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Hot deformation activation energy (Q_{HW}) of austenitic Fe–22Mn–1.5Al–1.5Si–0.4C TWIP steels microalloyed with Nb, V, and Ti

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ABSTRACT

The activation energy for hot deformation (Q_{HW}) of high-Mn microalloyed TWIP steels was determined from experimental uniaxial hot compression curves. The presence of microalloying elements such as Nb, V, and Ti, increases the Q_{HW} value from 366 in the non-microalloyed one to 446 kJ/mol in the V-microalloyed TWIP steel. This change represents an increase from 16% up to 22% of Q_{HW} values.

1. Introduction

The research works about high-Mn Twinning Induced Plasticity (TWIP) steels for automotive applications has been increasing in the last few years [1–6]. The deformation twinning effect in austenitic steels has a significant role on their mechanical properties. Although the twinning effect is mainly controlled by the stacking fault energy (SFE) which is related to the chemical composition, it can be partially affected by the grain size. As well as, the yield point of these steels in the as-received condition is relatively low. Several strategies have been adopted to solve the latter problem, being the grain refinement the preferred one. The control of the grain size requires a careful design of the hot deformation parameters during processing of TWIP steels. It is well known [7,8] that temperature (T), strain (ε), and strain rate ($\dot{\varepsilon}$) are some of the most important parameters on determining the hot deformation behavior of metals in general, particularly in austenitic steels.

The hot flow behavior is usually characterized by dynamic recovery (DRV) and/or dynamic recrystallization (DRX) mechanisms. Additionally, the activation energy (Q) represents the energy level to overcome in some atomistic mechanisms such as diffusion, deformation, and so on [7]. It could be modified because solute atoms could retard these mobility mechanisms [8], particularly at low temperature. It is derived from an Arrhenius relationship, which assumes that the microstructure remains constant. Accordingly, this energy is also called "apparent activation energy" because the microstructure effect is not taken into account [9]. For some metals, the activation energy for secondary creep equals that for self-diffusion (280 kJ/mol in γ-Fe), leading to the theory that cross slipping and climb of edge dislocations are the main deformation mechanisms [7,10]. However, in case of alloys where dynamic recrystallization (DRX) takes place, it is difficult to associate the activation energy with any specific mechanism, since it is usually 20% higher than that for self-diffusion in γ-Fe and much more higher than the necessary for grain boundary migration [11]. This fact supports the previous idea that because of the grain size and the morphology change during processing at high T and $\dot{\varepsilon}$, the activation energy must be considered as "apparent" [8,9].

Nowadays, there are limited referenced data on the hot deformation parameters of TWIP steels, particularly the effect of microalloying elements on their hot flow behavior. Cabañas et al. [12] studied the influence of Mn content on the flow stress behavior at elevated temperatures with calculation of the activation energy of binary Fe–Mn alloys (up to 20 wt%) by using hot torsion tests. They reported Q_{HW} values from 230.43 to 349.96 kJ/mol, and determined that Q_{HW} is a function of the Mn content with a limited strengthening effect in the low Mn levels. Hamada et al. [13–15] studied the high-temperature flow resistance of five different high-Mn TWIP steels bearing different Al contents by compression tests, they obtained Q_{HW} values from 300 to 397 kJ/mol. Recently, Li et al. [10,16] studied the hot deformation behavior of TWIP steels bearing different Mn

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contents, obtaining Q_{HW} values from 387.84 to 405.95 kJ/mol. A well detailed compilation of Q_{HW} values for Low-C, C–Mn, C–Mn–Nb, Mn–Al and austenitic stainless steels was previously reported by Hamada et al. [13]. They found higher Q_{HW} values for high-Mn steels than for C and C–Mn steels, but lower than for austenitic stainless steels. Then, the aim of this research work is to determine the influence of microalloying elements such as Nb, V, and Ti on the hot deformation activation energy (Q_{HW}) of high-Mn austenitic TWIP steels, in order to establish the appropriate requirements on the hot deformation process. It is well known that the Zener–Hollomon parameter (Z) (also known as strain rate compensated by temperature) is extensively used in hot deformation calculations. Therefore, a good calculation of the hot working activation energy (Q_{HW}) involved in the Z parameter must be taken into account. The results of Q_{HW} in this work can be used as reference data, in order to predict the hot flow behavior of TWIP steels during hot forming operations.

2. Experimental procedure

One non-microalloyed TWIP steel (TW-NM) and other three single microalloyed with Nb (TW-Nb), V (TW-V), and Ti (TW-Ti) steels were prepared by induction melting. The accurate chemical compositions were not possible to be obtained by only one analysis technique, because of the lack of calibrated curves to identify the chemical elements included in the studied high-Mn TWIP steels. Accordingly, the C content was determined by infrared spectroscopy (IRS); Nb was determined by spark optical emission spectroscopy (S-OES); Mn, Al, Ti, and V were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES), the Si content was determined by gravimetric analysis, and the N content was determined by thermal conductivity. The results are summarized in Table 1.

Table 1
Chemical analysis of the studied TWIP steels.

TWIP steel	Elements (wt%)							
	C	Mn	Al	Si	Nb	V	Ti	N	Fe
TW-NM	0.41	21.2	1.5	1.5	–	–	–	0.012	Bal.
TW-Nb	0.40	22.4	1.6	1.4	0.06	–	–	0.015	Bal.
TW-V	0.43	22.5	1.6	1.4	–	0.12	–	0.013	Bal.
TW-Ti	0.40	22.3	1.6	1.4	–	–	0.18	0.007	Bal.

After casting, specimens were homogenized at 1200 °C for 5 h to remove segregation and hot rolled up to 60% thickness reduction, followed by solution heat treatment at 1200 °C for 1 h and then water quenched to room temperature. The resulting microstructures of solution heat treatment are shown in Fig. 1. The respective average grain sizes calculated first using the ASTM standard test intercept method and then re-calculated by image analysis software were 104 ± 23 μm for TW-NM steel, 112 ± 12 μm for TW-Nb steel, 129 ± 16 μm for TW-V steel, and 63 ± 32 μm for TW-Ti steel. These grain sizes were considered as initial or previous to hot deformation. Variations of grain sizes are produced by the different effect of each microalloying element during the solution heat treatment. Previous results [9] in medium carbon microalloyed steels indicated that the effect of grain size must be considered on the flow stress, only if it is less than approximately 30 μm. On the other hand, El-Wahabi et al. [17], established that at high test temperatures the same steady state is achieved, irrespective of the initial grain size. Only a slight retardation on the discontinuous dynamic recrystallization (DDRX) is observed at large initial grain sizes in austenitic stainless steels as a consequence of the initial grain size. Consequently, differences of initial grain sizes in the current TWIP steels will not be considered affecting the stress levels.

Uniaxial hot compression tests were performed to cylindrical samples (7.4 mm × 11.2 mm) in an Instron tensile testing

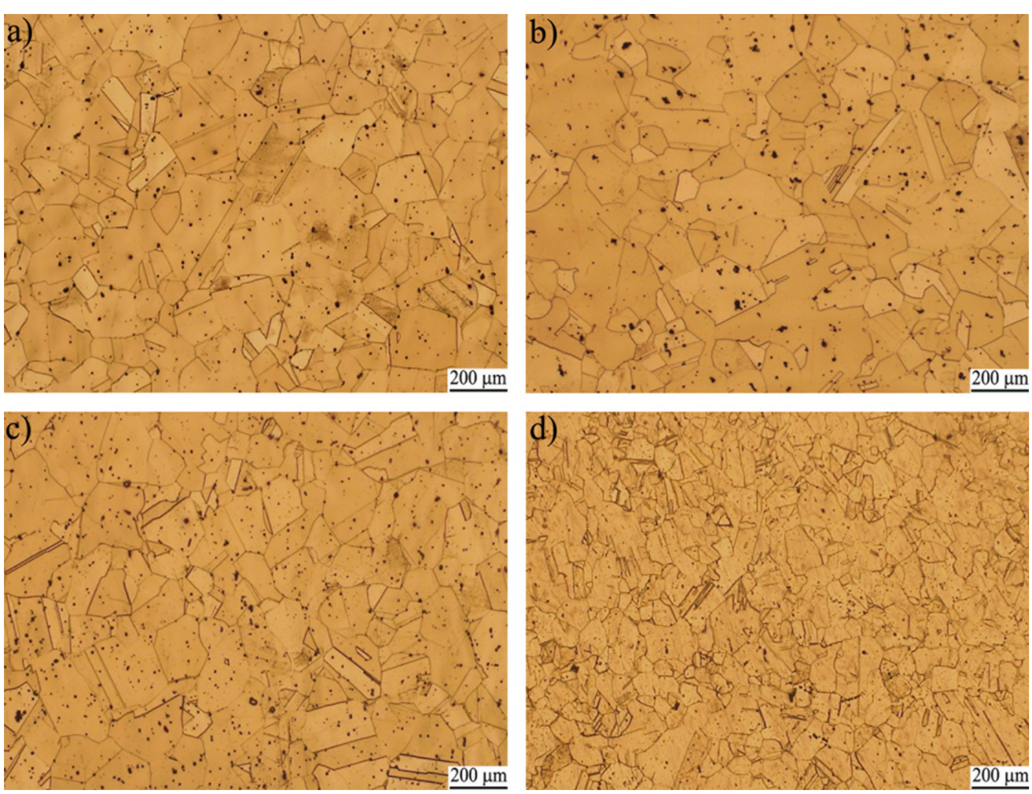

Fig. 1. Microstructures of studied TWIP steels after solution heat treatment, previous to hot compression tests: (a) TW-NM steel, (b) TW-Nb steel, (c) TW-V steel and (d) TW-Ti steel.