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Optimization of Machining cost and time in Heavy Machining Operation

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ABSTRACT

Investigation has been done to determine the optimal machining cost and time parameters for multi-pass operations with carbide tool (P-40) on cast steel material. The experiments were carried out on double column heavy duty turning and boring machine and were analyzed. The temperature, cutting force, surface roughness and tool life equations were obtained in terms of speed, feed and depth of cut. The expressions so developed were used to further optimize the numbers of tool passes to minimize the cost and time.

Keywords: *Optimization; Machining Cost; Time in Heavy Machining; Machining Operation.*

1.0 Introduction

In engineering applications, a desired shape and size is produce by removing significant amount of material from a fresh work during the machining process. The process of removal of material in most of the cases is carried out in number of passes. The selections of number of passes for the same metal removal rate are numerous. Selections are based upon rough, semi finish and finish passes. Different permutations and combinations involve different passes and hence machine hours and cost of metal removal rate vary accordingly. Roughing operation plays an important role in reducing the material from the original blank.

Researchers Reddy *et al* [1998], Rao and Chen [2000], Onwubolu and Kumalo [2001], Zuperl *et al* [2004], Bouzid [2005] etc have already worked on multiple/multi-pass machining. However the researchers till date have worked on machining in terms of roughing operation for maximum of 5 mm of depth of cut in one pass. The work beyond 5 mm has not been attempted so far. Therefore, the present work emphasizes on depth of cut between 5 mm and 15 mm in roughing operation in one pass. This is done with the objective to achieve faster material removal rate so to minimize the unit cost.

2.0 Mathematical Modeling

2.1. Single-pass turning operation

Based on the optimum unit cost and time criterion, the objective function for single pass turning operation can be given by the equation [Vipin *et al* [2008], [2011]]

$$C_u = C_o * (t_m + t_r) + \frac{t_m}{T} * (C_o * t_c + C_t) + C_o * t_h \tag{1}$$

$$T_u = t_m + t_r + \frac{t_m}{T} * t_c + t_h \tag{2}$$

The machining time $\mathbf{t_m}$ is the time taken by the tool for the cutting of work piece. For a constant depth of cut

$$t_m = \frac{\pi D L}{1000 V f} \tag{3}$$

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The tool-life is given in the typical extended Taylor equation as:

$$T V^{n} f^{n_1} d^{n_2} = k$$

The unit cost and time can be expressed as:

$$C_u = \frac{C_0 \pi D L}{1000 V f} + \frac{\pi D L V^{n-1} f^{n_1 - 1} d^{n_2}}{1000 k} (C_0 t_c + C_t) + C_0 t_h \quad (5)$$

$$T_u = \frac{\pi D L}{1000 V f} + \frac{\pi D L V^{n-1} f^{n_1 - 1} d^{n_2}}{1000 k} * t_c + t_h \quad (6)$$

Hence, the minimum unit cost (**C_u**) and time (**T_u**) can be derived by partial derivatives of Eq. (5) and (6) with respect to the cutting speed and feed is zero, and it will give the economic tool-life equations with respect to the cutting speed and feed, respectively,

$$\frac{k}{V^{n} * f^{n_1} * d^{n_2}} = (n-1)\left(t_c + \frac{C_t}{C_0}\right) = (n-1) t_e = T_V \quad (7)$$

$$\frac{k}{V^{n} * f^{n_1} * d^{n_2}} = (n-1)\left(t_c + \frac{C_t}{C_0}\right) = (n-1) t_e = T_f \quad (8)$$

Where

$$t_e = t_c + \frac{C_t}{C_o} \quad (9)$$

$$\frac{k}{V^{n} * f^{n_1} * d^{n_2}} = (n-1) t_c = T_V \quad (10)$$

$$\frac{k}{V^{n} * f^{n_1} * d^{n_2}} = (n-1) t_c = T_f \quad (11)$$

To satisfy Equations (7), (8), (10) and (11) requires **$n = n1$**. For common tool-work material combinations, **$n \geq n_1$**, , so that **V** and **f** for a minimum time per component does not exist. Therefore, it is necessary to study the unit cost characteristics in order to establish a approach for selecting the **V** and **f** such that the production cost per component is minimized.

2.2. Multi-pass turning operation

Based on the optimum unit cost and time criterion, the objective function for multiple pass turning operation can be given by the equation

$$C_{um} = \sum_{i=1}^{M} \left[C_o * (t_{mi} + t_r) + \frac{t_{mi}}{T_i} * (C_o * t_c + C_t) \right] + C_o * t_h \quad (12)$$

$$T_{um} = \sum_{i=1}^{M} \left[t_{mi} + t_r + \frac{t_{mi}}{T_i} * t_c \right] + t_h \quad (13)$$

Hence, the characteristics and strategies for minimizing **C_{um}** and **T_{um}** is similar although the optimum f and V for the criteria are not necessarily the same for the same constraint conditions.

Thus, the analyses for minimum cost per component have been outlined in this paper. As in the usual practice single pass machining optimization, only V and f need to be optimized, since it is expected that th, tr and tc have to be minimized using work study techniques with well-designed handling devices.

In practice, V and f should be selected to minimize **C_{um}** and **T_{um}** in Eq. (12) and (13) without violating any of the constraints [Rao and Chen [2000]; and Wang *et al* [2002]]. These constraints in fact limit the feasible domain of speed (V) and feed (f), and result in a constrained optimum **C_{um}** and **T_{um}**.

However in the present investigation rough turning operation using double column heavy duty turning and boring machine, the machine tool limiting force, spindle torque, maximum power, as well as the feed and speed have been considered. In addition, the minimum and maximum tool-life limits imposed by the production systems have been considered.

2.2.1. Constraints set

Practical limitations of the actual cutting conditions always exist for the optimization of the objective function.

For a given pass in a multi-pass operation, an optimum cutting speed and feed is chosen, thus balancing the conflict between machining cost and tool life, as well as the available horsepower. Additional limitations must be set with regard to the stability of the cutting process and quality specifications of the machined part.

Bounds on the cutting speed: The minimum and maximum bounds on the cutting speed are taken as:

$$V_L \leq V \leq V_U$$

Here the minimum bound (VL) is provided avoid the formation of built up edge, whereas the maximum bound (VU) is provided for the safety of the operator. *Bounds on the Feed*: The minimum and maximum feed is restricted as:

$$f_L \leq f \leq f_U \tag{15}$$

Bounds on the depth of cut: The minimum and maximum bounds on the depth of cut are taken as:

$$d_L \leq d \leq d_U \tag{16}$$

Restriction on the cutting force: It is necessary to put a restriction on the force because a higher value of force may produce excessive deflection of the work piece and require a larger power for the cutting operation and the constraint on Fc can be expressed as:

$$F_c \leq (F_c)_U$$

Constraint on Power: The cutting power required is as:

$$P_c = \frac{F_c * V}{4500} \tag{18}$$

This cutting power should not exceed the available power and constraint becomes

$$(P_c + W) \leq \eta_m * MHP \tag{19}$$

Temperature constraint: Even though various tool wear mechanisms do exist, it is generally known that the gradual tool wear is produced by temperature dependent mechanisms. The minimum and maximum constraint on temperature is taken as:

$$\theta_L \leq \theta \leq \theta_U$$

Bound on the Tool Life: The minimum and maximum bound on the tool life are taken as:

$$T_L \leq T \leq T_U$$

3.0 Multi-pass optimization

The procedure evaluates the objective function at each pass independently. The optimum numbers of passes are determined by considering a pre-defined number of sections for the total depth of cut based on the available constraints.

The constraint of speed, feed, and depth of cut for the particular tool-work piece combination should be used in order to proceed with the optimization of the cutting conditions for each pass.

The analysis for a multi-pass operation is generally more complex than that of a single-pass operation. The total depth of cut is divided into different sections of different sizes for each pass is an integer number of the pre-defined sections for roughing, semi-finish, and finish operations accordingly and can be represented as shown in the Fig. 1.

Fig 1: Schematic Representation of Total Depth of Cut for 'N' Number of Passes in Turning Operation

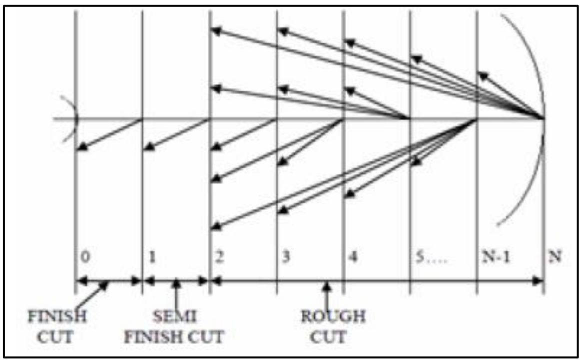
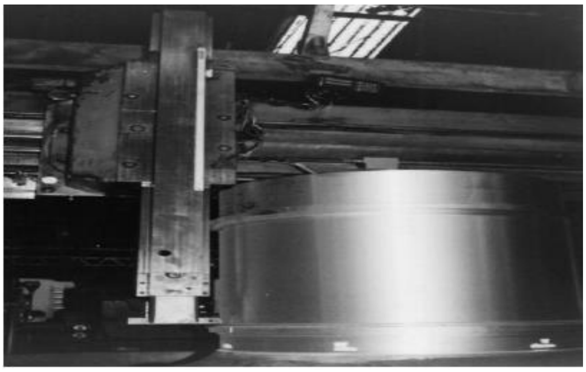


Fig 2: Double Column Vertical Boring and Turning Machine (TITAN)



4.0 Optimization Techniques

The optimum value of the number of passes and the corresponding speed, feed and depth of cut for each pass is obtained in a multi-pass process. A schematic representation of the total depth of cut for multi-pass turning operation procedure is given in Figure 1 and machine in Figure 2. It is a four variable problem, where the number of passes, depth of cut, feed and cutting speed for each pass is determined through the computer program given in Fig 3.

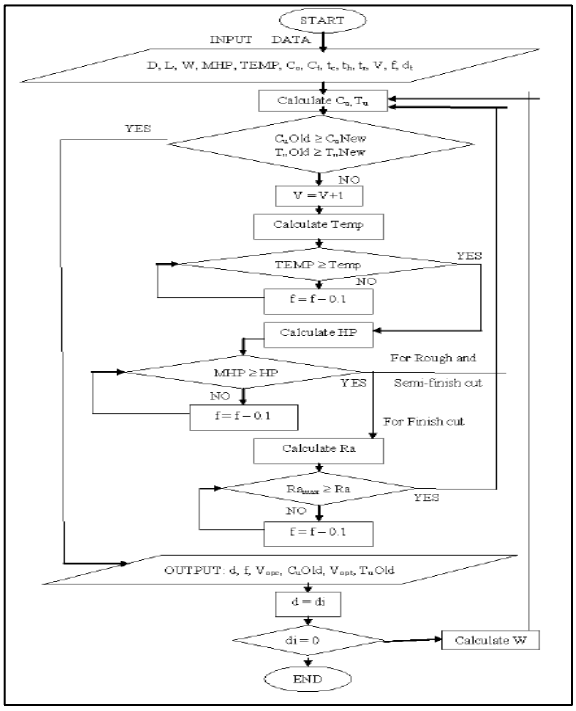
4.1. Investigation

The experiments were conducted in the industry and the equations of tool-life (rough, semi-finish and finish), cutting force, temperature and surface roughness are available at Vipin [2008]. The investigations were carried out for different number of passes and depth of cuts. The results presented here are the optimized results as achieved from the multi-objective programming optimization technique.

Table 1: Investigation Data

Blank diameter of the work piece	2928 mm
Inner diameter of the work piece	1084 mm
Length of the work piece	800 mm
Weight of the work piece	7730 kg
Machine horsepower	150 hp
Efficiency of machine	80 %
Surface roughness	20 µm
Total depth of cut in radius	22.5 mm

Fig 3: Flow Chart of Optimization Methodology for Multi-Pass Operation



From the above investigation, it can be seen that for achieving the objective function, the material removed from the work piece in rough pass should be maximum possible depth of cut and feed at optimum cutting speed. Further, it is clear that the optimized result is achieved for minimum numbers of passes for the problem under consideration.

5. Conclusions

1. The machining cost and time is optimum at the minimum number of passes for heavy machining.
2. The material removed from the work piece in rough pass should be maximum possible depth of cut and feed at optimum cutting speed with the constraint of possible power and capacity of the machine.
3. The tool life at a particular depth of cut is optimized at the predetermined maximum feed rate. At maximum feed rate, machine power and temperature are fully utilized.
4. For higher depth of cut, cutting speed of optimal time is higher than the cutting speed of optimal cost.

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Nomenclature

C_o – cost of operating time, Rs. /min
C_t – cost of tool, Rs. /cutting edge
C_u – total unit cost, Rs. /pc
C_{um} – total unit cost at multi-pass, Rs. /pc
d – Depth of cut, mm
D–outside diameter of work piece, mm
f – Feed, mm/rev
F_c – cutting force
k – tool life constant
L – work piece length to machine, mm
M – total number of passes
MHP – machine horsepower
n, n_1, n_2 - empirical constants for tool life equation
N – total number of sections
P_c – cutting power
t_c – tool-changing time, min. /cutting edge
t_h – handling time, min. /pc
t_m – machining time, min. /pc
t_r – tool resetting time, min
T – tool-life, min. /cutting edge
TEMP – temperature in °C
T_f– time with respect to feed, min
T_u – unit time
T_{um} – total unit time at multi-pass, min./pc
T_V – time with respect to cutting speed, min
V – Cutting speed, m/min
W – weight of job
θ - cutting temperature at tool-chip interface
η_m - mechanical efficiency of the drive

Subscripts

L – indicates minimum value
U - indicates maximum value