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Multi-response optimization of process parameters using Taguchi method and grey relational analysis during turning AA 7075/SiC composite in dry and spray cooling environments

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Turning experiments were carried out on AA 7075/SiC composite workpiece in dry and spray cooling environments based on L16 Taguchi design of experiments. Multiple performance optimization of process parameters was performed using grey relational analysis. The performance characteristics considered were average surface roughness, cutting tool temperature and material removal rate. Uncoated carbide inserts were used for machining the workpiece in a high speed precision lathe. A grey relational grade obtained from grey relational analysis was used to optimize the process parameters. Optimal combination of process parameters was then determined by the Taguchi method using the grey relational grade as the performance index. Experimental results indicated that the turning in spray cooling environment was beneficial compared to that in dry environment for the quality response characteristics under consideration. Analysis of variance showed that feed was the most significant parameter for the multiple performance characteristics during turning in both the environments.

1. Introduction

Silicon carbide (SiC) reinforced aluminum matrix composites (AMC) are significant for their high strength-to-weight ratio, superior tribological properties, high thermal stability and good corrosion resistance behavior, for which they are increasingly being used in automobile, marine and aerospace industries (Kumar et al., 2010; Suryanarayanan et al., 2013; Das et al., 2014). However, these are difficult-to-machine materials due to the presence of very hard ceramic reinforcements, which also leads to their poor machinability involving high tool wear and surface imperfections (Schubert & Nestler, 2011; Radhika et al., 2014). During turning AMCs, the integrity of machined surface is affected by particle fracture, interfacial de-lamination, particle pull out and matrix work-hardening (Hung et al., 1995). Gallab and Skald (1998) observed the presence of grooves and holes in the scanning electron micrographs of machined surfaces, due to pull out of SiC particles and fractured SiC particles, during dry high-speed turning of Al/SiC composites using poly crystalline diamond (PCD) inserts. Manna and Bhattacharyya (2002) while dry machining SiC reinforced Al 2080 matrix composites using some special

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tooling systems, observed the average surface roughness reduced with increasing cutting speed; however, that increased with increasing feed and depth of cut. Ciftci et al. (2004) during dry turning of Al 2014/SiC composites, reported that uncoated carbide tools produce better surface finish than coated carbide tools at lower cutting speeds, but Kilickap et al. (2005) observed better surface finish with TiN coated tools than that of uncoated tools, while machining 99.9% pure Al/SiC composites.

Use of coolant during turning increases abrasion between the tool flank and machined surface that leads to groove wear and deteriorates the surface quality (Ding et al., 2005). Surface quality deteriorates during wet turning of ceramic reinforced AMCs, due to flushing away of the partially de-bonded particles thus by creating voids and pit holes on the machined surface (Kannan & Kishawy, 2006; Kannan & Kishawy, 2008). Krishna and Reddy (2012) observed an increase in cutting temperature with the increase of either depth of cut or cutting speed, during turning AA 6061/SiC composite using K20 carbide insert. Chandrasekaran and Tamang (2014), while turning SiC reinforced AMCs using PCD inserts reported that feed rate was the most influencing parameter for average surface roughness and material removal rate. Lin (2004) adopted Taguchi method and grey relational analysis (GRA) to optimize cutting parameters for multi-response characteristics (tool life, cutting force and surface roughness) simultaneously, during turning S45C steel using P20 tungsten carbide insert and reported that cutting speed of 135 m/min, feed rate of 0.08 mm/rev and depth of cut of 0.6 mm were the optimal combination of cutting parameters for the multi-response characteristics. GRA based on Taguchi method was also adopted by Tzeng et al. (2009) to optimize the machining parameters for multiple surface quality targets (i.e. roughness average, roughness maximum and the roundness) simultaneously, during turning SKD 11 (a high carbon, high chromium alloy tool steel) using TiN coated carbide insert and reported that cutting speed of 155 m/min, feed rate of 0.12 mm/rev, depth of cut of 0.8 mm and cutting fluid ratio of 12% was the optimal combination of machining parameters for the multiple performance characteristics. Sreenivasulu and Rao (2012) applied Taguchi method and GRA to optimize drilling parameters for surface roughness and roundness error simultaneously. Gupta and Kumar (2013) also applied Taguchi method and GRA to optimize turning parameters for surface roughness and material removal rate simultaneously, during turning unidirectional glass fiber reinforced plastic composites; and observed that the depth of cut was the most influencing factor for surface roughness and material removal rate, followed by feed rate.

Krishnamurthy and Venkatesh (2013) in their work presented that during machining, attention should be focused on economy and product quality simultaneously. Surface quality of the product, cutting temperature and material removal rate are the most important factors which influence directly on the machining economy and product quality. Surface roughness is an important index of machinability that determines product quality. Products for precision works require a high degree of surface finish, especially to improve the tribological properties, fatigue strength and corrosion resistance. Machining of a material involves severe plastic deformation in primary and secondary deformation zones, due to which heat is generated and cutting temperature rises. The rise in cutting temperature leads to early wear of cutting tool and the dimensional inaccuracy of the finished product (Krishna & Reddy, 2012). Moreover; high material removal rate is desirable during machining to increase productivity. Use of coolant during machining the aluminum matrix composites reduces cutting temperature; however, the surface quality is deteriorated as compared to dry machining (Ding et al., 2005; Kannan & Kishawy, 2006; Kannan & Kishawy, 2008). In this experiment, a novel method of air-water spray cooling (SC) system has been developed for cooling the work-tool interface zone during turning a SiC reinforced AMC.

This paper presents a comparative study for the multiple quality response characteristics, i.e. average surface roughness (Ra), cutting tool temperature (T) and material removal rate (MRR), while turning the composite both in dry and SC environment for the same machining parameters. In addition to this, it includes a systematic way of optimization of machining process parameters for Ra, T and MRR considered simultaneously, using Taguchi method and GRA during turning the composite bar in both dry and SC environment.

2. Materials and methods

AA 7075 matrix composite reinforced with 20 wt. % SiC (of average particle size 8.18 µm) was used as work material for turning. Chemical composition test result of the matrix alloy is shown in Table 1. The composite was fabricated by conventional stir casting method in an electrical resistance furnace, mounted with a speed regulated stirring system and temperature controller.

Table 1
Chemical composition test result of AA 7075

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al	Others
Weight %	0.143	0.313	1.39	0.137	2.46	5.60	0.044	0.198	88.9	Rest

The matrix alloy was heated up to 820^0C in a steel crucible and then a vortex was created on the surface of the molten alloy by stirring at a speed of 160 rpm. The SiC particles, preheated to 900^0C for 2 hours, were then added in to the vortex of the molten alloy. The stirring was continued for 10 minutes at a speed of 220 rpm. Stirring blades were placed at about one third of the height of the molten metal from its bottom. Before pouring in to a steel mold, about 10 grams of solid Hexachloroethane tablet was dipped into the bottom of the composite slurry for degassing. The pouring temperature of the slurry was around 800^0C. Hardness of the fabricated composite bar was 82 HRB. Distribution of reinforced particles in the matrix phase was observed through a Lieca make DMI3000 M inverted optical microscope. Figure 1 represents the optical micrograph of the composite sample at 100X magnification, which depicts a uniform distribution of SiC particles in the matrix phase, with local agglomeration at some places. The red circular marks in the micrograph indicate the regions of local agglomeration. The composite bar fabricated for turning was of cylindrical shape. Diameter and length of the bar were 50 mm and 110 mm respectively. The machining length was 70 mm.

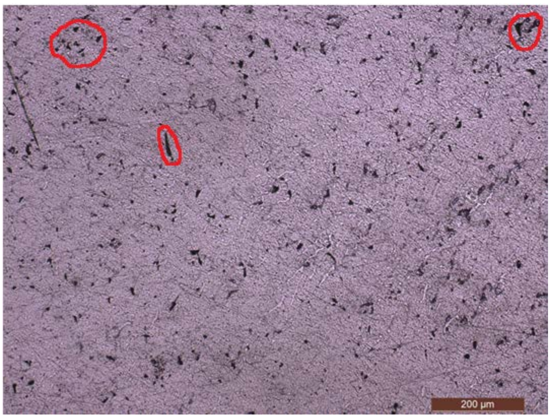

Fig. 1. Optical micrograph of AA 7075/SiC composite sample.

Turning experiments were conducted by a high speed precision lathe (NH 22, HMT) using uncoated carbide inserts of geometry SNMG 120408-THM, manufactured by Kennametal India Ltd. The inserts were clamped rigidly in a turning tool holder of code PSSNR 2525M-12. The experimental setup for generating air-water spray (Fig. 2) consists of an air compressor, a water pump, two pressure regulating valves (one for air and the other for water) and a spray nozzle. Compressed air and water at desired pressure levels are mixed and allowed to pass through the nozzle to produce the spray. Experiments were conducted both in dry and SC machining environments. A constant water pressure of 3 bar and air pressure at four different levels were used for turning the composite in SC environment.

(a) (b)

Fig. 2. Experimental setup for spray generation consisting (a) air compressor; (b) water pump and pressure regulating valves

Fig. 3 and Fig. 4 represent turning setups in dry and SC machining environments respectively. Also, A high-definition infrared thermal imager (FLUKE Ti32) was used to measure T during turning. Ra of machined surfaces was measured using a surface roughness tester (Taylor Hobson, Surtronic 25), as shown in Fig. 5.

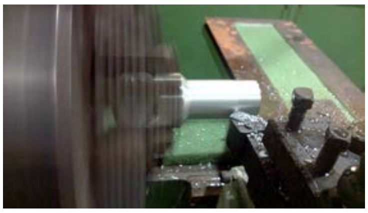

Fig. 3. Turning setup in dry machining environment

Fig. 4. Turning setup in SC machining environment

Fig. 5. Surface roughness measurement of machined composite bar

MRR was determined using Eq. (1).

$$MRR = \frac{\pi}{4}\left(D_1^2 - D_2^2\right) f \cdot \frac{N}{60} \text{ mm}^3\text{/sec,} \quad (1)$$

where D_1 = Workpiece diameter before cut (mm), D_2 = Workpiece diameter after cut (mm), f = feed (mm/rev) and N = Spindle speed of lathe (rpm).

Machining process parameters and their levels used for turning the composite in dry and SC environment are presented in Tables 2 and Table 3, respectively. Experiments were conducted using Taguchi L_{16} orthogonal array (Table 4).

Table 2
Process parameters and their levels for turning in dry environment

Process parameters	Notation	Unit	Levels of parameters			
			Level 1	Level 2	Level 3	Level 4
Depth of cut	d	mm	0.2	0.4	0.6	0.8
Feed	f	mm/rev	0.04	0.08	0.12	0.16
Spindle speed	N	rpm	325	420	550	930

Table 3
Process parameters and their levels for turning in SC environment

Process parameters	Notation	Unit	Levels of parameters			
			Level 1	Level 2	Level 3	Level 4
Depth of cut	d	mm	0.2	0.4	0.6	0.8
Feed	f	mm/rev	0.04	0.08	0.12	0.16
Spindle speed	N	rpm	325	420	550	930
Air pressure	Pa	bar	3	2.5	2	1.5

Table 4
Taguchi L_{16} orthogonal array

Dry environment				SC environment			
Run No.	d	f	N	d	f	N	Pa
1	1	1	1	1	1	1	1
2	1	2	2	1	2	2	2
3	1	3	3	1	3	3	3
4	1	4	4	1	4	4	4
5	2	1	2	2	1	2	3
6	2	2	1	2	2	1	4
7	2	3	4	2	3	4	1
8	2	4	3	2	4	3	2
9	3	1	3	3	1	3	4
10	3	2	4	3	2	4	3
11	3	3	1	3	3	1	2
12	3	4	2	3	4	2	1
13	4	1	4	4	1	4	2
14	4	2	3	4	2	3	1
15	4	3	2	4	3	2	4
16	4	4	1	4	4	1	3

4. Grey relational analysis

Taguchi method and GRA were used to optimize the machining process parameters for multiple response quality characteristics, i.e. Ra, T and MRR, during turning the composite both in dry and SC environment. GRA can be successfully applied to a system with less or incomplete information. Various steps involved in this method are:

(a) Normalization of experimental results or linear data processing or grey relational generation
(b) Determination of deviation coefficient and grey relational coefficient
(c) Determination of grey relational grades and their order sequencing
(d) Analysis of experimental results using the grey relational grades and statistical ANOVA
(e) Selection of optimal levels of machining parameters
(f) Verification of optimal machining parameters through confirmation experiment

Grey relational generation or linear data processing generates normalized data sequence for the experimental results within 0 and 1. If the target value of the original sequence is "smaller is better", then the original sequence is normalized as Eq. (2).

$$x_i^*(k) = \frac{\max\ x_i^0(k) - x_i^0(k)}{\max\ x_i^0(k) - \min\ x_i^0(k)}\ . \tag{2}$$

However, if the target value is "larger is better", then the original sequence is normalized as Eq. (3).

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max\ x_i^0(k) - \min\ x_i^0(k)}\ , \tag{3}$$

where $x_i^*(k)$ is the sequence after the data processing or compatibility sequence, $x_i^0(k)$ is the original sequence of the target value for i = 1, 2, 3…., m and k = 1, 2,…., n. m is total number of experiments and n is total number of process responses. For the present analysis, m = 16 and n = 3.

Next step is to determine the deviation coefficient, which is the absolute value of the difference between reference sequence and compatibility sequence, i.e.

$$\Delta_{0i}(k) = \left| x_0^*(k) - x_i^*(k) \right|, \tag{4}$$

where $\Delta_{0i}(k)$ is deviation coefficient $x_0^*(k)$ is reference sequence or ideal sequence. Grey relational coefficient is then determined using Eq. (5).

$$\gamma\left(x_0^*(k) \cdot x_i^*(k)\right) = \frac{\Delta_{\min} + \varsigma \cdot \Delta_{\max}}{\Delta_{0i}(k) + \varsigma \cdot \Delta_{\max}}, \tag{5}$$

where $\gamma\left(x_0^*(k) \cdot x_i^*(k)\right)$ is the grey relational coefficient and ζ is distinguishing coefficient (0~1).
Grey relational grade ($\gamma(x_0^*.x_i^*)$) is the weighted sum of the grey relational coefficients and represents the level of correlation between reference and compatibility sequence. It can be calculated using Eq. (6).

$$\gamma\left(x_0^* \cdot x_i^*\right) = \frac{1}{n}\sum_{k=1}^{n} \gamma\left(x_0^*(k) \cdot \gamma\left(x_i^*(k)\right)\right). \tag{6}$$

The grey relational grades are than sequenced in descending order. Higher value of grey relational grade represents the stronger relational degree between the reference sequence and compatibility sequence. The highest values of grey relational grade represent the optimal combination of machining parameters for the desired responses (Lin, 2004; Tzeng et al., 2009).

5. Results and discussion

5.1. Multi-response optimization of process parameters

Table 5 represents the experimental results and normalized data of Ra, T and MRR during turning in dry environment; and those for turning in SC environment are presented in Table 6. The target values of Ra and T are “smaller is better” and that for MRR is “larger is better”.

Table 5
Experimental results and data processing of performance characteristics during turning in dry environment

Run no.	Machining process parameters			Experimental results			Normalized data		
	d	f	N	Ra	T	MRR	Ra	T	MRR
Ideal sequence							1	1	1
1	1	1	1	0.84	36.5	4.27	1.0000	1.0000	0.0000
2	1	2	2	1.94	46.4	10.91	0.7679	0.8235	0.0721
3	1	3	3	2.98	55.3	24.51	0.5485	0.6649	0.2197
4	1	4	4	1.82	68.1	47.82	0.7932	0.4367	0.4727
5	2	1	2	1.82	48.2	12.40	0.7932	0.7914	0.0882
6	2	2	1	3.86	51.4	16.59	0.3629	0.7344	0.1337
7	2	3	4	1.92	90.4	79.60	0.7722	0.0392	0.8176
8	2	4	3	3.84	78.1	58.22	0.3671	0.2585	0.5855
9	3	1	3	1.30	68.3	38.68	0.9030	0.4332	0.3735
10	3	2	4	2.08	77.4	64.66	0.7384	0.2709	0.6554
11	3	3	1	5.01	58.0	23.75	0.1203	0.6168	0.2114
12	3	4	2	4.42	76.0	66.10	0.2447	0.2959	0.6710
13	4	1	4	2.01	92.6	96.41	0.7532	0.0000	1.0000
14	4	2	3	3.10	66.6	62.69	0.5232	0.4635	0.6340
15	4	3	2	3.58	57.8	44.34	0.4219	0.6203	0.4349
16	4	4	1	5.58	68.3	40.09	0.0000	0.4332	0.3888

From the experimental results, it is observed that the values of Ra and T during turning in SC environment are lower than those for dry turning, for the same levels of d, f and N. Further, the MRR values during SC turning are higher than those during dry turning, for the same levels of d, f and N. So, it is clearly evident that turning in SC environment produces better surface quality than that of dry environment. It may be due to the fact that the water particles are finely atomized in presence of compressed air while passing through the nozzle. It eliminates the problem of flush out of the partially de-bonded particles from the machined surface of composites, which is a common problem in wet machining (Kannan & Kishawy, 2006; Kannan & Kishawy, 2008). Moreover, due to cooling effect produced in the air-water spray environment, the temperature of the cutting tool reduces, thus by enhancing the tool life.

Table 6
Experimental results and data processing of performance characteristics during turning in SC environment

Run no.	Machining process parameters				Experimental results			Normalized data		
	d	f	N	Pa	Ra	T	MRR	Ra	T	MRR
Ideal sequence								1	1	1
1	1	1	1	1	0.80	32.3	4.38	0.9670	1.0000	0.0000
2	1	2	2	2	1.18	34.4	29.96	0.7582	0.7162	0.1928
3	1	3	3	3	1.08	36.6	56.62	0.8132	0.4189	0.3938
4	1	4	4	4	1.60	39.7	133.6	0.5275	0.0000	0.9741
5	2	1	2	3	0.74	33.4	8.39	1.0000	0.8514	0.0302
6	2	2	1	4	0.76	34.3	15.38	0.9890	0.7297	0.0829
7	2	3	4	1	0.94	36.5	53.77	0.8901	0.4324	0.3723
8	2	4	3	2	1.58	35.8	56.66	0.5385	0.5270	0.3941
9	3	1	3	4	0.74	35	36.81	1.0000	0.6351	0.2445
10	3	2	4	3	1.22	38.2	137.04	0.7363	0.2027	1.0000
11	3	3	1	2	1.44	34.5	63.64	0.6154	0.7027	0.4467
12	3	4	2	1	2.32	34.8	62.34	0.1319	0.6622	0.4369
13	4	1	4	2	0.96	37.4	132.92	0.8791	0.3108	0.9689
14	4	2	3	1	1.38	34.1	94.45	0.6484	0.7568	0.6790
15	4	3	2	4	1.20	36.5	79.91	0.7473	0.4324	0.5694
16	4	4	1	3	2.56	35.5	102.19	0.0000	0.5676	0.7373

Deviation coefficients and grey relational coefficients with $\zeta = 0.5$ are presented in Table 7 and Table 8 for dry turning and SC turning respectively.

Table 7
Deviation coefficients and grey relational coefficients during turning in dry environment

Run no.	Deviation Coefficient			Grey Relational coefficient		
	Ra	T	MRR	Ra	T	MRR
Ideal sequence				1	1	1
1	0.0000	0.0000	1.0000	1.0000	1.0000	0.3333
2	0.2321	0.1765	0.9279	0.6830	0.7391	0.3502
3	0.4515	0.3351	0.7803	0.5255	0.5987	0.3905
4	0.2068	0.5633	0.5273	0.7075	0.4702	0.4867
5	0.2068	0.2086	0.9118	0.7075	0.7057	0.3542
6	0.6371	0.2656	0.8663	0.4397	0.6531	0.3660
7	0.2278	0.9608	0.1824	0.6870	0.3423	0.7327
8	0.6329	0.7415	0.4145	0.4413	0.4027	0.5468
9	0.0970	0.5668	0.6265	0.8375	0.4687	0.4438
10	0.2616	0.7291	0.3446	0.6565	0.4068	0.5920
11	0.8797	0.3832	0.7886	0.3624	0.5661	0.3880
12	0.7553	0.7041	0.3290	0.3983	0.4152	0.6032
13	0.2468	1.0000	0.0000	0.6695	0.3333	1.0000
14	0.4768	0.5365	0.3660	0.5119	0.4824	0.5774
15	0.5781	0.3797	0.5651	0.4638	0.5684	0.4694
16	1.0000	0.5668	0.6112	0.3333	0.4687	0.4499

Table 8
Deviation coefficients and grey relational coefficients during turning in SC environment

Run no.	Deviation Coefficient			Grey Relational coefficient		
	Ra	T	MRR	Ra	T	MRR
Ideal sequence				1	1	1
1	0.0330	0.0000	1.0000	0.9381	1.0000	0.3333
2	0.2418	0.2838	0.8072	0.6741	0.6379	0.3825
3	0.1868	0.5811	0.6062	0.7280	0.4625	0.4520
4	0.4725	1.0000	0.0259	0.5141	0.3333	0.9507
5	0.0000	0.1486	0.9698	1.0000	0.7708	0.3402
6	0.0110	0.2703	0.9171	0.9785	0.6491	0.3528
7	0.1099	0.5676	0.6277	0.8198	0.4684	0.4434
8	0.4615	0.4730	0.6059	0.5200	0.5139	0.4521
9	0.0000	0.3649	0.7555	1.0000	0.5781	0.3982
10	0.2637	0.7973	0.0000	0.6547	0.3854	1.0000
11	0.3846	0.2973	0.5533	0.5652	0.6271	0.4747
12	0.8681	0.3378	0.5631	0.3655	0.5968	0.4703
13	0.1209	0.6892	0.0311	0.8053	0.4205	0.9415
14	0.3516	0.2432	0.3210	0.5871	0.6727	0.6090
15	0.2527	0.5676	0.4306	0.6642	0.4684	0.5373
16	1.0000	0.4324	0.2627	0.3333	0.5362	0.6556

Table 9 represents grey relational grades and their order for the multiple performance characteristics for turning in dry environment; and those for turning in SC environment are presented in Table 10.

Table 9
Grey relational grades and their order during turning in dry environment

Run no.	Grey relational grade	Order
1	0.7778	1
2	0.5908	3
3	0.5049	10
4	0.5548	7
5	0.5891	4
6	0.4862	12
7	0.5873	5
8	0.4636	14
9	0.5833	6
10	0.5518	8
11	0.4388	15
12	0.4722	13
13	0.6676	2
14	0.5239	9
15	0.5005	11
16	0.4173	16

Table 10
Grey relational grades and their order during turning in SC environment

Run no.	Grey	Order
1	0.7572	1
2	0.5648	10
3	0.5475	13
4	0.5994	8
5	0.7037	3
6	0.6602	5
7	0.5772	9
8	0.4953	15
9	0.6588	6
10	0.6800	4
11	0.5557	12
12	0.4775	16
13	0.7224	2
14	0.6229	7
15	0.5566	11
16	0.5084	14

Response tables were generated using Taguchi method to calculate the mean grey relational grade for each factor level, as illustrated in Table 11 for turning in dry environment and in Table 12 for turning in SC environment.

Table 11
Response table for means of grey relational grade during turning in dry environment

Process parameters	Grey relational grade				Max-min	Rank
	Level 1	Level 2	Level 3	Level 4		
d	0.6071	0.5315	0.5115	0.5273	0.0955	2
f	0.6544	0.5382	0.5079	0.4770	0.1775	1
N	0.5300	0.5381	0.5189	0.5904	0.0714	3

Total mean grey relational grade = 0.5444

Table 12
Response table for means of grey relational grade during turning in SC environment

Process parameters	Grey relational grade				Max-min	Rank
	Level 1	Level 2	Level 3	Level 4		
D	0.6172	0.6091	0.5930	0.6026	0.0242	4
F	0.7105	0.6320	0.5592	0.5201	0.1904	1
N	0.6204	0.5756	0.5811	0.6447	0.0691	2
Pa	0.6087	0.5845	0.6010	0.6187	0.0342	3

Total mean grey relational grade = 0.6055

In Table 11 the largest values of grey relational grade are obtained for the combination of d1-f1-N4, which indicates that the optimal combination of machining process parameters for the multiple performance characteristics during dry turning of the composite is depth of cut of 0.2 mm, feed of 0.04 mm/rev and spindle speed of 930 rpm. Similarly, in Table 12 the largest values of grey relational grade are obtained for the combination of d1-f1-N4-Pa4, indicating a depth of cut of 0.2 mm, feed of 0.04 mm/rev, spindle speed of 930 rpm and air pressure of 1.5 bar (at Pw = 3 bar) is the optimal parameter combination for the multiple performance characteristics during turning the composite in SC condition. The main effect plots for means of grey relational grade are shown in Figure 6 and Figure 7 for dry turning and spray cooled turning of the composite respectively. The dashed lines in the main effect plots represent the total mean of the grey relational grade.

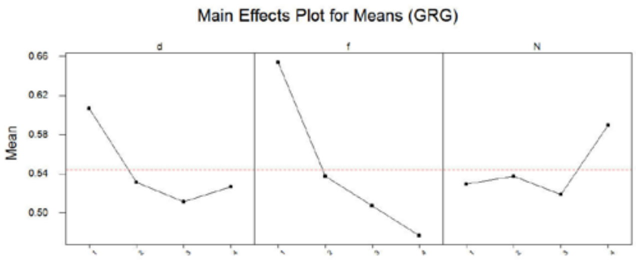

Fig. 6. Main effect plots for means of grey relational grade during turning in dry environment

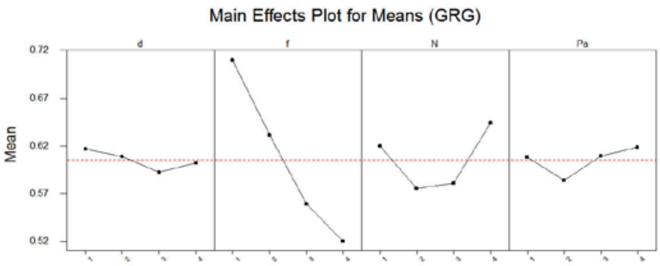

Fig. 7. Main effect plots for means of grey relational grade during turning in SC environment

5.2. Analysis of variance (ANOVA) for Grey relational grade

In order to investigate the significance of machining process parameters on the multiple performance characteristics, ANOVA was conducted for grey relational grade at 95% confidence level using MINITAB software. Total sum of squared deviations (SS_T) can be calculated using Eq. (7).

$$SS_T = \sum_{j=1}^{p} \left(\gamma_j - \gamma_m\right)^2 , \tag{7}$$

where p = number of experiments in the orthogonal array, γ_j = mean of grey relational grade for jth experiment and γ_m = total mean of grey relational grade.[16] Mean square (MS) can be obtained by dividing sum of squared deviations (SS) by the corresponding degree of freedom (DF), i.e.

$$MS = \frac{SS}{DF} \tag{8}$$

Fisher's value (F) and probability of significance (P) can be used to determine the significance of machining process parameters on the multiple performance characteristics. For a large value of F or small value of P the corresponding machining parameter has a significant effect on the performance characteristics. Percentage of contribution of a machining parameter can be calculated by dividing SS_T by the corresponding SS, as presented in Eq. (9).

$$\% \ of \ contribution = \frac{SS_T}{SS} \times 100 \quad (9)$$

Table 13 and Table 14 represent the ANOVA results for grey relational grade in dry and SC turning environments respectively. From the ANOVA tables it is observed that feed is the only significant machining process parameter for Ra, T and MRR considered simultaneously, during turning both in dry and SC environments. Percentage of contribution of feed for the multi-response characteristics is 58.33 for dry turning environment and that for SC turning environment is 79.29.

Table 13
ANOVA results for grey relational grade during turning in dry environment

Process	Degree of	Sum of squares	Mean square	F	P	Contribution (%)
d	3	0.0218	0.0072	2.48	0.159	17.64
f	3	0.0721	0.0240	8.17	0.015	58.33
N	3	0.0120	0.0040	1.36	0.341	9.71
Error	6	0.0176	0.0029			14.24
Total	15	0.1236				100.00

Table 14
ANOVA results for grey relational grade during turning in SC environment

Process	Degree of	Sum of	Mean square	F	P	Contribution
d	3	0.0013	0.0004	0.24	0.864	1.22
f	3	0.0846	0.0282	16.12	0.024	79.29
N	3	0.0130	0.0043	2.47	0.238	12.18
Pa	3	0.0026	0.0008	0.49	0.713	2.44
Error	3	0.0052	0.0017			4.87
Total	15	0.1067				100.00

5.3 Verification of optimal machining process parameters through confirmation experiment

After finding the optimal combination of machining process parameters and the most influencing factor for Ra, T and MRR, the final step is to verify for the responses by conducting some confirmation experiments. Table 15 and Table 16 show the results of the confirmation experiments during turning the composite in dry and SC environments respectively.

Table 15
Results of cutting performance using the initial and optimal process parameters during turning in dry environment

	Initial process parameters	Optimal process parameters	
		Prediction	Experiment
Level	d2-f2-N2	d1-f1-N4	d1-f1-N4
Ra	2.68		0.72
T	54.62		32.7
MRR	20.22		86.45
Grey relational grade	0.5158	0.7631	0.9407

Table 16
Results of cutting performance using the initial and optimal process parameters during turning in SC environment

	Initial process parameters	Optimal process parameters	
		Prediction	Experiment
Level	d2-f2-N2-Pa2	d1-f1-N4-Pa4	d1-f1-N4-Pa4
Ra	1.18		0.66
T	36.02		32.00
MRR	35.24		129.22
Grey relational grade	0.5223	0.7748	0.9635

In both the cases the values of Ra and T for optimal combination of process parameters were sufficiently lower as compared to those of initial process parameters. However, the MRR for optimal combination of process parameters was sufficiently higher than that of initial process parameters for both the cases. The improvements in grey relational grade for optimal parametric combination than that for initial process parameters are 0.4250 and 0.4412 for turning in dry and SC environments respectively. Further it is observed that for optimal process parameters the experimental values of Ra and T in case of turning in SC environment are lower and MRR is higher than those values in dry turning.

6. Conclusion

1. Turning SiC reinforced AMCs in spray cooled environment produces better surface quality, reduced cutting tool temperature and improved productivity as compared to dry turning.
2. From the response table, the largest values of the grey relational grade are achieved for the depth of cut of 0.2 mm, feed of 0.04 mm/rev and spindle speed of 930 rpm for dry turning of the composite. It is the recommended levels of cutting parameters for turning SiC reinforced AMCs in dry environment for minimizing average surface roughness, minimizing cutting tool temperature and maximizing the material removal rate, simultaneously considered. Similarly, during turning in SC environment, the largest values of the grey relational grade are obtained for the depth of cut of 0.2 mm, feed of 0.04 mm/rev, spindle speed of 930 rpm and air pressure of 1.5 bar (at water pressure of 3 bar). It is the recommended levels of cutting parameters for turning the composites in SC environment for the multi-response characteristics (Ra, T, and MRR).
3. ANOVA results for grey relational grade indicates that feed is the only significant machining process parameter for the multi-response characteristics under consideration, for both the dry and SC environments. The contribution of feed in SC environment is quite large as compared to that in dry environment.
4. Confirmation experiments reveal that the improvement in grey relational grade of optimal combination of parameters than the initial setting of parameters is 0.4250 for dry turning and 0.4412 for spray cooled turning of the composite.

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