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Published in:
IOP Conference Series: Materials Science and Engineering

Link to article, DOI:
10.1088/1757-899X/1249/1/012036

Publication date:
2022

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

Citation (APA):
Xiong, J. C., Zhao, J. F., Kong, L., Yang, H. K., Zhang, X. D., & Wang, Y. H. (2022). Heterogeneous lamellar-structured high manganese steel with excellent tensile properties. *IOP Conference Series: Materials Science and Engineering*, *1249*(1), Article 012036. https://doi.org/10.1088/1757-899X/1249/1/012036

IOP Conference Series: Materials Science and Engineering

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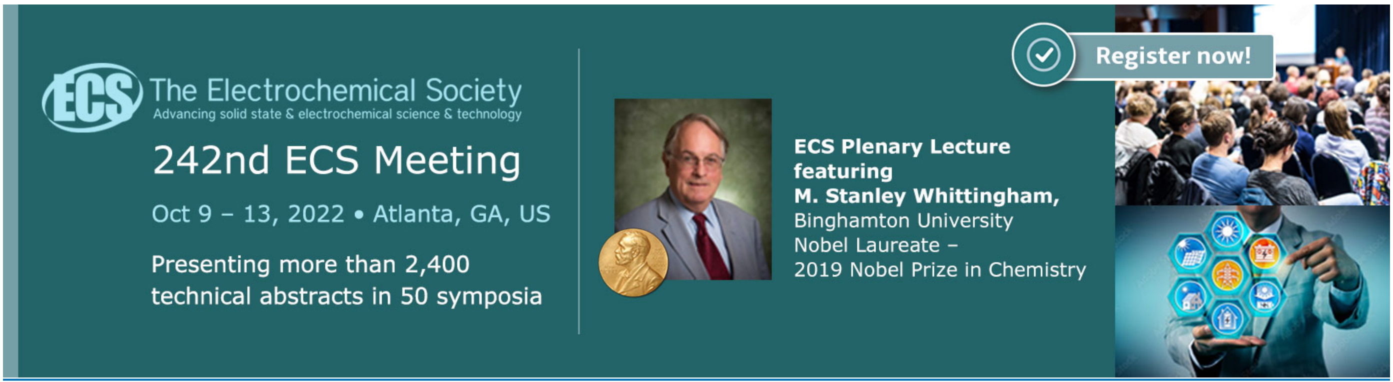
To cite this article: J C Xiong *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1249** 012036



42ND Risø International Symposium on Materials Science IOP Publishing
IOP Conf. Series: Materials Science and Engineering 1249 (2022) 012036 doi:10.1088/1757-899X/1249/1/012036

Heterogeneous lamellar-structured high manganese steel with excellent tensile properties

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Abstract. A single-phase Fe-30Mn-0.11C steel with a heterogeneous lamellar structure composed of micron-sized recrystallized grains (MRGs) and deformation bands (DBs) was successfully produced by cold rolling to 90% in thickness reduction and annealing at 550 °C for 120 min. The tensile properties of samples cut out along the rolling direction (RD) and transverse direction (TD) were investigated. The results indicate that the samples along the RD and TD both exhibit excellent tensile properties, with a yield strength of approximately 600 MPa and a total elongation of more than 30%.

1. Introduction

Many studies have reported that the strategy of designing heterogeneous structures can achieve superior mechanical properties for metallic materials. Heterogeneous structure materials such as heterogeneous lamellar structure, gradient structure and dual phase structure materials generally exhibit better mechanical properties than conventional homogeneous structure materials [1-5], and have attracted more and more attentions in recent years.

For single-phase metallic materials, it has been confirmed that heterogeneous lamellar structures can be obtained by cold rolling and subsequent annealing [6, 7]. Generally, the soft domain is the recrystallized structure, and the hard domain is the deformed structure has been observed in as heterogeneous lamellar-structured Fe-34.5Mn-0.04C steel [6] and pure Ti [8]. A heterogeneous lamellar structure was also obtained in 316L stainless steel by 85% cold rolling and annealing at 750 °C [7]. In addition, much work has focused on the strain hardening and plastic deformation mechanisms of heterogeneous lamellar-structured materials [9, 10].

Generally, multi-phase laminated composites are very sensitive to the loading direction, as a result of the inhomogeneous distribution of voids, cracks, oxides, intermetallic compounds and other impurities in the interfaces or the different degree of plastic deformation in the lamella [11-16]. However, there are few studies on mechanical properties of single-phase heterogeneous lamellar-structured alloys along the different directions, especially in high manganese austenitic steel.

In this work, a heterogeneous lamellar structure composed of MRGs and DBs was successfully obtained in the Fe-30Mn-0.11C steel by a combination of cold-rolling to 90% thickness reduction and annealing at 550 °C for 120 min. The tensile properties of samples cut out along RD and TD were investigated.

2. Experimental

The steel used has a nominal composition of Fe-30Mn-0.11C (wt.%). The steel was melted using the vacuum induction technique. The ingot was heated to 1000 °C and held for 1 h, and then forged at 800~1000 °C to produce a 21 mm thick plate. The hot forged plate was then cold rolled to a thickness reduction of 90%, followed by annealing at 550 °C for 120 min. Subsequently, the samples were water-quenched. The Fe-30Mn-0.11C steel has a stable austenitic structure after 90% cold rolling, which was characterized in our previous work [17-18].

Microstructure analyses were carried out using electron microscopy. The microstructure observations were all carried out on the longitudinal section along the rolling direction (RD) and the normal direction (ND). A field emission scanning electron microscope (FE-SEM) equipped with a backscatter electron (BSE) detector and an electron backscatter diffraction (EBSD) system operated at an accelerating voltage of 20 kV was used for microstructural characterization. The microstructure was also characterized using a FEI Talos F200s transmission electron microscope (TEM) operated at 200 kV. Tensile specimens with a gauge length of 10 mm, a width of 2 mm and a thickness of 2 mm were prepared from the annealed plates. Tensile tests were carried out using a Zwick Z050TEW testing machine with a strain rate of 10^{-3} s^{-1} at room temperature. The tensile testing was repeated 3 times.

3. Results and discussion

Figure 1 shows the microstructure of the cold rolled Fe-30Mn-0.11C steel. The EBSD IPF+IQ map of the cold-rolled sample in figure 1a, indicates that the microstructure is elongated along the RD. There are clear DBs along RD. The microstructure was significantly refined via cold rolling. The ECCI image (figure 1b) shows that the cold rolled microstructure contains DBs (white dashed area) and nano-twin bundles (NTBs) (blue dashed area) which were confirmed by TEM images. The microstructure after cold rolling is mainly a nano-lamellar structure (NLS) delineated by geometrically necessary dislocation boundaries (GNBs), as shown in figure 1c. Selected area electron diffraction (SAED) is ring-shaped, which matches the nanocrystalline structure. Figure 1d shows that there are NTBs in the microstructure, which are surrounded by the NLS. The above results show that the microstructure after 90% cold rolling mainly consist of NLS, DBs and NTBs.

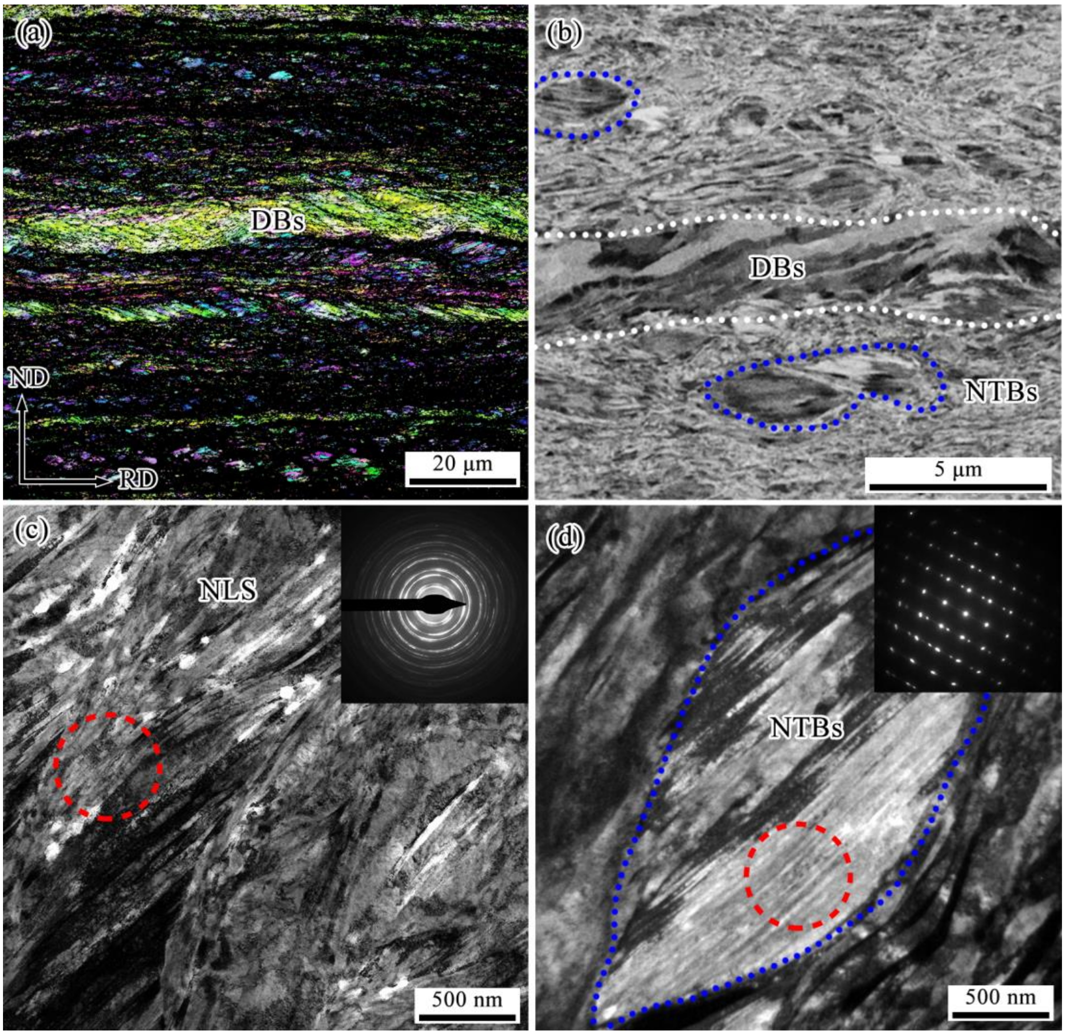

Figure 1. Microstructure of the cold rolled Fe-30Mn-0.11C steel (a) EBSD IPF+IQ image (b) electron channel contrast image (ECCI), (c) TEM image of NLS, the inset is the selected area diffraction pattern (SAED) of NLS， (d) TEM image of NTBs, the inset is the SAED of NTBs. The regions of SAEDs are circled by red dotted lines.

Figure 2 shows the heterogeneous lamellar structure consists of the MRGs and DBs after cold rolling and annealing at 550 °C for 120 min. The initial NLS has recrystallized and the recrystallization area is composed of MRGs (see figure 2b). The average grain size calculated by EBSD is 2.0 µm. Figure 2c shows DBs surrounded by MRGs. The DBs consist of nanocrystals delineated by dislocation boundaries, which is confirmed by SAED. Figure 2d shows that some NTBs still exist in the annealed structure.

Tensile tests were carried out along the RD and TD, as sketched in figure 3a. The engineering stress-strain curves (see figure 3b) of the samples show a discontinuous yielding behavior, which was also observed in the Fe-34.5Mn-0.04C steel [19]. This is attributed to a lack of dislocation sources in these fine-grained samples, similar to the behavior observed in many other materials with grain sizes in the near-micrometer regime, resulting also in an additional strengthening due to the lack of dislocation sources [20-21]. The yield drop phenomenon can be eliminated by additional slight cold rolling which introduce extra dislocations [19]. The yield strength and total elongation of the samples along RD and TD are 583 MPa, 37% and 625 MPa, 30%, respectively.

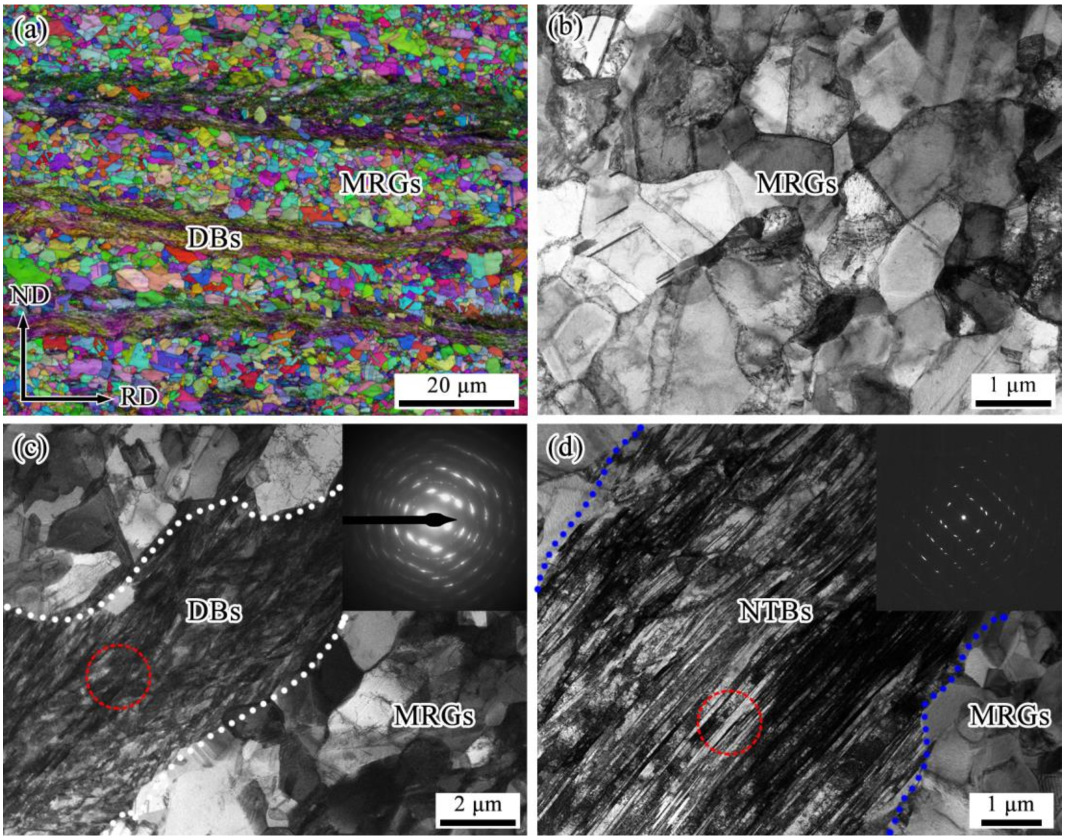

Figure 2. Microstructure of Fe-30Mn-0.11C steel after cold rolling and annealing at 550 °C for 120 min (a) EBSD IPF+IQ image (b) TEM image of recrystallized microstructure, (c) TEM image of a region with DBs, the inset is SAED of DBs (d) TEM image of a region with NTBs. The regions of SAEDs are circled by red dotted lines.

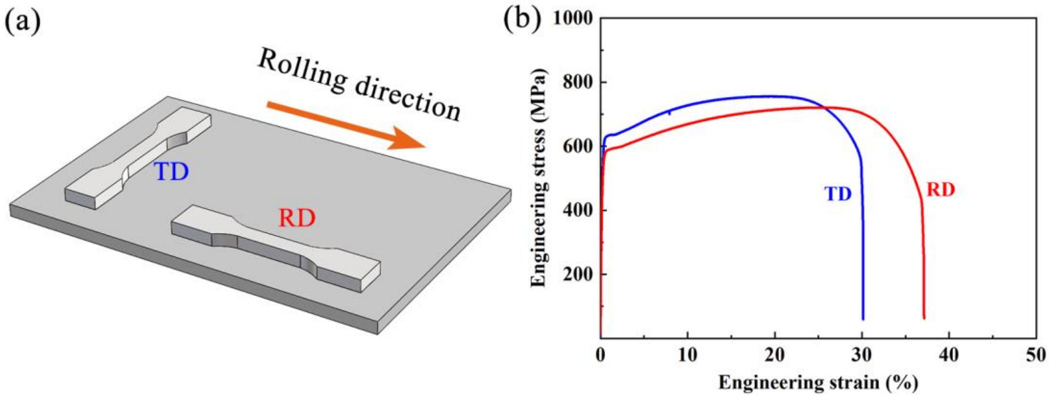

Figure 3. (a) Schematic diagram (b) engineering stress-strain curves of Fe-30Mn-0.11C steel annealed at 550 °C for 120 min.

Figure 4 shows the fractography of the RD sample. The fracture is cup-cone-shaped (see figure 4a) and the fracture appearance is composed of large and deep dimples (see figure 4b), indicating a ductile fracture mode.

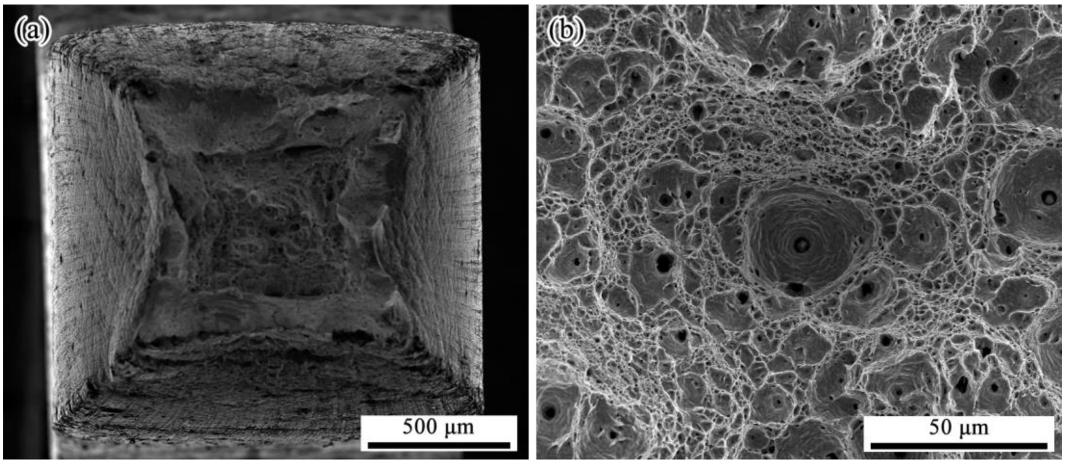

Figure 4. The fractography of the sample along the RD.

Generally, multi-phase laminated composites exhibit an obvious anisotropic mechanical behavior due to the inhomogeneous distribution of voids, cracks, oxides, intermetallic compounds and other impurities in the interfaces or different degree of plastic deformation in the lamella [11-16]. The Ti/Al laminated composites exhibited a significant anisotropy due to the difference in the microstructure and microhardness of the Ti and Al layer [12]. Moverare and Odén [11] reported load partitioning between austenitic and ferritic phase in cold-rolled duplex stainless which was dependent on the loading directions, leading to an obvious anisotropy in the mechanical properties.

However, it is worth noticing that the heterogeneous lamella structure of the Fe-30Mn-0.11C steel exhibit unexpected tensile properties along RD and TD, which is different from multi-phase laminated composites (such as duplex stainless [11], Ti-Al [12], Mg-Al [13]). This may be related to the following two aspects: i) the large difference in the grain size between the MRGs (2.0 μm) and DBs/NTBs (73 nm); ii) the remaining DBs/NTBs zones are well distributed. The detailed mechanisms for the observed excellent mechanical properties need to be investigated systematically, taking into account the strengthening contributions from different zones [21] and the dislocation-boundary interactions [22].

4. Summary

In this work, a heterogeneous lamellar structure composed of MRGs and DBs/NTBs was successfully produced in a single-phase Fe-30Mn-0.11C steel by cold-rolling to 90% thickness reduction followed by annealing at 550 °C for 120 min. Excellent tensile properties both along RD and TD were achieved: the yield strength and total elongation of the samples along RD and TD are 583 MPa, 37% and 625 MPa, 30%, respectively.

Acknowledgments

The authors gratefully acknowledge the support from the National Natural Science Foundation of China (Grant No. 51871194) and the National Natural Foundation of Hebei Province, China (Grant No. E2021203011, 226Z1003G). X. Zhang acknowledges the support from the European Research Council under the European Union Horizon 2020 research and innovation program (grant agreement No 788567-M4D).

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