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Process Parameter optimization of Cryogenic Turning of Ni-Cr Steel using Taguchi Grey Relational Analysis

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ABSTRACT

In the present research work, turning of Ni-Cr steel was done under both dry and cryogenic cooling and an attempt was taken to optimize the responses using integrated Taguchi method and Grey Relational Analysis (GRA). The experiments were conducted based on Taguchi L18 orthogonal array and then responses were optimized concurrently using Grey Relational Analysis (GRA). Two numerical factors cutting velocity and feed rate and one categorical factor (cutting condition) were selected as input variables. The effects of those input factors were investigated on surface roughness (Ra), coefficient of friction (μ) and chip tool interface temperature (θ) using two different geometry shaped cutting inserts. After optimization cryogenic cooling was found significant in reducing the selected responses. In case of multi-response optimization, Taguchi-GRA (supported by ANOVA) concluded that cutting condition exerts the domain influence on changing responses followed by feed and cutting speed. For multi-response optimization grey Taguchi results revealed that the optimal settings of input parameters are Vc1f1CC2 and Vc3f1CC2 by using SNMM 120408 and SNMG 120408 cutting inserts, respectively. At 95% confidence interval ANOVA results reveal that all parameters are statistically significant. Validation test results also coincide with statistically optimized results.

Keywords: Cryogenic cooling, Turning, Surface roughness, Coefficient of friction, Chip tool interface temperature, Taguchi-GRA based optimization.

1. Introduction

Dry turning of Ni-Cr based alloy is not an easy task due to build up edge formation, work hardening, affinity of chips in cutting direction at higher temperature that hampers the product quality [1]. But Ni-Cr based alloy provides higher tensile strength, shear strength, better ductility, corrosion resistance and suitable hardness [2] that attracts manufacturers to use this alloy in different industrial applications. Due to these excellent properties this alloy steel is chosen for typical industrial applications such as automotive, aircraft landing gears, shafts, molds, spindles, heavy duty shafts etc [2]. The most popular technique of improving machining performances is to reduce cutting temperature because this factor is the main culprit to reduce the productivity as well as product quality [3-5]. Traditionally, conventional cooling is used for reducing temperature and improving surface integrity [6]. But conventional technique (flood cooling) is not eco-friendly and biodegradable. Hong et al. [7] reported cryogenic cooling as an alternative to conventional cooling. Moreover this cooling is reported by researchers not only clean and eco-friendly [8-9] but also energy efficient [10]. In cryogenic cooling colorless and odorless [11] liquid N_2 ($-196^{O}C$) is used as cryogen which is highly biodegradable, safe, noncorrosive and non-combustible [12]. No additional steps are required for disposal of cutting fluids after use so saving of time and cost can be achieved successfully [13]. Considering those benefits cryogenic cooling was chosen as cooling method for this study.

Many researchers have already done their research works on cryogenic cooling for improving different machinability characteristics such as wear behavior of cutting tool [14,15], surface roughness and dimensional deviation [16,17], cutting force and friction [18], specific energy and chip morphology[19] in different machining operations. Dhar et al. [20] experimentally investigated surface finish; dimensional deviation and tool wear of turning Ni-Cr steel under cryogenic cooling and compared with dry turning. They observed the significant positive effects of cryogenic cooling on responses experimentally but no optimization was performed.

In recent decades optimization of different responses with variable input parameters has become one of the interesting scopes of research. To be upgraded with the modern era, it is tried to perform an optimization task in turning one of the most usable steels (Ni-Cr steel) in manufacturing industry. Taguchi technique is one of the most powerful and efficient optimization tools for single response optimization [21]. But this tool is unable to optimize multi-responses [22] and to avoid this weakness, in this research work Taguchi method was integrated with Grey Relational Analysis (GRA) due to its flexibility and easiness to change variable in computation. Other multi response optimization tools such as- response surface methodology (RSM) is time consuming, genetic algorithm (GA) and artificial neural network (ANN) are suitable for a huge number of trials, Support Vector Regression (SVR) requires complex steps of computation. Such type common complexities motivate authors to use Taguchi-GRA for optimization. At this point of view, this study is an attempt to optimize multiple turning responses- surface roughness (Ra), chip tool interface temperature (θ) and coefficient of friction (μ) concurrently.

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2. Experimental conditions and methodology

In this section, experimental set up with work material and tool specifications, design matrix of input factors, response selection and optimization methods are sequentially discussed in detail.

2.1 Experimental details

Ni-Cr steel has been selected as work material for experimentation due to its excellent mechanical properties. A rigid and powerful HMT lathe (15hp) was used for turning operation at industrial speed-feed combinations. For turning, two types uncoated carbide inserts (SNMM 120408, SNMG 120408-26 TTS, WIDIA) having configuration -6^{O}, -6^{O}, 6^{O}, 6^{O}, 15^{O}, 75^{O} and 0.8mm were employed with PSBNR 2525M12 specified tool holder. Dry and LN_2 assisted cryogenic cooling are selected as cutting environment. The schematic diagram of experimental set up for cryogenic cooling with specially designed nozzle is shown in Fig.1 which is constructed by one of the authors [20] of this paper.

In this study arithmetic surface roughness (R_a), coefficient of friction (μ) and chip tool interface temperature (θ) were selected as responses. This responses were determined experimentally at different speed feed combinations recommended by tool manufacturers for this selected tool work couples. For optimizing the responses cutting speed and feed rate were considered as numerical input variables with three levels and cutting condition was considered as categorical input factor with two levels listed in Table 1. In all cases depth of cut (a_p) was kept fixed at 1.5mm.

2.2 Taguchi method

For Taguchi design matrix the orthogonal array was formulated based on two factors of three levels (3^2) and one factor with two levels (2^1). Mixed level Taguchi L18 orthogonal array was selected. Table 2 represents the structured L18 orthogonal array of input factors. In other side, experimentally measured and computed responses are listed in Table 3.

Table 1 Investigated input variables in turning

Factors	Level 1	Level 2	Level 3
Cutting velocity, V_c (m/min)	80	104	134
Feed rate, f (mm/rev)	0.16	0.20	0.24
Cutting condition, CC	Dry	Cryogenic	-

2.3 Systematic approach of Taguchi-GRA

In case of multi-response optimization, it is tried to optimize the overall system rather than a specific response. Professor Deng developed grey system in 1982 which provides an appropriate solution in real situations with partial known environment. This theory is now highly applied in engineering and management for its easiness to use. Optimization of multiple responses, solutions of nonlinear and complex problems can be done using grey relational analysis [23]. The common phases of computation are graphically presented below in Fig. 2.

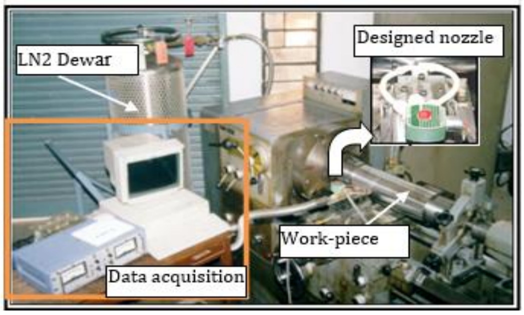

Fig. 1 Experimental set up of Ni-Cr steel turning under cryogenic cooling [20].

Table 2 L18 orthogonal array of input variables.

Experimental runs	Cutting velocity, (V_c) m/min	Feed, (f)mm/rev	Cutting condition, (CC)
1.	80	0.16	Dry
2.	80	0.20	Dry
3.	80	0.24	Dry
4.	104	0.16	Dry
5.	104	0.20	Dry
6.	104	0.24	Dry
7.	134	0.16	Dry
8.	134	0.20	Dry
9.	134	0.24	Dry
10.	80	0.16	Cryogenic
11.	80	0.20	Cryogenic
12.	80	0.24	Cryogenic
13.	104	0.16	Cryogenic
14.	104	0.20	Cryogenic
15.	104	0.24	Cryogenic
16.	134	0.16	Cryogenic
17.	134	0.20	Cryogenic
18.	134	0.24	Cryogenic

Table 3 Computed and measured responses (For SNMM and SNMG insert)

Experi-mental runs	SNMM 120408			SNMG 120408		
	Ra (µm)	µ	θ (^{O}C)	Ra (µm)	µ	θ (^{O}C)
1.	3.08	0.42	655	2.61	0.42	602
2.	3.50	0.37	665	2.86	0.40	621
3.	4.20	0.35	676	3.12	0.37	635
4.	2.95	0.43	693	2.30	0.44	630
5.	3.40	0.36	720	2.65	0.40	660
6.	4.00	0.34	730	2.83	0.38	680
7.	2.80	0.40	740	2.20	0.43	709
8.	3.25	0.39	760	2.50	0.37	730
9.	3.85	0.35	792	2.70	0.38	745
10.	2.80	0.42	555	2.35	0.42	512
11.	3.12	0.39	570	2.68	0.40	526
12.	3.76	0.34	586	3.03	0.37	547
13.	2.46	0.42	609	2.20	0.45	560
14.	2.91	0.37	622	2.58	0.41	576
15.	3.51	0.34	645	2.70	0.38	597
16.	2.28	0.37	683	2.00	0.44	570
17.	2.85	0.35	694	2.30	0.39	606
18.	3.30	0.31	710	2.50	0.36	623

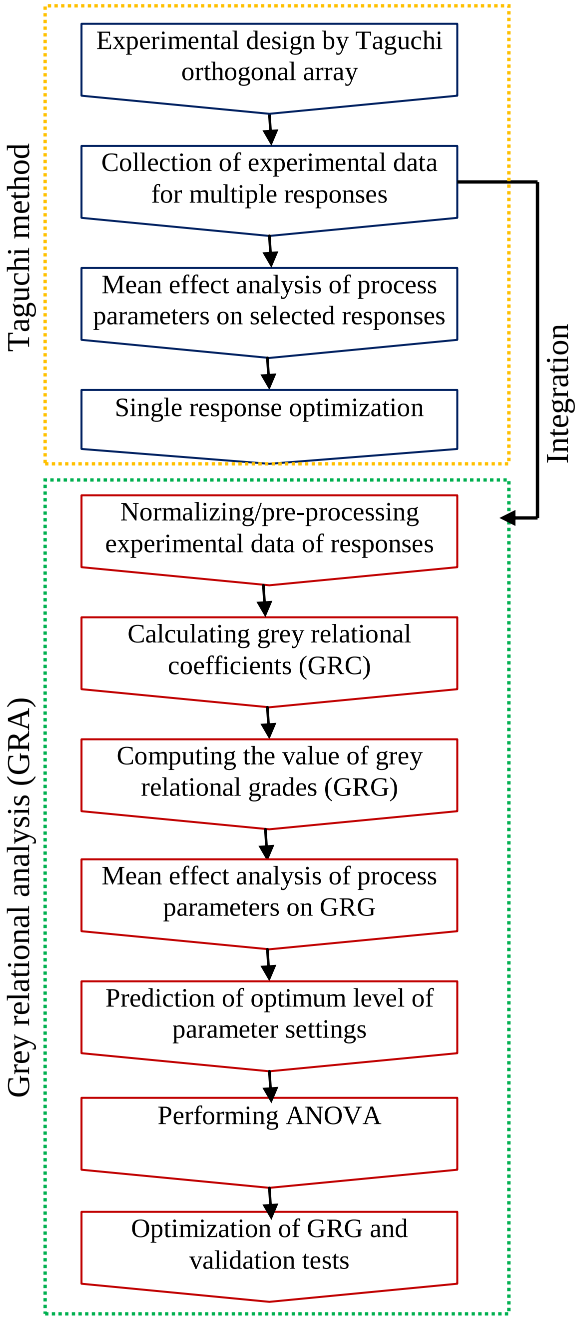

Fig. 2 Involved steps related to Taguchi -GRA

3. Results and discussions

The numerical results are represented in this section in a systematic way.

3.1 Mean effect analysis of process parameters on single response

Initially investigated responses such as surface roughness (R_a), coefficient of friction (μ) and chip tool interface temperature (θ) are numerically analysed as a single response. With varying input factors the changing trends of mean response individually can be understood easily by analysing the main effect plot as shown in Fig. 3 and Fig.4 for two different geometry shaped cutting insert [23]. One can easily see from Fig. 3(a) and Fig. 4(a), higher cutting speed (134 m/min) with lower feed rate (0.16 mm/rev) under cryogenic cooling provides minimum surface roughness for both type inserts. Raising tendency of surface roughness is higher with lowering cutting speed and increasing feed rate combination which is agreed with previous research result [24].

Similarly the changing trend of friction coefficient with respect to cutting condition, cutting velocity and feed rate are shown in Fig. 3(b) and Fig. 4(b) respectively for both type SNMM and SNMG cutting inserts. It is well known to practitioners that higher cutting velocity is the main influential factor for generating temperature at cutting zone [19]. It is noticeable from Fig. 3(c) and Fig. 4(c) that chip tool interface temperature is raised sharply with increasing cutting speed from V_c=80 m/min to 134 m/min and cooling condition has also significant impact on temperature changing.

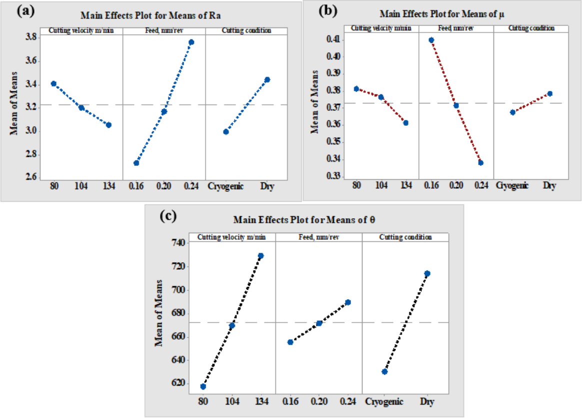

Fig. 3 Main effects plot for mean values of (a) surface roughness (Ra); (b) coefficient of friction (μ) and (c) chip tool interface temperature (θ) using uncoated SNMM 120408 insert. [Units: cutting speed V_c in m/min, feed rate f in mm/rev].

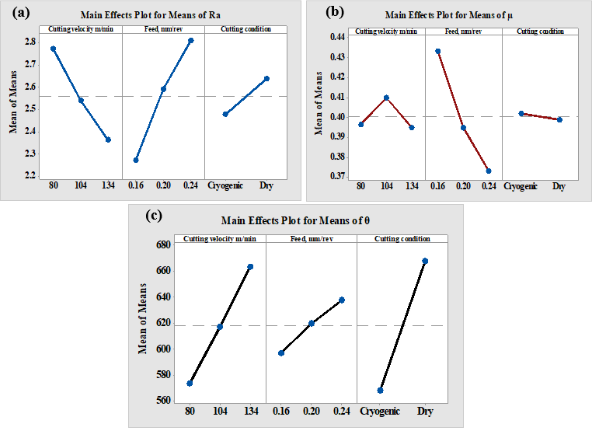

Fig. 4 Main effects plot for mean values of (a) surface roughness (Ra); (b) coefficient of friction (μ) and (c) chip tool interface temperature (θ) using uncoated SNMG 120408 insert. [Units: cutting speed V_c in m/min, feed rate f in mm/rev]

The above results dictate that it is not possible to conclude the decision about optimal settings of input process parameters for optimizing the total turning process based on investigated responses. So in next subsection multiple responses are tried to optimize using integrated Taguchi GRA method.

3.2 Multi-response optimization and mean effect analysis

Necessary calculations in grey relational analysis (GRA) - data pre-processing, deviation sequence, GRC and GRG for both type inserts are listed in Table 4 to Table 7, sequentially. According to calculation rule of Taguchi GRA, grey relational grade (GRG) is considered as a single index of multiple responses. So, in this stage the aim is to maximize the value of GRG because highest GRG value is an indication of system optimum result [24].One of the noticeable points in Table 7 is that the highest GRG value for both type inserts is found for similar levels of cutting speed (level 1), feed (level 1) and cutting condition (level 2).Using SNMM 120408 cutting insert, the highest GRG value is found 0.6670 and for SNMG 120408 insert, the highest GRG value is 0.6807.

The corresponding response values at optimal parameter settings are: optimum R_a= 2.80, optimum μ =0.42, optimum θ = 555^{O}C (for SNMM 120408 insert) and R_a= 2.35, optimum μ =0.42, optimum θ = 512^{O}C (for SNMG 120408 insert). From obtained experimental values one can notice easily that minimum μ and θ are not appear at this obtained optimum level. After this observation, it may be appeared incorrect but in this case the reminding fact is that GRA optimizes the selected responses by trade-off the individual benefits of responses [24].

Table 4 Pre-processing sequences of responses

Experimental runs	SNMM 120408			SNMG 120408		
	Ra	μ	θ	R_a	μ	θ
1.	0.5833	0.0833	0.5781	0.4554	0.3333	0.6137
2.	0.3646	0.5000	0.5359	0.2321	0.5556	0.5322
3.	0.0000	0.6667	0.4895	0.0000	0.8889	0.4721
4.	0.6510	0.0000	0.4177	0.7321	0.1111	0.4936
5.	0.4167	0.5833	0.3038	0.4196	0.5556	0.3648
6.	0.1042	0.7500	0.2616	0.2590	0.7778	0.2790
7.	0.7292	0.2500	0.2194	0.8214	0.2222	0.1545
8.	0.4948	0.3333	0.1350	0.5536	0.8889	0.0644
9.	0.1823	0.6667	0.0000	0.3750	0.7778	0.0000
10.	0.7292	0.0833	1.0000	0.6875	0.3333	1.0000
11.	0.5625	0.3333	0.9367	0.3929	0.5556	0.9399
12.	0.2292	0.7500	0.8692	0.0804	0.8889	0.8498
13.	0.9063	0.0833	0.7722	0.8214	0.0000	0.7940
14.	0.6719	0.5000	0.7173	0.4821	0.4444	0.7253
15.	0.3594	0.7500	0.6203	0.375	0.7778	0.6352
16.	1.0000	0.5000	0.4600	1.0000	0.1111	0.7511
17.	0.7031	0.6667	0.4135	0.7321	0.6667	0.5966
18.	0.4688	1.0000	0.3460	0.5536	1.0000	0.5236

The hybridization of Taguchi with GRA is represented sequentially in Table 8 and Table 9 for SNMM 120408 and SNMG 120408 insert. For each input factor the difference between maximum and minimum average GRG is also listed and ranked. From Table 8 it is found that cutting condition has the highest influence on responses followed by feed and then, cutting velocity. Table 9 manifests that cutting condition has the highest significance followed by cutting velocity and then, feed for SNMG 120408.

Table 5 Computed deviation sequences of responses

Experimental runs	SNMM 120408			SNMG 120408		
	Ra	μ	θ	R_a	μ	θ
1.	0.4167	0.9167	0.4219	0.5446	0.6667	0.3863
2.	0.6354	0.5000	0.4641	0.7679	0.4444	0.4678
3.	1.0000	0.3333	0.5105	1.0000	0.1111	0.5279
4.	0.3490	1.0000	0.5823	0.2679	0.8889	0.5064
5.	0.5833	0.4167	0.6962	0.5831	0.4444	0.6352
6.	0.8958	0.2500	0.7384	0.7410	0.2222	0.7210
7.	0.2708	0.7500	0.7806	0.1786	0.7778	0.8455
8.	0.5052	0.6667	0.8650	0.4464	0.1111	0.9356
9.	0.8177	0.3333	1.0000	0.6250	0.2222	1.0000
10.	0.2708	0.9167	0.0000	0.3125	0.6667	0.0000
11.	0.4375	0.6667	0.0633	0.6071	0.4444	0.0601
12.	0.7708	0.2500	0.1308	0.9196	0.1111	0.1502
13.	0.0937	0.9167	0.2278	0.1786	1.0000	0.2060
14.	0.3281	0.5000	0.2827	0.5179	0.5556	0.2747
15.	0.6406	0.2500	0.3797	0.6250	0.2222	0.3648
16.	0.0000	0.5000	0.5400	0.0000	0.8889	0.2489
17.	0.2969	0.3333	0.5865	0.2679	0.3333	0.4034
18.	0.5312	0.0000	0.6540	0.4464	0.0000	0.4764

Table 6 Determined GRC of responses

Experimental runs	SNMM 120408			SNMG 120408		
	GRC for,			GRC for,		
	Ra	μ	θ	R_a	M	θ
1.	0.5454	0.3529	0.5424	0.4787	0.4286	0.5641
2.	0.4404	0.5000	0.5186	0.3934	0.5294	0.5166
3.	0.3333	0.6000	0.4948	0.3333	0.8182	0.4864
4.	0.5889	0.3333	0.4620	0.6511	0.3600	0.4968
5.	0.4616	0.5454	0.4180	0.4616	0.5294	0.4405
6.	0.3582	0.6667	0.4037	0.4029	0.6923	0.4095
7.	0.6487	0.4000	0.3904	0.7368	0.3913	0.3716
8.	0.4974	0.4286	0.3663	0.5283	0.8182	0.3483
9.	0.3794	0.6000	0.3333	0.4444	0.6923	0.3333
10.	0.6487	0.3529	1.0000	0.6154	0.4286	1.0000
11.	0.5333	0.4286	0.8876	0.4516	0.5294	0.8927
12.	0.3935	0.6667	0.7926	0.3522	0.8182	0.7690
13.	0.8422	0.3529	0.6870	0.7368	0.3333	0.7082
14.	0.6038	0.5000	0.6388	0.4912	0.4737	0.6454
15.	0.4384	0.6667	0.5684	0.4444	0.6923	0.5782
16.	1.0000	0.5000	0.4808	1.0000	0.3600	0.6676
17.	0.6274	0.6000	0.4602	0.6511	0.6000	0.5535
18.	0.4849	1.0000	0.4333	0.5283	1.0000	0.5121

Table 7 Finally computed GRG of responses

Experimental runs	SNMM 120408		SNMG 120408	
	GRG	Rank	GRG	Rank
1.	0.4809	12	0.4903	15
2.	0.4859	10	0.4789	17
3.	0.4746	15	0.5438	10
4.	0.4627	16	0.5041	12
5.	0.4749	14	0.4770	18
6.	0.4750	13	0.5006	14
7.	0.4814	11	0.5023	13
8.	0.4314	18	0.5646	9
9.	0.4370	17	0.4895	16
10.	**0.6670**	**1**	**0.6807**	**1**
11.	0.6157	5	0.6228	5
12.	0.6154	6	0.6435	4
13.	0.6295	4	0.5942	7
14.	0.5811	7	0.5363	11
15.	0.5566	9	0.5704	8
16.	0.6637	2	0.6791	2
17.	0.5632	8	0.6020	6
18.	0.6379	3	0.6786	3

For each input factor the level containing the highest GRG values are considered as the optimum levels in Table 8 and Table 9 [24]. Main effect plots of average GRG for both type inserts are drawn in Fig.

5(a) and 5(b), respectively. It is found from mean effect plot that level 1 of cutting velocity (V_c=80 m/min), level 1 of feed rate (f=0.16 mm/rev) and level 2 of cutting condition (CC= cryogenic) are the optimum factor levels for average GRG using SNMM 120408 insert. In other side level 3 of cutting velocity (V_c=134 m/min), level 1 of feed rate (f=0.16 m/rev) and level 2 of cutting condition (CC= cryogenic) are selected as the optimum factor levels for average GRG of SNMG 120408 insert. This result indicate that the changes in cutting speed, feed rate and cutting condition vary surface quality, frictional behaviour and temperature.

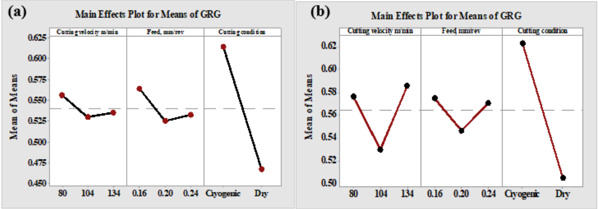

Fig. 5 Main effects plot for mean values of (a) GRG using uncoated SNMM 120408 insert and (b) GRG using uncoated SNMG 120408 insert [Units: cutting speed V_c in m/min, feed rate f, in mm/rev]

Table 8 Average GRG values at various levels of input factors using SNMM 120408 insert

Factors	Level 1	Level 2	Level 3	Max-Min	Rank
Cutting velocity	**0.5566**	0.5300	0.5358	0.0266	3
Feed	**0.5642**	0.5254	0.5328	0.0388	2
Cutting condition	0.4671	**0.6145**	-	0.1474	1

Table 9 Average GRG values at various levels of input factors using SNMG 120408 insert

Factors	Level 1	Level 2	Level 3	Max-Min	Rank
Cutting velocity	0.5767	0.5304	**0.5860**	0.0556	2
Feed	**0.5751**	0.5469	0.5711	0.0282	3
Cutting condition	0.5057	**0.6231**	-	0.1174	1

At the same time analysis of variance for GRG values are also calculated for both type cutting inserts and listed respectively in Table 10 and Table 11. Both table highlights that cutting condition has the highest (85.80% for SNMM and 58.53% for SNMG) influence on changing responses at a whole. Percent contributions of different input variables on selected responses and average GRG are also listed in the last column of Table 10 and Table 11.

3.3 Optimal parameter settings for grey relational grade (GRG)

Predicted values of optimum GRG are calculated using equation and the value of γ_{opt}=0.6537 for SNMM cutting insert type and γ_{opt}=0.6554 for SNMG cutting insert type. For validity checking of predicted results three confirmation experiments were performed at optimum level. After putting the values of confidence interval (CI) into following formula the range of GRG are calculated and listed in Table 12.

$$\gamma_{opt} - CI_{GRG} \leq \gamma_{opt} \leq \gamma_{opt} + CI_{GRG}$$

3.4 Validation tests

Validation test was carried out using the optimum GRG at levels *Vc1f1CC2* using SNMM 120408 cutting insert and *Vc3f1CC2* SNMG 120408 cutting insert. Validation test results are shown in Table 13. Within the 18 different experimental trials the actual optimum value of GRG was 0.6670 and 0.6791 for both type inserts, respectively. The predicted and experimental values of GRG are very close to each other so it can be concluded that the optimization was performed correctly.

Table 10 ANOVA for mean GRG using adjusted SS (For SNMM 120408 tool insert)

Response	Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	% (PC)
GRG	V_c	2	0.002	0.002	0.001	1.6	0.24	2.06
	F	2	0.005	0.005	0.003	3.5	0.06	4.48
	CC	1	0.097	0.097	0.098	134	0.00	85.8
	Error	12	0.009	0.009	0.001			7.66
	Total	17	0.113					100

Table 11 ANOVA for mean GRG using adjusted SS (For SNMG 120408 tool insert)

Response	Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	% (PC)
GRG	V_c	2	0.011	0.011	0.005	4.22	0.041	11.74
	f	2	0.003	0.003	0.001	1.10	0.363	3.08
	CC	1	0.062	0.062	0.062	49.2	0.000	68.48
	Error	12	0.015	0.015	0.001			16.70
	Total	17	0.091					100

Table 12 95% confidence interval of average GRG for two types cutting inserts

Cutting insert type	Lower value of GRG	Predicted optimum value	Higher value of GRG
SNMM 120408	0.6057	0.6537	0.7017
SNMG 120408	0.5924	0.6554	0.7184

Table 13 Validation test results for both type cutting inserts

Cutting insert type	Level	*GRG*		
		Experimental values	Predicted values	|Residual|
SNMM 120408	*Vc1f1CC2*	0.6670	0.6537	0.0133
SNMG 120408	*Vc3f1CC2*	0.6791	0.6554	0.0237

4. Conclusions

The main focus of this research study was to investigate the effect of process parameters on multiple responses (surface roughness, friction coefficient and chip tool interface temperature) and to optimize those responses at a time by applying statistical Taguchi-GRA technique supported by ANOVA. In addition, effect of cutting insert geometry was also checked out experimentally using two different type tool inserts. Based on the study the following remarks are concluded:

1. Experimental results has revealed that cryogenic cooling is an potential cooling technique for minimizing surface roughness and temperature but in terms of friction coefficient the effect of cooling is not clear at all. Feed rate is the most dominant influential factor for changing surface roughness and friction coefficient but speed exerts highest influence on changing temperature. ANOVA also coincides with this result.
2. Using GRA optimal input parameter settings are - cutting velocity 80m/min, feed rate 0.16 mm/rev and cryogenic cooling condition. Optimal level of cutting speed has been varied for different cutting inserts using Taguchi-GRA. ANOVA analysis for GRG showed that cutting condition has the maximum (85.8% for SNNM insert and 68.48% for SNMG insert) contribution to response variation. Actually this result is an indication of positive influence of cryogenic cooling on turning process.

This research work can be expanded by selecting more other responses (power, chip thickness, cutting force, chip morphology, wear rate etc.) to optimize. Additionally similar weights are considered for all responses in this research which can be improved for real application by computing relative weights using different methods (Principal component analysis, standard deviation method, and entropy weight method). Besides those limitations, it is expected that this research will be helpful for manufacturers and academicians to perform optimization in an easier and systematic way for other processes such as milling, drilling, grinding, abrasive jet machining etc.

8. References

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