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Influence of Al on internal friction spectrum of Fe–18Mn–0.6C twinning-induced plasticity steel

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The temperature dependence of the damping and the dynamic elastic modulus of Fe–18%Mn–0.6%C twinning-induced plasticity steel with different Al contents were investigated by the impulse excitation internal friction technique. The modulus effect was reduced and the Néel temperature was lowered by the Al addition. The activation energy of the Finkelshtein–Rosin peak increased with Al addition. The Finkelshtein–Rosin peak became broader due to diffusional jumps of the interstitial C with different activation energies resulting from the interaction with substitutional Mn atoms.
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High Mn twinning-induced plasticity (TWIP) steel is attractive for automotive applications due to its superior combination of strength and ductility [1,2]. The stress–strain curve of TWIP steels containing solute C shows clear evidence of room temperature dynamic strain aging (DSA) [1,2]. DSA results in an increase in flow stress and stress hardening but a decrease in post-uniform elongation and a reduction of area at fracture [2]. Lee et al. [3] proposed that the DSA effect is due to the single diffusive jump of the C atom in a point defect complex in the stacking fault region. Al increases the stacking fault energy and the critical strain for the initiation of DSA and enhances the post-uniform elongation, resulting in good formability. However, the effect of Al on the diffusion of the C atom in Fe Mn Al C alloy has not yet been reported. The internal friction (IF) technique is a powerful tool to determine the activation energy of diffusion phenomena of interstitials (C, N) in alloys. It is also very sensitive to modulus changes resulting from magnetic ordering [4]. The Finkelshtein–Rosin (FR) peak, which has similarities to the well-known Snoek relaxation in body-centered cubic (bcc) metals, is observed in face-centered cubic (fcc) metals and alloys contain interstitials. Whereas the Snoek peak is due to isolated interstital atoms and the elastic dipole associated with the local tetragonal lattice distortion caused by the presence of the interstitial atom, the FR peak is due to the stress-induced reorientation of the elastic dipole of substitutional–interstitial complexes [5]. An activation energy of 1.01 eV for the FR peak in Fe–18%Mn–0.6%C TWIP steel was reported using Debye peak fitting of measurements carried out at a single frequency [3]. In the present study, a more accurate value for the activation energy of the relaxation process giving rise to the FR peak was obtained by measuring the peak temperature at different frequencies. The addition of Al was found to have a clear effect on the activation energy. The broadening of the FR peak was also observed. In addition, the modulus anomaly due to the anti ferromagnetic to paramagnetic transition was observed and the addition of Al resulted in a reduction of the modulus anomaly.

Three austenitic TWIP steels with 18%Mn, 0.6%C and x%Al (in mass%) with $x = 0$, 1.5 and 2.5, referred to as Fe18Mn0.6C–xAl in the following paragraphs, were used in the present study. The content of other alloying elements was less than 100 ppm. Hot-rolled materials were cold-rolled to 1.2 mm in thickness and recrystallization-annealed. The material preparation is discussed in detail by Chin et al. [6]. The three steels had a fully austenitic microstructure at room temperature and when tested in uniaxial tensile deformation, TWIP behavior was observed for the three steels.

The IF spectra were measured in vacuum in the free flexural vibration mode by the impulse excitation technique. A detailed description of the equipment is given elsewhere [7]. Three types of rectangular specimens (65, 80 and 105 mm in length, and 20 mm in width) were used

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Table 1. Detailed data for calculation of activation energy.

Al (mass%)	Peak1		Peak2		Peak3		Q_{act} (eV)	Q_{act} (kJ mol^{-1})
	f_{peak} (Hz)	T_{peak} (K)	f_{peak} (Hz)	T_{peak} (K)	f_{peak} (Hz)	T_{peak} (K)		
0	547	654	947	672	1630	690	1.20	115.78
1.5	533	656	913	672	1620	687	1.39	134.11
2.5	530	659	905	670	1600	681	2.03	195.86

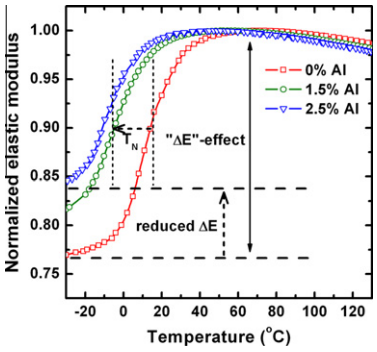

Figure 1. Modulus anomaly behavior of Fe18Mn0.6C–(0–2.5) Al alloys.

in order to obtain the three resonant frequencies listed in Table 1. The specimens were heated from −73 to 527 °C in a furnace using a heating rate of 12 °C min^{-1}. IF measurements were carried out on the as-annealed materials. The applied strain amplitude was approximately 4×10^{-5}.

Figure 1 shows the temperature dependence of the dynamic elastic modulus spectrum in the range of −30 to 130 °C. A modulus anomaly or "ΔE"-effect was observed below room temperature. The shift of the "ΔE"-effect to a lower temperature with increasing Al content is due to the lowering of the Néel temperature (T_N).

The magnetoelastic properties of anti ferromagnetic Fe–Mn Elinvar alloys have been studied extensively in the past [8,9]. Fe–Mn alloys are characterized by a pronounced modulus anomaly. The origin of this "ΔE"-effect is a spontaneous volume magnetostriction, i.e. a volume expansion caused by the anti ferromagnetic ordering when the alloy is cooled below the Néel temperature. This spontaneous expansion leads to a deviation from the normal temperature dependence of the modulus. The modulus is higher in the high-temperature paramagnetic state than in the low-temperature anti ferromagnetic state. The decrease in the modulus is due to the fact that the increase in the interatomic distances associated with the volume expansion also leads to a weaker interatomic bonding, i.e. a lower stiffness. The fundamental reason for this magnetoelastic effect lies in the fact that the interatomic distance influences the electronic structure, i.e. the density of states and the topology of the Fermi surface. The effect of the addition of non-transition elements such as Al to Fe–Mn alloys has been studied for alloys with a relatively high Mn content [10,11]. These Fe–Mn–Al ternary alloys are also anti ferromagnetic and a similar "ΔE"-effect, associated with the formation of anti ferromagnetic order below the Néel temperature, is observed.

Figure 1 shows the main effects of the Al additions on the "ΔE"-effect. It is worthwhile to review the effect of Al additions to understand the observations: Al causes (i) an increase in the stability of the austenitic phase above and below the Néel temperature [12]; (ii) an increase in the stacking fault energy [13]; (iii) an increase in the lattice parameter by 2.771×10^{-4} nmat.%$^{-1}$ Al [10]; and (iv) a change in the electronic structure of Fe–Mn alloys [14]. Using Mössbauer spectroscopy, Zhang and Zeng [14] have shown experimentally that the valence electron band of Al overlapped with the d band of the matrix and that this changed the electron distribution. Their results suggest that Al induces a localized net moment on the Fe sites and a weakening of the itinerant electron character of the Fe–Mn matrix. Recent ab initio calculations have confirmed theoretically the increase of the local magnetic moments on Fe sites resulting from the addition of Al [12]. As Fe–Mn alloys are itinerant electron anti ferromagnets [15], Al additions are expected to decrease the anti ferromagnetism of Fe–Mn alloys.

Note that the observed anomaly is clearly not associated with a structural change in the present Al-added Fe18Mn0.6C alloys: the alloys are single-phase austenitic in both the paramagnetic and the anti ferromagnetic state, and the internal twinning, on which the TWIP-effect is based, occurs only during plastic deformation. This is also verified by the absence of an IF peak associated with the "ΔE"-effect. The "ΔE"-effect is therefore brought about by changes in the electronic structure only. Figure 1 shows that the modulus anomaly is reduced and the Néel temperature is shifted to a lower temperature with increasing Al content. These observations clearly suggest that Al additions reduce the anti ferromagnetism of the Fe18Mn0.6C alloy.

As seen in Figure 1, the normalized elastic modulus is used in order to avoid the texture effect and to compare the "ΔE"-effect clearly since the samples used in this study were taken only from 90° to the rolling direction. We additionally examined the annealed texture of the Fe18Mn0.6C–xAl alloys with electron backscatter diffraction analysis and found that the texture became slightly random as the stacking fault energy decreased with reducing Al content.

The IF spectrum of the three Fe18Mn0.6C–xAl alloys showed a clear FR peak with a maximum in the

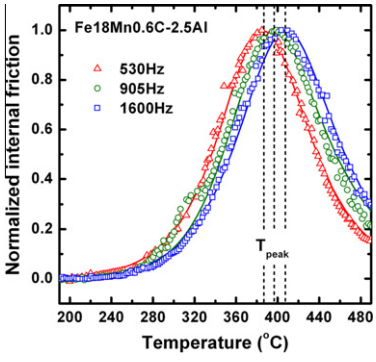

Figure 2. The FR peak shift in IF spectrum at different frequencies.

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