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Copper-Bearing High-Strength Sheet Steels

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Abstract:

A hot-rolled sheet steel and a cold-rolled sheet steel were newly developed. They combine in themselves good formability and high strength obtained through the evolution of a ferrite microstructure and the utilization of copper phase decomposition by temperature control. Each of these steels is an extralow-carbon grade with copper added in an amount exceeding 1 mass%. The new hot-rolled sheet steel has formability equal to or higher than JIS G 3113 Grade SAPH440 and is characteristic in that its strength is increased by about 200 N/mm² by short-time heat treatment after forming. The new cold-rolled sheet steel features a very high r̄ value at 1.90 and a tensile strength of 590 N/mm². In the cold-rolled sheet steel whose strength was changed over a wide range by changing the heat treating conditions, copper precipitates were observed by high-resolution transmission electron microscope and atom probe field ion microscope. When the steel exhibits the maximum strength, precipitate particles, about 3 nm in size and composed of almost pure copper, are observed.

1. Introduction

Copper in steel is known to cause precipitation hardening of the steel. High-strength low-alloy steels and stainless steels are commercially produced in plate form by utilizing this precipitation hardening effect of copper. For sheet products in which severe cold formability is required, however, the precipitation hardening effect of copper was seldom utilized because of a lack in formability. A hot-rolled sheet steel and cold-rolled sheet steel, both combining good formability and high strength, were newly developed by reducing the carbon content and developing a ferrite microstructure and at the same time by utilizing the phase decomposition of copper through temperature control. This article discusses the strength of the new steels and their r̄ value as an index of deep drawability, and presents the observation results of the phase decomposition of copper particles that a greatly influences their strength.

2. Heat Treatment-Strengthened Hot-Rolled Sheet Steel

An ideal sheet product should be soft and formable during forming and be strong after forming. Accordingly, addition of copper was studied as one approach to the development of sheet steel whose yield point and tensile strength as well could be increased by short-time heat treatment.

2.1 Assurance of formability in copper-bearing hot-rolled sheet steel

Extralow-carbon steel and titanium-microalloyed extralow-carbon steel with copper additions of up to 1.4 mass% were vacuum melted, hot rolled, air cooled to room temperature, and test-

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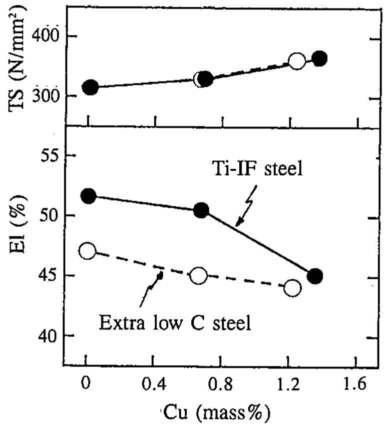


Fig. 1 Effect of copper addition on mechanical properties of extralow-carbon hot-rolled sheet steels

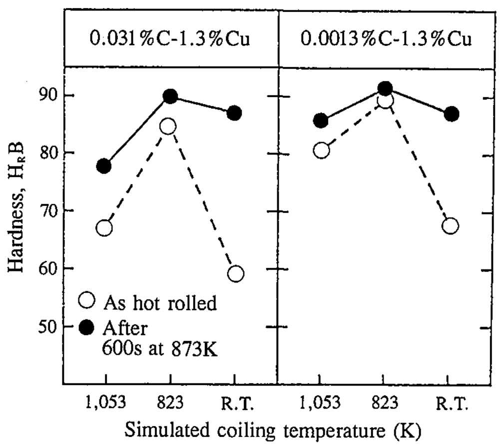


Fig. 2 Effects of carbon content and coiling temperature on hardness of 1.3%Cu hot-rolled sheet steel

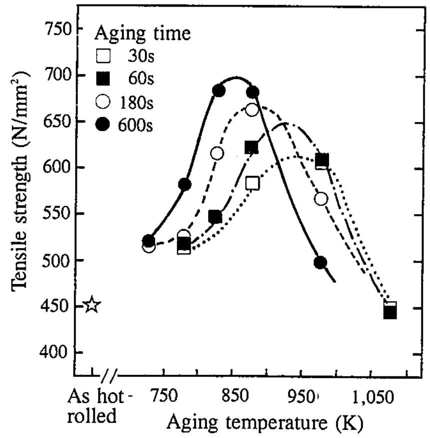


Fig. 3 Effects of aging temperature and time on tensile strength of 1.6%Cu hot-rolled sheet steel

Table 1 Mechanical properties of hot-rolled sheet steels

Steel	YP(N/mm²)	TS(N/mm²)	El(%)
Copper bearing	361	436	35.5
SAPH440	320	456	35.6

t=2.0mm

ed for tensile properties. **Fig. 1** shows the elongation and tensile strength values of the steels tested. The tensile strength of the steels almost linearly increases with increasing copper content, but the tensile strength increment is a small 40 to 50 N/mm² per 1% Cu. The elongation decreases with increasing tensile strength, but the titanium-microalloyed steel to which copper is added in amounts of up to 1.4% still has an elongation of over 40% with a sufficiently high formability. The addition of titanium improves elongation because it eliminates the interstitial elements carbon and nitrogen. This type of steel is called the interstitial-free (IF) steel.

Fig. 2 shows the effect of simulated coiling temperature on the hardness of hot-rolled sheet steels with the copper content fixed at 1.3% and the carbon content varied. The steels coiled at 1,053 and 832 K, respectively, were held at the temperature for 1 h on cooling after hot rolling and were then furnace cooled to room temperature. The steel coiled at room temperature was air cooled to room temperature after hot rolling. The open circles denote the hardness of each steel in the as-hot-rolled condition, while the solid circles denote the hardness of the steel that was held at 873 K for 600 s after hot rolling and then air cooled. The as-hot-rolled hardness and the heat-treating hardness increment widely change with the coiling temperature. The room temperature coiled steel is the softest and has the largest heat-treating hardness increment. Increasing the carbon content tends to increase the hardness of the hot-rolled sheet steel and to decrease its heat-treating hardness increment.

2.2 Effect of heat-treating conditions on strength

The heat-treating strength increment of copper-bearing extralow-carbon hot-rolled sheet steel changes with the copper content and heat-treating conditions. **Fig. 3** shows the effect of aging temperature and time on the tensile strength of 1.6%Cu steel. The test steel is a hot-rolled sheet steel coiled at a temperature lower than 573 K after hot rolling. Its mechanical properties are given in **Table 1**. There is the aging temperature at which the tensile strength of the steel becomes maximum. That aging temperature changes with the aging time. Increasing the aging time lowers the aging temperature and raises the maximum tensile strength. Holding at 823 K for 600 s provides an extremely large tensile strength increment of 230 N/mm². The change of tensile strength is due to copper phase decomposition. The observation results of the copper precipitates are described later.

3. Cold-Rolled Sheet Steel with High r̄ Value and Tensile Strength of 590 N/mm²

Many of the processes reported for manufacturing high-strength cold-rolled sheet steels with excellent deep drawability are concerned with a tensile strength of 390 N/mm² or lower. Few reports are available on processes that impart deep drawability to sheet steels with a tensile strength of 440 N/mm² or higher. Study was made on the process of producing this type of sheet steel on a continuous annealing line of high productivity by utilizing copper additions. The main issue to be investigated was the effect of copper on the recrystallization structure evolved by rapid heating during annealing and on the strength of the product.

3.1 Effect of copper on recrystallization structure

The effect of copper addition on the r̄ value of continuously annealed titanium-microalloyed IF steel is shown in **Fig. 4**. The

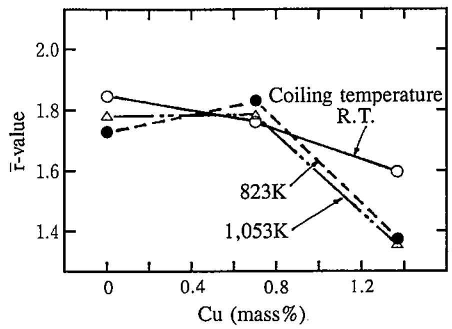


Fig. 4 Effects of copper content and coiling temperature on r̄ value of continuously annealed titanium-microalloyed IF steel

change in the r̄ value with the copper content varies with the coiling temperature in the hot rolling stage. In the 1,053 K coiled steel and 823 K coiled steel, the r̄ value markedly declines when copper is added in amounts exceeding 1%. The r̄ value of the room temperature coiled steel slightly changes with the copper content and decreases only a little when copper is added in amounts in excess of 1%.

The r̄ value of sheet steel to which copper is added in amounts over 1% changes with the coiling temperature, because the condition under which copper exists in the hot-rolled band changes with the coiling temperature. The copper is dissolved as supersaturated in the room temperature coiled steel. In the 1,053 K coiled steel and 832 K coiled steel, fine precipitates are present in the hot-rolled band as described later. These precipitates are involved in the selection of the slip system. In the cold rolling stage, there develops a small region where orientations near the {554}<225> rotate toward the {211}<011> orientation, centering on the <110> axis at 60 deg to the rolling direction. The small region meets the nucleation condition that the accumulated energy is high as compared with the {111} rolled structure. The evolution of a recrystallization structure with the orientation of the recrystallization nucleus is considered to reduce the r̄ value. To increase the r̄ value, therefore, it is essential to coil the steel at such a low temperature that copper precipitation does not occur.

3.2 Sheet steel strength increase after recrystallization

After recrystallization annealing, copper particles precipitate to increase the strength of the sheet steel. Since this precipitation treatment is conducted at a temperature under 950 K, there occurs no change in the microstructure and r̄ value. The effects of aging temperature and time on the tensile strength of 1.7%Cu titanium-niobium microalloyed IF steel are shown in **Fig. 5** as an example of precipitation treatment conditions. As can be seen from **Fig. 5**, a large strength increase is obtained from treatment over an extremely short duration of 600 s or less. The activation energy for the precipitation of copper is calculated to be 204 kJ/mol from the strength data of **Fig. 5** and is far smaller than the activation energy for the diffusion of substitutional solute elements in ferrite. This is presumably because the nucleation of copper particles is caused by the formation of metastable phases like zones, and because the activation energy for the nucleation of copper particles is diminished. This thinking does not run counter to the small-angle neutron scattering (SANS) experimental result[1)], which indicates that what precipitates in the initial phase decomposition stage of copper particles in the IF steel is not ε-copper, which is a face-centered cubic (fcc) equilibrium phase, but a body-centered cubic (bcc) nonequilibrium phase.

3.3 Formability

The chemical compositions of mill-produced steels tested for formability are given in **Table 2**, and their tensile test values are presented in **Table 3**. The new copper-bearing steel has a tensile strength of 610 N/mm², which is equivalent to that of the conventional 590-N/mm² steel, but its r̄ value is an extremely high 1.90. The main orientations in the microstructure of the new copper-bearing steel are {554}<225>, {111}<112>, and {111}<110>, as evident from the {100} pole figure shown in **Fig. 6**. The deep drawability evaluation results are given in **Table 4**. The limiting drawing ratio (LDR) of the new copper-bearing steel is 2.28, which is much better than that of the conventional 590-N/mm² steel, and is equivalent to that of the conventional 370-N/mm² steel. This result corresponds well to the r̄ value.

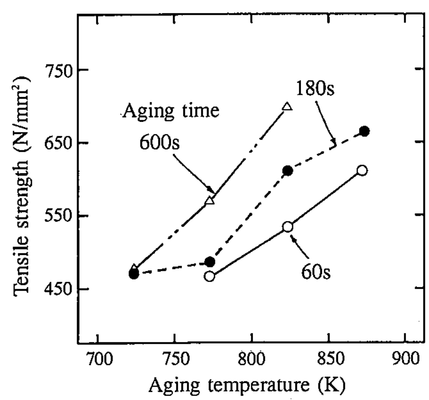


Fig. 5 Effects of aging temperature and time on tensile strength of continuously annealed 1.7%Cu titanium-niobium microalloyed IF sheet steel

Table 2 Chemical compositions of cold-rolled sheet steels tested (mass%)

Steel	C	Si	Mn	P	S	sol.Al	Ti	B	Cu	Ni
Copper bearing	0.0038	0.01	0.25	0.013	0.003	0.049	0.050	0.0005	1.26	0.44
Conv.590N/mm²	0.10	0.23	2.09	0.013	0.005	0.039	0.084	—	—	—
Conv.370N/mm²	0.0020	0.02	0.72	0.085	0.011	0.053	0.045	0.0009	—	—

Table 3 Mechanical properties of cold-rolled sheet steels tested

Steel	YP(N/mm²)	TS(N/mm²)	El(%)	r̄-value
Copper bearing	507	610	24.4	1.90
Conv.590N/mm²	429	610	23.9	1.10
Conv.370N/mm²	236	403	37.6	1.54

t=0.8mm

Table 4 Limiting drawing ratio (LDR) of cold-rolled sheet steels tested

Steel	LDR
Copper bearing	2.28
Conv.590N/mm²	2.05
Conv.370N/mm²	2.25

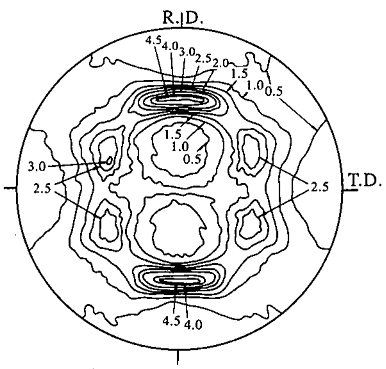


Fig. 6 {100} pole figure of new steel

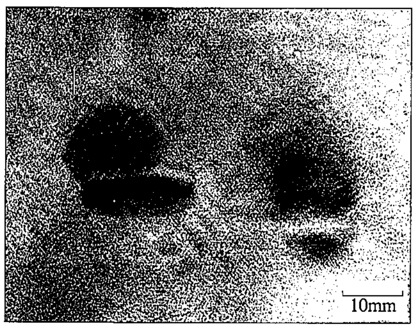
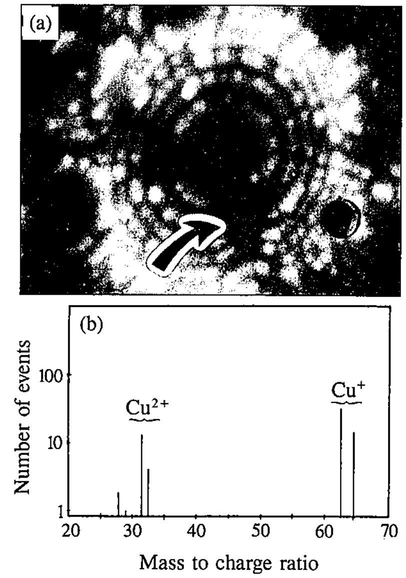


Photo 1 HR-TEM observation of 1.6%Cu titanium-microalloyed IF steel aged at 1,073 K for 30 s



(a) FIM image of a Cu rich precipitate

(b) AP spectrum of the Cu-rich prccipitate

Fig. 7 AP-FIM observation of 1.6%Cu titanium-microalloyed IF steel aged at 823 K for 600 s

4. Observation of Copper Precipitates

The copper precipitates in the 1.6%Cu steel whose strength was significantly changed by changing the heat-treating conditions were observed by high-resolution transmission electron microscope (HR-TEM) and atomic probe field ion microscope (AP-FIM). **Photo 1** is an HR-TEM micrograph of the copper precipitate in the 1.6%Cu titanium-microalloyed IF steel in the over-aged condition in which its strength was reduced from the maximum level. The precipitate is ε-copper, about 20 nm in size. A large strength increase cannot be expected from larger ε-copper precipitate particles.

Fig. 7 shows the AP-FIM observation and analysis results of the copper precipitate in the 1.6%Cu titanium-microalloyed IF steel precipitation heat treated under such conditions as to maximize the strength. A FIM image is shown in **Fig. 7**(a). The dark region denoted by the arrow is a copper-rich precipitate measuring about 3 nm in size. The composition of the precipitate as analyzed by AP-FIM is shown in **Fig. 7**(b). Few iron atoms are recognized in the parent phase, but Cu^{2+} and Cu^{+} are detected. This means that the precipitate is made up mostly of pure copper.

5. Conclusions

Two new sheet steels were developed by utilizing the decomposition of the copper phase. One is a hot-rolled sheet steel that has a tensile strength of 440 N/mm^2 and excellent formability during forming and is increased in strength by about 200 N/mm^2 by short-time heat treatment after forming. The other is a cold-rolled sheet steel that features a high strength of over 500 N/mm^2 and a high $\bar{r}$ value as well.

References

1) Asano, K., Okuda, K., Osamura, K., Furusaka, M., Kishida, K., Kurosawa, F.: Collected Abstracts of 1991 Autumn Meeting of Japan Inst. Metals, 1991, p. 260