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MULTI-CRITERIA OPTIMIZATION IN END MILLING OF AISI D2 HARDENED STEEL USING COATED CARBIDE INSERTS

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ABSTRACT

This paper proposes a multi-criteria optimization technique using the mathematical models developed by the response surface methodology (RSM) for the target responses combined with desirability indices for the determining the optimum cutting parameters in end milling of AISI D2 hardened steels. Different responses may require different targets either being maximized or minimized. Simultaneous achievement of the optimized (maximum or minimum) values of all the responses is very unlikely. In machining operations tool life and volume metal removed are targeted to be maximized whereas the machined surface roughness need to be at minimum level. Models showing the combined effect of the three control factors such as cutting speed, feed, and depth of cut are developed. However, a particular combination of parameter levels appears to be optimum for a particular response but not for all. Thus adoption of the method of consecutive searches with higher desirability values is found to be appropriate. In this study the desirability index reaches to a maximum value of 0.889 after five consecutive solution searching. At this stage, the optimum values of machining parameters - cutting speed, depth of cut and feed were determined as 44.27 m/min, 0.61 mm, 0.065 mm/tooth respectively. Under this set condition of machining operations a surface roughness of 0.348 μm and volume material removal of 7.45 cm^3 were the best results compared to the rest four set conditions. However, the tool life would be required to compromise slightly from the optimum value.

1.0 INTRODUCTION

The investigations of machining hard materials has grown substantially over time owing to the contribution from many branches of engineering, particularly in the mold and die industries and subsequently mostly contributed in making automotive and aerospace components with a common goal of achieving higher machining process efficiency. Selection of optimal machining conditions is a key factor in achieving this condition [1]. In any multi-stage metal cutting operation, the manufacturer seeks to set the process-related controllable variables at their optimal operating conditions with minimum effect of uncontrollable or noise variables on the levels and variability in the outputs. To design and implement an effective process control for metal cutting operation by parameter optimization, a manufacturer seeks to balance between quality and cost at each stage of operation resulting in improved delivery and reduced warranty or field failure of a product under consideration [2].

Modelling and process parameter optimization in the machining operations could be divided into two main categories: (i) modelling of input-output and in-process parameter relationship, and (ii) determination of optimal or near-optimal cutting conditions. Modelling of input–output and in-process parameter relationship is considered as an abstract representation of a process linking causes and effects or transforming process inputs into outputs. The resulting model provides the basic mathematical input required for formulation of the process objective function. An optimization technique provides optimal or near-optimal solutions to the overall optimization problem formulated, and subsequently implemented in actual metal cutting process.

The RSM is a dynamic and foremost important tool of design of experiment (DOE) wherein the relationship between response(s) of a process with its input decision variables is mapped to achieve the objective of maximization or minimization of the response properties [3]. It is a set of statistical DOE techniques, intrinsic regression modelling, and optimization methods useful for any field of engineering. Many researchers and practitioners use RSM in metal cutting process parameter optimization problems. Taramen [4] uses a contour plot technique to simultaneously optimize tool wear, surface finish, and tool force for finished turning operation. Lee, et al [5] provided an interactive algorithm using both RSM and mathematical modelling to solve a parameter optimization problem in turning operation. Fuh & Chang [6] analysed the effect of change in work piece material and each cutting parameter in various peripheral milling operations, and model the dimensional accuracy by a second order response surface design. El-Axir [7] concentrates on response surface design methodology to model the effect of machining parameters on distribution of residual stresses for five different materials in turning operations. Kaye, et al [8] used RSM in predicting tool flank wear using spindle speed change. A unique model has been developed which predicts tool flank wear, based on the spindle speed change, provided the initial flank wear at the beginning of the normal cutting stage is known.

In this paper, the process optimization of numerical and overlay contour plot for all the responses i.e. tool life, surface roughness and volume metal removed have been developed for end milling of hardened steel AISI D2 tool steel. The accuracy of the process optimization has been tested using the analysis of variance (ANOVA) with the aid of a statistical design of experiment software called Design-Expert version 6.0.

2.0 EXPERIMENTAL DESIGN AND METHODOLOGY

Experimental works were carried out on CNC Vertical Milling Center (VMC) Excell PMC-10T24 with 40 mm diameter tool holder. End milling operation was performed under dry cutting conditions with a 5 mm constant radial depth of cut. In this experiment only one insert was used for each set of experimental conditions so that the variation due to the wear of cutting tool edge is minimized among the trials. Machining was initiated with a sharp insert and moved every 100 mm pass of cut for flank wear measurement by Olympus Tool Maker microscope for which flank wear was recorded at 20 times magnification.

2.1 Experimental input data and the responses

The CCD is the most popular class of designs used for fitting these models and has been established as a very efficient design for fitting the second order model [3]. The cutting conditions following the CCD and the responses in the form of tool life and surface roughness are presented in Table 1. The three input parameters selected for the experiments are the cutting speed, depth of cut and feed, the values of which for 15 sets of experimental conditions along with the corresponding measured values of tool life and surface roughness are mentioned.

Table 1: Experimental data on coated carbide tool life and machined surface roughness under designed machining conditions

Std. run	Location in exp design (CCD)	Input variables			Response variables	
		Cutting speed (m/min)	Depth of cut (mm)	Feed (mm per tooth)	T (min)	R_a (µm)
1	Factorial	72.28	1.63	0.025	27.83	0.275
2	Factorial	72.28	0.61	0.079	8.81	0.325
3	Factorial	44.27	1.63	0.079	25.16	0.800
4	Factorial	44.27	0.61	0.025	124.93	0.350
5	Center	56.57	1.00	0.044	30.30	0.400
6	Center	56.57	1.00	0.044	32.50	0.350
7	Center	56.57	1.00	0.044	29.50	0.400
8	Center	56.57	1.00	0.044	31.70	0.350
9	Center	56.57	1.00	0.044	33.90	0.375
10	Axial	40.00	1.00	0.044	114.27	0.525
11	Axial	80.00	1.00	0.044	10.71	0.388
12	Axial	56.57	0.50	0.044	70.70	0.375
13	Axial	56.57	2.00	0.044	20.20	0.675
14	Axial	56.57	1.00	0.020	55.55	0.375
15	Axial	56.57	1.00	0.100	8.89	0.550

2.2 Optimization coupled with desirability function

Simultaneous optimization technique popularized by Derringer & Suich [10] is a useful approach for optimization of multiple responses. The procedure utilizes the application of desirability functions usually converting each response y_i into individual desirability function, d_i that varies over the range $0 \le d_i \le 1$. If the response y_i is at its goal or target, then $d_i = 1$, and if the response is outside the acceptable region, $d_i = 0$. The design variables are chosen to maximize the overall desirability as;

$$D = \left(d_1 d_2 .... d_m\right)^{1/m} \tag{2}$$

where m is the number of responses. If the target or goal T for the response y is a maximum value, then the desirability function, d can be expressed as;

$$d = \begin{cases} 0 & y < L \\ \left(\dfrac{y - L}{T - L}\right)^r & L \le y \le T \\ 1 & y > T \end{cases} \tag{3}$$

The exponent r in the above equation acts as a weight. When r is taken as unity, the desirability function becomes linear. Choosing $r > 1$ places more emphasis on being close to the target value, and choosing $0 < r < 1$ makes this less important.

Design-Expert software package was used to apply the approach of desirability function to identify the value of d of the responses.

3.0 MULTI-CRITERIA OPTIMIZATION AND DISCUSSION

Optimization can be performed numerically or graphically through overlay contour plot. The graphical approach is relatively straightforward for optimizing several responses which works well when there are only a few process variables overlaying the contour plots for each response. In this method, it is possible to visually examine the contour plot for determining the appropriate operating conditions. However, if there are more than three design variables, overlaying contour plots becomes awkward, as the contour plot is two-dimensional, and *k*-2 of the design variables must be held constant to construct the graph [10]. Often a lot of trial and error is required to determine which factors to hold constant and what levels to select to obtain the best view of the surface.

Therefore, practical interest lies in more formal optimization methods for multiple responses. A popular approach is to formulate and solve the problem as a constrained optimization problem. There are a number of numerical techniques that can be used to solve this kind of problem. Sometimes these techniques are referred to as nonlinear programming methods. By using the Design-Expert software package this sort of problem can be solved through a direct search procedure. In addition to this, numerical optimization algorithms can be employed to find the optimum.

In this study application of numerical optimization with the help of Design-Expert software is based on the determination of end milling parameters, corresponding to which the responses such as tool life and VMR are maximized whereas the surface roughness is minimized. The achievable ranges for each of the responses selected by taking into consideration of the following practical data for room temperature experiments:

- Tool life, $8.81 < T < 124.93$ minutes
- Surface roughness, $0.275 < R_a < 0.799$ µm
- Volume metal removed, $1.22 < VMR < 7.99$ cm^3

The possible optimal solutions generated by the software are given in Table 2.

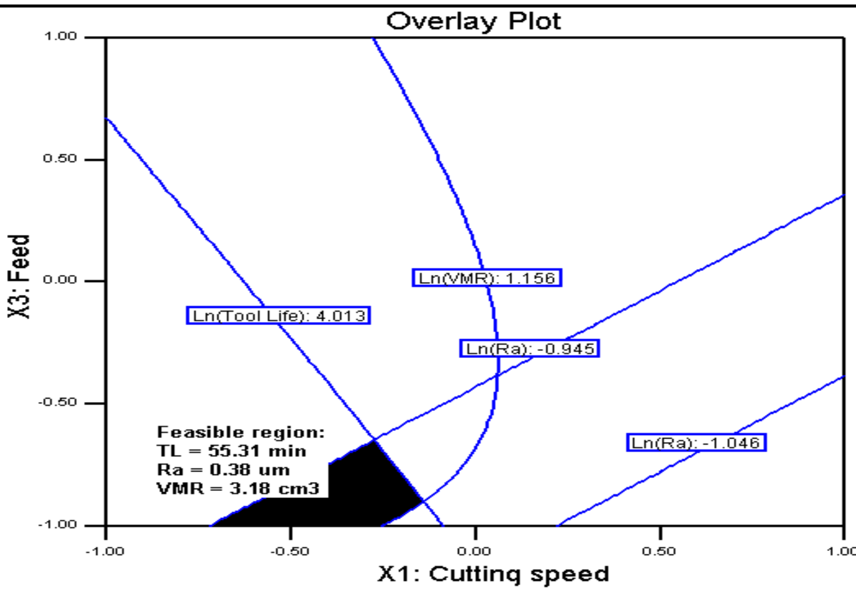
Table 2: Optimized solutions for room temperature machining with coated carbide insert

No	Optimized cutting conditions			Optimized Responses			Desirability D
	Cutting speed V (m/min)	Axial depth of cut, d (mm)	Feed f (mm/tooth)	Tool life T (min)	Surface roughness R_a (µm)	VMR (cm^3)	
1	44.27	0.61	0.065	106.10	0.348	7.45	0.889
2	44.27	0.61	0.064	106.70	0.348	7.43	0.889
3	44.27	0.61	0.064	107.23	0.349	7.41	0.889
4	44.36	0.61	0.064	107.23	0.349	7.35	0.887
5	44.27	0.61	0.037	130.32	0.363	5.24	0.830

These optimized responses are actually the predicted values corresponding to the machining conditions as shown in the three left hand columns. The respective index of desirability is mentioned on the right hand column. The higher the value of the index, the higher is the level of realization of the targeted or desired values of the responses.

These are the predicted values for the responses with the corresponding index of desirability. As mentioned earlier the target values for responses such as tool life and VMR were set for maximization whereas that for surface roughness was set for minimization. Thus the conditions imposed were to obtain the desirable cutting responses with lower surface roughness, longer tool life and higher volume of material removal. As shown in Table 2 for coated carbide insert with room temperature experiment, the best desirability index obtained was 0.889 after five consecutive solution searches. At this stage, the optimum values of machining parameters - cutting speed, depth of cut and feed were determined as 44.27 m/min, 0.61 mm, 0.065 mm/tooth respectively. Under this set condition of machining or end milling operation the surface roughness of 0.348 µm and volume of material removal of 7.45 cm^3 were the best results compared to the rest four set conditions. However, the tool life would be required to compromise slightly.

Graphical optimization or overlay contour plot developed by superimposing the contours for each of the responses. By defining the limits of the tool life, surface roughness, and VMR, the shaded portion of the overlay plot has been obtained as the feasible area. This encompasses the levels of the cutting parameters involved. The overlay contour plot as presented in Figure 1 for end milling of AISI D2 hardened steel is for room temperature machining conditions with coated carbide insert. The best possible combination of tool life, surface roughness and volume material removed in end milling of AISI D2 hardened using coated carbide inserts can be chosen. The corresponding values of cutting speed, depth of cut and feed can also be identified from the plot. The feasible region by overlay plot for room temperature experiments as indicated in Figure 1 demonstrates a minimum tool life of 55.31 minutes, maximum surface roughness of 0.380 µm, and a minimum volume of material removed of 3.18 cm^3.



a) Room temperature machining

Figure 1: Overlay contour plot for tool life, surface roughness and volume metal removed with coated carbide insert

4.0 CONCLUSION

The developed mathematical models for tool life and machined surface roughness can be reliably used as supported by ANOVA at 5% level of significance. Second order models were found to be more accurate having higher values of coefficients of determination.

Overlay plots showing the feasible region for various responses are conducive to multi-criteria optimization. These plots showing the feasible region for various responses are helpful to take decision under a situation of multiple criteria of tool life, surface roughness and volume of metal removed. Within the feasible region surrounded by boundary lines of various responses, some desirable and expected values can be targeted graphically and corresponding machining parameters are possible to be diagnosed. Scope of realization or achievement of certain responses at some target maximum or minimum values was evaluated by the desirability function. The higher the value of the desirability function, *d* the greater is the probability of achieving the target values. Thus, a compromising optimum level for each of the responses can be attainable.

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