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The Contribution of Dislocation - Impurities Interaction to Kinetics of Martensitic Transformation of Quenched f.c.c. Fe-Ni-Mo Alloys

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Abstract. The kinetics of martensitic transformation in austenitic Fe-Ni-Mo alloys depends on the carbon content. Analysis of carbon redistribution between f.c.c. solid solution and dislocation has been carried out with the help of internal friction (amplitude and temperature effects) study and stress relaxation tests. The martensitic transformation was proved by magnetic induction and thermal differential analyses. The increase of carbon content in quenched austenitic alloys leads to the saturation of dislocation atmospheres and to the supersaturation of f.c.c. solid solution. The type of martensitic transformation (athermal or isothermal) kinetics depends on different relaxation resistance of austenite which is controlled by different dislocation pinning degree. The strong correlation between the degree of dislocation pinning, the type of martensitic transformation and the stress relaxation effect allows to make the conclusion that the dislocation mobility plays an important role in the nucleation and formation of the low temperature structure of Fe-Ni-Mo alloys.

1. INTRODUCTION

The isothermal type of martensitic transformation (MT) was established in the very beginning of 50-th by Kurdjumov and Maksimova [1,2] and studied by their co-workers [3,4] while the MT having been treated as a first-order transition in the framework of classical nucleation and growth theory. In particular, the isothermal MT kinetics was found to take place in some Fe-Ni-Mn, Fe-Ni-Cr and Fe-Ni-Mo alloys with 22-26%Ni and 2-5% of third component. The general theory for athermal and isothermal MT was developed by Roitburd in [3]. Under real conditions a phase transformation development is always accompanied by plastic deformation. Nucleation and movement of interface boundaries take place simultaneously with the generation and movement of crystal defects. The interaction of nucleating and moving martensitic interfaces with the imperfections of crystalline lattice controls the real kinetics of MT. This could significantly disguise characteristic features of MT [5]. The study of dislocation motion induced by MT was done in [6-8]. Still no one pays attention to the very simple point that the dislocation mobility and correspondingly the stress relaxation in austenite depend on the dislocation-interstitial interaction. Using the well known possibilities of the internal friction method [9,10] for dislocation-interstitials interaction study, the influence of carbon content in Fe-Ni-Mo and its redistribution on the type of MT has been taken as the subject for this paper.

2. EXPERIMENTAL PROCEDURE

Temperature (TDIF) and amplitude (ADIF) dependent internal friction (IF) measurements of Fe-Ni (Fe-28%Ni-0.018%C, Fe-31.5%Ni-0.024%C), Fe-Ni-Mo (Fe-24.5%Ni-5%Mo with 0.002-0.067 wt.% C and Fe-25.9%Ni-4.4%Mo with 0.009...0.2 wt.%C) samples after water quenching from 1150°C were carried out by means of resonance bending apparatus (kHz range) and inverted torsion pendulum (Hz range) using free-decayed and forced oscillations in the temperature range -180...600 °C and amplitude of deformation range (0.2-100)·10⁻⁵. The MT during cooling with the cooling rate 10 K/min was proved by magnetic induction and thermal differential analyses (DSC Metravib apparatus). The value of stress relaxation was tested using Instron machine starting with stress equal to ~2/3 of yield point $\sigma_{0.2}$ during 20 min. at room temperature.

3. EXPERIMENTAL RESULTS

The influence of Ni content in binary Fe-(28..32%)Ni (<0.02 wt%C) on TDIF curves and martensitic points alloys obtained by IF method is given in Fig.1 and is generalized for (28-42%Ni) in Table (set I). The increase in Ni content as well as in C content decreases the martensitic points. Nevertheless the influence of carbon content is much more complicated in ternary Fe-25wt.%Ni-5wt.%Mo alloy where iso- and athermal MT are both possible. Even the type of MT could be changed due to change in carbon content or change in heat or cold-work treatments.

Figure 1. TDIF ($f \sim 1$ Hz) of water quenched from 1150 °C austenitic alloy Fe-28%Ni (a) and Fe-31.5%Ni (b) due to cooling from room temperature (1) and following heating (2).

Figure 2. Temperature dependent IF (1), magnetic (2) and heat (3) effects curves due to cooling of quenched austenitic alloy Fe-24.5%Ni-5%Mo with 0.002 %C (a) and Fe-25.9%Ni-4.4%Mo with 0.088%C (b).

Table 1. The influence of carbon content on $tg\alpha_{ADIF}$ and martensitic points.

	Composition and heat treatment	M _{iso} , °C	M _{sat} , °C	tg α_{ADIF}
SET I.				
1	Fe-28%Ni-0,018%C, water quenching from 1150 °C	-5		0.40
2	Fe-29%Ni (0,009%C) " " "	-10		
3	Fe-31,5%Ni-0,024%C " " "		-55	0.25
4	Fe-35,8%Ni (0,012%C) " " "		< -196	0.25
5	Fe-42%Ni (0,021%C) " " "		< -196	0.26
SET II.				
1	0,002 %C, water quenching from 1150 °C	+5	-178	0,42
2	0,018 %C, " " "	-30	-137	0,37
3	0,041 %C, " " "	-60	-120	0,26
4	0,067 %C, " " "	-80	-120	0,25
5	0,069 %C, " " "	-	-118	0,25
6	0,088 %C, " " "	-	-116	0,25
SET III.				
1	0,088 %C, w/quen. from 1150 °C+annealing 350 °C, 1 h			0,44
2	0,088 %C, " " 450 °C, 1 h		-128	0,85
3	0,088 %C, " " 500 °C, 1 h		-156	0,85
4	0,088 %C, " " 550 °C, 1 h		-150	0,45
5	0,088 %C, " " 600 °C, 1 h		-125	0,56

Kinetics of MT measured by means of IF and magnetometric methods both of quenched austenitic alloys Fe-25Ni-5Mo during cooling (from room temperature to -180 °C) depends strongly on carbon content. The smooth increase of IF values ($V \approx 5$ K/min; at $T < M_s$) was observed in Fe-28%

Ni (Fig. 1a) and Fe-Ni-Mo with $C < 0.04$ wt.% (Fig. 2a). Temperatures M_s^{at} and M_s^{iso} decreases with the increase of nickel (Fe-Ni) and carbon (Fe-Ni-Mo) content (Table, sets 1 and 2). MT kinetics of quenched austenitic steels depends on mutual location of temperature ranges of iso- and athermal ranges [10]. The athermal MT takes place with the increase in Ni content up to 31.5 wt.% in binary alloys or in carbon content $C > 0.04$ wt.% (Table, sets 1 and 2). The IF peak discovered by Finkel'shtain and Rosin (FRP) on TDIF curves, background of IF and slope of $ADIF(tg\alpha_{ADIF})$ are dynamic response on interstitial atoms (IA) redistribution in alloyed austenite [9]. The FRP appears on TDIF curves of Fe-Ni-Mo ($C > 0.018$ % for Fe-24.5%Ni-5%Mo and > 0.009 %C for Fe-25.9%Ni-4.4%Mo) at ~ 250 (f ~ 2 Hz) or at 360 C (0,7 kHz) with the activation energy 136 kJ/mol from T-f shift. The height of PFR increases with the increase of carbon content in alloy; at the same time $tg\alpha_{ADIF}$ decreases and reaches minimum when $C_{cr} (\approx 0,04 \text{ \%C})$. The study of this peak in austenitic alloys is the subject of another paper reported at this Conference [11]. With the increase in carbon content the value of $tg\alpha_{ADIF}$ (Table, set 2) decreases and reaches the minimum in Fe-24.5%Ni-5%Mo at $C_{cr} \approx 0,04 \text{ \%C}$. At $C > C_{cr}$ impurity atmospheres at dislocation become saturated and the increase in carbon content leads to the Q_{FR}^{-1} peak height increase. The dislocation pinning at $C < C_{cr}$ is accompanied by the decreasing of stress relaxation effect from $\Delta\sigma = 6,3 \text{ MPa}$ (0,002 %C) to $\Delta\sigma = 4,9 \pm 0,3 \text{ MPa}$ (0,041 - 0,088 %C).

Figure 3. The influence of carbon content in austenite on the parameters of IF (a) and MT (b) in Fe-24.5%Ni-5%Mo alloy with 0.002% C

The annealing of quenched austenitic alloys leads to the new thermodynamical equilibrium between dislocations and impurities: the Cottrell-type impurity atmospheres and segregations of substitutional atoms [8] take place. That redistribution leads to the decrease in $tg\alpha_{ADIF}$ up to annealing temperature $T=450$ °C and increase at $T > 500$ °C. The similar influence of annealing was observed in Fe-24%Ni-5%Mo [7]. The correlation of change in $tg\alpha_{ADIF}$ and M_s^{at} takes place in quenched and annealed states both: the decrease in $tg\alpha_{ADIF}$ leads to increase in M_s^{at} during cooling. Plastic deformation at room temperature (8.5%) decreases M_s^{at} temperature ($\Delta T \sim 100$ K) [7]. Corresponding relaxation effect in austenite is reported in [11]. Strain ageing studied in this work leads to the decrease in $tg\alpha_{ADIF}$ and to the rise M_s^{at} .

4. DISCUSSION

The dislocations influence kinetics of martensitic nucleations appearance and growth both. At least this influence is connected with the following items: (i) the dislocations role as the nucleation sites for martensitic embryos, (ii) the stress relaxation due to dislocation motion in austenite, (iii) the peculiarity of Ni, Mo and C atoms distribution in the vicinity of dislocation core.

The thermally activated motion of easy moveable screw dislocations in f.c.c. leads to the possibility of isothermal growth of martensitic embryos in Fe-25%Ni-5%Mo and indicates the C-type curve

MT kinetics reported in [10]. On the other hand, the intrinsic properties of dislocations as well as the dislocation mobility depend strongly on a degree of dislocation pinning by interstitial and substitutional atoms. This interaction is weaker than that is in b.c.c. Fe-based alloys but could not be neglected, which is proved by the $\text{tg}\alpha$ of amplitude dependent IF curves change with the change in carbon content. From this viewpoint the results obtained allow to make a considerable distinction between two states of Fe-Ni-Mo austenite:

I). the state with saturated dislocation atmospheres by interstitial atoms (minimum $\text{tg}\alpha$ and existence of FRP, which prove the dislocation pinning and supersaturating of f.c.c. solid solution) and athermal type of MT due to cooling;

II). the state with nonsaturated dislocation atmospheres ($\text{tg}\alpha > \text{min}$), nonsaturated by interstitials austenite (the absence of FRP) and isothermal type of MT due to cooling.

Annealing of quenched samples leads to the additional dislocation pinning by substitutional atoms up to annealing temperature 500° C. The formation of interstitial and substitutional atmospheres at dislocations lead to: 1) the decrease of elastic distortions around non-screw dislocations, thus it leads to the decrease of the role which dislocations play as heterogeneous places for martensite nucleation, i.e. to the increase of energetic barrier for MT beginning; 2) the increase in carbon content at dislocations leads to the increase in Ni content in cores of both screw and non-screw dislocations [12], and correspondingly that leads to the decrease of local martensitic points; 3) the dislocation pinning leads to the decrease in its mobility, i.e. to the decrease in the stress relaxation effect, that is confirmed by direct measurements of $\Delta\sigma$ value. The dislocation pinning must increase the activation energy (Q) for dislocation motion under an applied shear stress (τ) as [6]: $Q = Q_0 - (\tau - \tau_\mu) v$, where Q_0 is the activation energy in the absence of applied stress, τ_μ is the resistance of dislocation motion which is characterized by $\text{tg}\alpha_{\text{ADIF}}$; v is the activation value. So, it is experimentally proved that the type of martensitic transformation in Fe-Ni-Mo alloys with different carbon content is controlled by the different stress resistance of austenite, which is changed due to different pinning degree of dislocations by impurities atmospheres.

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