



## Effect Of Plasma Nitration Process At Various Temperatures On Wear Behavior Of AISI 4340 Steel

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### Abstract

In this study, AISI 4340 (34CrNiMo6) tempered steel was applied to the plasma nitration process at different temperatures and at different periods in order to increase the wear resistance of the outer surface without decreasing the hardness of the core under 40-44 HRC, and to prevent the component from distortion during heat treatment. The sufficient core strength and tensile stress of some mechanical elements such as mold, drill, U-Drill are required not to fall below a certain value. There were five different temperatures (450, 475, 500, 530 and 550 °C) and two different time values (18 and 32 hours) used with these temperatures utilized in the study. The study tried to identify the optimum nitriding temperature and time for the limit values determined by considering the wear value after nitriding. The wear characteristics of the samples in dry conditions were also investigated. It was observed that the ideal target values (core 40- 44 HR<sub>C</sub>) in the nitrided components were reached at 450 °C in 32 hours.

## 1. INTRODUCTION

AISI 4340 is a a nickel-chromium-molybdenum alloy used in the manufacture of components such as friction gear meshes, pivots, pistons, tie rods, front axles, and axle box etc. Such machine components are exposed to severe chemical environment and require high wear performance. Whereas the machine elements that the material has been used in perform the expected functions, the surfaces of the components may be exposed to higher tension and abrasive strength than the inner parts, depending on the operating conditions. These strengths cause the components to fragment, and lead to a loss in mass after a while. Therefore, the surface resistance of the materials exposed to these kinds of effects should be increased for a longer life. It is expected that while the surface resistance of the components are improved, the other mechanical properties shouldn't be affected. The aim of the study has been determined as improving the surface characteristics of AISI 4340 material without changing the mechanical properties of it.

Nitriding is a thermo chemical surface improving method which has a wide area of use, improving corrosion and wear resistance, and increasing fatigue strength and surface hardness of the metal materials [1-4]. With the nitriding process, a hard surface layer is obtained that includes metal-nitride compounds in the microstructure and the diffusion of nitrogen in the iron in the ferrite phase. The application is based on sending nitrogen atoms as an interstitial atom to the steel component surface. When nitriding is compared to other surface hardening processes (carbonitriding, nitrocarburising, etc.), the best advantage of it is that it can be performed at relatively lower temperatures such as 450-590 °C.

Since the type of nitriding and processes are performed at a certain temperature and time interval (18-80 h), some unexpected situations can occur. These situations consist of the grain growth surface deformation in the material, and the decrease in the hardness of the core, and it affects the mechanical properties of the material. Therefore, it becomes a requirement to identify the type, temperature, and time period of nitriding.

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AISI 4340 material have many usage areas such as machine parts exposed to fatigue in the automotive sectors, mold and piercer (U-Drill). There have been some plasma nitration studies in which AISI 4340 material has been used.

Sirin and Kaluc examined profile hardness value, compound layer thickness, surface hardness and surface roughness of an AISI 4340 steel subjected to ion nitration process at different exposure time and temperatures using different tests such as microhardness, optical microscopy, surface profilometer and X-ray diffraction. The authors reported significant increase in compound layer thickness with increasing exposure temperature and duration [5].

Furthermore it is also reported that surface roughness, surface and profile hardness, hardness depth, the compound layer thickness, and phase content vary depending on nitriding parameters such as temperature and duration. As a result; this study has emphasized that AISI 4340 optimal ion nitriding parameters should be determined based on service conditions.

On another study Sirin et al. investigated the effect of different temperature and exposure time in ion nitriding process for the fatigue and mechanical strength behaviour, microstructure, surface roughness of AISI 4340 steel. Of the two group testing in this work, the first group was hot rolled without ion nitriding for fatigue and mechanical tests, the second group was quenched and tempered. While the surface of the reduced section was being mechanically polished for the fatigue specimens, some specimens in the second group were not mechanically polished before ion nitriding to obtain a third fatigue tests specimens group. Results showed that significant improvement in fatigue and mechanical properties were obtained with quenched and tempered. The depth of the hardness obtained in the QT AISI 4340 was found deeper than that of hot-rolled AISI 4340 in ion nitriding conditions, and a linear relationship was obtained between fatigue and strength values and hardness depth for both steels. Furthermore, although the cracks occurring under the surface triggered the fatigue mechanism in ion nitrided steels, the effect of surface roughness on the fatigue strength tended to decrease [6].

Diaz et al. have conducted research on the effects of nitration current density on the hardness crystal phase compound, the thickness of the layer, and the rate of corrosion, by performing the pulsed plasma nitration process on AISI 4340 material. 525 °C process temperature and 50% N<sub>2</sub>-50% H<sub>2</sub> pressure of 173 Pa (1.3 Torr) for an exposure time of 4 hours were used as nitriding process parameters. In the study it was observed that increasing the current density proportionally increases the nitrided layer. it was also detected that the surface hardness and corrosion resistance improved regarding the component that was not nitrided [7].

Asadi and Mahboubi in a study, heat treatment of AISI 4340 having different thickness was conducted with conventional and screen plasma nitrided (CPN) method with 75%N<sub>2</sub> + 25%H<sub>2</sub> gas mixture in 500 °C to 540 °C heat treatment temperature under 4 torr pressure for 5 hours. In this study, the parameters such as the structure of nitride substrate, compound layer thickness, hardness depth, hardness change were examined. In the studies, it has been observed in both examples that the more the part width is, the more the hardness value, depth and the thickness of the compound layer. At the same time, it was observed in each sample that nitrogen atoms were implanted deeper in the part regions near the edge [8].

Ribeiro et al. made a comparison of cutting blades made from 4340 material and used in the plastic industry to cut the pieces in order to provide the recycling of plastic with the cutting blades sold commercially by performing the nitriding with “cathodic cage plasma nitriding technique” and they improved the practical life and hardness by 58% [9].

There are many studies on ion nitride structure, processes, wear performance and their service life. However, studies on the ion nitriding process of AISI 4340 steel, diffusion layer thickness, compound layer depth, surface roughness and abrasion performance are quite rare.

In this study, ion nitriding parameters were determined without compromising the core strength values of AISI 4340 steel and wear behaviors were investigated. When the ion nitriding process was chosen especially the heat treatment parameters above 520 °C for long processes, the harness layer thickness was observed to increase and in parallel with this, the decreases were observed in the hardness values in internal structure of the material. Therefore, it is required to keep the harness value in the internal structure within certain limits (40-45 HRC) in order not to decrease the sufficient core strength and tensile stress strength value of some machine parts. While the tensile strength of iron based material at 48 HRC hardness value is 1595 Mpa, this value at the hardness of 42 HRC is compromised around 1300 Mpa.

## 2. EXPERIMENTAL PROCEDURE

In the studies, firstly samples of Ø15x10 mm. size in order to measure the hardness value in the core and to identify the hardness layer values emerged in the samples, and samples in Ø70x10 mm. size were prepared in order to do the wear tests. The samples were subjected to the hardening process first. The samples were heated up to 860 °C and soaked in the oil at 100 °C for 1 hour. Then the samples were grinded with SIC rubber (220, 320, 400, 600 and 1200 mesh) both before nitriding and after nitriding SiC in a polishing machine and finish surface was obtained. In this way, the test conditions of the samples to be made friction test were ensured to be the same at first. The inner core hardness of the obtained samples is around 44 HRC levels. The surface roughness value made after the polishing process was measured as 0.04µm in average.

The samples were placed on cathode before the nitriding process and they were vacuumed until the pressure of the trading room was  $2,2 \cdot 10^{-2}$  mbar. Then, the hydrogen gas was piped inside until the gas pressure became 6 mbar for the dispersion process. With the dispersion process, a surface was obtained which has had suitable surface cleanliness and surface roughness for nitriding. The dispersion process was performed at 250 °C process temperature and in 30 minutes time. After this process, the nitriding process was performed at the determined temperature and periods in a process pressure of 6 mbar by giving 75% H<sub>2</sub>, 25% N<sub>2</sub> gas permanent to the vacuum room. The specimens were ion nitrided according to Table 1, voltage between 490 V and 540 V depending on the desired temperature.

Hardness transformation, the occurrence of the white layer and wear behaviours of the AISI 4340 applied to the plasma nitration processes at different temperatures and time periods, were investigated in these studies. Five different temperatures and two different time periods with these temperatures were used in the experiments (Table 1).

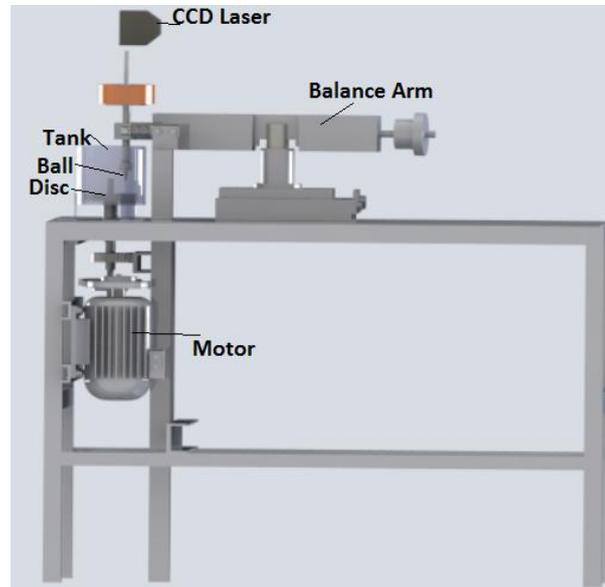
**Table 1.** Waiting times and temperature applied to the samples used in the experiments

450 °C		475 °C		500 °C		530 °C		550 °C	
Samples	Hour	Samples No	Hour						
N <sub>450</sub>	32	N <sub>475</sub>	18	N <sub>500</sub>	18	N <sub>530</sub>	18	N <sub>550</sub>	18

The ball on the disc (ASTM G99-05) (Figure 1) test device was used in this study for the purpose of examining the wear performances. A 100Cr6 ball of 10 mm diameter, having a HRC 66 hardness value used to wear the disk was used in the testing apparatus. Consider a typical disc-on-ball contact in which the ball is held stationary and the contact location on the disc is moving with velocity relative to the stationary contact area. The tangential friction force was measured by a load transducer attached to the specimen holder. The disk and ball were operated in a dry environment in the testing apparatus. The test device was operated for 2000 meters while the disk rotates at 0,75 m/sec speed and the results of the wear performances were obtained by applying different weight of 5 and 10 N.

The ball used to wear the disk in the testing apparatus was cleaned using acetone to clean the dirty layer that emerged before and after the test. Then, the ball was weighed in the scale in  $10^{-4}$  gr. precision and the wear rate was determined. In the experiments, the “Squirrel” data logger measuring set and instantaneous friction force was recorded. In the meantime, the CCD laser displacement meter sensor was placed on the pin that the ball is depended on in order to measure the wear depth to occur in the ball and

disk instantaneous, and the variation of the wear depth according to time was observed by recording the instant wear values. The precision of laser sensor is  $0.1\mu\text{m}$ . The wear tracks emerging on the disk and ball after the test were examined with surface microscopy, and the displays were taken with a Scanning Electron Microscope (SEM).



*Figure 1. The ball on the disc test (ASTM G99-05) test device*

### 3. RESULT AND DISCUSSION

In the components on which the plasma nitration process was performed at different temperatures and periods, the variation of the friction coefficient, the micro hardness, the wear rates on the ball and disk, the instant wear depth and nitration layer, and the wear SEM displays were obtained.

Different heat treatment processes are performed to increase wear, corrosion and fatigue resistance of the components used in industry. In this heat treatment process, not only the surface hardness is important, but also certain features of the internal structure are required to be kept. That the layer formed after nitriding process is deep and low core hardness in internal part may lead the nitriding layer to behave independent from the steel, i.e. to be carried of the whole load by nitriding layer. In such machinery and some applications such as mold, U-Drill, drilling edge, inner core hardness is desired not to fall below a certain value. The aim in this study is to evaluate the wear performance of the sample that had ion nitriding heat treatment that does not fall below 42HRC hardness compared to the other samples

Tempering temperatures of AISI 4340 steel should be between 450 and 600 °C. Tempering within the range 250 °C - 450 °C will result in temper brittleness and should be avoided. There is a tendency to decrease in tensile strength and an increase in elongation value with increasing tempering temperature [10]. Tempering temperatures should therefore be selected according to the required mechanical properties.

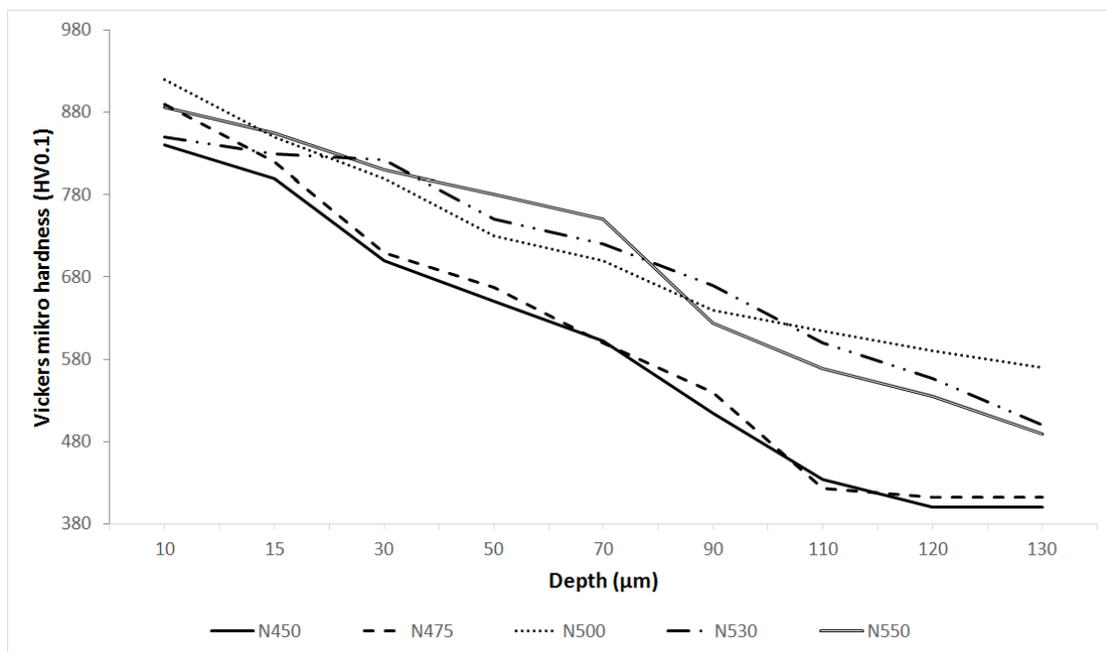
When the tempering temperature of AISI 4340 material increases up to 450-540 °C in general, the hardness value drops to 38-40 HRC. Thus, ion nitriding process is around tempering temperature. When increasing up to these temperatures, decreases are observed in core hardness even though being partly depending on the time.

#### 3.1. The Variation Of Micro Hardness

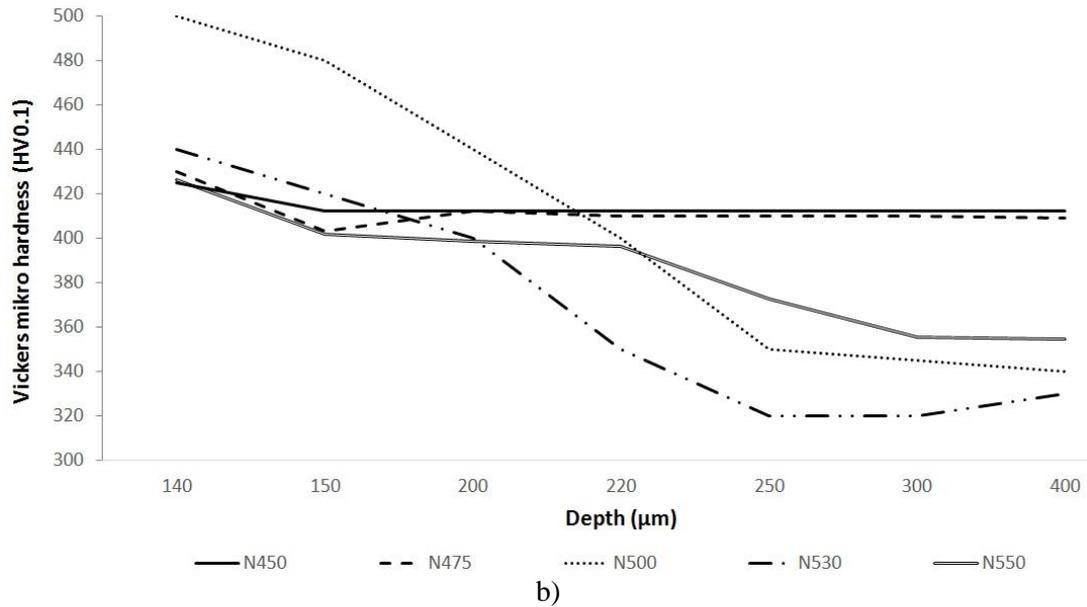
The aim was to reach the optimum nitration temperatures and periods that could increase the surface hardness without lowering the core hardness under 40 HRC. Since the hardness range of the 4340

material that provides the optimum toughness, endurance and durability values in the usage areas of the material is described as 40-44 HRC ( $\sim 380-435\text{HV}_{0.1}$ ). The Vickers micro hardness measurements obtained by taking a cross section of the samples subjected to the nitriding process at different temperatures and periods are shown in Figure 2 a and b. The  $N_{500}$  sample was the sample which had the highest surface hardness ( $920\text{HV}_{0.1}$ ). The values of the surface hardness belonging to the  $N_{450}$  and  $N_{475}$  samples were high (respectively  $1100\text{HV}_{0.1}$ ,  $1221\text{HV}_{0.1}$ ). The same samples remained almost constant value from  $140\text{ }\mu\text{m}$  depth and in the hardness value obtained with existing pre-heat treatment before nitriding process, very little hardness drop from 44HRC ( $417\text{HV}_{0.1}$ ) value was observed. Core hardness of  $N_{450}$  and  $N_{475}$  samples was measured to be at the levels of  $408\text{HV}_{0.1}$ ,  $412\text{HV}_{0.1}$  respectively (Figure 2b).

In  $N_{500}$ ,  $N_{530}$ , and  $N_{550}$  plasma nitriding process, the surface hardness was formed to be  $920\text{HV}_{0.1}$ ,  $850\text{HV}_{0.1}$  and  $887\text{HV}_{0.1}$  (Figure 2a) respectively. Although surface hardness increased with the increase in nitriding temperature, hardness occurred on the surface with the increase in the temperature due to coarse nitride condensation. In longer and higher temperatures, precipitate particles grow more and coarsening tendency occurs depending on the time and this causes lower hardness [11]. In particular, in  $N_{500}$ ,  $N_{530}$ , and  $N_{550}$  samples, inner core hardness value is formed around  $340\text{HV}_{0.1}$ ,  $330\text{HV}_{0.1}$  and  $350\text{HV}_{0.1}$  (Figure 2b) respectively after  $140\text{ }\mu\text{m}$  depth, i.e. core hardness of the material has fallen.



a)

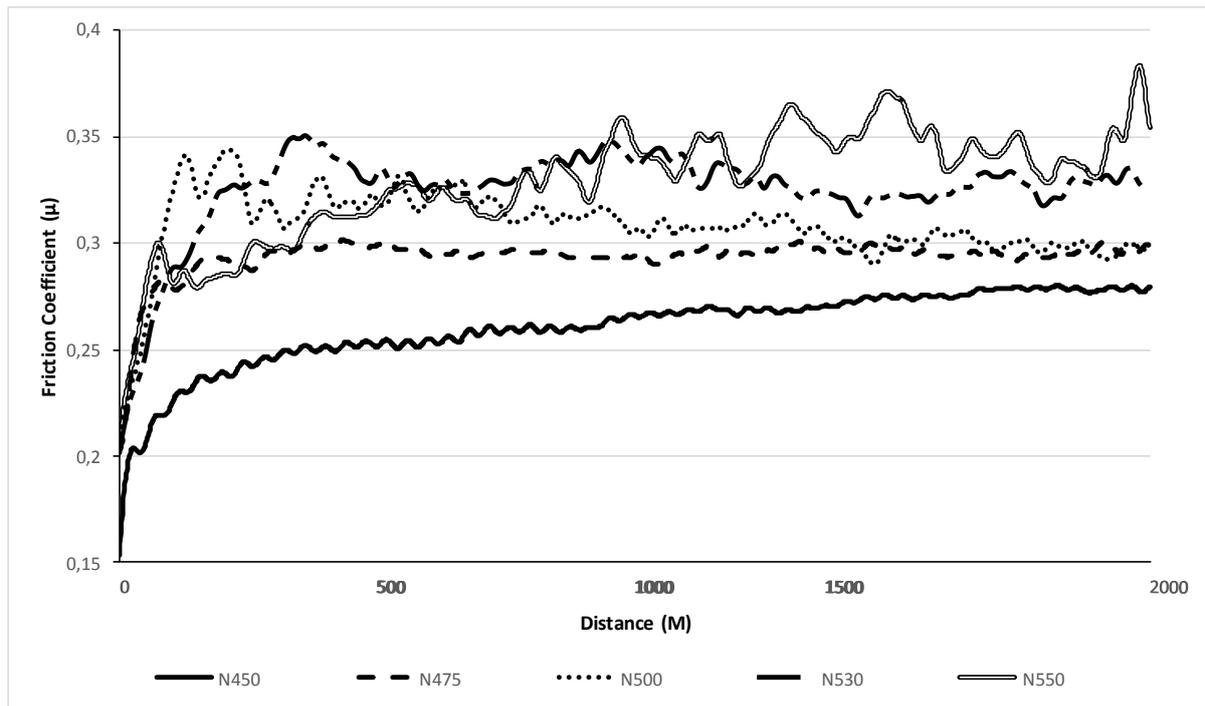


**Figure 2.** The variation of the micro hardness of the samples subjected to the nitration process at different temperatures, (a) general graphic, (b) detailed graphic for the micro hardness values obtained after 140 µm

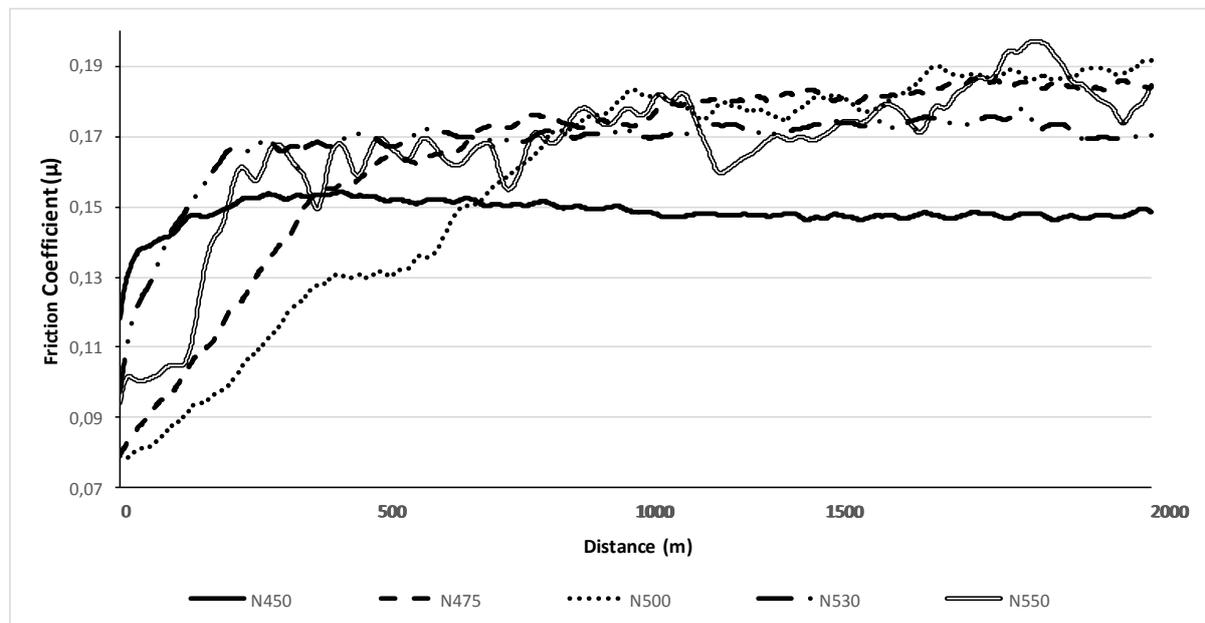
### 3.2. Friction Coefficient

Although initial surface roughness values in the abrasion tests start at the same level in all the samples, it has been seen that great masses went away with the breaking of the particles from the surface of the samples which were made nitriding at high temperatures due to nitride condensation occurring at high temperatures. Accordingly, an increase was observed in friction coefficients in the samples that nitration was made at high temperatures.

The variation of friction coefficient emerging under 5N (Figure 3a) and 10N (Figure 3b) load depending on the stroke in disks on which plasma nitration process has been applied at different temperatures and periods is seen in Figure 3. The mean of friction coefficient in the components being applied 5N load and different nitration temperatures during the test have been calculated as ( $\mu_{\text{mean}}$ )  $N_{450}=0,260$ ,  $N_{475}=0,293$ ,  $N_{500}=0,308$ ,  $N_{530}=0,326$ ,  $N_{550}=0,328$ . Examining the graphic, it has been observed that there has been an increase in friction coefficient as the stroke increases. The lowest friction coefficient has been seen in  $N_{450}$  sample that nitration process has been applied at 450 °C. The friction coefficient has been seen in approximately fixed order especially in 1000-1500 meters interval in  $N_{450}$ ,  $N_{475}$  and  $N_{500}$  samples. Since the white layer is thick especially in  $N_{530}$  and  $N_{550}$  samples in 5N load, it has been estimated that trilateral abrasion has emerged with the breaking of white layer and this situation leads to an increase in friction coefficient. When the graphic of friction coefficient belonging to  $N_{530}$  and  $N_{550}$  samples in 5N load has been examined (Figure 3a), it is thought that the reason of the fluctuation is the occurrence of trilateral abrasion with the breaking of white layer.



a-)



b-)

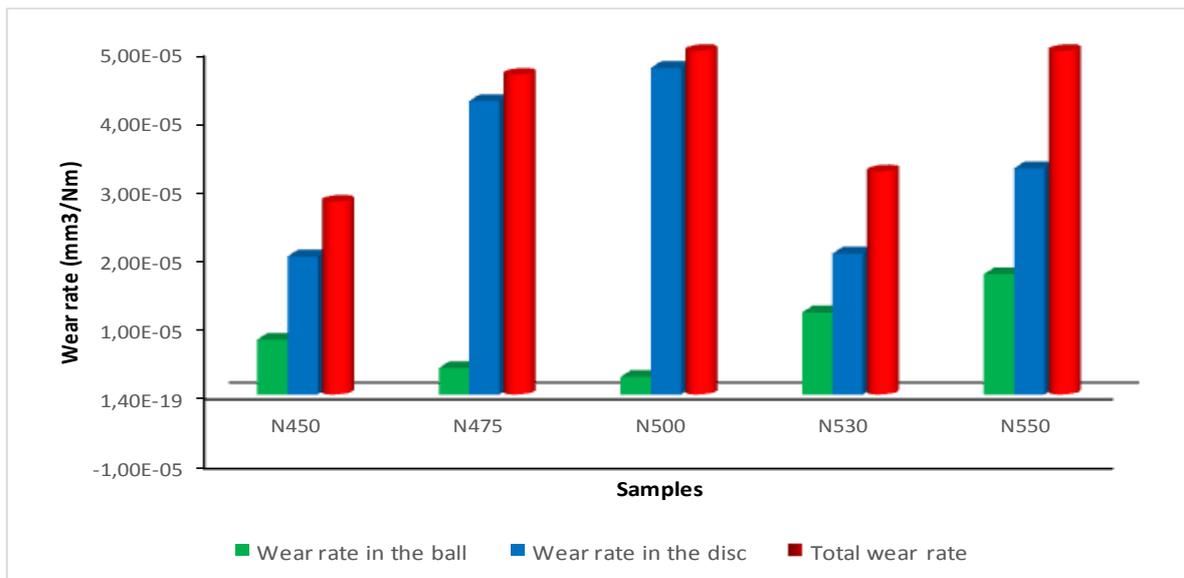
**Figure 3.** The variation of the friction coefficient occurring at different nitration temperatures  
a-) 5N load, b-) 10N load

The variation of the mean of the friction coefficient in the components on which 10N load was applied can be seen in Figure 3b. It is calculated as ( $\mu_{\text{mean}}$ )  $N_{450}=0,149$ ,  $N_{475}=0,165$ ,  $N_{500}=0,158$ ,  $N_{530}=0,168$ ,  $N_{550}=0,166$ . Looking at Figure 3b, it can be seen that there is an increase as the stroke increases. The lowest friction coefficient was seen in the  $N_{450}$  sample that the nitration process was applied to at  $450^{\circ}\text{C}$ . The friction coefficient was seen in an approximately fixed order, especially in the 1000-1500 meters interval in the  $N_{450}$  sample. This was not seen in the other samples. A similar fluctuation in the 10 N load was seen in the  $N_{530}$  and  $N_{550}$  and  $N_{500}$  samples. The reason for this is that the breaking of the white layer was accelerated with the increase in load, and the trilateral abrasion occurred among the broken layer, and

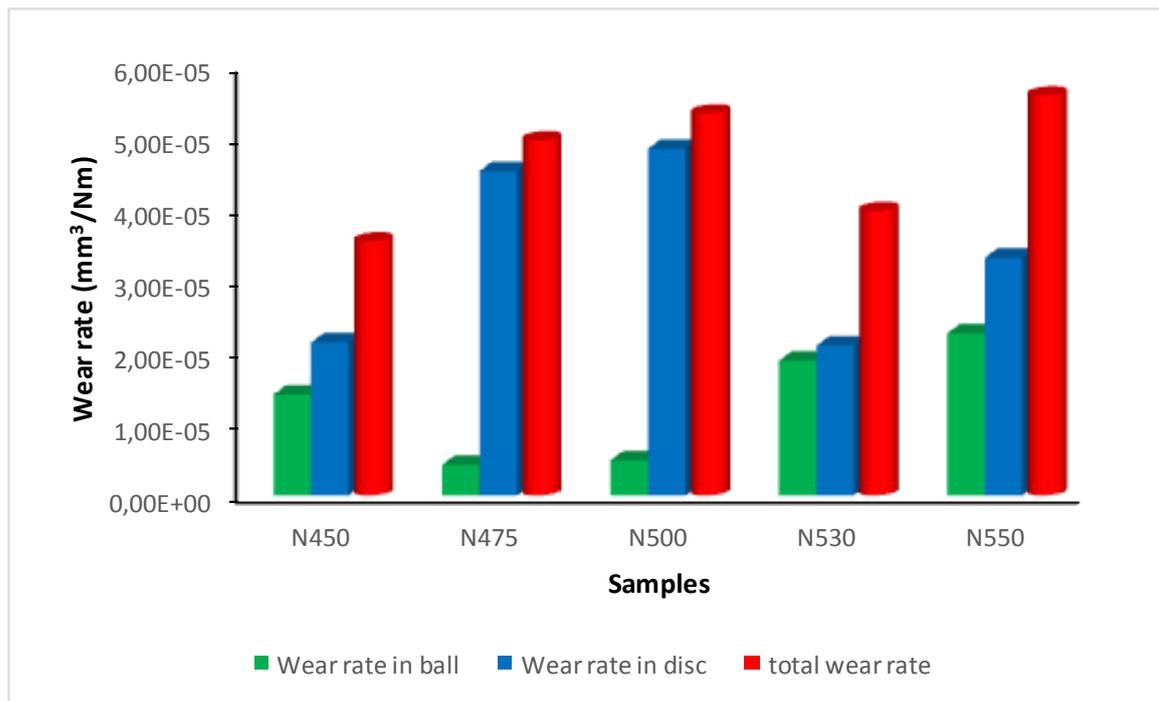
the disk and ball; accordingly, and brought about instant fluctuations. Tribological characteristics of the component are determined by compound layer, diffusion layer and surface hardness.

### 3.3. The Variation Of Wear Rate

It was seen when the study was evaluated that generally both the ball and the disk were worn down. The wear rates occurring in the ball and the disk at the 5N and 10N load during the tests are shown in Figure 4. It has been observed that in the wear rates of disk and ball which has been applied 5N strength (Figure 4a) especially in the sample performed nitration at 550 °C, the ball was worn down more due to the hardness of the surface, but the disk was also worn down with the breaking of the white layer in the sample. An important hardness value was obtained under 500 degrees; however, the wear rate in disk was more than the samples over 500 degrees after a certain value because the hardness layer depth was low due to limited time. Nonetheless, that the sample keeps the core hardness value at 42 HRC helps it to become more rigid in the areas of use. It was seen that the increase in the nitriding temperature in the wear rates in the ball and samples applied with 10N strength (Figure 4b) has affected the hardness increase. The risk of occurring breaks inside the layer situated at the top surface increases because the white layer is pretty hard and brittle and maximum shear stress occurs in the surface. Consequently, the white layer which is hard and brittle transforms into abrasive particles fragmenting on the load. When the nitrided samples were compared depending on the variation of treatment temperature, it was seen that the hardness of the white layer increased and accordingly the wear rates of the samples also, depending on the increase in brittleness. It is a desired situation that the thickness of the white layer is too thin in N<sub>450</sub> sample and even if it increases the wear resistance.



a)

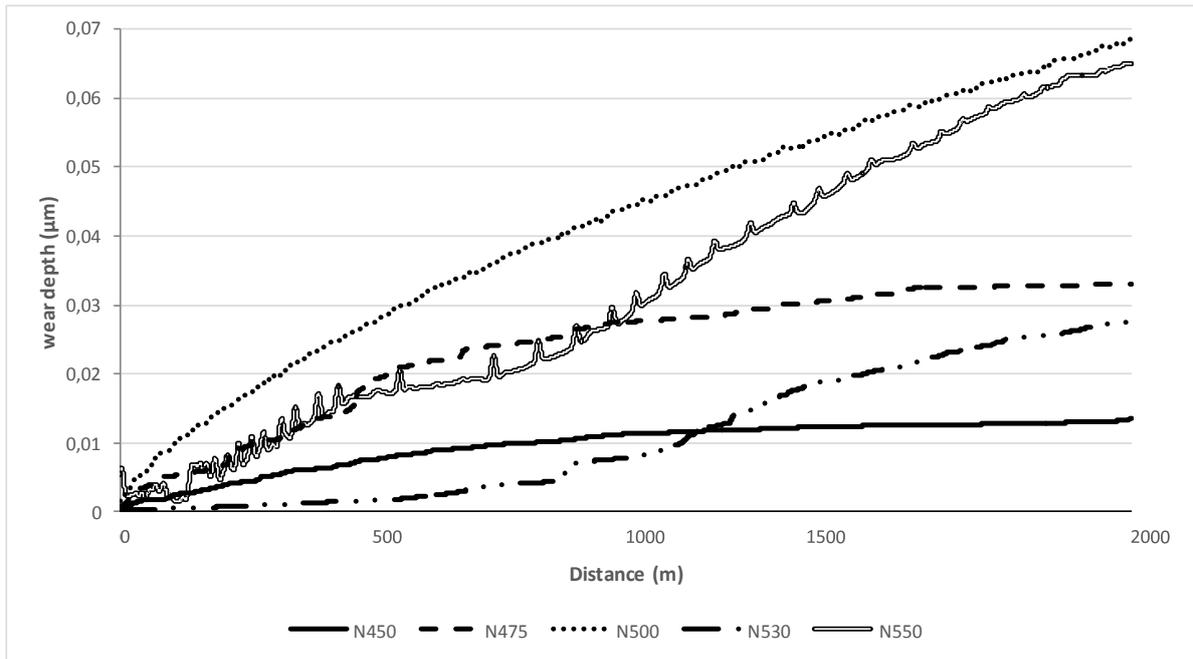


b-)

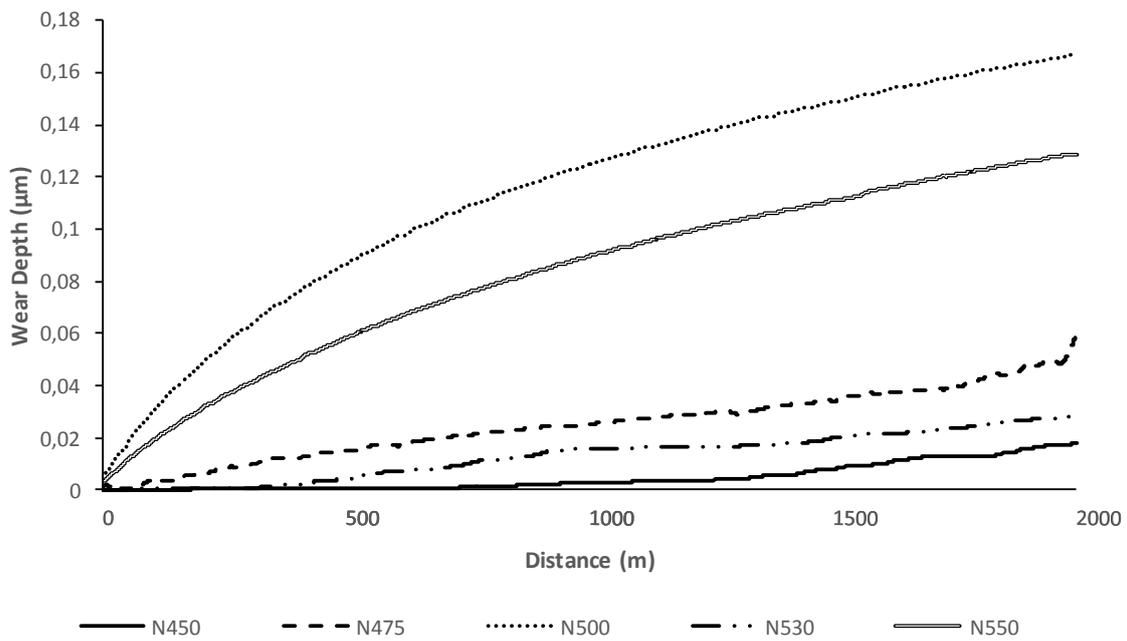
*Figure 4. 5N (a) and 10N (b) wear rates occurring in the ball and disk in load*

### 3.4. Wear Depth

The variation of wear depth according to time has been observed by measuring the amounts of wear depth in the ball at 0,  $1\mu\text{m}$  precision with a Keyence LK-G3001P high speed CCD laser displacement meter sensor during the test. The amounts of the wear depth shown in Figure 5 (a and b) are the total amount of the wear both in the disk and ball in the 5N and 10N force. The minimum wear depth has been seen in  $N_{450}$  sample in the studies. It is thought that the best wear depth value was obtained from the  $N_{450}$  sample because the surface layer reached a higher hardness value than the other samples depending on the process temperature and the plasma nitriding time applied to this sample and accordingly it makes it harder to separate component from the surface of the sample. Besides this, the thick white layer in  $N_{500}$  ve  $N_{550}$  samples were separated from the surface of the disk by through the breaking during the wear test, which caused a regular increase in the wear depth of the samples. As seen in Figure 5-a and b, it is clear that in the  $N_{500}$ ,  $N_{550}$  samples that the white layer moved away from the component quickly after 500 - 800 m.



a)



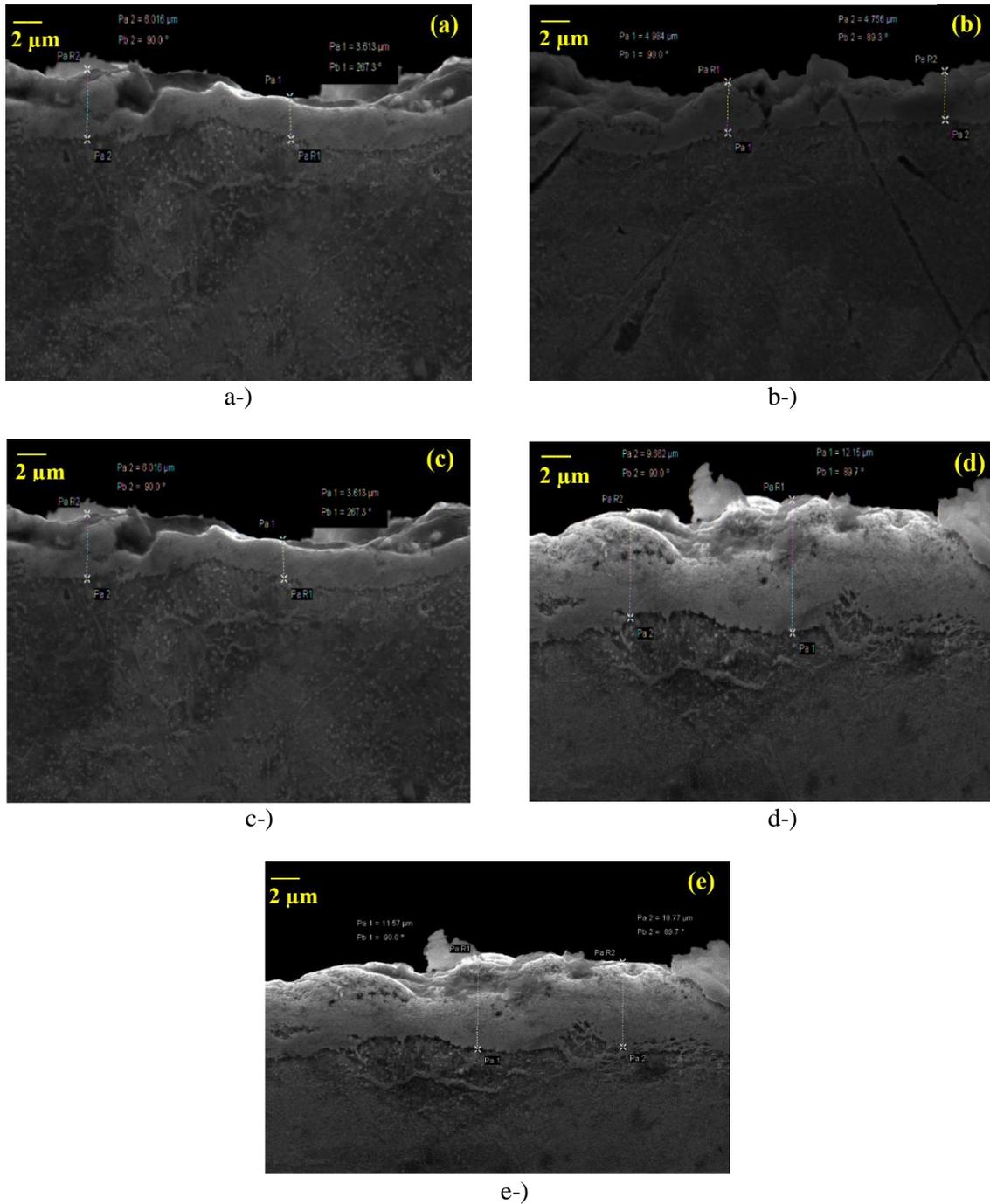
b)

Figure 5. Instant wear depth (a) 5N load, (b) 10N load

### 3.5. SEM displays and analysis of the samples

During nitriding process, the formation of nitriding reaction occurs not only on the surface but also on the lower surfaces from the surface to the inner core with the diffusion of nitrogen atom. Consequently, thin nitride layers form a structure called as compound layer or white layer. Iron nitride forming the white layer is in the structure of composite ceramics and it is a compound which does not show brittle and elastic elongation. While compound layer is providing positive effect due to high hardness, hard and brittle surface accelerates the abrasion during the abrasion of nitrided surface and this is seen as negative

effect. In this study, all the samples were examined under an optical microscope by using test samples in the same sizes.

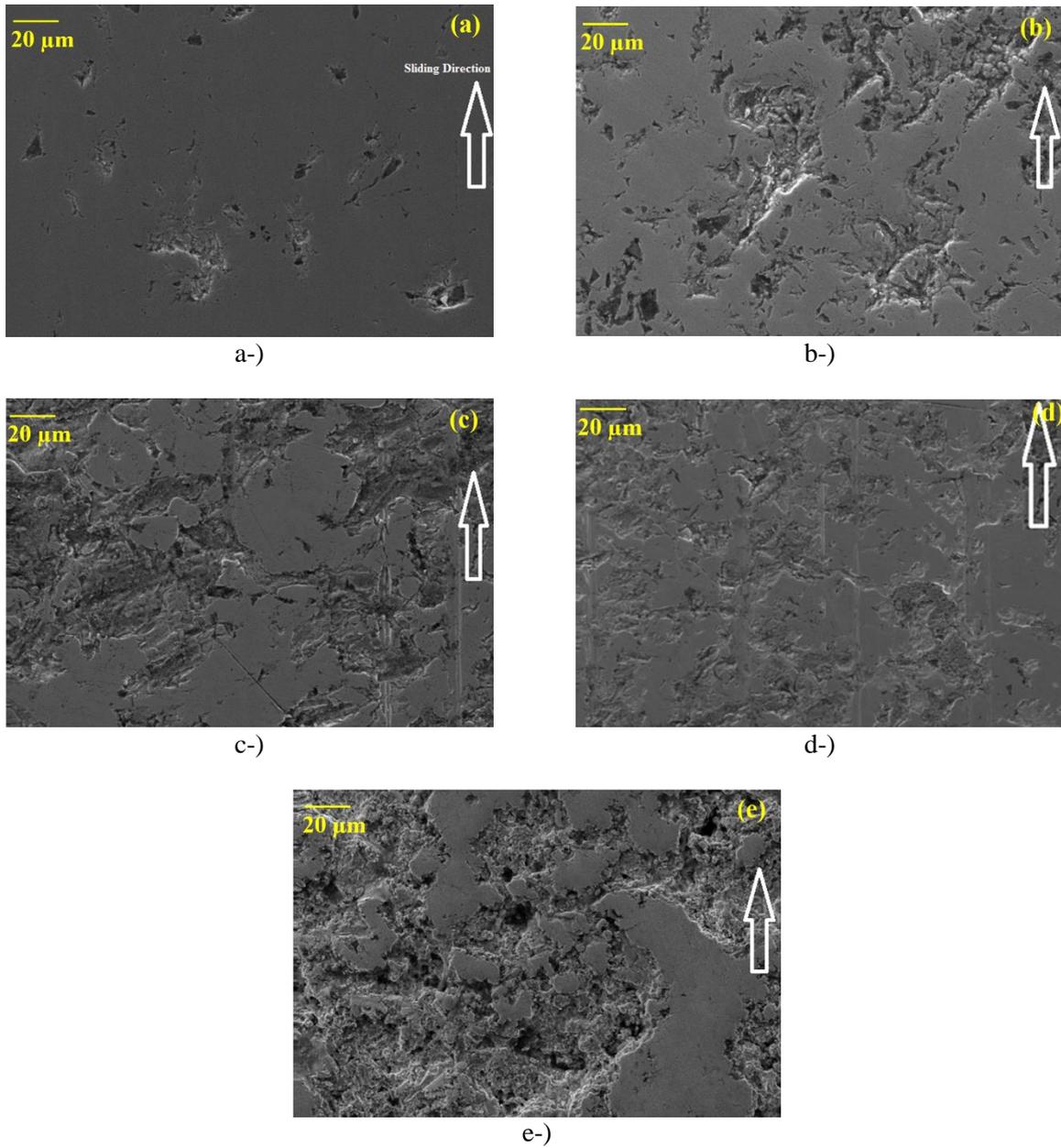


**Figure 6.** SEM displays the cross sections of the samples subjected to the nitriding process at different temperatures and periods,  $N_{450}$  (a),  $N_{475}$  (b),  $N_{500}$  (c),  $N_{530}$  (d),  $N_{550}$  (e)

SEM displays of the cross sections of the samples subjected to the nitriding process at different temperatures and periods are shown in Figure 6. It can be said that the white layer is seen clearly in the displays. It was observed that the thickness of the white layer increased depending on the nitriding temperature. In Table 2, the values of the white layer thickness changing depending on the nitriding period in the samples were given. The findings have shown parallelism with the literature [12]. The white layer emerging in the nitriding process is an unwanted formation because it had a hard and brittle structure.

**Table 2.** The thickness of the white layer in the samples

Samples	N <sub>450</sub>	N <sub>475</sub>	N <sub>500</sub>	N <sub>530</sub>	N <sub>550</sub>
White layer thickness	3.613μm	4.984μm	6.016μm	9.56μm	11,57 μm

**Figure 7.** The SEM displays of the wearing surface of the samples subjected to the nitriding process at different temperatures and periods, N<sub>450</sub> (a), N<sub>475</sub> (b), N<sub>500</sub> (c), N<sub>530</sub> (d), N<sub>550</sub> (e)

When the wearing surface of the component nitrided at 450 °C was examined, it was seen that a proper wearing occurred, and in some parts, the particles were separated from the surface to a small degree (Figure 7a). When the SEM surfaces of the nitrided components were at 475 °C and above, abrasive wearing tracks were seen during the process, and certain areas separated from the surface as flakes. These particles emerged with the fragmenting of the compound layer, which is very hard and brittle under load. This is more clearly seen in the nitrided components at 500 °C and 550 °C where the white layer fragmented as flakes because of the breaking in the surface and thus an increasing in the wear level

(Figure 7 c, e). As a result, it could be seen that the wear resistance of the samples nitrided above 500 °C was lower than that of the samples nitrided at 450 °C.

#### 4. CONCLUSION

In this study, AISI 4340 (34CrNiMo6) tempered steel was applied to the plasma nitration process at different temperatures and different periods in order to increase the wear resistance of the outer surface without decreasing the hardness of the core under 40-44 HRC, and to prevent the component from distortion during the heat treatment. Also, the wear characteristics of the samples in dry conditions were investigated. When improving the surface resistance of the components, the other mechanical properties of the component should not be affected. The aim of the study was identified as improving the surface characteristics of the AISI 4340 material without changing the other mechanical properties. The results are given below.

- When the mean of the friction coefficient ( $\mu_{\text{mean}}$ ) in the components was applied, the 5N and 10N load was examined, and it was seen that it had occurred in the N450 sample on which the nitration process was applied at 450 °C (N450=0,260 for the 5N pressure strength, and N450=0,149 for 10N weight).
- Although the compound layer generally has a hard and brittle structure, it is extremely ductile and resistant to abrasion and has a lower coefficient of friction as compared to the diffusion layer [13]. For this reason, it is not necessary to remove the white layer from the thin compound layer. However, as the thickness of the white layer increases, the broken particles during the service life cause triple abrasion. For this reason, the friction coefficient of the samples with thick compound layer is higher.
- The sample in which the hardness can increase through the component and surface without decreasing the core hardness under 40 HRC were determined as N450 and N475. In both samples, the value of the hardness (412 HV<sub>0,1</sub> approximately 42 HRc) was stabilized by reaching the core hardness at about 110  $\mu\text{m}$ . Whereas the approximately target hardness values (400-440 HV<sub>0,1</sub>) were observed up to 200  $\mu\text{m}$  depth in the N500, N530 and N550 samples, they decreased to a 320-354 HV<sub>0,1</sub> value after that depth was observed. It was shown that the target core hardness value decreases in the N500, N530 and N550 samples.
- The samples with internal hardness 44HRC before nitriding decreased the hardness value in the internal structure partly by nitriding temperature effect. The nitriding temperature showed the effect of tempering. For this reason, the nitriding temperature above 500 °C accelerated the reduction of internal hardness with the increase in nitriding time.
- When the variation of wear rate in the components applied 5N and 10N load were examined, it was observed that both disk and the ball were worn down. . It was seen particularly in the sample where nitration occurred at 550 °C, the ball was worn down more due to the hardness of the surface, but the disk was also worn down with the breaking of the white layer in the sample. It was seen that the increase in the nitriding temperature in the wear rates affected the increase in the hardness. The risk of occurring breaks inside the layer situated at the top surface increases because the white layer is hard and brittle, and a maximum shear stress occurs in the surface. The compound layer can have both positive and negative effects due to high hardness and brittleness respectively, and usually experiences earlier spalling of the surface on the wear resistance of the nitrided surface [14]. When the wear occurred in disk and ball has been examined, the best results of the variations of wear rates have been obtained in nitride components at 450 °C
- The minimum wear depth was seen in the N450 sample in the studies. It is thought that the best wear depth value was obtained from the N450 sample because the surface layer reached a higher hardness value than the other samples depending on the process temperature and plasma nitriding time applied to this sample. Thus, accordingly it makes it harder to separate the component from the surface of the sample.
- The increase in compound layer thickness during the nitrification phase partially increased the amount of wear due to highly fragile layer structure. Particularly in machine parts subject to

abrasion, this white layer must be removed or the nitriding time should be chosen longer at lower temperatures.

- It was observed that the thickness of the white layer increased depending on the nitriding temperature. The white layer emerging in the nitriding process was an unwanted formation because it has a hard and brittle structure. When the samples were examined, the thinnest white layer was measured as 3.613  $\mu\text{m}$  in the N450 sample. The highest value was measured as 11,57  $\mu\text{m}$  in the N550.
- At low nitriding temperatures diffusion is very slow. On the other hand, nitrate decomposition is very thin. These fine dissociations enhance formation hard nitride layers and hence resistance to abrasion.

## CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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