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ON THE HOT DEFORMATION AND STATIC RECRYSTALLIZATION CHARACTERISTICS OF Al-BEARING MICROALLOYED TWIP STEELS

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Abstract

The effects of microalloying (Nb, V) and aluminum on the constitutive flow behavior and static recrystallization (SRX) characteristics of microalloyed TWIP steels (Fe-20Mn-0.6C-Al-(Nb,V)) have been investigated using hot compression testing. The effects of temperature, strain and strain rate were determined to estimate the activation energy of SRX as well as the powers of strain and strain rate. While microalloying with V up to 0.3% seems to have little effect on the SRX kinetics, 0.026%Nb significantly slowed down the SRX rate. Addition of 4.9%Al not only increased the flow stress and deformation activation energy, but also retarded the SRX kinetics in comparison to that of the steels with low Al (1.5%), with or without V.

Introduction

The yield strength (YS) of austenitic TWIP (twinning induced plasticity) steels with 16-25% Mn is relatively low, below ≈ 400 MPa. One obvious method to improve the YS is to refine the grain size. Alternatively, precipitation strengthening by microalloying can be used to increase the YS similarly as in the case of ferritic steels, but not utilized to the same extent for TWIP steels. However, in literature, research on improving the performance of high-Mn TWIP steels using microalloying is scarcer, cf. [1]. Precipitation strengthening by Nb and V in microalloyed TWIP steels was also targeted in a project funded by the Research Fund for Coal and Steel (RFCS) [2].

While the influence of chemical composition on the microstructures and mechanical properties of TWIP steels at room temperature has been extensively investigated, only insufficient information is available on the constitutive flow behavior of these steels at high temperatures, cf. [3, 4, 5]. Hamada et al. [3, 4, 6] have investigated high temperature flow stress, dynamic (DRX) and static (SRX) recrystallization behaviors of Fe-24Mn-0.10C and Fe-26Mn-3.4Al-0.14C steels. This paper presents a summary of the constitutive flow behavior and analysis of SRX kinetics of select Al-bearing Nb- or V-microalloyed TWIP steels under hot deformation conditions. SRX characteristics were evaluated and kinetics modeled using a fractional softening approach to determine the time for 50% recrystallization (t_{50}) as a function of strain, strain rate, grain size and temperature by applying double-hit compression tests in a Gleeble simulator.

Experimental Procedures

The experimental TWIP steels with controlled additions of C, Mn, Al with or without Nb or V were supplied in the hot-rolled condition by ThyssenKrupp Steel Europe AG (TKSE), Germany.

Four 0.6C-20Mn-Al-(Nb/V) steels were selected for investigation. Their codes and compositions are presented in Table I. Steel Al-Mn with 1.5%Al without microalloying is used as a reference. To understand the effect of Al on SRX rate, both low (1.5%) and high (~5%) levels of Al were studied in V-microalloyed steels (Al-Mn-V and hAl-Mn-V, respectively, Table I). VC/NbC dissolution temperatures calculated using the solubility products in [2] are included in Table I.

Table I. Compositions of the High-Mn Steels with their Precipitate Dissolution Temperatures [2]

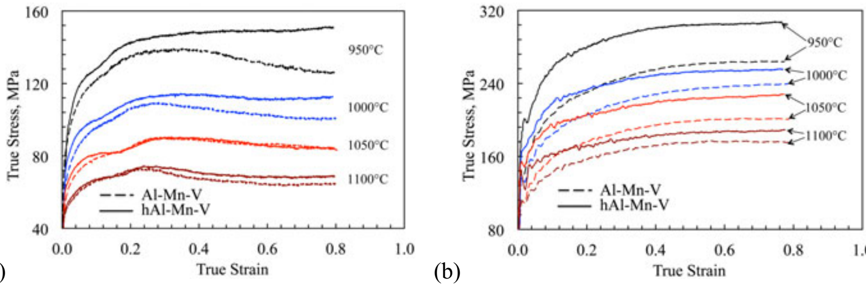
Steel Code	C	Mn	Al	V	Nb	Fe	VC/NbC Dissolution Temp., °C
Al-Mn	0.61	20.6	1.5	0	0	Bal	—
Al-Mn-Nb	0.61	20.1	1.6	0	0.026	Bal.	≈ 1180
Al-Mn-V	0.6	20	1.5	0.3	0	Bal.	≈ 965
hAl-Mn-V	0.62	20.4	4.9	0.31	0	Bal.	≈ 970

Bars of 12 x 12 mm cross section cut from the rolled plates were solution treated at 1220ºC for 10 min in order to dissolve the microalloying elements. Cylindrical specimens of φ8 x 10 mm were machined for axisymmetric hot compression testing on a Gleeble 1500 thermomechanical simulator. The specimens were reheated in vacuum at 10°C/s to 1200°C, held for 1 min, followed by cooling at 5°C/s to test temperatures in the range 950-1100°C. The specimens were then compressed to a true strain of 0.8 at a constant true strain rate in the range 0.01-5 s-1. The double-hit compression technique was employed to determine the SRX characteristics at temperatures in the range 950-1100°C and at different strains (0.125 – 0.3) and strain rates (0.01 – 5 s-1). The strain applied in the second hit was 0.2 and the inter-hit times ranged from 1 to 1000 s. In order to exclude the effect of recovery from the softening data, the flow stress at 5% total reloading strain was adopted in computing the recrystallized fraction, see [7, 8]. The average grain size following reheating at 1150°C for 2 min varied in a narrow range of 90 – 160 μm for all steels. Some specimens from each steel were reheated at 1250°C for 5 min prior to testing in order to produce coarser grain structure (240 – 430 μm) to understand the influence of grain size on SRX kinetics.

Results and Discussion

Flow Stress Behaviour

Examples of typical true stress - true strain curves obtained under various hot deformation conditions are presented in Figure 1. hAl-Mn-V with a high Al content (4.9 wt.%) displayed marginally higher flow resistance than both Al-Mn-V and Al-Mn-Nb bearing low Al content (1.5 wt.%). The strengthening effect of Al became even more significant with increasing strain rate and decreasing temperature. In agreement, Hamada et al. [3, 4, 6] reported that Al (up to 3 wt.%) increased the flow stress of high-Mn TWIP steels (14 MPa/wt.% Al). With higher Al content (>3 – 6%), the strengthening effect was found to be weak [4, 6]. Microalloying with Nb or V did not show any discernible effect on flow stress level, in accord with that observed for carbon steels, too [7]. Reyes-Calderón et al. [9] found only insignificant effect of microalloying elements (0.06Nb, 0.12V and 0.18Ti) on the hot flow behavior of high Mn TWIP steels. The activation energies of deformation (Q_{def}) estimated for the steels Al-Mn, Al-Mn-Nb, Al-Mn-V and hAl-Mn-V are 388, 402, 404 and 422 kJ/mol, respectively, as described elsewhere [10]. In agreement, Hamada et al. [4] reported Q_{def} values for ordinary Fe-25Mn-(0-6Al) TWIP steels in a narrow range 380-405 kJ/mol, revealing the positive influence Al has on the Q_{def}.



(a) (b)

Figure 1. Examples of true stress-true strain curves of Al-Mn-V and hAl-Mn-V steels obtained at various temperatures (950-1100°C) and strain rates (a) 0.01 s^{-1} and (b) 5 s^{-1}.

Static Recrystallization Kinetics

SRX kinetics have been studied using a fractional softening approach to determine t_{50} in accord with the modeling performed by Somani et al. [11, 12] using the empirical relation:

$$t_{50} = A\ \varepsilon^{p}\ \varepsilon'^{q}\ d^{s}\ \exp(Q_{app}/RT) \tag{1}$$

where A is a material constant, ε is strain, ε′ is strain rate, Q_{app} is the apparent activation energy of recrystallization, d is grain size, R is the gas constant and T is absolute temperature. The material dependent constants p, q and s describe the powers of the strain, strain rate and the grain size, respectively. The recrystallized fractions determined from the double-hit compression data using 5% total reloading strain method were then fitted with Avrami-type equations at about 50% recrystallization to enable an estimation of the SRX fraction as a function of holding time.

Effect of Temperature and Grain Size: An example of SRX fractional softening data for Al-Mn-Nb following deformation to 0.2 strain at 0.1 s^{-1} at four temperatures is presented in Figure 2. The fitting of sigmoidal Avrami-type curves was often poor for SRX fractions greater than about 70 – 80% as also noted elsewhere [8, 11]. It is evident that Nb has a significant influence on the SRX kinetics. For example, at 950°C, the SRX rate is very slow (fractional softening of ≈40% even after holding for 600 s). It is assumed that the precipitation of NbC around this temperature, further enhanced by concurrent deformation, impedes the SRX rate [13]. Data for the coarser grained sample (240 μm) reheated at 1250°C for 5 min and tested at 1050°C are also shown in Figure 2, which clearly reveals the retardation of recrystallization rate. Similarly, the SRX behavior of two V-microalloyed steels viz., Al-Mn-V and hAl-Mn-V, was characterized in the temperature range 950 – 1100°C. At 950°C, V too has a significant retarding influence on the SRX kinetics due to possible precipitation of VC. However, the SRX rate was enhanced as the temperature increased beyond 950°C (VC dissolution temperature ≈ 965°C [2]) and the SRX rate of Al-Mn-V was then comparable to that of Al-Mn suggesting only a small effect of V in solution. However, with the increased Al content of 4.9% in hAl-Mn-V, the SRX rate was further retarded.

Apparent Activation Energy of SRX (Q_{app}): The temperature dependence of SRX kinetics for all TWIP steels is shown in Figure 3. The Q_{app} values deduced from the data are ≈218, 273, 260 and 260 kJ/mol for Al-Mn, Al-Mn-Nb, Al-Mn-V and hAl-Mn-V, respectively. Earlier, a value of 257 kJ/mol was estimated for the Nb-free Fe-25Mn-1Al steel [6]. While Nb seems to have a large effect on Q_{app} (273 kJ/mol; Al-Mn-Nb), alloying with V seems to have somewhat lower effect (260 kJ/mol; Al-Mn-V and hAl-Mn-V). Despite varying Al contents in Al-Mn-V (1.5% Al) and hAl-Mn-V (4.9% Al), the Q_{app} value remains unchanged suggesting practically no effect of Al on Q_{app}. The Q_{app} values of microalloyed TWIP steels are comparable to those reported for 12Cr (265 kJ/mol) and Type 304 (283 kJ/mol) steels [14], for instance. All these values are of the same order and can be considered reasonable.

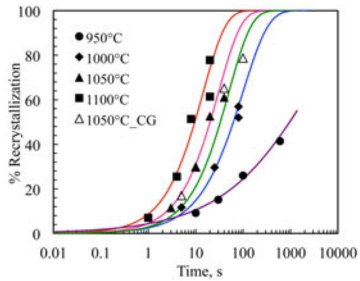


Figure 2. Recrystallization fractions fitted with Avrami-type curves for Al-Mn-Nb following deformation to 0.2 strain at 0.1 s^{-1}.

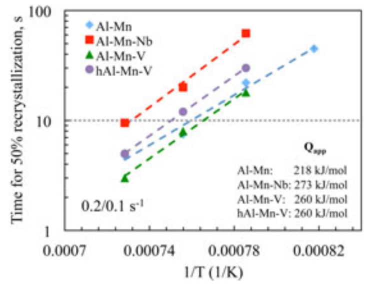


Figure 3. t_{50} times vs. the inverse absolute temperature for estimating the Q_{app} for the tested steels.

Strain and Strain Rate Exponents: The effects of strain and strain rate on t_{50} times are displayed in Figures 4 and 5, respectively. The powers of strain (p) and strain rate (q) are estimated based on the log-log plots of (i) t_{50} vs. strain at 1050°C/0.1 s^{-1} (Figure 4), and (ii) t_{50} vs. strain rate at 1050°C/0.2 strain (Figure 5), respectively. The power of strain (p) was estimated to be ≈ -3.0, irrespective of the steel type (Figure 4). Similarly, the power of strain rate (q) was estimated to vary in a narrow range -0.3 to -0.34 (Figure 5). The strain exponent values of -2.8 and -2.5 have been used for C/C-Mn/Nb/Ti/Nb-Ti and Mn-V steels, respectively [11]. Hamada et al. [6] used a value of -2.7 for Fe-25Mn-(0-6)Al TWIP steels and Karjalainen et al. [14] determined a value of -3.0 for Type 304 stainless steel. These values are in a narrow range and hence the measured estimates of -2.97 to -3.08 (Figure 4) for the present TWIP steels can be considered very reasonable. Similarly, the power of strain rate for some Fe-25Mn-(0-6)Al steels was determined to be ≈ -0.3 [6]. Karjalainen et al. [14] reported values of -0.30 and -0.33 for Type 304 and 12Cr stainless steels, respectively. In comparison, the strain rate exponents for Nb/Nb-Ti and also Mo-steels have been estimated to be ≈ -0.23 [11]. All these values indicate a weak dependence of SRX on strain rate and hence, the strain rate exponent (-0.3 to -0.34) can be considered reasonable.

Fractional Softening Equations for SRX: Taking the power of grain size (s) to be described by the following relation $s = 2.13d^{-0.105}$ proposed by Somani et al. [11, 12], as also used for Fe-25Mn-Al TWIP steels [9], together with the values for other parameters (Q_{app}, p and q) in Eq. (1)

gives the constant A for different TWIP steels. A summary of different constants (A, p, q) and activation energies (Q_{def} and Q_{app}) obtained for the four TWIP steels is presented in Table II.

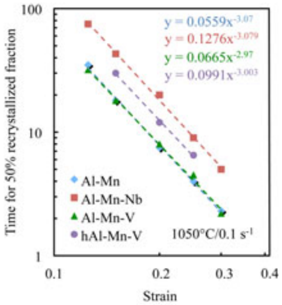


Figure 4. Plot of t_{50} vs. strain at 1050°C/ 0.1 s^{-1} for the studied steels.

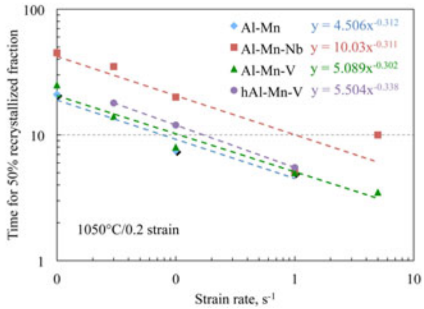


Figure 5. Plot of t_{50} vs. strain rate at 1050°C/ 0.2 strain for the studied steels.

Table II. A Summary of Various Constants and Activation Energies According to Eq. (1)

Steel code	A	p	q	Q_{def} (kJ/mol)	Q_{app} (kJ/mol)	Q_{rex} (kJ/mol)
Al-Mn	1.41×10^{-13}	-3.07	-0.312	388	218	339
Al-Mn-Nb	3.11×10^{-15}	-3.08	-0.311	402	273	398
Al-Mn-V	4.34×10^{-15}	-2.97	-0.302	404	260	382
hAl-Mn-V	5.07×10^{-15}	-3.00	-0.338	422	260	403

Activation Energy of Recrystallization (Q_{rex}): The Q_{rex} values for the present TWIP steels computed using the relation: $Q_{rex} = Q_{app} - q.Q_{def}$ are also included in Table II. As q and Q_{def} vary in a narrow range, the Q_{rex} data for microalloyed TWIP steels show a trend similar to Q_{app}.

The reliability of the fractional softening equations was further checked by carrying out a few confirmation experiments by varying experimental parameters and/or using a coarser grain size, which showed excellent agreement between the experimental and predicted t_{50} data, besides corroborating the applicability of the equation describing the power of grain size [11, 12].

Concluding Remarks

The constitutive flow and recrystallization characteristics of Nb- or V-microalloyed Al-bearing TWIP steels have been evaluated under hot deformation conditions using compression testing, including the double-hit compression technique. Microalloying additions in solution did not show any discernible effect on the flow stress, though they did increase the Q_{def}. In contrast, Al was found to increase the flow stress as well as Q_{def} of TWIP steels. The SRX kinetics was modeled using a fractional softening approach to determine t_{50} as a function of strain, strain rate, grain size and temperature. Powers of strain and strain rate varied in a narrow range and are comparable with those of austenitic stainless steels and other TWIP steels. Microalloying additions, particularly Nb, have a discernible effect on the Q_{app} and hence, Q_{rex}.

Acknowledgements

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