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Dynamic recrystallization behavior of new transformation–twinning induced plasticity steel

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ABSTRACT

The dynamic recrystallization behavior of new transformation–twinning induced plasticity steel composing of Fe–0.11C–21Mn–2.7Si–1.6Al has been studied from the numerical and experimental point of views. Accordingly, the hot compression tests have been conducted over the wide range of temperature and strain rate (100–1100 °C and 0.001–1 s^{-1}). The related stress and strain peaks, the critical stress and strain, the recrystallization volume fraction and the recrystallized grain size have been measured to quantify the recrystallization behavior of experimental alloy. Different dynamic recrystallization mechanisms including continuous, discontinuous and geometrical ones have been proposed to justify the corresponding results of various thermomechanical processing (TMP) schemes. Relying on these findings the processing maps have been also developed for more efficient development of the new materials.

1. Introduction

In recent years, new grades of advanced Fe–Mn–C austenitic steels have drawn much attention from steelmakers and downstream automotive industries due to their outstanding strength–formability balance [1–3]. The beneficial combination of the high strength and ductility mainly results from the austenite capacity to substantially work-harden up to the large strain levels [4–6]. The strain hardening is highly dictated by deformation induced structural barriers, such as mechanical twins and martensite plates (α or ε), which may obstruct the dislocations movement. The latter dominant deformation accommodation mechanisms which are mainly influenced by the amount of stacking fault energy conduct the classification of the alloys as either Transformation (TRIP) or Twinning (TWIP) Induced Plasticity or combined TRIP–TWIP ones [7–9]. As a matter of course, a significant increase of the strength and plasticity is obtained where the martensite transformation and twinning would simultaneously occur during deformation. However, if the TRIP–TWIP steels should be well developed and industrialized, their manufacturing processes would need to be optimized. Accordingly there is significant interest in the use of thermomechanical processing not only to break-up the cast structure or to shape the material, but specifically as a complementary process to refine the grain size, optimize the microstructure and reduce any inhomogeneities [10–14].

Up to date numerous investigations have been conducted to study the high temperature deformation characteristics of advanced austenitic steels to elucidate the restoration and deformation mechanisms [15–17]. The corresponding results show that the dynamic recrystallization, as the most effective restoration phenomenon, controls the microstructural evolutions under different thermomechanical conditions. In addition the size and distribution of the grain structure significantly affects the capability of the steels to work harden thereby the subsequent room temperature mechanical properties [17–19]. This may be reasoned considering the fact that the fraction of martensite plates and mechanical twins within the austenite is dictated by the initial grain size, so the prior hot-working conditions. This rational is overemphasized in the case of TRIP–TWIP steels owning to the activation of several deformation mechanisms interacting with each other during straining. The latter has been rarely considered to date, and there has been a lack of organized study on the recrystallization behavior of TRIP–TWIP steels. In this context, this project aims to positively impact enhancing the utilization of TRIP–TWIP steels by gaining a fundamental understanding of their recrystallization behavior under the compressive deformation regimes. The present work tries to develop a proper processing map from the numerical and experimental point of view for efficient development of any new TRIP–TWIP steels.

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2. Experimental methods

2.1. Material

The experimental steel composing of Fe–0.11C–21Mn–2.70Si–1.60Al–0.01Nb–0.01Ti–0.10Cr (in wt%) was received in as electro-slag remelted (ESRed) condition. The ESRed ingots were first homogenized at 1180 °C for 8 h to remove any possible elemental segregation, and then the homogenized material was subjected to 5 passes hot rolling scheme. The hot rolling cycles were carried out in the temperature range of 1100–1200 °C under the strain rate of 5 s^{-1}. The corresponding microstructure of the as-hot rolled steel is illustrated in Fig. 1. The microstructure is composed of equiaxed austenite grains with a mean grain size of 40 ± 5 μm and a large number of annealing twins.

2.2. Hot compression tests

The cylindrical compression specimens were machined directly from hot-rolled plates holding the dimension of $\Phi 8 \times H12$ with their longitudinal axes parallel to the rolling direction. In order to specify the proper range of the hot working conditions, the specimens were first compressed down to the strain of 0.7 in the temperature range of 25–1000 °C holding intervals of 100 °C under the strain rate of 0.01 s^{-1}. Considering the results of preliminary tests, the experiments were then conducted at 800, 900, 1000, and 1100 °C under the strain rates of 0.001, 0.01, 0.1 and 1 s^{-1} where the dynamic recrystallization might operate as the main restoration mechanism. A Gotech AI-7000 universal testing machine coupled with a programmable resistance furnace was utilized to perform the hot compression tests (according to ASTM E209 standard [20]). Prior to any tests, the specimens were soaked at the deformation temperature for 5 min to equilibrate the temperature throughout the specimens. To investigate the microstructure prior to straining, one heat treated specimen (soaked for 5 min in compression test temperature) was subjected to water quenched at each temperature. The specimens were then hot compressed up to a strain of 0.7 followed by immediate quenching in water right after straining in order to remain the deformed microstructural features. The variation of load was recorded using a high accuracy load cell (Model: SSM-DJM-20kN) with the capability of measuring the load forces down to 0.1 kg.

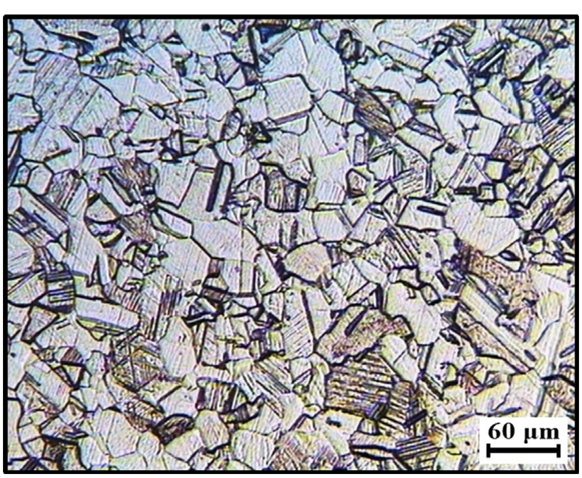

Fig. 1. The optical microstructure of the hot rolled TRIP/TWIP steel.

2.3. Characterization methods

The generated microstructures were examined through optical microscopy, for which the deformed specimens were cut longitudinally, ground, electro-polished and then electro-etched in 65% nitric acid solution to prevent the martensite formation during mechanical polishing. In order to investigate the occurrence of TRIP effects, the volume fraction of martensite phase was measured by means of a magneto-inductive device, Feritscope model FMP30 (FISCHER). The quantitative metallographic methods were conducted using proper image-analyzing software to measure the grain size and dynamically recrystallized fraction of the developed structures. For deeper investigations, the electron back scattered diffraction examination was performed through a Zeiss Ultra Plus scanning electron microscope equipped with an Oxford Instruments Nordlys Nano EBSD. The acceleration voltage applied was 15 kV. The EBSD pattern was acquired and evaluated using Oxford Instruments AZtec software package.

3. Results and discussion

The stacking fault energy is known to be the main factor in driving the different plasticity mechanisms (twinning, martensite transformation or dislocation glide) during deformation of steels (see Table 1 [1]). As is well established the plasticity is governed by SFE values in the following discipline: (i) the slipping and martensitic transformation (≤ 18 mJ/m^2), (ii) the mechanical twinning and partial dislocation slipping (18–60 mJ/m^2), and (iii) the perfect dislocations slipping (60–85 mJ/m^2) [1]. It is worth noting that the aforementioned chemical composition lies well in a range of stacking fault energy that twinning/transformation induced plasticity effects may coexist near to the room temperature [6,21,22]. However, the magnitude of SFE is increased by deformation temperature (as is shown in Fig. 2), so the share of TWIP or TRIP mechanism diminishes and dislocation slip becomes the main deformation mechanism. It is interesting to note that the slope clearly changes as the temperature increases. Furthermore, the region III corresponds to the condition

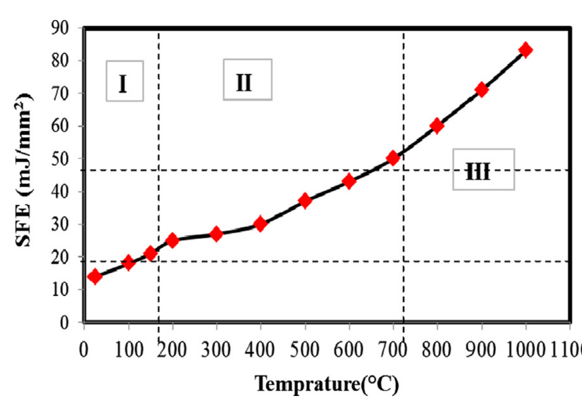

Fig. 2. The effect of deformation temperature on stacking fault energy values of the experimental steel (Grassel model [1] was employed to calculate the SFE values for the current testing temperatures).

Table 1
The effect of SFE values on the dominant deformation mechanism in TRIP/TWIP steels [1].

SFE	18 mJ/m^2 ≤	18–22 mJ/m^2	22–38 mJ/m^2	38–60 mJ/m^2	85 mJ/m^2–60
Deformation mechanism	ε-Martensite	ε+Twinning	Twinning	Twinning and partial dislocation	Slip