JOURNAL OF MATERIALS SCIENCE **39** (2004) 4679–4681 LETTERS

Excellent mechanical properties of a spray deposited ultrahigh carbon steel after hot rolling

G. M. LUO , J. S. WU
Key Lab. for High Temperature Materials & Tests of Ministry of Education, Shanghai Jiaotong University, Shanghai 200030, People's Republic of China
E-mail: gmluo@vip.sina.com

J. F. FAN , H. S. SHI, Y. J. LIN, J. G. ZHANG
Shanghai Baosteel Research Institute, Shanghai 201900, People's Republic of China

Ultrahigh carbon steels (UHCS), which are hypereutectoid steels containing 1.0 to 2.1% carbon, have been a topic of much interest for their unique superplasticity at elevated temperature and excellent mechanical properties at room temperature. Relationships between microstructure and mechanical properties have been published elsewhere [1, 2], and a good combined mechanical property at room temperature showing tensile strength of 1080 MPa and total elongation of 20% was achieved in spheroidized carbide microstructures [3, 4]. To obtain these excellent properties, some thermomechanical processing routes, including hot-and-warm working [5], a divorced eutectoid transformation (DET), a DET with associated deformation (DET-WAD) [6], and hot extrusion [7], have been carried out on UHCS to produce fine ferrite grain structure with a uniform distribution of fine spheroidized carbides.

In this investigation, similar high tensile mechanical properties were achieved in the spray formed UHCSs after a simple one-pass rolling or a controlled-cooling hot rolling process. We discovered that high tensile mechanical properties were not only obtained in spheroidized microstructure but also in a novel microstructure of fine pearlite colonies surrounded by spheroidized carbides after controlled hot rolling in the spray formed UHCS.

The studied UHCS alloy contains 1.2 wt% C, 2.0 wt% Si, 1.5 wt% Cr, 0.5 wt% Mn, and a balance of Fe (UHCS-1.2C). The addition of Si inhibits the formation of hypereutectoid carbide network and increases the A_1 transformation point (the Ac_1 of the present steel is 794 °C and the Ar_1 is 724 °C according to a thermal analysis test).

The UHCSs were melted in vacuum induction furnace and then cast into rods as the feedstock for spray forming. The as-received ingot of UHCSs was heated in a induction-furnace, and soaked for 20 min at a temperature of about 150 °C above the melting point. The molten metal was atomized into a spray of liquid droplets by nitrogen with a pressure of 2.2 MPa. The droplets were cooled and driven towards a revolving substrate to form a condensed product.

Rolling bars of 15 mm thickness and 20 mm width were cut from the deposited UHCS-1:2C. After soaking for 20 min at 850 °C, the deposited UHCS-1.2C bars were hot-rolled to 6.0 mm thick (60% reduction) by one pass at a strain rate of approximately 8 s^{-1}. Controlled hot rolling route was also carried out to further improve the mechanical properties of UHCS-1.2C steel. The bars were firstly hot rolled in 60% reduction at 1000 °C by one pass, then they were immediately put into resistance furnaces with temperatures of 700, 750, and 800 °C, soaking for 150 min followed by air cooling.

Tensile tests were performed at room temperature on the as-hot-rolled deposited UHCS-1.2C samples with the gauge length of 8 mm at an initial strain rate of 5×10^{-3}/s. Longitudinal sections of rolled steels were polished and etched in 2% Nital. A microstructural study was carried out by optical metallography and S-4200 field emission scanning electron microscope (SEM).

The room temperature tensile properties of the as-hot-rolled deposited UHCS-1.2C samples are shown in Table I. As it can be seen, all the tensile mechanical properties are promising. Fig. 1 shows the SEM microstructures of spray formed UHCS-1.2C steel that was rolled at 850 °C by 60% reduction. Fine spheroidized carbides are uniformly distributed in the ferrite matrix which can be explained by the following three reasons: one is that the microstructure of the spray formed UHCS-1.2C steel is fine and homogenous, second is that many undissolved carbide particles and some lamellar cementite plates remain after being soaked at 850 °C for 20 min, and the third is that lamellar

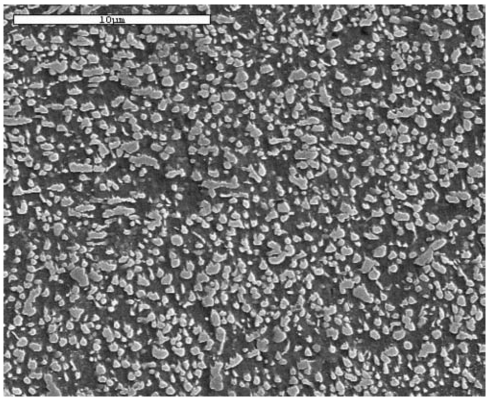

Figure 1 The SEM microstructure of spray formed UHCS-1.2C rolled at 850 °C.

TABLE I The room temperature tensile properties of UHCS-1.2C samples

Sample no.	Rolling temperature (°C)	Soaking temperature (°C)	Yield strength (MPa)	Fracture strength (MPa)	Elongation (%)
1	850	–	959.1	1161.0	17.5
2	1000	700	756.2	1087.9	19.6
3	1000	750	634.8	931.9	21.8
4	1000	800	862.6	1298.8	18.0

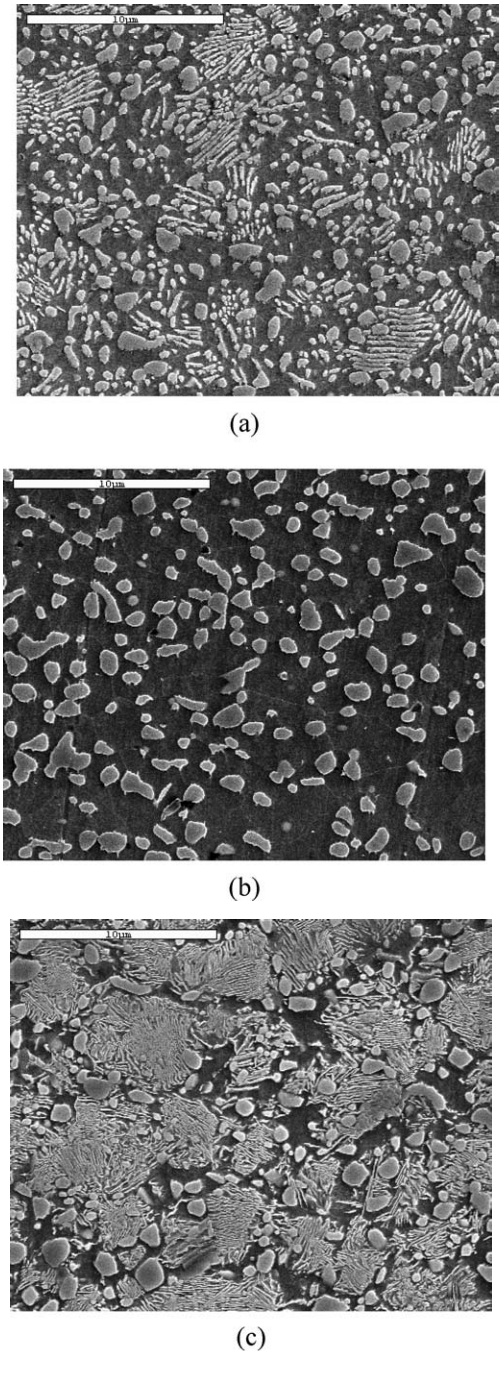

Figure 2 The SEM microstructures of UHCS-1.2C at different post-rolling isothermal soaking temperatures of 700 °C (a), 750 °C (b), and 800 °C (c).

cementite plates are broken into particles by heavy hot rolling deformation, and thus, the undissolved and broken carbide particles grow during air cooling below the Ar_1 point.

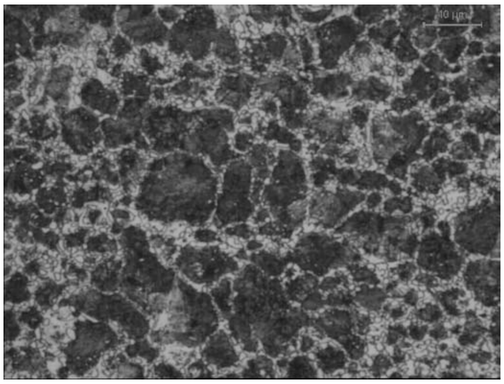

Figure 3 The optical microstructure of UHCS-1.2C at post-rolling isothermal soaking temperature of 800 °C.

The microstructures of the hot-rolled spray formed UHCS-1.2C samples at different post-rolling isothermal soaking temperatures after being rolled at 1000 °C are shown in Fig. 2. The post-rolling isothermal soaking temperature has great effect on the microstructure and tensile properties of the as-hot-rolled samples. Fully spheroidized carbide microstructure (Fig. 2b) was achieved at 750 °C isothermal soaking temperature and this is consistent with the isothermal annealing theory that spheroidization occurs when isothermal soaking at a temperature about 20 °C below the A_1 transformation point. The spheroidized samples have the same level tensile properties as those of other reported UHCSs but in a more simple processing route. Decreasing the post-rolling isothermal soaking temperature decreases the spheroidized carbide size and increases the amount of pearlite with coarse lamellar spacing (Fig. 2a), and thus increases the tensile strength and decreases the ductility slightly. Increasing the isothermal soaking temperature to 800 °C in the sample after being rolled at 1000 °C, a novel morphology of fine pearlite colonies surrounded by "grain boundary carbide networks" was observed in low magnification (Fig. 3); when observed in higher magnification, as shown in Fig. 2c, the lamellar spacing of the pearlite colonies is fine and the "grain boundary carbide networks" are carbide particles distributed in ferrite around the pearlite.

The microstructures shown in Fig. 2a and b are observed extensively in the UHCSs [8, 9]; the microstructure shown in Fig. 2c with high tensile mechanical properties, however, has not been reported elsewhere up to now. The pearlite colonies with fine interlamellar spacing contribute to high strength of UHCS, and the connective ferrite matrix with carbides distributed on it contributes to high elongation of UHCS.

All the microstructures and tensile properties above cannot be obtained in the as-received ingot metal of UHCS since thick carbide networks cannot be removed after hot rolling by one pass at 850 °C or 1000 °C. The spray forming technique, therefore, is of great benefit to the production of UHCSs and their subsequent hot working.

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Received 1 December 2003
and accepted 1 April 2004