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SCIENCE DIRECT®
Surface & Coatings Technology 200 (2006) 5334 – 5342
SURFACE & COATINGS TECHNOLOGY
www.elsevier.com/locate/surfcoat

Modification of high-speed steels by nitrogen compression plasma flow: Structure, element composition, tribological properties

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Received 22 December 2004; accepted in revised form 24 June 2005
Available online 11 August 2005

Abstract

The influence of the nitrogen compression plasma flow impact on the phase and element composition and tribological properties of AISI M2 and AISI T1 high-speed steels was investigated in this work. The bank capacitor initial voltage, the number of pulses and nitrogen pressure in the vacuum chamber varied during experiments, providing the change of energy deposited in the surface layer within the limits of 5–13 J/cm^2 per pulse. X-ray diffraction analysis, Auger electron spectroscopy, Rutherford backscattering analysis, scanning electron microscopy, optical microscopy, friction coefficient and microhardness measurements were used for the characterization of the treated samples. It was found that the treatment of both types of steel resulted in austenite formation in the surface layer and carbide partial dissolution. The growth of energy deposited in the surface layer leads to the increase of thickness of the affected by treatment layer up to 24 μm and to the decrease of MC and M_6C carbides volume fraction in the analyzed layer. Treatment leads to nitrogen penetration into the steel up to the depth of 400 nm and the redistribution of the alloying elements in the surface layer. The decrease of hardness due to dissolution of carbides was observed almost in all range of treatment parameters, thus making unsuitable the usage of the compression plasma flow treatment for high-speed steels tribological properties improvement as a stand-alone technique.

Keywords: High-speed steel; Plasma flow; Structure-phase transformation

1. Introduction

Different types of ion-plasma nitriding techniques are used for the modification of steel mechanical properties [1–9]. Some techniques, e.g., plasma immersion ion implantation, find their application in industry. A comparatively short treatment time (a few tens of minutes to a few hours) is the main advantage of these methods in comparison with convenient nitriding. The use of techniques based on the interaction of direct plasma flows with a material allows to decrease even this period [10–12]. Compression plasma flows (CPF), for example, with small divergence and high energy (up to 30 J/cm^2) can modify a layer with thickness of tens of micrometers in an extremely short time <1 s [12]. It was already shown [11,12] that treatment of low-alloyed steels by different types of direct plasma flows resulted in a substantial increase of their mechanical properties, thus allowing to consider that these methods are potentially interesting for industrial application.

Compression plasma flows are powerful plasma streams, the application of which in materials science is beginning to be investigated only now. Earlier, it was shown that CPF were capable of modifying silicon surface morphology by producing ordered submicron structures [13] and they could also increase mechanical properties of low-alloyed steels [12]. The aim of this work is to determine CPF nitriding technique suitability for the high-speed steel tribological

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doi:10.1016/j.surfcoat.2005.06.007

properties improvement. The problem of suitability arises when high-power energy flows are applied for the modification of materials the operating ability of which is traditionally achieved by complicated metallurgical thermal treatment such as in the case of high-speed steels. Nitrogen incorporation into the iron matrix should increase tribological properties of steel. At the same time, high-temperature, high-cooling speed in the surface layer of steel during CPF treatment can result in the change of carbide morphology, concentration of residual austenite, microstructure of martensite and austenite, possibly causing the hardness decrease. It means that CPF treatment of a high-speed steel could cause tribological properties improvement in a narrow range of treatment parameters only. That is why it is necessary to study the influence of CPF treatment parameters on tribological properties, phase and elemental composition of high-speed steels.

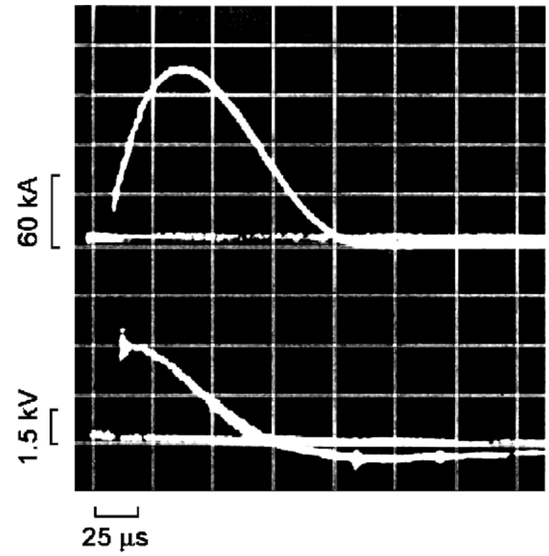

Fig. 1. Discharge current and voltage oscillograms in MPC.

2. Experimental

The effect of CPF treatment on two high-speed steels AISI M2 and AISI T1 was investigated in this work. The size of the sample was 2×15 mm ∅. Samples of AISI M2 steel had the following element composition: 0.8% C, 6.0% W, 5.0% Mo, 4.1% Cr, 1.9% V, 0.5% Co in wt.%. The element composition of AISI T1 samples was the following: 0.8% C, 18.7% W, 4.3% Cr, 1.9% V, in wt.%. T1 steel possesses higher thermal stability than M2 steel due to higher tungsten content. The steel samples were subjected to hardening quenching at 1123 K in NaCl during 1 min and at 1513 K in BaCl during 1 min with final two-folded annealing at 833 K during 30 min. The phase composition of the samples includes the following main phases: α-Fe doped with alloying elements, M_6C, MC and $M_{23}C_6$ carbides (M: Fe, W, Cr, Mo, V).

Compression plasma flows were obtained using a gas-discharge magneto-plasma compressor (MPC) of compact geometry powered with the capacitive storage of 1200 mF, operating at initial voltages (U_0) from 3 to 5 kV. The scheme of the discharge device was already shown in [13]. Nitrogen was used in the MPC as a plasma-forming gas. The pressure in the pre-evacuated vacuum chamber was 10^{-3} Pa. The pressure of plasma-forming gas (P) can be varied in the range of 100–10,000 Pa. The discharge duration in the MPC amounts to 100 µs and the peak value of the discharge current can reach 100 kA. Typical discharge oscillograms are shown in Fig. 1. Following the interelectrode gap breakdown, the generated plasma is accelerated in the discharge device by the Ampere force and outflows from the discharge unit. The velocity of the leading front of the plasma flow and its pressure both depend on the MPC initial parameters and the derivative of the total discharge current. The length of the plasma flow is about 10–12 cm. In the zone of maximum contraction, it constitutes 1 cm in diameter. The flow diverges in half-angles from 5° to 15°. The compression of the plasma flow takes place due to the interaction of the longitudinal component of the discharge current 'swept away' from the discharge device with the intrinsic azimuth magnetic field [13]. The plasma velocity in the compression flow amounts to $(4-7)\times10^6$ cm/s, depending on the initial parameters of acceleration. The concentration and temperature of electrons in the field of maximum contraction reach $(1-10)\times10^{17}$ cm^{-3} and 1–3 eV. The energy absorbed by the surface layer of the target as well as the content of nitrogen in it are dependent on the distance between the sample and the cathode, the bank capacitor initial voltage, the pressure of nitrogen in the vacuum chamber and the number of pulses.

Three types of experiments were carried out to study the influence of the treatment parameters on steels structure and tribological properties.

In the first type of experiments, the influence of the number of pulses (n) was investigated using M2 steel samples. This experiment was carried out at the nitrogen pressure of 0.4 kPa. The number of pulses was 1 and 5 at the bank capacitor initial voltage −4 kV. According to the calorimetric measurements, the value of the power density absorbed by the sample surface (Q) was approximately 13 J/cm^2 per pulse.

In the second type of experiments, the influence of the bank capacitor initial voltage was also investigated using M2 steel samples. The value of the nitrogen pressure in the vacuum chamber was the same—0.4 kPa. U_0 was equal to 2.9 kV and 3.6 kV at one pulse. The value of the power density absorbed by the sample surface was approximately 5 J/cm^2 for U_0=2.9 kV and 10 J/cm^2 for U_0=3.6 kV.

In the third type of experiments, the influence of the nitrogen pressure in the vacuum chamber was investigated using T1 samples. The nitrogen pressure varied in the range of 0.4–4.0 kPa in these experiments. The bank capacitor initial voltage was 3 kV, the number of pulses was 1 and 5.