Nucleation and Growth Kinetics in Cold Rolled and Annealed TWIP Steel

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Abstract
The nucleation of strain free grains and their growth at the expense of the deformed matrix are the key features of the microstructure evaluation during recrystallization. The aim of present work is to study the kinetics of isothermal recrystallization of a TWIP steel (C=0.35%, Mn-22.8%, Al-1.7%, Si-0.2%) after cold rolling. The steel was forged and cold rolled and then annealed at 700°C with soaking times ranging from 60s to 1800s. A JMAK based model was applied to describe nucleation and growth process. Complete recrystallization was observed after 900s at 700°C. It was found that with increasing annealing time, recrystallized fraction increases while nucleation and growth rate decreases which is in agreement with the results available for high Manganese steel.

Keywords
Cold Rolling, Annealing, Recrystallization, Nucleation and Growth

I. Introduction

The twinning Induced Plasticity (TWIP) steel is a promising material to meet the demand mainly from automobile industry, which requires high strength, high ductility and low specific weight and that will leads
to weight reduction, fuel economy, reduced CO_2 emissions and increased passengers safety [1].
Steels with Mn content (15-30wt%) and alloying elements C (≤0.6wt%), Al(0-3 wt%) and Si(0-3%) [1-2] posses high strength and excellent formability [3,4] due to the formation of extensive deformation twins under mechanical load which act as additional barriers to the movement of dislocations during plastic deformation, increasing the work hardening rate.
The TWIP effect occurs in stable austenite, where the Gibbs free energy of the martensitic reaction is positive (from 110 J/mol to 250 J/mol) and the stacking fault energy is relatively low (SFE≤30 mJ/m2). The increase in both energies is due to the high Mn content and the presence of Al. The high work hardening rate, the disorientation between grains and the formation of subgrains by the twins also speed up the recrystallization of high Mn steels [5, 6]. The nucleation of strain-free grains and their growth at the expense of the deformed matrix are the key points of the microstructure evolution during recrystallization.
The objective of this work is to complement an earlier study [7], providing an analysis of the recrystallization kinetics of a 20% Mn TWIP steel. The recrystallization kinetics is usually expressed by the JMAK (Johnson-Mehl-Avrami-Kolmogorov) model relates the recrystallized fraction (X_v) with the recrystallization time (t) [8]:

$$X_v = 1-\exp(-Bt^k) \quad (1)$$

This general equation is suitable for random nucleation and isotropic grain growth. The constant B depends on the material and the annealing temperatures while the exponent k depends on the type of nucleation and the growth dimension. Assuming three-dimensional growth, the theory predicts k = 3 for nucleation by saturation of sites and k = 4 for constant nucleation rate [8-9]. JMAK equation remains valid if 2 < k < 3 (two-dimensional growth) and 1 < k < 2 (one-dimensional growth). The case of k = 1 is equivalent to a homogeneous first-order reaction [9]. There are several investigations of materials like aluminum, copper and some steel for which k values of about 1 have been found [8, 10].
The volume fraction recrystallized (X_{vex}) and the interfacial area per unit volume (S_{vex}) in the extended volume can be defined as follows [11]:

$$X_{vex} = \ln\left(\frac{1}{1-X_v}\right) \quad (2)$$

$$S_{vex} = \frac{S_v}{1-X_v} \quad (3)$$

The interfacial area between recrystallized and deformed zones per unit volume is given by S_v = 2/D, where D is the average diameter of recrystallized grains [11-12]. Substitution of Eq. (2) into Eq. (1) yields $X_{vex} = Bt^k$, and a similar expression can be written for S_{vex} ($S_{vex} = Ct^m$).
Growth rates are determined by the method introduced by Cahn and Hagel which estimated an average interface migration rate using stereological parameters [11]:

$$\bar{G} = \frac{1}{S_v} \cdot \frac{dX_v}{dt} \quad (4)$$

Differentiation of Eq. (1) and substitution into Eq. (4) gives:

$$\bar{G} = \frac{B}{C} \cdot k . t^{(k-m-1)} \quad (5)$$

The nucleation rate for each annealing time
was evaluated based on the following equations, respectively related to the area and volume [11]:

$$\dot{N}(t) = \frac{4C}{K_v . P^3} \cdot \left[\frac{\Gamma(m+1)}{\Gamma(2k-2m+1).\Gamma(3m-2k)}\right] . t^{3m-2k-1} \quad (6)$$

$$\dot{N}(t) = \frac{8B}{K_v . P^3} \cdot \left[\frac{\Gamma(k+1)}{\Gamma(3k-3m+1).\Gamma(3m-2k)}\right] . t^{3m-2k-1} \quad (7)$$

$$P = \frac{2B}{C} \cdot \left(\frac{k}{k-m}\right) \quad (8)$$

In these equations K_v and K_s are geometry dependent factors and Γ is the Gamma function. Since the values given by Eq. (6) or (7) include phantom grains, the real nucleation rate for each annealing time can be calculated only for the deformed grains by [11]:

$$\dot{N}(t)_{real} = \dot{N}(t).(1-X_v) \quad (9)$$

II. Experimental Procedure

The experimental steel used was melted in open casting and cast in a rectangular ingot which was 110mm x 60mm x 25 mm in size. Each ingot was 2.5 kg and chemical composition is listed in table

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1. A 25mm thick plate was cut from ingot and homogenizes at 1200ºC for 2 h than forged with 50% thickness reduction following with air colling, resulting in 5 mm thick strip. Further thick strip of 5mm was cold rolled to 2.5 mm final thickness and samples cut from it were annealed at 700°C with soaking times ranging from 60s to 1800s.

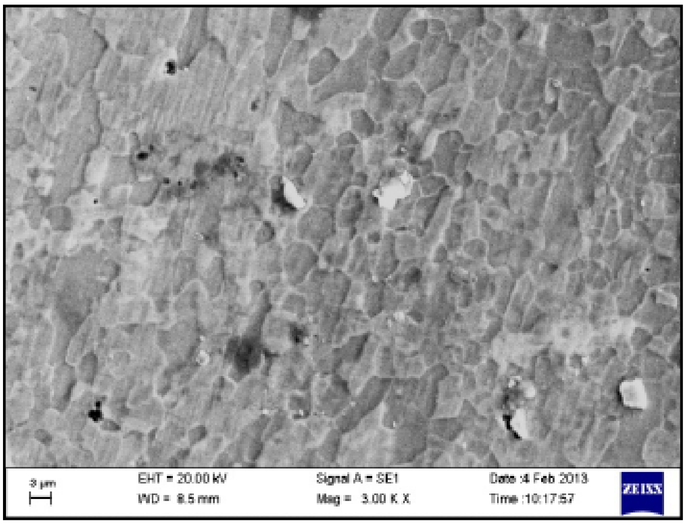
Table 1: Chemical Composition of Processed Steel

Material	C (wt %)	Mn (wt %)	Al (wt %)	Si (wt %)
Steel (S1)	0.35	22.8	1.7	0.20

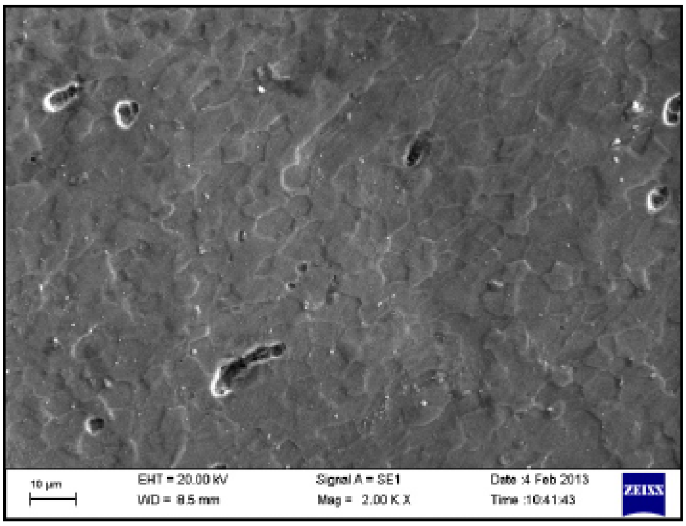
Metallographic analysis was performed on sections along the rolling direction after etching with 5% Nital. The recrystallized fraction was determined on optical micrographs by point counting while the average grain size was determined on scanning electron (SE) micrographs.

III. Results and Discussion

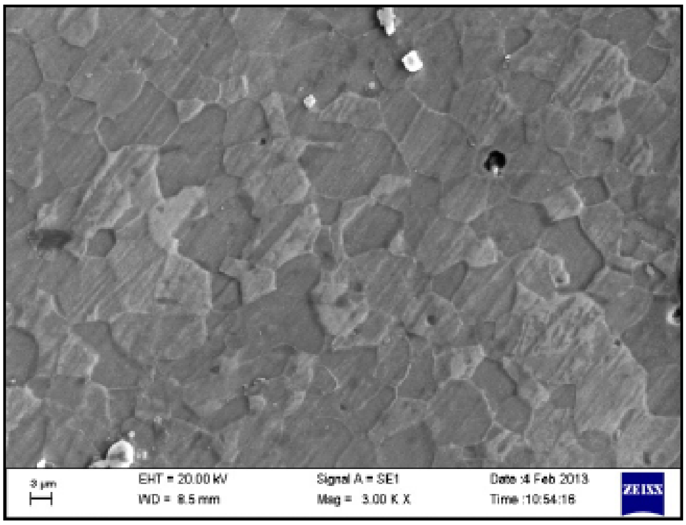
SEM micrographs of cold rolled sample for selected annealing times at 700°C are shown in Fig. 1. The experimental results of the average grain diameter and recrystallized fraction for each annealing time are shown in Fig. (1). The recrystallized fraction reaches 50% after about 300 s and the process is complete after 900 s (Fig. 1(b)), when significant grain growth is first identified in the microstructure (Fig. 1(c)).



(a)



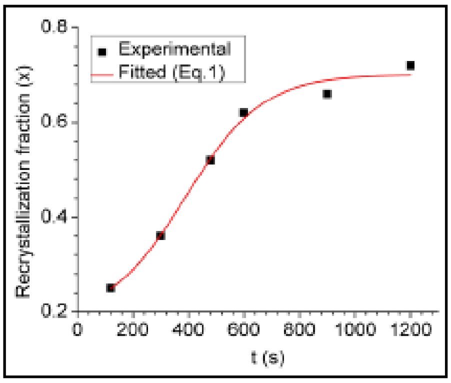
(b)



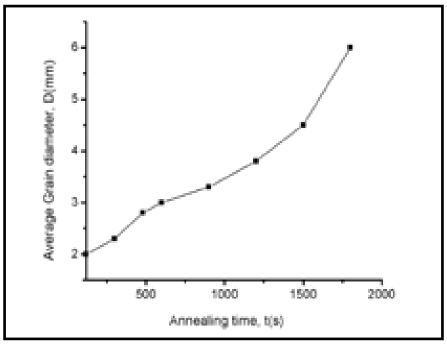
(c)

Fig. 1: Scanning Electron Micrographs of the TWIP Steel Annealed for Different Times (a) 300s (b) 900s and (c) 900s at 700°C.

The recrystallized fraction was plotted against the annealing time at 700°C (Fig. 1(a) and the data were linearized according to Eq. (1) and (2) yielding the values of k = 1.17 and B = 6.2 x 10-4. As discussed earlier, if k = 1 nucleation is homogeneous, but this condition differs from that observed experimentally. This difference may be due to the simplifying assumptions of the JMAK model, which considers only the parameters Xv and Xvex for the analysis of a complex process such as recrystallization [9, 13]. Linear analysis of Svex as a function of t (Fig. 3(b)) yielded m = 0.69 and C = 1.76 x 10-2. It is considered that the plots on Fig.2 do not include times less than 100 s where the material was still too deformed for the grain size to be measured. Also removed from Fig. 2 are the values corresponding to times longer than 1200s, where recrystallization was already complete.

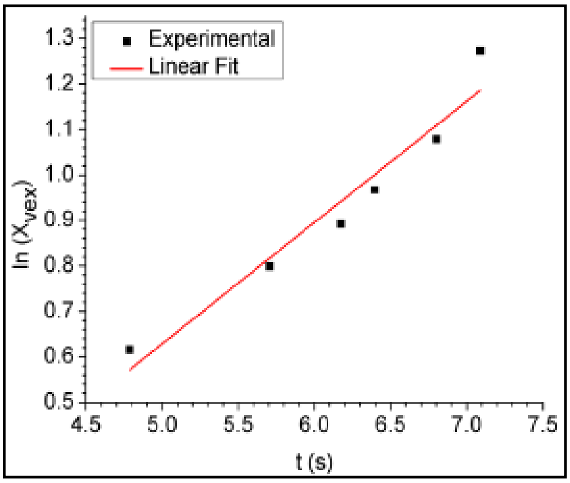


(a)

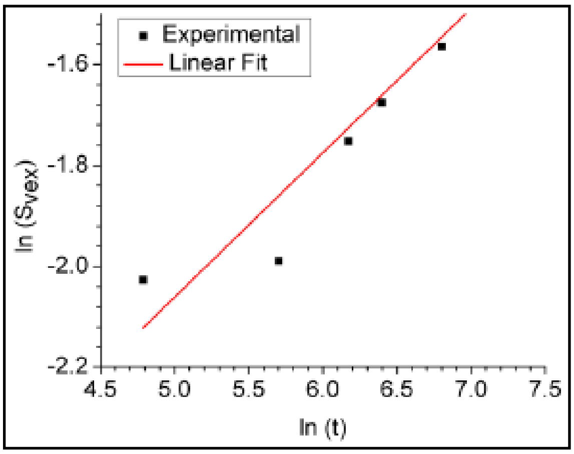


(b)

Fig. 2(a): Recrystallized Fraction and (b): Average Grain Size vs. Annealing Time at 70ºC



(a)



(b)

Fig. 3: Curves Used for Obtaining the Parameters (a) k and B and (b) m and C

After nucleation, each grain grows freely until it meets another growing core [8,13]. This so called "impingement" effect increases with the increasing recrystallized fraction, thus resulting increasing in grain growth rate with annealing times as shown in fig. 4 [6, 11]. In this figure only the data for times between 300 s and 1200 s were plotted, as in the case of fig. 3.

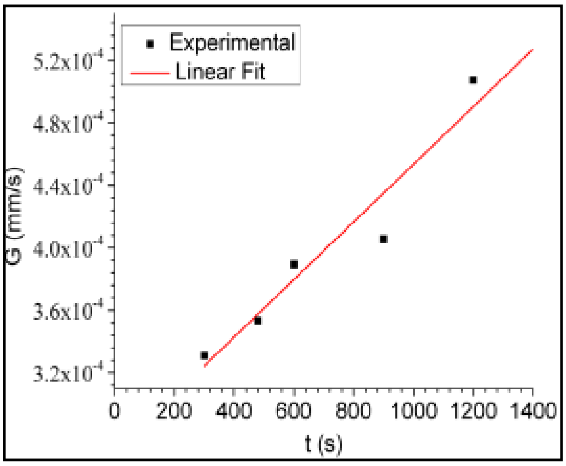
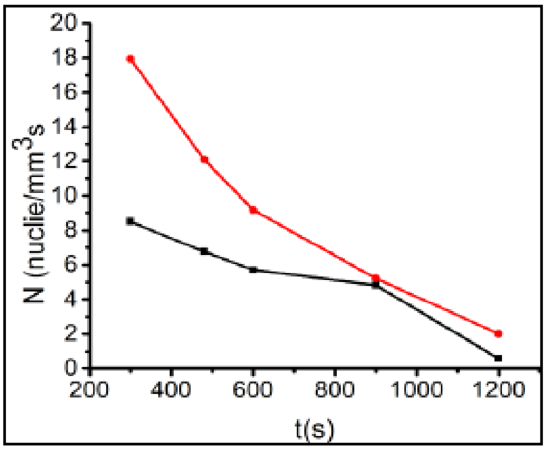
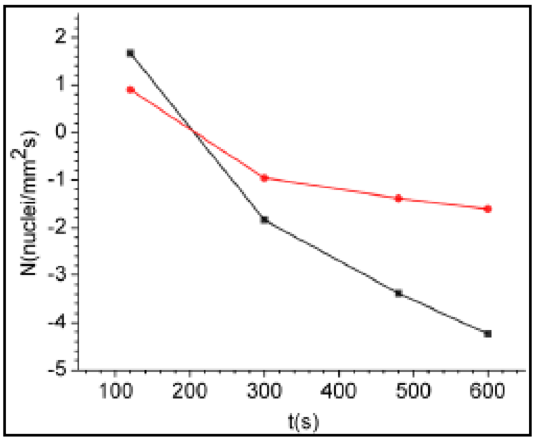


Fig. 4: Grain Growth Rate (G) as a Function of the Annealing Time (t)

The nucleation rates per unit area and unit volume for each annealing time, calculated using Eq. (6) and (7), are shown in Fig. 5 (a) and (b) respectively.



(a)



(b)

Fig. 5: Nucleation Rate Per Area (a) and Volume (b) as a Function of the Annealing Time

Also shown is the real nucleation rate calculated based on Eq. (9). It can be seen that as the annealing time increases the apparent nucleation rate decreases but the real nucleation rate decreases even faster from a certain annealing time on. As shown in fig. 6, this deviation is related to the increasingly fewer sites available for nucleation as the recrystallized fraction grows above around 50% [9, 10].

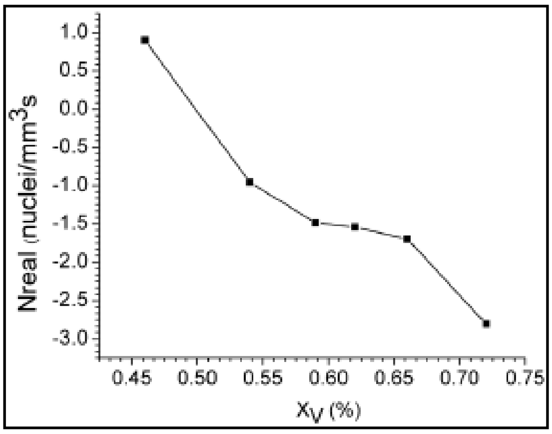


Fig. 6: Real Nucleation Rates as a Function of the Recrystallization

IV. Conclusion

Recrystallized grain sizes of 50% cold rolled sample were found to be 9μm at annealing time of 10 min. Steel studied shows recrystallization at 700°C of 62% after annealing time of 600s and was fully recrystallized by 900s.JMAK model was used as

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approach to quantify the recrystallized process of the steel.The constant of JMAK model applied to the experimental data suggest a homogeneous recrystallization, contrary to the experimental observations. It was found that nucleation and growth rates decreases with the annealing time in an agreement with the results for the medium carbon steels. These effects were associated respectively with the fewer non recrystallized sites available for nucleation and the increased impingement effect as the fraction recrystallized increases.

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