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Improvement of the fretting wear resistance of Ti6Al4V by application of hydrostatic ball burnishing.

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Abstract. The objective of the research was to improve the fretting wear resistance of titanium alloy by hydrostatic ball burnishing. Ball burnishing is an economic surface finishing process for wide range of components. It is based on pressing and rolling a hydraulically floated ball along the surface of the component being treated, to plastically deform surface asperities. This process generates a deep field of compressive residual stresses (up to 1.0 mm) in the outer layers of the component. The compressive residual stresses and the high quality of the surface finish improve the wear resistance of the part. Experiments were made using ball-on-disc tribotester in oscillatory motion. 100Cr6 sphere co-acted with a disc made of titanium alloy Ti–6Al–4V. The friction force was monitored as a function of time during the test. Wear of disc was measured after the test using the non-contact 3D surface profiler. The optimal ball burnishing parameters have been determined after conducting the Taguchi L9 matrix experiment. During tests, normal load was kept constant at 50 N within the contact with frequency of 50 Hz and displacement amplitude of 0.02 mm. The results confirmed that hydrostatic ball burnishing had a significant influence on friction and wear.

1. Introduction

Fretting is defined as a small amplitude oscillatory movement which occurs between two surfaces in contact. Partial slip or gross slip condition can be observed in the fretting contact. For the partial slip case there are parts of contact where no slip displacement occurs, but in gross slip case there is slip displacement across the whole contact [1]. The fretting regimes can be described as functions of normal load and displacements. This oscillatory movement often results in the formation of oxide debris and thus, is called “fretting wear” or “fretting corrosion”. In most cases, the cause of this movement is due to one of the members being placed under cyclic fatigue loading. The case where a fatigue loading is present is more damaging and is called “fretting fatigue”. The type of damage, wear or fatigue is related also to the sliding condition, i.e. partial slip or gross slip. The fretting fatigue is related with higher loads, a smaller amplitude of motion and contact within partial slip regime. Wear is leading in the gross slip regime [2]. Fretting fatigue is a common problem which has detrimental affects on a broad range of engineering parts. Several factors can affect crack nucleation under fretting fatigue. These factors are: the loading condition, the surface contact condition, and the operating environment. The relevant loading condition includes the contact slip amplitude normal contact pressure, and the bulk applied stress amplitude and mean stress. The surface contact condition includes the surface roughness, chemical composition of the contact region, residual surface stress and any coatings or lubricants on the surface.

IOP Conf. Series: Materials Science and Engineering **521** (2019) 012016 doi:10.1088/1757-899X/521/1/012016

Surface treatments have been shown to greatly improve the overall life of engineering components that undergo fretting wear. There are three major principles behind the types of treatments that are commonly used in cases of dry friction where regular lubricants cannot be maintained. First of all is to apply a low friction coating on the contact surface. Second is to apply a soft coating that easily shears away, creating a protective layer between the surface s of the material. The finale is to generate a compressive stress in the surface layer which resists the initiation and growth of the cracks. With a lower coefficient of friction between two surfaces the frictional force between the components is reduced, thus decreasing the amount of damage. This can be achieved by applying hard coatings such as TiN or diamond coatings. This method is most effective for the condition where gross slip is present. The different method to improve fretting wear is to apply a soft coating on the components that can easily shear. The resulting debris that is created from shearing forms a layer between the contacting surfaces preventing abrasive wear and initial welding which can occur during fretting. The debris can help decrease the coefficient of friction which also improves the fretting fatigue strength. The final major family of surface treatments involves a compressive stress in the surface layer, typically through a cold working process, which helps improve the fretting wear. The common cold working processes that can be employed in surface treatment application are shot peening, laser shock peening, and low plasticity burnishing. The principle in these processes is that it creates a compressive layer in the surface layer of the material that delays fretting wear [3].

Burnishing is an acknowledged method of mechanical surface treatment, to impart specific mechanical, physical and tribological properties. In low plasticity burnishing a smooth, free rolling spherical ball under a normal force makes a single pass over the surface of material leaving a residual compressive stress in the surface. Burnishing process is capable of improving resistance to wear, oxidation and corrosion. These enhancements can be extended to minimize friction and reduce adhesion [4,5].

Due to its excellent combination of toughness, strength and corrosion resistance, Ti6Al4V is one of the most widely used titanium alloys. However, Ti6Al4V alloy is known to possess poor wear resistance that restricts its application particularly in areas involving wear and friction. [6,7] . Many scientists studied the dry sliding wear behavior of Ti6Al4V alloy in sliding condition at different sliding velocity and applied loads to confirm the poor wear resistance of the alloy plastic deformation and low protection exerted by the surface oxidation. One of the approaches for enhancing the tribological properties of titanium alloys for improved fretting resistance is to apply surface modification for increased hardness and reduction in coefficient of friction [8,9,10]. In this study, the effect of machining parameters on the wear volume and coefficient of friction in the ball burnishing process of Ti6Al4V alloy were investigated.

2. Experimental details

Experiments were made using a ball-on-disc tribotester Optimol SRV in oscillatory motion. A steel ball from 100Cr6 of 60 HRC hardness and 10 mm diameter contacted a disc made of Ti6Al4V alloy under dry fretting condition. During the test, coefficient of friction ratio being the of the tangential force and the normal load was monitored as a function of time. Wear of the disc was measured by the white light interferometer Talysurf CCI Lite. During tests, normal load was kept constant at 50 N within the contact with frequency of 50 Hz and displacement stroke of 0.1 mm. Duration of each test was 15 min. In the present study, three parameters, namely, burnishing force, velocity and width were identified and the range for each of the process parameters was determined through the preliminary experiments [11]. The burnishing system used in this research is equipped with a high-pressure hydraulic pump and the 6 mm diameter burnishing tool, both connected via high-pressure hoses. Pressure was supplied by the hydraulic pump, which is equipped with its own coolant tank and pump at the coolant maximum pressure of 40 MPa. The process parameters and their levels in the current investigation of burnishing process are summarized in table 1. According to Taguchi design concept, L_9, orthogonal array was selected [12]. Each burnishing parameters is assigned to a column and nine different process parameters. The experimental matrix for the current investigation using L_9 array is shown in table 1.

Table 1. Formatting sections, subsections and subsubsections**.**

Expt. No.	Coded values			Actual values			Wear volume	Signal to noise ratio S/N	Avg. coefficient of friction - COF	Signal to noise ratio S/N
	A	B	C	P [MPa]	v [mm/min]	a [mm]	V [mm^3]	S/N V	COF	S/N COF
1	1	1	1	10	1000	0.04	0.017234	35.272	0.965	0.309
2	1	2	2	10	1500	0.06	0.017543	35.118	0.911	0.810
3	1	3	3	10	2000	0.08	0.017760	35.011	0.954	0.409
4	2	1	2	20	1000	0.06	0.016978	35.402	0.968	0.282
5	2	2	3	20	1500	0.08	0.016720	35.535	0.956	0.391
6	2	3	1	20	2000	0.04	0.016550	35.624	0.976	0.211
7	3	1	3	30	1000	0.08	0.015340	36.283	0.997	0.026
8	3	2	1	30	1500	0.04	0.014930	36.519	0.923	0.696
9	3	3	2	30	2000	0.06	0.014640	36.689	0.914	0.781
Surface before burnishing							0.017804		1.014	

3. Results and discussion

In the present study, the objective is to minimize the specific wear rate and confection of friction. Therefore, “smaller is better” category for the specific wear volume (V) and coefficient of friction (COF) has been selected. The S/N ratio associated with the objective function for each trial of the orthogonal array is given by:

$$\eta = -10 \times \log_{10}[(1/n) \times \sum \left(y_i^2\right)] \tag{1}$$

where n is the number of measurements in a trial/row and yi is the measured value in a run/row.
The corresponding S/N ratio for each experiment of L_9 orthogonal array were determined using eq. 1 and are presented in table 1. The means analysis based on S/N ratio was carried out to determine the optimal levels of process parameters. The results of analysis (for S/N ratio and means) for specific wear volume and coefficient of friction are presented in table 2 and 3, respectively. The level of the parameter with the highest value of S/N ratio is the best combination level. The optimal parameter setting is found to be A3, C1 and B3 for minimum specific wear volume. For the optimal parameter setting for minimum coefficient of friction is found to be A3, C1and B3. From the analysis of table 2 it is evident that the strongest influence on specific wear volume was exerted by the burnishing force (rank 1), burnishing width (rank 2) and burnishing velocity (rank 3). From figure 1, it is evident that wear volume is reduced or an increased in wear resistance is observed with the increase in burnishing force, and burnishing speed, whereas the wear volume decrease with increase burnishing width. This is due to the fact that as the burnishing force increased from 10 MPa to 30 MPa, hardness of the surface increased [13]. Further burnishing force increase compressive residual stress at the surface layer, thus hindering the growth of wear delamination.
From the analysis as shown in table 3, it is evident that the strongest influence on the coefficient of friction was exerted by the burnishing speed and burnishing width. Figure 2 illustrates the S/N ratio and main effect plot of burnishing parameters on coefficient of friction.
One can see from the analysis of figure 3a and 3b that build-ups with compacted debris were formed inside the disc scars, which is connected with higher wear of balls in corresponding places. The diameter of the wear scar in the burnished material is shorter than that in the unmodified material. Also, the depth of the wear scar in the modified material is shallower than that in the unmodified material.

IOP Conf. Series: Materials Science and Engineering **521** (2019) 012016 doi:10.1088/1757-899X/521/1/012016

Table 2. Response table for wear volume - S/N ratios (left side) and for the means (right side).

Level	Force [MPa]	Velocity [mm/min]	Width [mm]	Level	Force [MPa]	Velocity [mm/min]	Width [mm]
1	35.13	35.65	35.81	1	0.01751	0.01652	0.01624
2	35.52	35.72	35.74	2	0.01675	0.01640	0.01639
3	36.50	35.77	35.61	3	0.01497	0.01632	0.01661
Delta	1.36	0.12	0.20	Delta	0.00254	0.00020	0.00037
Rank	1	3	2	Rank	1	3	2

Table 3. Response table for coefficient of friction - S/N ratios (left side) and for the means (right side).

Level	Force [MPa]	Velocity [mm/min]	Width [mm]	Level	Force [MPa]	Velocity [mm/min]	Width [mm]
1	0.5094	0.2060	0.4055	1	0.9433	0.9767	0.9547
2	0.2948	0.6321	0.6244	2	0.9667	0.9300	0.9310
3	0.5010	0.4670	0.2753	3	0.9447	0.9480	0.9690
Delta	0.2146	0.4261	0.3491	Delta	0.0233	0.0467	0.0380
Rank	3	1	2	Rank	3	1	2

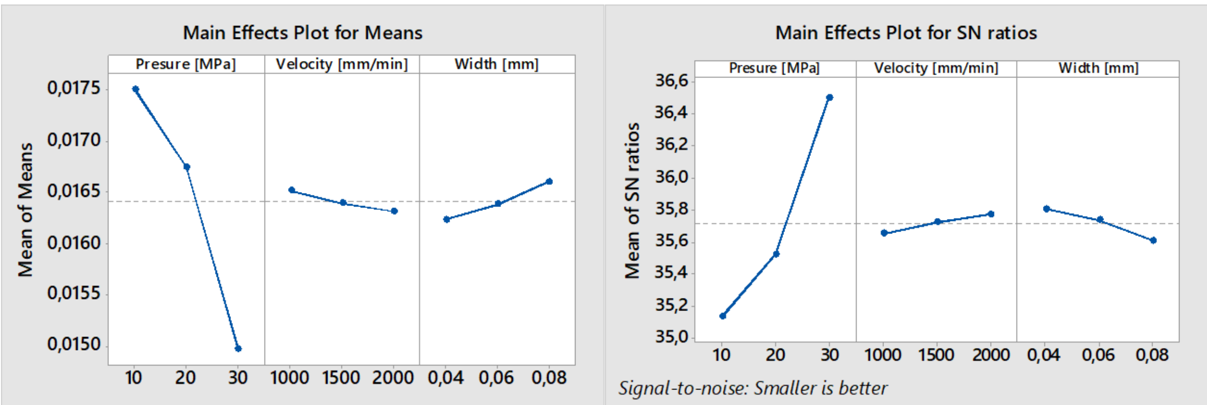

Figure 1. Main effect plot and S/N ratio for wear volume.

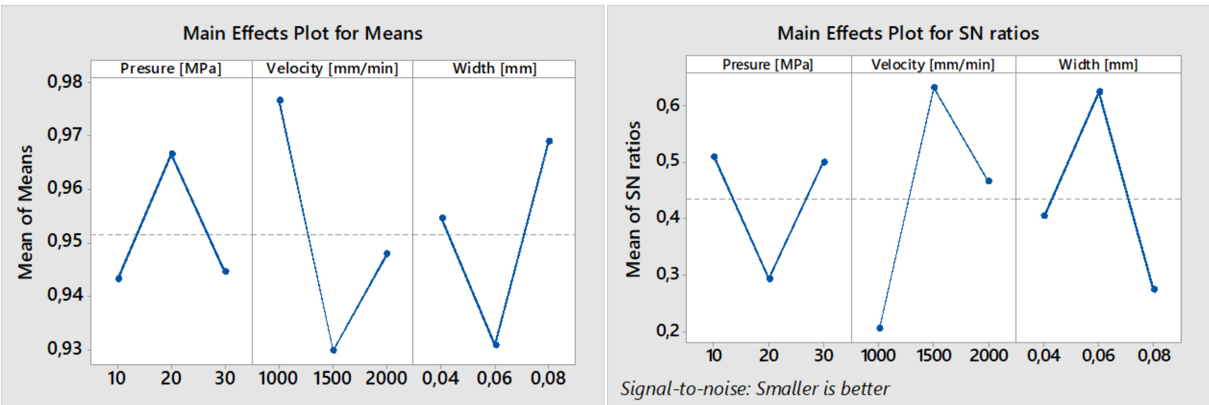

Figure 2. Main effect plot and S/N ratio for coefficient of friction .

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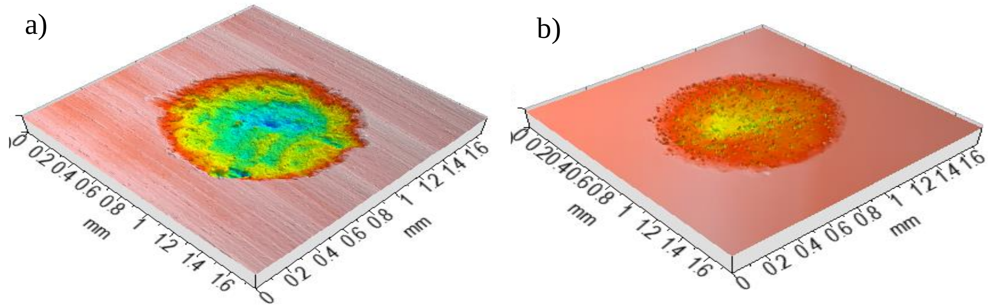

Figure 3. Isometric view of wear scars (a) before ball burnishing and (b) after ball burnishing.

4. Conclusion

Several fretting wear tests consisting Ti6Al4V on Ti6Al4V contacts were conducted. A combination of burnishing force in the high range and low burnishing width is helpful to minimize wear volume. However, medium range of burnishing force, speed and width could minimize the coefficient of friction. It is evident that specific, wear volume is reduced with the increase burnishing force. The burnishing force an burnishing width have major effect in minimizing the specific wear volume. Contrary the burnishing velocity have key role in minimizing the coefficient of friction.

Low plasticity burnishing treatment appears to be effective way to induce a compressive residual stress that inhibits fretting wear. The surface quality and tribological characteristics if titanium alloy Ti6Al4V can be improved by ball burnishing showing improved friction and wear performance.

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