Metallurgical Conditions Required for Superior Hot-workability of 13% Chromium Steels in a Seamless Rolling Process

Akira KAWAKAMI,1) Hitoshi ASAHI2) and Masakatsu UENO3)


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Hot-workability of 13% Cr steels was investigated in terms of microstructure by model elongator rolling tests and by tensile tests to develop modified types of 13% Cr steel seamless OCTGs (Oil Country Tubular Goods). Hot-workability deteriorated in both tests by the formation of δ-ferrite in austenite (γ) matrix; however, the deterioration occurred at lower temperatures in tensile tests than in model elongator tests. Materials are deformed more heavily in the latter than in the former, which is considered to be the cause of the difference. The result suggests that lower temperatures than the actual rolling temperature should be selected for the tensile tests in order to evaluate hot-workability of materials for seamless pipes. δ phase fraction during hot-working was almost equal to that estimated from the experimental phase diagram at a deformation temperature for plain C–13%Cr steels and at a primary heating temperature for Ni containing low C–13%Cr steels. This phenomenon is explained by a difference in the diffusion coefficient of C and that of Ni. Furthermore, it was clarified that isolated distribution and polygonal shape of δ prevented void-propagation during hot-working and was not harmful to hot-workability in plain C–13%Cr steels.

KEY WORDS: CTG (Oil Country Tubular Goods); seamless pipe; AISI420; hot-workability; δ-ferrite; phase diagram; solution annealing.

1. Introduction

The AISI type 420 steel (0.2%C–13Cr, % is mass% in this paper) is widely used for the corrosion resistant OCTG (Oil Country Tubular Goods) because of its good corrosion resistance in wet CO2 environments.1) The number of oil and gas wells with severer corrosion environments, to which the AISI 420 is not applicable, has increased recently. There has been increasing demand for modified types of 13% Cr steels with higher corrosion resistance than the AISI 420.2,5) In order to improve corrosion resistance, reduction in C content is effective since it suppresses the formation of chromium carbides, which results in maintaining chromium in solution.6) However, the reduction in C content simultaneously causes the formation of δ-ferrite (δ) phase in austenite (γ) matrix at elevated temperatures, which consequently deteriorates hot-workability.7,8)

It is widely known that a seamless hot-rolling process is one of the severest hot-working processes. In particular, an elongator, which is a main hot-rolling mill in the seamless rolling process, forces the material to deform largely in the shear direction.9) Therefore, superior hot-workability is required for materials used for a seamless hot-rolling process and it is necessary to establish an exclusive method and a new criterion to evaluate hot-workability of seamless pipe materials. However, a method that is practical and effective in evaluating hot-workability in a seamless rolling process has not been established so far.

In this study, hot-workability of 13% Cr steels was investigated in terms of microstructure by model elongator rolling tests and by tensile tests. Phase condition during hot-working was examined through experiments and was compared with the equilibrium phase diagram of Fe–C binary system containing 13% Cr. Moreover, the effect of δ-phase on hot-workability of plain C–13%Cr steels and low C Ni-added 13% Cr steels was examined in relation to the phase condition during hot-working.

2. Experimental Procedure

2.1. Hot Rolling Test in a Model Elongator Mill

The effect of microstructure on hot-workability in a seamless hot-rolling process was examined using a model elongator mill.10) Schematic diagrams of the model elongator are illustrated in Fig. 1. 100 kg ingots, whose chemical compositions are indicated as R-1 and R-2 in Table 1, were hot-rolled to round billets in two step rolling processes as the following condition (Condition 1).

(Condition 1)

• First rolling; Heated at 1 250°C for 3.6 ks, 190⇒170⇒150⇒135 square (mm)
• Second rolling; Heated at 1 250°C for 3.6 ks, 135⇒120⇒110⇒100⇒90 square (mm)

Hollow shell specimens with 75 mm in outer diameter, 14.25 mm in wall thickness and 350 mm in length were machined from the billets and were subjected to model elonga-
tor tests under the following conditions.
1) Aiming dimensions of pipes after hot-rolling: 75 mm in outer diameter and 5.0 mm in wall thickness
2) Heating condition: 1 250°C for 3.6 ks
3) Rolling start temperature: 1 100°C
4) Roll rotational speed: 1.24 m/s
5) Roll gap: 64.5 mm (gap between barrel rolls shown in Fig. 1)
6) Disk guide peripheral speed: 0.731 m/s
7) Disk guide gap: 75 mm (gap between disk guides shown in Fig. 1)
8) Feed angle: 8.5 deg (see Fig. 1)
9) Plug material: 3%Cr–1%Ni steel
10) Plug diameter: 60 mm in outer diameter
After being hot-rolled, the pipes were air-cooled to a room temperature and the surface appearance was observed by visual inspection.

2.2. Hot Tensile Test
The effects of &delta; phase and deformation temperature on hot-workability were investigated by tensile tests at elevated temperatures. 50 kg ingots, whose chemical compositions are indicated as CA-CD (plain C–13%Cr) and KI-KL (low C–2%Ni–13%Cr) in Table 1, were hot-rolled to 12 mm thick plates in the following conditions (Condition 2).

(Condition 2)
- Rough rolling: Heated at 1 250°C for 7.2 ks, 120 ⇒ 100 ⇒ 80 in thickness (mm)
- Cut into 40 mm in thickness
- Final rolling: Heated at 1 250°C for 7.2 ks, 30 ⇒ 22 ⇒ 15 ⇒ 12 in thickness (mm)

For CA-CD, cylindrical tensile specimens with 10 mm in diameter and 80 mm in length of parallel portion were machined in the longitudinal direction (AR-L) and in the transverse direction (AR-T) from the hot-rolled plates. In order to investigate the effect of deformation temperature on hot-workability, the specimens were heated and deformed under a condition shown in Fig. 2(a). The strain rate was 3 s⁻¹ and the heat pattern simulating a seamless hot-rolling process consisted of a primary heating at 1 250°C followed by lower deformation temperatures. The effect of primary heating temperature on hot-workability was investigated by the heat pattern shown in Fig. 2(b). Moreover, tensile specimens machined from plates, which were furnished with solution treatment (1 100°C for 7.2 ks

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Al</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1</td>
<td>0.019</td>
<td>0.09</td>
<td>0.50</td>
<td>0.012</td>
<td>0.001</td>
<td>3.87</td>
<td>13.99</td>
<td>-</td>
<td>-</td>
<td>0.011</td>
</tr>
<tr>
<td>R-2</td>
<td>0.019</td>
<td>0.09</td>
<td>0.50</td>
<td>0.012</td>
<td>0.001</td>
<td>3.87</td>
<td>13.94</td>
<td>1.01</td>
<td>0.011</td>
<td>0.0425</td>
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<tr>
<td>CA</td>
<td>0.11</td>
<td>0.36</td>
<td>0.45</td>
<td>0.010</td>
<td>0.001</td>
<td>-</td>
<td>13.01</td>
<td>-</td>
<td>-</td>
<td>0.027</td>
</tr>
<tr>
<td>CB</td>
<td>0.15</td>
<td>0.35</td>
<td>0.45</td>
<td>0.010</td>
<td>0.001</td>
<td>-</td>
<td>12.98</td>
<td>-</td>
<td>-</td>
<td>0.026</td>
</tr>
<tr>
<td>CC</td>
<td>0.17</td>
<td>0.36</td>
<td>0.45</td>
<td>0.011</td>
<td>0.001</td>
<td>-</td>
<td>13.01</td>
<td>-</td>
<td>-</td>
<td>0.026</td>
</tr>
<tr>
<td>CD</td>
<td>0.21</td>
<td>0.35</td>
<td>0.44</td>
<td>0.010</td>
<td>0.001</td>
<td>-</td>
<td>12.93</td>
<td>-</td>
<td>-</td>
<td>0.026</td>
</tr>
<tr>
<td>KJ</td>
<td>0.01</td>
<td>0.10</td>
<td>0.50</td>
<td>0.008</td>
<td>0.001</td>
<td>1.68</td>
<td>12.47</td>
<td>-</td>
<td>-</td>
<td>0.012</td>
</tr>
<tr>
<td>KJ</td>
<td>0.024</td>
<td>0.10</td>
<td>0.50</td>
<td>0.008</td>
<td>0.001</td>
<td>1.67</td>
<td>12.42</td>
<td>-</td>
<td>-</td>
<td>0.011</td>
</tr>
<tr>
<td>KJ</td>
<td>0.045</td>
<td>0.10</td>
<td>0.49</td>
<td>0.008</td>
<td>0.001</td>
<td>1.69</td>
<td>12.49</td>
<td>-</td>
<td>-</td>
<td>0.012</td>
</tr>
<tr>
<td>KL</td>
<td>0.088</td>
<td>0.10</td>
<td>0.50</td>
<td>0.008</td>
<td>0.001</td>
<td>1.68</td>
<td>12.43</td>
<td>-</td>
<td>-</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic diagrams of model elongator mill.

Fig. 2. Process for tensile tests at elevated temperatures.
in nitrogen atmosphere), were used to investigate the effect of shape of δ-phase on hot-workability. For KI-KL, the tensile specimens in the transverse direction (AR-T) were heated and deformed in the condition shown in Figs. 2(a) and 2(b). In the hot tensile tests, hot-workability was evaluated by reduction of area (R.A.) and fracture stress ($\sigma_f$).

### 2.3. Preparation of Phase Diagrams

Experimental phase diagrams were produced to make clear the phase condition during hot-working. Block samples cut from hot-rolled plates were enclosed in silica tubes in a vacuum ($\sim 10^{-2}$ Pa) to prevent the samples from decarburizing during heating since decarburizing may have an effect in changing the phase condition. Samples were heated at 800–1300°C for 7.2 ks in an electric furnace and were water-quenched. Then, the cross section perpendicular to a rolling direction was polished and etched with a solution of HNO$_3$ : HCl : H$_2$O = 1 : 3 : 4 (for plain C–13%Cr steels), 3 : 3 : 4 (for low C–Ni–13%Cr steels). The areal fraction of δ-phase was measured by a point-counting method.

### 3. Experimental Results

#### 3.1. Hot Rolling Test in a Model Elongator Mill

Hollow billet materials of R-1 and R-2 with 14.75 mm in wall thickness were hot rolled to pipes with 5 mm in wall thickness at 1100°C in the model elongator mill. Surface quality of hot rolled pipes of R-2 was inferior to that of R-1. On the inner surface of R-1, a few short and shallow cracks with 2–3 mm in length were recognized. In contrast, in R-2, numerous longer cracks, which were some 10 mm in length and approximately 1 mm in depth, were clearly observed on the inner surface. The frequency of surface crack formation per full length of each pipe (330 mm in length) is presented in Fig. 3. Considerably larger number of cracks formed in R-2 than in R-1. An optical micrograph of cross-section near a surface crack in R-2 is shown in Fig. 4. The microstructure consisted mostly of lath martensite matrix, which used to be austenite ($\gamma$) during hot-working (indicated as M($\gamma$) in the figure), and of a small amount (approximately 1%) of elongated δ-ferrite (indicated as $\delta$). It was clearly recognized that the crack propagated along the elongated $\delta$-ferrite. On the other hand, the microstructure of R-1 consisted of a single phase of M($\gamma$). It is apparent from these results that hot-workability of 13% Cr steels is drastically deteriorated by the formation of $\delta$ during hot-rolling. In order to maintain good hot-workability in 13% Cr steels in a seamless rolling process, it is necessary to prevent δ-phase formation during hot-working.

#### 3.2. The Effect of C Content on Hot-workability and Phase Condition of Plain C–13%Cr Steels

The effects of deformation temperature and C content on hot-workability in L-direction of plain C–13%Cr steels (AR-L) in tensile tests are illustrated in Fig. 5. R.A. lowered with a decrease in deformation temperature and with a decrease in C content. For example, in the case of deformation at 900°C, R.A. was 60% for 0.11%C–13%Cr steel (CA), while R.A. was 82% for 0.21%C–13%Cr steel (CD). Figure 6 shows the optical micrograph near the fractured portion of a deformed specimen. The microstructure consisted of martensite matrix, which used to be $\gamma$ during hot-working at 900°C (indicated as M($\gamma$)), and of $\delta$. Voids (indicated as V) formed and propagated mainly along the $\delta/\gamma$ or $\delta/\delta$ interface. In CB (0.15%C–13%Cr steel), the formation of voids accompanied by $\delta$ was also observed. In contrast, the microstructure consisted of a single phase of $\gamma$ and no void formation was observed in CC (0.17%C–13%Cr steel) and CD. $\sigma_f$ slightly decreased with a decrease in C content, as shown in Fig. 5(b). The results of hot-workability obtained for T-direction specimens (AR-T) were similar to those obtained for AR-L.

The effects of primary heating temperature and C content on hot-workability in L-direction are indicated in Fig. 7.
R.A. decreased as C content decreased; however, R.A. was almost constant irrespective of the primary heating temperature. Fig. 7(b). In conclusion, hot-workability of plain C–13%Cr steel depends on deformation temperature and C content irrespective of rolling direction and primary heating temperature.

A phase diagram in the hot-working temperature range was produced experimentally and phase conditions during hot working were estimated. Figure 8 presents a typical example of optical micrographs, which were obtained for specimens heated at 1250°C for 7.2 ks followed by water-quenching. In gray lath martensite matrix, white polygonal δ-ferrites were observed. The volume fraction of δ decreased as C content increased. In CD, a prior γ grain diameter was approximately 1000 μm, which was much larger than that observed in other specimens (100–300 μm). This result suggests that the prior γ grains grew in CD since the microstructure did not contain δ which prevents γ grains from growing due to the pinning effect.

An experimental phase diagram of Fe–C binary system containing 13% Cr obtained from a microstructural observation is illustrated in Fig. 9. At temperatures from 800 to 1300°C, three types of phases were recognized: γ, δ and precipitate (indicated as K). γ phase was observed throughout the investigated temperature range and all of the microstructures observed consisted either of a single phase of γ or of a mixture of γ-phase and other phase(s). δ-phase formed in the low C content region, such as in the region at 0.15% C or less, while precipitates formed at 950°C or at lower temperatures. A region which consisted of a single phase of γ is loop-shaped and the top point of the γ-loop (where the C content is lowest) is approximately 0.16% C at 1000°C. It can be seen from the diagram that at 900°C the microstructure of 0.11% C (CA) and 0.15% C (CB) was γ+δ dual phase, while that of 0.17% C (CC) and 0.21% C (CD) was a single phase of γ. The relationship between C content and phase condition in the phase diagram appeared to be similar to that obtained in the microstructures of CA-CD hot tensile specimens deformed at 900°C.

Microstructures of tensile specimens heated with a pattern shown in Fig. 2 were observed and a phase condition during hot-working was examined. Table 2 shows the areal fraction of δ-phase in CA and CB which were cooled from 1250 to 1200°C and to 900°C and kept at each temperature for 60 s (indicated as “60 s-heated”). δ-fraction obtained from the experimental phase diagram is also listed in the table (indicated as “7.2 ks-heated”) for comparison. δ-phase fractions in CA (and in CB) were similar irrespective of thermal history between 60 s and 7.2 ks, which suggests that heating for 60 s causes a phase condition to be almost the same as that obtained after heating for 7.2 ks in plain C–13%Cr system.

3.3. The Effect of Shape of δ-ferrite on Hot-workability of 13% Cr Steels

Hot-workability of plain C–13%Cr steels subjected to solution annealing treatment (1100°C for 3.6 ks, indicated as “SA”) is shown in Fig. 10. Hot-workability slightly depended on deformation temperature but not on C content, which indicates that hot-workability of CA and CB was improved by the solution treatment. Figures 11(a)–11(c) present the microstructures in L-cross section of tensile specimens of AR-L, AR-T and SA before tensile tests. δ-ferrites were elongated in the tensile direction in AR-L and AR-T specimens, while each δ grain had polygonal shape and was coherently isolated in SA. Thus, hot workability of plain C–13%Cr steels can be improved by solution annealing treatment, in which shapes and distribution of δ grains changed, even if the steels contained of a large amount of δ.
3.4. The Effect of C Content on Hot-workability and Phase Diagram of Low C—2%Ni—13%Cr Steels

The effects of C content and deformation temperature on hot-workability of plain C—13%Cr steels (Fig. 7).

Table 2. Areal fractions of δ-phase heated for 60 s and for 7.2 ks.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C:0.11%—C:13%Cr</th>
<th>C:0.15%—C:13%Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating temperature (°C)</td>
<td>900</td>
<td>1200</td>
</tr>
<tr>
<td>Areal fraction of δ-phase (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60sec-heating</td>
<td>18.3</td>
<td>31.1</td>
</tr>
<tr>
<td>7.2ks-heating</td>
<td>20.4</td>
<td>31.3</td>
</tr>
</tbody>
</table>

Fig. 8. Optical micrographs of plain C—13%Cr steels (heated at 1250°C for 7.2 ks and water-quenched, (a) CA: 0.11% C, (b) CB: 0.15% C, (c) CC: 0.17% C, (d) CD: 0.21% C).

Fig. 9. Experimental phase diagram of Fe—C binary system containing 13%C—0.02%N (heated for 7.2 ks).

Fig. 10. Effects of deformation temperature and C content on R.A. of plain C—13%Cr steels (SA: solution annealed).
hot-workability of 2%Ni–13%Cr–0.02%N steels are presented in Fig. 12. R.A. decreased as C content and deformation temperature decreased, which is similar to the results obtained for plain C–13%Cr steels. KI (0.010% C) and KJ (0.024% C) showed inferior hot-workability to KK (0.045% C) and KL (0.088% C). σ_f slightly decreased with a decrease in C content.

Experimental phase diagram of Fe–C binary system containing 2%Ni–13%Cr–0.02%N is shown in Fig. 13. A single phase of γ and γ+δ dual phase were observed as components of microstructure. As C content decreased, a temperature range for a single γ phase was narrowed, which was the same phenomenon observed in plain C–13%Cr steels. In contrast, KI (0.010% C) and KJ (0.024% C) showed poorer hot-workability than KK (0.045% C) and KL (0.088% C) at 950°C, where all of the steels are supposed to consist of a single phase of γ at 950°C according to the experimental phase diagram. Figure 14 presents typical optical micrographs of tensile specimens in the vicinity of a fractured portion. Elongated δ and propagated voids along the δ existed in KI, KJ and KK, while no δ was observed in the martensite matrix in KL.

The effects of C content and primary heating temperature on hot-workability of 2%Ni–13%Cr–0.02%N steels are shown in Fig. 15. Primary heating temperature differently affected hot-workability of these steels depending on C content. In KI and KJ, which contained lower C than KK and KL, R.A. kept low values and led to the minimum
4. Discussion

4.1. Relationship between Hot-workability of 13% Cr Steels in Model Elongator Mill Tests and in Tensile Tests

Deterioration in hot-workability of 13% Cr steels occurred due to the formation of δ during hot-working both in a model elongator rolling test and in a tensile test, and is considered to be caused by a difference in strength of γ and that of δ for both tests. The deformation strength of δ is lower than that of γ during hot-working, which is clearly suggested from the fact that σγ decreased with an increase in δ-fraction, as presented in Fig. 5(b). Strain introduced by hot-working concentrated in δ and voids formed once the strain exceeded the limit of its inherent elongation.

However, deterioration of hot-workability due to δ formation appeared at different deformation temperatures depending on test methods. In a model elongator rolling test, surface defects occurred along elongated δ in pipes deformed at 1100°C, while no obvious difference was seen in R.A. at 1100°C in tensile tests, although the steels with lower C contents contained δ during deformation. In tensile tests, R.A. clearly deteriorated below 950°C. A difference in deformation condition is considered to cause the difference in the “critical” deformation temperature for the deterioration of hot-workability depending on test methods. In an elongator mill test, the material deforms largely in a shear direction with a rotational force in the restrained space between barrel type skew rolls and guides. In contrast, shear strain is considerably smaller in tensile test than in a model elongator rolling test than a tensile test at the same deformation temperature.

In conclusion, lower test temperatures should be selected in tensile tests than the actual rolling temperature in an elongator mill in order to compensate the difference in hot working condition and to estimate hot-workability of seamless pipe materials appropriately. It appears optimum to apply R.A. at 900–950°C in tensile tests for evaluating hot-workability of materials which are in general hot-rolled in an elongator mill at around 1000–1100°C in a seamless hot rolling process.

4.2. Difference in δ Phase Stability in Plain C–13%Cr Steels and in Low C–2%Ni–13%Cr Steels

In plain C–13%Cr steels, a phase condition during hot-working was substantially similar to that obtained from the equilibrium phase diagram at deformation temperatures. In 2%Ni–13%Cr steels, on the other hand, δ-ferrites were observed in tensile test specimens that were heated and deformed at temperatures at which the phase is single γ in the phase diagram. It is apparent that δ phase, which formed at a primary heating temperature, is more stable in 2%Ni–13%Cr steels than in plain C–13%Cr steels.

The difference in δ-phase stability is considered to be caused by a difference in diffusion coefficients of C and Ni, which is dominant in stabilizing γ phase in plain C–13%Cr steels and in 2%Ni–13%Cr steels, respectively. Diffusion coefficients of C and Ni in Fe matrix at 1000°C were calculated and are listed in Table 3. At 1000°C, the diffusion coefficient of C is higher than that of Ni by 10^6 times. It is surmised from rough estimation of mean free paths, (Dt)_{1/2} of C and Ni in γ-Fe matrix that C atoms can move some 10 μm while Ni atoms can move only some 10 nm for 100 s, as indicated in Table 3. It is presumed that δ generated at a primary heating temperature remains at lower hot-working temperatures for 2%Ni–13%Cr steels due to the low mobility of Ni atoms. In contrast, transformation either from δ to γ or from γ to δ easily occurs in plain C–13%Cr steels for 60 s, in which C atoms can move a distance of grain diameter.

Thus, a phase condition during hot-working can be predicted from the experimental phase diagram at deformation temperatures for plain C–13%Cr steels, and at a primary heating temperature for Ni-containing low C–13%Cr steels. Regarding a phase condition during hot-working in plain C–13%Cr steels, alloy design of AISI 420 appears to be optimum since C addition of 0.2% is needed to keep a single phase of γ at hot-working temperatures. On the other hand, in low C–Ni–13%Cr steels, it is necessary to maintain a single phase of γ at a primary heating temperature, for example, at 1250°C, which is a typical heating temperature in an actual seamless hot-rolling process. To develop new 13% Cr steels with good hot-workability, it is necessary to
The experimental phase diagrams obtained in this study were compared with the published experimental phase diagrams and also with the calculated phase diagrams. Comparing with the experimental phase diagram by Bungardt, it is clear that χ phase region is wider in Bungardt’s phase diagram than in the phase diagram in this study. A difference between the phase diagram in this study and that obtained by “THERMO-CALC (CALPHAD)” was also investigated. SSOL was used for the database, FCC(γ), BCC(α and δ), M₆C₃ and M₂₃C₆ were selected as the components of the solid phases in CALPHAD and the result is presented in Fig. 16.

Fig. 16. Calculated phase diagram of Fe–C binary system containing 13%Cr–0.02%N (Thermo-Calc).14

All of the three mechanisms are the possible causes of deterioration of hot workability observed in this study. However, materials used in this study contained considerably low S and no void was observed in specimens heated with a pattern shown in Fig. 3. Therefore, it is considered more probable that the difference in strength of γ and that of δ and the consequent formation of voids is the main reason for deterioration of hot-workability.

Ueda et al.16 and Kawasaki et al.17 reported that polygonal shape and dispersed distribution of δ improves hot-workability of as-cast austenitic stainless steels, which was caused by arresting void-propagation due to the isolated δ and the uniform distribution of impurities. In this study, no clear coalescence of voids was observed in SA (Solution Annealed at 1 100°C for 7.2 ks) after deformation and the mechanism of improvement in hot-workability is considered to be similar to that in the previous studies. In their studies, R.A. improved from 40 to 60% due to homogenizing heat treatment in as-cast materials. It was found in the present study that R.A. was improved from 60 to 80% in high ductility range in hot-worked 13% Cr steels by solution annealing treatment.

However, the improvement in hot-workability by the solution annealing is applicable solely for a one-pass hot-rolling process. It seems difficult to put the effect directly into practice for a multi-pass hot-rolling process such as a seamless hot-rolling process. Therefore, it is considered to be difficult to manufacture plain C–13%Cr steels with lower C content than that of AISI420 in a seamless mill. In practice, it is difficult to manufacture AISI410 (0.10%C–13%Cr) without causing surface defects in the actual seamless mill.9

5. Conclusion

The effect of δ-ferrite on hot-workability of 13% Cr steels was investigated from viewpoints of phase conditions and the following results were obtained.

(1) In hot-working tests using a seamless elongator mill model, cracks formed along δ-ferrites and/or in the interior of δ-ferrites.

(2) In hot-tensile tests, reduction of area decreased in specimens including δ, which was due to the void-formation and propagation along the γ/δ or δ/δ interface. Hot-workability deteriorated at lower temperatures in tensile tests than in model elongator rolling tests.

(3) δ phase fraction during hot-working was similar to that estimated from the experimental phase diagram at deformation temperature for plain C–13%Cr steels and at primary heating temperature for Ni containing low C–13%Cr steels.

This difference is considered to be due to a difference in the diffusion coefficient of C and that of Ni, which is the main γ stabilizer in plain C–13%Cr steels and in Ni containing low C–13%Cr steels, respectively.

(4) Plain C–13%Cr steels furnished with solution annealing treatment indicated higher hot-workability than as-hot-rolled steels since polygonal shape and isolated distribution of δ arrested propagation of voids during hot-working.

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REFERENCES