The Improvement of Wear Characteristics on 316L Stainless Steel by Dual Surface Treatment Method

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Abstract*: *Stainless steel is used widespread in various industries, but it has poor wear resistance. Therefore, this study aims to investigate the wear resistance of enhanced surface of 316L stainless steel by applying the combination of surface treatments that consist of shot blasting followed by paste boronizing. Glass beads with diameter 250 microns and the blasting pressure of 6 bar has been used as the shot material in conducting shot blasting process. Paste boronizing process was conducted at temperature 950°C for 8 hours soaking. Data were collected and analyzed which concentrating on the samples' microstructure, microhardness and wear evaluation. Shot blasting improves the case depth of boride layers formed after performing paste boronizing by boosting the boron diffusion owing to the grain refinement created by shot blasting. The ultimate combination of shot blasting and paste boronizing parameters enhance the case depth of the smooth and compact boride layers with high boron content. The hardness performance increase 624% compared to untreated 316L stainless steel which also highly improve the wear resistance of the material. In this investigation, these dual processes of surface treatment which are shot blasting and paste boronizing can be applied in fabricating the improved 316L stainless steel for industrial usages.

Index Terms: 316L stainless steel, boronizing, case depth, shot blasting, pin on disk, wear.

I. INTRODUCTION

The 316 stainless steel is an austenitic stainless steel that is thermally non-hardenable but can be hardened by cold work and non-magnetic due to its face-centered cubic structures [1]. 316 stainless steel has chemical compositions of 16-18% Chromium, 10-14% Nickel, 2-3% Molybdenum, maximum of 2% Manganese, maximum of 1% Silicon, maximum of 0.08% Carbon, maximum of 0.04% Phosphorus and maximum of 0.03% Sulfur [2], [3], [4]. 316L stainless steel is a low carbon grade of 316 stainless steel with the maximum carbon composition is 0.03% [2]. 316L stainless steel is used widespread in various industries including marine, food and petrochemical industries [5]. However, the austenitic stainless steel such as 316L stainless steel has a limitation, poor tribological behaviour [6], [7].

Wear is the material removal from the surface of a solid body due to the mechanical action [8]. Shackelford (2004) [4] classified the main types of wear which consist of adhesive wear, abrasive wear, surface-fatigue wear and corrosive wear. Generally, wear effect will cause thickness depletion of a material that will alter its dimension. This effect will reduce its lifetime. Moreover, a material that has low wear resistance will easily suffer from crack and surface deterioration that will cost money to do repair and maintenance that will also lead to the increment of resource consumption. If no action has been taken, it can disable the functionality of a component or worse it may lead to an accident. Many industrial applications demand on the material which is not only good for welding but also has high wear resistance [9].

Surface treatment is a process of improving surface properties of a metal such as hardness and wear resistance by treating on its surface [10]. Case hardenings such as boronizing, nitriding and carburizing are some of the surface treatments that can be used in treating the metal's surface. Boronizing is a process of boron diffusion into the surface of a metal at elevated temperature to produce boride layers of FeB and Fe2B on its surface which can deliver the steel with a very hard surface layer compared to the other case hardenings [11], [12]. Shot blasting was implemented to create surface deformation on 316L stainless steel which increases the boron diffusion after performing paste boronizing. These processes eventually improve the wear resistance of 316L stainless steel by improving the case depth and hardness of boride layers produced. Most of the researchers studied the effect of shot peening and surface mechanical attrition treatment (SMAT) on the surface layer produced before conducting case hardenings but the study on the effect of shot blasting after conducting boronizing on 316L stainless steel is very little [11], [13], [14], [15].

Therefore, in this research, surface treatments that consist of shot blasting and paste boronizing were performed on the 316L stainless steel in order to enhance its wear resistance.

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II. EXPERIMENTAL PROCEDURE

For this research, the sample preparations involved were cutting and deburring, ultrasonic cleaning, hot mounting, grinding, polishing and etching. 316L stainless steel samples were prepared by referring to ASTM E3-01 Samples involved in this study are presented in Fig. 1. Shot blasting was used as a surface severe plastic deformation (SPD) technique that can perform surface deformation on a sample [16]. Shot blasting process was implemented on the overall surfaces of 316L stainless steel samples with glass beads using shot diameter 250 microns at blasting pressure of 6 bar. In this process, samples of 316L stainless steel were dipped in the boronizing paste and checked to be fully coated with the paste. Paste boronizing process was conducted at the temperature of 950°C at soaking time of 8 hours before let to cool to room temperature. Spectrometer test was conducted in order to confirm on the chemical composition of 316L stainless steel. Optical microscope Olympus BX60 with IMAPS version 4.0 professional edition software is used to observe on the microstructure of a sample under visible light. The samples involved in this research were observed under 200x magnification. Mitutoyo MVK-H1 Vickers Micro Hardness Tester was used to measure the sample's microhardness by applying 50 gf of indentation load on the samples for 15 seconds. Pin on disc test is a wear test that is performed to measure the wear resistance of a sample. In this project, DUCOM TR-20 LE pin on disc test were conducted at one hour with the rotation speed of 200 rpm, wear track radius of 40 mm and load of 19.62 N. Samples were weighed before and after conducting the wear test. WINDUCOM 2006 Pin on Disc Tester TR-20LE software was used to determine

the wear resistance of the samples in term of friction force and coefficient of friction (COF). The sample, weight loss and coefficient of friction were calculated based from the equation 1 and 2.

Weight Loss

Weight loss (g) = sample's weight before POD (g) – Sample's weight after POD (g) (1)

Coefficient of Friction (COF) (2)

$$COF = \frac{Friction\ Force}{Normal\ Force}$$

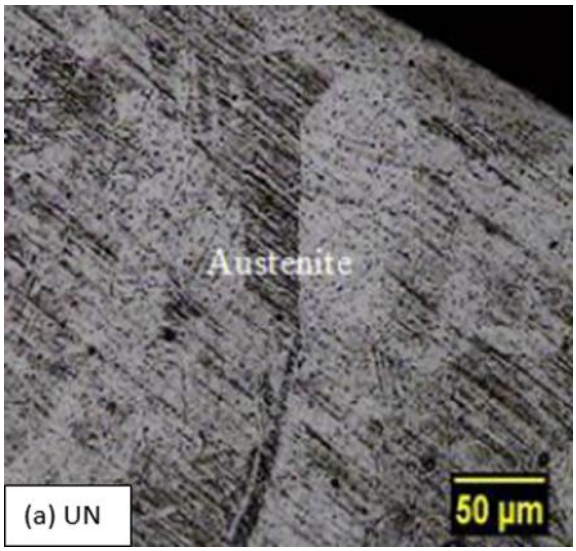
Table I: Samples Involved

Sample	Shot Blasting (Diameter Glass beads 250 micron, 6 bar pressure)	Paste Boronizing (950°C,8 hours)
UN	No	No
S25(6)	Yes	No
P95(8)	No	Yes
S25(6)P95(8)	Yes	Yes

III. RESULTS AND DISCUSSION

A. Microstructure Observation (Optical Microscope)

Fig. 1(a) shows optical micrograph of untreated 316L stainless steel. A shot blasted 316L stainless steel as illustrated in Fig. 1(b) shows that surface deformation with grain size reduction. The steel was shot blasted with 100% coverage of glass beads using shot diameter 250 microns at blasting pressure of 6 bar. The deformation region involves atomic dislocation with high dislocation density [13]. The surface deformation formed from the effect of shot blasting or other surface severe plastic deformation techniques is called as grain refinement. In the analysis, the average thickness of the deformed surface detected on the shot blasted sample is 95 µm. Fig. 1(c) shows the sample after boronized at 950°C for 8 hours. The average case depth of boride layers produced on the sample's surface is 48 µm. Case depth of Fe2B layer created on the sample"s surface is 37 µm while the remaining value from the total case depth of boride layers formed is the case depth of FeB layer. Formation of both FeB and Fe2B phases are observed on the boride layers. FeB has an orthorhombic crystalline structure while Fe2B has a tetragonal crystalline structure [15].



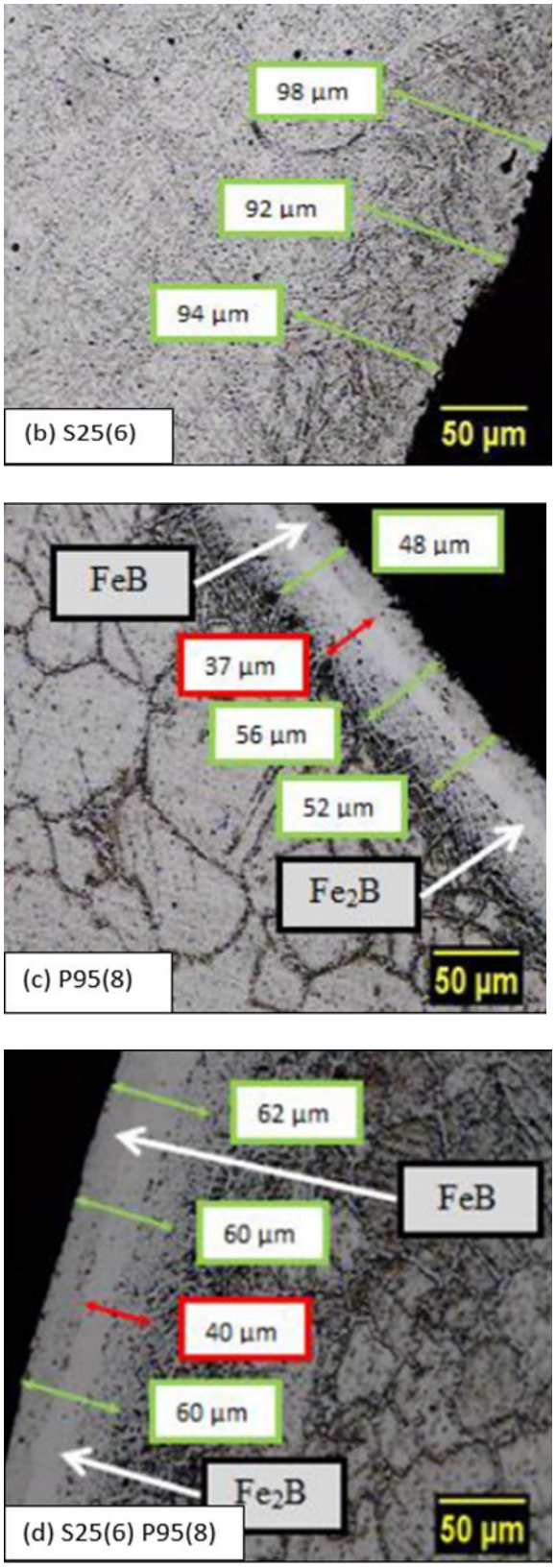


Fig. 1. Microstructure of (a) UN, (b) S25(6), (c) P95 (8) and (d) S25(6)P95(8) Under 200x Magnification.

As shown in Fig. 1 (d), after 316L stainless steel undergo the dual surface treatment (combination of shot blasting and paste boronizing), it yields the greatest average case depth of boride layers which is 61 µm. Case depth of Fe2B layer created on the sample's surface is 40µm while the remaining value from the total case depth of boride layers formed is the case depth of FeB layer There were no porosity or crack formation on the boride layers. It also proves that dual surface treatments involving shot blasting and paste boronizing enhance the case depth of boride layers formed better than implementing single surface treatment of paste boronizing.

B. Microhardness Test

Deng et al. (2015) specified that the hardness of boronized steel reduces from surface to the interior [17]. After the sample of S25(6)P95(8) had been shot blasted and paste boronized, the greatest hardness detected is 2589.0 HV. From the result of microhardness in Fig. 2, it can be seen that the effect of shot blasting together with paste boronizing improved the surface hardness of untreated 316L stainless steel. At meanwhile, the surface hardness achieved by samples of P95(8) is 2275.0 HV. This result shows that further depth of surface deformation which involve on increasing the atomic dislocation activity and paste boronizing process raised the boron content inside the boride layers. As a result, the surface hardness also increased. Deng et al. (2015) also stated that greater hardness of boride layer produced will be much valuable in industrial applications [17].

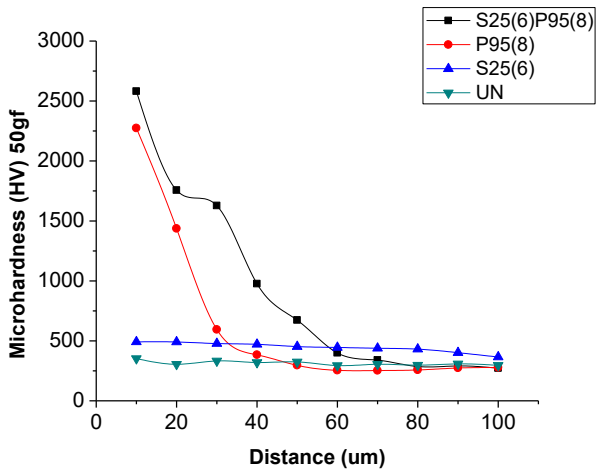


Fig. 2. Microhardness of untreated and surface treated sample of 316L stainless steel.

C. Pin on Disk Test

Determining the weight loss of samples is one of the criteria in comparing their wear resistance [14]. Table 2 and Fig. 3 show the weight loss versus sample after performing pin on disc test. The weight loss of UN sample, S25(6) sample, P95(8) sample and S25(6)P95(8) sample are 0.0613 g, 0.0548 g, 0.0335 g and 0.0113 g respectively. These values show that untreated 316L stainless steel leads on the amount of weight loss due to the pin on disc test while the effect of shot blasting reduces some of the amount of weight loss suffered by the metal. Implementing paste boronizing on 316L stainless steel reduces more on the amount of weight loss while the least amount of weight loss is confirmed on the shot blasted-paste boronized sample. Higher hardness of grain refinement and boride

layers protect 316L stainless steel from suffering a greater weight loss. Weight loss is associated with wear resistance where a material that has greater weight loss due to the wear test shows that it has lower wear resistance and vice versa [18].

Table II. Weight Loss of Samples Before and After Performing Pin on Disc Test (POD)

Sample	*Weight Before POD (g)*	*Weight After POD (g)*	*Weight Loss (g)*
UN	18.5174	18.4561	0.061
S25(6)	18.4379	18.3831	0.0548
P95(8)	18.2818	18.2483	0.0335
S25(6)P95(8)	18.5905	18.5792	0.0113

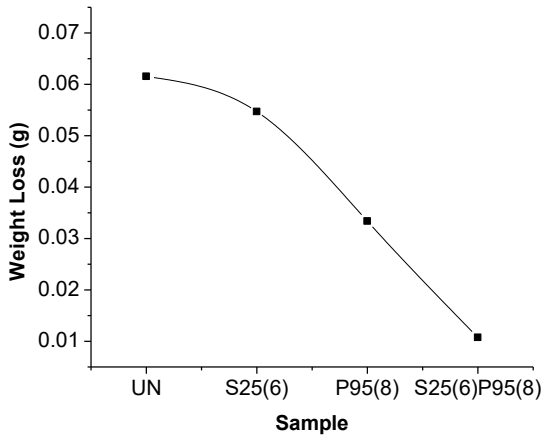


Fig. 3. Weight Loss of UN, S25(6), P95 (8) and S25(6)P95(8) Samples.

Coefficient of friction (COF) is the ratio of friction force to the normal force[19]. A metal with high coefficient of friction means it has low wear resistance and vice versa. Fig. 4 shows the coefficient of friction of 316L stainless steel samples with respect to time. From the graph, it can be observed that untreated 316L stainless steel has the lowest wear resistance due to its highest coefficient of friction compared to the other samples which the average coefficient of friction is 0.70 from 0 to 1300 seconds, 0.66 from 1300 to 3300 seconds and 0.65 from 3300 seconds to 3600 seconds. S25(6) sample has the lower coefficient of friction than the untreated sample mainly from 0 to 1300 seconds with average coefficient of friction of 0.65 from 0 to 1300 seconds, 0.66 from 1300 to 3300 seconds and slightly higher from 3300 seconds to 3600 seconds with the average of 0.66. P95(8) sample has lower coefficient of friction than the UN and S25(6) sample with average coefficient of friction of 0.58 from 0 to 1300 seconds, 0.59 from 1300 to 3300 seconds and 0.60 from 3300 seconds to 3600 seconds.

From 1300 seconds to 3300 seconds, the coefficient of friction achieved by S25(6)P95(8) sample is higher than P95(8) sample with average coefficient of friction of 0.63. However, the coefficient of friction of S25(6)P95(8) sample is lower than P95(8) sample at the beginning of the wear test which is from 0 to 1300 seconds with average coefficient of friction of 0.56 and the major change of weight loss of all of the samples seems to be happen at the beginning of the test which shows the greatest wear resistance achieved by S25(6)P95(8) sample with the lowest weight loss which is 66% lower than the weight loss of P95(8) sample. At higher than 3300 seconds of wear test also, it maintains the coefficient of friction to the lowest with average coefficient of friction of 0.56. Hashemi et al. (2011) also found that the untreated 316L stainless steel sample has the lowest wear resistance compared to the shot peened and nitrided samples. Both of the graphs presented in Fig. 3 and Fig. 4 show that the impact of shot blasting and paste boronizing enhance wear resistance of 316L stainless steel.

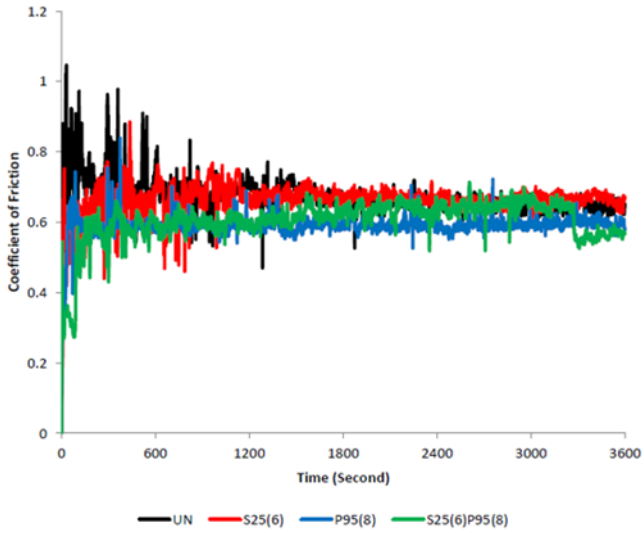


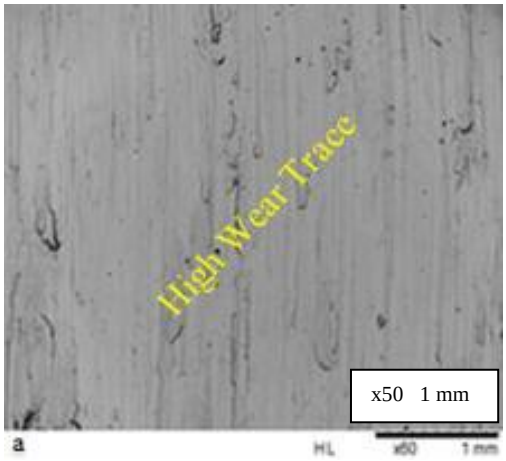
Fig. 4. Coefficient of Friction of UN, S25(6), P95(8) and S25(6)P95(8) Samples.

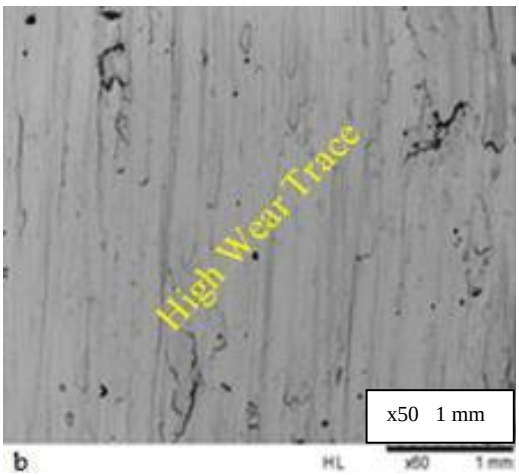
Enhancement on the hardness due to high case depth of boride layers formed after performing paste boronizing plays the main role in increasing the wear resistance of 316L stainless steel. Deng et al. (2015) found that boronizing greatly improves the wear resistance of Inconel 718 [17]. Tavakoli et al. (2015) also stated that the boride layers' production can raise the wear resistance of the components and equipment [20]. Combination of the process of shot blasting and paste boronizing raise the wear resistance of 316L stainless steel due to the grain refinement produced by the shot blasting which increases boron diffusivity into its surface after conducting paste boronizing. Past researches also proved that a surface severe plastic deformation technique, a case hardening and the combination of both of the surface treatments improve wear resistance of studied metals [14] [17].

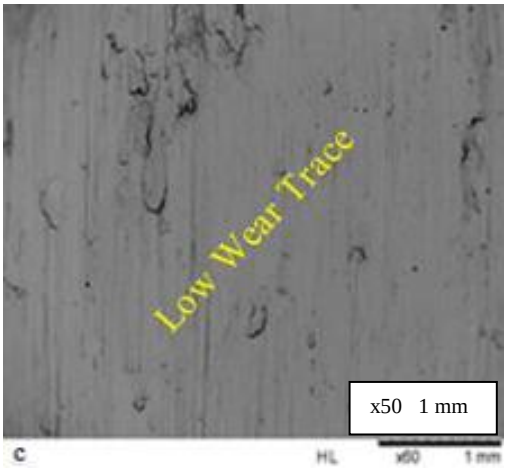
SEM micrographs of the worn surface after carrying out pin on disc test on 316L stainless steel samples are presented in Fig. 5. Untreated and shot blasted 316L stainless steel are the most suffer from the worn

surface due to the wear test compared to the other samples which high wear trace is detected on both of the samples. Paste boronizing reduce the wear damage caused by the tribological test which lower of wear trace is observed on the sample compared to UN and S25(6) samples due to the high wear resistance enhancement on the paste boronized sample (P95(8) sample).

The lowest wear damage with the lowest wear trace observed is detected on the tested shot blasted-paste boronized sample (S25(6)P95(8) sample). On this sample, even the boron coating is still visible on the surface after performing pin on disc test at one hour. High improvement on the wear resistance of the shot blasted-paste boronized sample causes the lowest wear trace and boron coating visibility on the surface of the tested sample. Hashemi et al. (2011) proved that the combination of surface treatments conducted involving shot peening (SPD technique) and nitriding (case hardening) reduce wear damage due to the wear testing on the surface of the studied metals even higher than performing nitriding alone [14].







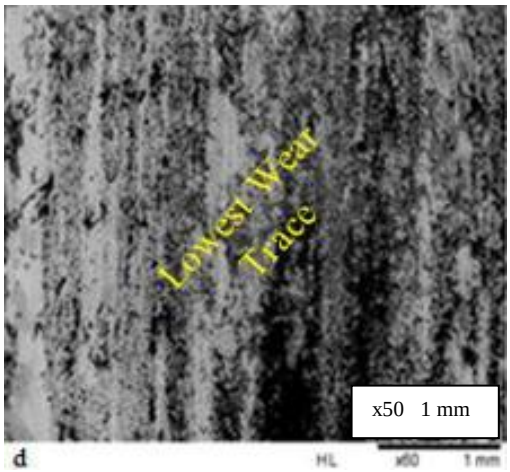


Fig. 5. SEM Micrographs (BEI mode) of Worn Surface on (a) UN (b) S25(6) (c) P95(8) and (d) S25(6)P95(8) Samples

Fig. 6 shows the wear depth of 316L stainless steel samples after performing pin on disc test. The highest wear depth is detected on untreated 316L stainless steel sample with the average wear depth value of 43.400 µm followed by S25(6) sample with the average wear depth value of 33.421 µm, P95(8) sample with the average wear depth value of 23.067 µm and S25(6)P95(8) sample with the average wear depth value of 14.441 µm. From the graph trend in Fig. 6, it demonstrates that shot blasting and paste boronizing reduce the wear depth caused by pin on disc test and the combined treatments reduce more on the wear depth due to high improvement in wear resistance of the surface treated 316L stainless steel. Yang et al. (2013) identified that boronized surface has lower wear depth value compared to the unboronized surface after carrying out a tribological testing [15].

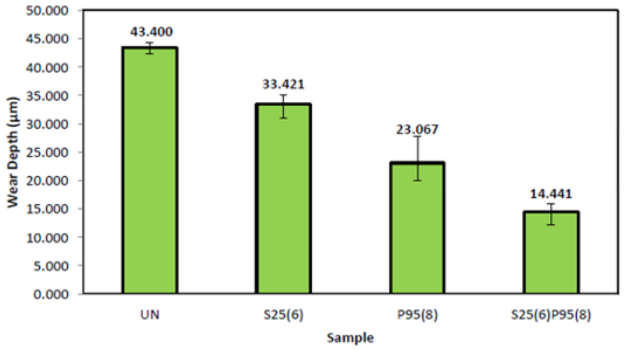


Fig. 6. Wear Depth of UN, S25(6), P95(8) and S25(6)P95(8) Samples.

IV. CONCLUSION

In conclusion, 316L stainless steel that was shot blasted using 250 micron of glass beads and 6 bar of blasting pressure (S25(6) sample) was discovered increased the case depth of boride layers formed after performing paste boronizing. It shows that high creation of grain refinement created on this sample improve boron diffusion that highly increase the case depth of boride layers which eventually increase the surface hardness of 316L stainless steel at the greatest achieved with 561% of percentage. The ultimate combination of shot blasting and paste boronizing parameters enhance the case depth of the smooth and compact boride layers with high boron content. Therefore, the hardness increased by 624% had improved the wear resistance of 316L stainless steel. An ideal sample is obtained by performing both of shot blasting using 250-micron diameter of glass beads and 6 bar of blasting pressure and paste boronizing using temperature of 950°C and soaking time of 8 hours. The combination of shot blasting and paste boronizing achieved from the end of this research can be used in fabricating the improved 316L stainless steel for the industrial usages. Therefore, the objective to enhance wear resistance of 316L stainless steel is achieved.

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