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Experimental investigation to optimize tool performance in high-speed drilling: a comparative study

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Abstract

In this study, the influence of drilling parameters on circularity error, tool tip temperature and flank wear is investigated while drilling of Ti–6Al–4V alloy specimens with dissimilar cutting tool materials under dry machining conditions. In addition, optimal control factors for circularity error, tool tip temperature and flank wear have been determined using Taguchi–Grey relational analysis. Rotational speed of the spindle, feed rate and drill bit material are considered as control factors. Numerous drilling experimental runs have been performed employing L27 orthogonal array on a CNC vertical machining centre with 12Ø-mm-diameter holes on 10-mm-thick plates. An infrared thermal camera FLIR E60 is employed to record the temperature at tool chip interface, and Kistler 8793 tri-axial accelerometer is used to get hold of vibration data in real time. Analysis of variance has been carried out to ascertain the most substantial control factors among rotational speed, feed rate and drill bit material and also to establish the effects of the same over circularity error (C_r), temperature (T) and flank wear (V_B).

Keywords Multi-objective optimization · Circularity error · Drilling · Infrared thermography · Grey relational analysis (GRA)

1 Introduction

In metal cutting machining, the main issues that affect cutting tool life are relative vibrations between the tool and the workpiece, chip temperature or tool tip temperature along with machining parameters like feed rate (f), spindle rotational speed (N), tool geometry, depth of cut (d), etc. Thus, it turns out to be important for the manufacturing industry to discover the appropriate intensities of cutting process factors for attaining optimum tool life. In metal cutting, heat generation is always a key topic to be studied [1]. As a part of process enhancement, it is certainly beneficial to proactive monitoring of quality directly in the machining process instead of the product; hence, the chances of parts with defects can be reduced or even eliminated.

Drilling is the most significant step in the whole of machining process. With an objective to enhance metal cutting procedures to bring down the cost of parts, the required framework level is used in metal cutting process model [2]. For better performance of a cutter, it is necessary to model the interactions of tool chip interface. Various methodologies are proposed for better cutter performance such as mechanistic, empirical, numerical and analytical. It has been accounted that one-third course of action of material subtraction processes performed in manufacturing firms is drilling operation [3]. For this motive, drilling is indispensable and all things considered adopted material removal procedure. Nevertheless, tool failure might yield in drilling operations as an outcome of tool wear. Consequently, in-process forecasting of tool wear in drilling operations should be explored [4]. An experimental investigation is presented on how the quality of hole is influenced by the parameters of drilling, i.e. feed rate and spindle rotational speed. The assessment included considering the size of hole, circularity error, burrs at the exit and entry and chip developments. Moreover, the quality of hole is investigated by establishing the involvement of parameters of cutting using ANOVA as well as conclusions are derived statistically [5]. Kivak et al. [6] studied the influence of cutting parameters on tool wear

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and the quality of the hole, i.e., circularity of hole diameter while the drilling Inconel 718 with uncoated and coated drill bits. It was concluded that the quality of the hole and the performance of the drill bit are very poor at higher rotational speed and feed rates. A severe wear of tool amplification is noticed at higher cutting speeds. The multiple responses of arduous interrelationships can be solved using GRA [7]. An advanced optimization was carried out in drilling operation performed on metal matrix composites by altering different cutting parameters with GRA of orthogonal array [8]. The multiple responses obtained by different parameters of drilling operation are optimized in this study such as torque, cutting force and roughness of the surface.

In this work, high-speed steel (HSS) drill, tungsten carbide drill and titanium nitride (TiN) coated are examined for the duration of dry drilling of Ti–6Al–4V alloy under dry machining condition. The drilling experiments were accomplished on 10-mm-thick aerospace quality workpiece material. The experimental runs are performed to probe the prominent outcome of the ideal operation of drilling framework and drilling cutter category on the interface temperature, quality of the hole and vibration factor displacement. By using Taguchi technique in GRA performance characteristics, the available experimental results were optimized.

2 Proposed methodology in the present work

In the present work, difficult-to-cut material like Ti–6Al–4V alloy was used as workpiece material. An attempt is made to investigate the effect and performance of different cutting tool materials in dry drilling operation. Analysis of infrared thermal images and regression analysis carried out in this work will validate the cutting tool performance physiognomies. The performance analyses have shown that the spindle rotational speed and feed rate are the most prevailing factors for the tool wear and cutting temperature, respectively. The confirmation test has certified the validity of the regression model industrialized in the present work. This kind of work is uncommon in the field of machining operations, particularly in drilling. Figure 1 gives the methodology in the present work. The test set-up used for investigation is a 3-axis CNC drilling machine with high-speed 3.5 KW spindle which is capable of drilling up to 18,000 RPM is presented in Fig. 2.

According to methodology proposed, drilling operation is selected to generate holes on most commonly used materials in aircraft and automobile industry such as titanium alloys (Ti–6Al–4V) of dimensions (150 mm × 150 mm × 10 mm). Steps planned to generate experimental data are listed below:

- The drilling operation is performed using a 2-flute drill bit on 3-axis high drilling machine as per combinations listed in Table 6.
- The workpiece is fixed firmly on the work table as presented in Fig. 2.
- An infrared thermal camera FLIR E60 is employed to collect the temperature at tool chip interface in real time.
- Every test is initiated with a new drill bit, and temperature at tool chip interface is acquired using thermal images, and machining is stopped after drilling the fifth hole in every test condition for circularity error under coordinate measuring machine (CMM) and tool wear measurement with direct method.
- Inspected the drilled holes for roundness measurement under CMM.
- Experimental runs are derived through Taguchi L_{27} orthogonal array, and the same procedure has been adopted to acquire experimental data.
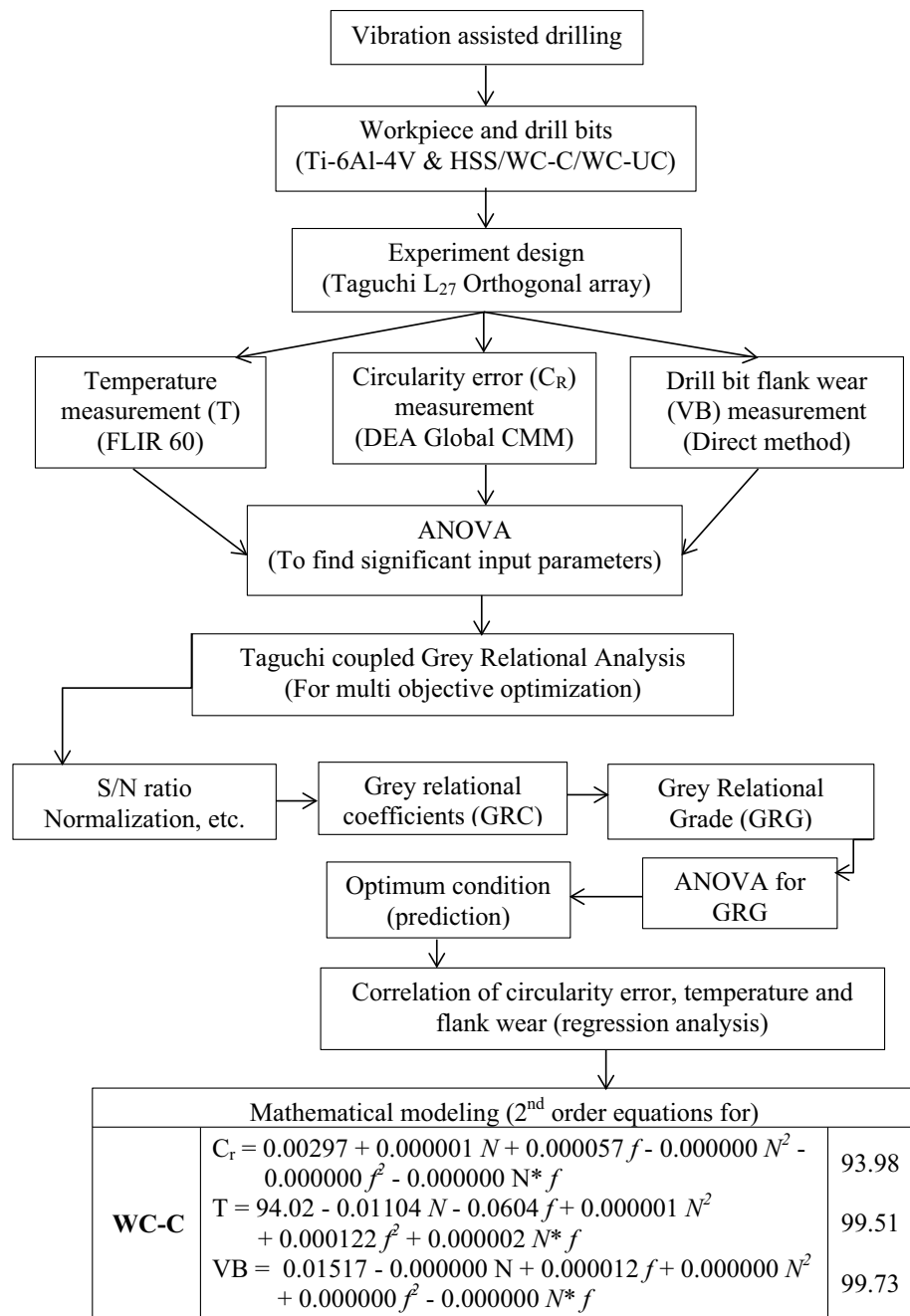- The above listed steps have been repeated to carry out experiments in real time.

Later, ANOVA is employed to determine the most influential process input parameter and the fraction of participation each contributing process parameter on the attributes of quality has been derived. Then, the optimum machining parameters are identified utilizing Taguchi's S/N ratio charts. The GRA in Taguchi method is adopted to perform multi-objective optimization for process parameters. After that, effect of machining parameters on cutting temperature, circularity error and tool wear is analysed by varying the tool material. Finally, regression analysis is carried out to determine the correlation of cutting temperature, circularity error and tool wear with drilling process parameters.

The multiple responses are assessed by a grey relational grade (GRG). Proportionately, the multiple response optimization will be transformed into an individual relational optimization grade. This proposed methodology gives ample scope for applying the combined Taguchi's with GRA method for optimization of drilling parameters as a part of drill bit tool performance evaluation. Hence, the current study attempts to present the application of GRA in choosing optimum order for drilling on multi-performance features, specifically the circularity error of the drilled hole, temperature and tool wear. Furthermore, the most substantial factors and the order of prominence of the manageable factors for drilling process have been generated.

2.1 Drill tool and workpiece materials employed in the experiment

The experiments are carried out on Ti–6Al–4V alloy material, and the chemical composition is tabulated in Table 1.

Fig. 1 Methodology of the present work

Vibration assisted drilling

Workpiece and drill bits
(Ti-6Al-4V & HSS/WC-C/WC-UC)

Experiment design
(Taguchi L_{27} Orthogonal array)

Temperature measurement (T) (FLIR 60)

Circularity error (C_R) measurement (DEA Global CMM)

Drill bit flank wear (VB) measurement (Direct method)

ANOVA
(To find significant input parameters)

Taguchi coupled Grey Relational Analysis
(For multi objective optimization)

S/N ratio Normalization, etc.

Grey relational coefficients (GRC)

Grey Relational Grade (GRG)

Optimum condition (prediction)

ANOVA for GRG

Correlation of circularity error, temperature and flank wear (regression analysis)

Mathematical modeling (2nd order equations for)		
WC-C	$C_r = 0.00297 + 0.000001\,N + 0.000057\,f - 0.000000\,N^2 - 0.000000\,f^2 - 0.000000\,N{*}f$	93.98
	$T = 94.02 - 0.01104\,N - 0.0604\,f + 0.000001\,N^2 + 0.000122\,f^2 + 0.000002\,N{*}f$	99.51
	$VB = 0.01517 - 0.000000\,N + 0.000012\,f + 0.000000\,N^2 + 0.000000\,f^2 - 0.000000\,N{*}f$	99.73

Drill bit tools made up of three different types namely high-speed steel, tungsten carbide (WC) and tungsten carbide with physical vapour deposition (PVD) TiN coating are cast-off in the experimental investigation. Specifications of the drill bit tools are shown in Table 2, and their properties are presented in Table 3. Chemical composition of the cutting tool materials is given in Table 4.

2.2 Equipment details and specifications

As part of the investigation, experiments have been carried out on a three axis high-speed CNC drilling machine and its specifications are mentioned as follows: CNC machine is programmed with Win CUT software package which runs on standard G/M codes.

Spindle motor of this machine is rated at 3.5 KW with a maximum spindle rotational speed up to 18,000 rpm. Kistler model 8793 accelerometer was mounted on spindle housing
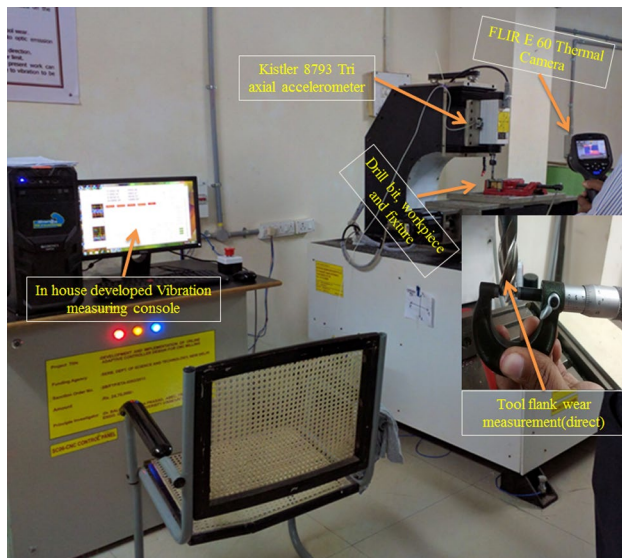
Fig. 2 Investigational test set-up

to enable vibration data acquisition for process monitoring in real time. Discussions related to vibration signal acquisition and signal features are intentionally not included in the present paper. Temperature rise during drilling is measured using FLIR E60 thermal camera [9]. Thermal camera is kept at a constant distance, i.e. 1 m away from the machining zone all through the investigation. Emissivity of Ti–6Al–4V is 0.35. The investigational test set-up is as shown in Fig. 2.

2.3 Experiment design

The design of experiments (DOE) facilitates the designers to resolve both the interactive and individual effects of many aspects simultaneously that can disturb the productivity in any design. In addition, DOE also offers a complete understanding of interaction among design elements. The DOE is a well-ordered course of action for scheduling experimentations so that attained data can be explored to

Table 1 Mechanical properties and chemical composition of workpiece materials Ti–6Al–4V alloy

Workpiece (Young's modulus)	Density (kg/m^3)	Hardness, HV	Yield strength (MPa)	Tensile strength (MPa)	Thermal conductivity (W/m K)
Mechanical properties					
Ti–6Al–4V (120 GPa)	4420	349	880	950	6.7
	Al	Fe	O	Ti	V
Chemical composition of workpiece materials					
Ti–6Al–4V	6	Max.25	Max.25	90	4

Table 2 Specifications of drill bits used for the investigation

Properties	HSS drill	WC drill	PVD (TiN)-coated WC drill
Standard	DIN 338	DIN 338	DIN 338
Diameter (mm)	10	10	10
Material	HSS	Tungsten carbide	Tungsten carbide
Type	2-flute twist drill	2-flute twist drill	2-flute twist drill
Length (mm)	133	133	133
Flute length (mm)	87	87	87
Number cutting edges	2	2	2
Lip length (mm)	4.5	4.5	4.5
Web thickness (mm)	2	2	2
Margin (mm)	1.25	1.25	1.25
Point angle (°)	118	118	118
Helix angle (°)	30	30	30
Relief angle (°)	8–12	8–12	8–12
Lip angle (°)	55	55	55
Coating	Uncoated	Uncoated	coated
Coating thickness (μm)	0	0	2–3
Thermal conductivity (W/m K) 200 °C	23.5	88	110
Cutting direction	Right	Right	Right

Table 3 Properties of the cutting tool materials

Property	HSS	Uncoated WC	PVD-coated (TiN) WC
Coefficient of thermal expansion (W/m K)	41.5	5.5	7.1×10^{-6}/K
Density (g/cm^3)	2.79	15.6	5.4 g/cm^3
Poisson's ratio	0.27–0.30	0.31	0.25
Specific heat (J/kg K)	418	292	184
Young's modulus (GPa)	210	700	250
Melting point (°C)	64	2870	2950
Thermal conductivity (W/m K) 200 °C	23.5	88	110
Hardness (HV)	870	1460	2200
Coating thickness (μm)	–	–	2–3

yield compelling, nearly exact and impartial conclusions. In the present study, three control factors with three levels are taken into consideration for investigation. Table 5 presents the selected levels of the process parameters for the investigation.

Identifying the objectives of the experiment is the initial points of DOE. In order to acquire maximum information possible, a well-defined investigational design should be used. Full factorial method is used for the design of experiments using Minitab-17 software. In full factorial design, if the number of levels is identical for individual factors, then the possible number of trials, N, can be expressed as:

$$N = L^m \tag{1}$$

where L = number of levels for each factor and m = number of factors. The experimentations have been done as per the orthogonal array L_{27} (3^3) as presented in Table 6, to estimate the relationship among the input and the output parameters response variables [10].

3 Modelling of output parameters

A statistical tool called Minitab version 17 is used for experimental data statistical analysis. The optimum machining parameters are identified utilizing Taguchi's S/N ratio charts. ANOVA is employed to determine the most influential process input parameter, and the fraction of participation each contributing process parameter on the attributes of quality has been derived. The GRA in Taguchi method is adopted to

perform multi-objective optimization for process parameters. The primary intension of the present work is to minimize the circularity error, temperature and flank wear. Therefore, in view of the quality features, the "smaller the better" has been preferred for the output response characteristics.

The method of least squares is primarily cast-off for the regression analysis to compute the regression coefficients. In addition, factual functional relationship can be established between Y_{xt} and the set of process parameters in a multiple linear regression model. The process variable of linear function will demonstrate the output response variables. The first-order approximating function is presented as follows:

$$y = \beta_0 + \beta_1 X_1 + \beta_1 X_1 + \cdots + \beta_k X_k \tag{2}$$

The second-order mode must employ the higher degree polynomial:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_{i^2} + \sum_{i} \sum_{<j} \beta_{ij} X_i X_j \tag{3}$$

Table 5 Parameters of the experimental design and their levels

Cutting parameters	Level 1	Level 2	Level 3
Rotational speed, N (rpm)	4200	8400	10,600
Feed rate, f (mm/min)	159	318	400
Drill bit material, D_M (WC-UC)	HSS	Coated tungsten carbide (WC-C)	Uncoated tungsten carbide

Table 4 Composition of drill bit tools

HSS	Si	V	C_r	Mn	Ni	Nb	Mo	Co	Fe
	3.709%	1.95%	3.97%	0.046%	0.688%	0.792%	6.469%	4.382%	77.993%
WC	W		Cu		Zn	Ni		Co	C
	54		20		16	4		3	3

Table 6 Experimental observations

S. no.	Spindle rotational speed, N (rpm)	Feed rate, f (mm/min)	Drill bit material (D_M)	Circularity error C_r (µm)	Cutting temperature, T (°C)	Flank wear, V_B (mm)
1	4200	159	HSS	0.022	351	0.18
2	4200	159	WC-C	0.012	59.9	0.022
3	4200	159	WC-UC	0.014	146.2	0.16
4	4200	318	HSS	0.024	389	0.21
5	4200	318	WC-C	0.015	61.3	0.027
6	4200	318	WC-UC	0.017	151.5	0.18
7	4200	400	HSS	0.028	408	0.23
8	4200	400	WC-C	0.018	63.1	0.033
9	4200	400	WC-UC	0.02	158.4	0.20
10	8400	159	HSS	0.016	462	0.26
11	8400	159	WC-C	0.009	64.6	0.036
12	8400	159	WC-UC	0.015	169.2	0.23
13	8400	318	HSS	0.019	481	0.27
14	8400	318	WC-C	0.012	68.7	0.040
15	8400	318	WC-UC	0.017	173.5	0.25
16	8400	400	HSS	0.02	498	0.30
17	8400	400	WC-C	0.014	73.4	0.042
18	8400	400	WC-UC	0.019	192.8	0.29
19	10,600	159	HSS	0.006	503	0.34
20	10,600	159	WC-C	0.005	83.7	0.047
21	10,600	159	WC-UC	0.011	249	0.32
22	10,600	318	HSS	0.008	557	0.38
23	10,600	318	WC-C	0.011	85.5	0.050
24	10,600	318	WC-UC	0.014	265.0	0.34
25	10,600	400	HSS	0.017	568	0.40
26	10,600	400	WC-C	0.009	90	0.053
27	10,600	400	WC-UC	0.016	289	0.36

One of these models is used in engineering problems for their implementation. Although it is uncertain that the polynomial model will provide exact outcomes for the true functional association over the complete space of the input drilling parameters, nevertheless for a comparatively small zone, they regularly work fairly well.

4 Results and discussion

With an increase in machining time, flank wear, temperature at the tip of the tool and circularity error are measured. The circularity error index (C_r) of the drilled hole represents the quality of the hole and can be determined through experimentation only. Experimental findings obtained concerning circularity error (C_r), temperature (T) and flank swear (V_B) are shown in Table 6.

From the observations presented in results in Table 6, it is established that circularity error drops with rise in rotational speed of the spindle from 4200 to 10,600 rpm, but it augments with raise in feed rate from 159 to 400 mm/min.

4.1 Effect of cutting parameters on circularity error (C_r)

A GLOBAL performance DEA CMM that is the most suitable for performing metrology-related measurements has been used. The new PC-DMIS adaptive scanning function permits the users of any level to grasp superlative scanning performance with accuracy from $1.5 + L/333$ µm. High exactness is ensured in temperature range 16–26 °C. A global performance coordinate measuring machine DEA (07075) is employed to measure the circularity error of drilled holes [11].

From Table 7, it is identified that the spindle rotational speed (N) is the principal effecting drilling parameter which influences the circularity error succeeded by drilling cutter feed rate and material type [12]. Spindle rotational speed affects the circularity error by 39.57%, feed rate by 19.06%

Table 7 Analysis of variance for circularity error

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	p	Contribution (%)
N	2	0.000300	0.000300	0.00015	21.83	0.000	39.57
f	2	0.000145	0.000145	0.000072	10.52	0.001	19.06
D_M	2	0.000176	0.000176	0.000088	12.81	0.000	23.22
Error	20	0.000138	0.000138	0.000007			
Total	26	0.000759					

$S = 0.0026226$; $R^2 = 95.87\%$; $R^2(\text{adj.}) = 94.43\%$

and drill bit material by 23.22%. In the present model, the p value < 0.005 illustrates that the drill tool material, feed rate and rotational speed are the key process parameters. Where, *DF* degree of freedom, Seq.SS sequence sum of square, Adj. SS adjacent sum of squares, Adj.MS adjacent mean square, *F* Fisher's value *P* probability of significance.

Figure 3 shows that a minutest quantity of circularity error transpired at the highest rotational speed considered in the study, i.e. 10,600 rpm and a squat feed rate of 159 mm/min with coated tungsten carbide (WC-C) drill bit.

4.2 Effect of machining parameters on cutting temperature

Figure 4 gives the thermal images which indicate the temperature variations with respect to different drill bit materials investigated in the present study. Figure 4a shows the drilling zone with work piece and drill bit set-up, and Fig. 4b gives the usage of FLIR E60 thermal camera for temperature measurement in real time. Temperature variations with HSS drill while drilling holes on Ti–6Al–4V specimens are presented in Fig. 4c, d. Figure 4c indicates the initial stage, and Fig. 4d represents the final stage with HSS drill tool. Similarly, Fig. 4e (uncoated WC drill bit tool) and Fig. 4g

(PVD-TiN-coated WC drill bit tool) shows the temperature rise at initial stages. Whereas Fig. 4f (uncoated WC drill bit tool) and Fig. 4h (PVD-TiN-coated WC drill bit tool) presents the temperature rise levels at ending stages of respective machining condition programmed in the investigation.

From Table 8, it is identified that the drill bit material type (D_M) is the key cutting parameter which influences the temperature followed by the spindle rotational speed (N) and feed rate (f). The drill bit material type affects the temperature by 91.54%, the rotational speed by 5.64% and feed rate by 0.44%.

From Table 8, the parameter p value < 0.005 specifies that the spindle rotational speed and drill tool material remain the major influential parameters of process in the model, whereas for temperature, the feed rate was observed to remain a less significant parameter. The outcome of variable rotational speed of the spindle, feed rate and drill tool material on temperature is displayed in Fig. 5. It can be observed from Fig. 6 that the temperature increases at augmented rotational speed from 4200 to 10,600 rpm and also ascends with amplified feed rate from 159 to 400 mm/min.

From Fig. 5, it is clear that the temperature rise is the highest while drilling the work piece with high-speed steel drill bit tool among three different drill bits, irrespective of

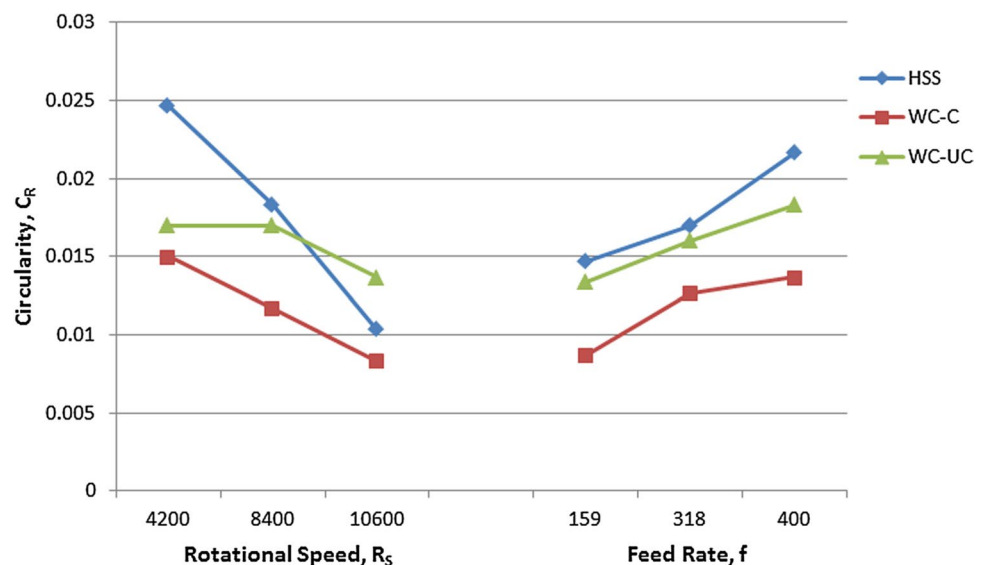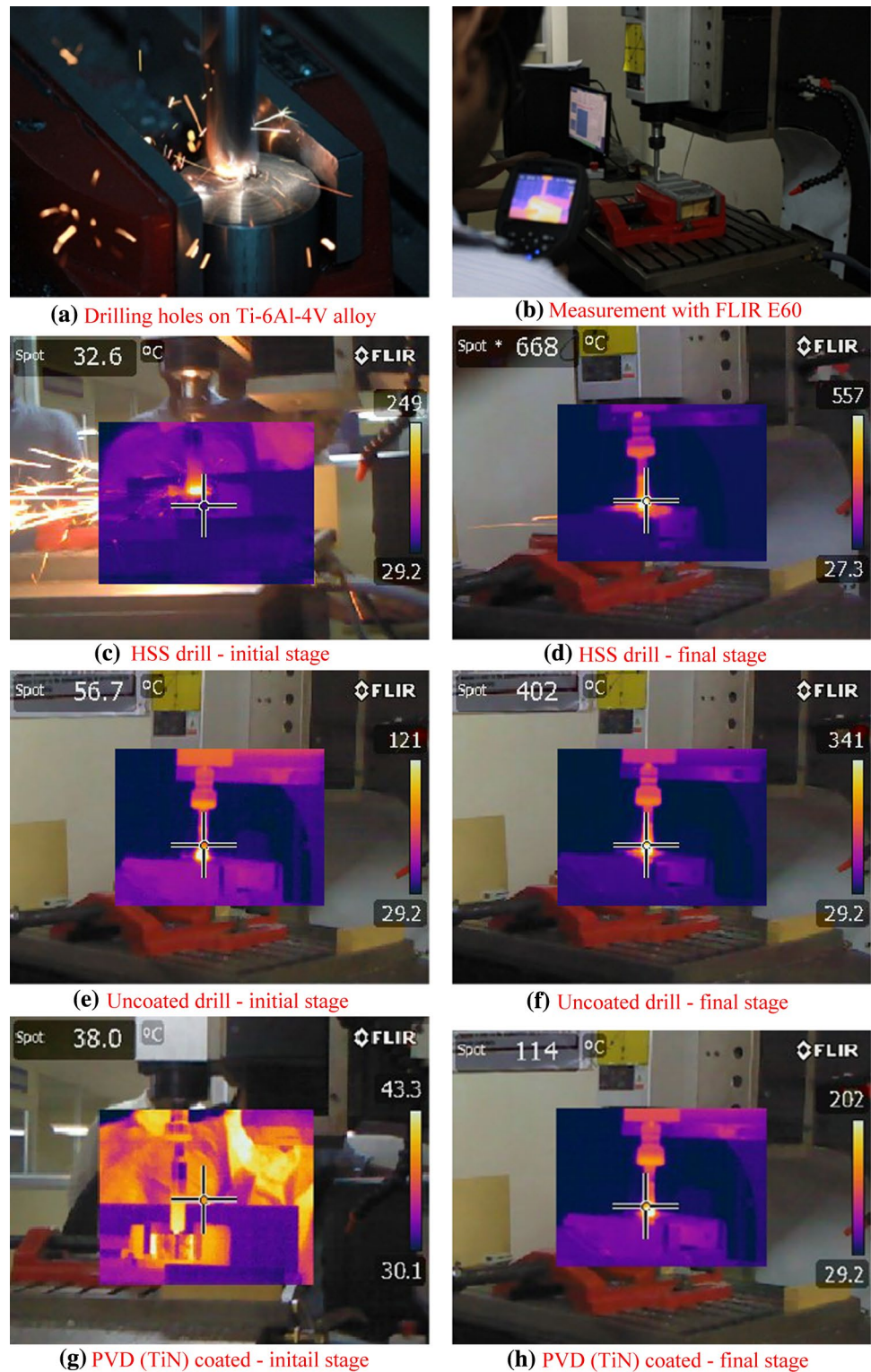**Fig. 3** Main effect plots for circularity error

Fig. 4 Temperature measurements with FLIR 60 thermal camera with different drill bits

(a) Drilling holes on Ti-6Al-4V alloy

(b) Measurement with FLIR E60

(c) HSS drill - initial stage

(d) HSS drill - final stage

(e) Uncoated drill - initial stage

(f) Uncoated drill - final stage

(g) PVD (TiN) coated - initail stage

(h) PVD (TiN) coated - final stage

machining combination. As expected [13], cutting temperature increased with the elevation of rotational speed in titanium drilling with PVD-coated drill as well, but this tendency is more predominant with HSS drill bit. The reason may be that material removal rate increased significantly with increase in the feed rate which resulted in increased heat generation [14].

Table 8 Analysis of variance for 'temperature'

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	p	Contribution (%)
N	2	45,413	45,413	22,707	23.80	0.000	5.64
f	2	3554	3554	1777	1.86	0.181	0.44
D_M	2	737,027	737,027	368,514	386.19	0.000	91.54
Error	20	19,085	19,085	954			
Total	26	805,080					

$S = 30.8906$; $R^2 = 97.63\%$; $R^2(\text{adj.}) = 96.92\%$
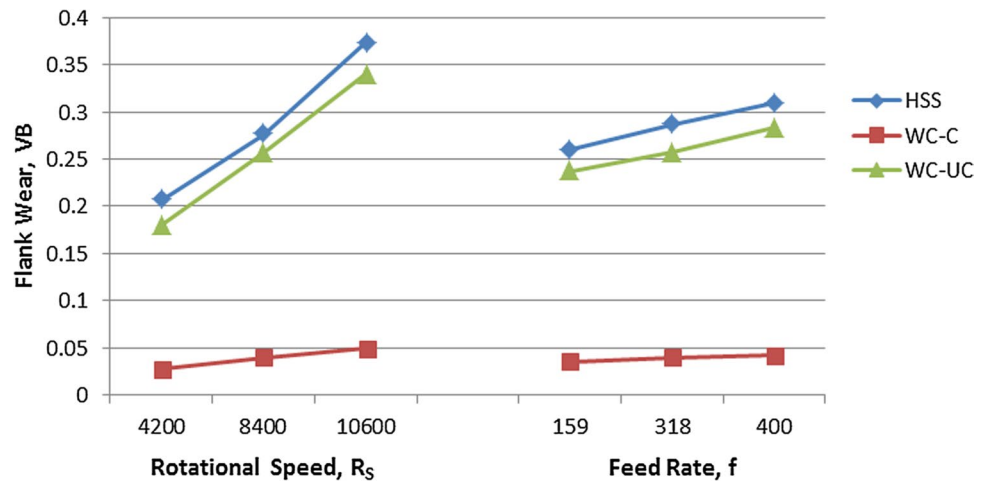
Fig. 5 Main effect plots for temperature
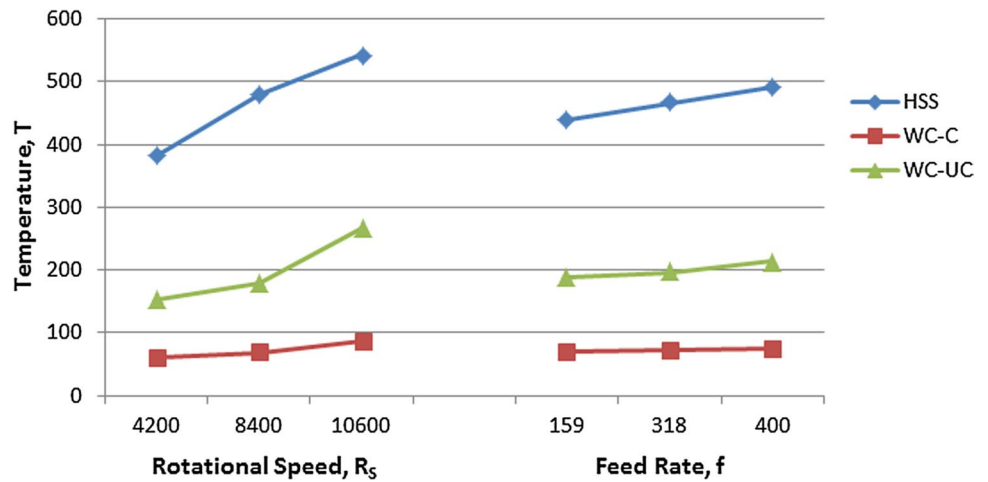
Fig. 6 Main effect plots for flank wear

4.3 Effect of cutting parameters on flank wear

Drill bit tool's flank wear can be measured by direct method as shown in Fig. 1. For a drill bit, flank wear is represented with (V_B) in mm, which can be calculated according to the following relation:

$$V_B = \left(\frac{1}{\tan\gamma - \tan\alpha} \right) * \left(\frac{\Delta D}{2} \right) \text{ mm} \qquad (4)$$

where α is the rake angle of the drill tool (in degrees), γ is the helix angle of the drill bit (in degrees) and ΔD is the change in the diameter of the drill bit (mm) due to tool wear. From Table 9, it is found that the drill bit material type is the chief impelling cutting process parameter which influences the drill bit flank wear (V_B) followed by the rotational speed of the spindle (N) and feed rate (f) [15]. The drill bit material type affects the flank wear by 78.79%, the rotational speed by 14.61% and feed rate by 1.3%. The statistical parameter p value < 0.05 implies that the drill bit material type and rotational speed are the two foremost process parameters in

Table 9 Analysis of variance for 'flank wear (V_B)'

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	p	Contribution (%)
N	2	0.061188	0.061188	0.030594	27.63	0.000	14.61
f	2	0.005444	0.005444	0.002722	2.46	0.111	1.30
D_M	2	0.329867	0.329867	0.164933	148.94	0.000	78.79
Error	20	0.022148	0.022148	0.001107			
Total	26	0.418647					

$S = 0.0332778$; $R^2 = 94.71\%$; $R^2(\text{adj.}) = 93.12\%$

the model, and it is also identified that the influence of feed rate is very minimal in the process.

Figure 6 shows the outcome of variable feed rate, spindle rotational speed and drill tool material on flank wear values. From Fig. 6, it can be observed that the wear of the flank is amassed with rise in rotational speed of the spindle from 4200 to 10,600 rpm. Flank wear values exhibit similar trend with increase in feed rate from 159 to 400 mm/min.

From Fig. 6, it is clear that the flank wear values are found to be small as long as machining is carried out with coated tungsten carbide drill.

4.4 Phases aimed at optimization by grey relational analysis (GRA)

In this work, GRA along with the Taguchi technique is used to optimize the process parameters of drilling. Computing the resultant responses is the foremost step, i.e. S/N ratio values either smaller is better or larger is better type problem based on the output variables [16, 17]. The normalized original order will attain the required objective value. Otherwise, original order can simply be normalized using straightforward methodology, i.e. allow the values of the inventive order be divided by the starting value of the order:

$$X_i^*(K) = \frac{X_i^0(K)}{X_i^0(1)} \tag{5}$$

where $X_i^*(K)$ is the order after the data pre-processing and X_i^0 is the desired value of $X_i^0(K)$, where $i = 1,2,3\ldots m$; $k = 1,2,3,\ldots n$. Where m is the experimental data item number, n is the parameter number and $X_i^0(K)$ denotes the original order [18]. Normalized S/N ratio value of the response variables and their results are tabulated in Table 10.

The next step in the grey relational analysis is to quantify the grey relation grade (GRG). The GRG is defined as the measure of relevancy among two orders or two systems. In the measurement of local grey relation, all the orders are compared with the reference order $X_i^0(K)$. After processing the data once, the Kth performance characteristics of the GRC in the ith experiment can be operated by:

Table 10 Grey relational coefficients and grey relational grade (GRG) values

Exp. no.	Grey relational coefficient (GRC)			Grey relational grade (GRG)	Rank
	C_r	T	V_B		
1	0.657	0.539	0.462	0.512	11
2	0.418	0.333	0.333	0.361	27
3	0.451	0.376	0.441	0.400	21
4	0.742	0.587	0.499	0.560	8
5	0.469	0.334	0.336	0.379	24
6	0.511	0.379	0.462	0.425	19
7	1.000	0.614	0.526	0.650	3
8	0.535	0.335	0.340	0.401	20
9	0.590	0.383	0.486	0.453	15
10	0.489	0.706	0.574	0.552	9
11	0.377	0.335	0.342	0.366	26
12	0.469	0.389	0.526	0.434	17
13	0.561	0.745	0.592	0.595	6
14	0.418	0.337	0.344	0.375	25
15	0.511	0.392	0.558	0.457	14
16	0.590	0.784	0.654	0.619	5
17	0.451	0.339	0.346	0.395	22
18	0.561	0.404	0.632	0.494	13
19	0.343	0.796	0.759	0.638	4
20	0.333	0.344	0.349	0.389	23
21	0.404	0.443	0.703	0.506	12
22	0.365	0.958	0.904	0.771	2
23	0.404	0.345	0.351	0.430	18
24	0.451	0.456	0.759	0.526	10
25	0.511	1.000	1.000	0.878	1
26	0.377	0.347	0.353	0.446	16
27	0.489	0.477	0.825	0.568	7

$$\zeta(K) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(K) + \zeta\Delta_{max}} \tag{6}$$

where $\Delta_{0i}(K)$ is the reference order $X_o^*(K)$ deviation and the comparability order $X_i^*(K)$. ξ is the coefficient of identification or distinctive well-defined in the range of $0 \leq \xi \leq 1$ (this value can be in tune with the real-world requirements of the

Table 11 Grey relational grade (GRG) average effects

Level	Rotational speed, N	Feed rate, f	Drill bit material, D_M
1	0.46	0.476	0.572
2	0.462	0.501	0.544
3	0.641	0.393	0.473
Delta	0.181	0.108	0.098
Rank	1	2	3

system). If the value of ξ is the small and the distinguished ability is the large, once grey relational coefficient (GRC) is determined, take the average of the GRC as the GRG. The following relationship is used to calculate GRG:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \zeta_i(K) \tag{7}$$

The GRA is carried out by evaluating the GRC for normalized S/N ratio values, and the resulting GRG values are shown in Table 11 using Eqs. (6) and (7).

4.5 Determination of optimum process parameter combination

From the analysis of drilling process, it is clearly evident that the lower circularity error and lesser cutting temperature value as well as lower value of tool flank wear provide drilled holes with better quality. Consequently, the data orders circularity error, cutting temperature and tool flank wear pinpoint the "smaller-the-better" characteristics. Higher GRG indicates better machinability combination hence the quality of the product is better. Consequently, on the basis of higher GRG or the rank, the optimal process parameters level can be achieved.

4.6 Identification of significant factor

In order to realize the remarkable factors on measurement, analysis of variance ANOVA for GRG is used as an analytical tool by observing the association among the proposed factor and response variable.

Taguchi method cannot choose the outcome of distinct drilling process parameters on the entire process; therefore, the fraction of involvement is premeditated by means of ANOVA on its behalf. Empirical Eq. (7) is utilized to compute average GRG values and is presented in Table 11. The specific effects of input factors on GRG are presented in Fig. 7. The utmost influencing factor on the GRG is

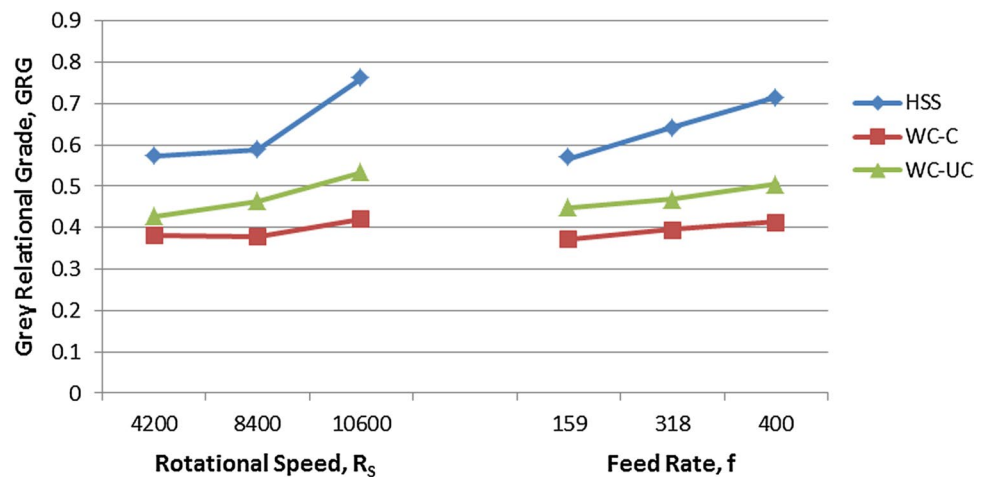**Fig. 7** Variation in factors on the grey relational grade (GRG)

Table 12 ANOVA for grey relational grade

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	Contribution (%)
N	2	0.06622	0.06622	0.033110	16.87	16
f	2	0.03085	0.03085	0.015423	7.86	7
D_M	2	0.28917	0.28917	0.144586	73.67	68
Error	20	0.03925	0.03925	0.001963		9
Total	26	0.42549				

identified as drill bit material type (68%), followed by the rotational speed (16%) and feed rate (7%), and these results are tabulated in Table 12.

4.7 Prediction of optimum condition

At the optimum condition, an anticipated mean is given by:

$$\mu_{pred} = \overline{V_3} + \overline{F_3} + \overline{DB_1} - 2x\overline{T_{AGG}} \tag{8}$$

where $\overline{V_3}$, $\overline{DB_2}$ and $\overline{F_1}$ are the average values of GRG concerning to the best operational condition input process parameters. $\overline{T_{AGG}}$ is the average GRG of the complete experimentations. Consequently, the optimum condition predicted mean from Eq. (9) is

$$\mu_{pred} = 0.9333. \tag{9}$$

5 Mathematical modelling

The regression analysis [19] is used to determine the correlation of cutting temperature; circularity error and tool wear with drilling process parameters. In the present work, to forecast the minimum cutting temperature, tool wear and circularity error under every condition with an objective to evaluate the tool performance level, regression analysis is used. The second-order equations of the circularity error, cutting temperature and tool wear are presented in Table 13.

6 Confirmation of the experimentation

The confirmation experimentation is carried out at the optimal conditions to confirm the quality features while drilling of Ti–6Al–4V alloy. The response values by the confirmation experimentation [20] succession at the optimal condition are $C_r = 0.009$ μm, $T = 90$ °C and $V_B = 0.053$ mm. The GRG value as per the above discussion is 0.9512. This outcome is inside the 95% confidence level of the anticipated optimal condition, and moreover, GRA value of confirmation experiment enhanced by 2% from the forecasted mean value. Therefore, the GRA built on Taguchi method for the optimization of the multi-response problems is a very beneficial tool for forecasting the circularity error, cutting temperature and drill bit tool wear in the drilling of Ti–6Al–4V alloy specimens.

7 Conclusions

Drilling experimentations have been carried out with high-speed steel, tungsten carbide and TiN-coated tungsten carbide twist drill and Ti–6Al–4V alloy as work material. Circularity error, cutting temperature and drill bit tool wear values have been collected under different machining conditions. The subsequent conclusions are drawn:

- Grey relational analysis together with Taguchi method for the optimization of the multi-response problems is a very beneficial means for forecasting the circularity error, cutting temperature and tool wear in the drilling.
- From the GRA analysis, it is discovered that cutting tool material, rotational speed of the spindle and feed rate are protuberant issues which disturb the drilling of difficult to cut material like Ti–6Al–4V alloy.
- Drill bit material influences ($D_M = 73.67\%$) more, followed by rotational speed ($N = 16.87\%$) and feed rate ($f = 7.86\%$). The best performance features are attained with TiN-coated tungsten carbide twist drill bit when drilling with higher feed of 400 mm/min and higher rotational speed of 10,600 rpm at constant cutting point angle.
- Confirmation test outcomes demonstrated that the determined optimal condition of drilling process parameters to fulfil the real necessities of drilling operation.

Table 13 Modelling for response-based experimental data

Eqn. no.	Drill bit material	Responses	R^2 (%)
10	HSS	$C_r = 0.0277 + 0.000002\,N - 0.000086\,f - 0.000000\,N^2 + 0.000000\,f^2 + 0.000000\,N{*}f$	95.90
11		$T = 243.8 + 0.0124\,N + 0.293\,f + 0.000001\,N^2 - 0.000173\,f^2 + 0.000003\,N{*}f$	99.18
12		$V_B = 0.2691 - 0.000038\,N - 0.000097\,f + 0.000000\,N^2 + 0.000000\,f^2 + 0.000000\,N{*}f$	99.49
13	WC-C	$C_r = 0.00297 + 0.000001\,N + 0.000057\,f - 0.000000\,N^2 - 0.000000\,f^2 - 0.000000\,N{*}f$	93.98
14		$T = 94.02 - 0.01104\,N - 0.0604\,f + 0.000001\,N^2 + 0.000122\,f^2 + 0.000002\,N{*}f$	99.51
15		$V_B = 0.01517 - 0.000000\,N + 0.000012\,f + 0.000000\,N^2 + 0.000000\,f^2 - 0.000000\,N{*}f$	99.73
16	WC-UC	$C_r = 0.00421 + 0.000003\,N - 0.000001\,f - 0.000000\,N^2 + 0.000000\,f^2 - 0.000000\,N{*}f$	98.74
17		$T = 362.2 - 0.06577\,N - 0.368\,f + 0.000005\,N^2 + 0.000624\,f^2 + 0.000016\,N{*}f$	99.80
18		$V_B = 0.2162 - 0.000021\,N - 0.000286\,f + 0.000000\,N^2 + 0.000001\,f^2 + 0.000000\,N{*}f$	99.58

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