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STUDYING THE EFFECT OF VARIOUS PARAMETERS ON DRY SLIDING WEAR BEHAVIOR OF TC21 TITANIUM ALLOY USING TAGUCHI EXPERIMENTAL DESIGN

Ali Abdelmoneim[1], Ramadan N. Elshaer[2], A. Sobh[3]& M. El-Shennawy[4]

[1,3,4]Faculty of Engineering, Helwan University, Cairo, Egypt

[2]Research Scholar, Tabbin Institute for Metallurgical Studies, Cairo, Egypt

ABSTRACT

This study investigates the effect of independent control factors of heat treatment, normal pressure and sliding speed on the dry sliding wear behavior of TC21 titanium alloy using Taguchi's experimental design. Dry sliding wear tests were carried out using a pin on disk testing device based on Taguchi's orthogonal arrays. Two heat treatment cycles were carried out to produce different microstructures with different hardness and hence, different wear resistance. Using signal-to-noise ratio and analysis of variance (ANOVA), the main controlling factors that influence the dry sliding wear were determined for this alloy. The normal pressure was the most significant control factor (~85 %) affecting the wear resistance followed by sliding speed (~8 %) and at last heat treatment (~5 %). A regression model has been developed and showed a good prediction ability with average absolute deviation less than 10 %. SEM analysis of worn surface revealed that the abrasive wear is the predominant mechanism under low levels of pressure and speed while adhesion and delamination mechanisms was predominant under high pressure and speed.

KEYWORDS: *Wear, Titanium Alloy TC21, Heat Treatment, Normal Pressure, Sliding Speed, Design of Experiment (DOE), Taguchi*

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INTRODUCTION

In many fields of engineering designers look for those materials that can supply high strength, fracture toughness, stiffness, and service temperatures all that along with virtue of low weight [1]. This can be offered by titanium and its alloys where they are used extensively in many vital sectors such as aerospace, automotive, marine, power generation, construction, biomedical, chemical processing industries [2]. However, a big obstacle encounters these alloys in field of friction due to the humble wear resistance when compared to other materials such as steels [3]. Through the literature, a lot of research done to improve the wear resistance of titanium and its alloys. Some researchers used traditional heat treatment processes [1, 4-14] and some others developed new surface and thermochemical treatments [15-20]. It is noticed that many research concerned to $\alpha+\beta$alloys especially conventional Ti-6Al-4V alloy because of its wide range of applications.

The wear test is classified as a destructive test. So, the cost is a considerable issue which must be reduced as much as possible without any influences on the results. Statistical approaches such as Taguchi is the best way to handle this dilemma. Taguchi method widely used in studying and optimizing wear properties specially in composites and powder metallurgy materials where the weight fraction of constituents is a significant control factor beside the load, sliding speed, and time [21-25]. Using Taguchi's L9 orthogonal array design, Sahoo et al [1] studied the influence of factors such as microstructural variation resulting from heat treatment process (lamellar, bimodal, and equiaxed), sliding velocity, normal load, and test duration on dry sliding wear behavior of Ti-6Al-4V alloy at room temperature. Results indicated that lamellar microstructure has the lowest sliding wear resistance compared with bimodal and equiaxed microstructure. Singh et al [13] also used Taguchi design with L25 orthogonal array to optimize the deep cryogenic treatment conditions for dry sliding behavior of Ti6Al4V alloy. They were used five control factors: soaking durations(t_{cs}), tempering temperatures (T_{tp}), sliding speed (v_s), contact pressure(p_c), and sliding time(t_s) with five level for each one. Results demonstrated that the deep cryogenic treatment successfully to reduce the wear rate. From all those investigations, obviously the normal load is the most significant control factor in dry sliding wear behavior.

As a new developed damage tolerated α+βtitanium alloys, TC21 alloy has a virtue of high strength, favorable fracture toughness, and a low crack propagation rate, so it has been used as a vital structural material in astronautics and aeronautics industry [3]. Being a new alloy, hence through the literature they are a few works involve the tribological characteristics of TC21 alloy [3, 26-29].

The aim of this research is studying the effect of various parameters including heat treatment, normal pressure, sliding speed on dry sliding wear behavior of the TC21 titanium alloy using Taguchi experimental design.It is aimed at developing a model for prediction of main controlling factor affecting wear resistance with minimum deviation.

EXPERIMENTAL WORK

Material and Heat Treatments

Rods with 7 mm diameter and 140 mm length of TC21 titanium alloy with chemical composition shown inTable 1, were cut into small specimens of length 12 mm using wire cutting machine. These specimens were classified into three groups according to the heat treatment applied. Heat treatment process is shown inFigure 1. First group was "as-received" samples, second group was solution treated at 1000^{o}C (above β transus temperature 950±5 ^{o}C[29]) for 15 min followed by air cooling (AC) and third group was solution treated at 1000^{o}C followed by water quenching (WQ).

Table 2summarizes the details of the heat treatments and resulted microstructures of treated specimens. To obtain the effect of different heat treatments on the microstructure and hardness of specimens Field Emission Scanning Electron Microscopy (FESEM) and Vickers hardness test have been used. The hardness test was carried out according to ASTM E92 standard. Five reading were recorded for each specimen ant the average was taken.

Table 1: Chemical Composition of TC21 Titanium Alloy

Main Alloying Elements as (wt. %)									
Element	**Al**	**Mo**	**Nb**	**Sn**	**Zr**	**Cr**	**Si**	**Fe**	**Ti**
%	6.5	3	1.9	2.2	2.2	1.5	0.09	0.05	Balance

Table 2: Heat Treatment Processes and Microstructure

Group	Heat Treatment	Microstructure
1	As received	Equiaxed α embedded within β matrix
2	Solution treatment at 1000^{0}C/15 min + AC	Lamellar of α and β-phases
3	Solution treatment at 1000^{0}C/15 min + WQ	Lamellar of $\alpha^{''}$ and β-phases

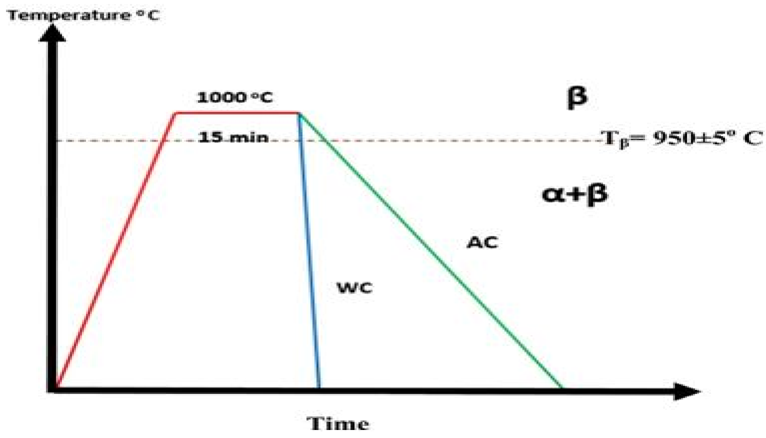

Figure 1: Heat Treatment Diagram.

Design of Experiment (DOE)

In the current investigation, Taguchi approach was applied for Design of Experiment (DOE). This method reduces cost and save time specially in destructive tests. Therefore, it is applied in both academic and industrial fields because it offers an efficient, simple, and systematic methodology to control any process input factors to achieve the optimum performance or revenue. Taguchi considered a partial factorial DOE which used to model and analyze the effect of different control factors on the output response of the process. This methodology is valuable specially when the control factors are qualitative and discrete [1].

Three parameters were used as control factors in this study: heat treatment, normal pressure and sliding speed. Each factor has three levels as illustrated inTable3. Mintab® 19 software package is used to assign the factors, their levels and to construct the Taguchi L9 Orthogonal Array as shown inTable 4Then, execute the post process Analysis of Variance (ANOVA).

Wear Test

Specimens were tested under dry sliding wear condition at ambient temperature using a pin on disk testing device as shown in**Figure 2** The disk is made of high-speed steel (HSS) with a hardness of 64 HRC. The specimens were grounded by emery papers up to 1000 grit. The disk was ground up to 1000 grit before every trail as well as both disk and specimen was cleaned with acetone then dried by an air blower. Each specimen was weighted before and after the wear test by means of an electronic balance with accuracy 0.1 mg to get mass loss. The test duration for each specimen set to 15 min. Then, the wear rate (WR) has been calculated as follows:

$$WR = \frac{\Delta m}{t} \text{g/min} \quad (1)$$

where, Δm: mass loss due to wear (g), and t: time (min).

The test was repeated and the average of WR considered at the same conditions was determined. Worn surfaces of some selected specimens were examined using Field Emission Scanning Electron Microscopy (FESEM) to evaluate and identify wear mechanisms.

Table 3: Control Factors and Their Levels

Factor	Code	Level		
		1	2	3
Heat Treatment	**A**	**As Received**	**AC**	**WQ**
Pressure, MPa	B	0.26	0.52	0.78
Sliding Speed, m/s	C	1.5	1.875	2.25

Table 4 Taguchi L9 Orthogonal Array DOE Resulted WR and Corresponding S/N Ratio

Trail Number	Heat Treatment	PressureMPa	Sliding Speedm/s	Wear Rate (WR)x10^{-3} g/min	S/NdB
1	As received	0.26	1.500	1.89	-5.5292
2	As received	0.52	1.875	3.07	-9.7428
3	As received	0.78	2.250	5.12	-14.1854
4	AC	0.26	1.875	2.13	-6.5676
5	AC	0.52	2.250	3.19	-10.0758
6	AC	0.78	1.500	3.87	-11.7542
7	WQ	0.26	2.250	2.03	-6.1499
8	WQ	0.52	1.500	2.41	-7.6403
9	WQ	0.78	1.875	3.91	-11.8435

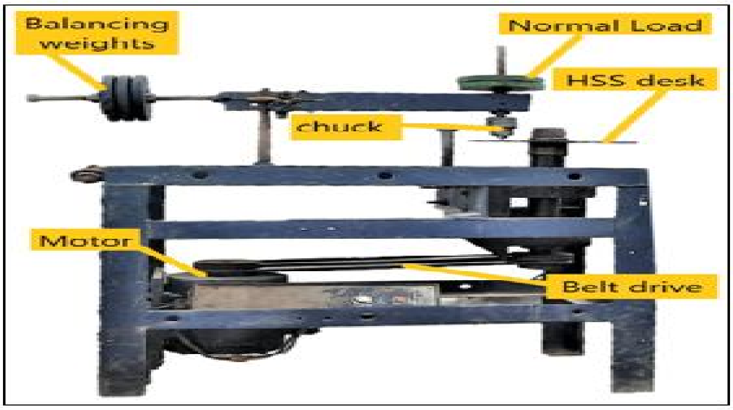

Figure 2: Pin on Disk Wear Testing Device.

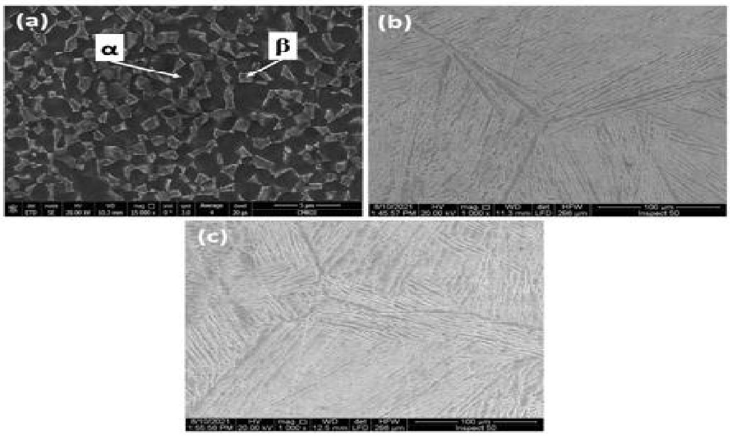

Figure 3: FESEM Micrograph Showing Microstructure for (a) As Received (b) AC (c) WQ Specimens.

RESULTS AND DISCUSSIONS

Microstructure and Hardness Characterization

The microstructure has great influence on properties and performance of material. Therefore, it is used to control these properties by means of thermal and thermomechanical treatments. Figure3 shows the microstructure of as received and heat-treated specimens. For as-received condition, Figure 3 (a), the microstructure consists of equiaxed α-phase on matrix of β-phase. After heat treatment this morphology has been changed to full lamellar microstructure for both AC and WQ conditions, Figures. 3 (b)&(c) and. As a result, hardness changed as shown in Figure 4. AC condition has the highest hardness (446HV) compared with as received (378 HV) and WQ (342HV). The degradation in hardness after WQ, although it seems to be intuitive, is attributed to formation of orthorhombic martensite phase (α'') [30] which has softening effect [31]. Reduction of hardness upon water quenching of TC21 was previously reported [32]

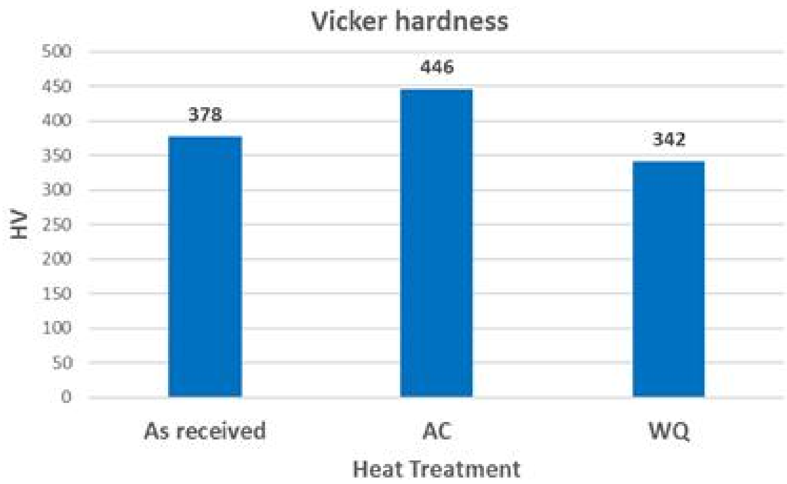

Figure 4: Vickers Hardness Test Results.

STATISTICAL ANALYSIS

A minimal squares-based ANOVA was used to determine to which degree each control factor affects the output response (WR) which expressed by signal to noise ratio (S/N). Signal refers to the mean of response while noise refers to variation about that mean. There are three loss function to choose from for S/N ratio; larger is better, nominal is better and smaller is better. In our case smaller is better has been chosen because WR should be as small as possible. Smaller is better S/N function is calculated by

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right) \quad (2)$$

Where, *n* is observations number, and *y* is observed response i.e., WR.

The S/N ratios for each set of control factors are presented in Table 4.Effect of control factors on WR is shown inFigures.5 & 6. They show how the mean and S/N could response to any change in any of control factor from level to another. Selecting the set of control factors corresponding to the highest S/N ratio results in the optimum quality with minimum variance i.e., in our case the minimum WR. This is achieved by setting heat treatment to WQ, pressure to 0.26 MPa, and sliding speed to 1.5 m/s. Figures. 5 shows sharp increase in WR when pressure increased.With less amount, WR increases when sliding speed is increased. WQ group showed better wear resistance compared with AC and as-received groups.

Tables 5 & 6 represent the means and S/N ratio responses, respectively. For each control factor, delta value is calculated, and significance of factors is ranked according to this value; namely, from most significant; highest delta, to less significant; lowest delta. As shown in Figures 5 & 6, pressure is the most significant control factor followed by sliding speed and then the heat treatment.

Table 7summarizes the ANOVA findings. ANOVA has been performed with significance level of 5 % i.e., confidence level of 95 %. The last column shows percentage contribution of each factor in the total variance. It can be observed that pressure has contribution to WR by 85.13 % followed by sliding speed (8.44 %) and then the heat treatment (5.33 %), finally, total error about 1.1 %. R squared (R-Sq) equals to 98.9 % which means that the model can explain 98.9 % of total variance and this is accepted

Table 5: Response Table for Means

Level	Heat Treatment	Pressure	Sliding Speed
1	3.360	2.017	2.723
2	3.063	2.890	3.037
3	2.783	4.300	3.447
Delta	0.577	2.283	0.723
Rank	3	1	2

Table 6: Response Table for S/N Rations

Level	Heat Treatment	Pressure	Sliding Speed
1	-9.819	-6.082	-8.308
2	-9.466	-9.153	-9.385
3	-8.545	-12.594	-10.137
Delta	1.275	6.512	1.829
Rank	3	1	2

Smaller is Better

Table 7: Analysis of Variance for Means.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of Contribution
Heat treatment	2	0.4990	0.4990	0.24948	4.85	0.171	5.33
Pressure	2	7.9644	7.9644	3.98221	77.46	0.013	85.13
Sliding Speed	2	0.7895	0.7895	0.39474	7.68	0.115	8.44
Residual Error	2	0.1028	0.1028	0.05141			1.1
Total	**8**	**9.3557**					**100**

Model Summary

R-Sq= 98.90 %,R-Sq(adj) = 95.60 %

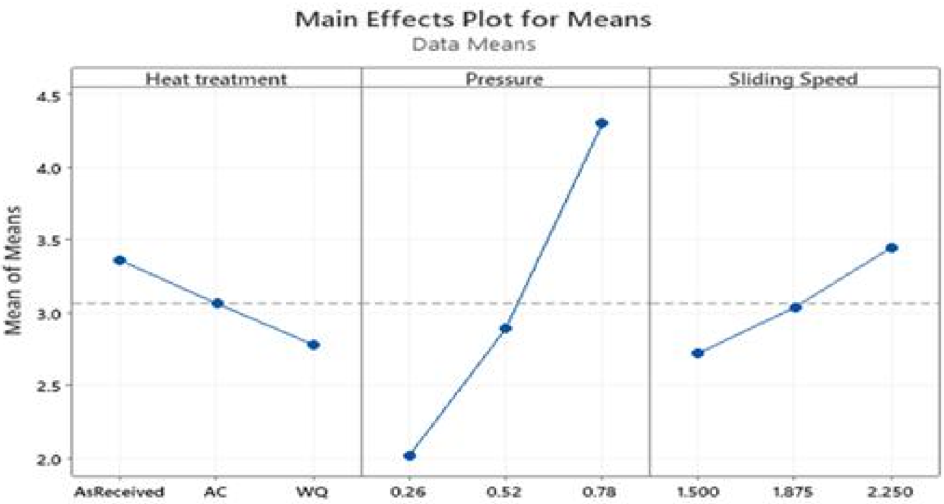

Figure 5: Main Effects for Means.

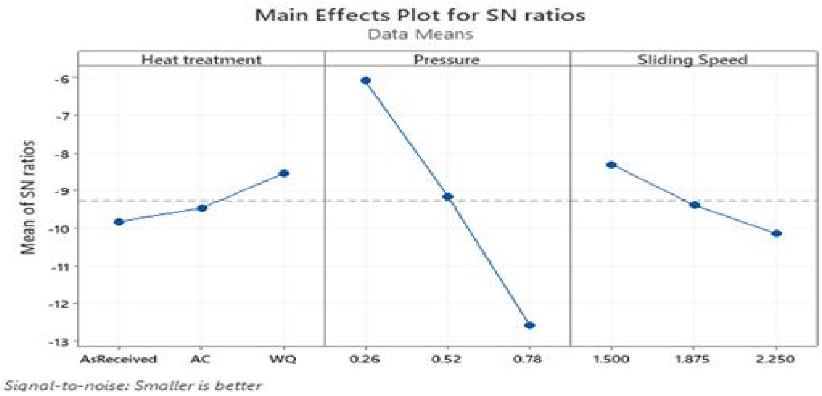

Figure 6: Main Effects for S/N Rations.

Regression Model

Based on observed WR results, linear model has been developed between independent predictors; heat treatment, pressure and sliding velocity as well as response; WR. The regression equations are:

$$\left.\begin{array}{lll} \text{As Received} & WR = 0.291 + 4.126\,(\text{Pressure}) + 0.505\,(\text{Sliding Speed}) \\ \text{AC} & WR = -0.006 + 4.126\,(\text{Pressure}) + 0.505\,(\text{Sliding Speed}) \\ \text{WQ} & WR = -0.286 + 4.126\,(\text{Pressure}) + 0.505\,(\text{Sliding Speed}) \end{array}\right\} \quad (3)$$

OPTIMIZATION AND CONFIRMATION

The optimum conditions in dry sliding wear are those resulting in minimum wear rate (WR). Based on previous ANOVA prediction, this can be obtained through setting the control factors to be as follows: heat treatment (WQ), pressure (0.26 MPa), and sliding speed (1.5 m/s) as shown in Figure 8By applying this set of control factors in the regression model and then conducting a confirmation test at those levels the following results shown in Table 8 could been obtained. The results showed that the experimental value of WR is close to the predicted one and within the 95 % confidence interval of the prediction model with 8.07 % (<10 %) of absolute deviation.

Figure 7 illustrates the residuals which are normally distributed. From the regression model ANOVA, it was found that R-sq = 99.51 % which indicates that the model can explain 99.51 % of total variance while R-sq (pred) = 98.54 %. that the model has a good prediction ability within the limits of control factors.

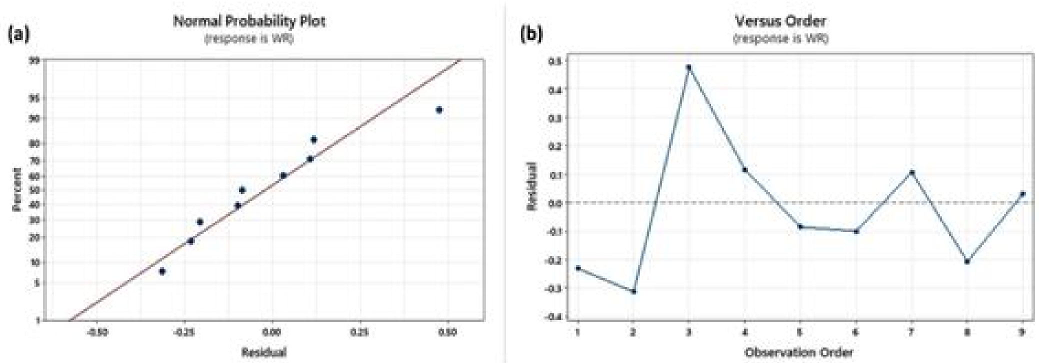

Figure 7: Normal Probability Graph of Residuals and Fits (a) Normal Probability Graph of Residuals (b) Graph of Residuals VS Fitted Values.

Table 8: Result of Confirmation Test VS Predicted Value of WR

Trail No.	Expl. WR	Pred. WR	95 % CI	95 % PI	%Ofabsolute Dev.
1	1.68	1.544	(1.091, 1.998)	(0.640, 2.449)	8.1
2	1.65	1.544	(1.091, 1.998)	(0.640, 2.449)	6.42
3	1.71	1.544	(1.091, 1.998)	(0.640, 2.449)	9.7
Average					**8.07**

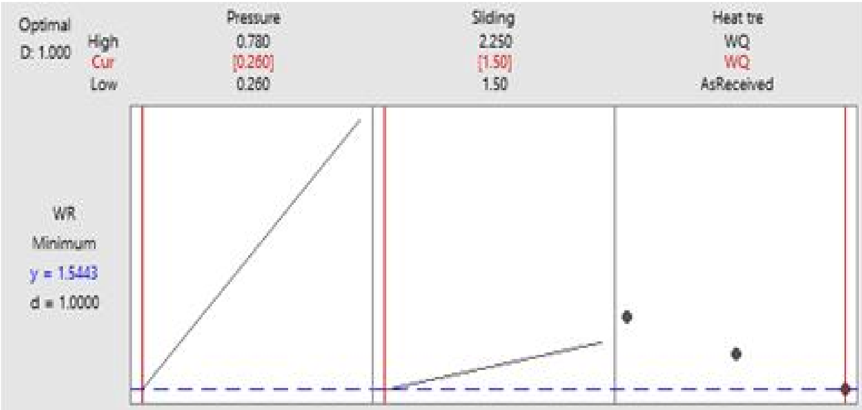

Figure 8: Optimum Levels Set of Control Factors.

Wear Mechanisms

Figure 9 shows the worn surface morphologies of some selected specimens of as-received, AC, and WQ. Figure 9 (a) illustrates worn surface of as-received condition under normal pressure of 0.26 MPa and sliding velocity of 1.5 m/s. It revealed uniformly distributed deep grooves with sign of plastic deformation occurrence (ploughing) which refers to an abrasive wear mechanism. Under the same conditions (pressure and speed), WQ worn surface shown in Figure9 (b) revealed a very fine and shallow scratches of abrasive wear and this explains why those conditions are corresponding to minimum WR obtained. This behavior could be attributed to the presence of orthorhombic martensite phase (α”). Figure 9(c) represents the worn surface of AC condition under highest pressure (0.78 MPa) at highest sliding speed (2.25 m/s). Presence of smooth compacted regions is observed, which refers to brittle damage [1]. Presence of some adhesive wear patches and large delamination region are also observed. Adhesive and delamination wear are most likely triggered by the frictional thermal effect at sever conditions of pressure and speed particularly with high chemical reactivity materials such as titanium.

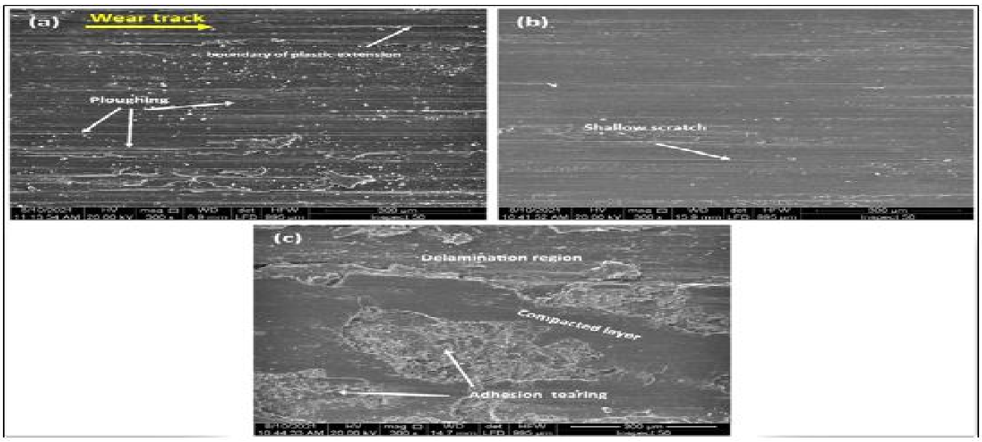

Figure 9: Worn Surfaces of Specimens at Different Conditions; (a) As Received at 0.26 MPa, 1.5 m/s, (b) WQ at 0.26 MPa, 1.5 m/s and (c) AC at 0.78 MPa, 3 m/s.

CONCLUSIONS

The effect of different control factors including heat treatment, normal pressure and sliding speed on dry sliding wear behavior of TC21 titanium alloy with equiaxed microstructure has been carried out using Taguchi's experimental design. The main concluding remarks are summarized below:

- Normal pressure is the most significant control factor (~85 %) on dry sliding wear of TC21 titanium alloy followed by sliding speed (~8 %) and then heat treatment (~5 %).
- Although the WQ specimens has the minimum hardness, they have the best wear resistance.
- Liner regression model developed based on obtained observations showed acceptable prediction of 95 % confidence of actual WR with average absolute deviation less than 10 % (~8 %).
- Under low normal pressure and sliding speed the wear mechanism is abrasive wear which turns to adhesive and delamination wear under high pressure and sliding speed.

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