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An ultrahigh strength steel with ultrafine-grained microstructure produced through superplastic forming

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ABSTRACT

A novel procedure combined with superplastic forming was applied to produce an ultrahigh strength steel with ultrafine-grained microstructure. Although the hardness reached HRC65 at room temperature, the value of $m = 0.38$ and flow stress of 57 MPa were found during superplastic forming at 1023 K and strain rate of $10^{-4}\ s^{-1}$. Due to reasonable composition design, ultrahigh strength was ensured within a wide range of cooling rate after superplastic forming without the need of supplementary heat treatment.

1. Introduction

The application of grain refinement has long been the focus of material research. In the metallic field, ultrafine-grained (UFG) and nanocrystalline (NC) microstructures usually exhibit superior properties and performance [1]. Generally speaking, there are two major routes to obtain UFG and NC microstructures for metallic material. One is to refine coarse-grained bulk metal through severe plastic deformation (SPD), including equal channel angular processing (ECAP) [2–4], high pressure torsion (HPT) [5], and wire drawing. The other is to compact NC powders via hot-pressing, hot isostatic pressing (HIP), etc. However, there exist some disadvantages on these methods: grain refinement is restricted by the difficulty of heat dissipation during ECAP; continuous production through ECAP and HPT is hard to realize because of the limited equipment capacity; preparation of NC powders is complicated, etc. Therefore, the above two routes do not seem suited for the conventional mass-production of metals.

In recent years, in the field of steel, several studies have attempted to achieve UFG microstructures by rolling and annealing of steels with various carbon contents and starting microstructures. In the cases of ferrite–pearlite [6], martensite [7], tempered martensite [8] and ferrite-martensite [9] as starting microstructures before rolling and subsequent annealing, submicrometer ferrite grains have been obtained. Unfortunately, these studies are mostly referred to low carbon steels and ferrite grains are prone to grow coarser during annealing at high temperature due to less pinning effect by a small amount of carbides. In addition, a few decades ago, Sherby et al. studied a ferrite (α) UFG structure with a uniform distribution of spheroidized cementite (θ) particles (i.e. $(\alpha+\theta)$ microduplex structure) [10,11], with the purpose of exploring the superplasticity of ultrahigh carbon steels. However, the methods of obtaining the $(\alpha+\theta)$ microduplex structure are also more or less complicated because of the necessity of divorced eutectoid transformation with associated deformation. On the other hand, an idea of forming the $(\alpha+\theta)$ microduplex structure without thermomechanical processing in ultrahigh carbon steels was addressed [12], but the heat treatment by multiple pass in this idea is a little time-consuming.

The present paper is to reveal a Mn-alloyed ultrahigh strength steel with UFG microstructure produced by a novel procedure. The key of the idea is selecting an optimal warm deformation condition to realize superplasticity of the steel and then ensuring ultrahigh strength after deformation without the need of supplementary heat treatment. Besides, special attention is paid to the effect of composition design and the microstructure refinement through predeformation. In this way, the procedure combined with superplastic forming for producing the ultrahigh strength steel is simplified.

2. Experimental

The Fe–0.56C–2.12Mn–1.76Si–0.95Cr–0.25Mo (mass%) steel was designed and used in this study. Fig. 1(a) shows schematic dia-

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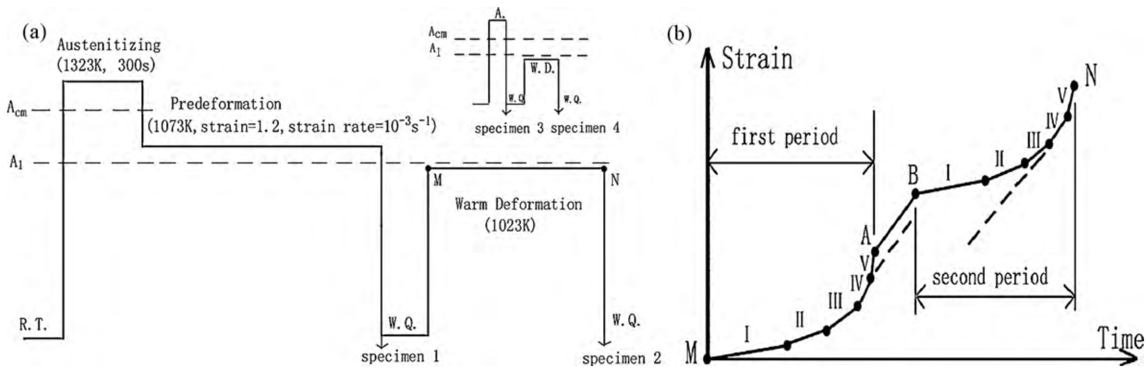
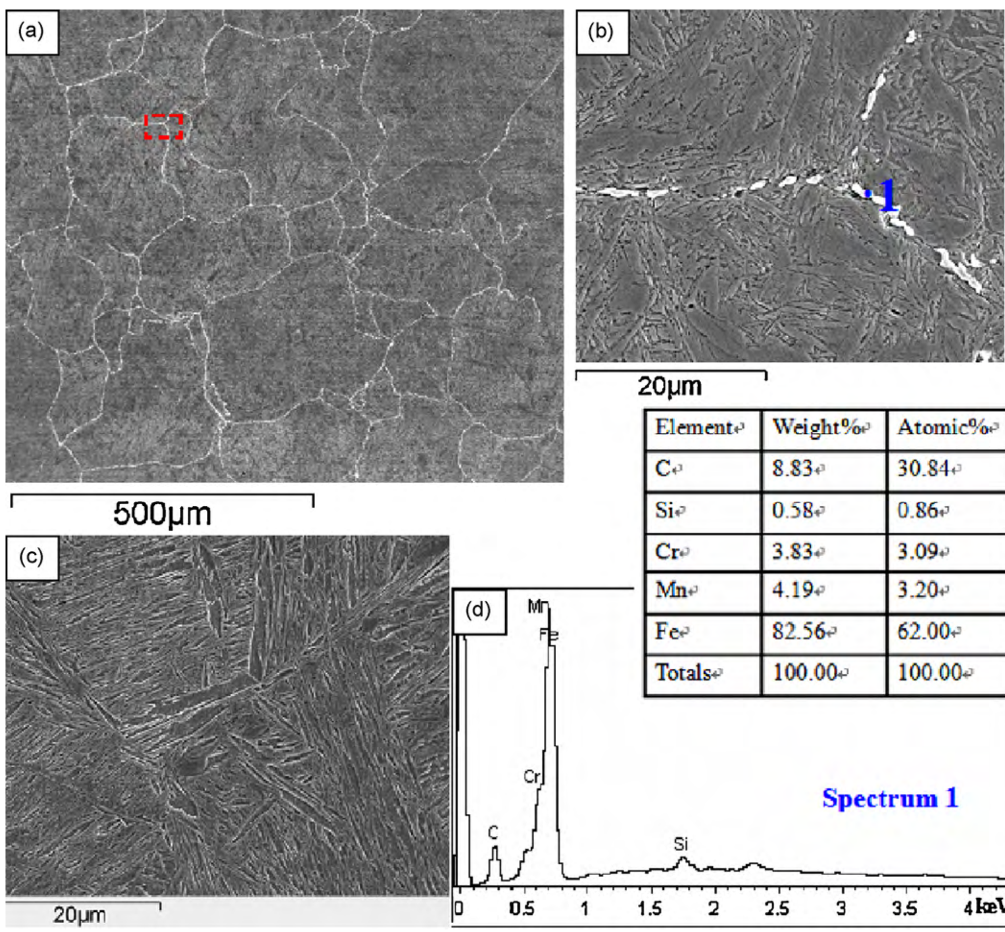


Fig. 1. (a) Schematic diagram of the novel procedure and (b) strain–time curve of the warm deformation step.



Element	Weight%	Atomic%
C	8.83	30.84
Si	0.58	0.86
Cr	3.83	3.09
Mn	4.19	3.20
Fe	82.56	62.00
Totals	100.00	100.00

Fig. 2. (a) The SEM morphology of specimen 1. (b) The magnification of the zone within the red dashed line frame in (a). (c) The SEM morphology of specimen 3. (d) The composition analysis on the blue spot in (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

gram of the procedure for producing the ultrahigh strength steel with UFG microstructure. A_1 and A_{cm} represent pearlite–austenite transformation (in equilibrium) temperature and pro-eutectoid cementite–austenite transformation (in equilibrium) temperature in Fe–C phase diagram, respectively. Here we consider the designed steel as a hypereutectoid steel since the alloying in the present work leads to a lower eutectoid carbon content (∼0.5%C) [13]. The procedure in Fig. 1(a) mainly includes three steps, i.e. austenitizing, predeformation and warm deformation. For simulation of this procedure, long cylinders 8 mm in diameter and 90 mm in length cut from forging billets were firstly used for austenitizing and predeformation. Then specimens 6 mm in diameter and 10 mm in length (hereafter, specimen 1) machined from the central deformation part of the long cylinders underwent warm deformation, leading to the formation of final product (hereafter, specimen 2). In addition, a procedure without the predeformation step was discussed for the purpose of comparison with the above procedure (the other steps kept unchanged, as shown briefly in the upper right side of Fig. 1(a)). The simulation of this procedure is as follows: long cylinders 8 mm in diameter and 90 mm in length cut from forging billets were used for austenitizing and then specimens 6 mm in diameter and 10 mm in length (hereafter, specimen 3) machined from the central part of the long cylinders underwent warm deformation, leading to the formation of specimen 4. Specimens 3 and 4 obtained during this procedure were used to compare with specimens 1 and 2, respectively. Water quenching (W.Q.) was applied