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Study on Wheel Life Parameters: Grinding Ratio and Wheel Loading in Grinding - Assisted Chemical Etching (GACE)

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Abstract

Grinding is one of the most important finishing operations in the manufacturing process. But, same as any other process, it faced with limitations. In this study, to overcome the limitations of the conventional grinding process, it is combined with the chemical machining process. As a result, hybrid machining process “Grinding Assisted Chemical Etching (GACE)” introduced. To assess the superiority of the GACE process with conventional grinding, several experiments have been conducted and effect of chemical etchant in wheel life parameters (G-ratio and wheel loading) and surface quality, compared with conventional grinding. To reach a better investigation, the results of GACE process were analyzed by Taguchi’s experimental design method. In this paper, the impact of the two effective factors, chemical- work and material removal rate (MRR), on output parameters such G-ratio, wheel loading and surface roughness were discussed. The results indicated that by applying the GACE method, wheel life parameter may significantly improve, and according to SEM image and surface roughness test, it is obvious that GACE process provides a smoother surface than grinding. Eventually, the optimized mode of input parameter’s (chemical work and MRR) which achieves efficient outputs (wheel life and surface quality) of GACE process was discussed.

Keywords: hybrid machining, grinding wheel life, surface roughness, grinding wheel loading, G ratio;

1. Introduction

In the recent decade, a sustaining effort has been made towards developing grinding process on some occasions, to increase the effectiveness of the grinding process, it combined with another machining process, for instance, in ceramic materials, ultrasonic assisted grinding (UAG) can be applied as a practicable production process [1]. Other studies have been conducted to investigate the ultrasonic assisted grinding. Tawakoli et al. researched on energy aspects and workpiece surface characteristics in ultrasonic-assisted grinding. They found that, by applying ultrasonic vibration in the conventional grinding process, surface roughness and cutting energy significantly reduced [2]. Combination grinding with ultrasonic vibration provides enormously reduced normal forces at slightly increased wheel wear and surface roughness [3]. Also, combined grinding process with lasers recently developed grinding process, which before the grinding wheel is engaging the workpiece area is heated directly, thus reducing the temperature gradient as well as, surface layer damage. Furthermore, the method permits high material removal rates, surface quality and reduced machining force [4].

Another approach, to develop grinding process, is hybrid mechanical – chemical process which, integrates chemical reaction and mechanical grinding between the abrasive wheel and specimen into one process. The process is also called in different names such as chemo-mechanical-grinding (CMG), chemical mechanical polishing (CMP), grinding assisted chemical etching (this term will be used in this paper) etc. [5]. This method has already been successfully utilized in industries for a long time particularly, the semiconductor industries. The most important features of this method are: reduce machining force and thermal effect, moreover many other advantages like surface roughness and improving MRR have also been reported by researchers [6].

In this work, by combining the conventional grinding process with the chemical etching process, novel grinding - assisted chemical etching (GACE) method is presented. The difference of this method from the previous process is that most of the mentioned process designed to finishing process, but the GACE process in addition to finishing process, it is also possible to exert to shaping process [7]. Another feature of the GACE process is a capability of grinding low melted point metals such as nonferrous metals. As known, grinding process produces a high temperature in the machining area. Nowadays, one of the

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manufacturing engineering challenges is grinding nonferrous metals such as aluminum. It melts easily, and in the grinding course of such materials, it would start to melt and frequently detaching chips may adhere to porosities between abrasive grains or weld to the top of cutting grains and coat the wheel (wheel loading phenomena) [8]. It causes to increases machining temperature, which leads to workpiece melting, and that's why more friction and grinding wheel heat up faster, the natural response at the wheel is to push the workpiece harder against the grinding wheel and intensifies wheel wear. Furthermore, by increasing the wheel temperature and machining friction, it can explode and cause damage. During our study, a remarkable difference in the results of wheel loading, G-ratio and surface roughness between the conventional grinding process and the GACE process was observed. Therefore, each process was investigated separately and the results compared. The aim of this study is to investigate the advantages of GACE process over conventional grinding process. Based on our previous study [7] wheel life parameters play a key role in GACE process to makes it economical. As well as, tool cost is one of the most impressive factors on cost of product. Furthermore, as grinding process usually is a final step of a machining procedure, excessive grinding tool wear could deteriorate both workpiece surface quality and its dimensional accuracy. So, this paper will discuss wheel life parameters (grinding ratio and wheel loading) and surface roughness in the GACE process on aluminum EN AW-7075 grinding. The effect of input parameters (MRR and chemical-work) investigated by Taguchi experimental design and the effectiveness of each parameter on output parameters (G-ratio, surface roughness and wheel loading) will also be discussed. Ultimately, in this research, the Taguchi method is used to achieve the optimum machining condition.

2. Mechanism of grinding-assisted chemical etching (GACE)

A basic principle of the material removing in the GACE process is explained in the following diagrams. Firstly, raw material is exposed to a chemical reagent which in this study is called etchant, and chemical absorption occurs on the surface layer of the specimen. In the next step, the chemical reaction produces the reacted layer, which might have other physical properties in comparison with the base material (Fig. 1) Finally, the mechanical machining process (grinding) is followed by the third step. Thus, this cycle continues until the workpiece reaches its desirable shape (Fig. 2).

The chemical reaction between aluminum (Al) and FeCl3 etchant can be described as follows:

$$3FeCl_3 + Al \rightarrow 3FeCl_2 + AlCl_3 \quad (1)$$

The chemically reacted layer thickness cannot be easily differentiated because the layer has a continuous mode between the changed surface and the raw material [6]

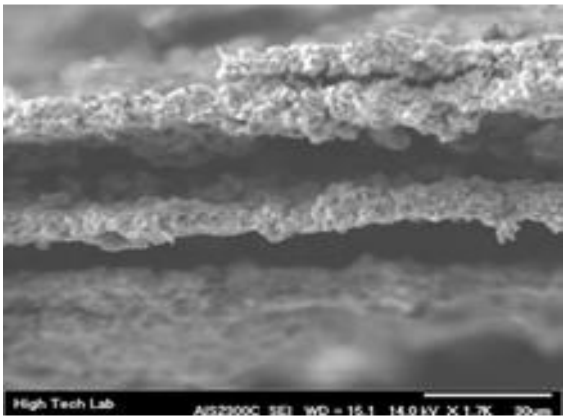

Figure 1. SEM image of aluminum 7075 reacted layer by applying $FeCL_3$ etchant.

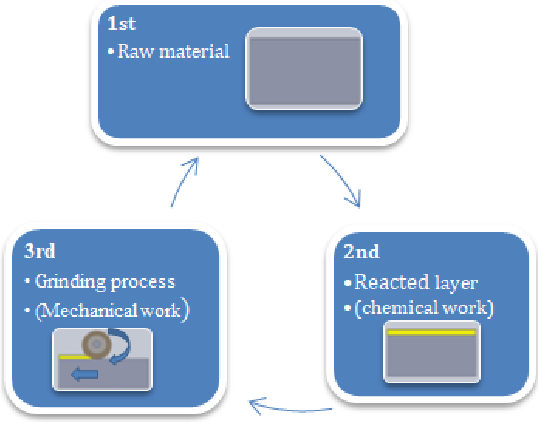

Figure 2. GACE process principle.

3. Experimentation

The experimental study of the GACE process was conducted by MELLO p58 grinder machine. In addition, a glass tank used to store etchant and it transferred by pump and hose to machining zone. To protect the grinder machine, parts against chemical corrosion wasted etchant collected by formed galvanized steel are fixed on the grinder magnetic chuck. Figure 3 shows the GACE process's experimental setup.

The selected material was EN AW-7075 aluminum. It is widely used for military purposes, automotive and aviation industry. Its chemical composition was given in Table 1. The aim of selecting aluminum as the specimen is that aluminum due to high wheel loading, wheel wear and the resulting low surface quality is the most challenging material for grinding. So, to challenge the GACE process the EN AW-7075 aluminum has opted.

Table 1. Chemical composition of EN AW-7075 aluminum

Chemical elements (%)									
Al	Si	Fe	Cu	MN	Mg	Cr	Zn	Ti	Others
96	0.4	0.5	1.2–2.0	0.3	2.1–2.9	0.18–0.28	5.1–6.1	0.2	0.05

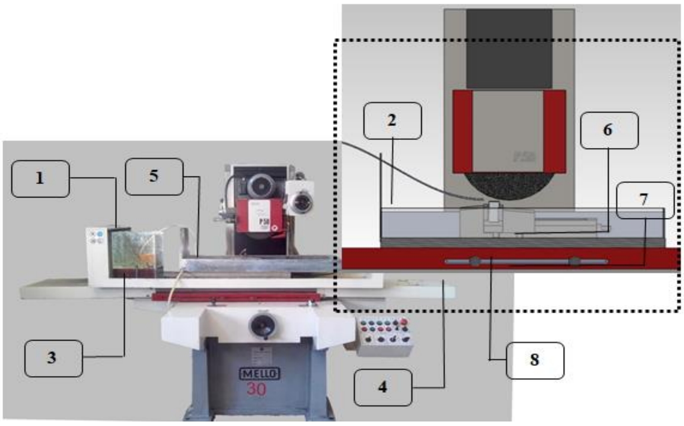

Figure 3. GACE setup: 1-glasess tank 2-transfer etch hose 3-temperatorgage 4- magnetic chuck 5-formed sheet 6-grinding wheel 7-vice 8-specimen

The selected etchant in this experiment is ferric chloride (FeCl3). Some research on different etchants for various engineering materials have been conducted and most of the researchers claimed that FeCl3 is the most operative etchant It is widely practiced for most of the materials such as aluminum, steels, copper, etc. It is economic and recyclable, plus it is easy to control during the etching process [9].

The specimens cut at 10mm×20mm×20mm dimensions. The preparation of specimens in this experiment is based on two steps, cleaning and masking. The cleaning step consists of removing objects and other contaminations which prevents the etchant from reaching the surface of the specimen. The next step is the coating cleaned workpiece with masking material. The selected masking material should be readily strippable mask, which is chemically impregnable and adherent enough to stand chemical abrasion during the GACE process. In this case, the resin epoxy was selected. Grinding conditions and wheel specifications are shown in Table2.

Table 2. Experimental conditions

Wheel diameter	400 mm
Etchant type	Felc3, dry
Temperature	25˚c
etchant flow rate	1000 ml/min
Workpiece	AL-EN AW-7075-10mm×20mm×20mm
Etchant Concentration	20 %wt.
Rotation of wheel	2025 RPM
Table speed	10m/min ± 1
Dresser	Single pointed diamond
cutting speed	42.4 m/s
Wheel type	32A60-JVBE

3.1. Determining the grinding ratio (G-ratio)

G-ratio is the most substantial factor to evaluate the performance of the grinding wheel indeed this parameter reported the amount of volumetric material removed from the workpiece in return for volumetric wear of wheel.

The G-ratio in surface grinding operations can be simply written as:

$$G-ratio = \frac{Q_w}{Q_s}$$

$$Q_w = b.L.t \tag{2}$$

$$Q_s = 2\pi r.b.\Delta r$$

Where Qw is the volumetric workpiece removal and Qs is the volumetric wheel wear. L involved length of a workpiece, and Δr is the radius reduction of the grinding wheel. It should be noticed that t and b are the depth of cut and the width of the grinding wheel respectively. Under any grinding condition as specified by Eq. 2, the grinding ratio reduces rapidly according to more radius reduction of the grinding wheel. While the higher grinding ratio is generally desirable, the more wear resistant wheel may give high forces and energies so that it increases a likelihood of thermal damages to a workpiece [8]. Some methods for measuring wheel wear are available, but the most accurate and common method is the"razor-blade" technique. In this method, a thin razor-blade paired with the specimen and grinding by the workpiece. After grinding the radial wear of wheel obtained from the difference between the depth of down feed which adjusted on grinding machine and the height of created groove on the blade which measured by using a profile projector (Fig. 4) [10].

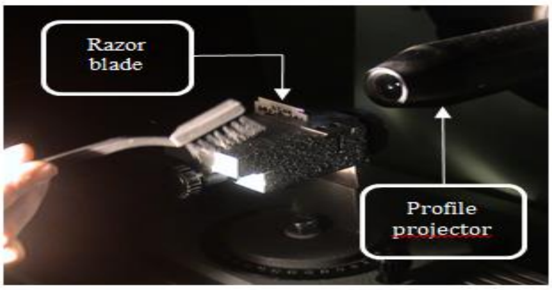

Figure 4. Grinding ratio measurement equipment.

3.2. Determining the wheel loading

Wheel wear and wheel loading are interdependent factors, which ultimately, effect on the workpiece accuracy and surface finishing. The condition of the grinding wheel during the machining process constantly changes as grits wear and chip accumulate in the wheel Pores. Chip accumulation (loading) is particularly problematic with fine grit wheel. This phenomenon occurs when the workpiece chip melted and either adhere to the top of grits or embed in the spaces between them. Wheel loading causes the wheel grits as cutting edges become dull, and the outer surface of the grinding wheel becomes glazed, which results in excessive rubbing rather than abrasion and generates excessive heat. This creates some seriously detrimental effects, such as deterioration of surface finish, reduced material removal rate, excessive vibration, an increase in grinding force, wheel temperature and reduced wheel life. Some methods are available to measure wheel loading, such as chemical detection, calorimetry, spectroscopy, eddy current sensing, magnetization and radio tracing. In this study, due to the ideal contrast between specimen and wheel, a simple approach was adopted for quantifying wheel loading that utilizes microscope images and image analysis [11]. In this method, a surface image of the grinding wheel, processed into black and white pixels, then the percentage of wheel loading is determined by counting white pixels (Fig. 5).

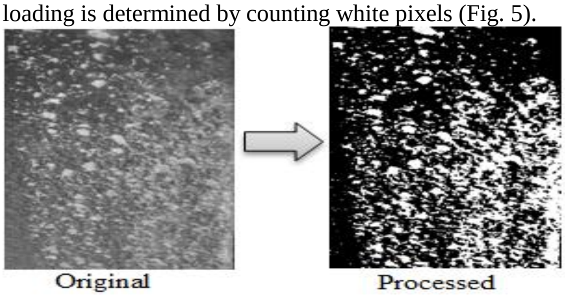

Figure 5. Wheel loading measurement process.

3.3. Determining the chemical – mechanical work

As mentioned, the GACE process is based on the chemical reactions and mechanical machining (Fig.6). It worth to noted that during the GACE process as long as grinding wheel involving with specimen, etching process temporarily stopped, and then by passing wheel cross the specimen etching process or chemical aspect of GACE immediately started. Thus, by considering the involved length of the specimen, table speed and table course of the grinding machine the portion of chemical and mechanical work can be achieved. The quantity of mechanical work and chemical work percentages calculated by Eq. 3. Where Δtm is the time of involved grinding wheel with the workpiece in the GACE process, Δtc is the time workpiece be chemical machining in GACE process and Tm is total machining time.

$$\mathrm{mechanical-work\%} = (\Delta\mathrm{tm})/\mathrm{Tm} \times 100 \qquad (3)$$
$$\mathrm{chemical-work\%} = \frac{\Delta\mathrm{tc}}{\mathrm{Tm}} \times 100$$

4. Experimental design and methodology

In this research, for further analysis result of GACE process are compared with the results of conventional grinding. As well as, eventually by using Taguchi method optimum conditions discussed.

Investigating the effect of input factors on machining ability of new process such as GACE is necessary, but not sufficient. Furthermore, studying and investigating optimized parameter of new machining process is engineering's controversial topic. Hence, in this study, Taguchi optimization method is used to achieve the best output parameters of GACE process.

The Signal-to-noise ratio is sometimes used informally to refer to the ratio of useful information to false or irrelevant data in a conversation or exchange. Usually, there are three categories of performance characteristics to analyze the S/N ratio. They are nominal-the-better, larger-the-better, and smaller-the-better (Eq. 4). It worth to notice that in this research, the optimization study is performed by using Minitab16 software.

$$\frac{S}{N} = -10Log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \qquad Smaller-the-better$$
$$\frac{S}{N} = 10Log\frac{\bar{Y}^2}{S^2} \qquad Nominal-the-better \qquad (4)$$
$$\frac{S}{N} = -10Log\frac{1}{n}\sum_{i=1}^{n}y_i^2 \qquad Larger-the-better$$

In accordance, Taguchi experimental design experiments were conducted with the factors and the levels as reported in Table3. So that, the chemical-work and MRR are considered as inputs and G-ratio, wheel loading and surface roughness are considered as output parameters. Other machining conditions also considered constant. The experimental layout with the opted values of the factors is reported in Table 4. To account for the variations that may occur due to the noise factors 25 experiments conducted and the results of the G-ratio, wheel loading and surface roughness listed in Table 4.

To investigate the repeatability of the process, the average (Avr) and Standard deviation (Std) of loading percentage for output parameters were calculated. In statistics, the standard deviation is a measure that is used to quantify the amount of variation or dispersion of a set of data values. A low standard deviation indicates that the data points tend to be close to the mean (also called the expected value) of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values. Figure 7 and Table 5 reported amount of standard division and averages of wheel loading, G-ratio and surface roughness of repeated experiments in same conditions. It is obvious that after a certain number of the experiment, the Std of output parameters remain steady state and remarkable variation has not been seen. It means that by increasing the number of experiments more than a certain extent the average amount of output parameters does not change. In this study, for improving the repeatability of results each experiment of wheel loading, G-ratio and surface roughness respectively repeated 6, 5 and 3 times and average values are recorded.

Table 3. Process parameters

Process parameter	Level 1	Level 2	Level 3	Level 4	Level 5
Chemical work	3%	5%	7%	10%	90%
MRR	12.5 mm³/min	25 mm³/min	62.5 mm³/min	87.5 mm³/min	125 mm³/min

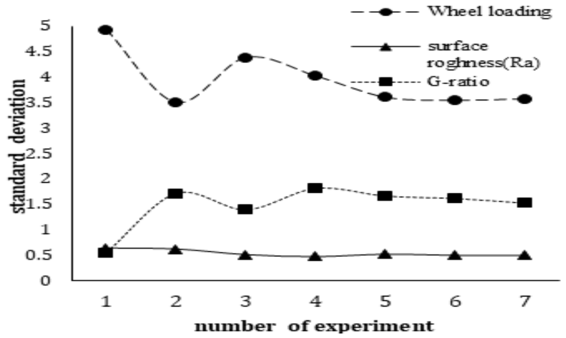

Figure 7. standard deviation of wheel loading percentage, surface roughness and G-ratio against number of experiments

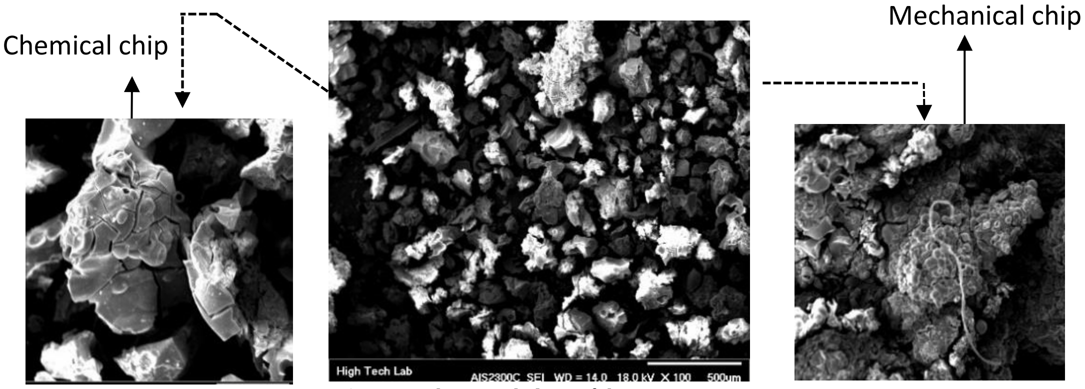

Figure 6. Chip morphology of the GACE process.

Table 4 Experimental results orthogonal array for L25Taguchi design

Exp No	MRR (level)	Chemical-work (level)	G-ratio	G-ratio SNR	Wheel loading (%)	Wheel loading (%) SNR	Surfaces roughness (Ra)	Surfaces roughness (Ra) SNR
1	1	1	20	26.0206	40	-32.0412	8.3	-18.3816
2	1	2	23	27.2346	37	-31.3640	4.2	-12.4650
3	1	3	25	27.9588	30	-29.5424	2.63	-8.3991
4	1	4	28	28.9432	24	-27.6042	3.76	-11.5038
5	1	5	44	32.8691	20	-26.0206	7.85	-17.8974
6	2	1	19	25.5751	43	-32.6694	10.5	-20.4238
7	2	2	24	27.6042	39	-31.8213	3.2	-10.1030
8	2	3	24.5	27.7833	36	-31.1261	1.9	-5.5751
9	2	4	26	28.2995	30	-29.5424	2.3	-7.2346
10	2	5	40	32.0412	27	-28.6273	6.2	-15.8478
11	3	1	17	24.6090	50	-33.9794	10	-20.0000
12	3	2	24	27.6042	42	-32.4650	3.75	-11.4806
13	3	3	24	27.6042	37	-31.3640	1.75	-4.8608
14	3	4	25	27.9588	32	-30.1030	1.9	-5.5751
15	3	5	39	31.8213	30	-29.5424	4.2	-12.4650
16	4	1	17	24.6090	53.5	-34.5671	12	-21.5836
17	4	2	18	25.1055	45	-33.0643	7.5	-17.5012
18	4	3	22	26.8485	38	-31.5957	2.35	-7.4214
19	4	4	24	27.6042	33	-30.3703	3.45	-10.7564
20	4	5	35	30.8814	31	-29.8272	9.5	-19.5545
21	5	1	5	13.9794	54	-34.6479	11.5	-21.2140
22	5	2	8	18.0618	47	-33.4420	7.8	-17.8419
23	5	3	12	21.5836	39	-31.8213	5.3	-14.4855
24	5	4	18	25.1055	31	-29.8272	4.2	-12.4650
25	5	5	25	27.9588	30	-29.5424	8.5	-18.5884

Table 5 Average and standard deviation of wheel loading percentage, surface roughness and G-ratio with different initial location point

Exp number	Wheel loading			Surface roughness			G-ratio		
	%loading	Avr	Std	Ra(μm)	Avr	Std	Wheel	Avr	Std
0	35			4.5			28.3		
1	28	31.5	4.94	3.58	4.004	0.650	27.5	27.9	0.56
2	32	31.6	3.51	3.29	3.79	0.63	25	26.93	1.72
3	25	30	4.39	3.98	3.83	0.52	27	26.95	1.40
4	27	29.4	4.03	4.2	3.91	0.48	30	27.56	1.82
5	30	29.5	3.61	3.16	3.75	0.528	28.4	27.7	1.67
6	33	30	3.55	4.18	3.84	0.505	26.2	27.48	1.62
7	26	29.5	3.55	3.34	3.77	0.502	26.7	27.38	1.53

5. Results and discussion

5.1. Effects of MRR and chemical – mechanical work on G-ratio

One of the most commonly used parameters in the machining processes is the material removal rate (MRR) which is defined as the amount of stock removed from the workpiece in a given amount of time. MRR in the grinding process is calculated by:

$$MRR = b.d.L.d_f \tag{5}$$

Where b,L, and df are the width of wheel engagement, length of stroke and downfeed speed, respectively. Figure 8 shows the comparison of G-ratio in different MRR conditions. Overall, in all terms G-ratio decreases as MRR increases, but there is a significant difference between GACE and conventional grinding. As known, grinding is a severe machining process, so the heat generated due to friction and cutting process, causes to the weakening of the adhesive between the wheel grains [5]. So, it leads to grains easily separated from the wheel surface and decreasing the G-ratio. On the other hand, rising machining temperature cases to adhere chips on top of abrasive grains and it leads to improving the forces that cause the grains separate. So, according to Eq. 2 by increasing wheel wear (Qs) G-ratio decreased. But, in the GACE process story is different. According to Fig. 8 G-ratio in GACE process proximally is two times higher than conventional grinding. In other words, tool wear in GACE process is less than conventional grinding.

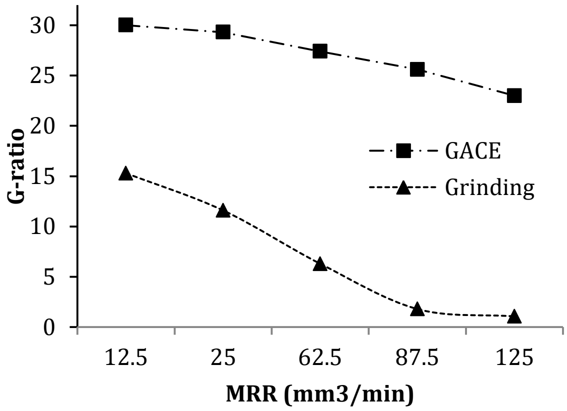

Figure 8. Comparison of G-ratio vs. MRR in grinding process and GACE process.

In the GACE process, the percentage of mechanical work increases with the increasing MRR, in contrast by applying a low MRR, the percentage of chemical work increased. Due to chemical corrosion, aluminum specimen transferred to $AlCl_3$ (Eq. 1) which has different properties, hence friction and temperature in the machining zone dramatically reduced. Figure 9 shows the effect of mechanical and chemical work percentages on G-ratio in GACE process. The mechanical and chemical work calculated by the Eq. 3. As can be discovered, with increasing percentage of mechanical work, the G-ratio decreased.

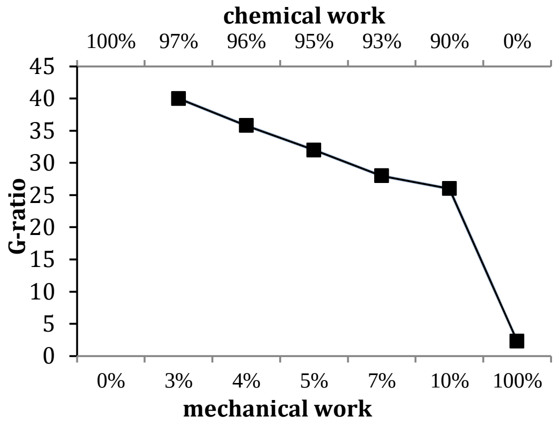

Figure 9. Effect of chemical-mechanical work on G-ratio.in GACE method.

Optimum mode of G-ratio in the GACE process

As known, in the grinding process, larger G-ratio is desirable. This means that more material removed which is followed by minimum tool wear. For calculating the G-ratio the objective function, "larger is better" type was used (Eq. 4). Figure 10 demonstrates the main of S/N ratios effect of MRR and chemical work on G-ratio. The factor levels corresponding to the highest S/N ratio were chosen to optimize the condition. From these linear graphs, the optimum values of the factors, and their levels occurred respectively in level 1 of MRR and level 5 of chemical-work.

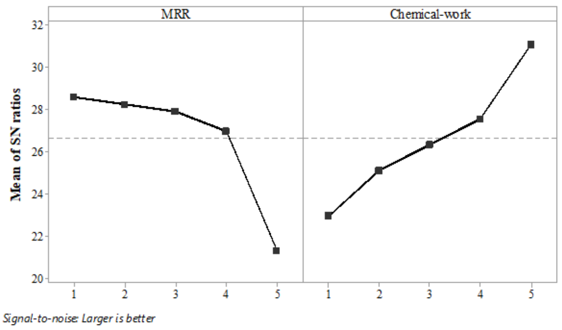

Figure 10. Main effects of signal to noise ratios effect of MRR and chemical work on G-ratio.

Figure 11 displays the surface plot of G-ratio vs chemical work and MRR. The Effect of each parameter investigated at five different levels. It is obvious that maximum G-ratio achieved at level 5 and 1 of MRR and chemical work respectively. Moreover, according to Fig. 11 by selecting level 1 and 5 for MRR and Chemical-work respectively G-ratio reach to the maximum value.

Table 6 Summarized mean values of the S/N ratios of G-ratio for all the process parameters at different levels. According to Table 6, it is identified that chemical-work has a higher delta value (8.16) in comparison with MRR by an amount of 7.27 delta. The Chemical-work has the highest influence on the S/N ratios of G-ratio due to its delta value and rank. Furthermore, the maximum value of the G-ratio occurred by setting MRR and chemical–work as 12.5 mm^3/min and 90% respectively (optimum point).

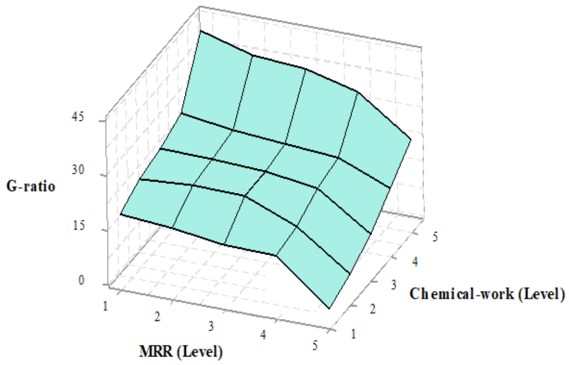

Figure 11. surface plot of G-ratio vs chemical work and MRR

Table 6. Response table for S/N ratios of G-ratio

Level	MRR	Chemical-work
1	28.61	22.96
2	28.26	25.12
3	27.92	26.36
4	27.01	27.58
5	21.34	31.11
Delta	7.27	8.16
Rank	2	1
Maximum G-ratio	Level1(12.5 mm^3/min)	Level 5(90%)
Minimum G-ratio	Level 5(125 mm^3/min)	Level 1(3%)

5.2. Effect of MRR and chemical – mechanical work on wheel loading

In this study, the wheel loading was measured by image analysis method. The percentage of the wheel loading can be calculated simply by dividing the pixels number of the loaded area (white pixels) to total pixel numbers. To

investigate the accuracy of the loading measurement process, the image analyzing method was examined. Figure 12.a is the original image and Fig. 12.b is the processed gradient mask image. The ratio of loading of a fresh wheel surface is calculated to be 0.086%. The error is less than 0.1% which is acceptable in surface monitoring for grinding wheels loading. It should be noticed that error might have a slightly higher value for the used and loaded grinding wheel.

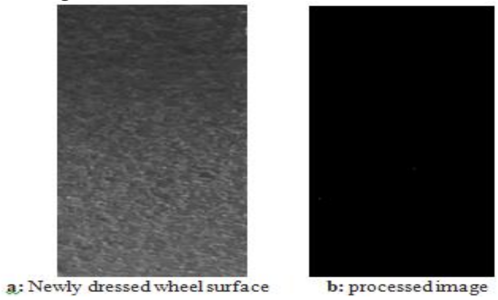

Figure 12. Processing of newly dressed wheel surface image

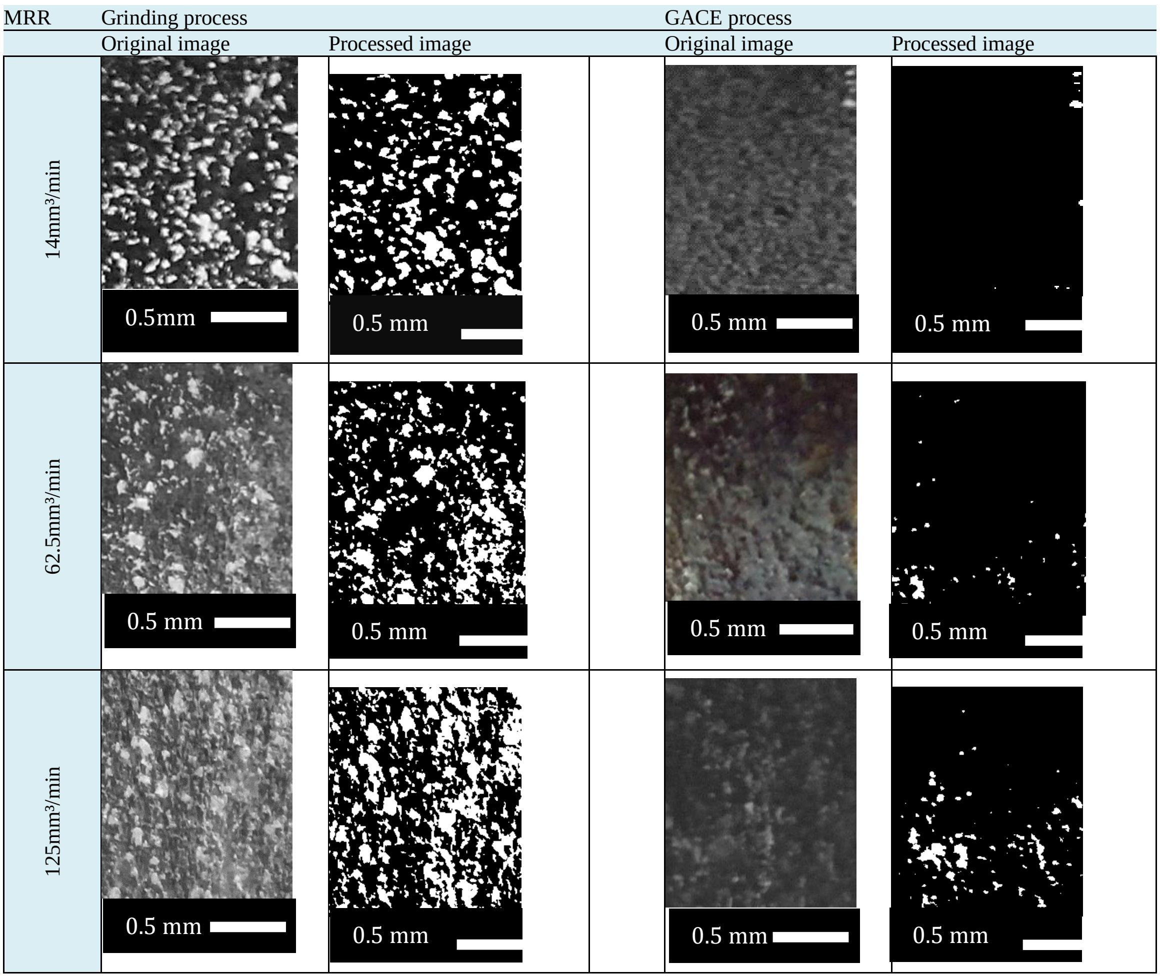

Figure 13. original and processed image of wheel loading in grinding vs. GACE in different material removal rate

Figure 13 makes a comparison of wheel loading images between conventional grinding and GACE processes in different MRR. As it is clear, there is considerable wheel loading difference between conventional grinding and GACE which by applying GACE process wheel loading significantly reduced.

Figure 14 illustrates the MRR variations according to loading percentage of conventional grinding and GACE method. In all cases, loading percentage increased gradually with increasing the MRR. As can be seen, wheel loading percentage of grinding and GACE are 30%-38% and 5%-12% respectively. In other words due to the effect of chemical-work the wheel loading in GACE process is approximately six times lower than the conventional grinding

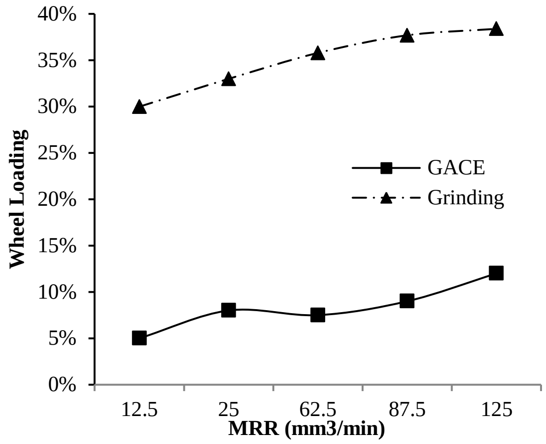

Figure 14. Wheel loading percentages against MRR in grinding process and GACE process

To investigate the chemical-mechanical effects on wheel loading in GACE process many experiments were carried out at different percentages of chemical-mechanical work. Figure 15 presents the effect of chemical- mechanical work on wheel loading. According to the figure, by reducing the chemical work the wheel loading increases significantly, therefore, in the case of 0% chemical work (100% mechanical work) the percentage of the wheel loading reaches to its maximum value (40%).

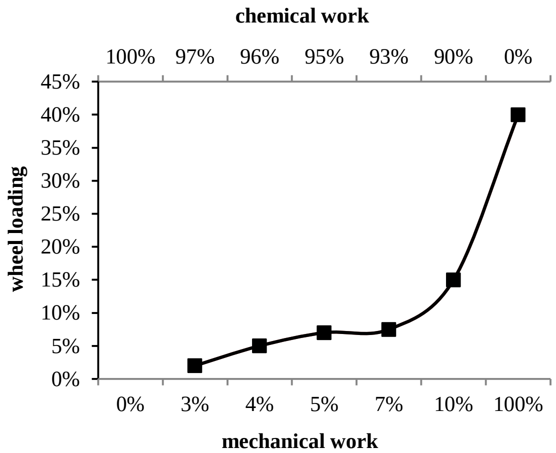

Figure 15. Effect of chemical-mechanical work wheel loading in GACE method.

Optimum mode of wheel loading in the GACE process

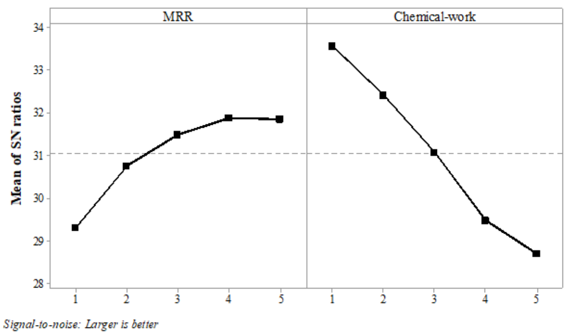

Figure 16. Main effects of signal to noise ratios effect of MRR and chemical work on wheel loading.

Figure 16 plotted mean of the signal to noise ratio of wheel loading in GACE process. As mentioned earlier, reducing wheel loading improve grinding efficiency. Therefore, for analyzing the S/N ratio of wheel loading in this case, objective function, “smaller is better” was used. By comparing the S/N ratio of input parameters it is evidence that chemical-work have higher S/N ratio than MRR and increased virtually linear with changes of chemical- work levels**.**

Figure 17 displays the surface plot of wheel loading vs MRR and chemical-work. As it is clear, by increasing chemical-work and decreasing MRR, wheel loading decreased. It is worth to note that the highest wheel loading obtained at level 1 and 5 of chemical –work and MRR respectively. Moreover, according to Table 7 by comparing the delta value and rank. It can be realized that chemical-work is more effective than MRR. As well as, by choosing level 1 (12.5 mm3/min) of MRR and level 5 (90%) of chemical –work the optimum point of wheel loading achieved.

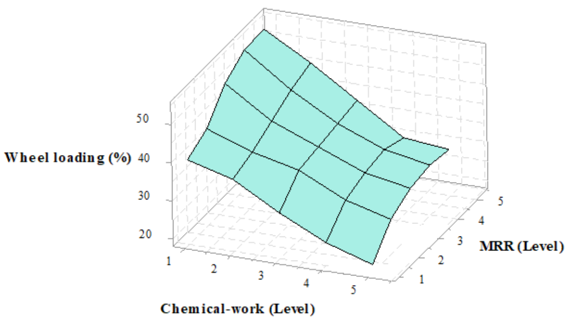

Figure 17. Surface plot of wheel loading vs MRR and chemical-work

Table 7 Response Table for Signal to Noise Ratios of wheel loading

Level	MRR	Chemical-work
1	-29.31	-33.58
2	-30.76	-32.43
3	-31.49	-31.09
4	-31.88	-29.49
5	-31.86	-28.71
Delta	2.57	4.87
Rank	2	1
Maximum Wheel loading	Level 5(125 mm^3/min)	Level 1(3%)
Minimum Wheel loading	Level 1(12.5 mm^3/min)	Level 5(90%)

5.3. Effects of MRR and chemical – mechanical work on surface roughness

Figure 18 illustrates a comparison of surface roughness in the GACE and grinding process in different MRR. It is obvious that by increasing MRR in grinding, surface roughness increased continuously. Whereas, in GACE surface roughness decreasing gradually with increasing MRR and reached to minimum roughness (Ra= 1.75µm) in MRR of 62.5 mm3/min then increased sharply. It should be noted that with increasing MRR the results of surface roughness in both methods tend to close together. It is due to that, by increasing MRR mechanical work increased and etchant had no adequate time for reacting with the specimen, so reacted layer goes to be thinner. On the other hand, by decreasing MRR mechanical-work decreased (or chemical work increased) and chemical side of GACE process is dominant in the material removal mechanism. As well known, in chemical machining due to the heterogeneous separation of atoms from the specimen, produced rough surface [12].

Figure 19 plotted the effect of chemical- mechanical work on surface roughness. It is obvious that by increasing either chemical – mechanical work, surface roughness increased. Figure 20 also illustrates the SEM image, AFM and surface profile of the grinding and GACE process. By comparison of produced surface of each process, it can be realized that GACE process resulted smother surface than conventional grinding.

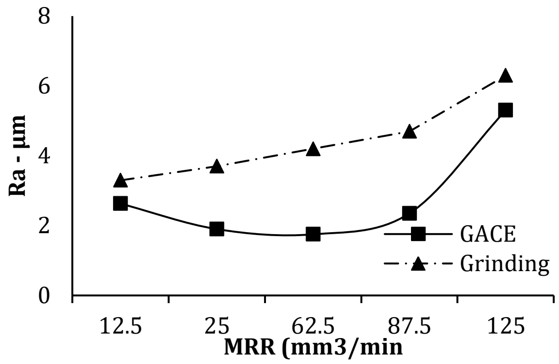

Figure 18. Surface roughness against MRR in grinding process and GACE process.

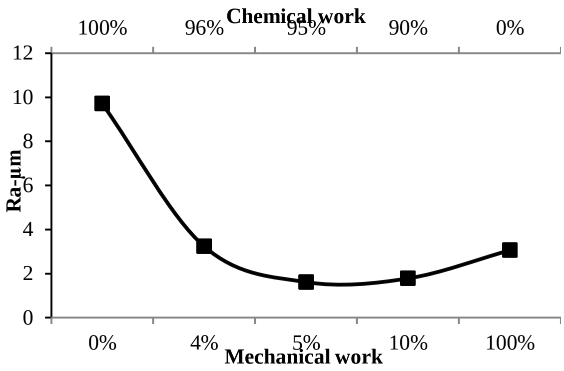

Figure 19. Effect of chemical-mechanical work on surface roughness in GACE process.

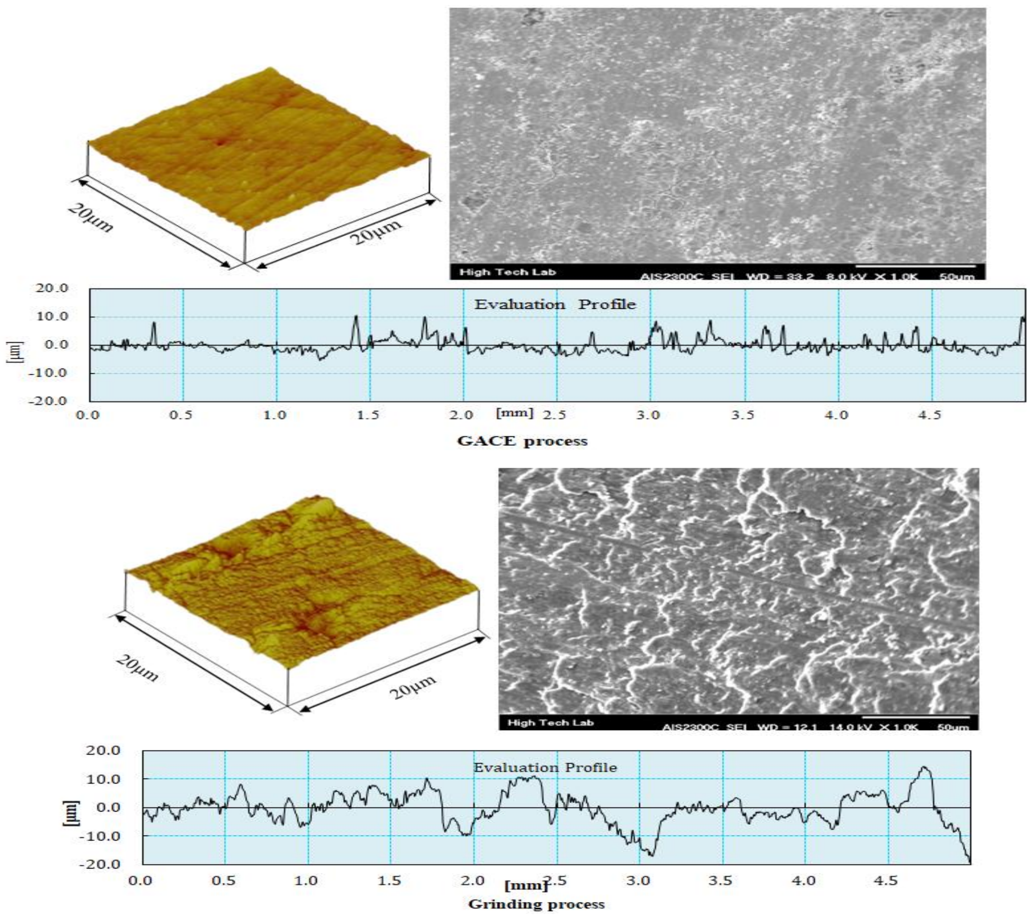

Figure 20. Surface profile, AFM surface scan and SEM image surface roughness comparison of GACE and conventional grinding

Optimum mode of surface roughness in the GACE process

Surface roughness is the most significant factor in the grinding process. Therefore, it is considered one of the GACE output parameters. Figure 21 discussed the main effect plot of S/N ratio for MRR and chemical- work factors. The highest S/N ratio achieved at level 3 for both parameters.

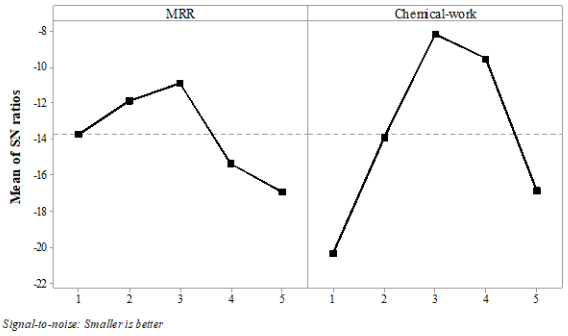

Figure 21. Main effects of signal to noise ratios effect of MRR and chemical work on surfaces roughness**.**

Also, by analyzing the surface plot of roughness vs MRR and chemical- work (Fig. 22) it is obvious that by increasing and diminishing both parameters (chemical-work and MRR) to a certain level, surface roughness increased. According to 3D plot, it has a concave shape and, the center of surface is the minimum point of roughness. Hence, by considering the value of Delta and rank (Table 8) the Chemical-work has the highest influence on the surface roughness in comparison with MRR. Therefore, the optimal condition for the input parameters of the GACE process are MRR=62.5 mm^3/min and chemical- work=7%.

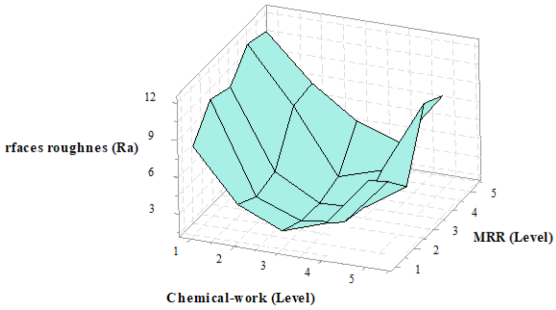

Figure 22. Surface plot of surface roughness vs MRR and chemical-work.

Table 8. Response Table for Signal to Noise Ratios of surfaces roughness

Level	MRR	Chemical-work
1	-13.729	-20.321
2	-11.837	-13.878
3	-10.876	-8.148
4	-15.363	-9.507
5	-16.919	-16.871
Delta	6.043	12.172
Rank	2	1
Maximum Surfaces roughness	Level 5(125 mm^3/min)	Level 1(3%)
Minimum Surfaces roughness	Level3(62.5 mm^3/min)	Level 3(7%)

6. Conclusion

In this work, an attempt was made to investigate the effect of important machining parameters on tool life parameters, such as G-ratio,wheel loading, and surface roughness in the grinding assisted chemical etching (GACE) process. Results were compared with conventional grinding and Taguchi's prediction. Factors such as chemical-work and MRR have been found to play a significant role in the GACE process. Taguchi's experimental design method applied to obtain the optimum parameter combination for maximizations of G-ratio, minimization of wheel loading and surface roughness.

Overall, by considering the findings of this study, the following features can be derived:

1. The grinding-assisted chemical etching process is an efficient approach to overcome the disadvantages of the conventional grinding process, such as a low material removal rate, high wheel loading, low G-ratio and low surface quality.
2. By comparison GACE process with conventional grinding, it can be concluded that the GACE process due to high tool life and surface quality has higher economic efficiency than conventional grinding process.
3. Grinding nonferrous metals due to low melting point and high wheel loading phenomena is a machining challenge which can be solved by applying the GACE method.
4. According to Taguchi's experimental design method, chemical-work is the most impressive factor in the G-ratio, wheel loading and surface roughness of the GACE process.

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

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