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BALL BURNISHING PROCESS OPTIMIZATION FOR ALUMINUM ALLOY USING TAGUCHI TECHNIQUE

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ABSTRACT

The purpose of this work is to study the relationships between surface finish, fatigue life and the ball burnishing process parameters. Non-ferrous surface are difficult-to-finish due to many problems encountered in grinding which is optimum for ferrous metals. Taguchi technique is employed to identify the effect of four burnishing parameters; namely, burnishing speed, burnishing feed, depth of penetration and number of passes on the surface finish and fatigue life of 6061-aluminum alloy. Experimental work was carried out on a CNC lathe. The surface roughness is determined. The number of cycles to failure is determined using a cantilever type fatigue machine, which is suitable for testing specimen requiring oscillatory or reciprocating motion. It was found that the optimal burnishing parameters for the best surface finish was obtained at burnishing speed of 25m/min, burnishing feed of 60 μm/rev, depth of penetration of 6μm/rev and number of passes of 1. The optimum performance for fatigue life was obtained at 125m/min burnishing speed, 100μm/rev burnishing feed, 9μm depth of penetration and 3passes.

KEYWORDS: Ball Burnishing Process, Fatigue Life, Surface Roughness, Taguchi Technique

INTRODUCTION

Surface quality is an important factor by which the technological quality of machined component can be evaluated [1]. Engineering components are usually subjected to high levels of stresses, temperature and speeds. The most suitable specification for a surface, hence, is dependent on its intended application. For this reason, surface geometry and function should be isolated, especially in investigating of a tribological nature.

Perfectly flat surface can never be generated. Surfaces have always irregularities in the form of peaks and valleys. Processes by which surfaces are finished differ in its capabilities concerning finishing action, mechanical and thermal damage, residual stresses and materials [1]. These processes are divided according to running in mechanisms into two types: one involves material loss such as grinding and the other depends on plastic squeezing of the surface where by a redistribution on material is performed with no material loss [2]. The latter is seen in finishing process such as burnishing which can be achieved by applying a highly polished and hard ball onto metallic surface under pressure as shown in Figure 1. This will cause the peaks of the metallic surface to spread out permanently, Figure 2, when the applied burnishing pressure exceeds the yield strength of the metallic material to fill the valleys and some form of smoothing takes place. Besides producing a good surface quality, the burnishing process has additional advantages over machining processes, such as securing increased hardness, corrosion resistance and fatigue life as a result of the produced compressive residual stress on the surfaces [3]. The characteristics of burnishing surface depend upon controlling burnishing parameters such as applied burnishing force (burnishing depth), burnishing speed, burnishing feed rate, and number of passes, geometry and material of burnishing tool, as well as the material of burnishing surface.

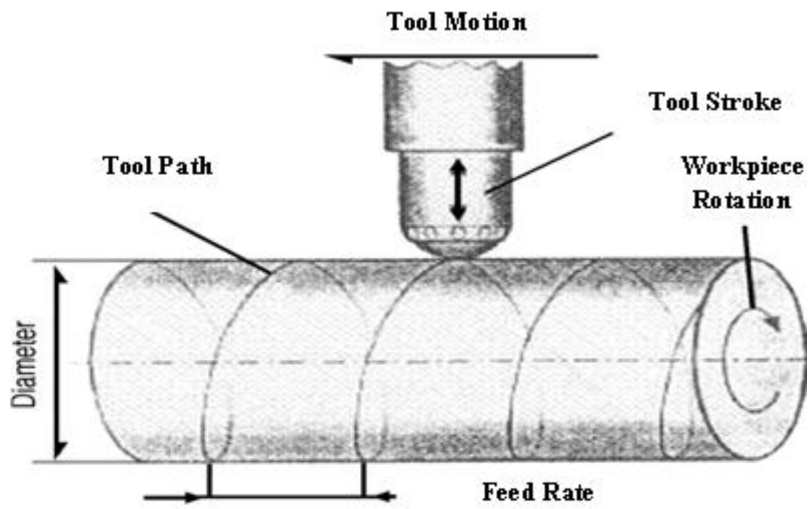

Figure 1: Schematic of Ball Burnishing

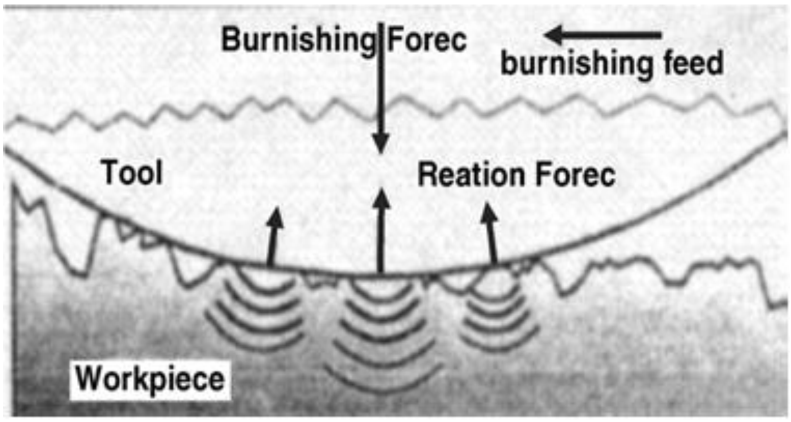

Figure 2: Material Flow from Peaks to the Valleys in the Burnishing Process

A literature survey shows that work on the burnishing process has been conducted by many researchers and the process improves the properties of the machined parts. El-Axir and Ibrahim [4] have introduced a new burnishing tool. They used the center rest of a lathe as ball burnishing tool. The result of their investigation showed that the surface characteristics were improved with this burnishing tool. The surface roughness was also improved and surface hardness was increased using burnishing tools[5-11]. At the same time, the use of milling roller burnishing increased surface hardness of the machined components [12]. The process also increased maximum residual stress in compression [13]. Burnishing has also decreased the roundness error of the specimens [14]. A fuzzy model was used to achieve the optimum burnishing parameters for non-ferrous components [15]. Loh et al. [16] reported that, ball burnishing parameters have an influence on surface hardness of the burnished component. These parameters also influenced burnished surface wear resistance [17]. Burnishing process has an influence on microstructure of the burnished components as well [18]. The parameters affecting the surface finish are: burnishing force, feed, ball or roller material, number of passes, workpiece material, and lubrication [5]. The effect of the process on specimens of different materials was studied by many authors. Lee et al. [19] reported that, the surface of 316 stainless steel was improved by ball burnishing process.

The review of previous work shows that there have been very few studies concerning the effect of burnishing parameters on the fatigue life [20–23]. They reported that burnishing process has several attractive advantages such as higher compressive stress, stronger work-hardened layer and relatively smoother surface. Therefore, process may be more effective in improving the fatigue properties than shot peening.

The techniques of Taguchi consist of a plan of experiments with the objective of acquiring data in a controlled way, executing these experiments analyzing data in order to obtain information about the behavior of a given process. These techniques use orthogonal arrays to define the experimental plans. It provides an efficient method to reduce the number of experiments and to obtain optimal process parameters. Many successful applications of Taguchi methods have been reported to improve several processes and product reliability and quality [24–28].

More research work is required to a better understanding and optimizing the relationships between surface geometry and functions. In the study presented in this paper, Taguchi's method is employed to explore the influences of some burnishing process parameters such as; speed, feed, depth of penetration and number of passes on the surface roughness (SR), fatigue life (FL) for 6061 aluminum alloy using a CNC lathe machine. The optimal combination levels of the burnishing process parameters for both surface roughness and fatigue life are determined.

EXPERIMENTAL WORK

Workpiece Material

Aluminum alloy 6061was used as a test material in this work because of its wide application in industry and being the material of many engineering components. The chemical analysis in weight percent and mechanical properties of this material are shown in Tables 1 and 2, respectively.

Table 1: The Chemical Composition of Work Material (Al. Alloy 6061)

Element	Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	Al
Weight%	0.85:1.0	0.7:0.8	0.7	0.2	0.2	0.15	0.15	0.04:0.2	Balance

Table 2: The Mechanical Properties of Al-Alloy 6061

Density (Kg/m^3)	2700
Ultimate tensile strength (Mpa)	110:152
Yield strength (Mpa)	50
Elongation (%)	16:20
Shear strength (Mpa)	95
Hardness (BHN)	30:33

Workpiece Preparation

In this study, 6061- aluminum alloy was used as workpieces material. The test material was received in the form of bars that were machined to workpieces as shown in Figure 3.

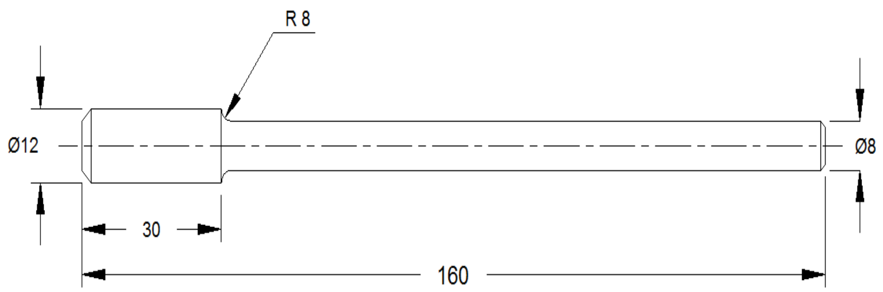

Figure 3: Workpiece Geometry

Design and Preparation of Burnishing Tool

A simple tool was designed for external ball burnishing process. The main parts of the tool are shown in Figure 4. A 8-mm diameter hard steel ball was used for burnishing. With this arrangement the ball was free to rotate in contact with the workpiece during burnishing process, due to the frictional forces developed. The ball could be easily removed from the tool for changing, readjusting or cleaning. The shank of this tool is designed in such a manner that it can be simply mounted or fixed onto the tool holder of the used CNC lathe machine.

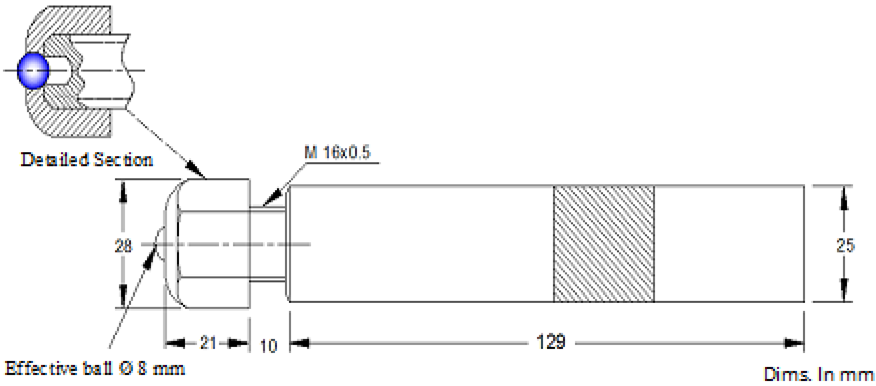

Figure 4: Ball Burnishing Tool

Burnishing Process Parameters

In order that the effect of each parameter on the surface characteristics of the workpiece can be thoroughly investigated, only four burnishing parameters were chosen namely; burnishing speed, feed, depth of penetration and number of passes. In this study the range of process parameters such as speed was selected as 25:125m/min, burnishing feed was selected as 20:100μm/rev, depth of penetration was selected as 3:15μm and number of passes was selected as 1:5 pass. The burnishing process parameters along with their ranges are given in Table 3.

Table 3: Burnishing Parameters with Range and Values at Five Levels

Burnishing speed, m/min	25, 50, 75, 100 and 125
Burnishing feed, μm/rev	20, 40, 60, 80 and 100
Depth of penetration, μm	3, 6, 9, 12 and 15
Number of passes	1, 2, 3, 4and 5
Ball diameter, mm	8
Lubrication	KUTWELL 42

Experimental Design

To evaluate the effect of burnishing parameters on some performance characteristics (surface roughness and fatigue life) and to identify the performance characteristics under the optimal burnishing parameters, a specially designed experimental procedure is required. Classical experimental design methods are complex and difficult to use. In this study, the Taguchi technique, a powerful tool for parameter design of performance characteristics, was used to determine optimal burnishing parameters for minimum surface roughness, maximum number of cycles to failure in burnishing process.

In the Taguchi technique, process parameters, which influence the products, are separated into two main group: control factors and noise factors [29]. The control factors are used to select the best conditions for stability in design of finishing process, whereas the noise factors denote all variation. Taguchi proposed to acquire the characteristic data by using orthogonal arrays, and to analyze the performance measure from the data to decide the optimal process parameters. This method uses a special design of orthogonal arrays to study the entire parameter space with small number of experiments only. In this study, four burnishing parameters were used as control factors and each parameter was designed to have five levels Table 3. According to the Taguchi quality design concept, an L25 orthogonal array table with 25 rows (corresponding to the number of experiments) was chosen for the experiments Table 4.

In Taguchi method [29], a loss function is used to calculate the deviation between the experimental value and the desired value. This loss function is further transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on type of characteristics; lower is better (LB), nominal is better (NB) and higher is better (HB). For HB and LB, the definitions of the loss function for burnishing performance results y_i of n repeated number are:

Smaller the better characteristics

$$L.\beta\eta = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{1}$$

Larger the better characteristics

$$H.\beta\eta = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{2}$$

For higher performance of product a low surface roughness is always desired. Hence, the response parameter surface roughness has been categorized as ‘lower is better’ type problem and the signal to noise ratio in this case has been calculated as η(Ra). Also, a high number of cycles to failure is intended. Hence, this response parameter has been categorized as ‘higher is better’. It may be noted that larger value of η(SR) and η(FL) is desirable in the burnishing process. Regardless of the category of the quality characteristics, a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of highest S/N ratio value. By applying equations (1) and (2), the S/N values for each experiment of L25, can be calculated Table 4. The relative importance of the burnishing parameters with respect to the SR and the FL was investigated to determine more accurately the optimum combinations of the burnishing parameters. Furthermore, a statistical analysis of variance (ANOVA) can be performed to see which parameter is statistically significant for each quality characteristics. In general, signal to noise (S/N) ratio (η, HB) represents quality characteristics for the observed data in the Taguchi design of experimental objective.

Table 4: Experimental Results and Calculated S/N Ratio of Each Response

No. Exp.	Speed, m/min		Feed, µm/Rev		Depth of Pent. µm		No. of Passes		Experimental Results and S/N Values			
	Code	Actual	Code	Actual	Code	Actual	Code	Actual	Ra (mm)	S/N Ratio	FL	S/N Ratio
1	1	12.5	1	20	1	3	1	1	0.15	16.47	17040	84.63
2	1	12.5	2	40	2	6	2	2	0.55	5.193	18300	85.25
3	1	12.5	3	60	3	9	3	3	0.55	5.193	19650	85.87
4	1	12.5	4	80	4	12	4	4	0.45	6.936	20130	86.08
5	1	12.5	5	100	5	15	5	5	0.65	3.742	18980	85.57
6	2	25	1	20	2	6	3	3	0.65	3.742	19980	86.01
7	2	25	2	40	3	9	4	4	0.45	6.936	20010	86.02
8	2	25	3	60	4	12	5	5	0.75	2.499	15180	83.63
9	2	25	4	80	5	15	1	1	0.95	0.445	16130	84.15
10	2	25	5	100	1	3	2	2	1.10	-0.83	16980	84.60
11	3	50	1	20	3	9	5	5	2.10	-6.44	16560	84.38
12	3	50	2	40	4	12	1	1	0.50	6.021	15060	83.56
13	3	50	3	60	5	15	2	2	0.55	5.193	18560	85.37
14	3	50	4	80	1	3	3	3	0.65	3.742	15360	83.73
15	3	50	5	100	2	6	4	4	0.70	3.098	18720	85.45
16	4	75	1	20	4	12	2	2	1.60	-4.08	13980	82.91
17	4	75	2	40	5	15	3	3	0.70	3.098	16160	84.17
18	4	75	3	60	1	3	4	4	0.80	1.938	15420	83.76

Table 4: Contd.,

19	4	75	4	80	2	6	5	5	0.90	0.915	18240	85.22
20	4	75	5	100	3	9	1	1	0.70	3.098	22080	85.88
21	5	100	1	20	5	15	4	4	3.65	-11.2	18260	85.23
22	5	100	2	40	1	3	5	5	1.55	-3.81	19530	85.81
23	5	100	3	60	2	6	1	1	0.45	6.936	22500	87.04
24	5	100	4	80	3	9	2	2	0.35	9.117	26400	88.43
25	5	100	5	100	4	12	3	3	1.75	-4.86	29400	89.39

RESULTS AND DISCUSSIONS BASED ON THE TAGUCHI METHODOLOGY

The objective of the experiment is to optimize the ball burnishing parameters to get better surface roughness, the smaller the better characteristic is used. However, to optimize the burnishing parameters to get better fatigue life, the larger the better characteristic is used. Table 4 shows the observed values, deduced from the experimental results for average surface roughness and number of cycles to failure (fatigue life). Tables 5 and 6 show the S/N ratio for each level of average surface roughness and fatigue life. These data were plotted as shown in Figures 4 and 5. According to the Taguchi method, analysis of variance (ANOVA) represents the contribution of each parameter on each response result. The optimization of the observed values was then determined through comparison with Taguchi signal-to-noise (S/N) ratio.

Table 5: Response Table for Signal to Noise of Ra

Level	Speed	Feed	Depth of Pent.	No. of Pssses
1	7.50823*	-0.31055	3.50472	6.59562*
2	2.55879	3.48810	3.97668*	2.91878
3	2.32175	4.35164*	3.58016	2.18270
4	0.99341	4.23136	1.30239	1.53238
5	-0.77177	0.84984	0.24644	-0.61907
Delta	8.28000	4.66219	3.73025	7.21469
Rank	**1**	**3**	**4**	**2**

*Optimum level

Table 6: ANOVA of Surface Roughness

Source of Variance	Sum of Square	DF	F-Ratio	P (%)
Burnishing speed	3.0974	4	1.67	23.8
Burnishing feed	3.4694	4	1.87	26.72
Depth of penetration	1.1904	4	0.64	9.16
No. of passes	1.5264	4	0.82	11.74
Error	3.7168	8		28.58
Total	**13.0004**	**24**		**100**

Surface Roughness

Surface roughness is a measure of the product quality and has a great influence on manufacture cost. It describes the geometry of the machined surface and combined with the surface texture and surface integrity. In this study, Ra was measured for Al-alloy 6061.

Figure 5 shows the main effect plot of burnishing parameters on the average S/N ratio for smaller the better for surface roughness. According to this figure, all burnishing parameters used in this work affect the surface roughness. In Taguchi method the higher the level S/N, the better the overall performance, meaning the factor levels with the highest S/N value should always be selected. Accordingly, the average for each experimental level was calculated using the highest S/N value at the level for each parameter to produce the response table (see table 5). As shown in both the response table and the main effects graphs Figure 5, the optimal burnishing parameters for surface roughness was obtained at burnishing speed (Level 1), burnishing feed (Level3), 6µm depth of penetration (Level 2) and number of passes (Level 1).

Furthermore, it shows that the influence of speed on Ra is greater compared with the other graphs. Hence, speed is the most significant parameter affecting Ra followed by number of passes, feed and depth of penetration.

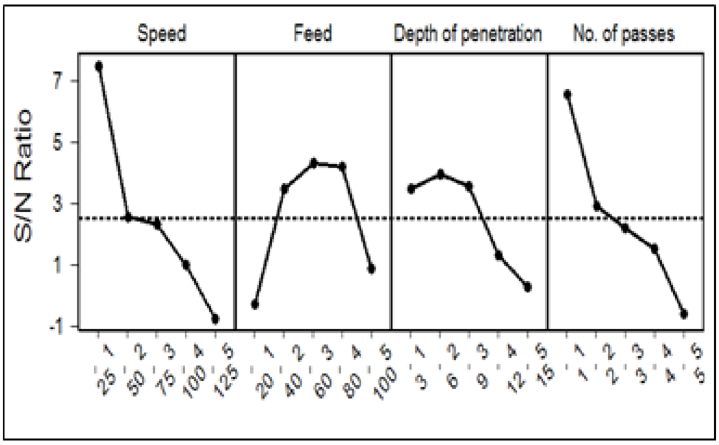

Figure 5: Main Effect Plot S/N Ratio for Surface Roughness (Dashed Line Indicates Mean Value)

According to Figure 6, the effect of speed is proportional with surface roughness. When the speed increases, the surface roughness increases. The surface roughness decreases at low feed, then it increase at high feed. Also, the surface roughness decreases at low depth of penetration, then it increases at high depth of penetration. From the same figure, it can be deduced that the surface roughness increases at low number of passes, then it decreases at high number of passes.

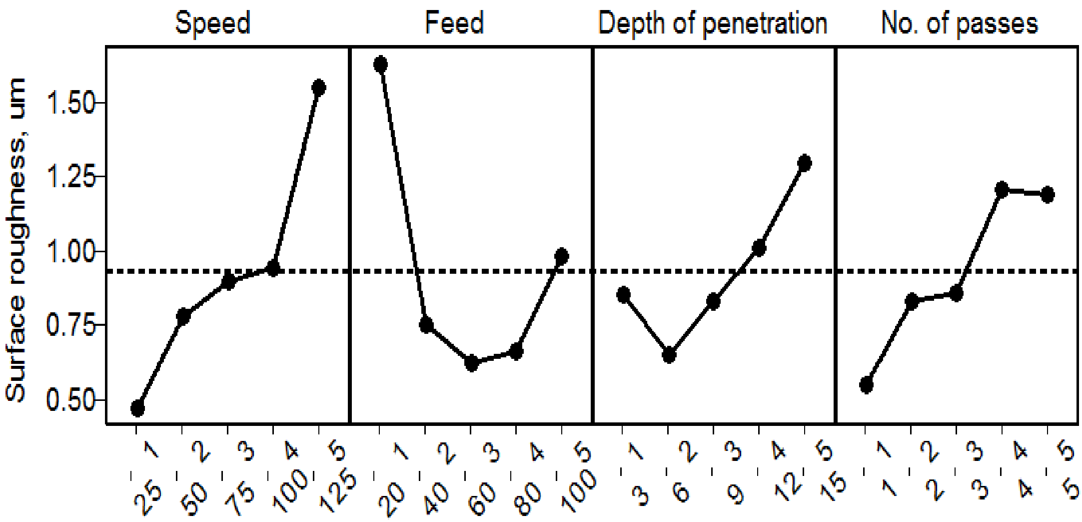

Figure 6: The Main Effect Plot for Means Roughness

The ANOVA table derived for surface roughness is shown in Table 6. The sum of squares provides a measure of the total variation present. The largest contribution to the total sum of squares is for burnishing feed followed by speed, number of passes and then depth of penetration. The larger is the contribution of particular factor to the total sum of squares, the larger is its ability to influence its quality characteristics.

In this study, the analysis was carried out for a level of significance of 5%, i.e. for a level of confidence of 95%. The last column of Table 6 and Figure 7 show the percentage of contribution (P) of each factor on the total variation indication then, the degree of influence on the result. From the analysis of Table 6, it can be observed that the burnishing feed factor (P=26.72), the burnishing speed (P=23.8), the number of passes (P=11.74) and depth of penetration (P=9.16) have statistical and physical significant on the surface roughness, especially the burnishing feed.

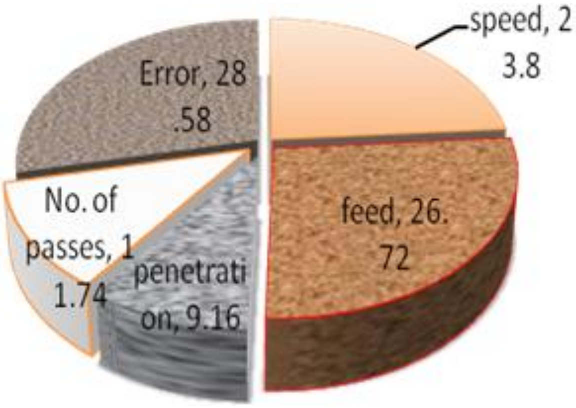

Figure 7: The Contribution Pie of Surface Roughness

The interaction plot- data means for surface roughness is presented in Figure 8. It can be realized that the effect of burnishing speed on surface roughness at different feeds, depth of penetration and number of passes for cases is not the same. It can also be seen that the trend of level (1) is not similar to the trend of the other feed levels in which the roughness value increases with an increase in speed reaching to (50m/min) of speed value, then it will decrease with an increase in speed until the speed value reaches (75m/min), after this the roughness value will begin to increase again reaching to the maximum value of speed. For other levels, the increase in burnishing speed leads, in general, to an increase in surface roughness reaching to higher value then surface roughness starts to decrease with a further increase in burnishing.

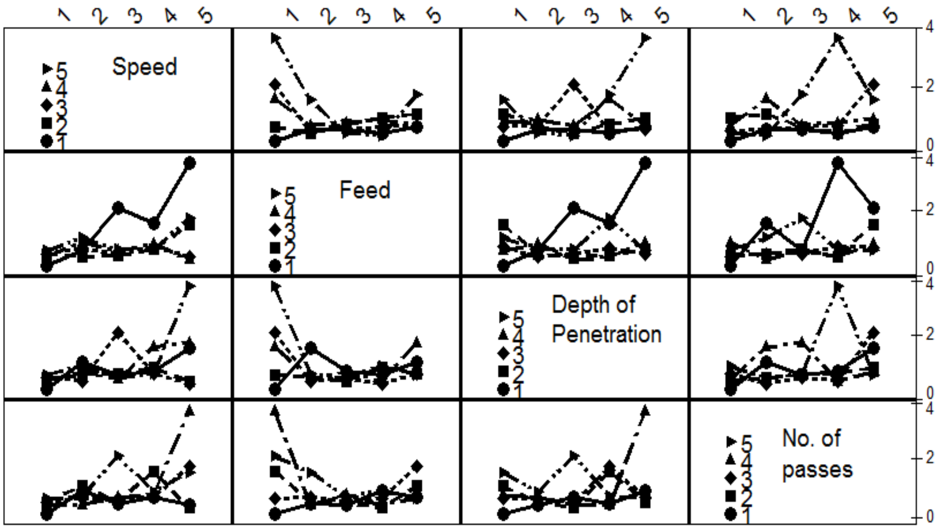

Figure 8: Interaction Plot-Data Means for Surface Roughness

The effect of burnishing feed on the average surface roughness is shown in Figure 8. The results show that the feed is one of the most significant factors affecting the surface roughness. It can be seen, from this figure, that the trend of the results for the effect of feed on surface average roughness for most levels of burnishing speed are similar. In general, for different levels of speed, depth of penetration and number of passes, an increase in burnishing feed reaching to (80µm) leads to a decrease in surface roughness and then surface roughness increases gradually with a further increase in feed.

The effect of depth of penetration on average surface roughness at various speeds, feeds, and number of passes can be assessed from Figure 8. The general trend of the results reveals that an increase in depth of penetration, within the range used in this study, first leads to a reduction in surface roughness reaching a minimum value at depth of penetration of (6-12µm). A further increase in depth of penetration cases an increase in average roughness. Therefore, medium depth of penetrations is favorable because the deformation action of ball burnishing tool is greater and metal flow is regular at this range.

Figure 8 presents the effect of the burnishing number of passes on average roughness at various speeds, feeds, and depth of penetration. It can be seen that there is interactions between number of passes and each of speeds, feeds and depth of penetration. At low speed, feed and depth of penetration, an increase in number of passes leads to a decrease in the average surface roughness whereas at high speeds, feeds, and depth of penetrations an increase in number of passes results in a considerable increase in surface roughness.

The highest average surface roughness was obtained with a combination of a high depth of penetration and high number of passes. Also, it can be realized that combination between high number of passes and speed and/or depth of penetration results in a considerable reduction in burnished surface roughness. This is because of the repeating action of the burnishing process on the same workpiece at low speed which leads to an increase in the surface structure homogeneity resulting in an increase in the surface finish.

Fatigue Life

Fatigue is the common name used to describe the unexpected failure of metal parts by progressive fracturing while in service. Metal fatigue is directly related to the number of stress cycles undergone by the metal part. The number of cycles to failure (fatigue life) measured by a cantilever fatigue testing apparatus in which a constant load is applied on the rotating specimen until it breaks.

The S/N ratio for five levels of each control factor is computed and the results are tabulated in Table 7. The best level for each control factor is the one with the highest S/N ratio. The average S/N ratio for larger the better for cycles to failure (fatigue life) is shown in Figure 9 which suggests that the burnishing speed is more significant. Feed is the second significant factor and depth of penetration is the third significant factor and number of passes is the lowest significant factor.

The highest value of burnishing speed and feed appear to be the best choice to get high value of cycles to failure (fatigue life), whereas the middle value of both depth of penetration and number of passes appear to be the best to obtain high value of fatigue life. The optimum performance for fatigue life was obtained at 125m/min burnishing speed (level 5), 100µm/rev burnishing feed (level 5), 9µm depth of penetration and 3passes (level 3).

Table 7: Response Table for Signal to Noise of Fatigue Life

Level	Speed	Feed	Depth of Pent.	No. of Passes
1	85.4777	84.6325	84.5063	85.2524
2	84.8827	84.9627	85.7942	85.3123
3	84.4966	85.1339	86.3171*	85.8339*
4	84.5882	85.5220	85.1125	85.3079
5	87.1827*	86.3769*	84.8978	84.9214
Delta	2.6860	1.7443	1.8108	0.9124
Rank	**1**	**2**	**3**	**4**

*Optimum level

Table 8: ANOVA of Fatigue Life

Source of Variance	Sum of Squares	DF	F-Ratio	P (%)
Burnishing speed	137028960	4	5.73	45.33
Feed	50676840	4	2.12	16.76
Depth of penetration	51320440	4	2.15	16.97
No. of passes	15541560	4	0.65	5.14
Error	47790000	8		15.8
Total	**302357800**	**24**		**100**

DF: degree of freedom P: percentage of contribution

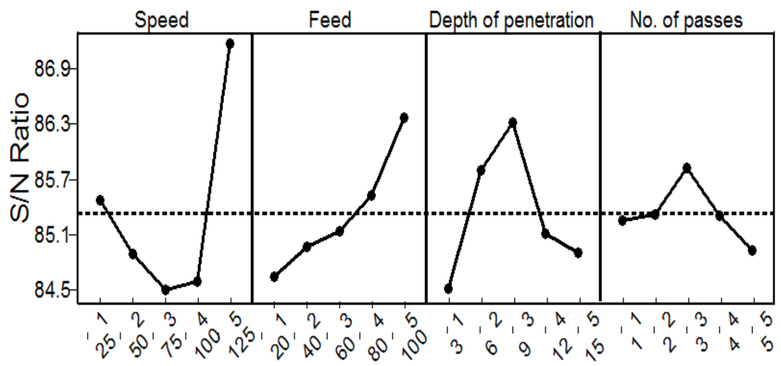

Figure 9: Main Effect Plot S/N Ratio for Fatigue Life (Dashed Line Indicates Mean Value)

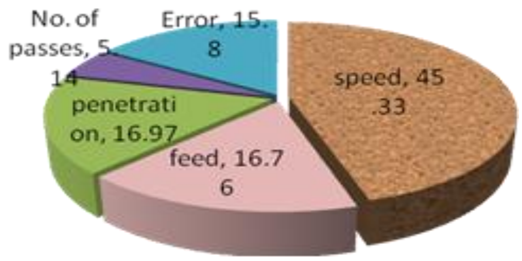

Figure 10: The Contribution Pie of Fatigue Life

The ANOVA for different factors including level average, sum of square, and contribution-enabled relative quality effect to be determined. The results of the ANOVA Table 8 and Figure 10 reveal that the burnishing speed which reached 45.33% made the major contribution to overall performance. The contribution percentage for depth of penetration and feed was 16.97% and 16.76%, respectively. The number of passes made the minor contribution of 5.14%.

Figure 11 shows the main effect of means for each parameter used in this work, whereas Figure 12 shows more details about the different relationship between the input burnishing process parameters and cycles to failure (fatigue life). It can be seen from Figure10 that the general trend of the main effect of means for the four input parameters used in this work is not the same. The cycles to failure decreases slightly with an increase in burnishing speed, reaching a minimum value at burnishing speed of 75m/min. A further increase in burnishing speed causes an increase in cycles to failure. This is may be due to the stability of the ball burnishing tool at high speeds. The general trend of the effect of burnishing feed on the cycles to failure as shown in Figure 11 is that an increase in feed leads to an increase in cycles to failure. From the same figure, the trend of the effect of both depth of penetration and number of passes is the same. An increase in depth of penetration and/or number of passes up to the middle value leads to an increase in cycles to failure. A further increase in depth of penetration and/or number of passes more than the middle value causes a decrease in cycles to failure (fatigue life).

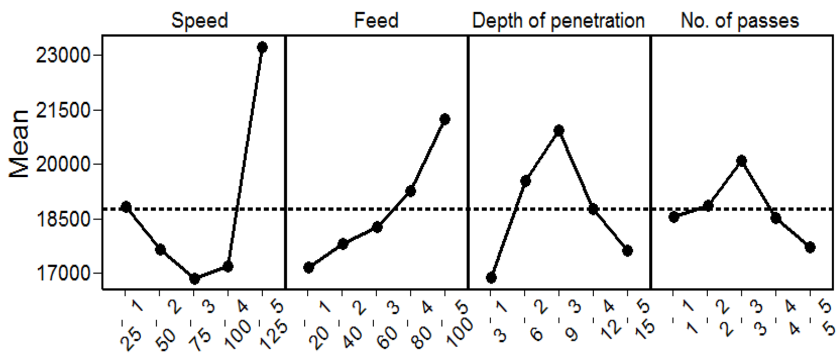

Figure 11: The Main Effect Plot for Means Roughness

More details about the different effects of each parameter at different levels of other parameters used in this work are presented in Figure 12. It can be seen from this figure that the effect of burnishing speed on cycles to failure for different feeds, depth of penetration and number of passes for all cases is not the same and there are some interactions between burnishing speed and other parameters. This means that the effect of burnishing speed on cycles to failure is not the same for all values of feeds, depth of penetration or number of passes. The higher cycles to failure was observed at conditions: 125m/min speed, 100µm feed, 9 µm depth of penetration and 3 number of passes.

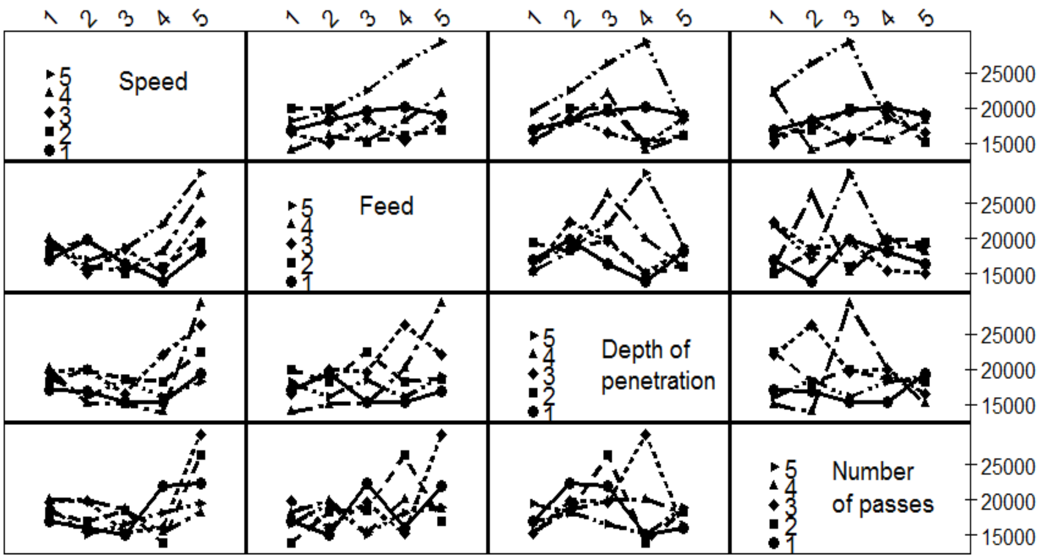

Figure 12: Interaction Plot-Data Means for Surface Roughness

CONCLUSIONS

In the present work, ball burnishing process of 6061 aluminum alloy based on the Taguchi technique has been investigated. Based on the analysis of experimental results, the following conclusions can be drawn:

- The output responses of burnished surface are mainly influenced by the four burnishing parameters used namely; burnishing speed, feed, depth of penetration and number of passes.
- The parameter design of Taguchi technique provides a simple, systematic and efficient methodology for optimization of the burnishing parameters.
- The burnishing feed with a contribution percent of 26.72% had the dominant effect on surface roughness followed by burnishing speed, number of passes and then by depth of penetration
- The burnishing speed with a contribution percent of 45.33% had the dominant effect on cycles to failure (fatigue life) followed by burnishing feed, depth of penetration and then by number of passes.
- The optimal burnishing parameters for surface roughness (the best surface finish) was obtained at burnishing speed of 25m/min, burnishing feed of 60µm, depth of penetration of 6µm and number of passes of 1.
- The optimum performance for fatigue life was obtained at 125m/min burnishing speed, 100µm/rev burnishing feed, 9µm depth of penetration, and 3 passes.

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