Mechanical property of lotus-type porous carbon steel fabricated by continuous casting method

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Abstract. Lotus-type porous carbon steel (AISI1018) with aligned cylindrical pores was fabricated by continuous casting method in a mixture gas atmosphere (P_N₂=0.8MPa, P_Ar=1.7MPa). Compressive yield strength of the nonporous and the lotus carbon steels was measured in the direction parallel to the transference direction. The compressive stress of the lotus carbon steel is lower than that of the nonporous carbon steel because of the existence of pores. The specific compressive yield strength (σ0.2/ρ) of as-cast lotus carbon steel is higher than that of as-cast nonporous carbon steel, which is due to the solid solution hardening of nitrogen. Although the microstructure of carbon steel changes from Widmannstätten to homogeneous ferrite and pearlite by normalizing, the yield strength does not change significantly by normalizing. The microstructure of lotus carbon steel changes from Widmannstätten to martensite by quenching so that the yield strength increases significantly.

1. Introduction

Lotus-type porous metals (lotus metals) with cylindrical pores aligned in one direction are attracted much attention because their specific strength does not decrease in the pore growth direction even if the porosity increases [1]. Recently, it became possible to fabricate lotus carbon steel homogeneously with using the continuous casting method in a nitrogen atmosphere [2]. Nitrogen is an important alloying element, which is widely used to improve corrosion resistance and mechanical properties of steels. Therefore, it is expected that the strength of lotus carbon steel increases by solid solution hardening of nitrogen [3]. In addition, it was reported that the mechanical properties of lotus carbon steel, which is fabricated in a hydrogen atmosphere by continuous zone melting method, can be changed by heat treatment [4]. Therefore, the mechanical properties of lotus carbon steel, fabricated in a nitrogen atmosphere by continuous casting method can also be improved.

In this study, lotus carbon steel was fabricated by the continuous casting method in the pressurized mixture gas of nitrogen and argon. The effects of heat treatments on the compressive strength of the lotus carbon steel were investigated.

2. Experimental procedure

Figure 1 shows the schematic illustration of the continuous casting apparatus of a pressurized gas chamber. Low carbon steel (AISI1018, Fe-0.16wt.%C) ingots were melted in the crucible by radio-
frequency induction heating in a mixture gas atmosphere (P_{N_2}=0.8\text{MPa}, P_{Ar}=1.7\text{MPa}). The molten steel was maintained for longer than 600s after the temperature reached about 1873K, and then pulled downwards at the transference velocity of 5mm/min through the mold (10 \times 30\text{mm}^2) cooled by circulated water. The lotus carbon steel plate was cut using a spark-erosion wire cutting machine (Model LNIW, Sodick Co.) in directions parallel and perpendicular to the transference direction (figure 2). The specific gravities $\rho$ and the porosities of the specimens were evaluated from their weight and volume. The diameter of the pores observed on a cross section perpendicular to the transference direction was measured by the image analyzer (Win Roof, Mitani Co.). The nitrogen concentration of the fabricated lotus carbon steel was analyzed using an oxygen-nitrogen analyzer (Model TC300, LECO Co.). As reference, a nonporous carbon steel was also fabricated in an argon atmosphere (P_{Ar}=2.5\text{MPa}).

Specimens for compression tests (7\times7\times7\text{mm}^3) were cut from the plates. The size of a specimen was determined so that the length of a side is larger than 10 times of the average pore diameter (0.45mm). Some of the specimens were compressed without heat treatment. The specimens for heat treatment were heated at 1200K for 3.6ks in an argon atmosphere, and then were cooled either by air-cooling (normalizing) or by water-quenching. Compression tests of the specimens before and after the heat treatments were carried out using a universal test machine (Model 4482, Instron Co. Ltd.). The cross-head speed was set up to be 0.2mm/min and no lubrication was used between the specimen and the spacers. The compression direction was parallel to the transference direction and the engineering stress and the engineering strain were measured. The stress at the plastic strain of 0.2% was defined as compressive yield strength $\sigma_{0.2}$ in the present work.

3. Results and discussion

3.1. Fabricated lotus carbon steel
Figure 2 shows the cross-sections perpendicular and parallel to the transference direction of the lotus carbon steel fabricated at 5mm/min. It is obvious that long cylindrical pores are aligned in the transference direction. The porosity and the average pore diameter of the lotus carbon steel are about 30% and 453 $\mu$m, respectively.

3.2. Compressive properties of nonporous and lotus carbon steel
The compressive stress-strain curves of as-cast nonporous and as-cast lotus carbon steel are shown in
The compressive stress of the lotus carbon steel is lower than that of the nonporous carbon steel because of the existence of pores. However, the specific yield strength ($\sigma_{0.2}/\rho$) of the lotus carbon steel, $42.1\times10^{-3}$ MPa m$^3$ kg$^{-1}$, is higher than that of nonporous carbon steel ($35.1\times10^{-3}$ MPa m$^3$ kg$^{-1}$). As there is not significant difference in microstructures between the nonporous and lotus carbon steel (Widmannstätten structure [5] shown in Figure 5 (a)), the morphologies of the microstructure does not effect the increase in the strength of lotus carbon steel. The nitrogen concentration in the matrix of the lotus carbon steel is 0.104 wt. %, which is almost equal to the nitrogen concentration which was reported to cause solid solution hardening of the same grade of steel [5]. Therefore, the increase in the stress of the lotus carbon steel may be attributed to the solid solution hardening of nitrogen.

3.3. Influence of heat treatment on the compressive properties

The compressive stress-strain curves of the lotus carbon steel before and after the heat treatments are shown in Figure 4. There is not significant difference in the compressive stress between the normalized lotus carbon steel and the as-cast lotus carbon steel. On the other hand, the stress of the quenched lotus carbon steel is higher than that of the as-cast lotus carbon steel. Figure 6 shows the compressive yield strength of the as-cast nonporous carbon steel and the lotus carbon steel before and after the heat treatments. The yield strength of the normalized lotus carbon steel is almost equal to the as-cast lotus carbon steel although the normalized lotus carbon steel has homogeneous ferrite and pearlite structure (Figure 5 (b)). On the other hand, the strength of the quenched lotus carbon steel is higher than that of the as-cast lotus carbon steel because the quenched lotus carbon steel has martensite structure (Figure 5 (c)). The strength of the quenched lotus carbon steel is higher than that of the as-cast nonporous carbon steel, as shown in figure 6. The specific strength of the quenched lotus carbon steel is 62% higher than that of the as-cast lotus carbon steel. This increase in the specific yield strength is considered to be attributed to the solid solution hardening of nitrogen and the martensitic transformation.

![Figure 3](image_url) Compressive stress-strain curves of as-cast nonporous and as-cast lotus carbon steel.

![Figure 4](image_url) Compressive stress-strain curves of lotus carbon steel before and after the heat treatments.

![Figure 5](image_url) Microstructures of lotus carbon steel: (a) as-cast (Widmannstätten structure), (b) normalized (ferrite and pearlite structure) and (c) quenched (martensite structure).
4. Conclusion

- Lotus-type porous carbon steel, whose porosity and average pore diameter are about 30% and 453 μm, was fabricated in a mixture gas atmosphere (P_N₂=0.8MPa, P_Ar=1.7MPa).
- The compressive stress of the lotus carbon steel is lower than that of the nonporous carbon steel because of the existence of pores. However, the specific yield strength (σ_{0.2}/ρ) of the lotus carbon steel is higher than that of nonporous carbon steel by solid solution hardening of nitrogen.
- Although the microstructure of lotus carbon steel changes from Widmannstätten to homogeneous ferrite and pearlite by normalizing, the yield strength does not change significantly. The microstructure of lotus carbon steel changes from Widmannstätten to martensite by quenching, and the yield strength becomes much higher than that of the as-cast lotus carbon steel.

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