UDK 669.14:533.9:539.92
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 47(2)177(2013)

WEAR PROPERTIES OF AISI 4140 STEEL MODIFIED WITH ELECTROLYTIC-PLASMA TECHNOLOGY

OBRABNE LASTNOSTI JEKLA AISI 4140, MODIFICIRANEGA S TEHNOLOGIJO ELEKTROLITSKE PLAZME

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Prejem rokopisa – received: 2012-08-29; sprejem za objavo – accepted for publication: 2012-10-09

An electrolytic-plasma treatment (EPT) was applied to the surface of AISI 4140 steel and the wear behavior under dry sliding conditions was studied for different treatment parameters. The modified samples were characterized before and after the wear testing using metallographic, SEM-microscope and microhardness techniques. The test results indicate that the wear resistance of the AISI 4140 steel can be improved by means of electrolytic-plasma technology (EPT). The wear resistance increases with an increased modified-layer hardness due to a transformation to the martensitic structure.

Keywords: plasma, microhardness, wear

Preučevane so bile obrabne lastnosti pri suhem drsenju in različnih parametrih z elektrolitsko plazmo obdelane površine jekla AISI 4140. Modificirani vzorci so bili karakterizirani pred preizkusom obrabe in po njem z uporabo metalografije, z vrstičnim elektronskim mikroskopom (SEM) in meritvijo trdote. Rezultati so pokazali, da se obrabna odpornost jekla AISI 4140 lahko poveča s tehnologijo elektrolitske plazme (EPT). Obrabna odpornost se povečuje s povišanjem trdote modificirane plasti zaradi pretvorbe v martenzitno mikrostrukturo.

Ključne besede: plazma, mikrotrdota, obraba

1 INTRODUCTION

As an advanced surface-processing technique, electrolytic-plasma treatment (EPT) has been successfully used to improve the hardness, the wear resistance and the corrosion resistance of materials[1]. When hardening is not necessary for a whole surface or bulk of material, EPT is a suitable method for treating a specific location on a surface[2]. Electrolytic-plasma (heating-quenching) hardening is a standard hardening mechanism involving two main steps: "austenitizing", during which the material is heated above the critical temperature for the austenite formation (but below the melting point) and "quenching" or cooling down, where austenite is transformed into martensite. The heating or quenching of medium and high-carbon steels can change the steel microstructures, which causes variations in the mechanical and physical properties and affects the behavior of the steels under service conditions and operations[3,4].

EPT is characterized by several process parameters: voltage, current, electrolyte, duration, and heating-quenching rate. All these parameters are strongly correlated to each other and affect the final hardening results; for this reason process modeling seems to be a good approach to the process optimization. In this study, the wear resistance of the electrolytic-plasma-modified AISI 4140 steel was evaluated under dry sliding conditions and compared with the AISI 4140 steel samples. The modified samples were characterized before and after the wear tests with metallographic, SEM microscope and microhardness techniques.

2 EXPERIMENTAL DETAILS

The test material was the commercial AISI 4140 low-alloy steel with the composition (in mass fractions, %) of 0.4 C, 0.22 Si, 0.77 Mn, 0.04 S, 0.035 P, 0.8 Cr and 0.25 Si. The diameter of cylindrical samples was 20 mm and the height was 10 mm. All the samples were modified with EPT. The EPT voltage, heating and cooling times were 310–260 V, 3 s and 3 s, respectively, depending upon the thermal cycle and the process temperature. The sample codes and the EPT parameters are listed in **Table 1**.

The morphology of the modification layer was investigated with a scanning electron microscope (SEM Joel, 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 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 wear tests were performed both on the original AISI 4140 and on the EPT-modified specimens to determine the optimum process parameters. All the wear

Table 1: EPT parameters
Tabela 1: EPT-parametri

Parameter code	Electrolytic solution	Heating (V)	Cooling (V)	Total time (s)	Thermal cycle
EPT–0	Original AISI 4140				
EPT–4	Na_2CO_3; 12 %	310	260	(3 and 3) s × 4 = 24 s	4
EPT–5	Na_2CO_3; 12 %	310	260	(3 and 3) s × 5 = 30 s	5
EPT–6	Na_2CO_3; 12 %	310	260	(3 and 3) s × 6 = 36 s	6

Table 2: Maximum surface-hardness, surface-temperature and wear-rate values
Tabela 2: Maksimalna trdota površine, temperatura površine, vrednosti obrabe

	Original AISI 4140 (EPT-0)	EPT-4	EPT-5	EPT-6
Max. surface hardness ($HV_{0.1}$)	200	800	900	930
Surface temperature (°C)	ø	600	780	835
Wear rate (mm^3/(N m))	9.06 E-05	5.05 E-05	4.87 E-05	4.66 E-05

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 (Φ = 6 mm) according to 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

The cross-sectional SEM images of the EPT-6 sample showed that it typically consisted of a modified diffusion zone (**Figure 1**). This figure shows the microstructure of the cross-section of the EPT-modified steel. The following zones are visible in the diffusion layer: the hardened zone (HZ), the heat-affected zone (HAZ) and the base material (BM). During EPT, austenite transforms completely or partially to martensite and thus the micro-

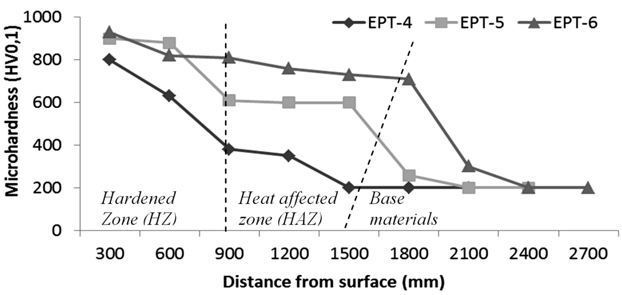

Figure 2: Microhardness profiles of the EPT-modified samples
Slika 2: Profili mikrotrdote vzorcev, modificiranih z EPT

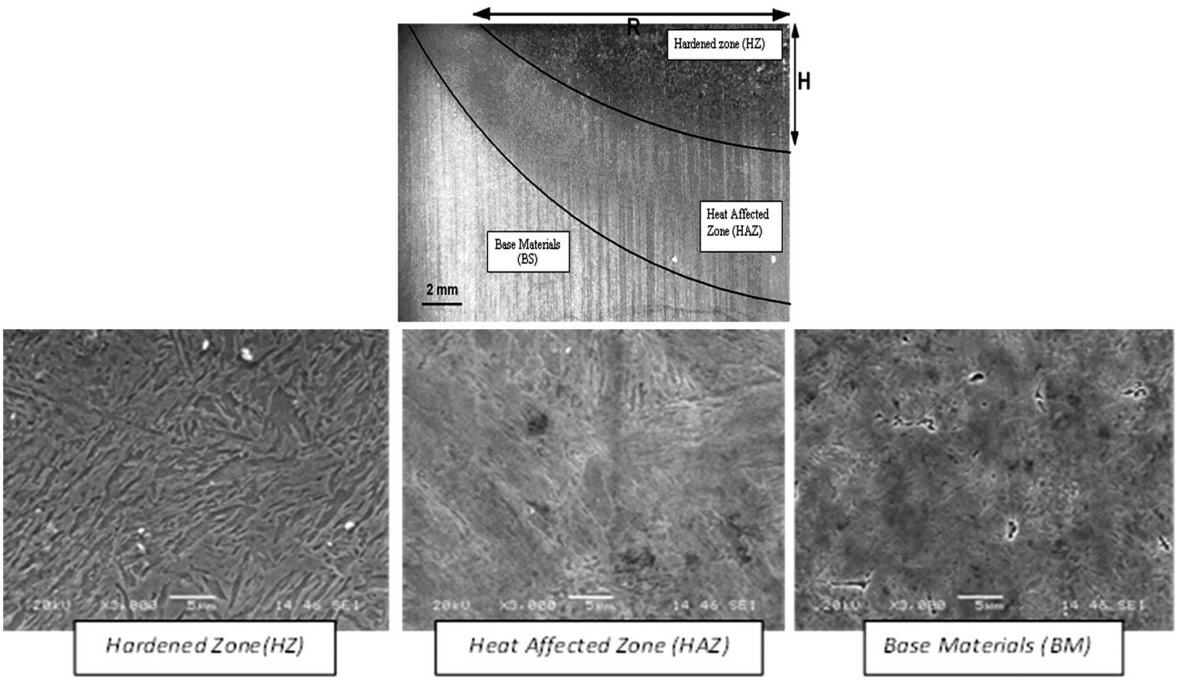

Figure 1: Cross-sectional appearance of the EPT-modified EPT-6 (*R* – radius of the modification area, *H* – HZ depth)
Slika 1: Prečni prerez vzorca EPT-6, modificiranega z EPT (*R* – polmer modificiranega področja, *H* – globina HZ)

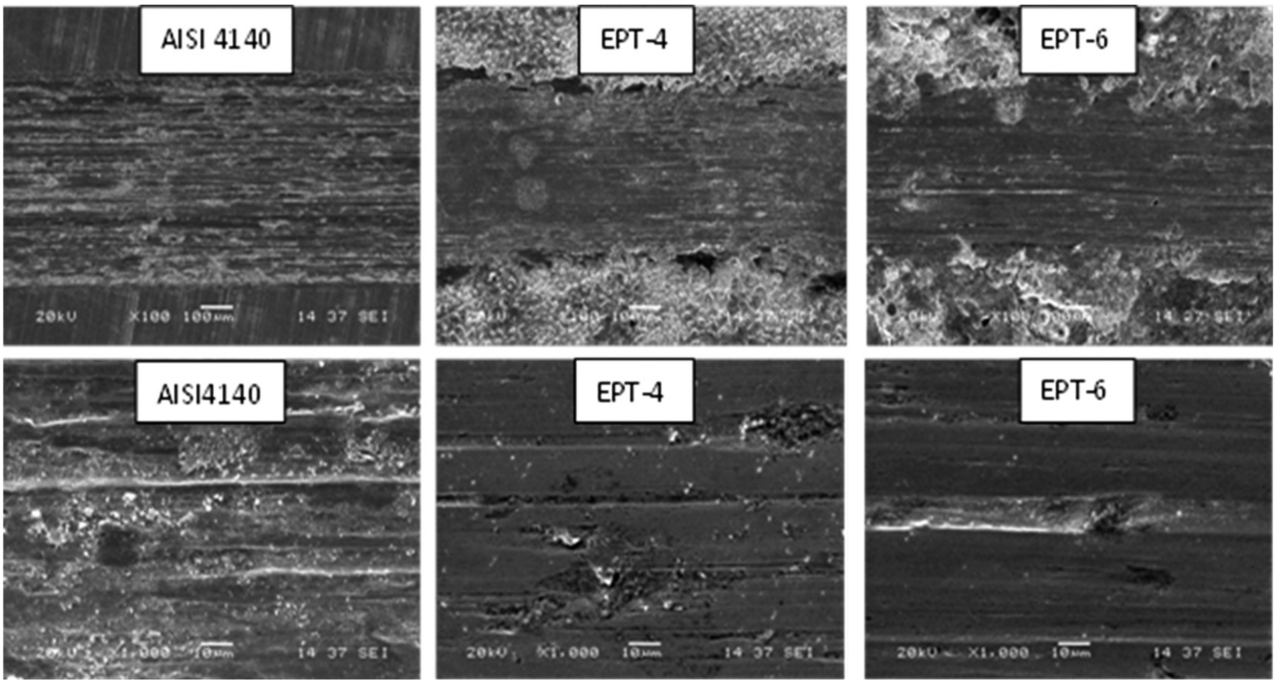

Figure 3: SEM micrographs of the original surface (EPT-0) and worn surfaces of AISI 4140, EPT-4 and EPT-6
Slika 3: SEM-posnetki originalne površine (EPT-0) in obrabljene površine AISI 4140, EPT-4 in EPT-6

structure of the HZ consists of martensite. An amount of the retained austenite may be present in this region[5]. In the neighborhood of the HZ with the base material, a narrow 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 Refs. [5,6]. The microstructure of the base material is composed of ferrite and pearlite. The maximum microhardness of this hardened zone was 930 $HV_{0.1}$. The maximum microhardness of the second zone (HAZ) was 800 $HV_{0.1}$. From the plasma surface to the base metal, the hardness values decreased and the phase structure changed into a ferritic-pearlitic matrix; in this zone the hardness was measured as 200 $HV_{0.1}$, which is shown in **Figure 2**.

The values obtained for the maximum surface hardness, surface temperature and wear rate of different specimen groups are listed in **Table 2**. It is evident that EPT markedly improves the wear performance of the steel and that the degree of improvement depends on the EPT parameters. This means that the wear resistance increases with an increase in the thermal cycle. The thermal cycle was effective at rising the surface temperature. A high surface temperature affects the modification depth and the surface hardness. The wear rate obtained for the EPT-6 sample was lower than the rates obtained for the original AISI 4140 (EPT-0) or for the EPT-4 and EPT-5 samples. This is due to the microstructure of the EPT-6 sample, which had a martensitic structure. The microstructure of the EPT-6 surface, after the EPT treatment, was finer and more homogenous in comparison with the surfaces of EPT-4 and EPT-5.

Figure 3 shows the wear surfaces of the original AISI 4140 (EPT-0), the EPT-4 and EPT-6 samples, tested at a load of 3 N. EPT-6 shows quite a smooth surface with shallow, abrasive wear scars due to the high hardness of the sample. The original AISI 4140 (EPT-0) steel was tested under a similar wear-test condition. The plastic deformation was obvious in this case and was caused by a low surface hardness as shown in **Figure 3**. The worn-surface analysis revealed a severe abrasive wear of the original AISI 4140 (EPT-0) accompanied with a high degree of plastic deformation (**Figure 3** –AISI 4140).

4 CONCLUSIONS

It is evident that the wear rate of steel is increased significantly by EPT. The degree of improvement depends on the EPT-process conditions. The modified layer thickness and the surface hardness increase with the increasing surface temperature and thermal cycle. The specimens with the maximum hardness showed the maximum resistance to wear. Thus, the hardness of the surface is a very important factor with respect to the wear rate. The hardness results arise from the microstructures of the modified samples that had martensitic structures. An increase in the thermal cycle increases the wear resistance of EPT-6 due to a finer and more homogenous hardened zone. It was observed that the longer the heating and the cooling times, the greater was the hardened-layer thickness. The initial microstructure was fully martensitic, especially in the HAZ zone after the EPT-6 sample processing. When processing the other samples, like EPT-4 and EPT-5, the microstructure transforms to a martensitic and also bainitic matrix. Therefore, the maximum microhardness values decrease from 930 HV to 200 HV during the experiments.

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