Suppression of Surface Hot Shortness due to Cu in Recycled Steels

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The most serious problem in the recycling of steel is the occurrence of surface hot shortness during hot deformation due to the mixing of Cu from scrap into steels. Tin accelerates the effect of Cu. The surface hot shortness is caused by liquid embrittlement, that is, formation of the liquid Cu-enriched phase through preferential oxidation of Fe atoms at the steel/scale interface during heating for hot deformation and penetration of this Cu-enriched phase into the grain boundaries. Decrease in the amount of the liquid Cu-enriched phase penetrating into grain boundaries can suppress the surface hot shortness. The amount of the liquid Cu-enriched phase penetrating into the grain boundaries can be reduced by the suppression of oxidation, occlusion of the Cu-enriched phase into the scale, back-diffusion of Cu into the steel matrix and suppression of penetration of the liquid Cu-enriched phase. Therefore, the effects of various elements and conditions of heating and deformation on the surface hot shortness, oxidation, amount of the Cu-enriched phase at the interface and the penetration were examined by tensile tests at high temperatures, thermogravimetry and optical microscopy. The conclusion can be summarized as follows. Silicon, Mn, S (+Mn) and B reduce the susceptibility to the surface hot shortness through decreasing the amount of Cu-enriched phase at the steel/scale interface. The effect of Si is significant. Carbon reduces the oxidation rate in LNG combustion gas. Phosphorus, Si, B and C reduce the susceptibility to the surface hot shortness through restraining the penetration of the Cu-enriched phase into grain boundaries. Heating at higher temperatures reduces the susceptibility mainly through a reduction in the amount of the Cu-enriched phase at the steel/scale interface, although the loss of steels by oxidation increases. A large grain size accelerates the surface hot shortness. A small amount of H2 O in air significantly accelerates the surface hot shortness. Effects of H2 O in heating atmosphere depend on the steel composition and more detailed research on this is desired. Very slow deformation does not cause liquid embrittlement through dynamical re-crystallization, while at a fast deformation rate the embrittlement is suppressed by an increase in the critical stress for the liquid embrittlement. Multiple methods using physical metallurgy suggested by the present research for suppressing the surface hot shortness should be applied together with other methods through separation, smelting and design of fabrication in order to promote the recycling of steels.

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Keywords: oxidation, liquid embrittlement, penetration, alloy elements, impurities, temperature, atmosphere, deformation rate, grain size, tin

1. Introduction

The amount of steel accumulation in Japan is steadily increasing year by year. As a natural result, the amount of steel scrap, especially obsolete steel scrap, is expected to increase at a considerable rate. Therefore the usage of steel scrap has become important in steel manufacturing in Japan from the viewpoints of resource saving and preventing environmental problems.

In addition, the quality of the steel scrap is decreasing. That is to say, concentrations of Cu and Sn, especially Cu, in steel scrap are increasing. Copper is mainly contained in the scrap of cars and home electronic appliances. Tin is mainly contained in the scrap of tin-coated cans. Once these elements are mixed into steels, it is difficult to remove them from the steels in the currently used steel smelting process. Therefore they travel between steels and scrap and accumulate in steels. Thus they are called tramp elements.

On the other hand, Cu generally increases the strength and corrosion resistance of steels and may decrease the environmental load during the lifecycle of steels. Copper, however, causes a serious problem during mechanical working at high temperatures such as hot rolling and forging. Namely, Cu causes many cracks to form on the steel surface during hot workings. This phenomenon has been known as surface hot shortness due to Cu. The surface hot shortness occurs through the following mechanism. Copper tends to be enriched at the steel/scale interface by selective oxidation of Fe atoms during the heating for hot workings. The Cu-enriched phase usually liquefies and penetrates into austenite grain boundaries under stress during hot rolling or forging to cause cracks on the steel surface. Tin accelerates this deterioration effect of Cu.

For this reason there are limits on the Cu and Sn contents in each kind of steel. But the concentration of Cu in a certain kind of steel scrap is now higher than the maximum tolerable limit. From the viewpoint of recycling of steel, the surface hot shortness is the most serious problem.

Several methods for suppression of the surface hot shortness can be considered. They are: 1 reduction of the amount of Cu used in appliances such as automobiles through design of structures and materials, 2 reduction of the amount of Cu in steel scrap as a raw material for steels through physical and chemical methods of separation and 3 reduction of the amount of Cu in steel through smelting. It seems impossible, however, that the method 1 will be feasible in the future. As for the methods 2 and 3, over the past ten years in Japan, tremendous efforts have been made in order to remove Cu and Sn from steel scrap and steels. In those activities, several methods have been proposed. But it has never been clarified whether they are applicable in the practical processes of steel recycling.

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Table 1 Present limitations of Cu and Sn concentration in typical steels and the aim of our research (mass%).

<table>
<thead>
<tr>
<th>Steels</th>
<th>Cu</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet</td>
<td>0.06 → 0.2</td>
<td>0.01 → 0.03</td>
</tr>
<tr>
<td>(drawing)</td>
<td>0.10 → 0.3</td>
<td>0.02 → 0.04</td>
</tr>
<tr>
<td>Sheet</td>
<td>0.30 → 0.4</td>
<td>0.03 → 0.05</td>
</tr>
<tr>
<td>(commercial)</td>
<td>0.40 → 0.5</td>
<td>0.06 → 0.08</td>
</tr>
</tbody>
</table>

Considering the above background, the present authors have stressed the necessity for the suppression of the surface hot shortness by physical metallurgy, namely, the method 4. The method 4 aims to suppress the surface hot shortness through controlling of microstructures near the steel/scale interface in order to reduce the amount of the liquid Cu-enriched phase penetrating into grain boundaries.

The amount of the liquid Cu-enriched phase penetrating into grain boundaries can be reduced by suppression of oxidation, occlusion of the phase into scale, back-diffusion of Cu-enriched phase penetrating into grain boundaries, and a controlled atmosphere of 74%N₂–16%H₂O–8%CO₂–2%O₂. The composition of the latter atmosphere is similar to that of the combustion gas of LNG.

2.2 Tensile tests at elevated temperature and evaluation of susceptibility to the surface hot shortness

Round bar specimens were machined from hot rolled plates. Length and diameter of the reduced region were 6.0 × 10⁻³ m and 3.0 × 10⁻² m, respectively. Tensile tests were carried out mainly at the strain rate of 2.8 × 10⁻² s⁻¹ after heating the specimen at 1373 K or 1473 K for 1800 s in oxidizing atmospheres. Similar tensile tests were also performed after heating in Ar gas. Susceptibility to the surface hot shortness was evaluated from values of the parameters calculated from the maximum load and total elongation using the following equations:

\[ E_A(\%) = \frac{(P_{Ar} - P)}{P_{Ar}} \times 100 \] (1)

\[ E_p(\%) = \frac{(P_{Ar} - P')}{P_{Ar}} \times 100 \] (2)

\[ E_\delta(\%) = \left(\delta_{Ar} - \delta\right)/\delta_{Ar} \times 100 \] (3)

where \(P_{Ar}\) and \(P\) are the maximum load in Ar gas and in oxidizing atmospheres, respectively. \(P'\) is the corrected value of the maximum load considering the reduction in the specimen diameter by oxidation. \(\delta_{Ar}\) and \(\delta\) are total elongation in Ar gas and in oxidizing atmospheres, respectively. Our previous research revealed that these parameters represented the susceptibility to the surface hot shortness very well. These parameters show larger values as the maximum depth of surface cracks increases.

Two kinds of oxidizing atmospheres were used: ambient air and a controlled atmosphere of 74%N₂–16%H₂O–8%CO₂–2%O₂. The composition of the latter atmosphere is similar to that of the combustion gas of LNG.

2.3 Observation of oxidation rate by thermo-gravimetry

A weight increase by oxidation of the steel was measured using a thermobalance in air and in the LNG combustion gas during heating at 0.33 K/s and holding at 1373 K for 1800 s. The specimen was a cylinder of 5.0 × 10⁻³ m diameter and 3.0 × 10⁻² m height.

2.4 Optical microscopy

Specimens of 10 × 10 × 10 × (10⁻³ m)⁻³ size were polished mechanically and heated in air or in the LNG combustion gas. After air-cooling from 1373 K or 1473 K they were mounted in epoxy resin and were polished mechanically for optical microscopy.

2.5 Tensile tests using specimens implanted with a rod of Cu or Cu alloy

In order to examine the effects of various elements in steels or the Cu-enriched phase on the penetration of the liquid Cu-enriched phase into grain boundaries, tensile tests were carried out in Ar gas after heating at 1373 K for 1800 s using round bar specimens implanted with a rod of tough-pitch Cu or Cu alloy in the hollow of 4.0 × 10⁻³ m diameter along the tensile axis. Length and diameter of the reduced region of the specimen were 1.0 × 10⁻² m and 2.0 × 10⁻² m, respectively.
Table 2 Chemical composition of the steels used to examine the effects of B, C and P (mass%).

<table>
<thead>
<tr>
<th>Steels</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Al</th>
<th>Ti</th>
<th>B</th>
<th>N</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.100</td>
<td>&lt;0.01</td>
<td>0.50</td>
<td>0.001</td>
<td>0.002</td>
<td>0.48</td>
<td>0.037</td>
<td>0.041</td>
<td>&lt;1</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>B2</td>
<td>0.100</td>
<td>&lt;0.01</td>
<td>0.51</td>
<td>0.001</td>
<td>0.001</td>
<td>0.48</td>
<td>0.051</td>
<td>0.041</td>
<td>7</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>B3</td>
<td>0.099</td>
<td>&lt;0.01</td>
<td>0.51</td>
<td>0.001</td>
<td>0.001</td>
<td>0.49</td>
<td>0.053</td>
<td>0.042</td>
<td>28</td>
<td>11</td>
<td>20</td>
</tr>
<tr>
<td>B4</td>
<td>0.098</td>
<td>&lt;0.01</td>
<td>0.51</td>
<td>0.001</td>
<td>0.001</td>
<td>0.48</td>
<td>0.053</td>
<td>0.042</td>
<td>48</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>CP1</td>
<td>0.001</td>
<td>&lt;0.01</td>
<td>0.16</td>
<td>0.001</td>
<td>0.001</td>
<td>0.21</td>
<td>0.040</td>
<td>0.040</td>
<td>&lt;1</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>CP2</td>
<td>0.098</td>
<td>&lt;0.01</td>
<td>0.16</td>
<td>0.001</td>
<td>0.001</td>
<td>0.21</td>
<td>0.040</td>
<td>0.040</td>
<td>&lt;1</td>
<td>14</td>
<td>30</td>
</tr>
<tr>
<td>CP3</td>
<td>0.470</td>
<td>&lt;0.01</td>
<td>0.16</td>
<td>0.001</td>
<td>0.001</td>
<td>0.22</td>
<td>0.048</td>
<td>0.039</td>
<td>&lt;1</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>CP4</td>
<td>0.001</td>
<td>&lt;0.01</td>
<td>0.16</td>
<td>0.100</td>
<td>0.001</td>
<td>0.20</td>
<td>0.044</td>
<td>0.043</td>
<td>&lt;1</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>PC1</td>
<td>0.46</td>
<td>0.020</td>
<td>0.48</td>
<td>0.001</td>
<td>0.001</td>
<td>0.49</td>
<td>0.010</td>
<td>0.001</td>
<td>&lt;1</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>PC2</td>
<td>0.48</td>
<td>0.020</td>
<td>0.49</td>
<td>0.019</td>
<td>0.001</td>
<td>0.50</td>
<td>0.028</td>
<td>0.001</td>
<td>&lt;1</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>PC3</td>
<td>0.10</td>
<td>0.015</td>
<td>0.49</td>
<td>0.020</td>
<td>0.001</td>
<td>0.49</td>
<td>0.019</td>
<td>0.001</td>
<td>&lt;1</td>
<td>6</td>
<td>40</td>
</tr>
</tbody>
</table>

(B, N, O: ppm)

3. Results

3.1 Effects of Si and P on the susceptibility to the surface hot shortness

In Fig. 1, the effects of Si and P on $E'_p$ of 0.1%C–0.5%Mn–0.5%Cu steels heated in air are shown. The susceptibility decreases as the content of Si increases. Steels of a very low content of P revealed higher susceptibility. The existence of about 200 ppm P in steel decreases the susceptibility. However, the addition of more P does not decrease the susceptibility much further.

Figure 2 shows effects of Si and Ni on $E'_p$ of 0.1%C–0.5%Mn–0.5%Cu steels heated in air. Addition of 0.5%Ni significantly decreases the susceptibility: this content of Ni is almost the same as that of Cu. Steels containing 0.4%Si reveal similar susceptibility by the addition of only 0.26%Ni. By adding Ni with Si, a smaller Ni addition can be used to reduce the susceptibility to the levels obtained by a single, larger addition of Ni.

3.2 Effects of B on the susceptibility to the surface hot shortness

Figure 3 shows the effects of B on the susceptibility parameters of 0.1%C–0.5%Mn–0.5%Cu steels heated at 1373 K in the LNG combustion gas. Addition of 7 ppm B decreases the susceptibility to the surface hot shortness. But the effect is reduced by a further addition of boron. Figure 4 exhibits effects of B on the susceptibility parameters of the same steels heated at 1473 K in the LNG combustion gas. Comparing with the results at 1373 K, the effects of B on the susceptibility parameters are not obvious. Remarkably high values of $E_e$ at 1473 K are attributed to the very large values of $\delta_{Ar}$ at this temperature.

3.3 Effects of Mn and S on the susceptibility to the surface hot shortness

Figure 5 shows the effects of Mn and S on $E_e$ and $E'_e$ of 0.1%C–0.5%Mn–0.5%Cu steels heated at 1373 K in air. The addi-
3.4 Effects of C and P on the susceptibility to the surface hot shortness

Figure 6 shows the effects of C and P on $E_p$ of 0.16%Mn–0.2%Cu steels listed in Table 2 heated at 1373 K in the LNG combustion gas. Ultralow C steel exhibits large susceptibility to the surface hot shortness. Addition of 0.1%C reduces the susceptibility. The steel containing 0.5%C shows slightly smaller $E_p$ than that of the 0.1%C steel. Addition of 0.1%P to the ultralow carbon steel reduces the susceptibility to the level of that of the 0.1%C steel.

4. Discussion

4.1 Effects of elements on oxidation rate

Figure 7 shows the effects of Si and P on the oxidation rate of 0.1%C–0.5%Mn–0.5%Cu steels heated at 1373 K in air. Single addition of Si does not change the oxidation rate, although the susceptibility to the surface hot shortness decreases with an increase in Si content (Fig. 1). A single addition of P increases oxidation rate, although a single addition of P decreases the susceptibility to the surface hot shortness (Fig. 1). Co-addition of Si and P decreases oxidation rate, and the susceptibility to the surface hot shortness is decreased by co-addition of Si and P (Fig. 1). Namely, the susceptibility to the surface hot shortness can be hardly explained solely by the effects of Si and P on oxidation rate.

Figure 8 exhibits the effects of B on the decrease in diameter of the tensile specimen of 0.1%C–0.5%Mn–0.5%Cu steels during heating in the LNG combustion gas.
hot shortness cannot be explained by the effect of B on the oxidation rate.

In the previous study, the present authors measured an increase in the specimen weight during heating in air and the LNG combustion gas and revealed that the effects of C and P on the susceptibility cannot be explained by the effects of such elements on oxidation rate.

4.2 Effects of elements on microstructure near steel/scale interface

Figure 9 shows the effect of Si on the Cu-enriched phase near the steel/scale interface of 0.1%C–0.5%Mn–0.02%P–0.5%Cu steels heated at 1373 K in air. It is revealed that some Cu-enriched phases are occluded into the scale and the amount of the Cu-enriched phase at the steel/scale interface is reduced in the steel containing 0.4%Si. Such reduction of the amount of the Cu-enriched phase contributes to the decrease in the susceptibility to the surface hot shortness. The occlusion of the Cu-enriched phase is caused by the internal oxidation of Si as mentioned by Nicholson and Murray. But the details of the effect of Si remain unknown.

Figure 10 shows the effects of P on the Cu-enriched phase near the steel/scale interface of 0.1%C–0.5%Mn–0.5%Cu steels heated at 1373 K in air. Steels are the same as those used for Fig. 1. (a) 0.002%P, (b) 0.02%P, (c) 0.1%P.

4.3 Effects of elements on penetration of liquid Cu into austenite grain boundaries

Figure 12 shows the effects of Si and P on stress-strain curves of Cu implanted specimens of 0.1%C–0.5%Mn–0.5%Cu steels. The stress decreases markedly at the critical point. It is thought that penetration of Cu into grain boundaries occurs rapidly and causes brittle fracture at the critical point. The strain at the critical point is increased by the addition of Si and P. Phosphorus increases the stress at the critical point. From these results, it is known that Si and P in steels restrain the penetration of the Cu-enriched phase into grain boundaries. Generally, the following equilibrium equation holds for the penetration of a liquid phase into a grain boundary at the surface.

\[ 2\gamma_{SL} \cos(\phi/2) = \gamma_b \]  

(4)
where $\gamma_{SL}$ is solid/liquid interface energy, $\gamma_b$ is boundary energy of solid and $\phi$ is dihedral angle. The rate of penetration of Cu is very slow when tensile stress does not exist. But under tensile stress, the penetration proceeds at a much higher rate. McLean proposed the following critical condition that the stress starts crack propagation by liquid embrittlement.

$$3\sigma b \geq 2\gamma_{SL} - \gamma_b$$

where $\sigma$ is applied stress and $b$ is atomic diameter. If P segregates along the grain boundary and decreases the grain boundary energy, the critical stress is expected to increase. This effect of P is contributable to the effect of P that restraints the surface hot shortness. However, the reason for the effect of Si suppressing the penetration of liquid Cu has remained unclarified.

In practice, the Cu-enriched phase is conceived to contain Si together with Fe, P, O and other elements. Therefore, in the future more detailed experiments should be performed in order to clarify the effects of elements in the Cu-enriched phase on the penetration of the liquid Cu-enriched phase.

Imai et al. reported that the concentration ratio of Sn to Cu in the Cu-enriched phase is nearly the same as the concentration ratio of Sn to Cu in steels. In order to clarify the effect of the dissolution of Sn in the Cu-enriched phase, the present authors performed tensile tests using specimens implanted with a rod of Cu–Sn alloys having various Sn contents. The result is shown in Fig. 13. Dissolution of Sn into Cu suppresses the penetration. From this result, it is known that the effects of the dissolution of elements into the Cu-enriched phase on the penetration cannot be neglected.

Figure 14 shows the effect of B on the penetration. As the content of B increases, the penetration is suppressed. Subsequent to the experimental results mentioned above, it has been clarified that B tends to enhance grain boundary oxidation, whereas B reduces the amount of the Cu-enriched phase at the steel/scale interface and the penetration. Therefore, the most beneficial effect of boron on the suppression of the surface hot shortness is observed upon the addition of 7 ppm.

The present authors observed the segregation of B along austenite grain boundaries in the previous study by using the alpha particle track etching method (auto-radiography using B$^{10}$) for the specimens of Steels B2, B3 and B4 water-quenched from 1373 K. Therefore, the suppression of the pen-
heating procedures is desired.

4.5 Effects of austenite grain size

Heating at a higher temperature results in coarser grains. Therefore, the effects of austenite grain size on load-elongation curves were examined using 0.11%C–0.52%Mn–0.50%Cu steel heated at higher temperatures in Ar gas before performing the tensile test at 1373 K. And it was observed that the surface hot shortness was enhanced in the specimens having larger grain size. Therefore, in the event of the restraining effect of heating at higher temperatures on the surface hot shortness, the suppression effects of the occlusion of the Cu-enriched phase and back-diffusion of Cu into the steel matrix are larger than the acceleration effects of coarser grains on the surface hot shortness. In addition, it was clarified that the effect of elements on austenite grain size was negligibly small in the present research.

4.6 Effects of atmosphere of heating furnace and deformation rate

In the present research, two oxidizing atmospheres were used: air and the LNG combustion gas. In the latter atmosphere, the concentration of H2O was higher than that in the former.

Maeda and Sato reported that H2O in heating atmosphere changed the microstructure of the scale: H2O formed many voids in layers parallel to the steel/scale interface in the scale. Such a change in the microstructure of the scale is expected to affect the oxidation rate and therefore the surface hot shortness. Hence, the susceptibility parameters were compared between specimens of 0.5%Mn–0.5%C Cu steels shown in Table 2 heated in air and in the LNG combustion gas. The results are shown in Fig. 15. In this figure, the effect of the atmosphere is very small. On the other hand, Fig. 16 shows the effects of atmosphere on the load-elongation curves of a 0.5%C–0.5%Mn–0.5%Cu steel heated in various atmospheres. Comparing the curves heated in air and in dry air, the effect of a small amount of H2O is remarkably large. Nicholson and Murray reported the effect of H2O on the surface hot shortness depending on oxygen content.

Uchino et al. showed that the oxidation rate of a 0.1%C–0.02%P steel is much higher in LNG combustion gas than in air, whereas the oxidation rate of a 0.5%C–0.02%P steel is similar in both atmospheres and the oxidation rate of 0.5%C–0.001%P steel is a little slower in LNG than in air. Therefore, effects of atmosphere depend on the chemical composition of steel. Details of the effects of atmosphere should be clarified in the future.

On the other hand, Seo et al. found that the susceptibility to the surface hot shortness depended on the strain rate and showed the maximum at around 1 × 10⁻¹ s⁻¹. Figure 17 shows the effect of strain rate on stress-elongation curves of specimens implanted with a Cu–20%Sn rod into 0.1%C–0.02%P steel. 0.1%C–0.5%Mn–0.5%Cu steel. It is revealed that the penetration of the Cu-enriched phase shows strain rate dependency. Therefore it is known that the penetration does not occur only through the static conditions such as shown by eq. (5) but also through dynamical conditions of which the details remain unknown.

Figure 17 shows that liquid embrittlement does not occur at the very low strain rate. Sasanuma et al. showed that the
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4.7 Feasibility of the suppression of surface hot shortness using physical metallurgy

The present research revealed that there are many methods using physical metallurgy for restraining the surface hot shortness due to Cu. In Fig. 18, such methods are shown schematically. Silicon, Mn, S (+Mn), C and B reduce the susceptibility to the surface hot shortness. Heating low carbon steels in low H₂O atmosphere and heating at a higher temperature also restrain the shortness. Very slow deformation suppresses the surface hot shortness, although the product efficiency decreases. Very fast deformation seems to be feasible for the suppression of the surface hot shortness under the precise control of each reduction. Fine grain size reduces the depth of the penetration of the Cu-enriched phase and restrains the surface hot shortness.

Indeed the effect of each of the above methods is not so large, but the multiple usage of these methods is conceived to be feasible. In order to promote recycling of steels, such methods using physical metallurgy should be applied together with other methods using separation, smelting and design of fabrication. Of course the methods employing physical metallurgy should not deteriorate other properties of steels and should not increase the environmental loading. Therefore optimization is desired in controlling chemical compositions of steels and conditions of heating and deformation.

5. Conclusion

Experimental results can be summarized as follows.

1. Silicon, Mn, S (+Mn), C and B reduce the susceptibility to the surface hot shortness through decreasing the amount of the Cu-enriched phase at the steel/scale interface. Significant occlusion of the Cu-enriched phase into the scale was observed in steels containing Si. Carbon decreases the amount of the Cu-enriched phase through reducing the oxidation rate in the LNG combustion gas.

2. Phosphorus, Si, B and C reduce the susceptibility to the surface hot shortness through restraining the penetration of the Cu-enriched phase into grain boundaries.

3. Heating at higher temperatures reduces the susceptibility, although the loss of steels by oxidation increases.

4. Larger grain size accelerates the surface hot shortness.

5. A small amount of H₂O in air accelerates significantly the surface hot shortness. Effects of H₂O in heating atmosphere depend on steel composition and more detailed research is desired.

6. Very slow deformation does not cause the embrittlement due to the liquid Cu-enriched phase, because the stress level is decreased by dynamic re-crystallization of steels. At
a fast deformation rate the embrittlement is suppressed by an increase in the critical stress for the liquid embrittlement.

(7) Multiple methods employing physical metallurgy suggested by the present authors for suppressing the surface hot shortness should be applied together with other methods through separation, smelting and design of fabrication in order to promote recycling of steels.

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