An Investigation on Full Annealing Temperature and Annealing Twins' Density in Fe-33Mn-3Si-2Al High-Manganese Steel

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ABSTRACT

Twinning induced plasticity (TWIP) steels with high manganese percentage (17-35%), are mostly used in automotive bodies. Their microstructure at room temperature is austenitic, anddue to the low stacking fault energy, major deformation mechanism in them is twinning inside austenite grainswhich leads to enhanced mechanical strength in the steel. Due tothe important effect of heat treatment process on mechanical properties, full annealing heat treatment and resultant twins were investigated in this study.To this aim, the steel was casted, hot rolled, and then heat treated at different times and temperatures and the obtained microstructures were analyzed using optical microscope. The results showed that the percentage of annealing twinsis increased with increasing annealing temperature up to 1100 °C, the peak point at which grain growth stage starts,and increasing temperature above that decreases twins' percentage. A relation between grain size and annealing twins' percentage was found. Full annealing temperature for this steel was determined to be 1100 °C.

Introduction

TWIP steels are high manganese steels (Mn: 17-35%) withausteniticmicrostructure even at room temperature. Due to low stacking fault energy (SFE) of these steels which makes slip to be more difficult, twinning of grains is the governing deformation mechanism. Creation and the volume of twins depend on the applied strain on the steel, and ahigherstrain will lead to a finer microstructure. Twin boundaries act like grain boundaries which causes the steel to have more strength [1].

Heat treatments, especially annealing treatment, have a significant effect on the rate of forming fine grains in TWIP steels. Nowadays, annealing treatment and resultant twinning as well as the influence of annealing twins on the strength of steels have attracted many researchers attention. Although the presence of coherent interfaces including twin boundaries inside polycrystal materials has a significant influence on mechanical properties of metals and alloys, there have not been enough qualitative studies on the impacts of twin boundaries on the mechanical properties of steels [2].

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Various models are presented regarding the formation of annealing twins. Most of the accepted models assume that twin coherent boundaries are formed on mobile boundaries of grains during the growth of them. There are {111} edges on grain boundaries which twins are formed on these plates due to the stacking fault of atoms during grain growth and motion of grain boundaries [3,4].

Twins may be formed during recovery and recrystallization processes or during growth of recrystallized grains [5,6]. Some important factors affect the rate of twins formation during grain growth including: rate of deformation before annealing, temperature and time of annealing heat treatment, grain size, energy of grain boundaries, migration velocity of grain boundaries, SFE, texture of grains and impurities [4].

The obtained results from studies on strain hardening regime and the development of microstructure during high strain rate compressive deformations of pure titanium revealed that after applying small strains, there is a sudden increase in the rate of strain hardening, as soon as mechanical twins are formed. Also, applying these results to Hall-Petch equation revealed that twin boundaries have caused grain size to be small [7]. So, it is expected that annealing twins have a significant influence on mechanical properties of materials following Hall-Petch equation [8]. Estimations of the slip of dislocations and twin boundaries, in both annealing and mechanical twins, revealed that these coherent boundaries have a strength high enough to stop the slip of dislocations. Although dislocations can pass through twin boundaries via dissociation, this is energetically undesirable as it needs 33% more energy level. Supplying this energy requires applying stress by locked displacements. For this reason, twins act like an obstacle against the movement of dislocations and most probably, they have a significant influence on yield stress of materials [9].

In this paper, variations of twins' percentage versus temperature and also, its relation to grain size in TWIP steel were investigated.

Table 1. Chemical composition of the investigated steel. (wt%)

C	Mn	Si	Al	S	Fe
0.13	32.9	3.0	2.0	<0.006	Ball

Experimental procedure

The chemical composition of the steel used in this study is shown in **Table 1**. The steel was cast in an inductive furnace under protected atmosphere. Then, it was normalized at 1200°C for 1 h in order to remove alloy elements,

especially manganese from grain boundaries. After that, it was hot rolled by 5 continuous passes with finishing temperature of 900°C and real strain of 70%; following by air cooling. In order to determine optimum annealing temperature, samples were cut out of the steel surface with the grain size of 160μm, and heat treated for 10, 30, 45 and 60 min. at temperatures ranging from 550to 1200°C and air cooled.

Rockwell Hardness was measured at 5 different points, and the average value was reported. A routine metallography sample preparation procedure, i.e. grinding, polishing and etching with Nital reagent was used in order to study microstructure of the steel. The prepared samples were studied using optical microscope (Olympus CK40M) and Grain size was determined according to ASTM E112 standard using Jefree's method. More over, to calculate the percentage of annealing twins in the microstructure, twins counting method and twins' area calculation were employed [10]. In this method, a 10×10 mm transparent checkered screen is placed on images which were magnified 150 times. The ratio of cells covering twins to total area of cells shows the percentage of twins in microstructure. 10 images from each sample at different temperatures were captured randomly and finally, the results of 10 images were averaged. In order to calculate the area of annealing twins, Image Tools software was used. Since the two methods had the same results i.e. in both methods maximum annealing twins were obtained at 1100°C, only the area calculations of annealing twins will be presented in the rest of this paper.

Results and Discussion

Annealing treatment cycles applied on the samples are shown in **Fig. 1**. As the steel has high manganese content, and its structure remains austenitic even at room temperature, it can be cooled in air [11]. Cooling it in furnace will lead to excessive growth of grains.

Captured images by optical microscope after 10 min. of sample holding at different annealing temperatures are shown in **Fig. 2** (The structures of steel in other holding times are the same as those of the 10 min.). As can be seen, recrystallization of grains was initiated at 550°C by nucleation. With increasing the annealing temperature, the surface area of recrystallized grains is increased. From the starting point of annealing treatment, the presence of twins which have been formed during hot rolling procedure [12,13], can be observed. It seems that in all time cycles, the recrystallization process is completed when annealing temperature rises up to 1100°C. Beyond this temperature, more grains grow [14]. With increasing the rate of recrystallization, the numbers of annealing twins is increased, so that a maximum number of twins are formed at 1100°C after 10 min. (**Fig. 3**).

Studies have revealed that the maximum annealing twins are formed at full annealing temperature [14,15,16]. Variations of the surface percentage of annealing twins and average grain size of the samples with annealing temperature are shown in **Fig. 4**.

It can be seen from **Fig. 3** and **4** that regardless of annealing times, as temperature rises up to 1100°C, the average size of grains is decreased and the percentage of annealing twins is increased. This happens due to recrystallization phenomenon which decreases the area of larger grains and increases the number and area of finer grains.

According to Grindraux et al. [14], the formation of annealing twins is basically a typical state in recrystallization process, whilein grain growth process, these twins aredisappeared and the formation of new twins isalmost impossible.

Mi et al [17], believes that as long as recrystallization process is not completed,

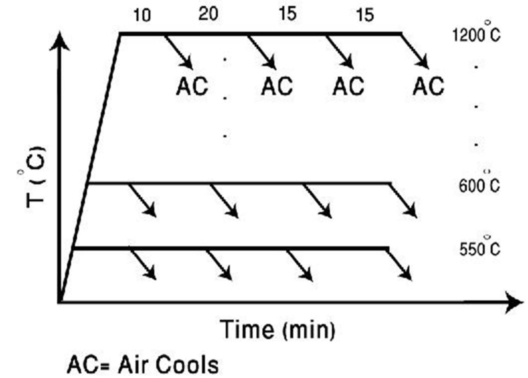

Fig. 1. Fullannealingheat treatingcyclesin the present work.

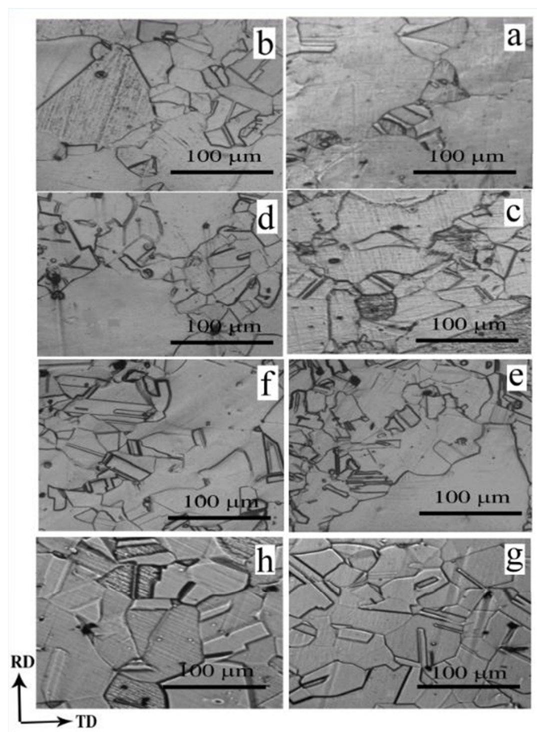

Fig. 2. Optical micrographofsamplesannealed for 10min at: a) 550, b) 600, c) 700, d) 800, e) 900, f)1000, g)1100, h)1200°C.

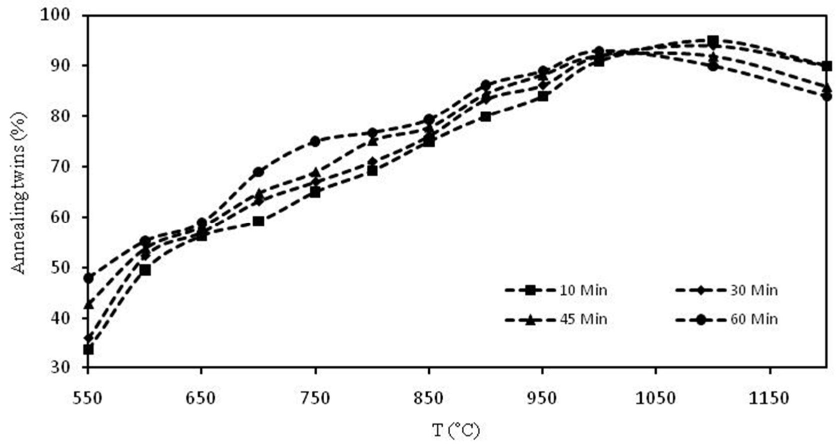

Fig. 3. Variations of annealing twins area percentage by annealing temperature at different annealing times.

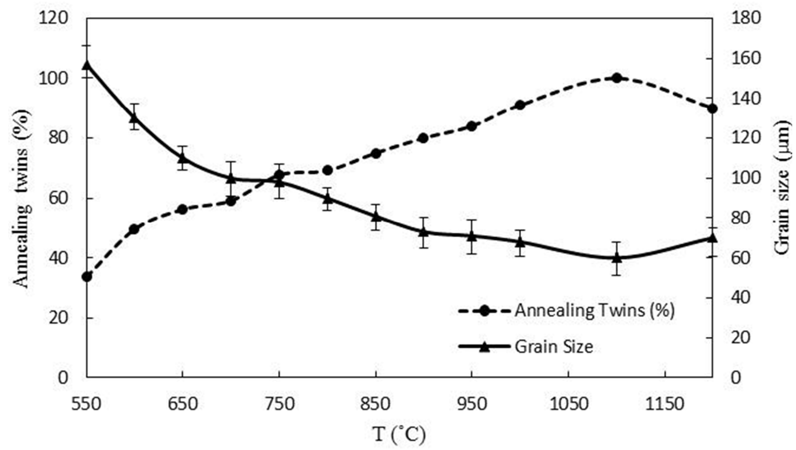

Fig. 4. Variations of grain size and annealing twins area percentage by annealing temperature.

twins will be fewer, and the size of annealing twins will be smaller. In other words, as recrystallization procedure proceeds, the size and number of twins are increased.

Variations of grain size and percentage of twins at 1100°C versus different time cycles are shown in **Fig. 5**. It can be seen that with increasing the annealing time, the growth rate of grains is increased and the percentage of annealing twins is decreased. As twins just grow in growth stage and no new twin is formed, [5,6] it could be said that with increasing holding time, steel enters to growth stage. Since during annealing treatment, the finest and most homogenous structure is formed at full annealing treatment temperature [5,14,17], it can be concluded that

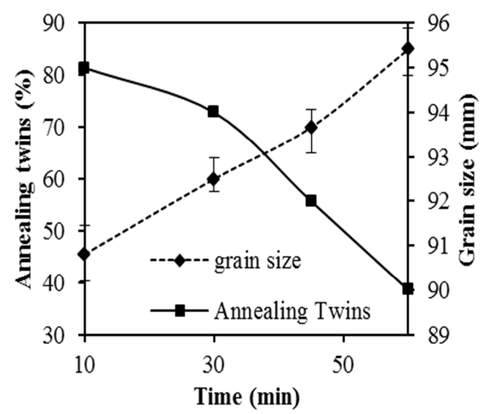

Fig. 5. Variations ofgrain size and annealing twins area percentagevs. timein the specimen annealedat 1100°C

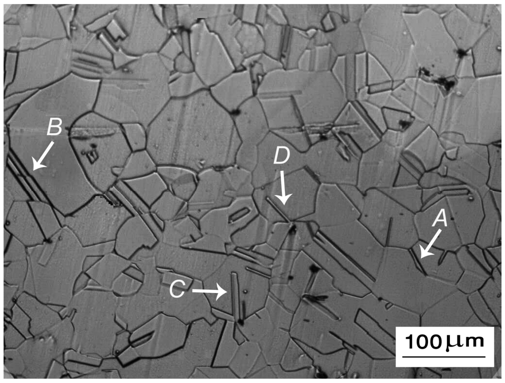

Fig.6. Various types of annealing twins observed in the specimen annealed at 1100 °C.

in this sample, steel full annealing treatment condition is met at 1100°C and 10 min.

The microstructure of the sample annealed at 1100°C is shown in **Fig. 6**. Symbols A to D stand for four different morphologiesobserved in annealing twins. A stands for corner twins, B for a special kind of twins connecting two sides of grain, C for another kind of twins which is limited inside the grain, and D for another kind of twins which is restricted inside the grain, but it is inclined towards grain boundary. The type A is the dominant twin formed in the microstructure. Based on different studies, this kind of twin requires less energy for growing than others, so it creates a bend in grain boundary which is concave towards a grain containing a twin. Therefore, the grain boundary moves towards the twin. It is stated that annealing twins can be formed in every stage of {111} edges transition during growing of grain boundaries. Therefore, an individual edge can create annealing twins with different thicknesses in different regions on grain boundaries, as well as dissipated twins inside grains.

From thermodynamic point of view, the free energy of grain is increased in the presence of twins which leads to instability of the grains. The instable grains become smaller during annealing treatment. This causes the migration of grain boundaries to be directional [18]. Based on this phenomenon, it can be said that during grain growth process, the presence of twins affects the migration

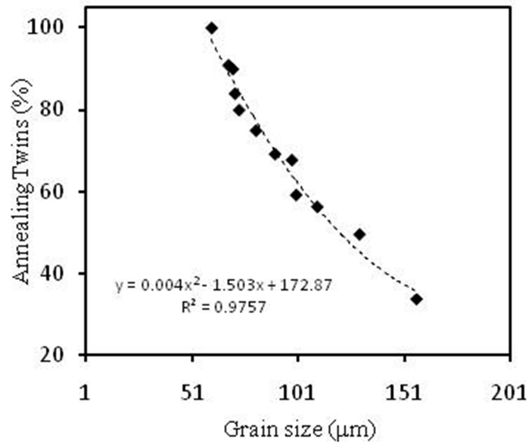

Fig. 7. The dependence of annealing twins percentage on Average grain size.

direction of boundariesas well as curvature of the grain boundaries [18].

Variation of area percentage of twins versus average grain size at each temperature during 10 min. of annealing treatment is shown in **Fig.7**. It can be seen that the percentage of twins is increased with increasing the grain size. These results are a direct illustration of the curves shown in **Fig. 4**. It can be observed that a second order relation may be applied to the curve. It seems that decreasing the size of grains will lead to a decrease in the migration range of boundaries, which in turn, will decrease the possibility of acting {111} edges as Shockly dislocation generator [4]. On the other hand, the smaller the radius of the grain boundary, the more the number of edges on it [4]. Thus, increasing grainsize and decreasing the grain's radius will lead to a decrease in the driving force and also, the number of edges on grain boundaries, which in turn, will decrease the number of twins [19].

Conclusions

In this study, full annealing conditions of a TWIP steel with the composition of Fe-33 Mn-3Si-2Al was determined through applying various annealing conditions. Also, the relation between the density of twins and grain size was specified. Considering full recrystallization and homogenous microstructure, full annealing conditions were determined to be reached at 1100°C-10 min. heat treatment. Under these conditions, the observed twins were completely annealing ones. The area percentage of annealing twins is a function of grain size, so that with increasing the grain size, the density of twins is decreased.

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