SELECTION OF APPROPRIATE FLUID DELIVERY TECHNIQUE FOR GRINDING TITANIUM GRADE-1 USING THE ANALYTIC HIERARCHY PROCESS

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ABSTRACT

Grinding is commonly used in industry for the finishing or semi-finishing of different mechanical components. In this process, a wheel is rotated at a high speed. The wheel is made of abrasive particles known as grits. During grinding, high grinding zone temperature is experienced leading to several grinding defects. To control these thermal defects grinding fluid is usually employed mainly to cool and lubricate the grinding region. However, most of the applied grinding fluid cannot reach the grinding zone as it is deflected by the stiff air layer formed around the wheel periphery. Several attempts have been made in the past to overcome this problem in order to guarantee better fluid delivery. In this paper, two newly developed methods, a pneumatic barrier and a compound nozzle are considered to serve this purpose. Grinding experiments are conducted on titanium grade-1 specimens under four environmental conditions, which include dry, flood cooling, flood cooling with pneumatic barrier set up and cooling using a compound nozzle. Under each environment, 10 grinding passes are undertaken using 10, 20 and 30 μm infeed. Data obtained are used to optimize the grinding performance by employing the Analytic Hierarchy Process (AHP). The AHP results show compound nozzle fluid delivery at 20 μm infeed to be the appropriate condition for grinding titanium grade-1 within this experimental domain. This condition is supposed to deliver grinding fluid deep into the grinding zone thereby controlling grinding temperature effectively and may be recommended to the industry.

Keywords: Grinding; grinding fluid; fluid delivery technique; pneumatic barrier; surface roughness; grinding forces; flood cooling nozzle; compound nozzle; Analytic Hierarchy Process; AHP; grinding titanium grade-1; optimization

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1. Introduction

Surface grinding is done using an abrasive wheel rotating at a high speed. In grinding, a high temperature is generated at the grinding zone, and this high temperature is the cause of several grinding defects. To control for these thermal defects grinding fluid is usually employed. Engineer et al. (1992) observed that only 4 to 30% of grinding fluid passes through the grinding zone in flood cooling systems, and hence, a large quantity of grinding fluid is wasted. Formation of a stiff air layer around the periphery of a rotating grinding wheel is the prime reason for wastage of the grinding fluid. Researchers (Inasaki, 1998; Rowe, 2009; Wu et al., 2007) have found that the generation of an air layer around a rotary grinding wheel is due to viscous friction between the wheel surface and the air in its vicinity, and because of the centrifugal force developed due to high rotational speed of the wheel. Morgan et al. (2008) and Parthasarathy & Malkin (2009) investigated the effect of different grinding fluid delivery systems on grinding performance, and finally recommended certain conditions of fluid delivery to give desired grindability. Several attempts were made to control this air layer and to increase the grinding fluid penetration into the grinding zone (Brinksmeier et al. 1999; Ebbrell et al., 2000; Irani et al., 2005; Morgan et al., 2008; Palhade et al., 2009; Parthasarathy & Malkin, 2009). Different grinding fluid delivery techniques were developed for this. Mandal et al. (2011a) reported that if rexine is pasted to both side faces of the grinding wheel, then less air pressure is developed near the wheel. This is likely due to the suppression of the axial suction of the air through the grinding wheel pores so that the centrifugal throw of air gets substantially reduced. A newly developed compound nozzle fluid delivery system and pneumatic barrier setup were reported to be successful grinding fluid delivery techniques (Mandal et al., 2011b; 2012; 2014).

The performance of applying a grinding fluid for different workpiece materials varies widely, particularly when grinding exotic, difficult-to-grind materials. Titanium alloys are an example of this kind of material due to their typical adhesion characteristics and mechanical properties. Titanium alloys are extensively used as bio transplants and in the areas of aeronautics, cryogenic vessels, etc. Hence, although it is a challenge to the machining person it is absolutely necessary to find the appropriate condition for good grinding performance. Turley (1985), Xu et al. (2003), Teicher et al. (2006) and Palhade et al. (2009) carried out detailed investigations on some titanium alloys under different grinding environments using different grinding wheel materials. They compared the grinding performance at each of the conditions used and put forward some recommendations. Biswas et al. (2012) and Mandal et al. (2013) carried out experimental investigations on grinding titanium grade 1 using silicon carbide and alumina wheels respectively. Biswas et al. (2012) could perform grinding operations in wet condition with some success using a typically designed compound nozzle, while Mandal et al. (2013) reported grinding a similar workpiece in wet conditions using a pneumatic barrier system.

The grindability of any material is generally dependent on the properties of the workpiece material, type of grinding wheel and parametric condition of grinding and its environment. Hence, it becomes difficult to make a decision about the appropriate grinding condition when variations of parameters and environmental conditions increase. Different methods using fuzzy set theory, genetic algorithm, neural networks, etc. were applied by different groups of researchers such as Morgan et al. (2008), Sun et al. (2001) and others to solve decision making problems and find the best alternative or condition among many choices. The Analytic Hierarchy Process (AHP) is widely used in various fields of managerial decision-making and similar cases to solve multi-objective decision making problems (Saaty, 1977; 1980; Vargas, 1990; Wu et al., 2007; Sabiruddin et al., 2013). It is a simple but powerful and flexible decision making tool to solve various complex multi-criteria decision making

(MCDM) problems hierarchically. Sun et al. (2001) reported a two-grade fuzzy synthetic decision-making system with the use of the Analytic Hierarchy Process (AHP) for evaluating the performance of grinding fluid. Some researchers also used the AHP to determine grinding performance (Huang et al., 2005; Wang et al., 2006; Shi et al., 2008).

In the present experimental work, grinding experiments are performed on a titanium grade 1 workpiece with varying infeed under different environmental conditions, such as dry, conventional flood cooling, flood cooling with pneumatic barrier and cooling with compound nozzle. A comparison is made among all these conditions with respect to grinding forces, surface quality, grinding chip, wheel wear, etc. The observations made in the grinding experiments are then used to determine the optimized condition to obtain good grindability using the Analytic Hierarchy Process (AHP).

2. The Analytical Hierarchy Process applied

In the present work, a simple Analytical Hierarchy Process (AHP) is considered which is similar to that used by Sabiruddin et al. (2013). The hierarchy structure chosen is shown in Figure 1. At the top of the hierarchy structure, there is the goal or the objective of this study which is the selection of a grinding condition with good grindability.

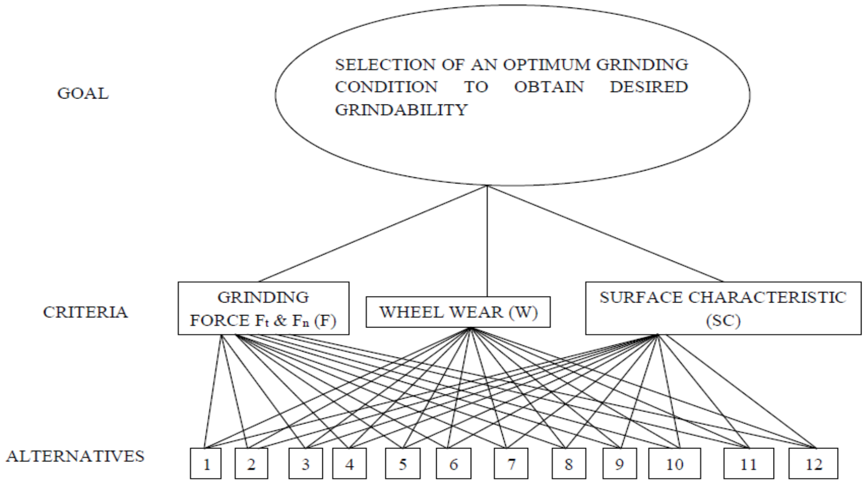

Figure 1. The hierarchy structure chosen

The grindability, or the ease of grinding of a workpiece-grinding wheel combine, is judged by (Engineer et al., 1992; Rowe, 2009):

i) Grinding force, grinding energy or specific grinding force (grinding force per unit volume of material removed) requirement, or F ratio (ratio of tangential force component and normal force component)
ii) Grinding temperature
iii) Wheel grit wear, wheel material loss, or G ratio (material removal rate, MRR / wheel material removal, WMR)
iv) Ground surface quality including surface finish and integrity, that is, absence of open and sub-surface cracks or tensile residual stresses
v) Favourable chip formation

For good grindability, grinding force or energy requirement should be less, grinding temperature is to be as low as possible, wheel grit wear or wheel material removal is

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to be low, and surface quality is to be good. Chips produced should be predominantly of the slice type with much less spherical type chips. In the present work, three grindability judgement characteristics are considered such as grinding force, wheel wear and surface integrity. Therefore, these three criteria are in the hierarchy structure (Figure 1). Twelve alternatives corresponding to the experimental runs conducted at three infeed and four environmental conditions are chosen in this work.

The pair wise comparison matrices are constructed by comparing an element with the elements of the next higher level. This helps to determine the local priority weights. A typical pair wise comparison matrix is shown in Equation 1.

$$A = \begin{array}{lllllll} \hline C & E_1 & E_2 & E_3 & \ldots\ldots\ldots & \ldots\ldots\ldots & E_n \\ \hline E_1 & a_{11} & a_{12} & a_{13} & \ldots\ldots\ldots & \ldots\ldots\ldots & a_{1n} \\ E_2 & a_{21} & a_{22} & a_{23} & \ldots\ldots\ldots & \ldots\ldots\ldots & a_{2n} \\ E_3 & a_{31} & a_{32} & a_{33} & \ldots\ldots\ldots & \ldots\ldots\ldots & a_{3n} \\ \ldots & \ldots & \ldots & \ldots & \ldots\ldots\ldots & \ldots\ldots\ldots & \ldots \\ E_n & a_{n1} & a_{n2} & a_{n3} & \ldots\ldots\ldots & \ldots\ldots\ldots & a_{nn} \\ \hline \end{array} \qquad \textbf{(1)}$$

In Equation 1, each matrix element, a_{ij} represents the strength of preference of the alternative E_i over E_j with respect to the criterion (C), $a_{ji} = 1/a_{ij}$ and $a_{ii} = 1$ for values of i and j from 1 to n. Values of a_{ij} are selected from the ratio scale enlisted in Table 1. Next, consistency of the matrix is checked through calculation of consistency ratio (CR) that is given by CR = (CI/RI).

Table 1
Ratio Scale of Comparison Matrix

Preferential Judgment	Rating
Extremely Preferred	9
Very Strongly to extremely preferred	8
Very strongly preferred	7
Strongly to very strongly preferred	6
Strongly preferred	5
Moderately to strongly preferred	4
Moderately preferred	3
Equally to moderately preferred	2
Equally preferred	1

The consistency index (CI) = $(\lambda_m\text{-}n)/(n\text{-}1)$ and the random index (RI) is the consistency index of a matrix with random numbers from (1/9, 1/8, 1/7, ……..1……..7, 8, 9) scale. λ_m is the largest Eigen value of the matrix A with n being the size of the matrix. A consistency ratio of less than or equal to 10% is acceptable.

Local weights, w_i are evaluated through Equation 2.

$$w_i = \sum_{j=1}^{n}(aij * wi)/\lambda m, \; i = 1, 2, 3, \ldots.. n \qquad \textbf{(2)}$$

When P_j (j = 1, 2, 3, ……. m) are the priority weights of n alternatives for the j^{th} criterion, and q_{ij} are the priority weights of the criteria, the global weights (r_i) of the alternatives are determined (Saaty, 1977; Saaty, 1980; Sabiruddin et al., 2013) from equation (3).

$$r_i = \sum_{j=1}^{m}(Pj * qij), \; i = 1, 2, 3, \ldots\ldots n \qquad \textbf{(3)}$$

The global weight of the largest value is considered to be the optimum value indicating the decision.

3. Experimental details

Experimental details are shown in Table 2. The grinding performance is observed under different conditions during surface grinding of a titanium grade 1 specimen. A wheel velocity of 30 m/s and a table feed of 7 m/min are maintained throughout the experiment. Three infeed of 10μm, 20 μm and 30 μm are chosen. Four environmental conditions including dry, flood cooling, flood cooling with pneumatic barrier and cooling with compound nozzle are considered to observe their effects. Up grinding mode is followed for all the experiments. Ten grinding passes are undertaken at each condition.

In flood cooling, the grinding fluid is allowed to pass through a commonly used nozzle (outer diameter 6 mm) placed 10 mm above the workpiece. Its discharge is 1000 ml/min. However, only 350 ml/min of the fluid was found to go through the wheel-workpiece contact zone (Mandal et al., 2014). Correspondingly, some cooling and lubricating effects could be observed. The grinding fluid is expected to have a better effect when the pneumatic barrier setup is used along with flood cooling, as the high air velocity coming out of the pneumatic nozzle may disturb the stiff air layer formed around the wheel resulting in better entry of the grinding fluid into the grinding zone. A pneumatic gauge pressure of 400 mm of water column, or 3.90 kPa, is employed. In this work, a pneumatic nozzle at a radial distance of 10 mm from the wheel periphery is positioned at a swivel angle (α) of 30^o and polar angle (θ) of 45^o as has been recommended in other works (Mandal et al., 2011b; 2012). This configuration is shown schematically in Figure 2, and its photograph is depicted in Figure 3. Discharge of grinding fluid is kept at 1000 ml/min.

For the compound nozzle fluid delivery system, a specially designed and fabricated nozzle is used. The fluid delivery through this nozzle is set at 475 ml/min, as this discharge (that is 52.5% less than that used in the flood cooling experiments) has already been reported by Mandal et al. (2014) to break the stiff air layer without using a pneumatic barrier. A schematic diagram indicating the compound nozzle is given in Figure 4.

Table 2
Experimental details

Grinding machine	Surface grinding machine Make: Maneklal & Sons, India Main motor power: 1.5 kW
Grinding wheel used	Specification: AA 46/54 K5 V8 Make: Carborandum Universal Limited, India Size : ϕ200 mm x 13 mm x ϕ31.75 mm
Dressing detail	Dressing tool: Single point 0.5 carat diamond dresser Dressing depth: 20 µm Speed of dressing: 0.36 m/min
Grinding condition	Mode of grinding: Up grinding Grinding wheel velocity (Vc): 30 m/s Table feed: 7 m/min Infeed: 10, 20 and 30 µm
Grinding environment	Dry Wet with water soluble oil (1:20) ➢ Flood cooling with a flow rate of 1000 ml/min ➢ Flood cooling using pneumatic barrier with a flow rate of 1000 ml/min ➢ Fluid delivery using compound nozzle with a flow rate of 475 ml/min
Pneumatic barrier setting	Polar angle (θ): 45^o Swivel angle (α): 30^o Pneumatic barrier pressure: 400 mm of water column (3.90 kPa)
Workpiece detail	Titanium grade- 1 Composition: 99.85% Ti, 0.01% N, 0.12% Fe and 0.02% O Hardness: 220 HB, Size: 120 mm x 65 mm x 6 mm

A Sushma Industries, Bengaluru, India made 3 channel strain gauge grinding dynamometer (model: SA116) is used for measuring grinding force components (tangential, Ft and normal, Fn). The surface roughness of the ground surface is measured after ten passes using Surtronic 3+ talysurf (make: Taylor Hobson, India). The ground surface is observed under a Mitutoyo, Japan made tool makers microscope. With it, the grinding chips collected during the 9th pass are examined in order to determine their forms. The grinding wheel wear is measured using a Mitutoyo, Japan made dial indicator. Wheel loading, that is, the phenomenon in which chip particles get attached within intergrit spaces, is noted visually after each experiment. All the experiments are replicated once, and the averaged data are used for the analysis.

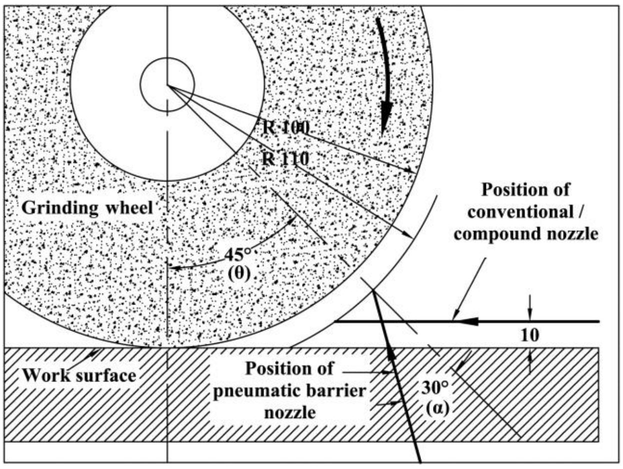

Figure 2. Schematic representation of the cooling arrangement

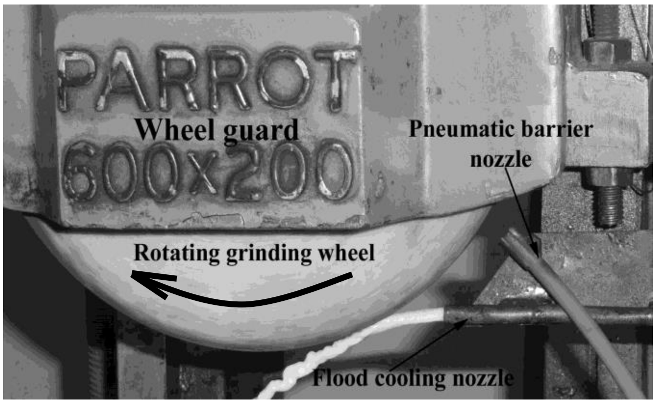

Figure 3. Photograph of the pneumatic barrier setup

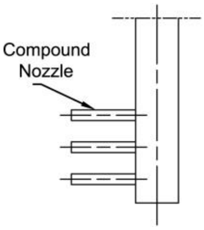

Figure 4. Schematic diagram of the compound nozzle

4. Experimental results and discussions

Results of the grinding experiments on titanium grade 1 under different grinding conditions are represented in Table 3. These data are used to determine the appropriate condition to obtain the best grindability within this experimental domain utilizing the AHP.

Both the tangential (Ft) and normal (Fn) grinding forces in all experimental conditions considered are presented in Table 3. The grinding forces at the 5th and 10th pass and their maximum values at each experiment are shown in Table 3. It is observed that both the grinding forces are lower at grinding with the compound nozzle fluid delivery system than that at the other environmental conditions. When the flood cooling with pneumatic barrier system is used, it requires slightly higher forces than with the compound nozzle system, but significantly less than the dry and flood cooling systems. This shows that there is better penetration of grinding fluid into the grinding zone with the pneumatic barrier than the common flood cooling system. The flood cooling also shows only small improvement over the dry condition as most of the grinding fluid applied cannot reach the grinding zone. Corresponding to this reason, expectedly, less chip re-deposition/ grit indentation and less presence of wheel wear are observed while using the compound nozzle. This indicates the favoured grinding situation with the compound nozzle fluid delivery system that may have caused better temperature control through supplying a larger quantity of the grinding fluid into the grinding zone by penetrating the stiff air layer covering the wheel. Better lubrication properties and longer retention of the grit sharpness may have resulted in less force requirement.

Table 3
Comparison of grinding environment for titanium grade- 1

Response		Grinding environment											
		Dry			Flood cooling			Flood cooling with pneumatic barrier			Cooling with Compound Nozzle		
		Infeed in µm			Infeed in µm			Infeed in µm			Infeed in µm		
		10	20	30	10	20	30	10	20	30	10	20	30
Ft (N)	5th pass	11.8	16.7	20.6	10.8	14.2	19.6	10.3	13.7	15.7	9.8	12.3	15.7
	10th pass	12.8	15.7	20.6	10.3	14.7	14.7	8.3	12.3	12.8	8.3	10.8	10.8
	Max	13.2	17.7	25.5	11.3	15.7	19.6	10.3	13.7	16.7	10.3	12.3	15.7
Fn (N)	5th pass	47.6	64.7	78.1	42.2	53.5	68.7	41.2	49.1	57.4	34.3	42.2	57.9
	10th pass	43.7	58.9	84.9	41.2	49.5	57.4	40.7	41.7	54.0	39.2	40.2	51.0
	Max	49.1	64.7	91.2	45.1	59.4	68.7	44.1	50.0	58.9	39.2	47.1	57.9
Average surface roughness		2.88	3.27	3.3	2.4	2.71	2.51	2.02	1.77	2.39	1.73	1.41	1.81
Surface burn		Few	Few	Severe	No	Few	Severe	No	No	Few	No	No	Few
Chip re-deposition		Few	Few	Large	Few	Few	Large	No	No	Few	No	No	Few
Surface cracks		No	Yes	Yes	No	No	Yes	No	No	Yes	No	No	Yes
Chip forms observed		S, Sl	S, Sl	S, Sl	S, Sl	S, Sl	S, Sl	S, Sl, L	S, Sl	S, Sl	S, Sl, L	S, Sl	S, Sl
		Note: L: Long curl chips, S: Short segmented chips, Sl: Slice type chips											

From Table 3, it is observed that the average roughness values under different infeed conditions are lower under the compound nozzle fluid delivery condition than the dry, the flood cooling and the flood cooling with pneumatic barrier conditions. Observing the surface burn, surface crack, chip formation and chip redeposition, it may be stated that there is no remarkable difference between the flood cooling with pneumatic barrier system and the fluid supply through compound nozzle system. Within these four grinding environments, it is observed that the compound nozzle system apparently performs better than the other three conditions. The AHP, a decision making tool, is used in this work to select the best fluid delivery technique within the domain of this experimental investigation.

5. Optimisation using the AHP

There are twelve alternatives corresponding to twelve sets of grinding experiments. There are three infeed which are 10 µm, 20 µm and 30µm, and four environmental conditions. Ten grinding passes are conducted at each experimental run. Values of different response parameters that are evaluated for obtaining the optimum grinding performance in this work are shown in Tables 4 through 7. Table 4 lists the average tangential force (F_t) and normal force (F_n) components of each experimental run or alternative. Values of force components obtained from the 6th through the 10th pass are noted, and their mean values are the averaged F_t or F_n values. Readings of the first five passes were not taken because after the initial four or five passes the grinding process gets somewhat stabilized and starts grinding truly with the set infeed value. It may be noted that the need for a high value of grinding force indicates poor grindability.

The depth of the wheel groove occurring at the periphery of the grinding wheel through grit wearing and subsequent dislodgement of abrasive grits is measured after ten grinding passes and is given in Table 5. The removal of wheel grits to a large extent is not desired for good grinding; however, a small quantity of wheel material removal is needed to remove chip loaded wheel grits.

Table 4
Average F_n and F_t force values for different alternatives

Alternative	Average F_n (N)	Average F_t (N)
A_1	46.8	12.6
A_2	59.4	16.4
A_3	84.8	21.8
A_4	41.8	10.6
A_5	53.2	14.8
A_6	59.2	15.6
A_7	41	9.4
A_8	42.6	13
A_9	52	13.6
A_{10}	38	8.6
A_{11}	39.4	11.2
A_{12}	44.8	10.6

The surface characteristic is determined from observations of surface roughness, surface burn, presence of grit indentation/redeposition of chips and presence of surface crack. Table 6 shows the weight given to those parameters and also the ratings given to different alternatives accordingly. A surface roughness rating is decided based on a 9 point scale as there are a wide range of roughness values possible during grinding, while for the others a 5 point scale rating is used. The experimental runs that give higher surface roughness, higher surface burn, large grit indentation or chip redeposition and surface cracks are assigned a lower rating, so that a large value surface characteristic (SC) corresponds to desired grindability. For example, experimental run A_1 and A_2 are assigned a surface roughness rating ‘1’ as high average surface roughness values are obtained at these conditions. On the other hand, a rating of ‘9’ is given to experiment run A_{11} which experiences the lowest surface roughness or high surface finish. Similarly, severe surface burn occurred in experiment runs A_3 and A_6 and a rating of ‘1’ is attributed to these. A rating of ‘5’ is given to those conditions showing no surface burn. In the same way, ratings of ‘1’ or ‘5’ are assigned to the case of large scale grit indentation and chip redeposition, or no such occurrence of indentation or redeposition respectively. A rating of ‘5’ indicates an absence of any surface crack following the same consideration. The weight of each of these four surface parameters is assigned following a 9 point scale. As the presence of a surface crack in a ground workpiece makes it unusable or not acceptable, a large weight of ‘9’ is attributed to it. Occurrence of surface burn and grit indentation/ chip redeposition on the ground surface are the next two important aspects to judge grindability and these are assigned a rating of ‘7’. Surface roughness is less important considering grindability than the other three surface parameters, and hence, a weight of ‘5’ is assigned to it. These weights and ratings have been selected by the authors led by S. Das based on their experience in grinding research during the last several years.

A summation of (weightage*rating) is made for each of the alternatives and given in Table 7. This value is divided by the summation of weights to get the relative weights of surface characteristic for each alternative. The table below shows the reading of relative weights for each alternative. The summation of weights = (5+7+7+9) = 28. It is evident that is the higher the value of weighted averages, the better the surface characteristic of ground surface showing good grindability.

Table 5
Wheel wear obtained after each experiment

Alternatives	Wheel wear (µm)
A_1	60
A_2	300
A_3	460
A_4	30
A_5	80
A_6	200
A_7	40
A_8	100
A_9	150
A_{10}	50
A_{11}	80
A_{12}	100

Table 6
Weight and rating of surface parameters for different alternatives to determine surface characteristic

Alternatives	Surface roughness		Surface burn		Grit indentation/ Chip redeposition		Surface crack	
	Wt.	Rating	Wt.	Rating	Wt.	Rating	Wt.	Rating
A_1	5	2	7	3	7	3	9	5
A_2		1		2		3		2
A_3		1		1		1		2
A_4		5		5		3		5
A_5		3		3		3		5
A_6		4		1		1		2
A_7		6		5		5		5
A_8		8		5		5		5
A_9		5		2		3		2
A_{10}		8		5		5		5
A_{11}		9		5		5		5
A_{12}		7		2		3		2

As was already mentioned, the objective or goal of this AHP problem is the selection of an optimum grinding condition to obtain the best grindability for a titanium grade 1 workpiece within the domain of the experiments performed. The criteria are grinding force (F_t and F_n), wheel wear (W) and surface characteristic (SC). There are twelve alternatives to correspond with the twelve sets of grinding conditions. The hierarchy structure of this AHP problem is shown in Figure1.

Table 7
Evaluation of weighted average of surface characteristic (SC) for each alternative

Alternatives	∑(Weight*Ratings)	Weighted averages = ∑(Weights*Ratings)/28
A_1	97	3.46
A_2	58	2.07
A_3	37	1.32
A_4	126	4.5
A_5	102	3.64
A_6	52	1.86
A_7	145	5.18
A_8	155	5.54
A_9	78	2.79
A_{10}	155	5.54
A_{11}	160	5.71
A_{12}	88	3.14

Table 8
Pair-wise comparison matrix for criteria

Goal	Grinding force (F_t & F_n)	Wheel wear (W)	Surface characteristic (SC)	Geometric mean (GM)	Criteria weight
F_t & F_n	1	5	1/3	1.18563	0.27178
W	1/5	1	1/8	0.2924	0.06703
SC	3	8	1	2.8845	0.6612

λ_m= 3.0455, CR= 0.007075.

Table 9
Pair-wise comparison matrix for alternatives for criterion 1 (Grinding Force, Ft & Fn)

F_t & F_n	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	GM	Local wt.
A_1	1	4	6	1/3	3	4	1/3	1/3	3	1/5	1/4	1/2	0.98	0.05
A_2	1/4	1	3	1/5	1/2	1	1/5	1/5	1/2	1/6	1/6	1/4	0.38	0.02
A_3	1/6	1/3	1	1/8	1/4	1/3	1/8	1/7	1/4	1/9	1/9	1/7	0.20	0.01
A_4	3	5	8	1	4	5	1/2	2	4	1/4	1/3	3	1.91	0.11
A_5	1/3	2	4	1/4	1	2	1/4	1/4	1/2	1/6	1/5	1/3	0.53	0.03
A_6	1/4	1	3	1/5	1/2	1	1/5	1/5	1/3	1/6	1/6	1/4	0.37	0.02
A_7	3	5	8	2	4	5	1	2	4	1/4	1/3	3	2.15	0.12
A_8	3	5	7	1/2	4	5	1/2	1	4	1/4	1/3	2	1.63	0.09
A_9	1/3	2	4	1/4	2	2	1/4	1/4	1	1/6	1/5	1/3	0.59	0.03
A_{10}	5	6	9	4	6	6	4	4	6	1	2	5	4.27	0.24
A_{11}	4	6	9	3	5	6	3	3	5	1/2	1	4	3.31	0.19
A_{12}	2	4	7	1/5	3	4	1/3	1/2	3	1/5	1/4	1	1.15	0.06

The pair-wise comparison matrix for the three criteria with respect to the goal is constructed as per Equation 1 and is shown in Table 8. Local weights are obtained by normalising the geometric means of strength of preferences of each criterion over the other with respect to the goal. It is understood that grinding force is more important than wheel wear, but surface characteristic had a larger influence than the other criteria considering grindability. The pair-wise comparison matrices for 12 alternatives for each of the 3 criteria are constructed, and local weights are calculated. Weights of the alternative matrices are chosen based on the experimental observations as detailed in Tables 3 through 7. Maximum eigen value, λ_m and consistency ratio, CR are computed for each pair-wise comparison matrix, and CR is found to be well below 10% for these matrices indicating consistency of the matrices (Tables 8 through 11).

The global weights (r_i) of the alternatives are determined following Equation 3 and are given in Table 12 arranged in a decreasing order. It can be seen that the global weight of alternative A_{11} is the maximum that corresponds to an infeed of 20µm with the compound nozzle cooling arrangement. So, it can be concluded that this corresponds to the optimum grindability condition for a titanium grade 1 workpiece when the alumina wheel is used. Therefore, the condition of 20µm infeed with compound nozzle cooling arrangement can be recommended for surface grinding operations in related industry that match the obtained surface characteristic. The next best condition that can also be adopted corresponds to an infeed of 10µm with the compound nozzle cooling arrangement.

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Table 10
Pair-wise comparison matrix for alternatives for criterion 2 (Wheel wear)

Wheel wear	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	GM	Local wt.
A_1	1	6	7	1/4	2	5	1/3	3	4	1/2	2	3	1.81	0.10
A_2	1/6	1	2	1/8	1/5	½	1/7	1/4	1/3	1/7	1/5	1/4	0.29	0.02
A_3	1/7	1/2	1	1/9	1/6	1/3	1/8	1/5	1/3	1/8	1/6	1/5	0.22	0.02
A_4	4	8	9	1	4	7	2	5	6	2	4	5	4.05	0.23
A_5	1/2	5	6	1/4	1	4	1/3	1/2	3	1/3	1	2	1.28	0.07
A_6	1/5	2	3	1/7	1/4	1	1/6	1/3	1/2	1/6	1/4	1/3	0.4	0.02
A_7	3	7	8	1/2	3	6	1	4	5	2	3	4	3.08	0.18
A_8	1/3	4	5	1/5	1/2	3	¼	1	2	1/4	1/2	1	0.84	0.05
A_9	1/4	3	4	1/6	1/3	2	1/5	1/2	1	1/5	1/3	1/2	0.57	0.03
A_{10}	2	7	8	1/2	3	6	½	4	5	1	3	4	2.65	0.15
A_{11}	1/2	5	6	1/4	1	4	1/3	1/2	3	1/3	1	2	1.28	0.07
A_{12}	1/3	4	5	1/5	1/2	3	¼	1	2	1/4	1/2	1	0.84	0.05

Table 11
Pair-wise comparison matrix for alternatives for criterion 3 (Surface characteristic)

SC	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	GM	Local wt.
A_1	1	2	3	1/4	1/2	3	1/5	1/6	1	1/6	1/7	1/3	0.54	0.03
A_2	½	1	2	1/5	1/3	1	1/6	1/7	1/2	1/7	1/8	1/4	0.35	0.02
A_3	1/3	1/2	1	1/6	1/4	1/2	1/7	1/8	1/3	1/8	1/9	1/5	0.25	0.01
A_4	4	5	6	1	3	5	1/2	1/3	4	1/3	1/4	2	1.56	0.09
A_5	2	3	4	1/3	1	3	1/4	1/5	2	1/5	1/6	1/2	0.76	0.04
A_6	1/3	1	2	1/5	1/3	1	1/6	1/7	1/2	1/7	1/8	1/4	0.34	0.02
A_7	5	6	7	2	4	6	1	1/2	5	1/2	1/3	3	2.2	0.12
A_8	6	7	8	3	5	7	2	1	6	1	1/2	4	3.12	0.17
A_9	1	2	2	1/4	1/2	2	1/5	1/6	1	1/6	1/7	1/3	0.52	0.03
A_{10}	6	7	7	3	5	7	2	1	6	1	1/2	4	3.12	0.17
A_{11}	7	8	8	4	6	8	3	2	7	2	1	5	4.31	0.24
A_{12}	3	4	4	1/2	2	4	1/3	1/4	3	1/4	1/5	1	1.1	0.06

Table 12
Global weights for alternatives

Alternatives	Global weights
A_{11}	0.21328
A_{10}	0.19029
A_8	0.14215
A_7	0.12528
A_4	0.10204
A_{12}	0.06110
A_1	0.04188
A_5	0.04102
A_9	0.03036
A_2	0.01989
A_6	0.01969
A_3	0.01306

6. Conclusions

The Analytical Hierarchy Process (AHP) is employed in this work to determine the optimum conditions for obtaining the desired grindability for the grinding of titanium grade-1 with an alumina grinding wheel. The three criteria that were considered are grinding force, wheel wear and surface characteristic.

The alternative A_{11} was determined to be the optimum condition and employed the compound nozzle with 20 μm infeed. This result is also agreeable with the experimental findings. The compound nozzle system of grinding fluid delivery may have penetrated the stiff air layer around the grinding wheel thereby suppressing a steep rise in grinding zone temperature, and hence, reducing thermal related problems in grinding. However, at 30 μm infeed, large material removal takes place and force and temperature are naturally higher than at a lower infeed. Therefore, the optimal condition of 20 μm infeed is justified.

It can be said that the AHP can be efficiently used for solving multiple objective decision making problems such as finding out the best grinding condition to have desire grindability.

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