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Structural and tribological properties of carbon steels modified by plasma pulses containing inert and active ions

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Abstract

It is known that phase transformations into austenite can take place in the surface layer of steels irradiated with intense pulses of laser, ion or plasma beams. Due to the presence of nitrogen and carbon expanded austenite in stainless steel, good corrosion resistance is maintained while the wear resistance is increased. A series of carbon steels with various carbon contents was irradiated with high intensity (5–6 J/cm^2), short (μs range) nitrogen and argon plasma pulses. The pulsed energy was high enough to melt the surface region of the samples. This paper reports the results of investigations of structural and tribological properties of the near surface layer of carbon steels induced by such treatment. The identified phases and wear resistance of the modified layer are presented.

Keywords: Intense pulsed plasma beams; Carbon steels; Expanded austenite; Structural properties; Tribological properties

1. Introduction

It is well documented in the literature that when stainless steel is exposed to nitrogen incorporation at elevated temperature, several nitrides are formed depending on the process conditions. Among all phases formed in this way an expanded austenite attracts special interest from many authors [1–6]. Nitrogen and carbon expanded austenite (γ_N and γ_C) combines high hardness, good wear and corrosion resistance in austenitic stainless steels. It is generally assumed that a conventional stationary process can only form such phases if the system contains Fe, Cr and Ni elements e.g. [4,7]. As was shown in previous experiments this does not hold true if a process of transient melting and recrystalization of the near surface layer of the substrate is applied [8–10]. In this case γ_N can be formed even in pure iron [11]. The expanded austenite is an interstitial solution of N or C where the nitrogen or carbon atoms are in octahedral interstitial sites in the fcc (face cubic centered) crystal lattice of the austenite. Increase of fcc structure lattice parameter depends on the content of interstitials. Nitrogen atoms have smaller radii compared to carbon, but cause a higher dilatation being dissolved in fcc lattice. The percentage increase of the lattice parameter per atomic percent of carbon and nitrogen is 0.119 and 0.221, respectively. This behaviour is a result of electron exchange in austenitic carbon and nitrogen steels. Nitrogen atoms in austenite increase the concentration of free electrons, i.e. enhance the metallic component of atomic interactions. Carbon atoms are expected to contribute to the localised electrons i.e. to enhance covalent bonds [12].

Taking into account these facts, systematic studies of structural and tribological properties of carbon steels irradiated with short intense pulsed plasma beams were carried out.

2. Experimental

Carbon steels with different concentration of carbon: Armco-iron, steels C22, C45, C66D and CT90 (EN: 10083-2 1991, 10016-2 1994 and Euronorm 96-79) were used. The plasma

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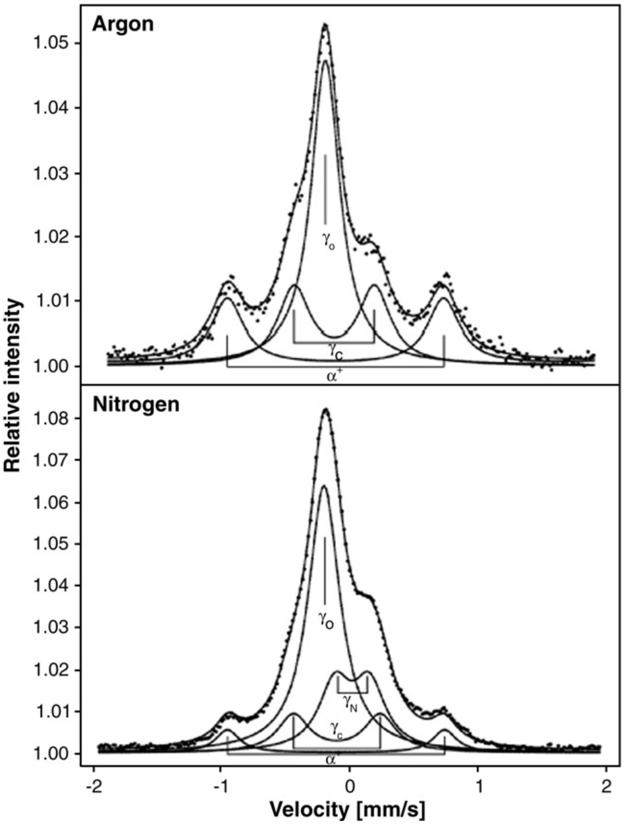

Fig. 1. CEMS spectra with fitted identified phases for steel C66D modified with intense pulsed plasma beams.

pulses were generated in a rod plasma injector [13]. The samples were irradiated with five intense (about 5 J/cm^2) but short (μs range) plasma pulses. Two kinds of plasma pulses were used to compare the effects of thermal process (argon) and supplied reactive gas (nitrogen). The energy was high enough to melt the near surface layer. The cooling rate was in the range of 10^7–10^8 K/s.

The samples were characterised by the following methods: nuclear reaction analysis (NRA) $^{14}N(d,\alpha)^{12}C$, scanning electron microscopy (SEM), conversion electron Mössbauer spectroscopy (CEMS), X-ray diffraction analysis (GXRD) with grazing incidence angle between 0.5° and 2° and Amsler wear tests (PN-82H-04332).

3. Results and discussion

Of all nitrogen plasma treated samples we selected for studies (using NRA) only those in which the retained dose of nitrogen is equal to $1.2\times10^{17}\pm2\times10^{16}$ N/cm^2. SEM observations showed that the morphologies of the pulse treated samples, both Ar and N plasma, are identical. Craters and droplets are uniformly distributed over the surface, which is typical for melted and rapidly recrystalized top layers. The thickness of the modified layers (1.2–1.6 μm) is in agreement with computer simulation of heat evolution of steel samples subjected to transient energy deposition [10,11].

CEMS spectra for initial samples exhibit the Zeeman patterns typical for iron in magnetically ordered phases. After pulse irradiation the complex paramagnetic patterns arrives in the central part of the spectra. They are different for Ar and N pulses. Computer fitting based on the literature data allowed us to identify without doubt the following fcc phases: γ_0 (fcc with no interstitial nearest neighbours C, N at Fe atoms), γ_C and γ_N i.e. carbon and nitrogen expanded austenite respectively. They are shown in the spectra of Fig. 1. Combined computer fitting of the CEMS spectra taken with full and reduced velocity scale enabled us to determine the contribution of the of each identified phase: ferritic (Fe-α), martensitic (α′), austenitic (γ_0, γ_C, γ_N) and ε — Table 1. The general observation is that nitrogen is much more efficient than argon in ausenitization of carbon steel.

In Table 2 we collected the average values of the hyperfine parameters: isomeric shift — IS and quadruple splitting — QS determined in our measurements and for comparison some results taken from literature. As seen, the values of IS for γ_N and γ_C reported for Fe–N and for Fe–C in [12] are shifted more toward greater values that in our case. This is certainly caused by greater nitrogen and carbon contents: 2.5 wt.% N and 1.9 wt.% C than in our samples 0.4 wt.% N and 0.3–0.9 wt.% C. It is commonly known that the presence of solute atoms in the neighbourhood of Fe atoms leads to decrease of the charge density of s-electrons of the iron nucleus hence leading to shift IS toward the positive value more effectively for N than C. This tendency is clearly seen when comparing the IS values from Table 2. All values of QS cited in Table 2 are practically very close to each other. At first glance it seems surprising that there is no difference between QS in stainless steel, although an amount of Ni differs in the given examples by a factor of two. Nickel is known as an effective donor of free electrons, which reduce a deviation from spherical symmetry of the charge distribution at iron nuclei and hence reduce the electric field gradient. However, one should keep in mind that Ni starts to be very effective only at aconcentration above 15 wt.% Ni [5,12], so perhaps concentrations on the level 4–2 wt.% Ni are not sufficient to influence noticeably the QS parameter.

Table 1
Content of phases (vol.%) identified in the surface layer of initial and modified carbon steels

Material		Argon				Nitrogen				
Steel	%C	α-Fe	α'	γ_0	γ_C	α-Fe	γ_0	γ_C	γ_N	ε-Fe$_3$N
Armco	0.018	100				68.04	11.85	1.35	11.06	7.71
C22	0.28	78.1	12.58	6.22	3.1	35.24	33.5	11.39	14.99	4.87
C45	0.52	71.33	13.19	10.56	4.91	27.76	39.12	8.87	20.34	3.91
C66D	0.63	54.48	10.22	22.89	12.41	27.01	35.23	10.54	17.85	9.37
CT90	0.93	47.91	6.61	27.83	17.65	26.6	36.73	17.25	13.67	5.64