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EFFECT OF PRE-HEAT TREATMENT ON FATIGUE BEHAVIOR OF SEVERE SHOT PEENED AND PLASMA NITRIDED AISI 4140 STEEL

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ABSTRACT

In this study, the pre-heat treatment applications (annealing, normalizing, oil quenching, tempering) influence is to be determined on the fatigue behavior of mechanically and thermally surface treated AISI 4140 low alloy steel. The plastically deformed, ultra fined and oriented grain layer has been created by means of severe shot peening and improved by pulsed plasma nitriding. The specimens were characterized by optical, scanning electron microscopy, X-ray diffraction and full width at half maximum (FWHM) analysis. The surface is investigated by surface roughness measurements before the understanding fatigue behavior of the specimens under different pre-heat treatments. The results demonstrate severe shot peening and plasma nitriding improves the fatigue limit of the material effectively. Also the combination of the treatments provides comparable fatigue limit of the annealed and normalized specimens compared to tempered one.

Keywords: *Severe Shot Peening, Plasma Nitriding, Fatigue, FWHM, Ultrafine Grain Layer.*

ÖN ISIL İŞLEMİN BİLYALI DÖVÜLMÜŞ VE PLAZMA NİTRÜRLENMİŞ AISI 4140 ÇELİĞİNİN YORULMA DAVRANIŞI ÜZERİNDEKİ ETKİSİ

ÖZET

Bu çalışmada, mekanik ve termal yüzey işlemi uygulanmış AISI 4140 düşük alaşımlı çeliğin yorulma davranışı üzerinde ön ısıl işlem uygulamalarının (tavlama, normalizasyon, yağda su verme, temperleme) etkisinin belirlenmesi amaçlanmaktadır. Plastik olarak deforme olmuş, aşırı derecede inceltilmiş ve yönlendirilmiş taneli tabaka aşırı bilyalı dövme yoluyla elde edilmiş ve darbeli plazma nitrürleme ile yüzey fiziksle ve mekanik özellikleri iyileştirilmiştir. Numuneler, optik, taramalı elektron mikroskopisi, X-ışını kırınımı ve yarı yükseklik pik genişliği (YYPG) analizi ile karakterize edilmiş olup, yüzey topoğrafyası farklı ön-ısıl işlemler altındaki numunelerin yorulma davranışlarını belirlemeden önce yüzey pürüzlülüğü ölçümleri ile incelenmeye çalışılmıştır. Sonucçlar, bilyalı dövme ve plazma nitrürleme kombinasyonun tüm numunelerde yorulma dayanımın iyileştirdiği hatta tavlanmış ve normalizasyon ısıl işlemi görmüş numunelerin yorulma limitlerini sadece temperlenmiş numunelerle kıyaslanabilir seviyelere iyileştirmiştir.

Anahtar Kelimeler: *Aşırı Bilyalı Dövme, Plazma Nitrürleme, Yorulma, YYPG, Ultra-ince Taneli Tabaka.*

1. INTRODUCTION

Heat treatments are exposed to alter the properties of metals. The treatments could be distinguished by changing temperature and duration to adjust the mechanical properties such as strength, hardness, toughness and ductility [1]. Besides, the stress relief, recrystallization and homogenization could be provided. Annealing and normalizing treatments softening the materials and increasing the ductility at once [2]. Meanwhile, cold working processes have the ability to raise the strength and decrease the ductility of annealed parts. Tempering provides the balance of strength and ductility for critical dynamic loaded applications [3].

Metallic materials are generally failed from surface since, most of the failures begin from surface and propagates the interior [4]. Particularly fatigue and corrosion are surface based failures, mechanical surface treatments (shot peening, ultrasonic peening, deep rolling) and thermal surface treatments (nitriding, carburising, plasma nitriding, boriding) exhibit superior mechanical and chemical properties to retard the crack occurrence and propagation [5, 6]. Shot peening has been selected for grain refinement and also severe plastic deformation instead of improving fatigue limits for decades. Severe shot peening induces high compressive residual stress and leads to formation of ultrafine grained layer on the surface [7]. The dislocation densed, deformed nanocrystalline layer enhances the nitriding layer and diffusion depth after nitriding and carburising processes. Deeper diffusion and compressed layer retards and/or prevents the crack initiation on topmost layer [8]. Therefore, the combination of surface treatments contributes the surface unique desired properties. In other words pre-application of mechanical surface treatments could reduce the temperature and duration of thermal surface treatments due to the existence of diclocation and boundary densed unstable layer. The desired diffusion depth and surface hardness with deeper stress layer could be deserved at shorter durations [9, 10].

The aim of this study is to determine the effect of combined surface and pre-heat treatments on fatigue resistance of AISI 4140 low alloy steel by means of microstructural investigations and also fatigue resistance and surface topography analysis.

2. EXPERIMENTAL METHODS

AISI 4140 (1.7225/42CrMo4) low alloy steel (Table 1) has been selected for shot peening and plasma nitriding processes.

The specimens which are heat treated (T0) oil quenched and tempered at 500^{0}C-1 hour per inch diameter obtained first then exposed to different heat treatment processes to detect the influence of the treatments on fatigue limit. Heat treatments are shown in Table 2.

Severe shot peening process is performed Peenmatic 2000S air blast shot peening equipment manually within closed chamber by using cast steel shot. The shot peening (SP) treatment conditions are shown in Table 3. Plasma nitriding is applied with a unique condition similar with shot peening due to compare the pre-heat treatments on fatigue properties. Pulsed plasma nitriding at 475^{0}C with a duration of 4 hours under 5 mbar vacuum pressure and the voltage of 500 V.

Nikon Eclipse MA100 is used for optical microscopy (OM) and Carl Zeiss Gemini Sigma is used for FESEM analysis. The phase, FWHM and crystallite size analysis are investigated by using Rigaku SmartLab diffractometer using CuKα radiation (scanning speed: 20 min; voltage: 40 kV, scanning angle: 200-900 and current: 30 mA). Surface roughness measurements are performed on 3 different location via Mitutoyo Surface Roughness Tester. Optical microscopy (OM) and field emission scanning electron microscopy (FESEM). The fatigue tests are constructed by using BESMAK T-250 rotating bending fatigue tester with a frequency of 50 Hz and stress ratio R= -1.

Table 1. Chemical composition of AISI 4140 low alloy steel (weight %).

C	Mn	Si	Cr	Mo	P	S	Fe
0.40	0.85	0.25	1.00	0.25	0.035	0.040	Bal.

Table 2. Heat treatment conditions of AISI 4140 low alloy steel.

Heat Treatment	Conditions	
	Temperature / Duration	Cooling Environment
Annealing (A)	840 ^{0}C / up to 25 ^{0}C	Furnace
Normalizing (N)	880 ^{0}C / up to 25^{0}C	Air
Tempering (T1)	450 ^{0}C / 1h	Air
Tempering (T2)	550 ^{0}C / 1h	Air
Quenching (Q)	840 ^{0}C	Oil

Table 3. Different applied SP treatments conditions.

Test No.	Shot standard	Shot diameter (mm)	Projection Pressure (psi)	Almen intensity (mm)	Peening time (s)	Surface Coverage	Arc height (mm)
1	S230	0.5842	70	35A	20	200%	0,35
2	S230	0.5842	20	7N	2	200%	0,7

3. RESULTS AND DISCUSSION

3.1 Microstructural Investigations

The steel has been delivered in form of oil quenched and tempered at 500^0C for 1 hour per inch diameter. Once after the whole specimens have been applied to oil quenched at 840^0C then furnace cooled (Figure 1a), air cooled (Figure 1b), just oil quenched (1c), tempered at 450^0C (Figure 1d) and tempered at 550^0C (Figure 1e). Although the existence of bainitic matrix on Figure 1b, Figure 1a and 1b mainly demonstrates ferrite and also pearlite structure and the phases can be distinguished by only the sizes due to the difference of cooling conditions. Figure 1c results martensitic structure completely. Figure 1d and 1e have similar microstructure with tempered martensite with ultrafine ferrite phases. However, in literature, the tempering time increase up to 2 hours homogenize the microstructure with tempered martensite and also ferrite-fine particle Fe_3C carbides [11].

Severe shot peening induces cold severe plastic deformation on the surface of as received T0 (quenched and tempered at 500^0C) and disturbs surface homogeneity thus creates highly oriented grains on topmost surface [12, 13]. The most influenced surface has been distinguished from the core interior by losing the avareage grain size and shape and also orienting in only one way. The deepness of the layer is also changeable due to the deformation capacity and surface character (Figure 2).

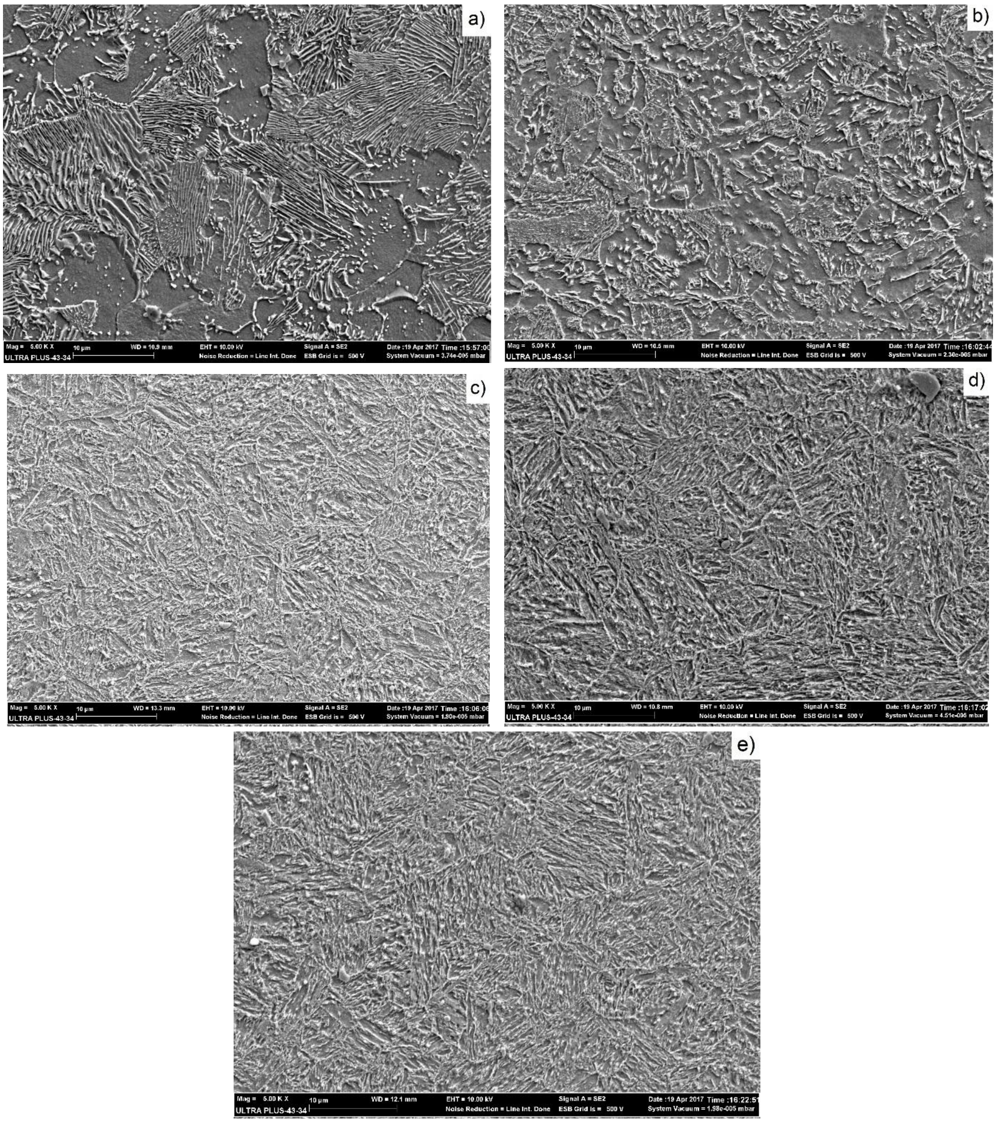

Figure 1. Optical microscope observations of internal structure of a) annealed b) normalized c) quenched d) quenched and 450^0C tempered e) quenched and 550^0C tempered AISI 4140 specimens.

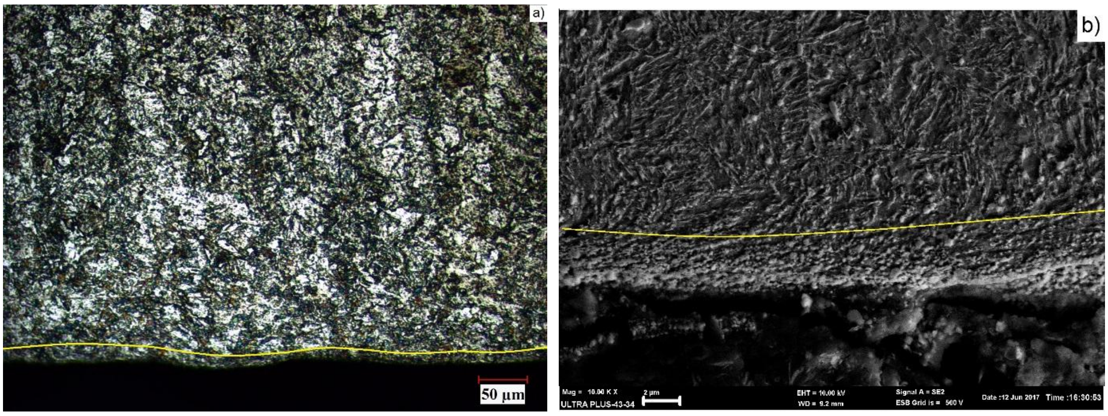

Figure 2. Cross section microscopic observations of severe shot peened AISI 4140 a) optical microscopy (OM) b) scanning electron microscopy (SEM).

The X-ray measurements of severe shot peened and as received specimens are shown in Figure 3. The X-ray diffraction peak has no difference since, severe shot peening is merely construct a mechanical alteration without any chemical reaction or any compound and new phase formation [14]. Therefore, the change can be observed by evaluating the FWHM by Pseudo-Voigt function method [15]. The FWHM of α (211) is raised up to 2.522 from 0.879. The studies present the FWHM increase is occupied with the effective grain size reduction particularly on metallic materials [16, 17].

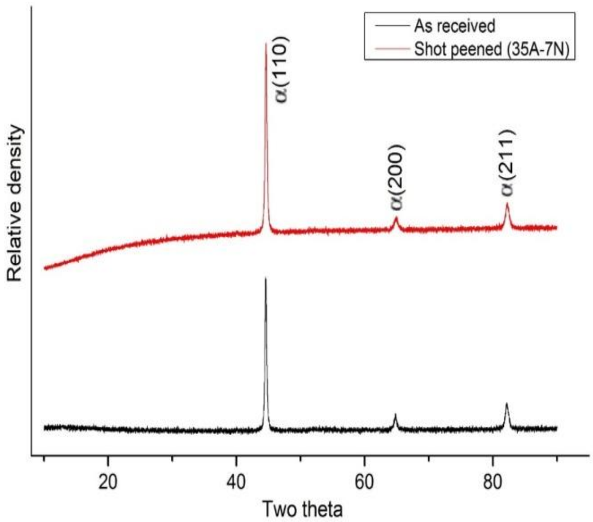

Figure 3. X-ray diffraction graphs of as received and shot peened specimens.

Typical micrographs of the pulsed plasma nitrided with different heat treated specimens have been shown in Figure 4. Pulsed plasma nitriding condition at 475^{0}C for 4 hours achieves nitrided compound layer and provides nitrogen diffusion through interior. The compound layer could be distinguished by dark white layer. The continuous and homogenous white layer becomes thicker for oil quenched and tempered at 550^{0}C. In addition, some studies reveal the transformed intermediate austenite zone layer is formed between compound layer and also diffusion layer particularly in 590^{0}C since austenite phase is stabilized by nitrogen and after cooling it transforms to ɤ’(Fe_4N) and α-Fe phases [18].

Figure 5 presents the X-ray graphs of different heat treated severe shot peened and plasma nitrided specimens. The annealed condition X-ray patterns show the descent α-Fe phases. This phase is substantially released on normalized and tempered ones and vanished for oil quenched specimens. The transformed peaks ε($Fe_{2\text{-}3}N$) and ɤ’(Fe_4N) are both strong enough at 475^{0}C for 4 hours pulsed plasma nitriding condition. The phases could be changed according to the carbon (C) amount of the steel, treatment time and temperature. The increasing time and temperature transforms the phase ε($Fe_{2\text{-}3}N$) to ɤ’(Fe_4N).

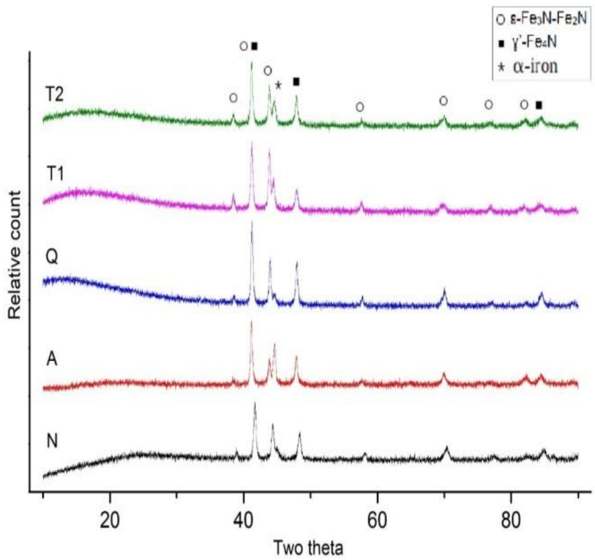

Figure 5. X-ray diffraction graphs of shot peened and plasma nitrided specimens.

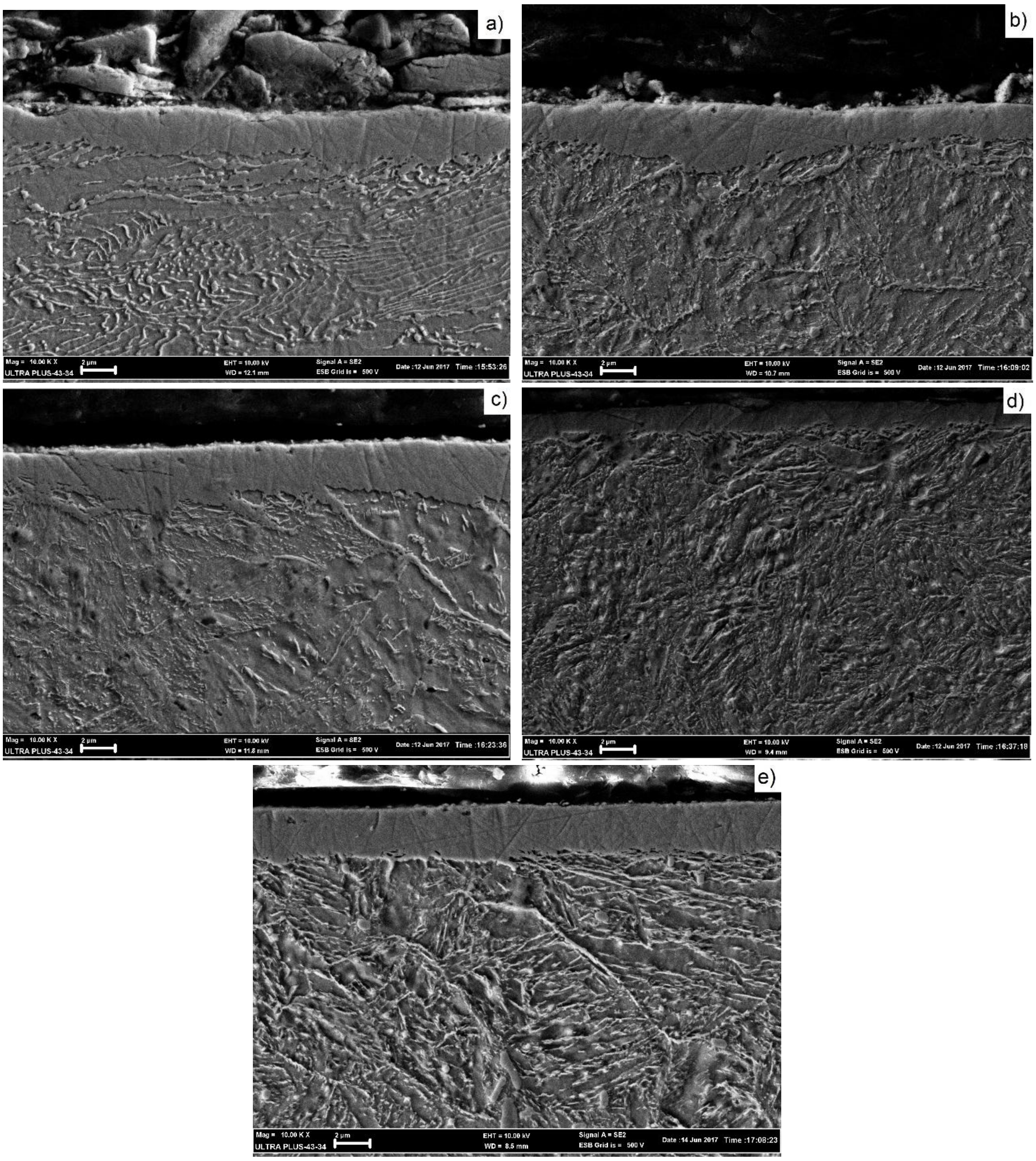

Figure 4. SEM investigations of shot peened plasma nitrided specimens a) annealed b) normalized c) quenched d) tempered (450^0C) e) tempered (550^0C).

3.2. Fatigue Tests

The fatigue test specimens are machined according to DIN 50113 rotating bending fatigue test standard. Then specimens' nominal zone is to be grounded and polished in order to eliminate the machining deficiencies. Once after the shot peening and plasma nitriding treatments are performed and the surface roughness measurements according to heat treatments are revealed in Figure 6. The as received (AR) specimen's Ra is lower than 0.5 µm.

Severe shot peening leads to deteriorate the surface, raise the roughness of annealed and normalized specimens at certain levels. In contrast, the hardening of surface after quenching and tempering prevents the influence of shot peening in terms of surface topography.

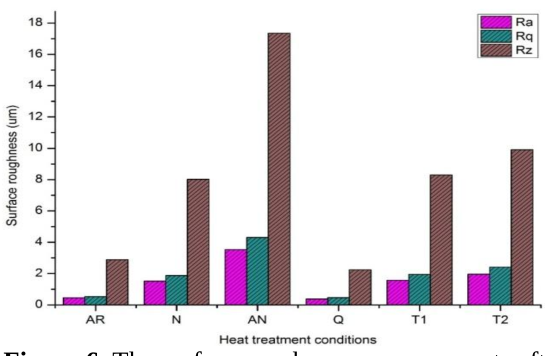

Figure 6. The surface roughness measurements after shot peening and plasma nitriding.

The shot peening and plasma nitriding combination improves the fatigue resistance effectively with respect to as received tempered (T0) condition (Figure 7). The fatigue limit of normalized and annealed specimens are less however the limits can be comparable with the T0 condition subsequent to surface treatment combination. The phenomena of fatigue is related with the surface characteristics since surface hardness could enhance the fatigue resistance. Moreover, the crack initiation start point moves through the interior according to the hardness of the surface [19].

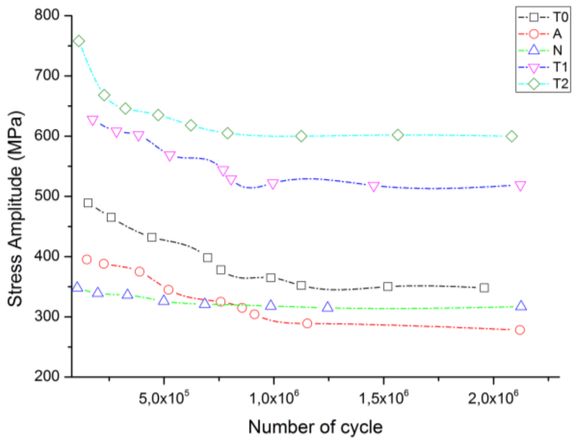

Figure 7. S-N curves of severe shot peened and plasma nitrided specimens with different pre-heat treated.

4. CONCLUSIONS

The influence of pre-heat treatment on fatigue behavior of severe shot peened and plasma nitrided specimens have been studied. The outputs can be summarized as follows:

- The bainitic matrix could be observed in normalized specimens however, ferrite and also pearlite structures come into existence in annealed in furnace or atmosphere.
- Oil quenching homogenize the microstructure with martensite and effective tempering provides also ferrite-fine particle Fe_3C carbides.
- Severe shot peening induces cold severe plastic deformation and leads to reduction of grain size according to FWHM analysis with oriented and dislocation densed layer.
- Pulsed plasma nitriding conditions at 475^0C for 4 hours achieve construction of compound layer. The layer could be observed the thickest on tempering condition at 550^0C.
- Heat treatment of normalized, oil quenched and tempered ones except annealing could accomplish to transform the α-Fe phases into the phases ε($Fe_{2\text{-}3}N$) and ɤ'(Fe_4N). Moreover the increase of temperature and duration provides formation of ɤ'(Fe_4N) completely.
- The fatigue limits of normalized and annealed specimens are lower with compared to T0, T1 and T2 due to the limited bulk strength. In contrast mechanical and thermal surface treatment combination makes them comparible with as received tempered one (T0).

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VITAE

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Dr. Unal gains bachelor degree from Gaziantep University and doctor of philosophy at Suleyman Demirel University. He has worked in several projects and interested in shot peening, plasma nitriding, severe plastic deformation and fatigue characteristics of metallic materials. He is currently faculty member in the Mechanical Engineering Department at Karabuk University.