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Optimization of CGI during Milling using Tungsten Carbide Tool

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Abstract – CGI has many desirable mechanical properties but its machining is a challenge. In present work the milling of CGI was carried out using uncoated tungsten carbide tool. Major input parameters were optimize for achieving minimum tool wear, tool vibration, surface roughness and cutting forces. Design of experiments based on central composite Design of Response Surface methodology was used. An empirical model was developed and equation made between experimental and model result was obtained.

Index Terms – Central Composite Design, Tool Wear, MRR, Vibration, Force Response Surface Methodology.

1. INTRODUCTION

The Compacted graphite iron has been known for more than forty years, and possesses good properties i.e. High Tensile strength, Fatigue strength and light in weight. Therefore it is highly suitable for automotive engines. However CGI has limitation that it has lower machinability properties and high tool wear as compared to materials which are commonly used for same purpose. Automotive engines are traditionally made of grey cast iron. This is because grey cast iron materials contain flake graphite dispersed in a silicon iron matrix. The sharp edges of the flakes provide a very effective stress riser for the machining loads exerted by cutting edge. When the shear plane approaches a graphite pocket, cracks starts to propagate from the edge of the flake. The fracture starts at the stress riser and ends in an adjacent pocket until the shear load builds up to the fracture strength of the next stress riser. In CGI, the graphite is in vermicular form. During machining of CGI, it will shear through a graphite pocket which has the least resistance to shear forces. The round edges of the compacted graphite do not help in cracks initiation as the sharp edges of the flake graphite in grey cast iron, which leads to higher cutting forces while machining of CGI. Therefore it is experimentally investigate the performance of uncoated tungsten carbide tools in milling of CGI.

2. LITERATURE REVIEW

A. Kara S. and Li W. [1] developed an empirical model to find the relationship between energy and cutting parameters for material removal rate during turning and milling processes. MRR is considered as the main focus because it not only depends on the cutting parameters but also depends on the specification of the tool and work piece. This model suggests that for removing the same volume of material the high MRR result in less energy consumption, which leads to the increase in the productivity and saving the time of machining. By applying the coolant on the hard material during machining we get the higher MRR and it also increased the life of the tool. This model suggests that the type of material, tool and cutting parameters have a great impact on the energy consumption. Aouici et al. [2] calculated the impacts of machining parameters like spindle speed, feed, doc and work piece hardness on the response parameters i.e. Cutting Force and Surface Roughness of AISI H11 steel by using Cubic Boron Nitride (CBN) tool. High Cutting speed and lowest feed rate give the best surface finish. The depth of cut is the most influencing parameter to calculate the forces, cutting speed has the very less effect on it. It is concluded that the cutting force is mostly influenced by the doc and hardness of work piece. Yan J. and Li L. [3] presented a model which deals with to evaluate the trade of between the sustainability, cutting quality and production rate during the milling process. The main motive of the optimization is to improve the quality of products, increasing the rate and reducing the cutting energy. At higher material removal rate cutting energy get decrease and power demand increases. The width of cut has the most influence on the MRR and Cutting Energy while other parameters seem to have slightly lower effects than the width of cut. Surface roughness is also highly influenced by the width of cut as compared to other parameters. Experimental it was found that for milling low cutting speed is more energy efficient than conventional speed for milling. Nair et al. [4] experimentally investigated that effect of different process parameters on surface roughness on Brass material on CNC milling machine with TiN coated carbide insert tool and results are analyzed using Taguchi method. They found for multi optimization that best combination of the cutting parameters. Jin et al. [5] studied the effect of cutting speed on the micro hardness, machined surface roughness, white layer and plastic deformation on FGH95 PM Super alloy on CNC milling using coated carbide insert. The experimental results show that higher cutting speeds better surface roughness. Also the machined surface and white layer thickness increases as cutting speed increases. Different kind of surface defects appeared on the machined surface of FGH95 super alloy including, tearing, micro crack, nonmetallic dragging, smearing, void and adhered oxide. Hassanpour et al. [6] studied the effect of four parameters like Speed, axial and radial cut depth as well as feed rate on white layer thickness, micro hardness testing and surface roughness on the AISI 4340 (EN-24) with the use of minimum quantity of lubrication on end milling .The results show that feed rate had note worthy effect of followed by cutting speed, radial and axial depth of cut on Surface roughness. Mocellin et al. [7] Established that CGI has achieved remarkable value in automotive industry. Mainly last decade.CGI is use as exhaust manifolds, diesel engine blocks, discs of brake and engine heads. Superior Properties over grey iron like strength, due to high strength the wall thickness of cylinder made by CGI is thinner therefore generating lighter engine. And cylinders made by CGI are higher pressure operating combustion chambers so lower emission and higher efficiency achieved .CGI has excellent potential qualities but there is some technical challenges to overcome, mainly related to machining Waydande et al. [8] Worked on online monitoring system for tool wear in order to improve the quality of Machining parts, to reduce machining cost and reduce the machinine damage. Machining of hard material cutting tool subjected to heavy mechanical load and thermal stress due to high heat generation during machining tool material like coated carbide, tungsten coated tool. Cutting tool geometry, work piece material hardness and parameters affects the cutting forces, tool wear, surface roughness and vibration signal. It is concluded that to predict the progression of tool wear during hard machining process parameters cutting force, surface roughness and vibration signal used suitable feed rates. Bouska et al. [9] studied that compacted graphite iron, also known as semi ductile cast iron or vermicular cast iron is a modern material, increase in production of CGI globally. It concluded that the chemical composition of cast iron is predictable easily due to low variability of the whole production in all manufacturing phases. The Connections between wall thickness of casting and chemical composition of cast iron have been verified. To control the graphite modification before pouring is an important factor for production of CGI castings is mainly. Che Haron et al. [10] performed machining test under dry and wet cutting conditions at various cutting speeds, while the depth of cut and feed rate were kept constant. A strategy was adopted to avoid concentrated impact load and to obtain smooth initial wear so 5mm precut at entry used coated tungsten carbide tool better and give smooth flank wear. Gastel et al. [11] investigated the wear CBN tools is used for the machining of compacted graphite iron (CGI). Factors responsible for tool wear are mainly two factors are responsible are oxidation of the tool and inter dilution of constituting elements between tool and CGI. Both in CGI and CI machining both factors involve more or less. Mns layer form on CI give the difference in tool life Mns layer is missing in CGI. Mns layer act as diffusion barrier and a lubricant so less wear of tool while machining of CI.

3. EXPERIMENTAL SETUP

Experimental setup is an important step for any experimental research. It plays a vital role in the completion of the research. In this study, The Hurco VM10 CNC milling machine is used to perform the experiments.

3.1 WORK MATERIAL

Compacted Graphite iron grade GJV 450. Shown in Fig.3.1.

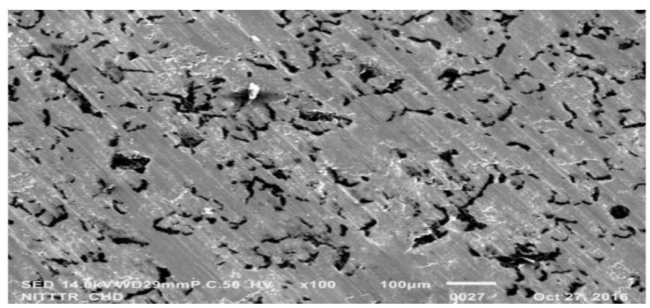

Figure 3.1 SEM image of CGI microstructure containing 10% nodularity.

Table 3.1 Chemical compostion of CGI

		CHEMICAL COMPOSITION (PERCENTAGE)							
Heat No Date	Reqd	C	SI	Mn	Cu	Cr	P	S	Mg
	Max	-	-	-	-	-	-	-	-
	Min	-	-	-	-	-	-	-	-
A		3.41	2.59	0.30	0.20	0.019	0.027	0.008	0.02

The microstructure of compacted graphite iron is taking from SEM at 100X is shown in figure . CGI having shorter and thick flaks which is rounded at the corner.

Material composition and Properties

The Workpiece material selected for the Experimental work is Compacted Graphite Iron. On the basis of literature Study CGI grade GJV450 is used as workpiece material. Mechanical properties of CGI GJV 450 grade at 10% Nodularity.

Table 3.2 Properties of CGI

Parameter	Value
Ultimate Tensile Strength (MPa)	465
0.2% Yield Strength (MPa)	350
Elastic Modulus (GPa)	145
Elongation (%)	1 – 2
Thermal Conductivity (W/m-K)	36
Density(g/cc)	7 – 7.2
Brinell Hardness Number(BHN)	207 – 255
Fatigue Strength Reduction Factor	1.20 – 1.60

3.2 TOOL MATERIAL

Ucoated Tungsten Carbide inserts of triangular shape were used as cutting tool for performing the experimentation.

Table 3.3 Tool Specification

Parameter	Value
Material	Tungsten Carbide
Grade	TPAN 2204 PDR-THM
Shape	Triangular bit 60°
Cutting edge length	22 mm
Thickness	4.76 mm
Nose radius	0.8 mm
Clearance angle	11°

3.3 DESIGN OF EXPERIMENTS

Table 3.4 Level of control factors for machining of CGI

Level	Cutting Velocity (m/min)	Tool Feed Rate (mm/tooth)	Depth of Cut (mm)
-1 (low)	150	0.10	1
0 (medium)	200	0.15	1.5
+1 (high)	250	0.20	2

In present work, RSM is used to design the experiments for machining of CGI with the help of central composite design method in Design Expert-10 software. Cutting Speed, Feed and Depth of Cut are taken as input process parameters and three levels for each parameter have been selected according to the pilot experiments. After selecting the input process parameters and their levels, the experimental run order is generated by using Response surface methodology with the help of CCD (central composite design) for machining of CGI, which has given 20 experiment runs and experiments conducted according to the run order produced by the RSM.

3.4 MILLING OPERATION

Vertical milling machine was used to perform the experiments with uncoated tungsten carbide insert.

Figure 3.2 HURCO VM10 CNC milling machine

4. RESULTS AND DISCUSSIONS

Table 4.1 Factors and Response Table

	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3	Response 4	Response 5
Run	A:Cutting Velocity	B:Feed	C:Depth of cut	Wear	Surface roughness	MRR	Vibration	Force
	m/min	mm/tooth	mm	um	um	mm3/min	um	KN
1	200	0.15	1.5	172	0.9533	24975.5	7.34343	0.014533
2	200	0.15	0.659104	86	1.231	11655.23	6.525564	0.016254
3	200	0.15	1.5	172	0.9533	24975.5	7.34343	0.014533
4	250	0.1	1	198	0.936	14593.33	9.10241	0.01539
5	284.0896	0.15	1.5	175	0.88	22374	9.834025	0.014847
6	200	0.23409	1.5	133	1.366	20487.5	8.556	0.014459
7	200	0.15	1.5	172	0.9533	24975.5	7.34343	0.014533
8	200	0.15	1.5	172	0.9533	24975.5	7.34343	0.014533
9	150	0.1	1	205	1.026	15335.83	7.384417	0.014816
10	115.9104	0.15	1.5	136.5	1.37	24376	6.687761	0.017767
11	200	0.15	2.340896	107.5	0.999	36280.2	9.998488	0.014047
12	200	0.06591	1.5	203	0.92	23677.5	6.903913	0.017596
13	200	0.15	1.5	172	0.9533	24975.5	7.34343	0.014533
14	250	0.2	2	311	1.3	32105.33	8.671954	0.015085
15	250	0.1	2	161.5	0.873	33564.67	6.895632	0.014594
16	150	0.2	1	100.5	1.123	17526.67	5.842346	0.015201
17	250	0.2	1	169.5	0.993	16052.67	6.903913	0.0168
18	150	0.1	2	105.5	0.9633	35053.33	6.716819	0.018073
19	150	0.2	2	140	1.103	35053.33	8.52032	0.014612
20	200	0.15	1.5	172	0.9533	24975.5	7.34343	0.014533

For optimizing the process parameters the experiments were performed with the variation in input parameters i.e. cutting speed, feed and depth of cut using design of experiments approach. ANOVA was used to obtain mathematical models.

Results of mathematical models were validated with experimental results

4.2 MULTI RESPONSE OPTIMIZATION USING DESIRABILITY APPROACH

The maximum value of Wear is 133.641 µm, Surface Roughness is 1.02453 µm, MRR is 3389 mm^3/min, Amplitude of Vibration is 6.97258 m/s^2 and Force is 0.0158373 KN with Cutting Speed 208.784 m/min, Feed 0.1 mm/tooth and Depth of Cut 1.99 mm which had desirability value of 0.815 which means the experimental result is closer to predicted results.

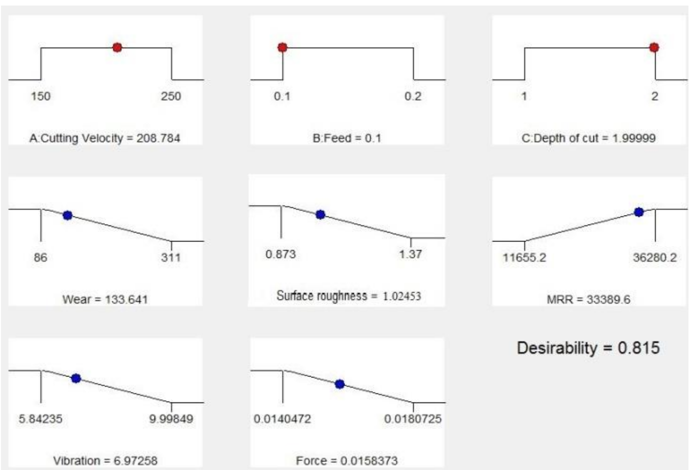

Figure 4.1 Predicted results of multiple variables by ramp plot

Desirability plot for multi response is shown in figure 4.2 for Wear, Surface roughness, MRR, Vibration and force with input parameter cutting Speed, feed, depth of cut.

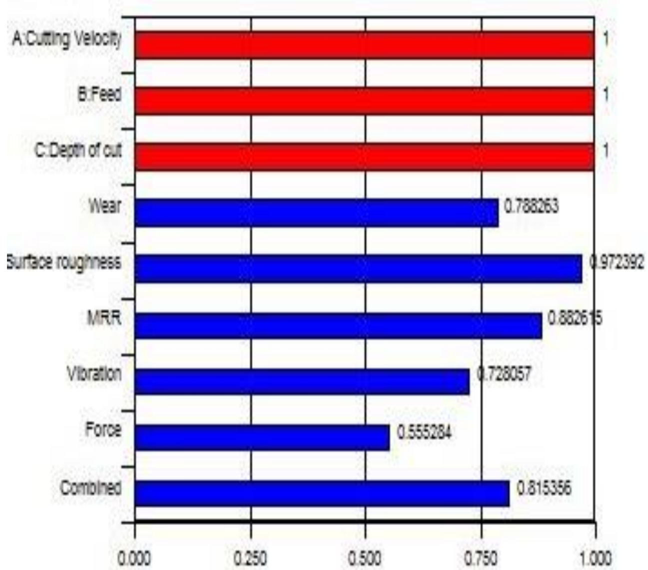

Figure 4.2 Predicted results of multiple variables by Desirability bar graph

4.3 INDIVIDUAL PLOTS OF EFFECT OF PROCESS PARAMETER

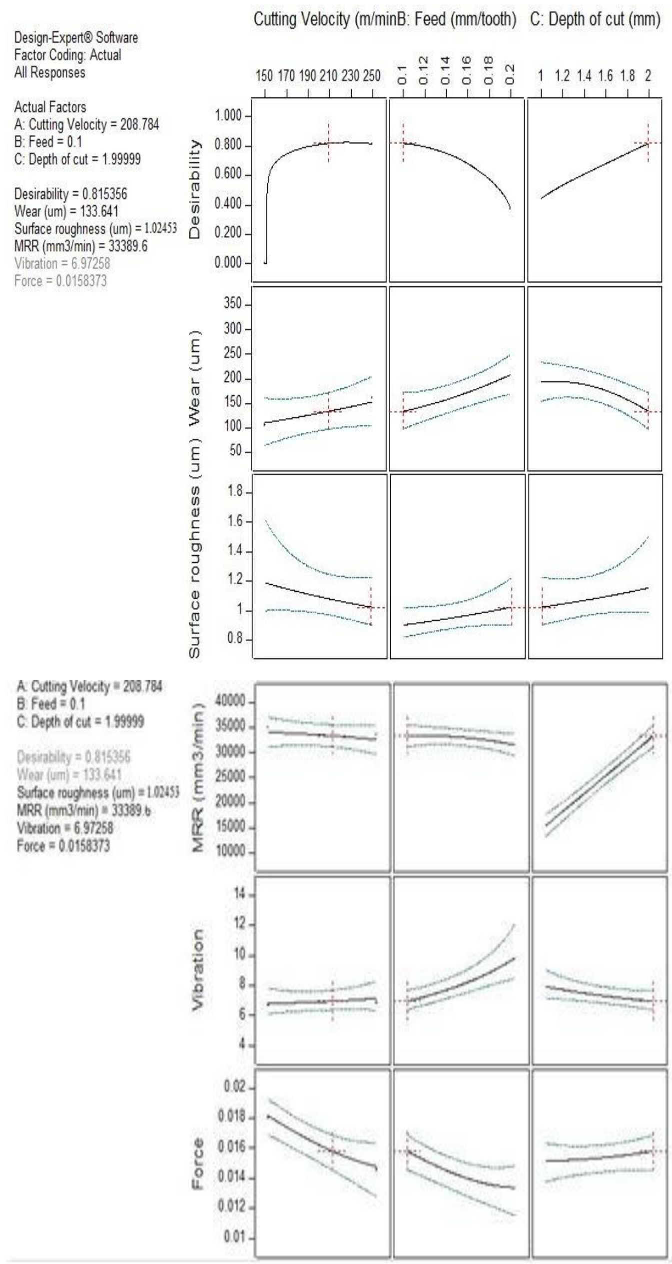

Figure 4.3 Effect of individual parameter on Desirability, Wear and Surface roughness, MRR, Vibration and Force

4.4 COUNTOUR PLOTS

The contour plot is a two-dimensional (2D) representation of the response plotted against combinations of numeric factors and/or mixture components. It can show the relationship between the responses, mixture components and/or numeric factors.

Contour Plots between Cutting Speed and Depth of Cut at constant Feed for different response factor

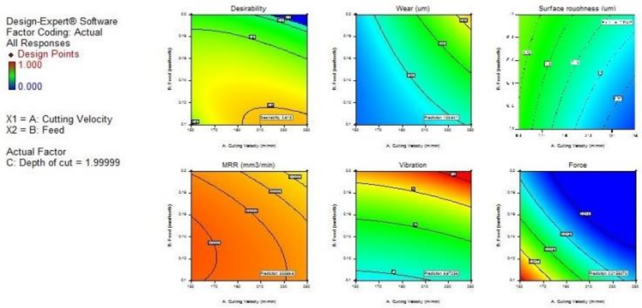

Figure 4.4 Contour Plot at constant Feed

For the given contour, plot is generated so as to obtain the optimum operating area in the given range of parameters. Feed is constant and plot between Cutting Speed and Depth of Cut with respect to response parameter optimum value is shown for all output parameters.

Contour Plots between Cutting Speed and Feed at constant Depth of Cut for different response factors

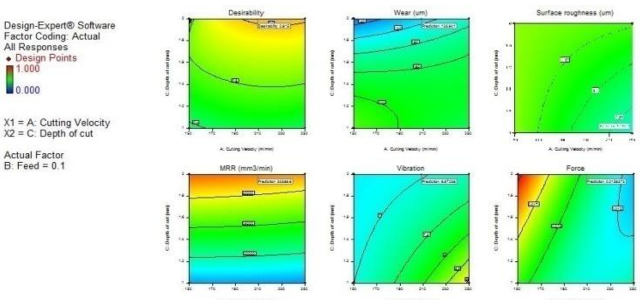

Figure 4.5 Contour Plots at constant Depth of Cut

For the given contour, plot is generated so as to obtain the optimum operating area in the given range of parameters. Depth of Cut is constant and plot between Cutting Speed and Feed with respect to response parameter optimum value is shown for all output parameters.

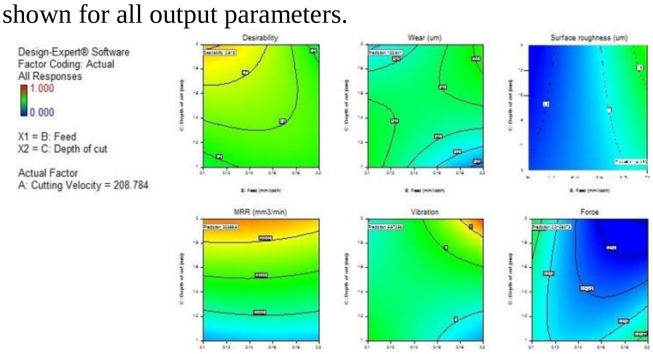

Figure 4.6 Contour Plots at constant Cutting Speed

Contour Plots between Depth of Cut and Feed at constant Cutting Speed for different response factors

For the given contour, plot is generated so as to obtain the optimum operating area in the given range of parameters. Cutting Speed is constant and plot between Feed and Depth of Cut with respect to response parameter optimum value is shown for all output parameter shown From the contour plots in fig.4.7

4.5 SURFACE PLOTS

The 3D Surface plot is a projection of the contour plot giving shape in addition to the color and contour.

Surface Plot between Two Parameters of Desirability

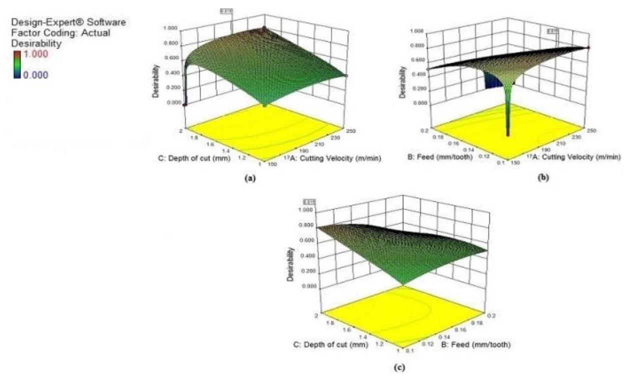

Figure 4.7 Surface plots for Desirability

The surface plot between Desirability versus Depth of Cut and Cutting Speed is shown in fig.4.8 (a) Feed is kept constant in this plot. The surface plot between Desirability versus Feed and Cutting Speed is shown in fig.4.8 (b). Depth of Cut is kept constant in this plot. The surface plot between Desirability versus Depth of Cut and Feed is shown in fig.4.8 (c). Cutting Speed is kept constant in this plot. The observation made from figs indicates that the maximum Desirability is 0.815.

Surface Plot between Two Parameters of Wear

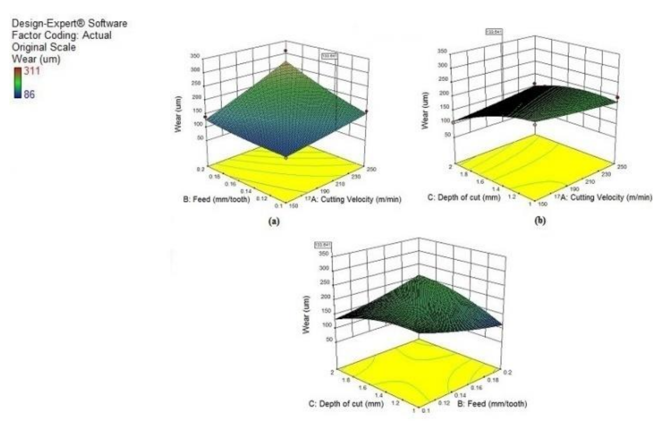

Figure 4.8 Surface plots for wear

The surface plot between Wear versus Feed and Cutting Speed is shown in fig.4.9 (a) Depth of Cut is kept constant in this plot .The surface plot between Wear versus Depth of Cut and Cutting Speed is shown in fig.4.9 (b) Feed is kept constant in this plot. The surface plot between Wear versus Depth of Cut and Feed is shown in fig.4.9 (c). Cutting Speed is kept constant in this plot. The observation made from figs indicates that the maximum Wear is 133.641 µm.

Surface Plot between Two Parameters of Surface Roughness

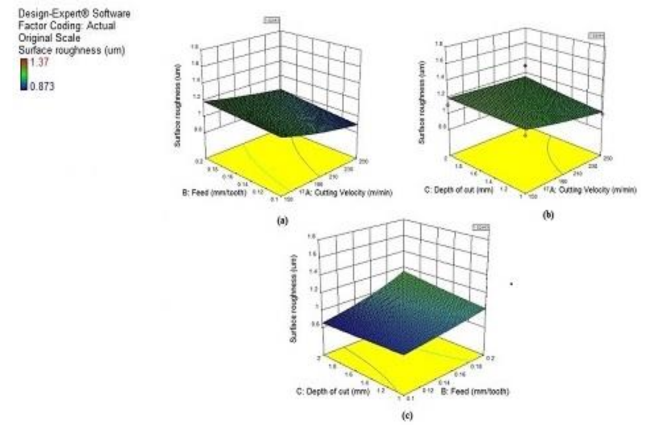

Figure 4.9 Surface plots for Surface Roughness

The surface plot between Surface Roughness versus Feed and Cutting Speed is shown in fig.4.10 (a) Depth of Cut is kept constant in this plot .The surface plot between Surface Roughness versus Depth of Cut and Cutting Speed is shown in fig.4.10 (b) Feed is kept constant in this plot. The surface plot between Surface Roughness versus Depth of Cut and Feed is shown in fig.4.10 (c). Cutting Speed is kept constant in this plot. The observation made from figs indicates that the maximum Surface Roughness is 0.815 µm.

Surface Plot between Two Parameters of MRR

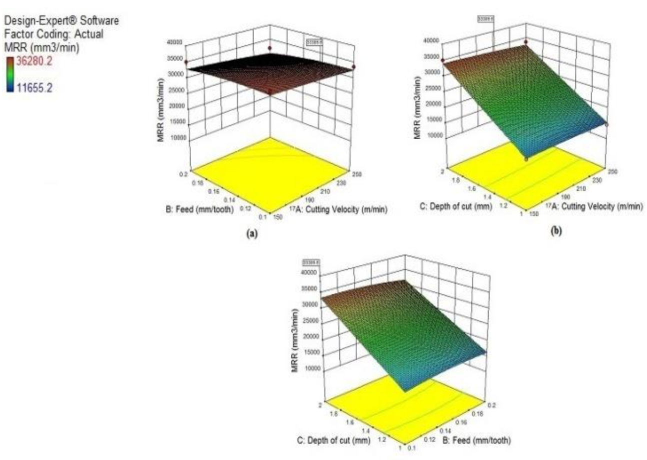

Figure 4.10 Surface plots for MRR

The surface plot between MRR versus Feed and Cutting Speed is shown in fig.4.11 (a) Depth of Cut is kept constant in this plot .The surface plot between MRR versus Depth of Cut and Cutting Speed is shown in fig.4.11 (b) Feed is kept constant in this plot. The surface plot between MRR versus Depth of Cut and Feed is shown in fig.4.11 (c). Cutting Speed is kept constant in this plot. The observation made from figs indicates that the maximum MRR is 33389.6 mm^3/min.

Surface Plot between Two Parameters of Vibration

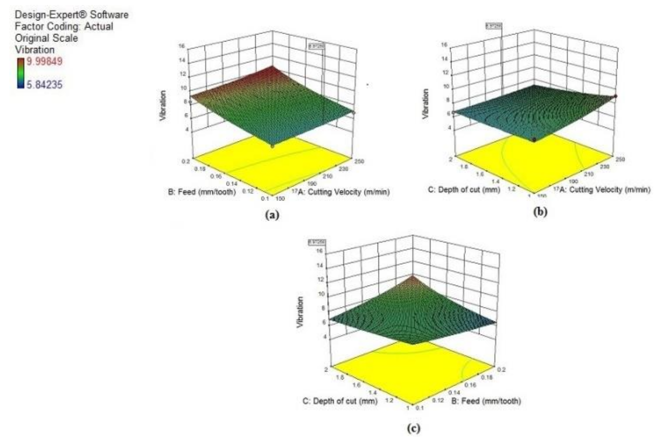

Figure4.11 Surface plots for Vibration

The surface plot between Vibration versus Feed and Cutting Speed is shown in fig.4.12 (a) Depth of Cut is kept constant in this plot .The surface plot between Vibration versus Depth of Cut and Cutting Speed is shown in fig.4.12 (b) Feed is kept constant in this plot. The surface plot between Vibration versus Depth of Cut and Feed is shown in fig.4.12 (c). Cutting Speed is kept constant in this plot. The observation made from figs indicates that the maximum Amplitude of Vibration is 6.97258 m/s^2.

Surface Plot between Two Parameters of Force

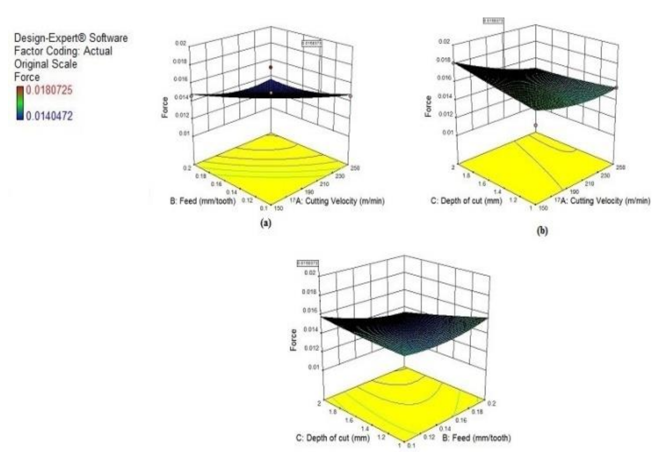

Figure 4.12 Surface plots for Force

The surface plot between Force versus Feed and Cutting Speed is shown in fig.4.13 (a) Depth of Cut is kept constant in this plot .The surface plot between Force versus Depth of Cut and Cutting Speed is shown in fig.4.13 (b) Feed is kept constant in this plot. The surface plot between Force versus Depth of Cut and Feed is shown in fig.4.13 (c). Cutting Speed is kept constant in this plot. The observation made from figs indicates that the maximum Force is 0.0158373KN.

4.6 EXPERIMENTAL VALUES

Cutting Force (KN)

Dynamometer was used for the measuring the force during experimentation on milling machine. Cutting forces signal is obtained by using software DynoWare. The maximum force obtained F_z is 0.015496KN

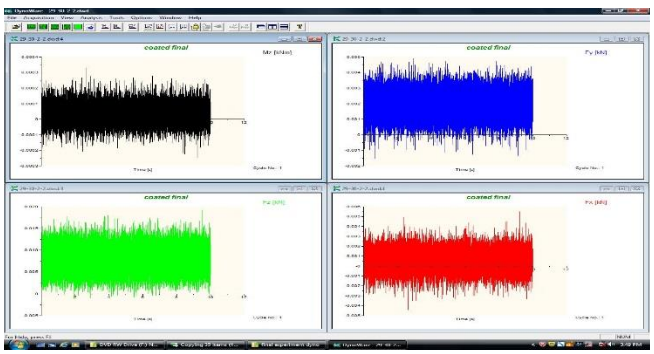

Figure4.13 showing Four Forces graph during machining of CGI

Tool Vibration (m/s^2)

Labview software is used to determine the vibration produce during milling of CGI. Accelerometer reading for maximum vibration produce during the operation is 7.15862 m/s^2.

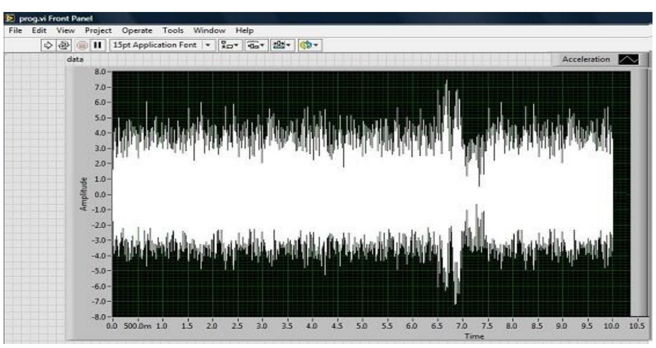

Figure4.14 showing Amplitude of Vibration graph during machining of CGI

Tool Wear (µm)

Machine vison is used to check the tool wear the maximum wear obtained is 134.500

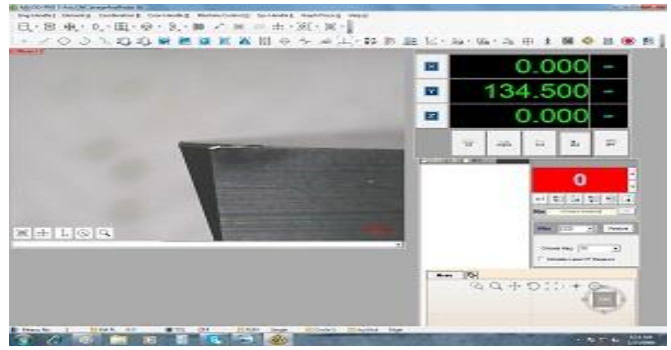

Figure 4.15 Showing Tool Wear in machine vision

Metal Removal Rate (mm^3/min)

MRR is calculated using simple formula

$Q = A_p \times A_e \times f_z \times N \times Z$ (mm^3/min)

Calculated MRR is 34188 mm^3/min

Surface Roughness (µm)

For measurement of surface roughness, Surftest SJ-301 model of Mitutoyo was used. Surface roughness is the main aim for every machined component. For certain application surface quality is the most important. For every cutting process the surface roughness is measured at three different location of specimen and average is taken as the output surface roughness. The optimum Surface Roughness obtained from experiment is 1.067.

Validation

After experimentation the result obtained and compare with predicted value and check the error. Table 4.2 shows the validation result

Table 4.2 Experimental and Predicted value with Error

Responses	Predicted Values	Experimental Values	Error%
Wear (µm)	133.641	134.500	0.642
Surface Roughness (µm)	1.0245	1.067	4.148
MRR (mm^3/min)	33389.6	34188	2.39
Vibration	6.97258	7015862	2.6681
Force (KN)	0.0158373	0.016196	2.264

5. CONCLUSIONS

The optimum combination for plain tungsten carbide insert was found to be Cutting Speed 208.784 m/min, Depth of Cut 1.99 mm and Tool Feed Rate 0.10 for achieving Wear of 134.500µm, Surface Roughness is 1.067µm, Material removal rate is 34188 mm^3/min, Vibration is 7.15862 m/s^2 and Force is 0.016196 KN mm/tooth for achieving the Surface Roughness.

5.1 LIMITATIONS OF THE PRESENT WORK

The result was obtained for dry machining condition Only and one grade of material was used in present work.

5.2 SCOPE OF FUTURE WORK

The optimization of process parameters for machining of compacted graphite iron was carried out from the simple machining point of view of different CGI are available in the market. There are following work which can be done in future studies:

- Coated milling tool insert can be used for machining.
- The concept of cryogenic treatment before and after coating can be analyzed for tool life improvement.
- For better surface roughness cutting fluid may used for improving the tool life because in the present work dry machining was done.
- The effect of other cutting parameters such as tool tip temperature, chip morphology responses could be investigated.

REFERENCES

[1] New Science of Strong Materials by J.E. Gordon Princeton University Press, 2006.
[2] www.sintercast.com/technology.
[3] A. Sahm, E. Abele and H. Schulz, "Machining of Compacted Graphite Iron (CGI)" Materwiss. Werksttech, Volume 33, 2002, pp. 501–506.
[4] Serope kalpakjaion, Steven R Schmid, "Manufacturing Science and Technology", 6th Edition, Pearson, 2009.
[5] www.generalcarbide.com.The Designer's Guide to Tungsten Carbide.
[6] B. R. Dabhi, K. V. Parmar, "A Review Paper on Latest Trend on Face Milling Tool" International Journal of Advanced Engineering and Research, Volume 2, Issue1,January-2015, pp.59-61.
[7] M. Y. Kumar and G. Shankaraiah, "Cutting Parameters Optimization in Milling of P20 Tool Steel and EN31B" IOSR Journal of Mechanical and Civil Engineering,Volume 8, Issue 5, Sep. - Oct. 2013, pp. 38-47.
[8] M. Singh, S. Verma, S. K. Jain, "A literature review on machining of different Materials with CNC " International Journal of Engineering Research in Managment & Technology, Volume-3, Issue 8, August-2014, pp. 50-53.
[9] S. Kara and W. Li, "Unit Process Energy Consumption Models for Material Removal Processes" CIRP Annals - Manufacturing Technology, Vol. 60,2011, pp. 37–40.
[10] H. Aouici, M. A. Yallese, K. Chaoui, T. Mabrouki, and J. F. Rigal, "Analysis of Surface Roughness and Cutting Force Components in Hard Turning with CBN tool Prediction model and cutting conditions optimization " Measurement Journal of the International Measurement Confederation, Vol. 45, 2012, pp. 344–353.
[11] J. Yan and L. Li, "Multi-Objective Optimization of Milling Parameters-the Trade offs between Energy, Production Rate and Cutting Quality" Journal of Cleaner Production, Vol. 52, 2013, pp. 462–471.
[12] Anish Nair and P Govindan, "Optimization of CNC End Milling of Brass Using Hybrid Taguchi Method Using PCA And Grey Relational Analysis" International Journal of Mechanical and Production Engineering Research and Development, Vol. 3, Issue 1, 2013, pp. 227-240.
[13] Du Jin. Zhanqiang Liu, "Damage of the machined surface and sub surface in orthogonal milling of FGH95 super-alloy", Int J Adv Manuf Tech, Springer 2013.
[14] H. Hassanpour, M. H. Sadeghi, A. Rasti, and S. Shajari, "Investigation of surface roughness, microhardness and white layer thickness in hard milling of AISI 4340 using minimum quantity lubrication " Journal Clean Production, Vol.120, 2016, pp24-134.
[15] F. Mocellin, E. Melleras and W. L. Guesser "Study of the Machinability of Compacted Graphite Iron for Drilling Process" Tupy Fundições Ltda R. Albano Schmidt, 3400 89206-900 Joinville, SC. Brazil
[16] Prashant Waydande, Nitin Ambhore and Satish Chinchanikar "A Review on Tool Wear Monitoring System" Journal of Mechanical Engineering and Automation 2016, 6(5A) pp49-53
[17] Sunday Joshua Ojolo and Olugbenga Ogunkomaiya "A study of effects of machining parameters on tool life" International Journal of Materials Science and applications Vol. 3, No. 5, 2014, pp. 183-199.
[18] O. Bouska a, J. Heunisch a, A. Zadera b, K. Nedelova a,and F. Kobersky "Development of a manufacturing technology of compacted graphite iron castingsfrom a cupola furnace" ISSN (1897-3310) Volume 12 Issue 1/2012 pp125 – 129
[19] Che Haron,C.H Gainting, A and Goh J.H. "Wear of coated and uncoated carbide in turning tool steel" Journal of Materials Processing Technology, pp 49-54.
[20] E.O. Ezugwu, R.B. Da Silva, J. Bonney A.R. Machado "Evaluation of the performance of CBN tools when turning Ti–6Al–4V alloy with high pressure coolant supplies" International Journal of Machine Tools & Manufacture 45 (2005)pp1009–1014
[21] M. Gastel , C. Konetschny , U. Reuter , C. Fasel , H. Schulz , R. Riedel, H.M. Ortner "Investigation of the wear mechanism of cubic boron nitride tools used for machining of compacted graphite iron and grey cast iron" International Journal of Refractory Metals & Hard Materials 18 (2000) pp287-296
[22] J.A. Arsecularatne, L.C. Zhang, C. Montross "Wear and tool life of tungsten carbide, PCBN and PCD cutting tools" International Journal of Machine Tools & Manufacture 46 (2006) pp482–491.
[23] Anders Berglund "Criteria for Machinability Evaluation of compacted Graphite Iron" KTH Royal institute of technology Stockholm, Sweden 2011.
[24] John Vaccari, How to machine compacted graphite iron By John Vaccari November 2000. Machine shop guide.l.3, Issue:1, January ,2015, pp.1-9