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EFFECT OF DIFFERENT SURFACE-HEAT-TREATMENT METHODS ON THE SURFACE PROPERTIES OF AISI 4140 STEEL

VPLIV RAZLIČNIH TOPLOTNIH OBDELAV POVRŠINE NA LASTNOSTI POVRŠINE JEKLA AISI 4140

Aysun Ayday, Mehmet Durman

Sakarya University, Faculty of Engineering, Department of Metallurgical and Materials Engineering, Sakarya 54187, Turkey
aayday@sakarya.edu.tr

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In this study, the effect of different heat treatments on the hardness and wear properties of AISI 4140 steel was investigated. Sample surfaces of AISI 4140 steel were modified with traditional induction heat treatment and the new treatment of electrolytic-plasma hardening. The microstructural characteristics of surface-treated steel samples were examined with scanning electron microscopy (SEM). The mechanical properties of the samples including the surface microhardness and modified-layer thickness were also evaluated. The test results indicate that the wear resistance increases with the increasing modified-layer hardness, due to the transformation of the martensitic structure. The electrolytic-plasma hardening is as suitable a technique for improving the mechanical properties of AISI 4140 steel as the traditional hardening method.

Keywords: electrolytic-plasma treatment (EPT), induction, hardness, wear

V tej študiji je bil preiskovan vpliv različnih toplotnih obdelav na trdoto in obrabne lastnosti jekla AISI 4140. Površina vzorcev jekla AISI 4140 je bila obdelana z navadnim indukcijskim kaljenjem in z novim postopkom elektrolitskega utrjevanja s plazmo. Značilnosti mikrostrukture površinsko obdelanih vzorcev jekla so bile preiskane z vrstičnim elektronskim mikroskopom (SEM). Ovrednotene so bile mehanske lastnosti vzorcev, vključno z mikrotrdoto površine in debelino spremenjenega sloja. Rezultati preizkusov kažejo, da se povečuje odpornost proti obrabi s povečanjem trdote modificiranega sloja zaradi pretvorbe v martenzitno mikrostrukturo. Elektrolitsko utrjevanje s plazmo je enako primerna tehnika za izboljšanje mehanskih lastnosti jekla AISI 4140, kot običajna metoda utrjevanja površine.

Ključne besede: elektrolitska obdelava s plazmo (EPT), indukcija, trdota, obraba

1 INTRODUCTION

AISI 4140 steel (DIN 42CrMo4) is a widely used material in industrial applications, such as automotive, aerospace and manufacturing industries. However, the parts required for mechanical working must have not only high strength but also toughness, abrasion resistance and corrosion resistance. AISI 4140 steel includes Cr and Mo alloying elements that provide high hardenability and toughness after the surface treatments.[1,2]

Induction hardening (IH) is one of the most widely employed treatments to improve component durability. It determines, in a workpiece, a tough core with tensile residual stresses and a hard surface layer with compressive stresses, which have proved to be very effective in extending a component's fatigue life and wear resistance.[3,4] On the other hand, the conventional induction-hardening treatment has some disadvantages: distortion, change of coil, surface deformation, etc.[5–7]

Nowadays, the novel electrolytic-plasma treatment (EPT) is one of the most promising surface-hardening methods as an alternative to the induction hardening. EPT has been successfully used to improve the hardness, the wear resistance and the corrosion resistance of materials.[8] When hardening is not necessary for the whole surface or bulk of a material, EPT is a suitable method for treating a specific location on the surface, like the induction hardening.[9] The standard mechanisms of the two hardening treatments include two main steps: the austenitization, during which the material is heated above the critical temperature (but below the melting point) to achieve the austenite formation and the quenching or cooling down, when austenite is transformed into martensite.[10,11] Also, with EPT, the surface-treated zones have an average depth of 0.1–10 mm, exhibiting an increased hardness, improved resistance to wear, better corrosion resistance and higher fatigue strength (e.g., piston ring groove, valve seat, compressor screws, diesel-engine cylinder liners, gears, etc.).[8,12]

The present study aims at determining the wear resistance of AISI 4140 steel treated with different surface-hardening procedures: the induction hardening and the electrolytic-plasma hardening. The modified samples were characterized before and after the wear tests with metallographic, SEM microscopy and microhardness techniques.

2 EXPERIMENTAL PROCEDURE

AISI 4140 steel was selected for the present study and **Table 1** shows its chemical composition. The diameter of cylindrical samples was 20 mm and the height was 10 mm. All the samples were modified with EPT and induction hardening. The EPT voltage, heating and cooling times were 310–260 V, 3 s and 3 s, respectively, and a constant thermal cycle was selected. The specimens were induction hardened with 30 kW and 300 kHz for 6 s and quenched in water. The sample codes and EPT parameters are listed in **Table 2**.

The morphology of the modified layers was investigated with a scanning electron microscope (SEM Jeol, JSM 6060-LU). The hardness measurements were conducted on the cross-sections of the samples with a Vickers microhardness tester. The test load was 100 g for the hardness measurements at the cross-sections. The hardness value was obtained by averaging the results of three measurements. The temperature distribution of the samples from the plasma-treated side to the internal side was investigated via thermocouples during the process. The surface temperature data were collected from the system with the aid of a computer-data-acquisition system. The volume fractions of different phases were measured with an image analyzer on the metallographic sections.

Table 1: Chemical composition (*w*/%) of AISI 4140 steel
Tabela 1: Kemijska sestava (*w*/%) jekla AISI 4140

C	Si	Mn	Cr	Mo	P	S	Fe
0.41	0.21	0.8	0.95	0.18	0.025	0.027	Balance

Table 2: Treatment parameters
Tabela 2: Parametri obdelave

Parameter code	Electrolytic solution	Heating (V)	Cooling (V)	Total time	Thermal cycle
Untreated	Original AISI 4140				
EPT–6	Na_2CO_3; 12 %	310	260	(3 s and 3 s) × 6 = 36 s	6
IH	30 kW, 300 kHz, 6 s				

The wear tests were performed on the original AISI 4140 and on the modified specimens to determine the best process and parameters. All the wear tests were carried out under dry sliding conditions at room temperature using a ball-on-disc (CSM tribometer), friction- and wear-test machine. The counterpart was an Al_2O_3 ball (Ø = 6 mm) used in accordance with DIN 50 324 and ASTM G 99-95a. The tests were performed with a nominal load of 3 N and a sliding speed of 0.10 m/s for the total sliding distance of 200 m.

3 RESULTS AND DISCUSSION

Figure 1 shows the features of the modified layers, observed on the cross-sections of the EPT and induction materials. During both modification treatments, austenite transforms completely or partially into martensite on the surface called the hardened zone (HZ). An amount of the retained austenite may be present in this region.[13] In the neighborhood of the HZ with the base material, a narrow

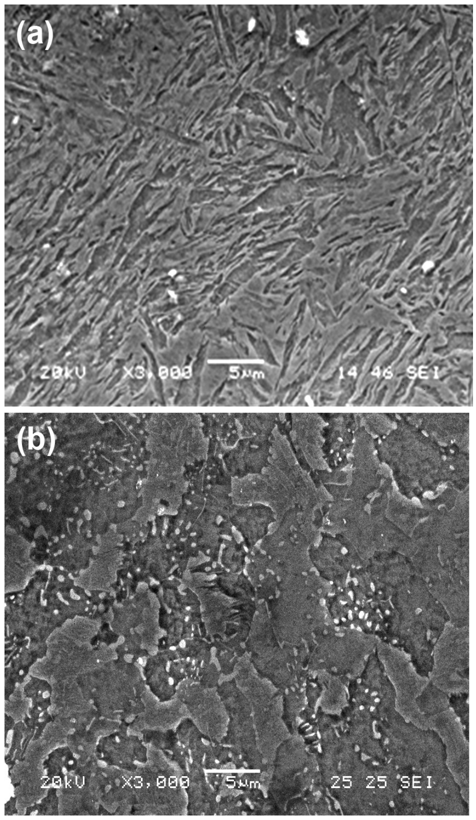

Figure 1: Cross-sectional appearance of modified samples: a) EPT, b) IH
Slika 1: Prerez modificiranega vzorca: a) z EPT, b) z IH

Table 3: General results for modified samples
Tabela 3: Rezultati na modificiranih vzorcih

	Thickness (mm)	Hardness ($HV_{0.1}$)	Surface temperature (°C)	MVF (%)	Friction coefficient	Wear rate (mm^3/(N m))
Untreated	–	200	–	–	0.2	9.06 E–05
EPT	5.2	930	835	47.4	0.203	4.66 E–05
IH	2.1	810	800	39.4	0.377	4.96 E–05

heat-affected zone was observed, consisting of martensite, bainite and some traces of the initial pearlitic structure. These are the most probable structures according to[13,14]. The base-material microstructure is composed of ferrite and pearlite. All the experimental data showing the results of the mechanical tests are given in **Table 3**. The maximum layer thicknesses of the modified surfaces were 5.2 mm for the EPT and 2.1 mm for the IH (**Table 3**). An effective increase in the hardness was observed after the surface heat treatments. The EPT-sample hardness was higher than that of the induction-hardened samples, as shown in **Table 3**. The hardness of the modified layers depends on the martensitic transformation, and its high hardness is usually explained with the martensite volume fraction (MVF).[15,16] The volume fractions of martensite are given in **Table 3**. The martensite volume fraction of the EPT and induction hardening

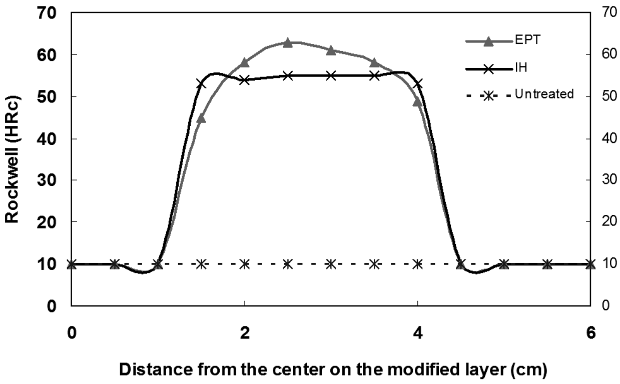

Figure 2: Surface-hardness profiles of untreated AISI 4140, EPT and IH samples
Slika 2: Profil trdote neobdelanega AISI 4140, EPT in IH vzorca

were 47.4 % and 39.4 %, respectively. As shown in **Table 3**, the EPT volume fraction of martensite is higher than in the case of induction because of the surface temperature.

Figure 2 shows the longitudinal hardness profiles for both specimen types. A significant surface hardening was observed on all the modified samples. The hardness of the AISI 4140 steel was 10 HRC. The surface hardness of the specimens increased considerably after the surface-hardening treatments. The surface-hardening behavior of the steel depended on its microstructure constituents, i.e., the martensite (or bainite) morphology and volume fraction with reference to[12,15,17]. The EPT-modified sample shows the maximum hardness in the center, corresponding to the martensitic structure. The hardness along the EPT track decreases rapidly for about 20 mm from its center, while the induction-hardened sample has a single hardness value. This fact can be explained by examining the shape and the intensity profile of the EPT. In addition, the exposure (heating) time is lower at the border of the EPT tracks due to the elliptical nozzle shape. The combination of these two effects results in significantly lower temperatures reached at the external limits of the modified zone, at which the austenization does not take place, so no hard-quenched martensite can be achieved.

Figure 3 shows the wear surfaces of the original AISI 4140, EPT and induction-modified samples, tested at a load of 3 N. The modified samples have quite smooth surfaces with shallow abrasive-wear scars due to the high hardness of the samples. The original AISI 4140 steel was tested under a similar wear-test condition. In this case, the plastic deformation caused due to a low surface hardness is obvious, as shown in **Figure 3**. The lowest wear rate was obtained for the EPT-modified sample followed by the induction-hardened and untreated AISI 4140 samples (**Table 3**). This is due to the microstructure of the sample, consisting of martensite (47.4 % MVF) and having the highest hardness among the tested samples.

4 CONCLUSIONS

In this study, the following results were observed:

AISI 4140 steel surfaces were successfully hardened with the electrolytic-plasma technique and the traditional induction-hardening method. The maximum surface hardness was obtained with the EPT. The maximum microhardness value increased from 200 $HV_{0.1}$ to 930 $HV_{0.1}$ during the experiments. After the wear experiments, the EPT-modified samples had the lowest wear rate, showing almost the same wear resistance as observed for the induction-hardened samples. The untreated samples, as expected, had the highest wear rate. The hardness of the surface is a very important factor with respect to the wear rate. It is a result of the microstructure of the modified samples, which consisted of martensite.

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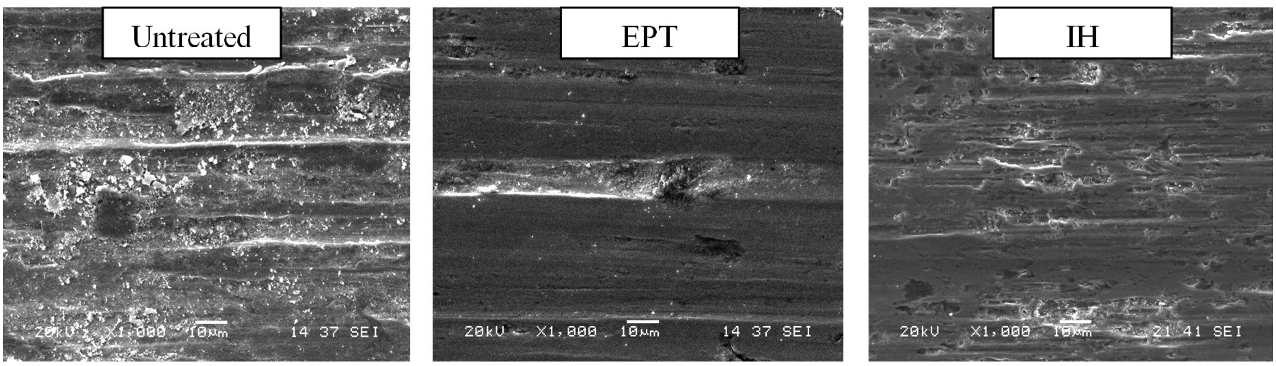

Figure 3: SEM micrographs of worn surfaces of untreated AISI 4140, EPT and IH samples
Slika 3: SEM-posnetki obrabljene površine neobdelanega AISI 4140, EPT in IH vzorca

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