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Development of Carbon Steels with High Strength and Ductility by Repetitive Side Extrusion and Heat Treatment

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The development of an ultrafine-grained carbon steel during repetitive shear deformation of side extrusion and the properties after heat treatment were investigated. Side extrusions were carried out at room temperature using materials of 0.50%C, 0.25%C, 0.15%C and ultralow-carbon steel. The repetitive side extrusions with a constant lateral pressure were carried out up to 3 passes without rotation. These steel specimens after 3 passes were annealed at a constant temperature of 600°C for various treatment times. After side extrusion and heat treatment, the tensile strength became lower and total elongation increased with decreasing hardness. The uniform elongation of tensile experiments increased with increasing heat treatment time for all materials.

Key words: Shear deformation, Ultrafine grain, ECAE, Tensile strength, Vickers hardness

1. INTRODUCTION

Several severe plastic deformation processes such as the ECAE (equal channel angular extrusion) process [1-5], ARB (accumulate roll bonding) process [6], and ball-milling process [7] are effective for obtaining high-strength materials. Among these processes, pure shear deformation can be repeatedly imposed on materials in ECAE, so that intense plastic strain is produced within the materials without any change in the cross-sectional dimensions of the workpiece. Many studies researches have been reported concerning with aluminum, aluminum alloys and copper deformed by the ECAE process. The authors reported the properties of ultralow-carbon steel deformed by repetitive side extrusion [8-10]. Ultrafine-grained steel with dimensions of 0.5 x 0.2μm was developed and its tensile strength was above 1000MPa after 10 deformation passes. However, uniform elongation of the deformed specimens was almost zero.

In this paper, in order to obtain high-strength steel with balanced ductility, carbon steel samples with various carbon contents are deformed by the repetitive shear deformation process and then heat treated. The properties of the materials, such as Vickers hardness, tensile strength, total elongation and microstructure, are examined.

2. EXPERIMENTAL

2.1 Experimental apparatus

The multiaxis experimental apparatus was used for the side extrusion (ECAE) process [11]. Four punch-pull rams can generate force of up to 160kN and travel a distance of up to 100mm driven by pressurized oil flowing through the servo valves, which are controlled by manual operation, a function generator with a maximum frequency of 100Hz, or the personal computer. The two columns and the crosshead in the middle of the apparatus are for supporting a manual hydraulic jack that holds down the cover plates of the fixture for side extrusion with a force of up to 700kN. The dimensions of the channels are 7 x 7mm or 10 x 10mm and the inner surface is polished to a smooth finish.

The heat treatment processes were carried out by means of an infrared image furnace. In the furnace, there are 15 infrared lamps in the upper and the lower parts respectively. The electric powers of the lamp and the furnace are 1000W at 100V and 30kW at 200V, respectively. The electric current of the furnace is controlled manually. Argon gas supplied into the furnace to protect the infrared lamps and to prevent the oxidation of workpieces.

2.2 Experimental materials

The experiments were carried out using 0.50%C, 0.25%C, 0.15%C and ultralow-carbon steel workpieces. The chemical compositions are shown in table I. As-received materials were steel plates after hot rolling. The initial Vickers hardnesses were HV97 for ULC, HV126 for 0.15%C, HV189 for 0.25%C and HV273 for 0.50%C.

The specimens were machined, in the rolling direction, to the dimensions of 10 x 10 x 35mm for ULC and 7 x 7 x 30mm for the other carbon steel samples.

2.3 Experimental procedures

In the repetitive side extrusion process, the specimen was extruded without rotation at each pass, as shown in

Table I Chemical compositions of carbon steels

	C	Si	Mn	P	S	Fe
Ultra low carbon steel	0.0015	0.009	0.09	0.005	0.004	bal.
0.15%C steel	0.15	0.06	0.32	0.014	0.016	bal.
0.25%C steel	0.25	0.21	0.54	0.023	0.021	bal.
0.50%C steel	0.49	0.18	0.66	0.015	0.01	bal.

(wt%)

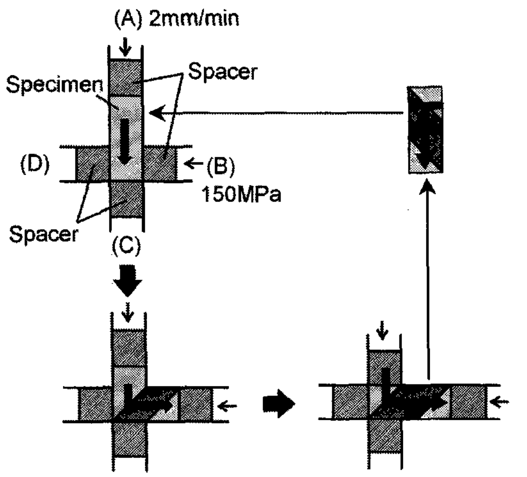

Fig.1 Schematic representation of repetitive side extrusion process

figure 1. This process is called route A. The experiments were carried out at a constant speed of 2mm/min using polytetrafloeraethylene (PTFE) sprayed film as a lubricant. A constant lateral pressure of 150MPa was applied to the specimens. The experiments were carried out at room temperature. The specimens were side-extruded up to 3 passes. For the present experiments, the equivalent strain for one pass is 1.15 [12].

After 3 passes, the side-extruded specimens were annealed at a constant temperature of 600°C, varying the heat treatment time from 1min to 60min in Ar atmosphere. Vickers hardness was used as a measure of heat treatment adequacy. The hardness of specimens was measured after each heat treatment by means of the Vickers hardness tester with a load of 5000g for a duration of 15s. Heat treatment was repeated when decrease in hardness was inadequate.

After side extrusions and heat treatment, the tensile strength and the elongation were measured. For the tensile tests, tensile specimens with a width of 4.5mm and a gage length of 5mm were machined from the side-extruded specimens. Tensile testing using by means of the testing machine of the Shimadzu Autograph AG-50kNE were carried out at a constant crosshead speed of 0.5mm/min.

The optical microstructural observation was carried out using a specimen etched with 1% Nital, which was machined from a rectangular side-extruded specimen into a plate parallel to the top plane along the longitudinal axis of the specimen. The microstructures were observed by transmission electron microscopy.

3. RESULTS and DISCUSSION

3.1 Mechanical properties after repetitive side extrusion

All carbon steel samples could be deformed by repetitive shear deformation without any failure.

Figure 2 shows the relationship between Vickers hardness and number of passes of shear deformation. For all carbon steel samples, Vickers hardness after 1 pass increases to 100 compared with the initial hardness. Hardness increases with increasing number of passes of shear deformation. Hardnesses after 3 passes were HV223 for ULC, HV253 for 0.15%C, HV330 for

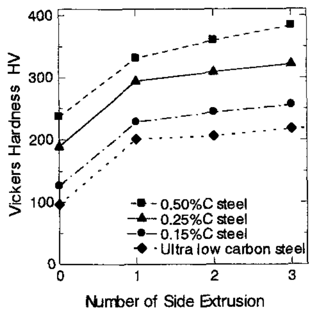

Fig.2 Relationship between Vickers hardness and number of passes of side extrusion

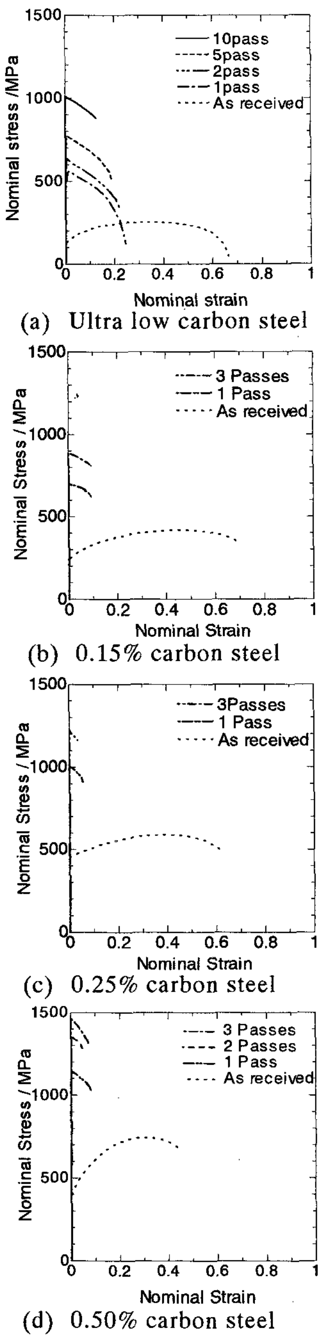

Fig.3 Relationship between nominal stress and nominal strain for the as-received specimen and specimens after side extrusions

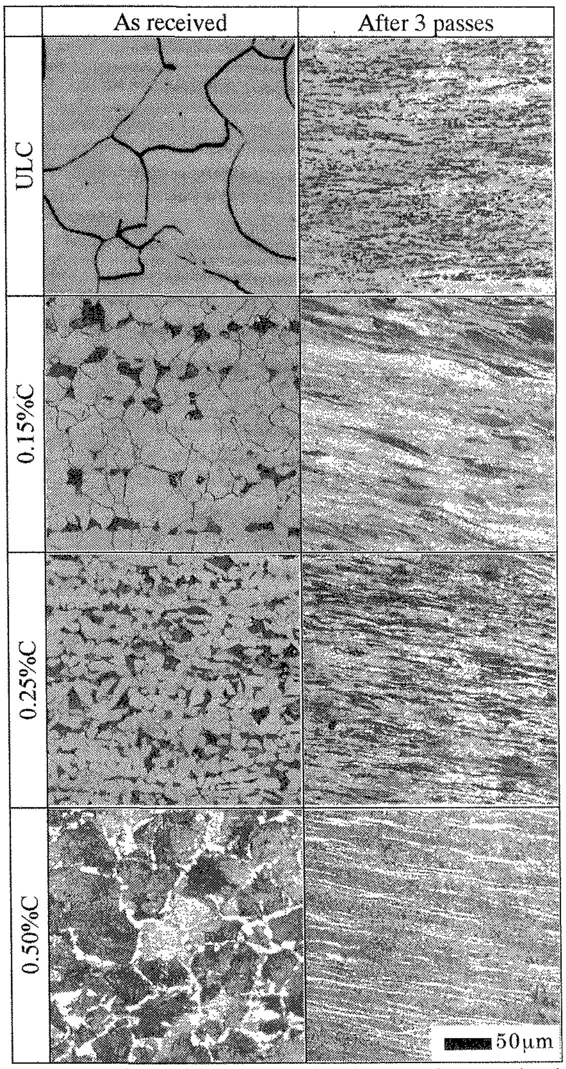

Fig.4 Optical micrographs of carbon steel as received and after 3 passes of side extrusion

0.25%C and HV384 for 0.50%C, respectively. Figure 3 shows nominal stress and nominal strain curves of all carbon steel samples after side extrusion. From the results of tensile testing, the as-received material is found to exhibit a stress-strain curve that indicates normal strain hardening, while the materials after side extrusion do not exhibit strain hardening. The stress for each specimen increases rapidly with increasing strain and reaches a maximum at lower strain. Tensile strength increases with increasing number of passes of side extrusion.

3.2 Microstructure after repetitive side extrusion.

The optical microstructures of the specimens in as-received, extruded of ULC, 0.15%C, 0.25%C and 0.50%C steel samples with 3 passes are shown in figure 4. The microstructure of the as-received 0.15%, 0.25% and 0.50% carbon steel samples consists of a dark area of the pearlite phase and a white area of the ferrite phase. The ratio of the pearlite phase increases with increasing carbon content. It is found that stronger filamentary microstructures of the ferrite phase and the pearlite phase are developed with increasing number of passes of pure shear deformation.

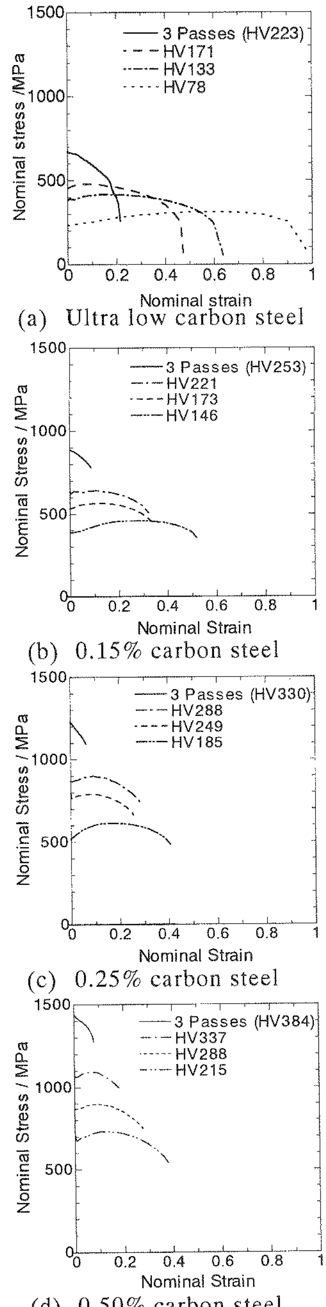

Fig.5 Nominal stress and nominal strain curves of specimens after 3 passes of side extrusion and heat treatment

From the TEM microstructure after 3 passes, the deformed structure due to plastic deformation of the ferrite phase with sub-micrometer size was observed. It was also observed that the cementite in the pearlite phase was deformed plastically.

3.3 Mechanical properties after heat treatment

Ultralow-carbon steel samples with the hardnesses of 171, 133 and 78 were obtained from the specimens after 3 passes and heat treatment. The 0.15%C steel samples of HV221, 173, and 146 were obtained from the specimens after 3 passes and heat treatment. The 0.25%C steel samples of HV288, 249 and 185 were

Table II Mechanical properties of specimens after heat treatment

	Vickers Hardness HV	Tensile Strength /MPa	Total Elongation /%	Uniform Elongation /%
ULC	223	670	15	
	171	480	30	
	133	410	50	15
	78	310	80	50
0.15%C	253	880	8	
	221	640	30	10
	173	560	35	15
	146	460	50	30
0.25%C	330	1230	6	
	288	890	18	3
	249	790	25	8
	185	640	40	20
0.50%C	384	1440	8	
	337	1090	20	7
	288	900	28	10
	215	730	38	13

obtained from the specimen after 3 passes and heat treatment. The 0.50%C steel samples of HV337, 288 and 215 were obtained from the specimen after 3 passes and heat treatment.

Figure 5 shows nominal stress and nominal strain curves of all carbon steel samples after 3 passes and heat treatment. All results of tensile testing are shown in table II. The tensile strengths become lower and total elongation increases with decreasing Vickers hardness. The uniform elongation increases with decreasing hardness for all carbon steel samples. In particular, 0.5%C steel with a tensile strength of 900MPa and a total elongation of over 20% is obtained.

3.4 Microstructure after heat treatment.

After heat treatment, the microstructures become a mingled structure and the static recovery and grain growth of the ferrite phase can be observed on all carbon steel samples with decreasing Vickers hardness.

The TEM micrographs of 0.25%C and 0.50%C steel specimens after 3 passes and specimens after heat treatment are shown in figure 6. From the results of TEM observation, the ferrite phase with a grain size of 1μm was observed in the microstructure of all carbon steel samples after heat treatment, and the grain size became larger with decreasing Vickers hardness. It is almost the same hardness as those of specimens for which uniform elongation was observed on the stress-strain curve and of specimens for which a static recovery process is observed.

In the pearlite phase, the cohesion of cementite from the lamellar structure occurs after heat treatment. Then the nanoscale spherulitic cementite is observed. The grain size of ferrite of the pearlite phase is sub-micrometer scale due to the presence of the ultrafine spherulitic cementite. Considering the Hall-Petch relation, it is believed that the structure maintains high strength after heat treatment because the grain size of ferrite remains an almost sub-micrometer order.

From these results, it is estimated that the presence of grains with the size of approximately 1μm in the ferrite phase and the presence of nanoscale spherulitic cementite in the pearlite phase are very important for the uniform elongation and for the strength, respectively.

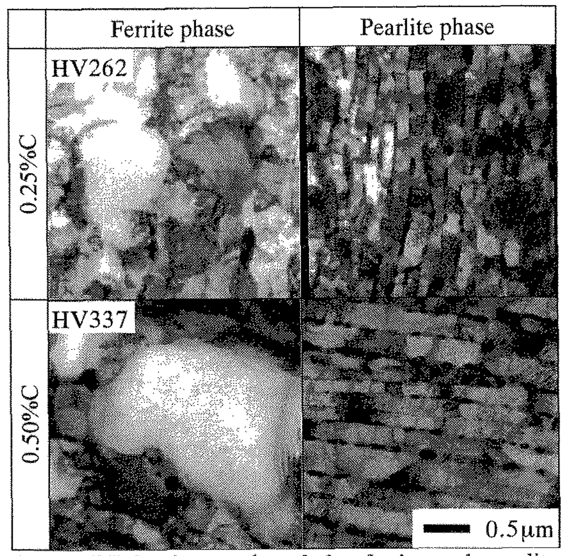

Fig.6 TEM micrographs of the ferrite and pearlite microstructures of 0.25%C steel sample with HV262 and 0.50%C sample with HV337 after 3 passes and heat treatment

4. CONCLUSION

The repetitive side extrusion processes with a constant lateral pressure and the heat treatment process were carried out using ULC, 0.15%C, 0.25%C and 0.50%C steel samples. The results are as follows.

(1) After 600°C heat treatment of the specimen after 3 passes, the tensile strength became lower and total elongation increased with decreasing hardness. In particular, the 0.5%C steel sample with a tensile strength of 900MPa and a total elongation of over 20% was obtained.

(2) The microstructure became mingled, and static recovery and grain growth of the ferrite phase could be observed with decreasing hardness.

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