Multi-Objective Optimization of Hard Turning Process Parameters of H11 Material Using Taguchi Based Grey Relational Analysis.

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Abstract— In this study, the effects of cutting speed, feed rate, work piece hardness and depth of cut on surface roughness and tool tip temperature in the hard turning were experimentally investigated. AISI H11 (X38CrMoV5-1) steel was hardened to (40; 45 and 50) HRC, machined using cubic boron nitride (CBN 7025 from Sandvik Company) which is essentially made of 60% CBN. L27 orthogonal array based Taguchi optimization technique is used to optimize the effect of various cutting parameter for surface roughness and tool tip temperature of H11 work material in turning operation. An orthogonal array, signal to noise (S/N) ratio and analysis of variance (ANOVA) are to be employed to analyze the effects and contributions of cutting parameter on the response variables. Attempt was further made to simultaneously optimize the machining parameters using Grey relational analysis. The feed rate is the most significant factor for minimize both surface roughness and tool tip temperature. The surface roughness was measured using surface roughness tester (Mitutoyo surftest-SJ210). Tool tip temperature was measured using Optex Thermo Hunter.

Key words: H11, CNC Lathe, Surface Roughness, Tool tip temperature, Taguchi, Design of Experiments, Grey Relational Analysis

I. Introduction

Taguchi techniques and statistical analysis are used to optimize machining processes. Turning is one of the important machining operations, widely used in most of the manufacturing industries due to its capability of producing complex geometric surfaces with reasonable accuracy and surface finish. Hard turning process differs from conventional turning because of the work piece hardness, the required cutting tool, and the mechanisms involved during chip formation. Whenever machining given parts straightforwardly after they have been hardened, hard turning offers a number of potential advantages over traditional grinding, including lower equipment costs, shorter setup time, fewer process steps, greater part geometry flexibility, and usually there is no need cutting fluid use.

In turning operation, it is important to select cutting parameters so achieved. Selection of desired cutting parameters by operator's experience or using handbook does not ensure that the selected cutting parameters are optimal for a particular machine and environment. The effect of cutting parameters is reflected on surface roughness, surface texture and dimensional deviations of the product. Surface roughness, which is used to determine and to evaluate the quality of a product, is one of the major quality attributes of a turning product. Surface roughness is a measure of quality of a product which factor greatly influences manufacturing cost. It describes the geometry of the machined surfaces and combined with the surface texture. Taguchi uses experimental design for minimizing variation around a target value and for designing the processes to be robust to environmental conditions and to component variations. Analysis of variance (ANOVA) is use to analyze experimental data for influence of it on output characteristics. This paper presents work using the Taguchi based Grey relational analysis for optimizing a finishing turning process. The objective of the experiment is to optimize cutting parameters so as to get the lowest values of surface roughness and of tool tip temperature by the machine during all the machining process.

Dureja et al. applied the response surface methodology (RSM) to investigate the effect of cutting parameters on flank wear and surface roughness in hard turning of AISI H11 steel with a coated-mixed ceramic tool. The study indicated that the flank wear is influenced principally by feed rate, depth of cut and work piece hardness [21]. Özel and Karpat [23] used regression and artificial neural network models for predicting the surface roughness and tool wear in hard turning of AISI H11 steel using CBN inserts. In an original work carried out by Caydas, the effects of the cutting speed, feed rate, depth of cut, work piece hardness, and cutting tool type on surface roughness, tool flank wear, and maximum tool–chip interface temperature during an orthogonal hard turning of hardened/tempered AISI 4340 steels were investigated [22]. The best surface roughness is obtained with CBN tools followed by mixed ceramic and then the carbide tools. Based on the ANOVA outcomes, the contributions of the hard turning parameters on surface roughness followed the order (1) cutting tool type, (2) feed rate, (3) work piece hardness, (4) cutting speed and (5) depth of cut.

An attempt has been made to optimize quality and temperature in a manner that these multi-criterions could be fulfilled simultaneously up to the expected level. Multi-objectives related to quality and productivity has been accumulated to evaluate an equivalent single quality index (called grey relational grade); which has been optimized finally by Taguchi based Grey relational method. The Grey Relational Analysis had been used by Yang et al., [17] to find the optimal cutting parameters, i.e. cutting speed, feed rate and depth of cut for surface roughness in turning operation based on experimental results done on S45C steel bars using tungsten carbide cutting tools.

However, the optimizations of multiple performance characteristics find more applications. Many authors [7-10] have proposed different methods for solving multiple performance characteristic problems. Mahamani et al.[7] studied tool wear, surface roughness and cutting force in the turning of Al-6061-6% TiB2 in-situ metal matrix composite using GRA. Ramanujam et al. [13] also used desirability function analysis for optimizing multiple performance characteristics namely surface roughness and power consumption in turning Al-15%SiCp metal matrix composites. R. K. Suresh et al. [3] Multi Response

Optimization in Turning of AISI 8620 Alloy Steel with CVD Tool Using Desirability Factor Analysis and Grey relational analysis- a comparative study had been done to optimize parameters. The optimal turning parameters are determined by composite desirability index and grey relational grade. Analysis of variance (ANOVA) is used to determine the influence of parameters which significantly affect the responses. Also applied analysis of variance (ANOVA) to study the performance characteristics of machining process parameters such as cutting speed, feed, depth of cut with consideration of multiple responses, i.e. material removal rate, surface finish, tool temperature. Taguchi method integrated with grey relation theory for solving multi-objective optimization problem has been proposed by Farhad Kolahan [22] et al.

A. *Taguchi Method*

The Taguchi method is a well-known technique that provides a systematic and efficient methodology for process optimization and this is a powerful tool for the design of high quality systems. Taguchi approach to design of experiments in easy to adopt and apply for users with limited knowledge of statistics, hence gained wide popularity in the engineering and scientific community. This is an engineering methodology for obtaining product and process condition, which are minimally sensitive to the various causes of variation, and which produce high-quality products with low development and manufacturing costs. Traditional experimental design methods are very complicated and difficult to use. Additionally, these methods require a large number of experiments when the number of process parameters increases. In order to minimize the number of tests required, Taguchi experimental design method, a powerful tool for designing high-quality system, was developed by Taguchi. This method uses a design of orthogonal arrays to study the entire parameter space with small number of experiments only. Taguchi recommends analyzing the mean response for each run in the inner array, and he also suggests to analyze variation using an appropriately chosen signal-to-noise ratio (S/N). [5] There are 3 Signal-to-Noise ratios of common interest for optimization of static problems:

- Smaller-the-better: - S/N (η) = -10logi2} i=1, 2, 3...r
- Larger-the-better: - S/N (η) = -10logi2} i=1, 2, 3 ...r
- Nominal-the-best: - S/N (η) = 10log {R2/S2}

Where, Ri is value of surface roughness for the ith trial in r number of tests.

Regardless of category of the performance characteristics, the higher S/N ratio corresponds to a better performance. Therefore, the optimal level of the process parameters is the level with the highest S/N value. The statistical analysis of the data is performed by analysis of variance (ANOVA) to study the contribution of the various factors and interactions and to explore the effects of each process on the observed values

II. Experimental setup

A. *Work Piece*

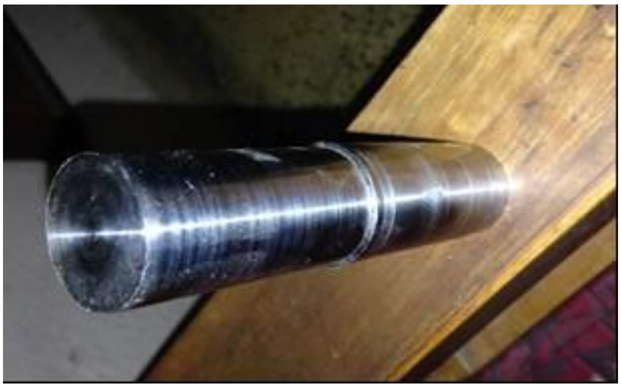

Fig. 1: EN353 Case Hardened Material

The work piece material is AISI H11 steel in the form of round bars of 28 mm diameter and length of 100 mm axial cutting length.
The composition of material is

Typical chemical composition of H11 Steel						
C	Mn	Cr	Si	Mo	V	Ni+Cu
0.36%	0.3%	4.8%	0.9%	1.1%	0.3%	0.75%
0.42%	0.5%	5.5%	1.2%	1.4%	0.5%	

Table 1: Composition of H11

H11 is widely used for Machining components in various industries. This material has significant application in Die casting industry, hot form pressing. Its resistance to high temperature and its aptitude for polishing enable it to answer most requests for hot dieing and molding under pressure. The work piece was through-hardened followed by a tempering process to attain three different hardness levels, namely 40; 45 and 50 HRC (Rockwell hardness). A rough turning pass was conducted initially to eliminate the run out of the work piece, after that diameter obtained for experimentation is approximately 27mm

B. *Cutting Tool:*

Fig. 2: BXC50 T-CBN Tool

CBN insert CNGX120408 L025-18AXA manufactured by Sandvik tools. It is suitable for medium interrupted to heavy interrupted turning of hardened steels and other hard materials with hardness up to 65 HRC. It features bimodal grain sized (1&3µm) CBN sintered with a special ceramic binder. It contains 60% CBN with high fracture resistance makes it a very versatile grade for hard part turning

C. *Machine:*

A high speed precision CNC Lathe (HASS - MAKE) having Maximum turning diameter 406mm, Height of centers over carriage 60 mm Maximum turning length: 762mm, Headstock A2-5 / CAMLOCK D1-3’’ Spindle speed 2,000 rev/min, AC motor drive: Power consumption 9kW, Transverse stroke X-axis 209mm, AC motor drive: intermittent torque 4 to 14 Nm Longitudinal stroke, Z-axis 762mm, Number of fixed tool stations/rotating tool stations. Weight of CNC Lathe 1860kg Power Requirement: 9KVA, 1-Phase:240V@40A, 3-Phase: 208V

Fig. 3: CNC Lathe Machine

D. Experimental Observations and Details:

In this study, four machining parameters were selected as control factors, and each parameter was designed to have three levels, denoted 1, 2, and 3 (Table 2). The experimental design was according to an L'27 array based on Taguchi method. The use of Taguchi orthogonal array reduces the number of experiments. A set of experiments designed using the Taguchi method was conducted to investigate the relation between the process parameters and response factor. Minitab 16 software is used for optimization and graphical analysis of obtained data.

By performing OVAT analysis and studying research papers it is found that cutting speed, feed rate, depth of cut and Hardness are influencing parameters on Surface Finish. According to OVAT analysis following input parameters namely cutting speed, feed rate, depth of cut and work piece Hardness are selected by keeping other process parameters constant at minimum level which is less influencing on surface finish [15].

Parameters	Units	Level 1	Level 2	Level 3
Speed (V)	Rpm	1315	1430	1545
Feed (F)	mm/rev	0.05	0.07	0.09
DOC (D)	mm	0.05	0.09	0.13
Hardness (H)	HRC	40	45	50

Table 3: Selection of Levels from OVAT Analysis

ExptNo	Speed	Feed	DOC	Hard	Ra Avg	Temp
1	1315	0.05	0.05	40	0.430333	37
2	1315	0.05	0.05	45	0.438	41
3	1315	0.05	0.05	50	0.381	43
4	1315	0.07	0.09	40	0.475333	44
5	1315	0.07	0.09	45	0.549	49
6	1315	0.07	0.09	50	0.388667	52
7	1315	0.09	0.13	40	0.555333	45
8	1315	0.09	0.13	45	0.582667	51
9	1315	0.09	0.13	50	0.431667	55
10	1430	0.07	0.13	40	0.417667	46
11	1430	0.07	0.13	45	0.47	54
12	1430	0.07	0.13	50	0.353667	60
13	1430	0.09	0.05	40	0.492	50
14	1430	0.09	0.05	45	0.537	54
15	1430	0.09	0.05	50	0.369667	62
16	1430	0.05	0.09	40	0.393	38
17	1430	0.05	0.09	45	0.408333	40
18	1430	0.05	0.09	50	0.340667	42
19	1545	0.09	0.09	40	0.447333	65
20	1545	0.09	0.09	45	0.465667	70
21	1545	0.09	0.09	50	0.352333	73
22	1545	0.05	0.13	40	0.381333	47
23	1545	0.05	0.13	45	0.387667	53
24	1545	0.05	0.13	50	0.235333	56
25	1545	0.07	0.05	40	0.441333	57
26	1545	0.07	0.05	45	0.457	61
27	1545	0.07	0.05	50	0.351	63

Table 4: Results from Design of Experiments and calculations

Level	Speed	Feed	Depth of Cut	Hard
1	6.650	8.588	7.342	7.024
2	7.624	7.339	7.534	6.498
3	8.318	6.665	7.715	9.070
Delta (max - min)	1.668	1.923	0.373	2.573
Rank	3	2	4	1

Table 5: Response Table for Signal to Noise Ratios for Surface Roughness

Level	Speed	Feed	Depth of Cut	Hard
1	-33.26	-32.81	-34.18	-33.44
2	-33.78	-34.59	-34.17	-34.29
3	-35.57	-35.21	-34.26	-34.88
Delta (max - min)	2.31	2.40	0.10	1.44
Rank	2	1	4	3

Table 6: Response Table for Signal to Noise Ratios for Tool tip Temperature

III. GREY RELATIONAL ANALYSIS

GRA is a new analysis method, which has been proposed in the Grey system theory and it is founded by Professor Deng Julong from Huazhong University of Science and Technology, People's Republic of China. GRA is based on geometrical mathematics, which compliance with the principles of normality, symmetry, entirety, and proximity. GRA is suitable for solving complicated interrelationships between multiple factors and variables and has been successfully applied on cluster analysis, robot path planning, project selection, prediction analysis, performance evaluation, and factor effect evaluation and multiple criteria decision [17]. Detailed explanation about GRA method is presented in the following section

A. Taguchi based Grey relation analysis:

Regardless of the category of the performance characteristics, the higher S/N ratio corresponds to a better performance. Therefore, the optimal level of the process parameters is the level with the highest S/N value. The statistical analysis of the data is performed by analysis of variance (ANOVA) to study the contribution of the various factors and interactions and to explore the effects of each process on the observed values. The use of Taguchi method with grey relational analysis to optimize the turning process with multiple performance characteristics includes the following steps [6]:

1) Identify the performance characteristics and cutting parameters to be evaluated.
2) Determine the number of levels for the process parameters.
3) Select the appropriate orthogonal array and assign the cutting parameters to the orthogonal array.
4) Conduct the experiments based on the arrangement of the orthogonal array.
5) Normalize the experiment results of surface roughness and metal removal rate.
6) Perform the grey relational generating and calculate the grey relational coefficient.
7) Calculate the grey relational grade by averaging the grey relational coefficient.
8) Analyze the experimental results using the grey relational grade and statistical ANOVA.
9) Select the optimal levels of cutting parameters.

B. Data Pre-Processing:

In grey relational analysis, the data pre-processing is the first step performed to normalize the random grey data with different measurement units to transform them to dimensionless parameters. Thus, data pre-processing converts the original sequences to a set of comparable sequences. Experimental data i.e. measured features of quality characteristics of the product are first normalized ranging from zero to one. This process is known as grey relational generation [6].

In grey relational generation, the normalized data corresponding to lower-the-better (LB) criterion can be expressed as:

$$x_i^*(k) = \frac{x_{imax}(k) - x_i(k)}{x_{imax}(k) - x_{imin}(k)}$$

For higher-the-better (HB) criterion, the normalized data can be expressed as:

$$x_i^*(k) = \frac{x_i(k) - x_{imin}(k)}{x_{imax}(k) - x_{imin}(k)}$$

Where,

$x_i^*(k)$ and $x_i(k)$ are the normalized data and observed data, respectively, for i^{th} experiment using k^{th} response. The smallest and largest values of $x_i(k)$ in the k^{th} response are $x_{imin}(k)$ and $x_{imax}(k)$, respectively.

After pre-processing the data, the grey relation coefficient (GRC) $\zeta_i(k)$ for the k^{th} response characteristics in the i^{th} experiment can be expressed as following:

$$\zeta_i(k) = \frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_i(k)+\zeta\Delta_{max}}$$

1) $x_i^*(k)$= denotes reference sequence.
2) $x_j^*(k)$ = denotes the comparability sequence
3) $\zeta \in$ [0, 1] is the distinguishing factor; 0.5 is widely accepted.
4) $\Delta_i = x_i^*(k) - x_j^*(k)$ = difference in absolute value between $x_i^*(k)$ and $x_j^*(k)$
5) Δ_{min}=$min_{(\forall j\in i)} min_{(\forall k)} \mid x_o^*(k) - x_j^*(k) \mid$ = smallest value of Δ_i.
6) Δ_{max}=$max_{(\forall j\in i)} max_{(\forall k)} \mid x_o^*(k) - x_j^*(k) \mid$= largest value of Δ_i.

After calculating GRC, the grey relational grade (GRG) is obtained as:

$$\gamma_i = \frac{1}{m}\sum_{k=1}^{n} w\,\zeta_i(k)$$

Here is the Grey Relational Grade, n is the number of responses, m is the number of run and w is the weight factor. We can control the amount of influence of a response in deciding the optimum machining parameters varying the value of w keeping in mind that it should be equal to 1.

The higher value of the GRG corresponds to a relational degree between the Reference Sequence and the given sequence . The Reference Sequence represents the best process sequence. Therefore, a higher GRG means that the corresponding parameter combination is closer to the optimal. The mean response for the GRG and the main effect plot of the GRG are very important because the optimal process condition can be evaluated from this plot [11].

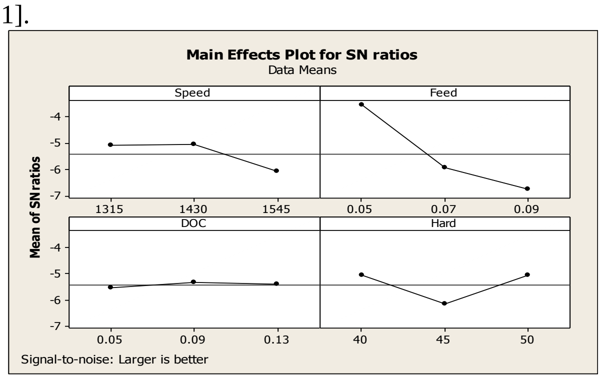

Fig. 4: Main effects plot for S/N ratio for GRG

From the graphs, it can be said that finest combination values for maximizing the multiple performance characteristics or grey relational grade (GRG) were cutting speed of 1430 rpm, feed rate of 0.05 mm/rev, depth of cut of 0.09 mm and hardness of 40 HRC. The response table for the S/N ratios of grey relational grade is shown in Table 8.

ANOVA output of the multiple performance characteristics was given in Table. 10. From the analysis of

Normalized Values		Grey Relational Coefficient		Grey Relational Grades	Rank Order
Ra	Temp.	Ra	Temp.		
0.43858	1	0.471067	1	0.735533	3
0.416507	0.88888	0.46147	0.818182	0.639826	7
0.580614	0.83333	0.543841	0.75	0.646921	6
0.309021	0.80555	0.419823	0.72	0.569911	10
0.096929	0.66666	0.356361	0.6	0.478181	19
0.558541	0.58333	0.531091	0.545455	0.538273	11
0.078695	0.77777	0.351789	0.692308	0.522049	13
0	0.61111	0.333333	0.5625	0.447917	23
0.434741	0.5	0.469369	0.5	0.484685	18
0.475048	0.75	0.487828	0.666667	0.577247	9
0.324376	0.52777	0.425306	0.514286	0.469796	20
0.659309	0.36111	0.594749	0.439024	0.516887	14
0.261036	0.63888	0.403563	0.580645	0.492104	16
0.131478	0.52777	0.365358	0.514286	0.439822	24
0.613244	0.30555	0.563853	0.418605	0.491229	17
0.546065	0.97222	0.524145	0.947368	0.735757	2
0.501919	0.91666	0.500962	0.857143	0.679052	5
0.696737	0.86111	0.622461	0.782609	0.702535	4
0.389635	0.22222	0.450303	0.391304	0.420803	26
0.336852	0.08333	0.429868	0.352941	0.391405	27
0.663148	0	0.597477	0.333333	0.465405	22
0.579655	0.72222	0.543274	0.642857	0.593066	8
0.56142	0.55555	0.53272	0.529412	0.531066	12
1	0.47222	1	0.486486	0.743243	1
0.40691	0.44444	0.457419	0.473684	0.465551	21
0.361804	0.33333	0.439292	0.428571	0.433932	25
0.666987	0.27777	0.60023	0.409091	0.504661	15

Table 7: Grey Relational Analysis Calculations

Table 10, it is concluded that feed rate followed by work piece hardness followed by cutting speed and then depth of cut are significantly affecting the grey relational grade.

Level	Speed	Feed	Depth of Cut	Hard
1	-5.102	-3.560	-5.514	-5.055
2	-5.070	-5.952	-5.342	-6.135
3	-6.084	-6.743	-5.399	-5.065
Delta (max - min)	1.014	3.184	0.173	1.081
Rank	3	1	4	2

Table 8 Response Table for S/N ratios for GRG

Level	Speed	Feed	Depth of Cut	Hard
1	0.5626	0.6674	0.5388	0.5680
2	0.5672	0.5060	0.5535	0.5012
3	0.5055	0.4617	0.5429	0.5660
Delta (max-min)	0.0617	0.2057	0.0146	0.0668
Rank	3	1	4	2

Table 9: Response Table for Means for GRG

Average mean Ym = 0.5450

Source	DF	Seq SS	Adj SS	Adj MS	F	P	C%
Speed	2	0.021274	0.021274	0.010637	7.38	0.005	7.46
Feed	2	0.211019	0.211019	0.105509	73.18	0.000	73.98
DOC	2	0.001029	0.001029	0.000514	0.36	0.705	0.36
Hard	2	0.025973	0.025973	0.012986	9.01	0.002	9.1
Error	18	0.025954	0.025954	0.001442			9.09
Total	26	0.285248					100

S = 0.0379720 R-Sq = 90.90% R-Sq(adj) = 86.86%

Table 10: ANOVA for grey relational grade

IV. CONFORMATION EXPERIMENTS

After the optimal level has been selected, one could predict the optimum response using the following equation:

$$\gamma_{predicted} = \gamma_m + \sum_{i=1}^{n} (\gamma_i - \gamma_m)$$

Where, is the total mean from Table 9, is the mean S/N ratio at optimal level, n is the number of main design parameters that affect the quality characteristics [11]. The purpose of this confirmation experiment is to verify the improvement in the quality characteristics. Based on the above equation, the grey relational grade (GRG) is predicted for the optimal combination of parameters (V2-F1-D2-H1) and its value is 0.7208. Last confirmation test was conducted using the optimum combination of parameters (V2-F1-D2-H1). Table No. 11. Shows the comparison of predicted multiple performance characteristics (GRG) with the actual one.

Applying this relation, predicted values of GRG, Temp and Ra at the optimum conditions are calculated as:

1) γ (GRG) = 0.7208
2) γ (Temp) = 38 °C
3) γ (Ra) = 0.389µm

The robustness of this parameter optimization is verified experimentally. This requires the confirmation run at the predicted optimum conditions. The experiment is conducted twice at the predicted optimum conditions.

V. VERIFICATIONS:

A. Verification for Tool Tip Temperature

The measured value of Tool tip temperature at the optimum condition (V2-F1-D2-H1) is 40 °C. The error in the predicted optimum value (38) and the measured value (40) is only 5%.

B. Verification for Surface Roughness (Ra)

The measured value of Surface Roughness at the optimum condition (V2-F1-D2-H1) is 0.402µm. The error in the predicted optimum value (0.389) and the measured value (0.402) is only 3.23%.

Improvement of Grey Relational Grade: 0.7208 - 0.4208 =0.3

	Initial Cutting Parameters	Optimal Cutting Parameters	
		Prediction	Experimental
Level	V3F3D2H1	V2F1D1H1	V2F1D1H1
Ra	0.4473	0.389	0.402
Temp	65	38	40
GRG Code	0.4208	0.7208	

Table 11: Comparison of Actual and Predicted Values and Improvement

Hence, so good agreement between the actual and the predicted results is observed. Since the percentage error is less than 5%, it confirms excellent reproducibility of the results. The results show that using the optimal parameter setting (V2-F1-D2-H1) a with lower tool tip temperature and lower surface roughness is achieved

VI. CONCLUSIONS

The present work has successfully demonstrated the application of Taguchi based grey relational analysis for multi response optimization of process parameters in Turning of H11 Hardened Steel.

The surface roughness (Ra) and tool tip temperature were measured under different cutting conditions for diverse combinations of machining parameters. The final conclusions arrived, at the end of this work are as follows:

1) The increase in cutting speed produces better surface finish (i.e., surface roughness reduces). The surface roughness decreases from level one to level three with depth of cut, whereas with increase in feed rate the surface roughness increases throughout, while surface roughness increases from level one to level two and tremendously decreases to level three with increase in hardness.
2) From this analysis, it is revealed that feed rate, Hardness and speed are prominent factors which affect the turning of H11 hardened steel. The feed rate (C= 73.98%) is the most influencing factor in determining the multiple performance characteristics or grey relational grade (GRG) followed by Hardness (C= 9.1 %), cutting speed (C = 7.46%) and depth of cut (C = 0.36%).
3) The best multiple performance characteristics was obtained with CBN insert when turning H11 hardened steel with the cutting speed of 1430 rpm, lower feed rate of 0.05 mm/rev, medium depth of cut of 0.09 mm and lower Hardness of 40 HRC with the estimated multiple performance characteristics (GRG) of 0.7208 & the experimental value of GRG for this combination of parameters is 0.7327.
4) The percentage of error between the predicted and experimental values of the multiple performance characteristics during the confirmation experiments is within 1.62%.
5) The value of multiple performance characteristics obtained from confirmation experiment is within the 95% confidence interval of the predicted optimum condition.
6) Hence it is concluded that feed rate has significant effect on both surface roughness and tool tip temperature.

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