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Influence of pre-existing martensite on the wear resistance of metastable austenitic stainless steels

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ABSTRACT

The effect of pre-existing martensite on the sliding wear behavior of a commercial metastable austenitic stainless steel was investigated. Two different steel conditions were considered: annealed (with a fully austenitic microstructure) and cold rolled, consisting of mixtures of austenite and martensite. Wear tests were carried out using ball on disc technique at constant velocity and different sliding distances. Correlation between microstructure and wear mechanisms was performed by X-ray diffraction, electron back-scattered diffraction and focus ion beam. Results show that wear resistance decreases at increasing the amount of pre-existing martensite. In this sense, more strain-induced martensite developed for cold rolled samples, hardening the surface and consequently reducing wedge formation, which induced material removal from the surface. The detailed analysis of the wear track demonstrated the formation of an ultrafine-grain layer just below the surface, not only for annealed but also for cold rolled steel.

1. Introduction

Recent developments of steel manufacturers have led to the commercialization of multiphase TRIP (Transformation Induced Plasticity) steels in order to produce lightweight vehicles that reduce fuel consumption and also contaminant emissions [1]. TRIP steels present a metastable austenitic phase which transforms to martensite due to plastic deformation, either during forming or under service conditions [2]. The martensite induced by forming processes is called pre-existing martensite. This phase transformation acts as a reinforcing mechanisms which make those steels ideal materials to replace the conventional steel grades due to their excellent combination of formability, crash-absorbing capability, and also good corrosion resistance [3].

Two types of martensite may form in austenitic stainless steels: ε and α'. ε-martensite has a hcp crystallographic structure, while α' has a bcc one [4]. The typical transformation sequence can be summarized as: γ–ε–α', where the $\gamma \rightarrow \varepsilon$ transformation has been proposed for austenitic stainless steels deformed under tension, as well as by rolling [5,6]. On the other hand, the direct transformation of austenite to α'-martensite ($\gamma \rightarrow \alpha'$) has been observed too, as found elsewhere [7]. The amount of induced martensite depends on processing parameters, such as stress rate, temperature and rate of deformation [8], as well as composition [9–11]. Furthermore, plastic deformation of austenite creates the proper defect structure which acts as nucleation site for martensite formation [12]. The dislocation arrangements in the deformed austenite are strongly dependent upon the alloy chemistry, stress, strain, stress triaxiality, strain rate, initial micro-textures, slip systems, temperature of deformation and the extent of deformation-induced phase transformation [13].

Numerous investigations have shown that pre-existing martensite enhance mechanical properties [14–20]. In this sense, the higher the percentage of martensite, the higher the values of yield stress, ultimate strength, and hardness. Regarding fatigue response, there are extensive studies in the literature which demonstrated that metastable stainless steels display different behaviors depending on the testing conditions [21–25]. The presence of martensite is known to be harmful in the low cycle fatigue regime (i.e. under strain-control), while a small amount of martensite can be beneficial in the high cycle fatigue regime.

The present work was performed with the purpose of investigating the wear behavior of metastable austenitic stainless steels. Some research on this topic can be found in the literature, where several studies demonstrated that strain-induced martensite was formed during dry sliding tests [26–30]. However, no information exists about the influence of pre-existing martensite. In this sense, four different steel conditions were selected: annealed, with fully austenitic microstructure, and cold rolled up to 10%, 20% and 40% thickness reduction, with a biphasic microstructure composed by austenite and martensite phases. In order to correlate microstructural characteristics and wear mechanisms, several techniques such as X-ray diffraction, Scanning Electron Microscopy (SEM), EBSD, and Focus Ion Beam (FIB), have been used.

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2. Experimental process

The experimental material was a commercial AISI 301 LN austenitic stainless steel (corresponding to standard EN 1.4318) provided by OCAS NV, Arcelor-Mittal R&D Industry Gent (Belgium). Its chemical composition was (in wt%): Fe–0.03C–17.36Cr–7.18Ni–1.68Mn–0.23Mo–0.55Si–0.14N.

Sheets of 1.5 mm in thickness were supplied in four different conditions. The condition named AR corresponded to cold rolling, annealing and pickling. Its microstructure showed equiaxial austenitic grains (average grain size of 11.7 ± 4.1 μm), randomly oriented, with twins created during annealing treatment. The three other conditions had an additional last cold rolling step performed to achieve different percentages of pre-existing martensite. The thickness reductions were 10%, 20% and 40%, that will be referred in the present work as 10CR, 20CR and 40CR, respectively. The amount of martensite and the corresponding mechanical properties of the four steel conditions are found elsewhere [20] and also summarized in Table 1.

In order to reduce chemical and physical interactions between surfaces, a WC ball with higher hardness than the studied steel was used with a diameter that provides a wear track from it was feasible to observed wear mechanism developed during tests.

For wear tests, specimens were polished up to roughness values lower than R_a=0.7 μm, following the guidelines of ASTM G99 standard [31]. Sliding wear tests were performed using ball on disc technique in a tribometer TRM-1000 of Wazau GmbH. The ball used was of tungsten carbide in order to reduce chemical and physical interactions between surfaces and its hardness was of 1600 HV10, which is higher than that of studied steel. Ball diameter was 10 mm, size adequate to, provide a wear track which made feasible to observe wear mechanisms developed during testing. Dry sliding wear tests were carried out at a constant load of 10 N and a mean linear velocity of 0.048 m/s for all sliding distances: 100, 200, 300, 500 and 1000 m. These tests conditions were selected considering that the present work is a preliminary study of the understanding of the correlation between microstructure and wear mechanisms. For that reason, low values of load and sliding velocity were studied, while sliding distances were increased until a plateau of wear rate was achieved. Before and after each wear test, balls and specimens were ultrasonically cleaned for 15 min in acetone, subsequently dried with a pure air, and weighted in an electronic balance having a resolution of ± 0.1 mg. The wear rate was achieved by measuring the wear volume divided by the constant load applied during tests (10 N) and each particularly sliding distance. Wear volume was determined using weight loss measurements and wear track profile method. In the latter case, wear volume was determined by measuring the cross-section area of removed material at eight equidistant positions along the wear track. Moreover, wedge formation as a result of material displaced to the sides of the wear track (also known as pile-up) was also measured at the same positions.

The amount of induced-martensite as a consequence of the deformation introduced by the ball in contact with surface during wear tests was achieved by X-ray diffraction. The phase components were identified with Copper radiation (2θ from 40° to 100°) which was expected to measure the first 15–20 μm from the surface. Determination of martensite content was carried out by the method corresponding to reference intensity ratio (RIR), according to ASTM E975-03 [32]. This method allows determining the mass fractions of austenite and martensite by using Eq. (1):

$$\frac{X_{\alpha'}}{X_{\gamma}} = \frac{RIR_{\gamma}}{RIR_{\alpha'}} \times \frac{I_{\alpha',\ observed}}{I_{\gamma,\ observed}} \times \frac{I_{\gamma,\ reference}}{I_{\alpha',\ reference}} \quad (1)$$

where X_{α} and X_{γ} are the mass fractions of α'-martensite and γ-austenite, respectively; RIR_{γ} and RIR_{α} are their respective reference intensity ratios; $I_{observed}$ and $I_{reference}$ are the observed and the reference intensities [32].

EBSD scans were performed in a JSM-7001F field emission scanning electron microscope (FESEM) equipped with Channel 5 system (HKL Technology), operating at 20 kV with specimens tilted 70°.

Hardness profiles were performed on cross-section specimens in order to elucidate the strengthening of austenite in subsurface due to wear tests. Vickers hardness measurements at 0.1 kg load were carried on at the deepest zone of the wear track until the center of the sheet (0.8 mm) or at least to a constant hardness value. An array of 4 columns of indents spaced 100 μm was performed in order to get statistical signification.

The deformed microstructure on the subsurface was analyzed by a dual FIB/FESEM. A thin platinum layer was deposited on the sample prior to FIB machining in order to minimize ion beam damage. A Ga^+ ion source was used to mill the surface at a voltage of 5 kV. The final polishing of the cross-sections was made at 500 pA.

Wear tracks and the induced surface damage were examined by optical microscopy (OM), confocal laser scanning microscopy (CLSM), scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) to elucidate the wear mechanisms developed for each studied steel condition.

Table 1
Martensite content and mechanical properties for the studied steel conditions.

	% Martensite	σ_{YS} (MPa)	σ_{UTS} (MPa)	% A	HV0.1
AR	<3	360 ± 10	902 ± 15	42 ± 1	246 ± 8
10CR	9 ± 3	650 ± 14	967 ± 18	38 ± 3	290 ± 10
20CR	28 ± 7	926 ± 17	1113 ± 17	30 ± 3	400 ± 5
40CR	38 ± 5	1148 ± 16	1173 ± 19	22 ± 2	440 ± 8

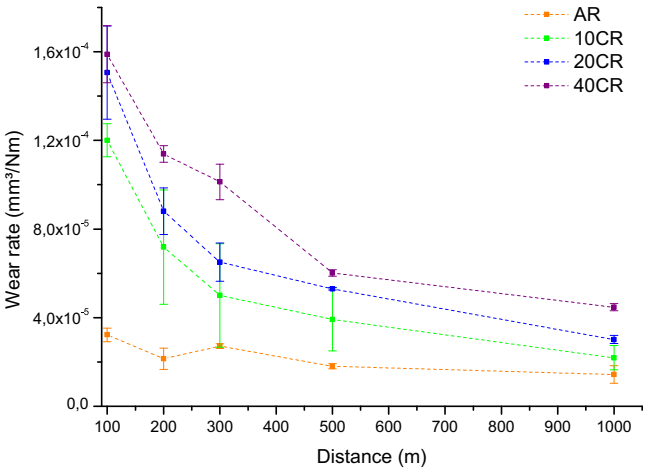

Fig. 1. Wear rate for all the studied steel conditions as a function of sliding distances.

3. Results and discussion

The wear rate as a function of the sliding distances for all studied steel conditions is given in Fig. 1. A strong influence of the amount of pre-existing martensite is clearly observed. In this regard, the higher the cold rolled thickness reduction, i.e. larger initial content of martensite, specimens displayed high wear rate. Differences between annealed and cold rolled conditions were especially relevant for the first 300 m. Even specimens with the smallest percentage of pre-existing martensite (10CR) showed, for