Effect of Nano-Scale Copper Sulfide Precipitation on Mechanical Properties and Microstructure of Rapidly Solidified Steel with Tramp Copper Element

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Copper is one of the main residual elements in steel, especially in recycled scrap steel, whereas sulfur is one of the main impurities in steel. A large quantity of slag and CO₂ is produced during the process of removing the sulfur from the steel. However, copper and sulfur may combine to form copper sulfide, especially during the rapid cooling process. In this paper samples containing and not containing fine copper sulfide are prepared by the rapid solidification process. The microstructure, sulfide precipitates, and the mechanical properties of the samples are investigated by optical microscopy, Scanning Electron Microscope (SEM), Transmission Electron Microscopy (TEM), and the tensile testing. A large difference in the yield strength between the samples containing and not containing copper sulfides is observed. Each contribution of solid solution strengthening, grain refining strengthening, and sulfide precipitates strengthening in the samples with and without copper sulfide has been discussed. Particular attention has been paid to effect of the nano-scale copper sulfides, that is, main factor contributing to the alloy strengthening. Contribution of reduction of the copper sulfide particle size has also been discussed by comparing the results of two rapid solidification processes with different cooling rates. [doi:10.2320/matertrans.47.2312]

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1. Introduction

Copper is one of the major residual elements in steel because it is difficult to remove during the steelmaking process. The concentration of copper in steel has been increasing gradually due to the continuous recycling of scrap steel. Copper may cause hot shortness at high temperatures since it is harder to be oxidized than the iron matrix. However, it could be used as an alloying element in some steels to improve the corrosion resistance and to enhance the mechanical properties.¹⁻³⁾

Sulfur is an undesirable impurity in steel since it may lead to low toughness and poor weldability. Sulfides in steel also cause problems due to their size and morphology. Large sulfides usually result in bad mechanical properties, and non-spherical sulfides cause some properties with anisotropy. However, the removal of sulfur from steel results in a large quantity of slag and CO₂ exhaust.

A lot of attention has been given to the strengthening effects from the copper solid solution or the copper particle precipitates in steel.¹⁻³⁾ However, copper and sulfur in steel may form copper sulfide on a nano-scale size, especially during the rapid solidification/cooling process.^{4,5)} These nano-scale copper sulfides may also increase the strength and work hardening ability of steel. In a previous paper,⁵⁾ the present authors have investigated the microstructure, sulfide precipitates, and the tensile test properties of an as-cast (strip casting) sample and an annealed sample. Nano-scale copper sulfide that were found in the as-cast samples contributed the most to the difference in the yield strength between the as-cast and the annealed samples. However, the as-cast and the annealed samples had very different microstructure. Therefore, it may not be appropriate to use the same criterion for the as-cast sample and the annealed sample when estimating the contribution of the copper sulfide to the yield strength and strain hardening ability.

In this paper, two as-cast samples, one with copper sulfide

and the other without copper sulfide, are prepared by the rapid solidification process in the laboratory to make sure that they have almost the same microstructures. The microstructures, sulfide precipitates, and the mechanical properties are investigated to understand the copper sulfide precipitation during the rapid solidification process and the precipitates' contribution to the yield strength and strain hardening ability. In addition, the factors affecting the size of the copper sulfide are discussed by comparing the results of the laboratory Cu mould casting process with those of the strip casting process.

2. Experimental Procedures

2.1 Materials and casting conditions

The chemical compositions for four kinds of steel samples, which are designated as 8Cu0S and 8Cu1S as well as AC and HA steel, are shown in Table 1. 8Cu0S and 8Cu1S samples are prepared in an induction heating furnace under vacuum atmosphere in the laboratory. After 3 kg of electrolytic iron is melted, the alloying elements (Mn, Si, Cu, S) are added to the melted iron. The melt is then cast into a water cooled copper mould. A specimen with a 3 × 60 × 200 mm steel plate on one side and a 5 × 60 × 200 mm steel plate on the other side can be obtained as shown in Fig. 1. Hereafter, this casting process is named as Cu mould casting process and only the plates with the 3 mm thickness are discussed in the paper. As shown in Fig. 1(b), a set of temperatures is measured at the center of the point on the 3 mm thickness plate during the casting process. AC sample is a strip casting sample produced by a twin drum caster at the Mitsubishi Heavy

Table 1 The chemical composition of the samples, mass%.

Sample	C	Si	Mn	P	S	Cu	Al _T	thickness
8Cu0S	0.072	0.17	0.68	0.016	0.0023	0.085	0.004	3 mm
8Cu1S	0.075	0.16	0.68	0.019	0.0132	0.086	0.003	3 mm
AC/HA	0.08	0.05	0.54	0.12	0.010	0.07	0.01	3.6 mm

Fig. 1 As-cast samples produced by lab rapid solidification process.

Industries Ltd., Hiroshima R&D Center. The casting speed is 0.333 m/s, the casting temperature is about 1846 K, the casting weight is 200 kg, and the mold width is 600 mm. One type of post-treatment, homogenization annealing, is applied to the AC sample to homogenize the microstructure in the fluid argon atmosphere for 1.08×10^4 s at 1473 K and then furnace cooled to room temperature. Hereafter the treated strip is called the HA sample. More detail description of the preparation of AC and HA samples could be found in a previous paper.⁵⁾

2.2 Analysis methods

The microstructure, grain size distribution and the precipitates are investigated on the section of 1/4 thickness of

sample by optical microscopy, SEM and TEM. Samples are etched with 3 vol% nitric acid (Nital) to reveal their microstructures. The grain size distribution is performed on a LEO 1550 SEM coupled with an orientation image microscopy (OIM) electron backscattering diffraction technique (EBSD) system after the sample is electrochemically polished. Carbon extraction replicas are prepared through the standard procedures for TEM observation. The replicas are floated on molybdenum grids, and a beryllium specimen holder is used to avoid a possible detection of Cu from the grid and the specimen holder. The TEM observation is performed on a JEM-2000FXII microscope operated at 200 kV and coupled to an Energy Dispersive X-Ray Spectroscopy (EDS).

The tensile properties of the samples in the Transverse Direction (TD) are measured with a Shimadzu AG-50KNG universal test machine at a strain rate of $2.5 \times 10^{-4} \text{ s}^{-1}$ at ambient temperature. The gage section of these tensile specimens has a width of 8 mm, a length of 25 mm, and a thickness of 2.6 mm for 8Cu0S and 8Cu1S samples while 10 mm (width), 30 mm (length) and 3.2 mm (thickness) for AC and HA samples. Four specimens are tested for each sample and the tensile properties are determined by the displacement-load curves. The displacement is measured by an extensometer. All the initial displacements to about 10% were successfully acquired although the full range of displacement could not always be obtained for all the specimens. Therefore the analysis of the strain-hardening rate for strains up to about 10% is performed for all the specimens on the displacement-load curves.

3. Experimental Results and Discussion

3.1 Dendrite structure and cooling history

Figure 2 shows the dendrite structure in the longitudinal section of the AC, 8Cu0S and 8Cu1S samples. Dendrites are well developed almost throughout the thickness regardless of the chemical composition of samples. Equiaxed crystals are seldom observed except for the surface layer and few central regions in the 8Cu0S and 8Cu1S samples; while in the AC sample a thin layer of equiaxed crystals is observed in the central regions.

The primary dendrite arm spacing, d_I , is about $55 \mu\text{m}$, and the secondary dendrite arm spacing, d_{II} , is about $(18\text{--}28) \mu\text{m}$ in both the 8Cu0S and 8Cu1S samples. These data are about $40 \mu\text{m}$ and $(12\text{--}25) \mu\text{m}$, respectively in AC sample. The secondary dendrite arm spacing of the conventional slab is about $(100\text{--}200) \mu\text{m}$ while $(10\text{--}20) \mu\text{m}$ for 2.2 mm thick strip

Fig. 2 Dendrite structure in the longitudinal section of the AC (a), 8Cu0S (b) and 8Cu1S (c) samples.

Fig. 3 Measured temperature history for the 8Cu1S sample (a) and the estimated temperature history for strip casting 0.1C-0.15Si-0.60Mn-0.2P steel (b).

casting steels.⁶⁾ The secondary dendrite arm spacing in the 8Cu0S and 8Cu1S samples are far less than that of the conventional slab while a little larger than that of the strip casting of 2 or 3 mm thick samples. The cooling rate on the solidification of the 8Cu0S and 8Cu1S samples could be estimated as about 250 K/s from the second dendrite arm spacing based on the following equation,⁷⁾ where R is the cooling rate on the solidification in K/s. For the AC sample, the cooling rate on solidification is about 600 K/s.

$$d_{II} = 688(60 \times R)^{-0.36}, \mu\text{m} \quad (1)$$

The cooling rates on solidification of the 8Cu1S and 8Cu0S samples are about 100 times larger than that of the conventional slab while only one third of that of the AC sample. Figure 3(a) shows the measured temperature history of the 8Cu1S sample during casting. For comparison, Figure 3(b) shows the estimated continuous cooling curve from liquids to 973 K for a 0.1C-0.15Si-0.60Mn-0.20P (in mass) strip casting steel (strip thickness 2.2 mm) by Hirata,⁶⁾ which was cast by the same twin drum caster as the AC sample. The cooling history of the AC sample may be roughly estimated from that curve. For the 8Cu1S sample, it was obvious that the first cooling rate, hereafter means the cooling rate on solidification, was lower than that during strip casting process; while the second cooling rate, hereafter means the cooling rate after solidification, was higher than that during strip casting process. For example, the temperature of the 8Cu1S sample at 28 seconds after casting is about 500 K while it is about 970 K in strip casting process. After

casting, the 8Cu1S and 8Cu0S samples were still cooled by the water-cooled mould until ambient temperature; while the sample produced by strip casting process was radiantly cooled on the transportation rollers table. That results in the different cooling history after solidification for the above two casting process.

There are two retarded periods on the temperature curves in Fig. 3(a). These periods correspond to the two large anti-peaks on the cooling rate curve as shown in Fig. 3(a). They also correspond to the $\delta \rightarrow \gamma$ and $\gamma \rightarrow \alpha$ phase transformation, respectively. If we estimate the equilibrium phase transformation temperature by the following equations,^{8,9)} the undercooling degrees to the $\delta \rightarrow \gamma$ and $\gamma \rightarrow \alpha$ phase transformation are about 70 and 370 K, respectively, for the Cu mould casting process.

$$\begin{aligned} T_{A4} &= 1665 + 1122[\%C] - 60[\%Si] \\ &\quad + 12[\%Mn] - 550[\%P] - 160[\%S], \text{ K} \\ T_{A3} &= 1183 - 203[\%C]^{0.5} + 44.7[\%Si] - 30[\%Mn] \\ &\quad + 700[\%P] - 20[\%Cu], \text{ K} \end{aligned}$$

From the above analysis, we can see that the first and the second cooling rates for the Cu mould casting process and the strip casting process are quite different. The first cooling rate of the Cu mould casting process is somewhat lower than that of the strip casting process; while the second cooling rate is much higher than that of the strip casting process. These differences cause some discrepancy in the size of the copper sulfide and the ferrite grain, which will be discussed in later sections.

3.2 Ferrite structure

Figure 4 represents the microstructures of the AC and HA strips. Both of acicular ferrites and irregular polygonal ferrites are detected in the AC strip. Through the homogenization annealing, the irregular and acicular ferrites are converted into a more regular polygonal structure, as shown in Figure 4(b). The difference in the structure is difficult to evaluate using only the optical microscopy photos. Thus, the OIM analysis coupled to SEM is conducted to measure the size distribution of these samples.¹⁰⁾ The grain boundaries in the polished surface are determined by spatial misorientations of more than 5° between two probed points. The grain area is transformed into a grain diameter by the cycle-shape approximation. The mean diameters of ferrite grains in the AC and the HA strips were measured as 62.6 and 98.2 μm , respectively.

Figure 5 shows the ferrite structure of the 8Cu0S and 8Cu1S samples taken by optical microscopy. Both the acicular ferrites and irregular polygonal ferrites are observed in both samples. These structures are similar with those in AC sample. The structures in the 8Cu1S and 8Cu0S samples obviously belong to the same category and it is possible and reasonable to use the same criterion to estimate their contribution to the tensile properties. Figure 6 shows the ferrite structure that was developed by the OIM analysis. Figure 7 shows the distribution of the measured grain area and the grain number in the 8Cu0S and 8Cu1S samples. The distributions of the grain area and the grain number in both samples are similar, for example the diameters of most of the

Fig. 4 Microstructure of (a) AC sample and (b) HA sample.

Fig. 5 Ferrite structure in the 8Cu0S (a) and 8Cu1S (b) samples. Optical microscopy image, etched by Nital.

Fig. 6 Ferrite structure that was developed after the OIM analysis.

grains (more than 90%) in both samples are less than 10 µm. However, the fraction of small size grains in the 8Cu1S sample is slightly higher than that in the 8Cu0S sample; while

the fraction of large size grains is the opposite. The measured mean diameters of the ferrite grains in the 8Cu1S and 8Cu0S samples are 38.48 and 50.97 µm, respectively. These data are

Fig. 7 The distribution of grain area and size analyzed by OIM.

a little smaller than those in the AC and HA samples, which were believed due to the higher second cooling rates of the Cu mould casting process compared with the strip casting process.

Although the 8Cu1S and the 8Cu0S samples show similar temperature history, the ferrite grain size in the 8Cu1S sample is somewhat smaller than that in the 8Cu0S sample. It may have been caused by the fine copper sulfide particles existing in the 8Cu1S sample and will be discussed later.

3.3 Second phase precipitates

A lot of tiny particles are observed in 8Cu1S sample as shown in Fig. 8. These particles are less than 50 nm and the EDS analysis shows the main composition of these particles are Cu and S including a little Mn and Fe. The mean size of these tiny copper sulfide particles is about 34 nm. Some larger size sulfide particles are also observed in the 8Cu1S sample. The concentration of Mn in sulfide particles increases with particle's size increasing while that of Cu decreases as shown in Fig. 9. The sulfides with largest size and high Mn concentration are speculated to precipitate at high temperature such as on or just after solidification.

A lot of the tiny copper sulfides are also observed in the AC sample as shown in Fig. 10. These sulfides are with a size of less than 50 nm and are composed of mainly Cu and S including a little Fe (Fig. 10(b)). The mean size is about 15 nm. In the AC strip, sulfide particle with a size of larger than 100 nm is also observed which is usually a type of (Mn,

Fig. 8 Morphology and size of copper sulfides in the 8Cu1S sample. (a) TEM image, extraction replica specimen; (b) EDS spectrum.

Cu, Fe)S. In the HA strip, the sulfides are grown up and the number of sulfides decreases as clearly shown in Fig. 11. The sulfides in HA sample are about (100–800) nm in size and their compositions are mainly MnS.

In the AC sample the copper sulfide had smaller size than those in the 8Cu1S sample. Lower precipitating temperature and higher super-saturation on precipitating could result in finer size particles. In previous papers,^{5,11–13} the present authors have discussed the effects of the following factors on copper sulfide precipitation in steel: the slope of the solubility curve, the orientation relationship between copper sulfide and matrix, the chemical composition of steel especially the concentration of phosphorus in steel. Copper sulfide is easier to obtain higher super-saturation compared with manganese sulfide at the same cooling rate. This is due to the quite sharper solubility curve of copper sulfide compared with that of manganese sulfide. The sharp solubility curve results in large solubility of Cu and S in steel at high temperature, such as on and just after solidification; while low solubility of Cu and S in steel at low temperature, such as in α -Fe region. The coherent relationship between Cu_2S and α -Fe greatly decreases the critical activation energy for nucleation and increases the nucleation rate when Cu_2S precipitates from α -Fe phase. Then MnS has an advantage to precipitate at high temperature range, while the precipitation of Cu_2S is dominant at low temperature range, especially from α -Fe phase.

Fig. 9 Morphology and size of large sulfides in the 8Cu1S sample. (a) TEM image, extraction replica specimen; EDS spectrum of (b) point B and (c) point C.

Fig. 11 SEM image (a) and EDS spectrum (b) of sulfide precipitates in HA sample.

Fig. 10 TEM image (extraction replica specimen) (a) and EDS spectrum (b) of fine copper sulfide in AC sample.

Phosphorus has greatly effects on the phase transformation temperature and process. Phosphorus could quietly decrease the solidus temperature as well as the transformation temperature from δ -Fe to γ -Fe. MnS usually precipitates at the last stage of solidification due to micro-segregation of S and Mn elements. In addition, MnS has larger solubility in δ -Fe compared with in γ -Fe. Then phosphorus could suppress the MnS precipitation at the last stage of solidification and during the δ/γ transformation. That means the precipitation

of MnS at high temperature is retarded to lower temperature range. On the other hand, phosphorus could increase the γ/α transformation temperature. Then more sulfides could precipitate from α -Fe instead of from γ -Fe in steel containing high phosphorus, especially during rapid cooling process, at which the MnS precipitation at high temperature is also suppressed by the high cooling rate to some extent. Since AC sample contains high phosphorus while there are no such effects from solutes such as phosphorus in the 8Cu1S sample, this may be one of the reasons for the size difference of copper sulfides in AC and 8Cu1S samples.

Except for the factors discussed above, cooling history of sample also may have some effect on the formation of copper sulfide in steel. The cooling rate on solidification of the 8Cu1S sample is quite lower than that of the AC sample. Some MnS may precipitate on solidification, such as the MnS particles with large size in Fig. 9(a), and these MnS may lure copper sulfide to precipitate at higher temperature by acting as the nucleation site in the 8Cu1S sample.

In addition, the Cu and S concentration in the 8Cu1S sample are higher than those in the strip casting AC sample, in which they are 0.07 and 0.010% in mass, respectively.

Fig. 12 Tensile stress-strain curves of (a) 8Cu1S and 8Cu0S samples and (b) AC and HA samples.

Therefore, the equilibrium precipitation temperature of copper sulfide in the 8Cu1S sample is higher than that in the AC sample.

Therefore, to obtain finer copper sulfide particles in steel, firstly it is important to suppress MnS precipitation on solidification or at a high temperature by using a high cooling rate and a composition design such as adding phosphorus. Secondly, it is also significant to decrease the copper sulfide precipitating temperature or to promote copper sulfide to precipitate from ferrite iron instead of from austenite iron by using a high cooling rate and a proper composition design that includes the solutes of Cu, S, Mn and P.

3.4 Mechanical properties of nano-scale copper sulfides dispersed steel and its strengthening mechanism

The stress-strain curves and the tensile properties of the 8Cu1S and 8Cu0S as well as AC and HA samples are shown in Fig. 12 and Table 2, respectively. It is clear that the samples containing nano-scale copper sulfides (8Cu1S and AC samples) have higher yield strength and tensile strength than the samples not containing nano-scale copper sulfides (8Cu0S and HA samples). Since AC and HA samples have different microstructure while 8Cu0S and 8Cu1S samples may have the similar as-cast structure, hereafter the discussion will mainly focus on 8Cu0S and 8Cu1S samples.

The yield strength (YS) and the tensile strength (TS) of the

Table 2 Tensile test properties of 8Cu1S and 8Cu0S samples.

Sample	YS (MPa)	TS (MPa)	UE (%)	TE (%)	TS-YS	YS/TS
8Cu1S-1	445	555	10.4	23	110	0.8
8Cu1S-2	433					
8Cu1S-3	440					
8Cu1S-4	425	552	10.4	25	127	0.77
8Cu1S-mean	436	553.5	10.4	24	118.5	0.79
8Cu0S-1	375					
8Cu0S-2	387					
8Cu0S-3	365	477	11.2	28	112	0.77
8Cu0S-4	368	474	11.5	30	106	0.78
8Cu0S-mean	374	475.5	11.4	29	109	0.775

8Cu1S sample are 436 MPa and 554 MPa, respectively; and of the 8Cu0S sample are 374 MPa and 476 MPa, respectively. The strengths of the 8Cu1S sample are higher than those of the 8Cu0S sample. The work hardening ability of steel has been known to decrease with increasing of the strength level.¹⁴⁾ However, the value of TS-YS is 119 MPa for the 8Cu1S sample and 109 MPa for the 8Cu0S sample, which means that although the 8Cu1S sample has a higher strength level, it has a slightly better strain hardening ability than the 8Cu0S sample.

The 8Cu1S sample also has a higher YS as well as a larger TS-YS than that of the 8Cu0S. On the other hand, the total elongation (TE) and the uniform elongation (UE) of the 8Cu1S sample (24% and 10.4%, respectively) are only slightly lower than those of the 8Cu0S sample (29% and 11.4%, respectively).

Figure 13(a) shows the strain-hardening rate changes by the true strain in the 8Cu1S and 8Cu0S samples. The strain-hardening rate in the 8Cu1S sample is slightly higher than that in the 8Cu0S sample for the entire true strain range, especially in the initial stage. Figure 13(b) shows that the 8Cu1S sample maintains good strain-hardening at a higher strength level compared to that of the 8Cu0S sample.

Table 2 shows that the difference in yield strength between the 8Cu1S and 8Cu0S samples is 62 MPa. The yield strength can be increased by one or more strengthening mechanisms such as solid solution strengthening, grain refining strengthening, and dispersion (or precipitation) strengthening, as described in eq. (2).¹⁵⁾

$$\sigma_y = \sigma_i + \sum_1^j k_j c_j + 17.4d^{-1/2} + (10.8f^{1/2}/X)(\ln X/6.125 * 10^{-4}) \quad (2)$$

where σ_y is the yield strength, σ_i is the friction stress of iron, c_j is the concentration of the j th solute, k_j is the strengthening coefficient of the j th solute, d is the grain diameter in cm, f is the volume fraction of second phase particles, and X is the diameter of the second phase particles in μm .

The solid solution strengthening in steel can be calculated as the following:¹⁶⁾

$$\sigma_y = \sum_1^j C_j = 4620C_C + 678C_P + 123C_{Sn} + 83C_{Si} + 39C_{Cu} + 32C_{Mn} \quad (3)$$

Fig. 13 Strain hardening rate vs. true strain (a) and true stress (b) curves of the 8Cu1S and 8Cu0S samples.

Table 3 The estimated contribution of grain size, solid solution and particles to the difference in the yield strength between the 8Cu1S and 8Cu0S samples.

Items	Grain size	Solid solution	Particles	Total
$\Delta\sigma_y/\text{MPa}$	11.6	10.4	33.8	55.8
$\Delta\sigma_y/\Delta\sigma_{y,\text{Total}} (\%)$	18.7	16.8	54.5	100

Since 8Cu1S and 8Cu0S samples have similar structures, a same criterion such as eqs. (2) and (3) can be used to estimate the contribution of the solid solution strengthening, grain refining strengthening and second phase particle strengthening to the yield strength difference between the 8Cu1S and 8Cu0S samples.

Assuming that 80% of sulfur in steel precipitates as fine copper sulfides and 20% of sulfur as the solid solution element or the few large sulfide particles in the 8Cu1S sample, the YS difference due to the sulfide particles is about 33.8 MPa. The YS differences due to the solid solution and grain size are 10.4 and 11.6 MPa, respectively, according to eqs. (2) and (3). The calculation results are listed in Table 3.

The total YS difference due to the different solid solution strengthening, grain refining strengthening, and sulfide particle strengthening between 8Cu0S and 8Cu1S samples is about 55.8 MPa. This value is slightly less than the

measured value of 62 MPa. One possible reason for this difference is that although the samples have uneven as-cast structures, eq. (2) was based on a uniform structure such as a structure after aging or deformation.^{17,18)} Refiner grains in such uneven structures may have higher strengthening roles compared to those in the uniform structure, which means that it may be better if the coefficients, such as 17.4 and 10.8, in eq. (2) are slightly enlarged when the samples have uneven as-cast structures.

Although it may be better to modify eqs. (2) and (3) to make it more suitable for samples with as-cast structures, we can conclude that most of the difference in the YS between the 8Cu1S and 8Cu0S samples results from the finer copper sulfide particles in the 8Cu1S sample. These particles are also necessary for the 8Cu1S sample to obtain good work hardening ability.

4. Conclusions

As-cast samples with and without copper sulfide, are prepared by the water cooled Cu mould casting process in the laboratory and strip casting process. The Cu mould casting process has a lower cooling rate on solidification and a higher cooling rate after solidification and then produces samples that have a solidification microstructure with a larger second dendrite arm spacing and a finer as-cast ferrite structure compared to that from the strip casting process.

Nano-scale copper sulfides of less than 50 nm are obtained from the as-cast sample that was produced by both rapid solidification processes. Three factors are important for obtaining the finer copper sulfide particles: (1) Suppressing the precipitation of MnS on solidification or at a high temperature by using a high cooling rate and a composition designing such as adding phosphorus to the steel. Such MnS precipitation will decrease the supersaturation when copper sulfide precipitates and will lure copper sulfide to precipitate at a higher temperature. (2) Decreasing the precipitating temperature of copper sulfide and increasing its supersaturation on precipitation by using a high cooling rate and a composition design with proper Cu, S, and Mn concentrations in steel. (3) Promoting copper sulfide to precipitate from alpha ferrite iron instead of from austenite by adding some element such as phosphorus which could change the phase transformation temperature.

A clear difference in the yield strength between samples with and without finer copper sulfides is observed. Solid solution strengthening, grain refining strengthening, and copper sulfide particles strengthening are responsible for to this difference, while finer copper sulfide particles is the main contributor to this difference. Finer copper sulfide particles also contribute to the finer structure and good work hardening ability of the sample at the higher strength level.

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