Multi - Objective Optimization of Milling Parameters in HCHCr (D3) Steel by Genetic Algorithm

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***Abstract*— This work presents an experimental study and optimization of milling operation in HCHCr D3 grade steel using intelligent Genetic Algorithm. The aim of the work was to minimize the surface roughness and cutting force simultaneously, thus making the milling operation more economic and productive. The dry milling operation was done under regulated cutting parameters comprising Spindle Speed, Feed Rate and Depth of Cut. The experiments were designed using Taguchi's orthogonal array consisting of 9 experimental runs. The experimental output were analysed using ANOVA to determine the most significant parameter that affects the surface roughness and cutting force. Then using Regression analysis, a mathematical model of the milling operation is formulated to predict the performance measures of surface roughness and cutting force. Optimization was done using the Genetic Algorithm by the mathematical model formulated under the selected parameter constraints.**

Keywords*— Milling , Genetic Algorithm , ANOVA , Regression Analysis

I. Introduction

Using modern manufacturing technologies, we can accomplish shorter manufacturing times, higher capabilities and manufacturing costs. This leads to either final product price reduction or gaining higher profits. So we tend to choose solutions which make our production lines more efficient, cost effective, and most of all accurate. In past, the parameters for machining were easily obtainable in order to achieve proper surface quality, however this required certain time and expert, who has years of valuable experience in machining, the rest of data can be obtained from machining handbooks[1]. The advancement in manufacturing techniques significantly improve the whole manufacturing process and products by the use of most innovative techniques. Most frequently used technologies are computer technologies, automation, process technologies and information technology. Additional techniques include control systems, custom manufacturing, high performance computing and robotics. These techniques have extremely high potential to enhance the production output.The major tool behind all the techniques is optimization.

Several factors will influence the final surface roughness in a CNC milling operation such as controllable factors like spindle speed, feed rate and depth of cut. Process optimization means the resources which are utilizing the process should be used effectively and efficiently at minimum cost & maximum output. Good machinability is an optimal combination of input parameters that provide better response factors [2].

As milling is a commonly and widely used machining process in industries, a lot of analysis and optimizations are required to obtain the best possible ways of achieving productivity, improved tool life and maintaining the dynamics of machine also. Minimizing the surface roughness leads to better product quality in most cases except a few situations where roughness is indeed a requirement. While achieving the best surface roughness (finish) mostly it depletes the tool life and also machine dynamics which is not easily recognizable. Thus Cutting force is integrated in this work to achieve it's minimum thereby not compromising the surface finish. Cutting forces can lead to more power consumption, greater heat generation, changing the machine dynamics and tool geometry too.

This work integrates surface roughness and cutting forces in milling operation to be optimized simultaneously, which could provide better machining conditions, surface quality, gain in tool life, maintain the machine dynamics and also leads to lower power consumption. Optimization using intelligent Genetic Algorithm facilitates in determining the best possible set of milling parameters providing better surface finish and lower cutting forces.

II. Experiment Details

The milling operation was done on High Carbon High Chromium (HCHCr) D3 grade steel of the dimensions 110 mm x 40 mm x 20 mm (l x b x h).D3 Steel is an air hardening, high-carbon, high-chromium tool steel. It displays excellent abrasion/wear resistance and has good dimensional stability and high compressive strength. It is heat treatable and will offer a hardness in the range 58-64 HRC. D3 steel is selected due to it's wide applications in manufacturing of tools and gauges. The chemical composition of HCHCr D3 grade steel is shown in the Table 1

Table 1 : HCHCr D3 steel Chemical Composition

Elements	C	Si	Cr	Mn	Ni
% Composition	2.10	0.30	11.50	0.40	0.31

The experimentation was done in HAAS CNC Vertical Tool Room Mill (TM-1) having a maximum spindle speed of 4000 RPM and main spindle power 5.6 kw. The machine is shown in Figure 1

Figure:1 HAAS CNC Vertical Tool Room Mill (TM-1)

Tungsten Carbide tool (uncoated carbide) of 10 mm diameter with 28˚ helical flutes (4 flutes) is selected as cutter. They generally produce a better finish on parts, and their temperature resistance allows faster machining. Tungsten carbide cutting tools are very abrasion resistant and can also withstand higher temperatures than standard high speed steel tools. The Tool used in the experiment is shown in Figure 2

Figure 2: Tungsten Carbide tool

The output parameters like surface roughness and cutting force was to be measured for the analysis and optimization purpose.Good surface roughness provides important improvements in the tribologic characteristics, fatigue strength, corrosion resistance and aesthetic appearance of the product[3]. parts. In addition, the surface roughness affects several attributes of machined parts such as friction, wear, and heat transmission[4]. Surface roughness was measured using Mitutoyo Surface Roughness Tester SJ- 410 with wide range, high-resolution detector Measuring range / resolution 800µm /0.01 µm ; 80 µm /0.001 µm ; 8 µm /0.0001 µm respectively. The colour graphic LCD with excellent visibility displays calculated results and assessed profiles even clearer. The device used to determine the surface roughness in the experiment is shown in the Figure 3. There are many different roughness parameters in use, but Ra is by far the most commonly used. The Mean Roughness (Roughness Average Ra) is the arithmetic average of the absolute values of the roughness profile ordinates. Ra is one of the most effective surface roughness measures commonly adopted in general engineering practice. It gives a good general description of the height variations in the surface.

Figure 3: Mitutoyo Surface Roughness SJ-410 Tester

Cutting Force from the experiment is measured using Unitech Milling Dynamometer (UIMD-14). The workpiece is clamped directly to the dynamometer, and the whole dynamometer including the workpiece is attached to working machine table. Machine tool dynamometers are increasingly used for the accurate measurement of forces and for optimizing the machining process. All three direction forces are measured simultaneously and displayed. Optimizing cutting force not only enhances tool life, it also positively influences the properties of finished workpiece. The 3 components of cutting forces are related to other factors of the experiment as well as to factors possibly not included in the experiment[5]. The dynamometer is connected to a digital display that amplifies the force into 3 individual force components X, Y & Z respectively. The milling tool dynamometer used for the experiment is shown in Figure 4

Figure 4: Unitech Milling Tool Dynamometer (UIMD-14)

The experiment is designed using Taguchi's orthogonal array. Three parameters are controlled like spindle speed, feed rate and depth of cut with three levels each like low, medium and high denoted by 1, 2 and 3 respectively. Thus L_9 orthogonal array is selected for the experiment. This array is chosen due to the ease of experimentation and simplicity. Table 2 shows the cutting parameters and their levels considered for experimentation

Table 2: Control Parameters and levels

Process Parameters	Level 1	Level 2	Level 3
Spindle Speed (RPM)	2000	2500	3000
Feed Rate (mm/min)	100	200	300
Depth of Cut (mm)	0.02	0.04	0.06

Using L_9 orthogonal array, the experiment is designed. All the 9 runs are carried out. The experiment was conducted as per the table 3 and the response factors were recorded for the analytical and optimization purpose. The experimental results are given in Table 3.

Table 3: Experiment Results

Ex No	SS (RPM)	FR (mm/min)	DoC (mm)	S.R R_a (μm)	C.F (kgf)
1	2000	100	0.02	1.390	1.414213562
2	2000	200	0.04	1.681	1.732050808
3	2000	300	0.06	1.868	2.449489743
4	2500	100	0.04	1.369	1.414213562
5	2500	200	0.06	1.502	1.732050808
6	2500	300	0.02	1.627	2.449489743
7	3000	100	0.06	1.258	2.236067977
8	3000	200	0.02	1.101	2.449489743
9	3000	300	0.04	1.519	3.000000000

III. Statistical Analysis

A. Analysis Of Variance (ANOVA)

ANOVA provides a statistical test of whether or not the means of several groups are all equal, and therefore generalizes t-test to more than two groups. ANOVA is used in the analysis of comparative experiments, those in which only the difference in outcomes is of interest. Analysis of variance (ANOVA) is an extremely important method in exploratory and confirmatory data analysis [6]. ANOVA is a statistical tool used in several ways to develop and confirm an explanation for the observed data and also provides multiple sample comparison. Analysis of variance for surface roughness and cutting force is provided in Table 4 and 5 respectively.

Table 4 : ANOVA for Surface Roughness

Source	DOF	Adj SS	Adj MS	F-Value	P-Value
Spindle Speed	2	0.189400	0.094700	20.96	0.046
Feed Rate	2	0.177578	0.088789	19.65	0.048
Depth of Cut	2	0.051887	0.025943	5.74	0.148
Error	2	0.009038	0.004519		
Total	8	0.427902			
Model Summary					
S = 0.0672219		R-Sq = 97.89 %		RSq-(adj)=91.55%	

From Table 4, the P-value gives the data about the effects of parameters on surface roughness. P-value less than 0.05 is taken as the significant factor, thus from the table it is clearly evident that spindle speed affects the surface roughness followed by feed rate and depth of cut.

Table 5 : ANOVA for Cutting Force

Source	DOF	Adj SS	Adj MS	F-Value	P-Value
Spindle Speed	2	0.97051	0.485253	77.71	0.013
Feed Rate	2	1.41078	0.705391	112.97	0.009
Depth of Cut	2	0.01249	0.006244	1.00	0.500
Error	2	0.01249	0.006244		
Total	8	2.40626			
Model Summary					
S = 0.0790202		R-Sq = 99.48 %		RSq-(adj) =91.55%	

From Table 5, the P-value gives the data about the effects of parameters on cutting force. Thus from the table it is clearly evident that feed rate affects the cutting force followed by spindle speed and depth of cut.

Main effects plots are generated form ANOVA for depicting the effects of parameters graphically which makes easy in determining the effects of parameters in different levels .Main effect is the effect of an independent variable on a dependent variable averaging across the levels of any other independent variables. Main effects plot examine differences between level means for one or more factors. The main effect plots for Surface roughness and Cutting forces are shown in Figure 5 and 6 respectively.

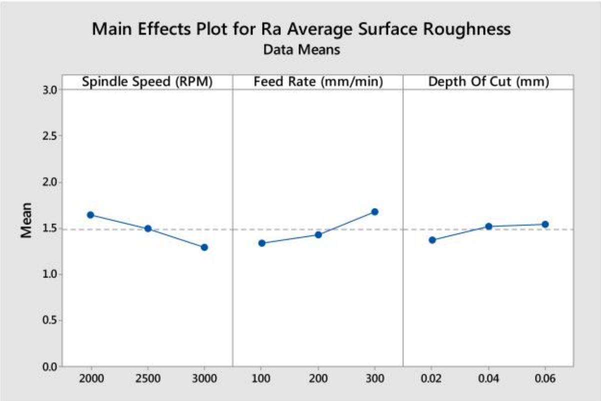

Figure 5: Main effects plot for Surface Roughness

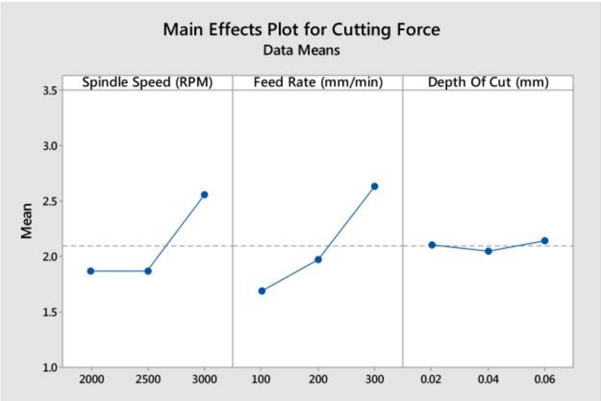

Figure 6: Main effects plot for Cutting Force

B. Regression Analysis

Regression analysis is a statistical process for evaluating the relationship between variables. It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. Regression analysis estimates the conditional expectation of the dependent variable given the independent variables that is, the average value of dependent variable when independent variables are fixed. A mathematical model is developed using regression to define the milling operation using the experimental results. The formulated mathematical model represents the entire operation that has been done. The regression equation was used to optimize the milling process. The mathematical model for surface roughness and cutting force is given below.

Surface Roughness = 1.861 - 0.000354 Spindle Speed (RPM) + 0.001662 Feed Rate (mm/min) + 4.25 Depth of Cut (mm)

Cutting Force = 0.624 + 0.000697 Spindle Speed (RPM) + 0.00472 Feed Rate (mm/min) + 0.87 Depth of Cut (mm)

IV. OPTIMIZATION

A. Genetic Algorithm

Genetic algorithm (GA), In the field of Artificial Intelligence (AI) are adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics [7]. The basic techniques of the GAs are designed to simulate processes in natural systems necessary for evolution, specially those follow the principles first laid down by Charles Darwin of "survival of the fittest". Since in nature, competition among individuals for scanty resources results in the fittest individuals dominating over the weaker ones. A more striking difference between GA and most traditional optimization is that GA uses a population of points at one time in contrast to the single point approach by traditional methods[7]. The basic steps in genetic algorithm is shown in Figure 7.

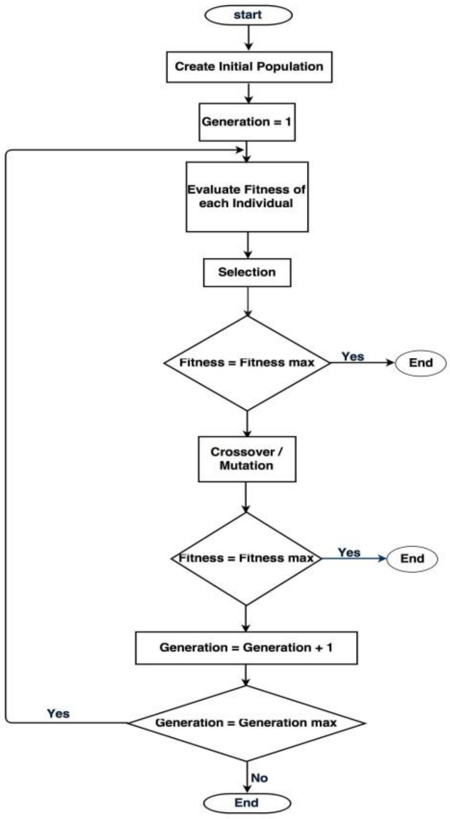

Figure 7: Flowchart of Genetic Algorithm

The input milling parameters were coded into the GA program. The code was developed in MATLAB 2014. The GA program optimize the operators to anticipate the values of milling parameters for minimum Surface finish and cutting force. When the program was run, optimized results were obtained showing the minimum output parameter values with respect to input parameters. So it has been possible to determine the optimum parameter levels at which the experiment has to be run in order to obtain minimum surface roughness and cutting force.

V. Results and Discussion

A. Genetic Algorithm Optimization

The results after optimization using GA is given in Table 6

Table 6: Paretian Points from GA Optimization

Sl. No	Cutting Force (kgf)	Surface Rough-ness (µm)	Spindle Speed (RPM)	Feed Rate (mm/ min)	Depth of Cut (mm)
1	1.2594	1.4042	2000.000	100.000	0.020000
2	1.7958	1.1322	2769.289	100.031	0.020071
3	1.7424	1.1619	2692.062	100.026	0.020632
4	1.4275	1.3214	2240.463	100.012	0.020562
5	1.8267	1.1163	2813.728	100.029	0.020034
6	1.3464	1.3683	2122.627	100.005	0.021781
7	1.7753	1.1447	2739.343	100.029	0.020533
8	1.2594	1.4042	2000.000	100.000	0.020000
9	1.4634	1.3006	2292.644	100.010	0.020012
10	1.3683	1.3504	2155.881	100.008	0.020327
11	1.5826	1.2403	2463.623	100.015	0.020055
12	1.5870	1.2381	2469.878	100.020	0.020053
13	1.5415	1.2624	2404.165	100.031	0.020309
14	1.6254	1.2269	2522.660	100.034	0.021815
15	1.8634	1.0976	2866.450	100.028	0.020033
16	1.2771	1.3963	2025.179	100.015	0.020532
17	1.5095	1.2797	2358.063	100.032	0.020535
18	1.4771	1.2957	2311.706	100.028	0.020424

The pareto plot corresponding to the results is shown in Figure 8. The paretian points are numbered sequentially for the plot from GA results.

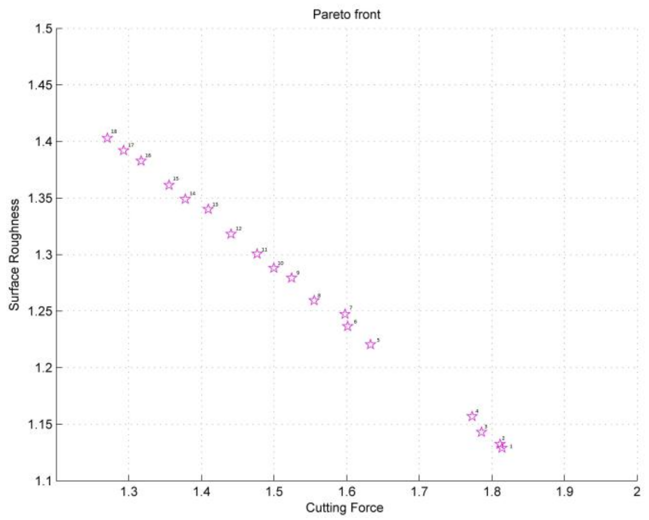

Figure 8: Pareto Front for GA optimized results

Analysing the plot, at point 1 lowest surface roughness but highest cutting force is obtained. The corresponding parameters at the point 1 gives maximum surface finish which is desired but demands great cutting force. On the other hand, at the extreme point 18, the highest value of surface finish and lowest cutting force is obtained. The corresponding parameters at point 18 gives minimum cutting force but undesirable surface finish. The intermediate points from 8 to 10 gives the desirable surface roughness and minimum cutting force.

VI. Validation

From the results of genetic algorithm, 3 experimental runs were run to confirm the optimized proposal. Thus 3 experimental runs were selected form the result table. Run number 1, 9 & 18 was selected and conducted to evaluate the output parameters. The graph showing the comparison between the experimental runs and GA predicted values are shown in Figure 9 and 10.

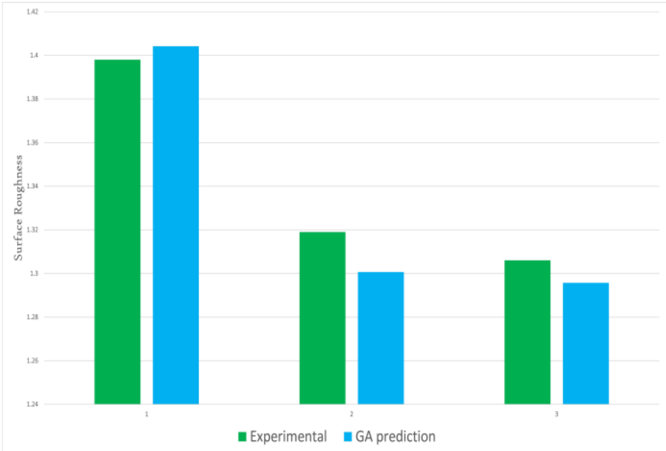

Figure 9: Experimental Vs GA predicted comparison for surface roughness

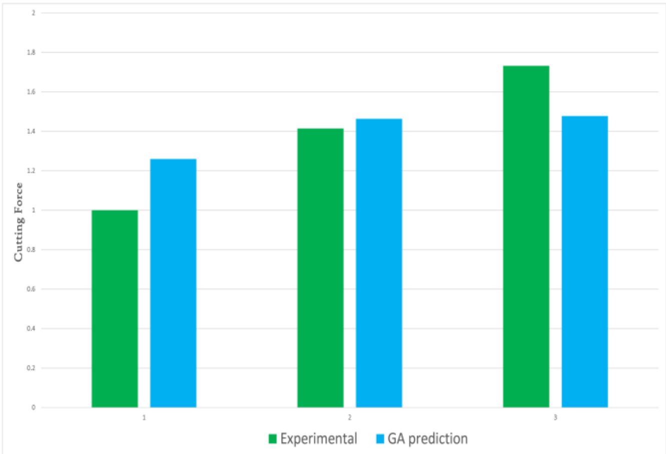

Figure 10: Experimental Vs GA predicted comparison for cutting force

From the confirmation experimental runs, the response showed very positive agreement to the GA predicted results. Thus the GA optimization was very successful in determining the set of input parameter for obtaining the optimized surface roughness and cutting force.

VII. CONCLUSION

The current work depicts Multi-Objective optimization of milling parameters using Genetic Algorithm. Emerging approaches on multi-objective optimizations enhances the flexibility and productivity in selection of optimal parameters for milling operations in HCHCr D3 grade steel and also in any materials. This work focussed on minimizing the surface roughness and cutting forces simultaneously by determining the optimal parameters (Spindle Speed, Feed Rate, Depth of Cut) under bounded constraints. The experiment was designed using Taguchi's Design Of Experiment (DOE) and the experimenation was done. The experimental results were statistically analysed using ANOVA for determining the most influencing parameters and a mathematical model of the objective was created using Regression Analysis. The heuristic based Genetic Algorithm was used to collect a set of results which were uniformly distributed and to plot a pareto front. The pareto front helps in determining the optimal milling conditions for different output conditions. There was a good compliance with the experimental results and the GA proposed results when confirmation test was conducted. Thus it was capable to determine the proper combination of spindle speed, feed rate and depth of cut to gain better Surface finish and low Cutting forces.

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