Multi-response optimization of hard milling process: RSM coupled with grey relational analysis

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***Abstract*— This paper presents the effect of process parameters on cutting forces, workpiece surface temperature and sound pressure level in hard milling of 100MnCrW4 tool steel using TiN+TiAlN coated WC inserts. A response surface methodology based box-behnken design coupled with grey relational analysis was utilized for statistical optimization. The individual weight of each quality characteristic is determined by employing the entropy measurement method and a GRG obtained from the GRA is used to optimize the hard milling process. The optimum process parameters are determined by the GRG as the overall performance index. An empirical relationship was established to predict the GRG by incorporating independently controllable hard milling process parameters effectively. In ANOVA indicate, the work material hardness, feed rate per tooth and axial depth of cut showed as the most influential factors associated with the grey relational grade. To validate the study, confirmation experiment has been carried out at optimal set of parameters, and predicted results have been found to be in good agreement with experimental findings. The optimal results show that the RSM-Grey relational analysis was successful in improving the hard milling performance.**

Keywords- Cutting forces, entropy measurement, grey relational analysis, hard milling, sound, temperature

I. INTRODUCTION

Hard milling process is an advanced material machining technology to machine the different steels with hardened state (i.e. 45 HRC and higher).The potential benefits are higher metal removal rate with greater flexibility, shortest route with less capital investment and less environmental hazards as compared with EDM and EDM and grinding operations[1]. However, the limitations are severe cutting forces, tool temperatures are produced.This criticaly affecting surface finish of the workpiece and tool wear in the cutting zone. Ding et al. [2] developed linear mathematical models for feed force (F_x), the normal force (F_y) and axial force (F_z) components and quadratic model for surface finish. The feed force is strongly influenced by axial depth of cut. The cutting forces increase with increase of width of cut, depth of cut and chip load per tooth. The obtained surface roughness was less than 0.25 µm, which confirms that hard milling replacing the grinding process as semi finish stage. Gopalswamy et al.[3] investigated the machinability study of hardened IMPAX Hi-Hard (55 HRC) tool steel using coated WC inserts.In rough machining,the width of cut and axial depth of cut are more influenced parameters on metal removal rate, tool wear and tool life. While, a cutting speed as identified the most influenced parameter on surface roughness, tool wear and tool life in finish machining. Palanisamy et al. [4] agreed that increase of an axial depth of cut promotes more contact area in the cutting zone leads higher cutting forces.The variation of cutting forces quantifies the surface finish. Due to the tribological interaction between cutter flank face and work piece, the observed F_y was 34% higher than F_x.The temperatures of shear and friction zone increases with increase of cutting speed. Lu et al. [5] machined SKD 61 tool steel (40HRC) using TiAlN coated WC inserts in high speed cutting range between 12000 to 20000rpm. A metal removal rate and two zones of tool wear (at the end cutting edge and peripheral cutting edge) were measured. A grey relational analysis coupled with the principal component analysis procedure was applied to select the optimal values. According to Toh [6], the induced F_y is 89% higher than F_x in all axial depths of cut in down milling. While, in up milling the F_y is 23% lower than F_x force was observed. However, the F_z component of forces is a similar trend in both milling orientations. The F_y and F_z forces are more sensitive related to tool wear for all axial depth cut. Tamizharasan et al. [7] experimentally studied the influence of material hardness with cutting conditions in the machining of the axle shaft. The flank wear, audible AE signal and surface roughness were optimized through a simulated annealing algorithm. The detected audible AE signals are valuable data to observe the tool wear in on-line process. Chen et al. [8] performed high speed machining experiments in DIN

1.2344 tool steel. A grey relational analysis performed to obtain optimal parameters. The cutting speed and feed per tooth are significant contributions covered on 76.46%.The reviewed literature tracked the state of art research in hard machining process. The present work is to propose a methodical approach of the Resposne surface methodology coupled with grey relational analysis to obtain a suitable cutting conditions for a 100MnCrW4 (Type O1) tool steelusing TiN+TiAlN coated WC inserts. During machining, the important responses of cutting forces, workpiece surface temperature (WST) and machining sound pressure level(SPL)are measured and optimized in order to quantify the quality of machined surfaces.

II. ANALYSIS METHOD

2.1 Grey relational analysis via entropy

In a grey relational analysis [9], first the linear normalization is performed in the range between zero to one. In this case, all force components, WST and SPL corresponding to lower-the-better criterion which can be expressed as

$$x_i^*(k) = \frac{\max\ x_i^0(k) - x_i^0(k)}{\max\ x_i^0(k) - \min\ x_i^0(k)} \qquad (1)$$

Where i=1,2,3…,n; k=1,2,3….,p; n is the number of experimental items, and p is the number of performance characteristics. $x_i^0(k)$ denotes original sequence, $x_i^*(k)$ the sequence after the data processing. $\max x_i^0(k)$ the largest value of $x_i^0(k)$, $\min x_i^0(k)$ the smallest of $x_i^0(k)$. The grey relational co-efficient is calculated to display for all the sequences are the relationship between the best and actual normalized data. After the data processing, the grey relational coefficient can be expressed as

$$\xi_i^*(k) = \frac{\Delta \min + \zeta.\Delta \max}{\Delta_{0,i}(k) + \zeta.\Delta \max} \qquad (2)$$

Where,

$$\Delta_{0,i} = \left| x_0^*(k) - x_i^*(k) \right|$$

$$\Delta \max = \max_i \max_k \left| x_0^*(k) - x_i^*(k) \right|$$

$$\Delta \min = \min_i \min_k \left| x_0^*(k) - x_i^*(k) \right|$$

Where, $\Delta_{0,i}(k)$ is the deviation sequence of the reference sequence and the comparability sequence. ζ is a distinguishing or identification coefficient. The ζ value lies between zero and one. In general, it is set as 0.50, because all the process parameters are of equal length. Normally; the average of grey relational coefficient is the grey relational grade. In a real situation, the importance of each performance characteristics may be different. Therefore the individual weight of each performance characteristic is computed by using entropy measurement. In information theory, entropy is a measure of how disorganized a system is. As applied to the concept of entropy to weight measurement, an attribute with large entropy means it has a great diversity of responses so the attribute has a more significant influence to the response. Wen et al. [10] defined the entropy as mapping function $f_i : [0,1] \rightarrow [0,1]$ used in entropy should satisfy all these conditions: (1) $f_i(0) = 0$,(2) $f_i(x) = f_i(1-x)$,(3) $f_i(x)$ is monotonically increasing in the range $x \in (0,0.5)$. Thus, the following function $w_e(x)$ can be used as the mapping function in the entropy measure:

$$w_e(x) = xe^{(1-x)} + (1-x)e^x - 1 \qquad (3)$$

The maximum value of this function occurs at $x = 0.5$ .For the function of x , the entropy function is defined as

$$W \equiv \frac{1}{(e^{0.5} - 1)} \sum_{i=1}^{n} w_e(x_i) \qquad (4)$$

The following step-by-step procedure is adopted to find individual weights.

1. First, the sum of grey relational coefficient in all sequences for each performance characteristics can be computed

$$D_j = \sum_{i=1}^{n} \xi_i(j), \ j = 1,2,....,p. \qquad (5)$$

2. Find normalized coefficient

$$k = \frac{1}{(e^{0.5} - 1) \times n}. \qquad (6)$$

3. Calculation of entropy of the each performance characteristics

$$e_j = k \sum_{i=1}^{n} w_e \left(\frac{\xi_i(j)}{D_j} \right), \; j = 1,2,....,p. \quad (7)$$

4. Finding total sum of Entropy

$$E = \sum_{i=1}^{p} e_j, \qquad (8)$$

5. Estimating the weight of each performance characteristics

$$w_j = \frac{1/p - E[1 - e_j]}{\sum_{j=1}^{p} 1/p - E[1 - e_j]}, \; j = 1,2,....,p. \, (9)$$

Then, the grey relational grade is determined by multiplying the grey relational co-efficient with their corresponding weight of each performance characteristics.

$$\Gamma_{0,i} = \sum_{k=1}^{p} w_k \xi_{0,i}(k), \; i = 1,2,....,n. \, (10)$$

III. EXPERIMENTAL DETAILS

3.1 Experimental design

In the present investigation, a response surface methodology (RSM) based box-behnken design was selected. The reason is to develop the quadratic mathematical models with reasonable number of experiments [11]. A BBD matrix was developed for five factors with each in three equal intervals. Such as, the work material hardness(*HRC*) (i.e. 45,50,55HRC); nose radius (r_e) (i.e. 0.80,2.0,3.2mm); feed per tooth (f_z) (i.e. 0.05,0.125,0.200 mm per tooth); radial depth of cut (a_e) (i.e. 0.30 ,0.55,0.80mm) and axial depth of cut (a_p) (i.e. 0.5,1.0,1.5mm). The range each factor was selected based on preliminary trials and literature study. A series of 46 experiments with six centre points were formulated to carry out experimental work.

Fig.1. Hard milling process experimental setup

Table I
Box-Behnken design matrix with responses

Std	Run	HRC	r_e	f_z	a_e	a_p	F_x N	F_y N	F_z N	WST °C	SPL dB
1	28	45	0.8	0.125	0.55	1.0	541.344	402.052	366.766	266.44	71.08
2	5	55	0.8	0.125	0.55	1.0	794.334	1165.1	1255.07	417.13	71.87
3	7	45	3.2	0.125	0.55	1.0	593.345	605.389	790.048	513.8	83.54
4	39	55	3.2	0.125	0.55	1.0	610.789	1256.78	1293.7	590.11	84.58
5	36	50	2.0	0.050	0.30	1.0	312.565	526.442	470.184	367.2	60.72
6	37	50	2.0	0.200	0.30	1.0	352.903	959.159	968.76	560.65	90.98
7	3	50	2.0	0.050	0.80	1.0	204.456	644.382	635.102	480.35	67.09
8	17	50	2.0	0.200	0.80	1.0	807.456	1129.46	1097.47	569.35	96.77
9	40	50	0.8	0.125	0.55	0.5	542.577	749.463	701.976	413.98	67.76
10	25	50	3.2	0.125	0.55	0.5	311.234	600.125	786.241	491.04	70.85
11	21	50	0.8	0.125	0.55	1.5	833.545	588.848	799.533	530.05	79.69
12	24	50	3.2	0.125	0.55	1.5	675.107	1043.02	1053.46	724.03	100.9
13	46	45	2.0	0.050	0.55	1.0	550.234	335.643	361.05	358.51	60.08
14	29	55	2.0	0.050	0.55	1.0	472.898	1017.98	1015.48	388.51	68.96
15	18	45	2.0	0.200	0.55	1.0	456.343	756.317	763.887	470.12	86.88
16	20	55	2.0	0.200	0.55	1.0	854.456	1467.65	1429.41	678.51	97.03
17	43	50	2.0	0.125	0.30	0.5	183.676	547.682	591.277	429.66	63.23
18	13	50	2.0	0.125	0.80	0.5	249.465	762.243	769.873	459.89	64.96
19	33	50	2.0	0.125	0.30	1.5	609.676	752.899	872.341	618.42	95.55
20	4	50	2.0	0.125	0.80	1.5	747.566	869.941	966.837	660.87	107.8
21	16	50	0.8	0.050	0.55	1.0	787.345	519.132	498.691	339.64	54.65
22	31	50	3.2	0.050	0.55	1.0	295.676	667.009	744.185	501.27	70.88
23	12	50	0.8	0.200	0.55	1.0	743.567	980.879	994.768	478.51	87.04
24	8	50	3.2	0.200	0.55	1.0	797.678	1126.34	1158.71	696.34	90.78
25	14	45	2.0	0.125	0.30	1.0	527.678	391.256	409.272	381.2	83.04
26	1	55	2.0	0.125	0.30	1.0	301.345	1188.19	1214.51	441.51	83.54
27	10	45	2.0	0.125	0.80	1.0	302.876	621.473	627.694	362.66	88.37
28	6	55	2.0	0.125	0.80	1.0	672.676	1237.58	1250.01	522.74	89.01
29	23	50	2.0	0.050	0.55	0.5	234.244	523.624	528.865	419.43	58.98
30	9	50	2.0	0.200	0.55	0.5	383.675	863.451	891.236	555.12	79.76
31	35	50	2.0	0.050	0.55	1.5	430.567	585.164	718.69	529.66	83.76
32	11	50	2.0	0.200	0.55	1.5	878.768	1136.16	1147.52	740.58	104.6
33	22	45	2.0	0.125	0.55	0.5	186.456	438.467	442.855	398.2	68.02
34	41	55	2.0	0.125	0.55	0.5	569.799	1057.69	1197.31	379.51	68.98
35	15	45	2.0	0.125	0.55	1.5	656.455	508.953	691.836	434.89	98.77
36	45	55	2.0	0.125	0.55	1.5	843.244	1298.52	1311.51	720.97	95.84
37	19	50	0.8	0.125	0.30	1.0	623.566	536.827	563.564	347.82	80.92
38	2	50	3.2	0.125	0.30	1.0	287.885	851.031	915.949	542.19	81.56
39	42	50	0.8	0.125	0.80	1.0	538.676	841.264	871.841	395.28	86.41
40	32	50	3.2	0.125	0.80	1.0	583.788	846.221	848.025	582.42	90.66
41	34	50	2.0	0.125	0.55	1.0	424.788	655.224	644.178	437.12	86.56
42	38	50	2.0	0.125	0.55	1.0	380.657	660.613	670.045	439.12	85.01
43	44	50	2.0	0.125	0.55	1.0	464.897	657.346	636.709	421.12	83.71
44	27	50	2.0	0.125	0.55	1.0	453.084	671.794	656.856	410.12	86.89
45	30	50	2.0	0.125	0.55	1.0	494.345	679.438	640.691	434.12	90.28
46	26	50	2.0	0.125	0.55	1.0	433.736	663.421	661.059	432.12	87.67

3.2 Tool, Tool holder and machine

A tool designation of APKT 09T308R, 20R, 32R-EM (TT9080) and tool holder type 2S-TE90AP 216-W16-09[12] were selected. The insert was a screw clamped in tool holder with a diameter of 20mm.A industrial type BFW (Bharat Fritz Werner Ltd, Bangalore, India) heavy duty vertical milling machine was used for the tests. The machine equipped with 5 HP motor, spindle speed range 45- 3400 RPM and a table feed rate range 16 -800mm/min capacity.

3.3 Work piece material

The work piece material in the present work as 100CrMnW4 tool steel and it contains the chemical composition as 0.95%C, 1.1%Mn, 0.6%Cr, 0.6W and etc. The main industrial uses are blanking dies, trim dies, bushings, forming dies, master tools, forming rolls and gauges, etc. The work pieces were heat treated and tempered to get desired hardness levels of 45, 50 and 55 HRC. The measured each hardness value kept within ±0.5 HRC accuracy. The work pieces were cleaned and face milled to remove the surface defects due to the heat treatment and ensure the flat surfaces. The final dimensions were obtained as 100×100×20 mm for all the workpieces.

IV. EXPERIMENTAL PROCEDURE

The experiments were conducted according to 'RUN' column of the box- behnken design matrix and responses as shown in Table .I. In each experiment a fresh insert was used and replicated as three times in order to improve the reliability of results. The cutting speed was kept constant 188.49m/min, in order to understand the effect of variation of material hardness [13].A down milling orientation was employed and no coolant was preferred for all the experiments. The tool moves along the x- direction and length of each cut were set to 100mm. In order to avoid nose radius effect of the insert, the marks generated by prior cutting pass were removed before passing the next fresh insert in each time. A hard milling experimental setup as shown in Fig.1.

Table II
Normalized and deviation sequences

Data normalization						Deviation Sequence				
Exp.No	**F_x**	**F_y**	**F_z**	**WST**	**SPL**	**F_x**	**F_y**	**F_z**	**WST**	**SPL**
1	0.485	0.941	0.995	1.000	0.691	0.515	0.059	0.005	0.000	0.309
2	0.121	0.267	0.163	0.682	0.676	0.879	0.733	0.837	0.318	0.324
3	0.411	0.762	0.598	0.478	0.456	0.589	0.238	0.402	0.522	0.544
4	0.386	0.186	0.127	0.317	0.436	0.614	0.814	0.873	0.683	0.564
5	0.815	0.831	0.898	0.787	0.886	0.185	0.169	0.102	0.213	0.114
6	0.757	0.449	0.431	0.379	0.316	0.243	0.551	0.569	0.621	0.684
7	0.970	0.727	0.743	0.549	0.766	0.030	0.273	0.257	0.451	0.234
8	0.103	0.299	0.311	0.361	0.207	0.897	0.701	0.689	0.639	0.793
9	0.484	0.634	0.681	0.689	0.753	0.516	0.366	0.319	0.311	0.247
10	0.816	0.766	0.602	0.526	0.695	0.184	0.234	0.398	0.474	0.305
11	0.065	0.776	0.590	0.444	0.529	0.935	0.224	0.410	0.556	0.471
12	0.293	0.375	0.352	0.035	0.130	0.707	0.625	0.648	0.965	0.870
13	0.473	1.000	1.000	0.806	0.898	0.527	0.000	0.000	0.194	0.102
14	0.584	0.397	0.387	0.743	0.731	0.416	0.603	0.613	0.257	0.269
15	0.608	0.628	0.623	0.570	0.393	0.392	0.372	0.377	0.430	0.607
16	0.035	0.000	0.000	0.131	0.202	0.965	1.000	1.000	0.869	0.798
17	1.000	0.813	0.785	0.656	0.838	0.000	0.187	0.215	0.344	0.162
18	0.905	0.623	0.617	0.592	0.806	0.095	0.377	0.383	0.408	0.194
19	0.387	0.631	0.521	0.258	0.230	0.613	0.369	0.479	0.742	0.770
20	0.189	0.528	0.433	0.168	0.000	0.811	0.472	0.567	0.832	1.000
21	0.132	0.838	0.871	0.846	1.000	0.868	0.162	0.129	0.154	0.000
22	0.839	0.707	0.641	0.505	0.694	0.161	0.293	0.359	0.495	0.306
23	0.195	0.430	0.407	0.553	0.390	0.805	0.570	0.593	0.447	0.610
24	0.117	0.302	0.253	0.093	0.320	0.883	0.698	0.747	0.907	0.680
25	0.505	0.951	0.955	0.758	0.465	0.495	0.049	0.045	0.242	0.535
26	0.831	0.247	0.201	0.631	0.456	0.169	0.753	0.799	0.369	0.544
27	0.829	0.747	0.750	0.797	0.365	0.171	0.253	0.250	0.203	0.635
28	0.296	0.203	0.168	0.459	0.353	0.704	0.797	0.832	0.541	0.647
29	0.927	0.834	0.843	0.677	0.918	0.073	0.166	0.157	0.323	0.082
30	0.712	0.534	0.504	0.391	0.527	0.288	0.466	0.496	0.609	0.473
31	0.645	0.780	0.665	0.445	0.452	0.355	0.220	0.335	0.555	0.548
32	0.000	0.293	0.264	0.000	0.060	1.000	0.707	0.736	1.000	0.940
33	0.996	0.909	0.923	0.722	0.748	0.004	0.091	0.077	0.278	0.252
34	0.445	0.362	0.217	0.762	0.730	0.555	0.638	0.783	0.238	0.270
35	0.320	0.847	0.690	0.645	0.169	0.680	0.153	0.310	0.355	0.831
36	0.051	0.149	0.110	0.041	0.224	0.949	0.851	0.890	0.959	0.776
37	0.367	0.822	0.810	0.828	0.505	0.633	0.178	0.190	0.172	0.495
38	0.850	0.545	0.481	0.418	0.493	0.150	0.455	0.519	0.582	0.507
39	0.489	0.553	0.522	0.728	0.402	0.511	0.447	0.478	0.272	0.598
40	0.424	0.549	0.544	0.334	0.322	0.576	0.451	0.456	0.666	0.678
41	0.653	0.718	0.735	0.640	0.399	0.347	0.282	0.265	0.360	0.601
42	0.717	0.713	0.711	0.636	0.428	0.283	0.287	0.289	0.364	0.572
43	0.595	0.716	0.742	0.674	0.453	0.405	0.284	0.258	0.326	0.547
44	0.612	0.703	0.723	0.697	0.393	0.388	0.297	0.277	0.303	0.607
45	0.553	0.696	0.738	0.646	0.329	0.447	0.304	0.262	0.354	0.671
46	0.640	0.710	0.719	0.651	0.378	0.360	0.290	0.281	0.349	0.622

The cutting force data acquisition system consists of piezoelectric dynamometer (Kistler force type 9257B), multi-channel charge amplifier (Type 5070) and computer with dynaware software. The sampling frequency of data was set to into 1 KHz and the sensitivity of F_x, Fy and F_z were set as -7.930pC/N, -7.904pC/N and -3.694pC/N accordingly. When the tool nose was fully immersed in the work piece (under steady state), the corresponding instantaneous force signals along x, y and z directions were considered for evaluating the cutting forces. A fifteen peak force values of per replication with ten points of fully immersed condition was chosen and

Table III
GRC,GRG and Rank Table

Exp.no	GRC					GRG	Rank
	F_x	F_y	F_z	WST	SPL		
1	0.49	0.90	0.99	1.00	0.62	0.8	3
2	0.36	0.41	0.37	0.61	0.61	0.47	35
3	0.46	0.68	0.55	0.49	0.48	0.53	27
4	0.45	0.38	0.36	0.42	0.47	0.42	39
5	0.73	0.75	0.83	0.70	0.81	0.76	5
6	0.67	0.48	0.47	0.45	0.42	0.5	33
7	0.94	0.65	0.66	0.53	0.68	0.69	9
8	0.36	0.42	0.42	0.44	0.39	0.4	41
9	0.49	0.58	0.61	0.62	0.67	0.59	15
10	0.73	0.68	0.56	0.51	0.62	0.62	13
11	0.35	0.69	0.55	0.47	0.51	0.52	32
12	0.41	0.44	0.44	0.34	0.37	0.4	42
13	0.49	1.00	1.00	0.72	0.83	0.81	1
14	0.55	0.45	0.45	0.66	0.65	0.55	24
15	0.56	0.57	0.57	0.54	0.45	0.54	26
16	0.34	0.33	0.33	0.37	0.39	0.35	46
17	1.00	0.73	0.70	0.59	0.76	0.75	6
18	0.84	0.57	0.57	0.55	0.72	0.65	10
19	0.45	0.58	0.51	0.40	0.39	0.47	36
20	0.38	0.51	0.47	0.38	0.33	0.41	40
21	0.37	0.76	0.80	0.76	1.00	0.74	7
22	0.76	0.63	0.58	0.50	0.62	0.62	14
23	0.38	0.47	0.46	0.53	0.45	0.46	37
24	0.36	0.42	0.40	0.36	0.42	0.39	43
25	0.50	0.91	0.92	0.67	0.48	0.7	8
26	0.75	0.40	0.39	0.58	0.48	0.52	31
27	0.74	0.66	0.67	0.71	0.44	0.65	11
28	0.42	0.39	0.38	0.48	0.44	0.42	38
29	0.87	0.75	0.76	0.61	0.86	0.77	4
30	0.63	0.52	0.50	0.45	0.51	0.52	30
31	0.58	0.69	0.60	0.47	0.48	0.57	21
32	0.33	0.41	0.40	0.33	0.35	0.37	44
33	0.99	0.85	0.87	0.64	0.67	0.8	2
34	0.47	0.44	0.39	0.68	0.65	0.53	29
35	0.42	0.77	0.62	0.58	0.38	0.55	23
36	0.35	0.37	0.36	0.34	0.39	0.36	45
37	0.44	0.74	0.73	0.74	0.50	0.63	12
38	0.77	0.52	0.49	0.46	0.50	0.55	25
39	0.49	0.53	0.51	0.65	0.46	0.53	28
40	0.46	0.53	0.52	0.43	0.42	0.47	34
41	0.59	0.64	0.65	0.58	0.45	0.58	26
42	0.64	0.64	0.63	0.58	0.47	0.59	16
43	0.55	0.64	0.66	0.61	0.48	0.59	17
44	0.56	0.63	0.64	0.62	0.45	0.58	19
45	0.53	0.62	0.66	0.59	0.43	0.56	22
46	0.58	0.63	0.64	0.59	0.45	0.58	20

averaged for each replication. Further, an average of three replicated force values per experimental run was done to evaluate the cutting force in each direction. An infrared thermometer (fluke type 8839) was used to measure workpiece surface temperature. The laser beam was single spot focused to capture the noticeable temperatures at underneath of the insert (near the flank wear zone) by adjusting the focus point (range 5-200mm) [14] with emissivity value of 0.8. A maximum of ten values per replication were selected and averaged for each replication. Then, the average of three replicated WST values per experimental run was computed to obtain WST. A micro-phone was placed near the cutting zone to capture the audible cutting sound pressure level [7]. An average of ten audible sound pressure level values per each run with three replications was estimated for analysis.

V.ANALYSIS OF RESPONSES

In grey relational analysis, the first step is pre-process the obtained data. In this case, all the output responses are indications of "Lower-the-Better" characteristics is considered. All the original sequences are normalized using equation (1).The original sequence denoted as $x_0^*(k)$ and reference sequence is denoted as $x_i^*(k)$.Next step, the deviation sequence Δ_{0i} is calculated and both normalized and deviation sequences as listed in Table. II. Further, the grey relation coefficient is computed using equation (2). By facilitating entropy measurement technique [16] , the exact weight values of all performance characteristics were found by utilizing the equations (5) to (9).The obtained exact weight values for F_x, F_y, F_z, WST and SPL are 0.200000005, 0.199999956, 0.20000007, 0.200000049 and 0.199999921 respectively. In general, a grey relational analysis technique is used to convert the multi-objective problem into a single objective problem. Therefore, a grey relational grade (GRG) was estimated using the equation (10) in account of these optimal weight values. The worked out calculations showed that the maximum GRG obtained in experiment number 13, which is having highest rank 1 as listed in Table.III. This indicates that the optimal values are closer to this input setting.

V. RESULTS AND DISCUSSIONS

A statistical analysis was performed using MINITAB 16.0 software [16]. Initially, a full regression model was developed for predicting GRG. The R^2 and R^2 (Adj) values are obtained 97.31% and 95.17% respectively. The *p*-values more than 0.05 were considered as insignificant model terms at 95% confidence intervals. Then, the insignificant models were removed one by one using a backward elimination procedure to fit a final quadratic model. After removing these terms, still the model contains linear, square and interaction terms are significant .The modified quadratic equation (11) as presented below

$$GRG=2.79003-0.03970\times HRC-0.34512\times r_e-1.64616\times f_z+0.03545\times a_p-0.01892\times r_e^2-0.05800\times a_p^2+0.00885\times HRC\times r_e-0.05956\times r_e\times a_p \quad (11)$$

The reduced quadratic model R^2 and R^2 (Adj) values are achieved at 92.66% and 87.15% respectively. These values are smaller than full model values, which show the evidence of significant connection between the responses and the input conditions. A residual analysis plot for GRG as shown in Fig.2.

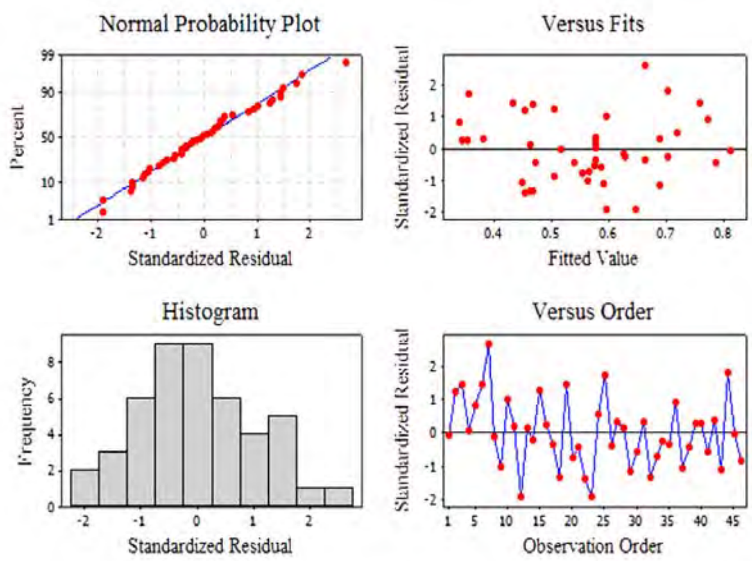

Fig.2. Residual analysis plot for GRG

In normal probability plot, the residuals are tracked along the straight line, which indicates errors are normally distributed. In histogram plot, the residuals approximately normally distributed on each side and many residuals lie between -1 to 1. However, some of the residuals are near to -2 and 2.The versus plot depicts the unrecognizable pattern is appeared and the detection of residuals are randomly scattered about zero. This implies that reduced quadratic models having high adequacy with respect to error variables. The residuals of each experiment are randomly positioned on the positive and negative side on versus plot. Therefore, the above said reduced model accepted for validation. The main effects plot in Fig. 3 indicates the mean effect of each level of GRG. The desired GRG always require as high as possible. So, the peak points of all independent variables as45HRC hardness, 0.8mm nose radius, feed of 0.050 mm per tooth, 0.30mm radial depth of cut and 0.5mm axial depth of cut are selected. This is the exact optimal condition in order to minimize the response variables to improvise the hard milling process significantly. From the plot observed that the highly influenced factors are identified as work material hardness, feed per tooth and axial depth of cut. When the hardness 55 HRC, the corresponding the GRG as shown as low value, it has been attributed that the tool penetrates severely in the work material to form the chip and instantly produce extreme cutting forces [1]. While, at 45HRC the trend was reversed. Thus, the high GRG shown at this point at peak level. The feed rate per tooth and axial depth of cut were greater influence on all responses [17].

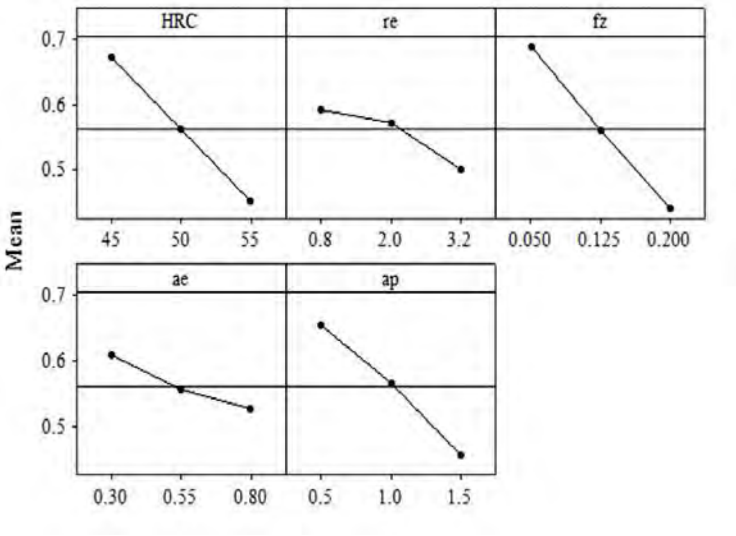

Fig.3. Main effects plot for GRG

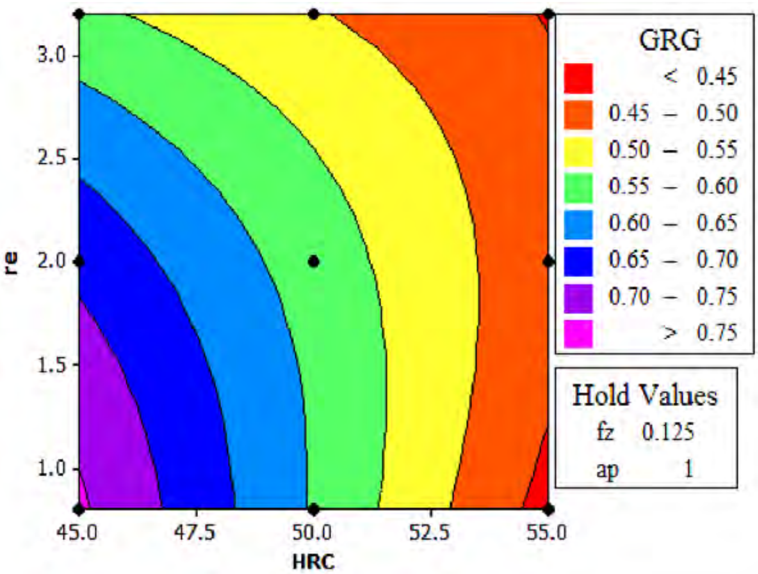

Fig.4. Contour plot of HRC vs r_e

For 0.200mm per tooth the resulting GRG was low comparatively with 0.05mm per tooth. This supports that, in down milling orientation at initial entry of the chip load per tooth maximum and exit at minimum [17]. The mean GRG exists a lower value at 1.5 mm axial depth of cut, this is accepted that the tool spent much energy to deform the metal plastically due to an increased axial depth of cut makes more contact length in the cutting zone. Thus, all the energy converted into heat during the hard milling [2]. On the other hand, for 0.5 mm axial depth of cut, the related GRG value was seen as much as high possibly. Because, the trend was revoked. The remaining factors are nose radius and radial depth of cut showed as less significant variations between the levels on GRG.A Contour plot of HRC V_s r_e on GRG as shown in Fig.4 and other factor levels are kept in middle level. For illustration, the highest GRG was reached in the region of 0.8 to 1.85mm nose radius and 45 to 47 material hardness. The contour plot of r_e V_s a_p as depicted in Fig. 5. It illustrates the interaction effect of the nose radius and axial depth of cut on the GRG. It is seen that minimum axial depth of cut and medium nose radius facilitate to reach higher GRG.

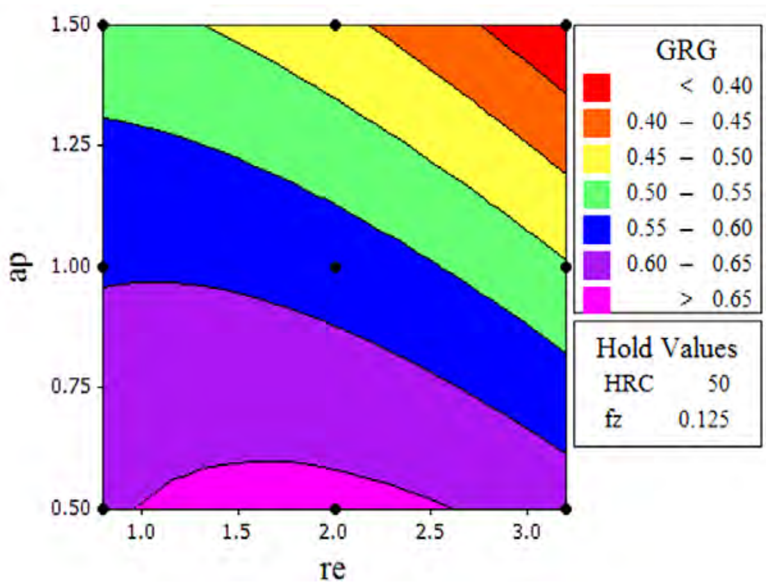

Fig.5. Contour plot of HRC Vs r_e

Increase of nose radius and axial depth of cut leads higher cutting temperature and sound pressure level [18] in the cutting zone due to the increased contact length of the tool [3]. This may lead a coating peel off near the cutting edge through a SEM analysis of the tool as indicated in Fig.6.

Table IV
ANOVA table for GRG

Source	DF	Seq SS	Adj MS	F	*p*	% of Contribution
Regression	8	0.6552	0.0819	58.400	0.000	92.66
Linear	4	0.6301	0.1039	74.100	0.000	89.11
A	1	0.1936	0.0520	37.100	0.000	27.38
B	1	0.0332	0.0063	4.500	0.041	4.69
C	1	0.2439	0.2439	174.000	0.000	34.49
E	1	0.1595	0.0001	0.100	0.758	22.55
Square	2	0.0087	0.0044	3.100	0.057	1.23
B^2	1	0.0066	0.0076	5.400	0.026	0.93
E^2	1	0.0021	0.0021	1.530	0.224	0.30
Interaction	2	0.0164	0.0082	5.840	0.006	2.32
AB	1	0.0113	0.0113	8.040	0.007	1.59
BE	1	0.0051	0.0051	3.640	0.064	0.72
Residual error	37	0.0552	0.0014			
Lack-of-fit	24	0.0233	0.0010	0.440	0.960	
Pure error	13	0.0286	0.0022			
Total	45	0.7071				

The analysis of variance (ANOVA) for the model is given in Table IV. Referring to the ANOVA table, the feed per tooth exists the largest value of percentage contribution is 34.49%. The regression model *p*-value showed 0.000, which indicated that the model more significant and lack-of-fit value showed 0.960, which is not significant in related to the pure error. Thus, the model is more suitable to predict the values. Next, the material hardness covers 27.38% and followed by axial depth of cut 22.55%. The rest model of the terms shows as least contribution in related to GRG.

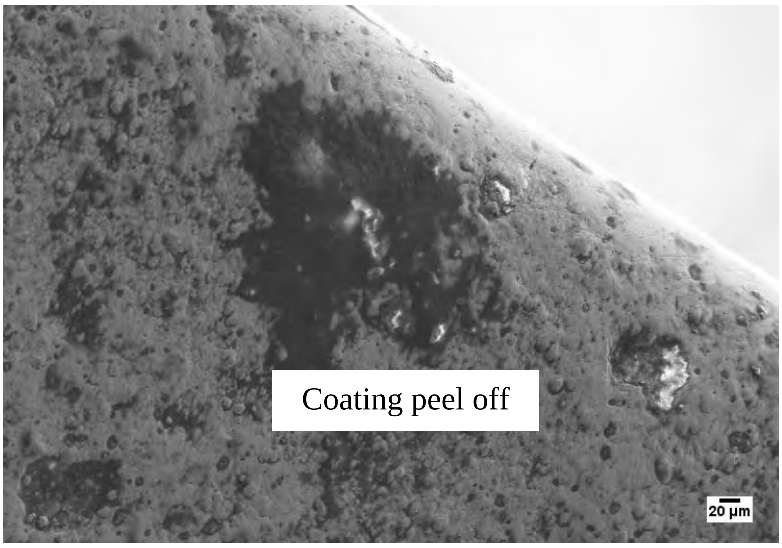

Fig.6. Coating peel off near the cutting edge

VII. CONFIRMATION OF EXPERIMENT

Once the optimal condition was identified through the analysis and need to verify such a condition to predict the responses. The confirmation experiment are performed at the condition (work piece hardness=45HRC, nose radius= 0.8mm, feed per tooth=0.05, radial depth of cut=0.3 mm and axial depth of cut=0.5mm) for the cutting forces, work piece surface temperature and sound pressure level in the same machine. The results are experiment as listed in Table. V.

Table V
Confirmation results

Optimum condition					**F_x**	**F_y**	**F_z**	**WST**	**SPL**
HRC	**r_e**	**f_z**	**a_e**	**a_p**	**N**	**N**	**N**	**°C**	**dB**
45	0.8	0.05	0.3	0.5	434.545	397.536	310.788	201.143	68.25

VIII. CONCLUSION

The proposed response surface methodology coupled with grey relational analysis was effectively used for in hard milling of tool steel using coated carbide inserts. Based on the experimental work and statistical calculations, the following conclusions were arrived.

1. A quadratic equation was developed for predicting the grey relational grade with a good accuracy (R^2=0. 9266) and fitted with adequate errors. This confirms that box-behnken design can be effectively used for experimental design analysis.
2. Through the multi-response optimization technique the optimal value of all responses (F_x, F_y, F_z, WST and SPL) are obtained under the following combination of process parameters: work material hardness=45HRC, r_e=0.8mm, f_z=0.050mm/tooth, a_e=0. 30mm and a_p=0. 50mm and the effectiveness of this approach have been verified by confirmation experiment.
3. Increase of nose radius gives better cutter stability and directly proportional to increase of cutting forces, temperature and sound.
4. On tool rake face of the tool, a coating peel off was observed in certain experiments due to higher hardness of the work material and high heat generation in the cutting zone investigated through SEM analysis.
5. The material hardness, feed per tooth and axial depth of cut are most dominant parameters that affect all responses.

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