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ScienceDirect

Scripta Materialia 65 (2011) 404–407

Scripta MATERIALIA

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Effect of initial microstructure on ultrafine grain formation through warm deformation in medium-carbon steels

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Received 9 February 2011; revised 15 May 2011; accepted 16 May 2011
Available online 20 May 2011

The microstructural change caused by one-pass warm deformation in medium-carbon steels with various initial microstructures has been examined. Fine equiaxed ferrite grains having a mean diameter of 0.5 μm surrounded by high angle boundaries are formed by dynamic recrystallization when the initial microstructure is lath martensite. Although ferrite–pearlite, spheroidized structure and upper bainite also have fine initial microstructures, uniform fine ferrite grains are not obtained. The microstructures have been characterized in terms of grain boundary misorientation, grain size and dislocation density.

Keywords: Ultrafine grained microstructure; Dynamic recrystallization; Medium-carbon steels; Forging; Electron backscattering diffraction (EBSD)

In medium-carbon steels for automotive applications, increasing the yield strength and reducing the size of hot forged components are the conventional ways to reduce CO_2 emission through improving the fuel efficiency. Grain refinement, which can achieve an excellent balance of high yield strength and high toughness, is one of the most effective methods to realize the desired properties. Torizuka et al. [1] indicated the relationship between ferrite grain size and Vickers hardness, which has good correlation with yield strength, in low-carbon steels through experiments using high-reduction warm rolling to produce fine grain structures. Torizuka et al. found that when the ferrite grain size is 1–2 μm, the hardness range is about HV 200–230, which is almost comparable with the hardness level of normalized medium carbon ferrite–pearlite steels. The hardness of the fine-grained steel should be higher than that of ferrite–pearlite for the fine ferrite structure to have an advantage, so further grain refinement to below 1 μm is necessary to strengthen forged machine components in medium-carbon steels. Many studies have been performed to produce fine-grained structures with a grain size smaller than 1 μm in low-carbon steels [2–12]. Dynamic recrystallization (DRX) is one of the most notable ways to obtain fine ferrite grains surrounded by high angle boundaries in steels. The characteristics of DRX behavior are determined by the deformation temperature and strain rate, which are incorporated into the Zener–Hollomon parameter [13]. The strain necessary for completion of DRX increases with increasing Z value [10]. In the case of low-carbon ferrite–pearlite steels, a strain over 2.4 is necessary to obtain ultrafine ferrite grains surrounded by high angle boundaries [11]. Such a severe deformation is impractical for conventional forging processes.

Tsuji et al. [12] have shown that the critical strain for DRX is decreased considerably when as-quenched martensite is used as the starting microstructure in hot deformation in a low-carbon steel. They succeeded in producing uniform fine ferrite grains with an average grain size of 3–3.5 μm only after a strain of 0.8 in hot compression [12]. Poorganji et al. [14] also reported that a large fraction of equiaxed ferrite grains, with an average grain size of 1.3 μm and surrounded by high angle boundaries, were formed through DRX by deformation of lath martensite in a high-carbon steel. Little attention has been given to the grain refinement in medium-carbon steels, which are mainly used as machine components. These results indicate that fine ferrite grains with high angle boundaries can be obtained by the deformation of martensite mainly due to its fine initial microstructure, but they also suggest that it is hard to reduce ferrite grain sizes below 1 μm by the deformation of martensite with a

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doi:10.1016/j.scriptamat.2011.05.018

strain level of 0.8–1.0. There are different types of fine microstructures in carbon steels, which may be used as starting microstructures for thermomechanical processing to obtain fine ferrite structures, i.e. pearlite structure, fine ferrite with spheroidized cementite and bainite. It is not clear, however, which initial microstructures are the most effective for producing an ultrafine ferrite structure. The present study aims to discover the most effective initial microstructures to obtain ultrafine grains with a mean grain size smaller than 1 μm through DRX in medium-carbon steels.

An Fe–0.45C–0.25Si–1.5Mn–0.2Cr (mass%) steel was used in this study. The A3 and A1 temperatures calculated by Thermocalc for the present alloy are 1026 and 970 K, respectively. The steel was forged down to a bar 40 mm in diameter after heating at 1473 K for 3.6 ks followed by homogenizing at 1523 K for 36 ks, then normalized at 1123 K for 1.8 ks to produce a completely ferrite–pearlite microstructure. It was machined into cylindrical specimens 8 mm in diameter and 12 mm in length, and then heated and deformed using a thermomechanical simulator (Fuji-denpa-koki Thermecmastor-Z). In this study, specimens with four different types of starting microstructure, i.e. ferrite–pearlite, upper bainite, lath martensite and ferrite with spheroidized cementite, were compressed to determine which kind of starting microstructure is the most effective to produce an ultrafine ferrite structure. Upper bainite was obtained by isothermal treatment at 723 K for 200 s after austenitizing at 1323 K for 180 s, and lath martensite was obtained by quenching after the same austenitizing treatment. The specimen with the lath martensite microstructure was heated at 988 K for 25.2 ks followed by slow cooling to 873 K at a cooling rate of 18 K h^{-1} to obtain a ferrite structure surrounded by high angle boundaries with uniformly dispersed spheroidized cementite particles. (This is called "spheroidized structure" hereafter.) These specimens were reheated at 923 K, isothermally held for 60 s, compressed to a 60% reduction in height (true strain of about 1.0) at a strain rate of 10 s^{-1}, which is almost the same deformation speed as that of conventional forging process, and then quenched in He gas to room temperature. The microstructures were observed by optical microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The misorientations in the obtained structures were measured by electron backscattering diffraction pattern (EBSD) analysis. The average ferrite grain sizes were determined by the mean linear intercept method from the SEM micrographs.

The initial optical microstructures of the specimens are shown in Figure 1. They are typical ferrite–pearlite (a), spheroidized structure (b), which consists of approximately spherical particles of cementite in a matrix of ferrite, upper bainite (c) and lath martensite (d) in the medium-carbon steel, respectively. Figure 1 also shows image quality maps (e–h) and boundary maps (i–l) of four different initial microstructures obtained by EBSD analysis. Thick and thin lines in boundary maps represent high angle boundary ($\theta \geqslant 15°$, θ: misorientation angle) and low angle boundary ($1.5° \leqslant \theta < 15°$), respectively. In the ferrite–pearlite structure (Fig. 1(i)), each pearlite block is regarded as a ferrite grain in the EBSD boundary map, because the ferrite orientation in the same block is nearly the same and each cementite plate is too thin to be detected by EBSD measurement. The mean interlamellar spacing in the pearlite structure measured from SEM micrographs is 0.18 μm and the average ferrite grain size surrounded by high angle boundaries is 6.5 μm. In the spheroidized structure, most of the ferrite grains are surrounded by high angle boundaries and the average ferrite grain size is 1.9 μm. Although upper bainite seems to have a fine structure in the image quality map (g), the EBSD boundary map clearly shows that most of the grain boundaries are low angle ones and the mean substantial grain size is 11.7 μm. Lath martensite has very fine block

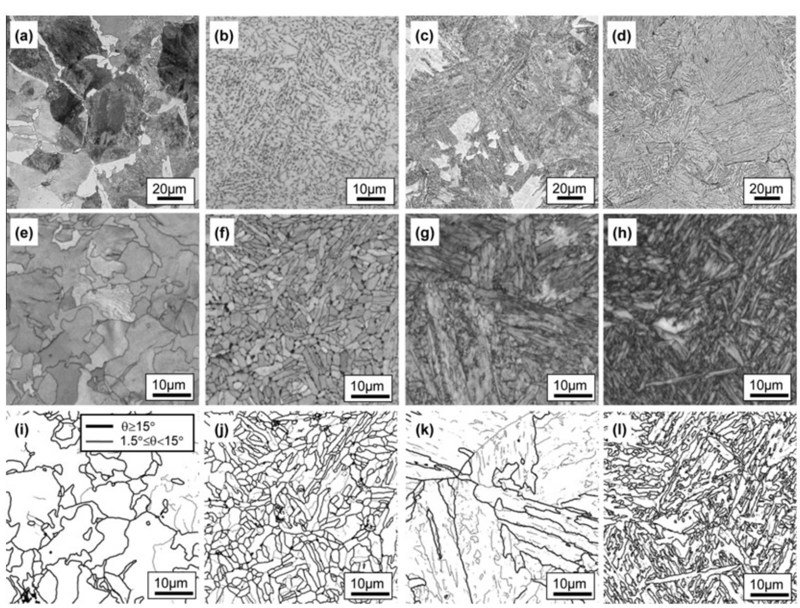

Figure 1. Optical micrographs (a–d), image quality maps (e–h) and boundary maps (i–l) obtained from EBSD analysis for the specimens before deformation. (a, e and i) Ferrite–pearlite; (b, f and j) spheroidized structure; (c, g and k) upper bainite; (d, h and l) lath martensite. Thick and thin lines represent high angle boundary and low angle boundary, respectively.