and operation conditions*

- *setups*
- *sequences*
- possible *machine routings*
- *fixtures*

Process planning is a complex activity that affects overall productivity in the production of a part/product. Here we shall look at some aspects of it related to machining of single parts [IMPORTANT: please note that process plan must be made for all manufacturing processes, including product assembly]. However, we will restrict our study to examples on process planning for machining.

Figure 28 (a) shows the cut-out (sectioned) view of a simple rotational part. Assume that we decide to cut this part out of round bar stock material on a lathe. It is clear that we cannot cut the entire shape in one operation, using a single tool (why ?). We first break the entire ***removal volume*** into sub-volumes, each of which can be removed in one (or one set of) operation(s). We must determine whether all operations can be done on the same machine, or we will need multiple machines. For example, the counter-bored holes may be cut on the lathe, or on a drill, or a machining center. Also, if there are very tight precision requirements on some portions, we may have to perform finishing operations on additional machines. ***Operations planning***: for each operation, we must select the appropriate tool (***tool selection***), and set up the tool path, cutting speed, feed etc. Next, we must determine how to hold the part while machining is taking place; this is called ***fixture planning***. This will determine whether we can group some operations so that we don't have to remove the part from the fixture while machining the entire group. Such groups are called ***setups***. Then, ***operations sequencing*** must be performed – within each setup, we must determine the sequence of each operation; also, we must sequence the setups. Note that the decisions of removal volume determination, operation selection, fixture planning, setup planning, and sequencing are sometimes inter-dependent – how you plan in one stage will affect the choices you have in the other stages.

The ***process plan*** specifies all of these details (*operations*; *tools, path plan and operation conditions*; *setups*; *sequences*; possible *machine routings*; and *fixtures*).

Usually, the ***operations plan*** is documented as a table. A simplified operations plan for the part in the above figure may be composed as shown in the following table. For simplicity, many details have been left out (which can be generated given the details about the tools, materials, tolerances, etc.). Note that the process plan will also contain

additional documents to the operations plan; in particular, if the part will be machined on numerical control machines (NC machines), the programs containing the details of the tool path and cutting conditions are also part of the process plan documentation.

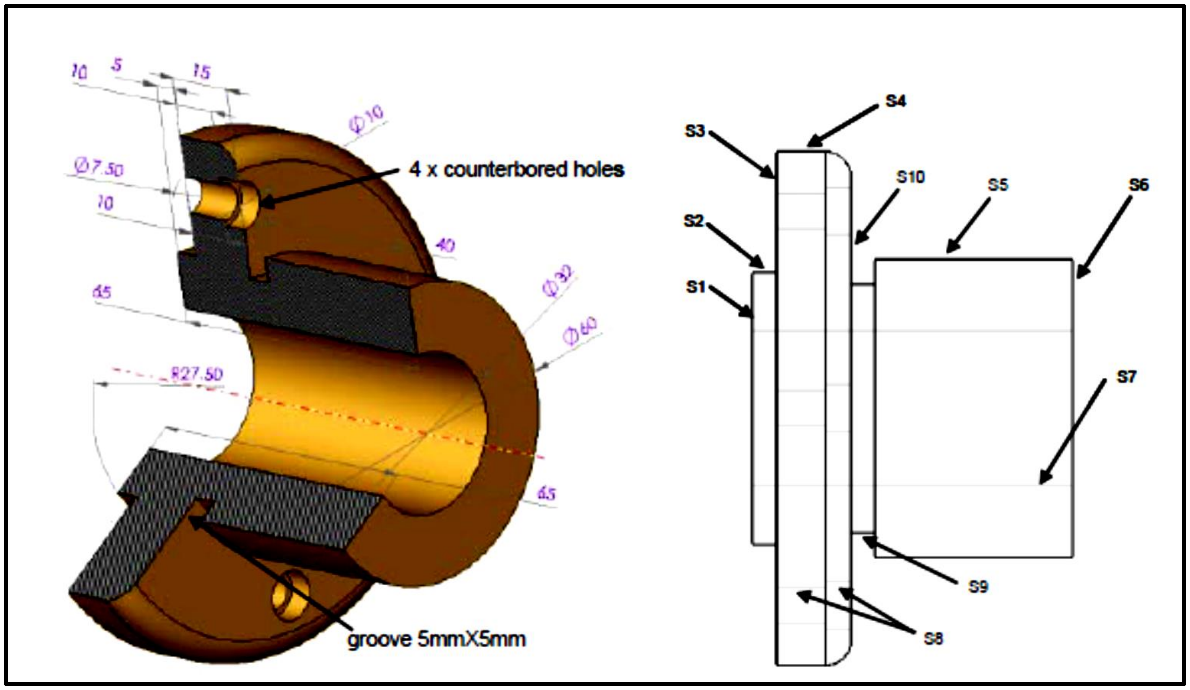


Figure 28 (a) Sectioned view of rotational part (b) The marked surfaces identify removal operations

Generation of the process plan requires some logical planning, as well as some optimization. A simple example of local optimization is setting the optimum feed, speed etc. for each tool, in each operation. An example of logical planning is the decision to sequence the setups as above, rather that doing them, for example, in the sequence Setup 1 → Setup 3 → Setup 2 (which may require longer setup times due to changing of machine tool). Some other examples of operations sequencing can be seen from the example below, of a prismatic part to be machined on a 3-axis vertical milling machine.

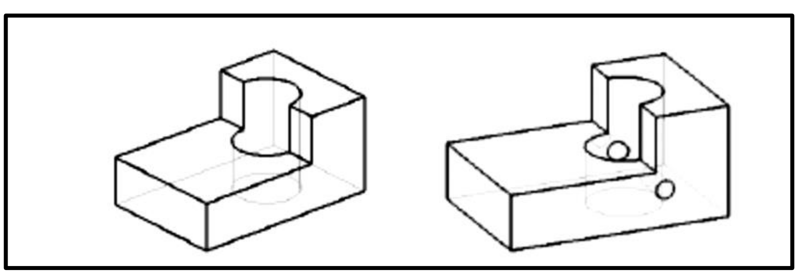


Figure. Preferred sequences: (a) Cut Hole → L-slot (b) Small hole → (Big hole → L-slot)

Job # :	Stock: bar stock diameter: 105	Batch size= N pieces
Fixture: 3-jaw chuck on lathe; Strap clamp + parallel bars on drill-press	Legend:	V: cutting speed m/min f : feed mm/rev S: spindle rpm d: depth of cut mm L: Tool path length, min Tc: cutting time, min Ts: setup time, min

Description	V	f	S	d	L	Tc	Ts
Setup 1: Part in chuck							
[HSS 1-pt tool] turn S4 to ϕ104							
[HSS 1-pt tool] turn S2 to ϕ55							
[HSS 1-pt tool] face S1							
[HSS 1-pt tool] face S3							
[Drill in tailstock] Center drill							
[Drill in tailstock] Drill ϕ32							
Setup 2: Chuck part on S4							
[HSS 1-pt tool] turn S5 to ϕ60, face S10, fillet edge on S4							
[HSS 1-pt tool] Face S6							
[5mm groove cutter] Groove S9							
Setup 3: Clamp part on Drill press, Locate using: S3, S7							
[Center drill] mark, center-drill 4 holes							
[7.5mm Drill] drill 4 holes ϕ7.5							
[10mm counterbore] Counterbore 5mm							

Figure. Sample operations plan for the rotational part

Cutting Fluids (Coolants)

Coolants *are used to decrease tool operating temperature and improve cutting performance. A good cutting fluid should act as a lubricant as well as removing the heat (coolant) from the cutting zone. Water is a good coolant, but is a poor lubricant and presents corrosion (rust) hazard.*

On the other hand, oil is a good lubricant but is less effective in cooling. In practice, emulsion combinations of oil and water or wax and water are used as cutting fluids.

Advantages *Gained by Using Cutting Fluids*

1. *Tool life is increased.*

2. *Surface finish of the workpiece is improved.*

3. *Built-up edge formation is prevented.*

4. *Power consumed by the machine tool is reduced.*
5. *Corrosion hazard is reduced.*
6. *Chips are washed away and the cutting zone is kept clear.*