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Optimization of multi-task turning operations under minimal tool waste consideration ☆

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A B S T R A C T

Most of the literatures on machining economics problems tend to focus on single cutting operations. However, in reality most parts that need to be machined require more than one operation. In addition, machining technology has been developed to the point that a single computer numerical control (CNC) machine is capable of performing multiple operations, even simultaneously, employing multiple spindles and cutting tools. When several operations are performed on a CNC turning machine, various tools are required for the cutting operations. Determining the life of these cutting tools under different machining conditions is an arduous task for the operators. They usually replace the tools based on their experience or according to the specific cutting tool handbook. Frequent tool replacements may result in wasted tools and tool utilization, while infrequent tool replacements may result in poorly machined parts. In this study we propose a mathematical model in which several different turning operations (turning, drilling, and parting) with proper constraints are performed. The issue of tool replacement is taken into account in the proposed cutting model. In addition, an evolutionary strategy (ES)-based optimization approach is developed to optimize the cutting conditions of the multiple turning-related operations while taking into account the minimizing unit cost criteria under the economical tool replacement strategy.

1. Introduction

Over the past two decades, the effective utilization of CNC machines, with their high initial cost and their high operating costs is becoming increasingly important to the shop floor manager. As a result, the decision regarding the selection of the correct values for the machining parameters such as cutting speed, feed rate, and depth of cut have a significant impact on product quality, production rate, and ultimately manufacturing cost. In practice, the machining parameters for specific cutting conditions are usually determined based on the shop floor operator's experience or by following the guidelines in the handbook of the specific machine tool or equipment manufacturers. However, taking into account the real world constraints such as limited machine power, maximum cutting force of the cutting tools, and the cutting temperature that may reduce tool life and affect the dimensional accuracies of the work piece as well as the surface finish, etc. it is not easy to determine these parameters. In turning operations, a cutting process can possibly be completed with a single pass or it may require multiple passes. In the machining industry, multi-pass turning is preferred over single-pass turning for economic reasons [1]. A multi-pass cutting operation involves several roughing cuts and a single finishing cut. This makes determining the optimal cutting conditions both difficult and complicated. To obtain the parameters for the optimal cutting conditions for a complex turning operation, it is necessary to develop a mathematical model for this turning operation.

When it comes to the machining economics problem in the literature, most studies focus on the single operation. In reality, however, producing a part with an intricate geometry may require a series of machining operations. Today's modern CNC machines are capable of performing various tasks, such various turning and related operations like drilling, threading, facing, parting, etc. with different cutting tools on a single CNC turning center. The cutting tools are held on a 6–8 station turret that is capable of indexing up to the tools into position. Hence, due to the ability to quickly change cutting tools, the turret lathe is used for high-production work, requiring a sequence of cuts to be made on the part [2]. In such highly automated machining equipment, manual operations like part handling and tool replacement become extremely important. How often the parts are to be handled is readily determined, but the intervals for tool replacements are much harder to establish since the tools wear gradually. Therefore, frequent tool replacements may result in wasted tools and wasted tool utilization, while infrequent tool replacements may result in poorly machined parts.

We therefore propose a new cutting model that takes into consideration the machine condition optimization for performing multiple turning-related operations using a single CNC turning

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Nomenclature

UC unit production cost except material cost ($/piece)
C_M cutting cost based on the actual time per cut ($/piece)
C_I machine idle cost due to loading and unloading operations and tool idle motion time ($/piece)
C_R tool replacement cost ($/piece)
C_T tool cost ($/piece)
C_W tool waste cost ($/piece)
V_{t_L} V_{t_U} lower and upper bounds of cutting speed for machining (m/min)
$V_{d_1\_L}$ $V_{d_1\_U}$ lower and upper bounds of cutting speed for drill no.1 (m/min)
$V_{d_2\_L}$ $V_{d_2\_U}$ lower and upper bounds of cutting speed for drill no.2 (m/min)
V_{c_L} V_{c_U} lower and upper bounds of cutting speed for parting (m/min)
f_{t_L} f_{t_U} lower and upper bounds of feed rate for machining (mm/rev)
$f_{d_1\_L}$ $f_{d_1\_U}$ lower and upper bounds of feed rate for drill no.1 (mm/rev)
$f_{d_2\_L}$ $f_{d_2\_U}$ lower and upper bounds of feed rate for drill no.2 (mm/rev)
f_{c_L} f_{c_U} lower and upper bounds of feed rate for parting (mm/rev)
d_{t_L} d_{t_U} lower and upper bounds for depth of cut (mm)
V_{t_r} V_{t_s} cutting speeds for rough and finished machining (m/min)
f_{t_r} f_{t_s} feed rates in rough and finished machining (mm/rev)
d_{t_r} d_{t_s} d_{t_t} depths of cut for each pass of rough and finished machining (mm); total depths of metal to be removed (mm)
V_d V_c cutting speeds for drilling and parting (m/min)
f_d f_c feed rates in drilling and parting (mm/rev)
d_c d_{d_1} d_{d_2} depths of cut for parting; depths of cut for drilling(mm)
D_0 L_0 D_1 turning diameter, length of turning, and parting diameter (mm)
D_d L_d D_{d_av} drill diameter, length of drilling, and expected drill diameter (mm)
n_{t_r} n_d number of rough cuts an integer, number of drill
h_{1t} h_{2t} h_{1c} h_{2c} constants pertaining to turning tool depart time (min), constants pertaining to cutting tool depart time (min)
h_{1d} h_{2d} constants pertaining to drill depart time (min)
t_c t_{e_t} t_{e_d} t_{e_c} preparation time including loading and unloading (min), time required to exchange a tool for drilling and parting (min)
T_{min} the lowest tool life of the three kinds of operations (min)
T_{t_r} T_{t_s} the expected tool life for roughing, and the expected tool life for finishing (min)
T_d T_c tool life for drill and cutting tool (min)
k_0 k_{t_t} k_{d_t} k_{c_t} machining cost per unit time ($/min), turning tool, drill, and cutting tool cost ($/procedure)
p q r C constants of turning tool life (turning tool and parting tool)
$\kappa_1 \mu \nu$ constants of cutting force equation
P_U η maximum allowable cutting power (kW) and power efficiency
$\lambda \upsilon R$ constants related to the expression of the stable cutting region, nose radius of the cutting tool (mm)
$\kappa_2 \tau \varphi \varsigma$ constants related to the equation of the chip–tool interface temperature (turning tool and drill)
k_3 k_4 k_5 constants for the relationships between roughing and finishing parameters
m C_v z_v K_v y_v x_v constants for drill life
C_f z_f y_f x_f K_f E constants for drill contact force
C_m z_m y_m x_m K_m constants for drill torque
C_p z_p y_p x_p K_p constants for drill power
f_{s_1} f_{s_2} safety constants for drill contact force, torque
SR_U maximum allowable surface roughness (mm)
M_{d_1} M_{d_2} upper bounds of torque for drill no.1, upper bounds of torque for drill no.2
F_{t_U} F_{c_U} F_{d_U} upper bounds of turning tool (external turning tool and cutting tool) and drill (kgf)
SC_{τ_d} limit of stable cutting region constraint, drill strength
Q_{t_U} Q_{d_U} Q_{c_U} upper bounds of turning tool and drill chip–tool interface temperature during rough and finish machining (°C)

center. Unlike other studies, the tool replacement strategy for minimizing the number of tool replacements and tool waste is embedded in this machining model. We proposed an optimization heuristic approach based on the evolutionary strategy for solving the complicated non-linear machining problem. The capabilities of our proposed approach are demonstrated in a practical example.

2. Literature review

2.1. Optimization of machining conditions for a single turning operation

Shin and Joo [3] developed a mathematical model for multi-pass turning operations. Their model is frequently benchmarked and extended in other studies. They provided a numerical example and proposed an approach for solving it that combined the Fibonacci search and dynamic programming. Afterwards, Gupta et al. [4] solved the same problem in two steps. The first step of their approach is to calculate the minimum production cost for the roughing and finishing operations for the various depths of cut. The second step is to determine the optimal combination of depth of cut for roughing and the finishing operation. Their approach determines a production cost, which is substantially less than when using Shin and Joo's method. Alberti and Perrone [5] suggested a multi-objective possibilistic programming model in which the optimal solution is obtained using a genetic algorithm. They compared their results with the results obtained by Gupta et al. [4] for the same examples. Although their results were never worse than those obtained by Gupta et al., in two of the six examples their solutions showed a very tiny violation of the cutting force constraint.

Chen and Tsai [1] extended the multi-pass turning operation model of Shin and Joo by adding seven more constraints. They also proposed an approach combining the simulated annealing algorithm and a pattern search technique for solving the extended model. Onwubolu and Kumalo [6,7] proposed a technique based on a genetic algorithm to determine the optimal machining parameters for the extended model of Chen and Tsai. They arrived at an even