EFFECT OF MULTIPLE DISPERSION OF HARD VC AND SOFT Cu PARTICLES ON MECHANICAL PROPERTIES IN FERRITIC STEEL[1]

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Abstract

The tensile deformation behavior of the ferritic steel containing both hard VC and soft Cu particles was compared with the results of VC or Cu single dispersion ferritic steels. The work hardening rate during tensile deformation is much larger in VC single dispersion steel than in Cu single dispersion steel. Since the interaction with dislocation is different between hard VC particle and soft Cu particle, the density of geometrically dislocations tends to be more increased in VC dispersion steel than in Cu dispersion steel, leading to the larger work hardening rate of VC steel. On the other hand, the multiple dispersion of VC and Cu particles leads to the significant increase in the yield strength as well as tensile strength without reducing ductility compared with the VC or Cu single dispersion steels. This is because a large work hardening rate is kept in spite of the high strength in the VC-Cu multiple dispersion steel.

Key words: Particle dispersion strengthening; Work hardening; Vanadium carbide; Copper; Multiple dispersion.

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1 INTRODUCTION

Particle dispersion strengthening is one of the effective strengthening mechanisms of metals. In most of practical steels, precipitates of carbide and nitride are used as the dispersion particles. Such precipitates usually have higher shear modulus compared to iron matrix and exhibit repulsive interaction with dislocations, and thus, the increment of yield strength of the steel is explained by the Orowan mechanism.[1,2] On the other hand, authors reported that soft copper precipitate (Cu particle) is also effective for increasing yield strength of steel. Since the soft Cu particles interact attractively with dislocations, the increment of yield strength in Cu steel is realized by another manner, that is, cutting mechanism.[3]

In addition to the effect on yield strength, we found that there is a difference also in the effect on work hardening behavior between hard and soft particles.[4] In the case of hard carbide dispersion steel, the stress concentration caused near the particles during deformation is relaxed by generating geometrically necessary dislocations within the matrix, while in the soft Cu dispersion steel, the stress relaxation can partially take place by plastic deformation of Cu particle itself, meaning a less amount of dislocations is introduced. This results in the higher work hardening in carbide dispersion steel compared with the soft Cu dispersion steel.

However, it has been still unclear how the yielding and work hardening behavior is influenced by the dispersed particles when the hard and soft particles are dispersed simultaneously. The dislocations introduced by straining would interact differently with each particle and form a complicated dislocation substructure. In the practical point of view, Cu would not be used in a single addition but in multiple addition together with other alloying elements including carbon. Therefore, it is important to understand the multiple effect of hard carbide and soft Cu particles on the tensile deformation behavior of steel.

In this study, a multiple dispersion ferritic steel containing both soft Cu particles and hard VC carbide particles was prepared, and then its tensile deformation behavior was compared with the results of single dispersion ferritic steels, namely, Cu dispersion steel and VC dispersion steel. The deformation substructures of these steels were then observed with TEM to discuss the effect of multiple dispersion of hard and soft particles on the mechanical properties in ferritic steel.

2 EXPERIMENTAL PROCEDURE

Table 1 represents chemical compositions of specimens used in this study. The VC-Cu steel was used for the multiple dispersion ferritic steel, while VC steel and Cu steel were the referential materials of single dispersion ferritic steels. In order to control the particle size and ferrite grain size to be identical in each steel, different heat treatment was carried out for each steel (Figure 1). VC-Cu steel and VC steel were firstly subjected to the solution treatment at 1473K for 1.8ks followed by water quenching to obtain martensitic structure, and then tempered at 873K for 3.6ks to disperse VC particles uniformly within martensite matrix. After that, the tempered VC steel and VC-Cu steel was reheated to 1273K in (austenite + VC) two phase region, kept at the temperature for 180s, and then furnace-cooled to cause ferritic transformation. On the other hand, the Cu steel was solution-treated at 1173K for 600s (austenite single phase region), and then aged at 923K for 180ks (ferrite + Cu region) to make ε-Cu (fcc) particles disperse within ferrite matrix. The volume fraction of VC particles in VC steel and VC-Cu steel is 1.41vol.% when the carbon is fully precipitated as VC carbide. In contrast, the volume fraction of Cu particles in Cu steel can be calculated to 1.45vol.% by using phase diagram. But the volume fraction of Cu particles in VC-Cu steel is difficult to be calculate, because Cu precipitated during furnace-cooling. If the precipitation reaction of Cu particle is interrupted at 723K, the volume fraction can be estimated at 1.85vol.%.

Table 1. Chemical composition of specimen used in this study. (mass%)

	C	Si	Mn	P	S	V	Cu	O	N
VC steel	0.19	0.08	0.09	0.004	0.0008	0.96	0.02	0.0030	0.0024
Cu steel	0.007	0.01	0.008	0.001	0.0011	-	1.98	0.0014	0.0037
VC-Cu steel	0.19	0.08	0.09	0.004	0.0009	0.96	2.15	0.0006	0.0027

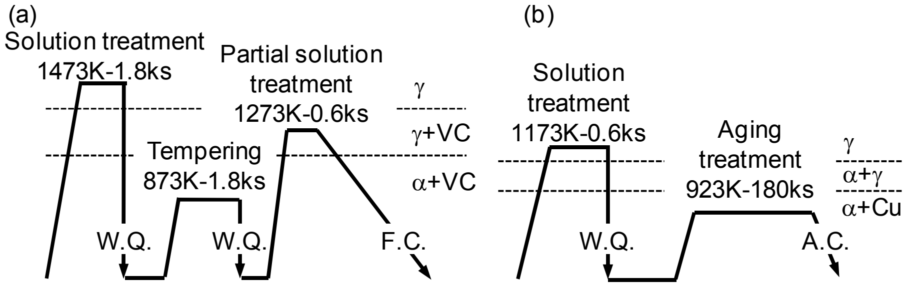

Figure 1. Heat treatment routes for VC-Cu steel, VC steel (a) and Cu steel (b).

For all the specimens obtained, microstructural observation, tensile tests and measurement of dislocation density were carried out. Microstructure was observed with an optical microscope (OM) and transmission electron microscope (TEM). Tensile testing was carried out with Instron-type testing machine at an initial strain rate of 5.6×10^{-4} s^{-1} for plate test pieces with the gauge dimension of $6mm^{l}\times3mm^{w}\times1mm^{t}$. Dislocation density (ρ) in ferrite matrix was evaluated by X-ray diffraction method using Co-Kα radiation in accordance with following equation, where b is the burgers vector (0.25nm) and η is the local strain obtained by Hall-Williamson's method.[5]

$$\rho = \frac{14.4 \times \eta^2}{b^2} \ (m^{-2})$$

3 RESULTS AND DISCUSSION

3.1 Microstructure

Figure 2 represents OM images of VC steel (a), Cu steel (b) and VC-Cu steel (c). The dislocation density of each steel is shown above the OM images. All steels have equiaxial-grained ferritic structure with low dislocation density although the grain boundaries are curved irregularly. These steels were found to have similar grain size ranging between 17 and 26μm. Figure 3 displays TEM images of VC steel (a), Cu steel (b) and VC-Cu steel (c). There is little difference in the shape and dispersion between VC and Cu particles: they have roughly spherical shape and disperse uniformly within ferrite matrix with low dislocation density. Figure 4 represents particle diameter dispersion histograms of VC steel (a), Cu steel (b) and VC-Cu steel (c), although it was impossible to distinguish between VC and Cu particles in VC-Cu steel. The average particle sizes were measured at 37nm (a), 35nm (b) and 36nm (c) in VC steel, Cu steel and VC-Cu steel, respectively.

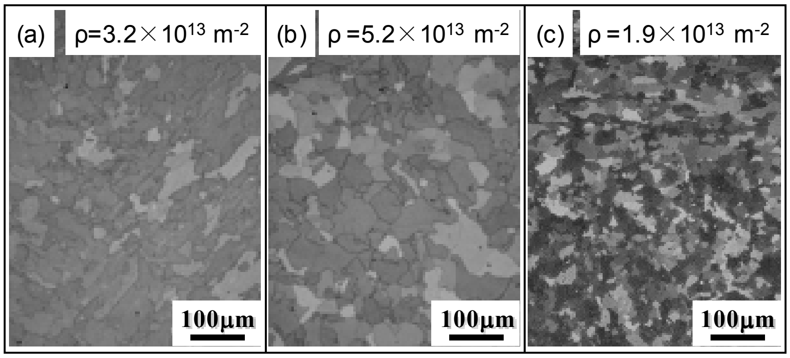

Figure 2. OM images of VC steel (a), Cu steel (b) and VC-Cu steel (c).

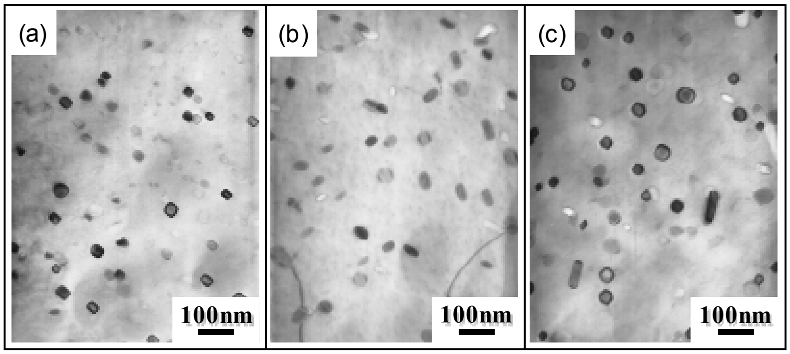

Figure 3. TEM images of VC steel (a), Cu steel (b) and VC-Cu steel (c).

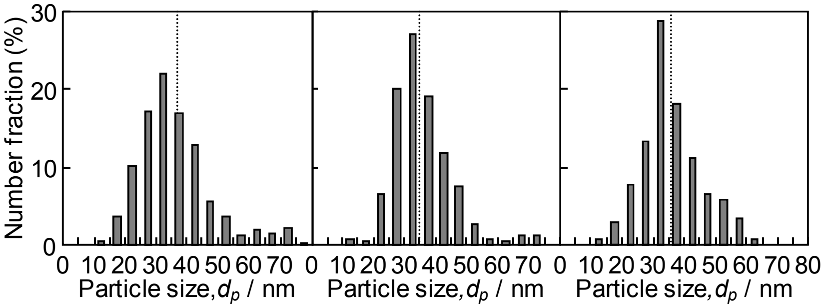

Figure 4. Particle diameter dispersion histograms of VC steel (a), Cu steel (b) and VC-Cu steel (c).

3.2 Difference in Contribution to Work Hardening Behavior Between Hard VC and Soft Cu Particles in Single Dispersion Steels

Figure 5 represents nominal stress – nominal strain curves of VC steel and Cu steel. It is clearly found that the work hardening behavior is completely different between the two specimens, while the yield stresses are in the same level. The work hardening rate of VC steel is twice as large as that of Cu steel at 5% strain. Figure 6 shows TEM images of VC steel and Cu steel tensile-deformed by 2% and 5% in nominal strain. In the VC steel, irregularly curved dislocations exist around VC particles, which suggests the cross slipped dislocations repulsively interacted each other and caused tangling, while in Cu steel, straight dislocations interacting attractively with Cu particles were observed, and besides, the dislocation density seems to be lower than that in the VC steel. Figure 7 represents changes in dislocation density during tensile deformation. It was found that the dislocation density is rapidly increased in VC steel; however that in Cu steel is not increased significantly.

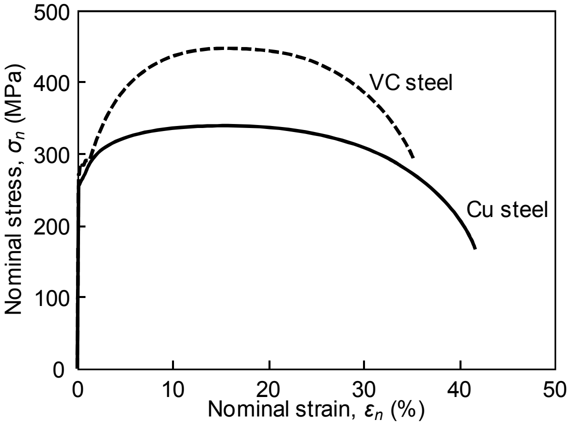

Figure 5. Nominal stress – nominal strain curves of VC steel and Cu steel.

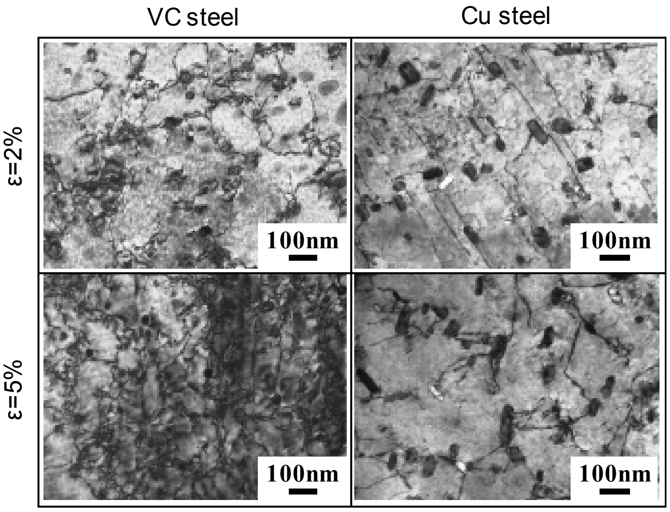

Figure 6. TEM images of VC and Cu steel tensile-deformed.

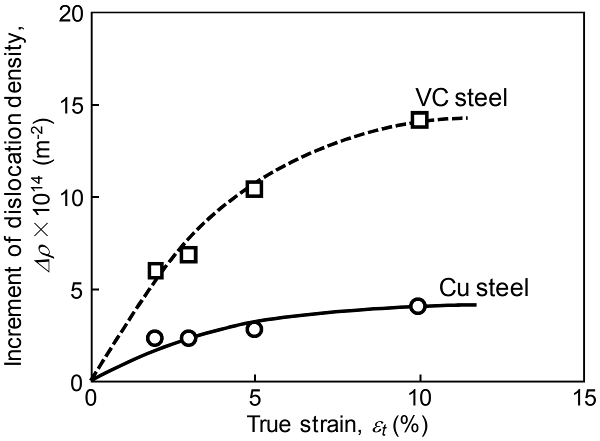

Figure 7. Change in dislocation density during tensile-deformation.

The difference in contribution to work hardening behavior between hard VC and soft Cu particles could be explained on the basis of Ashby's theory.[6] When the material containing hard particles is deformed, geometrically necessary dislocations must be nucleated around particles to accommodate the gradients of plastic deformation between matrix and dispersion particle. The increment of geometrically necessary dislocation density contribute to work hardening. On the other hand, when the particles are soft enough to be plastically deformed by the shear stress, the gradients of plastic deformation between matrix and dispersion particle are accommodated by plastic deformation of soft Cu particle. Therefore, the accumulation of geometrically necessary dislocations is retarded, resulting in the less work hardening rate in the Cu dispersion steel.

3.3 Effect of Multiple Dispersion of Hard VC and Soft Cu Particles on Tensile Deformation Behavior

Figure 8 represents nominal stress - nominal strain curve of VC-Cu steel, and those of VC steel and Cu steel shown in the Figure 5 for comparison. The multiple dispersion of VC and Cu particles leads to the significant increase in the yield strength as well as tensile strength. It should be noted that the VC-Cu steel exhibit sufficiently large work hardening rate and elongation in spite of the high strength. Figure 9 shows the change in true stress and work hardening rate during tensile testing as a function of true stress in the VC, Cu, and VC-Cu steels. The work hardening curves reveals that the VC-Cu steel possesses the same level of work hardening rate as that of VC steel. As a result, the start point of plastic instability (intersection of work hardening curve and true stress curve) is kept up to a high strain of around 13%, leading to the sufficiently large elongation in VC-Cu steel. Figure 10 represents a TEM image showing interaction between dislocations and the dispersed particles in a VC-Cu steel specimen tensile-deformed at 5%. The arrows (a) and (b) seem to correspond to VC and Cu particles, respectively. It was found that each particle interact with dislocations in each manner; repulsive interaction for VC particle, interactive interaction for Cu particle. Consequently, the VC-Cu multiple dispersion steel exhibited the characteristics of both single dispersion steels.

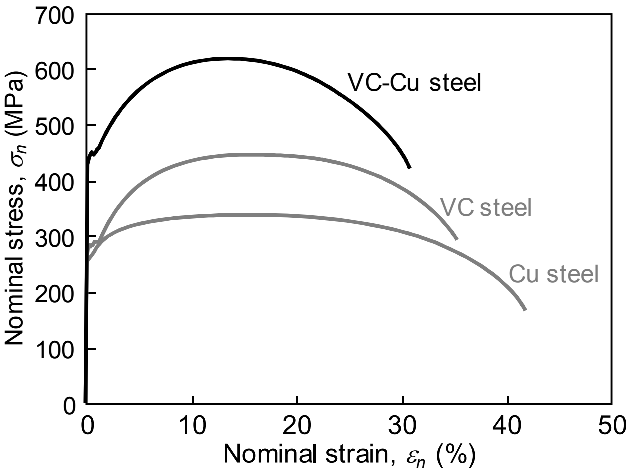

Figure 8. Nominal stress – nominal strain curve of VC-Cu steel.

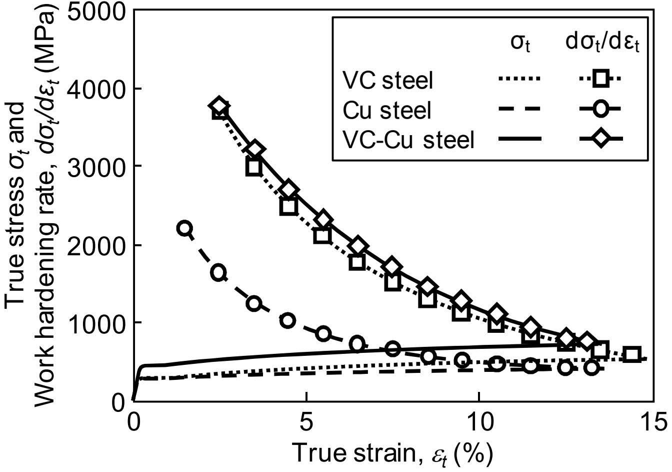

Figure 9. True stress and work hardening rate as a function of true strain.

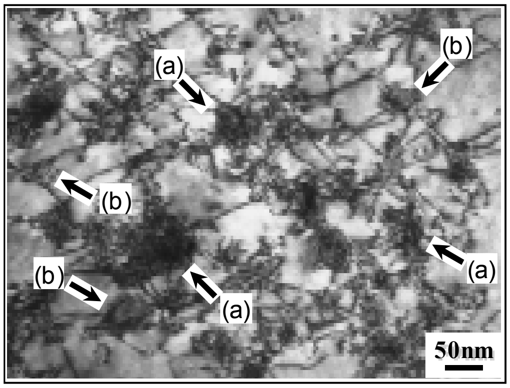

Figure 10. TEM image of VC-Cu steel tensile-deformed by 5%.

4 SUMMARY

1. Work hardening rate during tensile deformation is much larger in VC dispersion steel than in Cu dispersion steel.

2. Since the interaction with dislocation is different between hard VC particle and soft Cu particle, the density of geometrically dislocations tends to be more increased in VC steel than in Cu steel, leading to the larger work hardening rate of VC steel.

3. The multiple dispersion of VC and Cu particles leads to the significant increase in the yield strength as well as tensile strength without reducing ductility compared with the VC or Cu single dispersion steels. This is because a large work hardening rate is kept in spite of the high strength in the VC-Cu multiple dispersion steel.

REFERENCES

1 E. Orowan: Discussion in The Symposium on Internal Stresses in Metals and Alloys, Inst. Metals, London, p. 451-453, 1948.
2 T. Kitaura, H. Hidaka, T. Tsuchiyama and S. Takaki: *Tetsu-to-Hagane*, v. 91, p. 796-802, 2005.
3 K. Nakashima, Y. Futamura, T. Tsuchiyama and S. Takaki: *ISIJ Int.*, v. 42, p. 1541-1545, 2002.
4 Y. Imanami, M. Murakami, N. Nakada, T. Tsuchiyama and S. Takaki: *ISIJ Int.*, v. 49, p. 1225-1228, 2009.
5 G. K. Williams and R. E. Smallman: *Phil. Mag.*, v. 8, p. 34-46, 1956.
6 M. F. Ashby: *Phil. Mag.*, v. 14, p. 1157-1178, 1966.