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Hall-Petch strengthening in Fe-34.5Mn-0.04C steel cold-rolled, partially recrystallized and fully recrystallized

Y.H. Wang [a,b], J.M. Kang [a], Y. Peng [b], T.S. Wang [a,*], N. Hansen [c], X. Huang [d,e,**]

[a] State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, Qinhuangdao 066004, China
[b] National Engineering Research Center for Equipment and Technology of Cold Strip Rolling, Yanshan University, Qinhuangdao 066004, China
[c] Risø Campus, Technical University of Denmark, DK-4000 Roskilde, Denmark
[d] College of Materials Science and Engineering, Chongqing University, Chongqing 400045, China
[e] Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

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ABSTRACT

An Fe-34.5Mn-0.04C steel has been processed by cold rolling and annealing to prepare samples with a lamellar structure, a recrystallized grain structure and a composite structure of layers of recovered and recrystallized structures. For the recrystallized grain structure and the lamellar structure, the flow stress has been analyzed by applying Hall-Petch formulations. For the composite structure, the rule of mixture has been applied to calculate the flow stress, revealing an extra strengthening from a constraint effect. An excellent combination of strength and ductility has been found in a composite with 10% hard lamellae in a recrystallized grain structure.
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A combination of high strength and ductility is important in the design and processing of metals and alloys for engineering applications [1–3]. Successful results have been obtained by combining in a structure of hard and soft volume elements contributing respectively to the strength and ductility of the material. Examples are a bimodal distribution of grain sizes in Cu [4] and a heterogeneous lamella structure in Ti [5]. In both examples the processing route is rolling and annealing and the structure is subdivided by boundaries of low, medium and high angle. In a recent study [6], a laminated structure composed of hard layers of recovered lamellar structures and soft layers of recrystallized equiaxed grains was produced in a single phase austenitic steel Fe-34.5Mn-0.04C by cold-rolling and annealing. Enhanced yield stress was obtained in the composite structure while maintaining tensile ductility as good as the fully recrystallized grain structure.

This study aims at further exploring the strengthening mechanisms in that laminated composite based on the rule of mixture that normally is applied in the analysis of the strength of composites. In doing so, it is suggested to establish Hall-Petch relationships for the lamellar structure and the recrystallized equiaxed grain structure. For testing a series of samples with three different types of microstructure were prepared by cold rolling and annealing: (1) lamellar structures of different lamellar boundary spacings, (2) recrystallized equiaxed grain structures of different grain sizes, and (3) composite structures. An ingot was produced using a vacuum induction furnace, and then forged in the temperature range of 800–1100°C to form a 13 mm thick plate [6]. The plate was cold-rolled to 90% in thickness reduction. Annealing treatments under different conditions (see Table 1) were carried out to obtain the three types of microstructure desired. In total, eight samples were prepared, as listed in Table 1, for microstructural characterization and tensile testing. The microstructure was characterized by transmission electron microscopy (TEM) with a JEM-2100 electron microscope operated at 200 kV, and by scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) with a Hitachi S-3400N-II scanning electron microscope. The step size for the EBSD scanning was 100 nm. All the microstructural observations were conducted on the longitudinal section containing the rolling direction (RD) and the normal direction (ND). Tensile specimens with gage dimensions of 10 mm long and 5 mm wide were prepared such that the tensile direction was parallel to the RD. Tensile tests were conducted at ambient temperature with an initial strain rate of 10^{-3} s^{-1}. An extensometer was attached on the specimen during the tensile test for a precise measurement of the tensile strain.

Figs. 1–3 show the microstructure in the cold-rolled state and after annealing under several selected conditions illustrating the lamellar structure, laminated composite structure and recrystallized equiaxed

* Corresponding author.
** Corresponding author at: College of Materials Science and Engineering, Chongqing University, Chongqing 400045, China.
E-mail addresses: tswang@ysu.edu.cn, (T.S. Wang), xihu@mek.dtu.dk (X. Huang).

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Table 1
Microstructure and structural parameters determined for eight samples of Fe-34.5Mn-0.04C steel cold rolled to 90% followed by annealing at different conditions.

Sample	Cold rolling and annealing	Microstructure	Boundary spacing (d_{GNB})/grain size (d_g), (μm)
1	Cold-rolled to 90%	Lamellar structure	0.047 (boundary spacing)
2	500 °C, 1 h	Lamellar structure	0.067 (boundary spacing)
3	550 °C, 1 h	Composite structure: Lamellar (77%) Equiaxed grains (23%)	0.083 (boundary spacing) 1.40 (grain size)
4	600 °C, 1 h	Composite structure: Lamellar (10%) Equiaxed grains (90%)	0.14 (boundary spacing) 2.2 (grain size)
5	700 °C, 1 h	Equiaxed grains	2.3
6	800 °C, 1 h	Equiaxed grains	3.8
7	900 °C, 1 h	Equiaxed grains	10.8
8	1000 °C, 1 h	Equiaxed grains	21.0

grain structure. The composite structure is characterized by layers of recovered lamellar structures and layers of recrystallized fine grains. The formation of this composite structure may have its cause in a structural subdivision during cold rolling into lamellae separating different texture components. The layers may have different stored energies and therefore recover and recrystallize with different rates [7] forming the composite structure. A summary of the identification of three types of microstructure and the quantification of the lamellar boundary spacing (d_{GNB}) for the lamellar structure (samples 1 and 2) and the grain size (d_g) for the recrystallized grain structure (samples 5–8) is shown in Table 1. The boundary spacing is the distance between lamellar boundaries measured perpendicular to the rolling plane. For the composite structure (sample 3 and 4), the lamellar boundary spacing, the grain size, and the volume fractions of the lamellar structure and recrystallized grains were determined separately. The structural parameters have been determined as average values with an acceptable standard deviation based on examination of relatively large areas. It is realized that an average value is an approximation as both the deformed and recovered structures show heterogeneity for example S-bands or microshear bands (see Fig. 1a). However as the structural parameters find their application in strength-structure relationship which also are approximations, the effect of local heterogeneity may not be significant when analyzing the engineering properties.

Fig. 4a shows the tensile stress-strain curves for the eight samples tested. It is seen that a continuous flow occurs in samples 1 and 2 with the lamellar structure and in samples 6, 7 and 8 with relatively large grain sizes of 3.8, 10.8 and 21.0 μm. However, a discontinuous flow associated with a small Lüders elongation takes place in sample 4 (composite structure) and sample 5 (with a fine grain size of 2.3 μm). Note that the two samples with composite structures show a remarkable combination of strength and ductility (curves 3 and 4 in Fig. 4a): sample 3 with 77% recovered lamellar structures (boundary spacing 83 nm) and

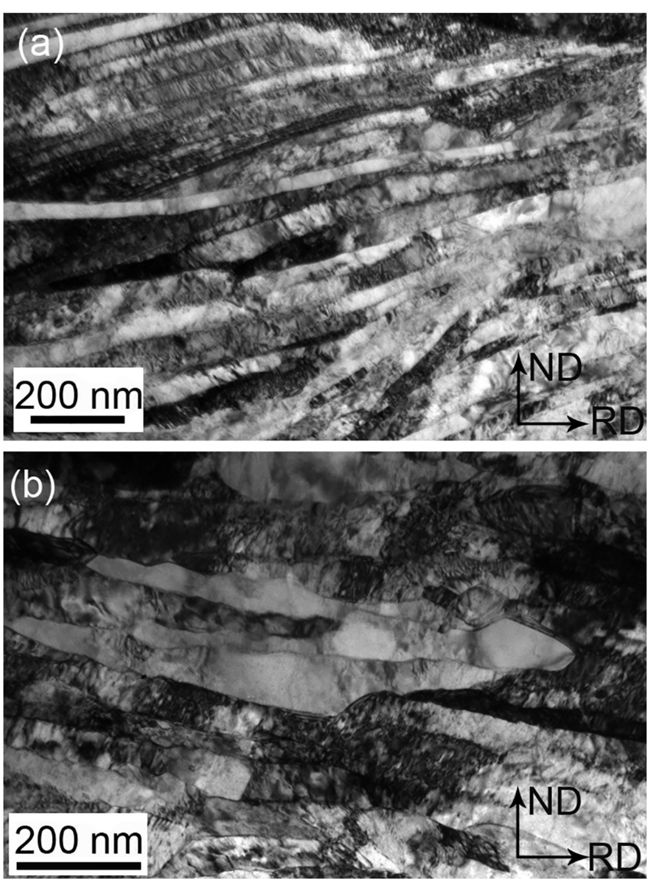

Fig. 1. TEM images of the Fe-34.5Mn-0.04C steel showing the lamellar structure. (a) Cold-rolled to 90% and (b) subsequently annealed at 500 °C for 1 h.

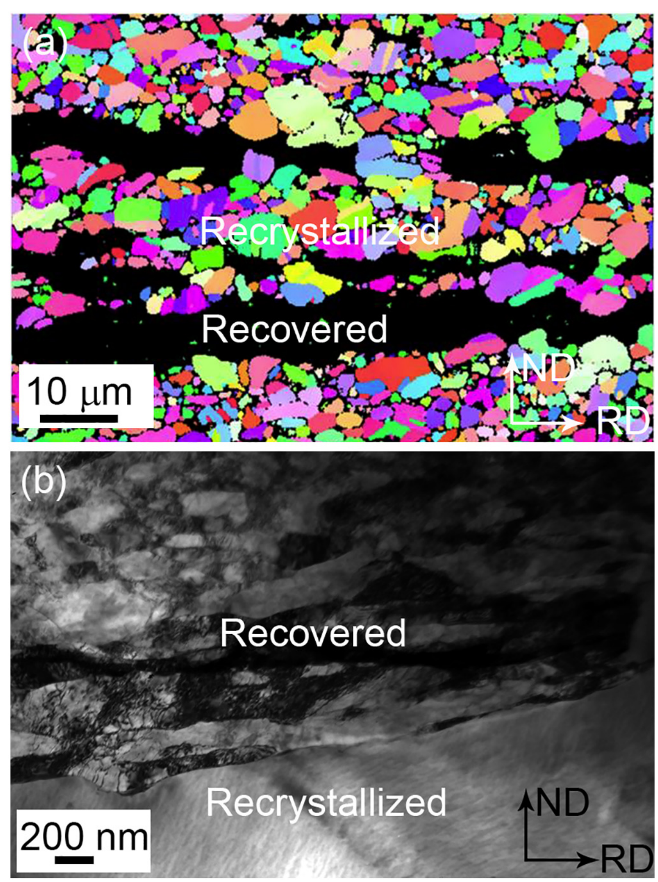

Fig. 2. (a) EBSD map and (b) TEM image showing the laminated composite structure of the Fe-34.5Mn-0.04C steel cold-rolled to 90% and subsequently annealed for 1 h at 600 °C.

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