Simultaneous enhancement of strength and ductility in a finegrained Fe-30Mn-0.11C steel at 77 K

Paper

Wang, Y. H.; Kang, J. M.; Chen, X. M.; Yu, T.; Hansen, N.; Huang, X.

Published in:
I O P Conference Series: Materials Science and Engineering

Link to article, DOI:
10.1088/1757-899x/580/1/012050

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Wang, Y. H., Kang, J. M., Chen, X. M., Yu, T., Hansen, N., & Huang, X. (2019). Simultaneous enhancement of strength and ductility in a finegrained Fe-30Mn-0.11C steel at 77 K: Paper. *I O P Conference Series: Materials Science and Engineering*, *580*(1), Article 012050. https://doi.org/10.1088/1757-899x/580/1/012050

IOP Conference Series: Materials Science and Engineering

Simultaneous enhancement of strength and ductility in a finegrained Fe-30Mn-0.11C steel at 77 K

To cite this article: Y H Wang *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **580** 012050

40th Risø International Symposium on Material Science IOP Publishing
IOP Conf. Series: Materials Science and Engineering **580** (2019) 012050 doi:10.1088/1757-899X/580/1/012050

Simultaneous enhancement of strength and ductility in a fine-grained Fe-30Mn-0.11C steel at 77 K

Y H Wang[1,2*], J M Kang[1], X M Chen[1], T Yu[2], N Hansen[3,4] and X Huang[2,4]
[1]National Engineering Research Center for Equipment and Technology of Cold Strip Rolling, Yanshan University, Qinhuangdao 066004, P. R. China
[2]Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
[3]Risø Campus, Technical University of Denmark, DK-4000 Roskilde, Denmark
[4]College of Materials Science and Engineering, Chongqing University, 400044 Chongqing, P. R. China

Email: yhwang@ysu.edu.cn

Abstract. High Mn austenitic steels are a class of materials for cryogenic applications. Previous studies on Fe-34.5Mn-0.04C austenitic steels have shown that refining grain size can suppress the formation of deformation-induced ε and α' martensite and improve the tensile strength and ductility at temperatures down to 123 K. Here we report a new observation of simultaneous increase of strength and ductility at liquid nitrogen temperature (77 K) in a fine grained Fe-30Mn-0.11C (wt. %) steel where the addition of 0.11%C stabilizes the austenite. This improvement is attributed to complete suppression of martensitic transformation and enhanced occurrence of deformation twinning.

1. Introduction

High manganese austenitic steels have been widely studied for their outstanding tensile strength and ductility [1-3]. Some high Mn austenitic steels have also been investigated for cryogenic applications [4, 5]. However, ε-martensitic transformation may occur in this class of high Mn steels during plastic deformation, which often causes premature fracture through the interactions of ε-martensite/ε-martensite, ε-martensite/annealing twin boundaries, and ε-martensite/grain boundaries. In our previous studies on Fe-34Mn-0.04C austenitic steels it has been shown that refining the grain size can suppress martensitic transformation at grain boundaries and in the grain interior regions, and as a result the tensile strength and ductility is significantly improved at temperatures even down to 123 K. However, at 93 K, the Fe-34.5Mn-0.04C steel showed a decrease in elongation and tensile strength due to premature fracture caused by the formation of deformation-induced α′-martensite [6] and ε-martensite [7].

There are two effective methods to suppress the ε-martensitic transformation. One method is to refine the austenite grain size [8]. A previous study has shown that the embrittlement was eliminated by grain refinement to 460 nm in Fe-17Mn-0.6C steel [9]. The other method is to add alloying elements such as carbon [10], aluminium [11] and manganese [12, 13] that are austenite stabilizers. It is possible to obtain stable austenite even at cryogenic temperatures when enough carbon and manganese are added. An early investigation has reported that for the binary Fe-Mn system, when the Mn content increases to 30~40%, the dominant plastic deformation mechanism is dislocation slip and martensitic transformation is suppressed. When the Mn content was increased to 36%, no ε-martensite was observed in samples tensile tested at room temperature, and only 4.2% ε-martensite was formed after tensile deformation to a strain of more than 60% at liquid nitrogen temperature. To enhance the stability of austenite, we added 0.11%C to an Fe-30Mn alloy to produce an Fe-30Mn-0.11C austenitic steel. A fully recrystallized fine-grained sample with a mean grain size of 5.6 µm was prepared by conventional cold rolling and annealing. The tensile properties of this fine-grained steel were tested at 293 K and 77K. The strength and ductility at 77K are increased simultaneously and significantly as compared with the results at room temperature. This enhancement is attributed to the complete elimination of grain boundary ε-martensite and the enhanced formation of deformation twins within the grains.

2. Experimental

The steel studied was melted using a vacuum induction technique and had a main chemical composition of Fe-30Mn-0.11C (wt.%). The ingot was heated to 1000 ºC and held for 1 h, and then forged at 800~1000 ºC to produce a 20 mm thick plate. The plate was cold rolled by 50% in thickness reduction. Then, annealing was carried out at 700 ºC for 2h to obtain a fully recrystallized grain structure with a mean grain size of 5.6 µm.

Tensile specimens with a gauge length of 10 mm, a width of 1.8 mm and a thickness of 1.8 mm were prepared from the cold rolled and annealed sample. Uniaxial tensile tests with the tensile axis aligned along the rolling direction (RD) were carried on an MTS tensile testing machine equipped with a cryogenic chamber. Tensile tests were carried out at an initial strain rate of 10^{-3} s^{-1} at RT and 77 K.

A field emission scanning electron microscope (FE-SEM) equipped with a backscattered electron (BSE) detector and an electron backscatter diffraction (EBSD) system was employed for characterization of the microstructure and fracture morphology.

3. Results and discussion

3.1. Microstructure

Figure 1a shows the microstructure after 50% cold rolling. The original austenite grains are elongated along the RD and deformation twins are formed within many of the grains. X-ray diffraction (XRD) analysis shows diffraction peaks corresponding to austenite (Figure 1b). However it is seen that the γ (200) diffraction peak is very weak, whereas the γ (111) diffraction peak is very strong, suggesting the evolution of a texture in the material.

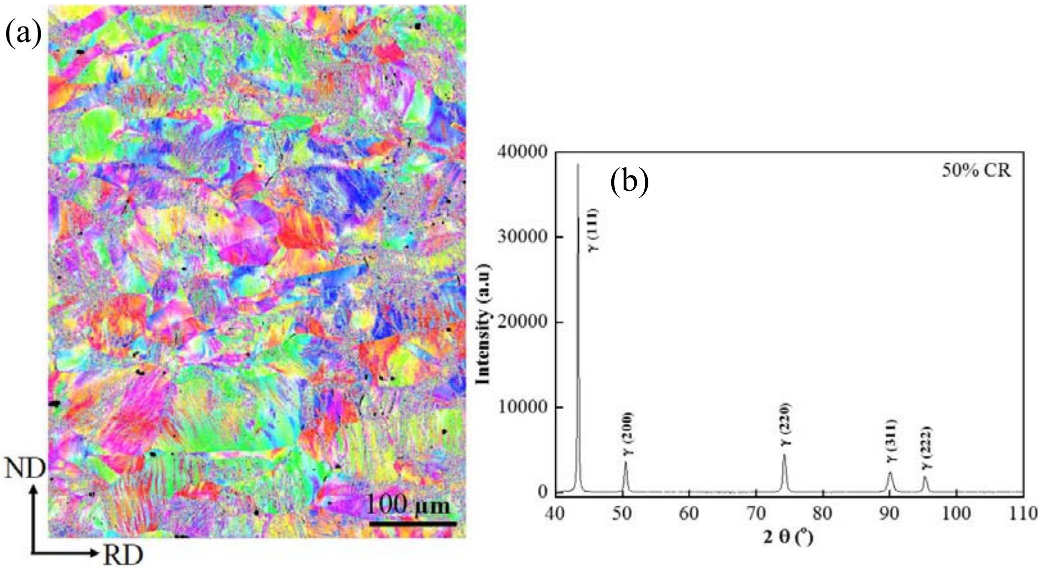


Figure 1. (a) EBSD map of the sample cold rolled to 50% showing the morphology of deformed grains and the formation of deformation twins in the grains. (b) XRD pattern showing austenite single phase.

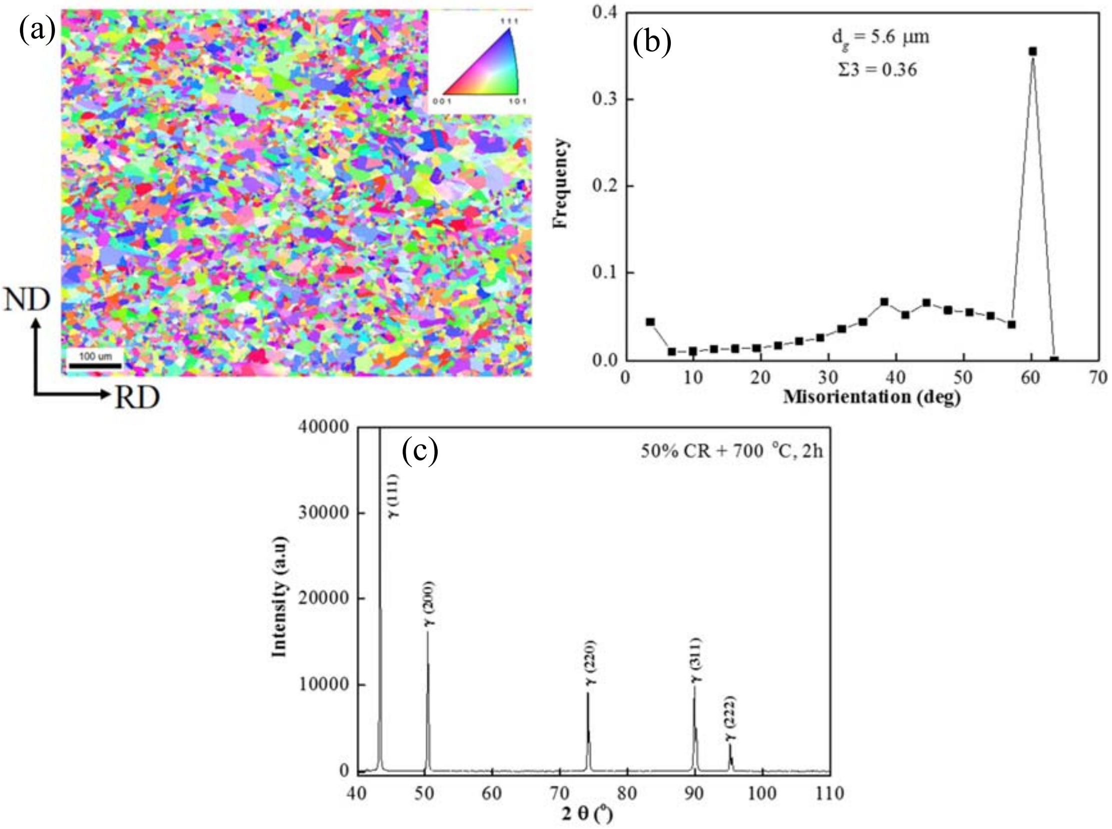


Figure 2. Microstructural analysis of the sample cold rolled to 50% thickness followed by annealing at 700 ºC for 2 h. (a) EBSD orientation map showing the recrystallized grain structure containing annealing twins, (b) misorientation distribution and (c) XRD pattern.

Cold rolling to 50% thickness followed by annealing for 2h at 700 ºC led to full recrystallization, resulting in the formation of a fine grain structure containing many annealing twins (figure 2a). The area fraction of Σ3 boundaries was measured to be 0.36 (figure 2b). By taking the twin boundaries into account, the mean grain size was measured to be 5.6 μm. XRD measurement shows a single austenite phase (figure 2c), with no detection of either ε-martensite nor α′-martensite. It is concluded that a fully recrystallized fine grain structure is obtained in Fe-30Mn-0.11C steel through conventional cold-rolling and annealing treatment.

3.2. Tensile properties and fracture morphologies

Figure 3a shows the engineering stress-strain curves of Fe-30Mn-0.11C steel tested at room temperature (293 K) and 77 K. At 293 K, the Fe-30Mn-0.11C steel shows yield and tensile strengths of 230 MPa and 531 MPa, respectively, along with a total elongation of 65%. At 77 K, higher yield and tensile strengths (360 and 860 MPa) and higher total elongation (84%) are observed.

The work-hardening rates of the two tested Fe-30Mn-0.11C samples were calculated from the corresponding true stress-true stain curves and are shown in figure 3b. Both samples exhibit good work hardening capacity, leading to the occurrence of tensile instability following the Considère's criterion:

$$\frac{d\sigma}{d\varepsilon} = \sigma \tag{1}$$

where σ and ε are the true stress and true strain, respectively. Note that a higher work hardening rate over the entire tensile strain range is observed at 77 K than 293 K, resulting in a larger uniform elongation at 77 K.

Figure 3a also shows stress-strain curves of the Fe-34.5Mn-0.04C steel tested at 293 K, 193 K, 123 K and 93 K from literature [6]. At 293 K, the yield strength, ultimate tensile strength and uniform elongation are 274 MPa, 564 MPa and 45%, respectively. With decreasing temperature, the yield strength gradually increases, but the tensile strength and the uniform elongation do not show a continuous increase with deceasing temperature. At 193K, the uniform elongation reaches a maximum value of about 54%; at lower temperatures the uniform elongation decreases and premature fracture takes place at 93 K with a total elongation less of than 20% [6]. Clearly the present alloy shows an enhanced combination of strength and ductility compared with the Fe-34.5Mn-0.04C alloy at cryogenic temperatures.

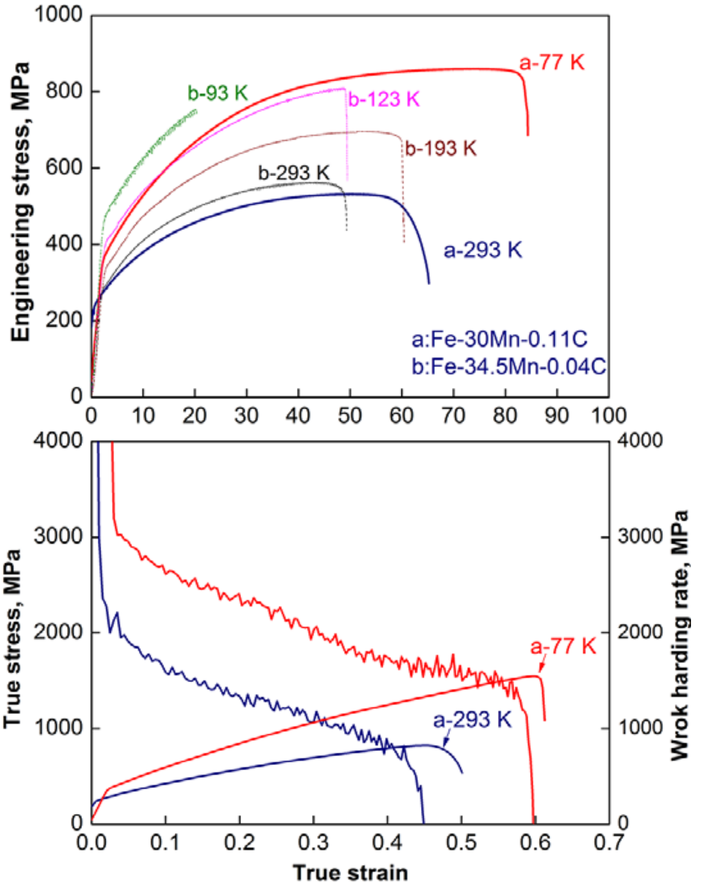


Figure 3. (a) Engineering stress-strain curve of the sample with a mean grain size of 5.6 μm of Fe-30Mn-0.11C steel and 3.8 μm of Fe-34.5Mn-0.04C steel, and (b) the corresponding work hardening rate of Fe-30Mn-0.11C.

Typical SEM micrographs obtained from the fracture surfaces of samples tensile tested at 293 K and 77 K are presented in figure 4. The fracture surface at both temperatures is mostly composed of dimples, showing ductile fracture.

3.3 Microstructural evolution after tensile-tested at 77 K

Figure 5 a-c shows inverse pole figure (IPF), image quality (IQ), and phase maps constructed from the EBSD data, as observed in longitudinal-section in the area beneath tensile-fractured surface of Fe-30Mn-0.11C steel tested at 77 K. Deformations twins are observed in many grains (see figure 5a and b) with no α'-martensite or ε-martensite detected. The suppression of martensite formation and the formation of deformation twins are considered to contribute to the enhancement of both strength and ductility at 77 K.

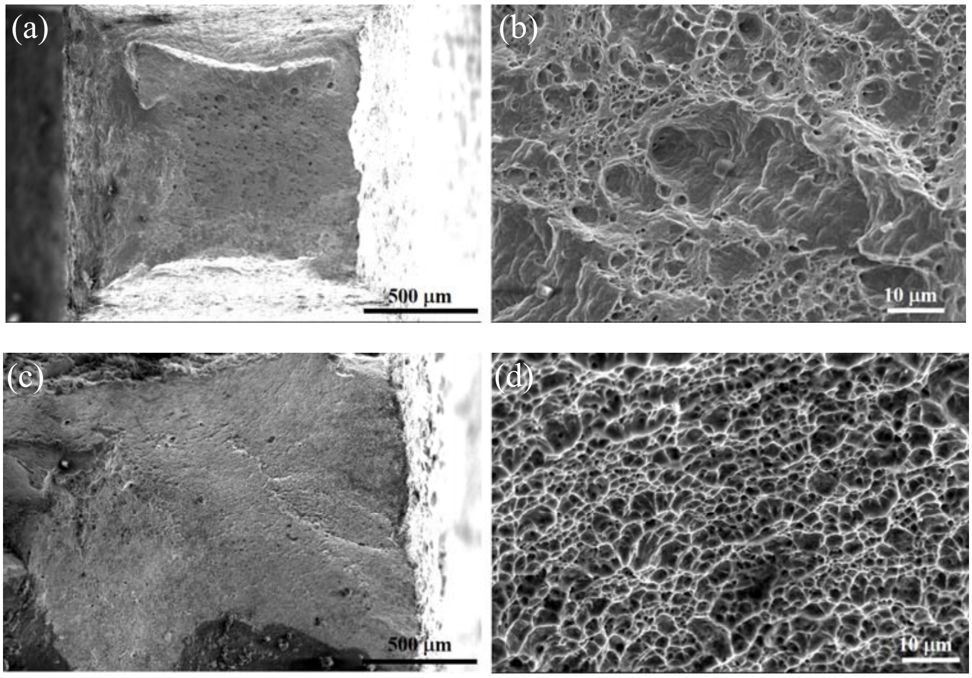
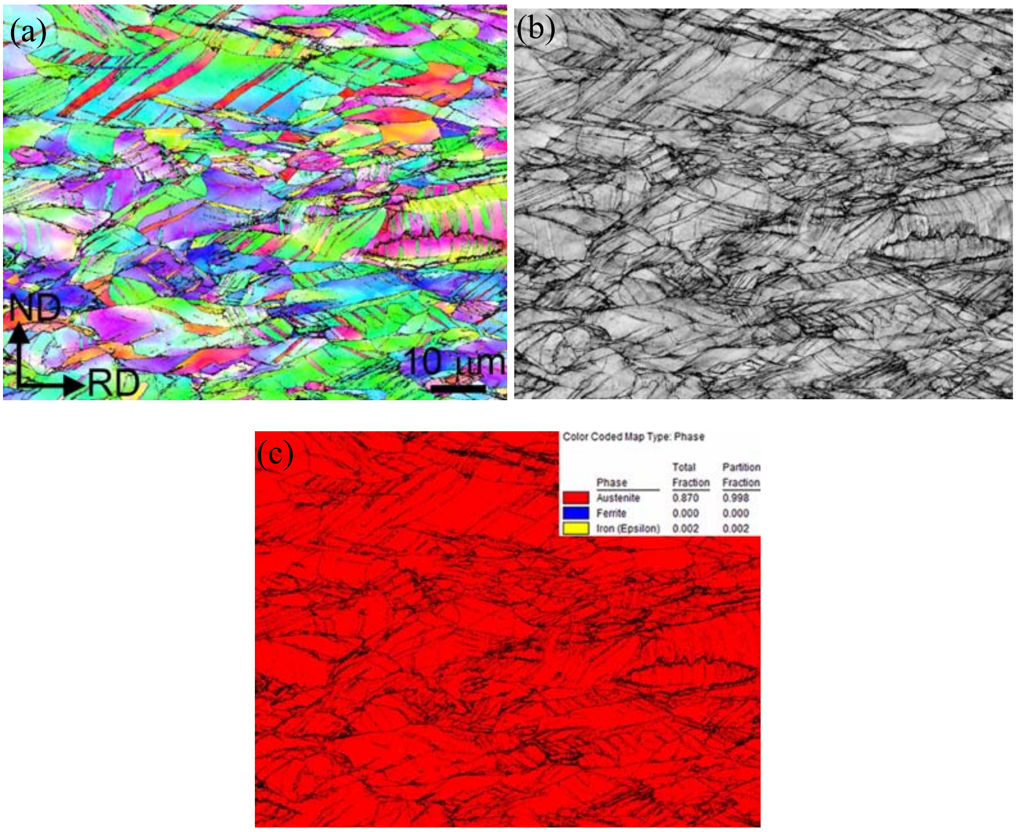


Figure 4. SEM fractographs of the tensile specimen fractured at (a) and (b) 293 K and (c) and (d) 77 K.



	Phase	Total Fraction	Partition Fraction
🟥	Austenite	0.870	0.998
🟦	Ferrite	0.000	0.000
🟨	Iron (Epsilon)	0.002	0.002

Figure 5 Inverse pole figure (IPF) map (a), image quality (IQ) map (b) and phase map (c) from an EBSD scan of the Fe-30Mn-0.11C steel after tensile-tested at 77 K.

4. Summary

A fine grained Fe-30Mn-0.11C steel with a mean grain size of 5.6 μm was successfully produced through traditional cold rolling and annealing. The strength and ductility was found to increased simultaneously with decreasing temperature in the range from 293 K to 77 K. This enhancement is attributed to full suppression of martensitic transformation and the activation of deformation-induced twins within the grains at cryogenic temperatures.

Acknowledgments

The authors gratefully acknowledge support from the National Nature Science Foundation of China (Grant No. 51871194) and the National Natural Foundation of Hebei Province, China (Grant No. E2018203312). XH thanks the support of State Key Research and Development Program of MOST of China (2016YFB0700403, 2016YFB0700401). NH thanks the support of the 111 Project (B16007) by the Ministry of Education and the State Administration of Foreign Experts Affairs of China.

References

[1] Bouaziz O, Allain S, Scott C P, Cugy P and Barbier D 2011 *Current Opinion in Solid State and Materials Science* 15(4) 141-168.
[2] Wang Y H, Kang J M, Peng Y, Wang T S, Hansen N and Huang X 2018 *Scr. Mater.* 155 41-5.
[3] Wang Y H, Kang J M, Peng Y, Wang T S, Hanse N n and Huang X 2018 *Journal of Materials Science & Technology* 34(10) 1939-1943.
[4] Grässel O, Kruge L r, Frommeyer G and Meyer L W 2000 *International Journal of Plasticity* 16 1391-1409.
[5] Wang Y H, Shi B D, He Y M, Zhang H W, Peng Y and Wang T S 2018 *Materials* 11(2).
[6] Wang Y H, Peng Y, He Y M, Wan g T S and Huang X 2014 *Proceedings of the 35th Risø Internaional Symposium on Materials Science*. 471-474.
[7] Wang Y H, Kang J M, Chen X M, Yu T B, Hansen N and Huang X X 2019 unpublished.
[8] Koyama M, Lee T, Lee C S and Tsuzaki K 2013 *Materials & Design* 49 234-241.
[9] Koyama M, Sawaguchi T, Lee T, Lee C S and Tsuzaki K 2011 *Materials Science and Engineering: A* 528(24) 7310-7316.
[10] Seol J B, Jung J E, Jang Y W and Park C G 2013 *Acta Materialia* 61(2) 558-578.
[11] Sohn S S, Hong S, Lee J, Suh B C, Kim S K, Lee B J, Kim N J and Lee S 2015 *Acta Mater*100 39-52.
[12] Tomota Y, Strum M and Jr. J W Morris 1988 *Metallurgical Transactions A* (19A) 1563-1568.
[13] Tomota Y, Strum M and Jr. J W Morris 1986 *Metallurgical Transactions A* (17A) 537-547.