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Correlation between the internal friction and fracture mechanism in quenched and tempered carbon steels

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ABSTRACT

The mechanical behavior of quenched and tempered steels is analyzed by mechanical spectroscopy (internal friction), hardness measurements, Charpy impact and tensile mechanical tests. In quenched steels, the high dislocation density leads to a stress relaxation mainly based on the Snoek-Köster relaxation, and inhibits the plastic deformation, leading to a predominantly intergranular mechanism of fracture. During tempering, the martensite decomposition decreases the dislocation density and hardness. This leads to a stress relaxation based on both dislocation-enhanced Snoek and Snoek-Koster relaxations, and promotes the fracture mechanism transition from brittle to ductile. This suggests that the Snoek-Köster and dislocation-enhanced Snoek relaxations are correlated with the intergranular and ductile fracture mechanisms, respectively. Nevertheless, the tempered martensite embrittlement cannot be detected by means of internal friction since the strain rate associated to this technique is more similar to the strain rate observed in tensile mechanical test than that observed in Charpy impact test. On the other hand, the risk of embrittlement is increased when the retained austenite is thermally instable.

1. Introduction

The quenched and tempered carbon steels are widely used in engineering applications. Therefore, a better understanding of the correlation between its microstructure and mechanical properties is the main interest. In particular, more research is required on the embrittlement phenomena and interactions of dislocations with point defects such as carbon atoms and carbide precipitates [1].

In the last years, correlations between the internal friction spectrum and the microstructure of quenched and tempered steels have been established [2–4]. Three internal friction peaks have been reported above room temperature. The peak P1 that appears at 350 K is related to the Snoek effect, and takes place in ferrite or martensite with low tetragonality [2]. The peak P2 (low temperature shoulder internal friction peak of Snoek-Köster peak, LTS-SK peak) that appears at 380 K have been related to a non-thermally activated background, the precipitation of transition carbides, and the interaction between twin boundaries and interstitial carbon in solid solution [2–4]. Its amplitude is proportional to the interstitial carbon content in martensite. The peak P3 that appears at 480 K is attributed to the Snoek-Köster (SK) or Snoek-Kê-Köster (SKK) relaxations, and its amplitude is proportional to density of dislocations [2,3,5]. Nevertheless, the interpretation of these peaks is currently under analysis because the heating involved during the measurements acts as a tempering and thus several phenomena could be overlapped [2,4]. Furthermore, these peaks could be overlapped or mixed-up during measurements at high frequencies since the temperature of the thermally activated peaks (P1 and P3) is higher when the frequency is increased, while the temperature of non-thermally activated peaks (P2 or LTS-SK peak) remains constant. This could lead to misunderstanding about the nature of each peak.

On the other hand, the internal friction has not been used for the evaluation or prediction of the mechanical behavior of these steels [1–5]. In this work, the fracture mechanism transition from brittle to ductile is analyzed through the changes of the internal friction spectrum. In addition, the temper martensite embrittlement is associated to the decomposition of retained austenite in the presence of the previous austenite grains boundaries.

2. Experimental

Carbon steel samples (Table 1) were machined to 15 mm × 2.5 mm × 1 mm for microstructural characterization,

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Table 1
Chemical composition of carbon steel measured in an optical emission spectrometer.

Element	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Sn	Ti	Sb	Fe
(wt%, 10^{-2})	70.8	30.2	76.2	1.8	1.6	4.9	2.9	1.4	3.2	0.4	0.	0.9	–

internal friction and hardness measurements. Subsize specimens were used for Charpy impact test (48 mm × 10 mm × 1 mm with a notch at 45° and 2 mm of deep) and tensile mechanical test (102 mm × 10 mm × 1 mm with a width of 6.25 in the middle section).

The samples were austenitized in salt bath, and then rapidly cooled into water (quenched). After quenching, the samples were tempered in order to obtain several fracture mechanisms. As it is indicated in the Table 2, the samples were divided into four groups based on the temperature and time of austenitizing. In some results, abbreviations are used to indicate heat treatments such as Aged (tempering at 293 K for 1 year), T380K (tempering at 380 K for 10 min) and T580KH (tempering at 580 K for 20 h).

The microstructure characterization was made by Scanning Electronic Microscopy (SEM), etching the polished surfaces with 2% nital solution (2 ml HNO3+98 ml of ethanol), and by X-Ray Diffraction (XRD) measurements, scanning from 20° to 99° with a step of 0.01°, and CuKα radiation ($\lambda=1.542\times10^{-10}$ m).

The difference of angular positions, Δ(2θ), of the pair of diffraction lines is calculated with the peak positions, and used to interpolate the carbon interstitial content, x (wt%), according to the model of Hall and Winchell (Eq. (1)) [6], where h, k, l, are Miller indices, a and c are the lattice parameters (Eqs. (2) and (3), respectively). On a semi-quantitative level, the dislocation density was estimated from the carbon content in martensite (Eq. (4)), using the correlation of Morito et al. [7].

$$\frac{\Delta(2\theta)}{2} = \sin^{-1}\left(\sqrt{\frac{\lambda^2}{4}\left(\frac{h_1^2+k_1^2}{(a)^2}+\frac{l_1^2}{(c)^2}\right)}\right) - \sin^{-1}\left(\sqrt{\frac{\lambda^2}{4}\left(\frac{h_2^2+k_2^2}{(a)^2}+\frac{l_2^2}{(c)^2}\right)}\right) \quad (1)$$

$$a = (2.861 - 0.013x)10^{-10} \quad (2)$$

$$c = (2.861 + 0.116x)10^{-10} \quad (3)$$

$$\rho = (0.7 + 3.5x)10^{15}\left[m^{-2}\right] \quad (4)$$

Hardness measurements were made in a Vickers HV durometer with a charge of 1 kg, and five tests on each sample, reporting the mean value. The Charpy impact test was realized in a tensometer balanced impact with a precision of 0.025 mKg. The tensile mechanical test was made in a universal testing machine, with a strain rate of 0.5 mm/s.

Finally, internal friction was measured in a torsion pendulum by forced vibrations method at 3 Hz, in a temperature range from 290 K to 600 K with amplitude of deformation of 3×10^{-6} and heating rate 0.8 K/min. The deconvolution of peaks is made with a background exponential, and Debye functions (Eq. (5)), φ, where Δ is the relaxation amplitude, ω is the angular frequency, α is the peak broadening factor (it is equal to 1 when the peak is symmetrical), and τ is the relaxation time of the involved process [1].

$$\varphi=\Delta\frac{(\omega\tau)^\alpha}{1+\left(\omega^2\tau^2\right)^\alpha},0<\alpha\le1 \quad (5)$$

3. Results

In quenched samples, the increase of the temperature and time of austenitizing increases the carbon content in solid solution, the dislocation density in martensite and the retained austenite

Table 2
Description of heat treatments.

Group	Sample	Austenitizing temperature, K	Austenitizing time, min	Tempering temperature, K	Tempering time
G1	A1093K5	1093	5	–	–
G1	A1093K5	1093	5	293	1 year
G1	A1093K5T380K	1093	5	380	10 min
G1	A1093K5T380KH	1093	5	380	20 h
G1	A1093K5T580K	1093	5	580	10 min
G1	A1093K5T580KH	1093	5	580	20 h
G1	A1093K5T780K	1093	5	780	10 min
G2	A1093K10	1093	10	–	–
G2	A1093K10E	1093	10	293	1 year
G2	A1093K10T380K	1093	10	380	10 min
G2	A1093K10T380KH	1093	10	380	20 h
G2	A1093K10T580K	1093	10	580	10 min
G2	A1093K10T580KH	1093	10	580	20 h
G2	A1093K10T780K	1093	10	780	10 min
G3	A1173K5	1173	5	–	–
G3	A1173K5E	1173	5	293	1 year
G3	A1173K5T380K	1173	5	380	10 min
G3	A1173K5T380KH	1173	5	380	20 h
G3	A1093K5T580K	1173	5	580	10 min
G3	A1093K5T580KH	1173	5	580	20 h
G3	A1093K5T780K	1173	5	780	10 min
G4	A1173K10	1173	10	–	–
G4	A1173K10E	1173	10	293	1 year
G4	A1173K10T380K	1173	10	380	10 min
G4	A1173K10T380KH	1173	10	380	20 h
G4	A1093K10T580K	1173	10	580	10 min
G4	A1093K10T580KH	1173	10	580	20 h
G4	A1173K10T780K	1173	10	780	10 min