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Development of Medium Carbon Steel Wire Rods for Cold Heading by Isothermal Transformation Treatment

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Abstract

In order to improve the formability, low tensile strength and high ductility are required for medium carbon steel wire rods for cold heading. In this study, effects of microstructure on mechanical properties of spheroidizing annealed medium carbon steel wire rods and control methods of microstructure of medium carbon steel wire rods were investigated. The fine dispersed cementites and coarse ferrite grain after the spheroidizing annealing were observed in the medium carbon steel wire rods manufactured by isothermal transformation treatment. Developed medium carbon steel wire rod had excellent formability.

1. Introduction

Medium carbon steel wire rods are widely used as materials for mechanical parts such as bolts. For such mechanical parts, although strength is required at their final product stage, formability during processing is also required. **Figure 1** shows an example of the production process of bolts. Hot-rolled wire rods undergo spheroidizing annealing (hereinafter referred to as SA) and the wire drawing process, and then bolts are produced by cold-heading followed by quench and temper heat treatment and plating treatment. In the case of cold heading of parts of complicated configuration, higher formability is required for the material. Therefore, as shown in Fig. 1 by the broken line, a method of reapplying SA after the completion of an SA and wire drawing is adopted. In the SA process, retention immediately below the A_1 point or slow cooling starting in the ferrite/austenite region is conducted, either of which requires a long heat treatment time. Therefore, this study pursued improvement of the production cost, reduction of the SA process and/or lowering of the treatment temperature and shortening of the treatment time.

Cold heading is applied to form various mechanical parts due to its short processing time and excellent productivity in addition to the high material yield. However, in recent years, along with the growth of the material strength, the abrasion and/or the fracture of the dies used for cold heading and the working cracks developed in the material have increased. In order to solve these problems, it is effective to lower the deformation resistance of the material (to lower strength) and to enhance ductility. In this research, the influence of the microstructure developed by SA on the strength and ductility was investigated and the method of controlling the microstructure of the medium carbon steel wire was studied. Furthermore, the microstructure and the formability of the developed medium carbon steel wire rod for cold heading were investigated.

2. Relationship between Microstructure and Mechanical Properties of Medium Carbon Steel Wire Rod for Cold Heading

2.1 Relationship between microstructure and mechanical properties after SA

By the Hall-Petch relation, the strength of steel is proportional to the power of −1/2 of the grain size[1]. Furthermore, it is reported that, according to the Orowan model[2], the strength of the steel that contains dispersed particles is proportional to the power of −1 of the interparticle spacing, or to the power of −1/2 of the interparticle spacing according to the dislocation pile-up model[3]. Thus, the strength of steel is influenced by the grain size and the interparticle spacing.

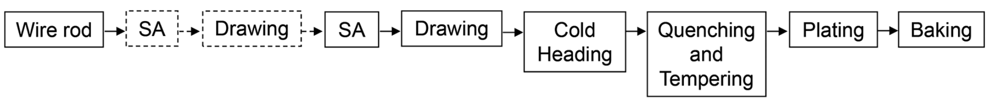

Fig. 1 Example of manufacturing process of cold heading bolts

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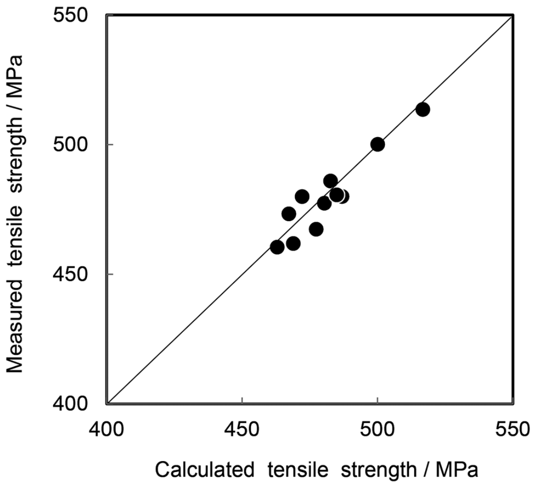

Fig. 2 Comparison of measured and calculated tensile strengths

The yield strength of the steel such as the medium carbon steel for cold heading wherein spheroidized cementite is dispersed is reported to be influenced by both the ferrite grain size and the interparticle spacing of cementite[4, 5].

A medium carbon steel wire rod containing 0.43 mass% carbon was provided for trial. The as-rolled wire rod and the wire after drawing with an area reduction of 30% were SA-treated in the temperature range between 700°C–730°C. Thus, different microstructures were developed and the relationship between the microstructure and the tensile strength was investigated. The following formula was developed as a result of the regression analysis of the measured tensile strength σ_B (MPa) with respect to the average ferrite grain size D_α (μm) and the average interparticle spacing of cementite λ (μm) obtained from the observation of the microstructures.

$$\sigma_B = 320 + 450 D_\alpha^{-1/2} + 100 \lambda^{-1} \quad (1)$$

The relationship between the measured tensile strength values and those calculated from Formula (1) is shown in **Fig. 2**. The deviation of the measured values from the calculated ones is small and they approximately agree with each other. This result indicates that the tensile strength of SA-treated medium carbon steel can mostly be arranged by the power of −1/2 of the average ferrite grain size and the power of −1 of the average interparticle spacing of cementite. Similar to yield strength, the tensile strength after SA becomes lower along with the growth of the average ferrite grain size and the average interparticle spacing of cementite.

2.2 Relationship between microstructure and ductility after SA

The reduction of area obtained in the tensile test was used as the index for the evaluation of ductility. The reduction of area becomes higher along with the reduction in ferrite grain size[6]. On the other hand, it is reported that the reduction of area and the fracture strain of the medium carbon steel wherein spheroidized cementite is dispersed are influenced by the cementite size[5, 7].

In this research, medium carbon steel wire rods containing 0.43 mass% carbon were used. The as-rolled wire rod and the wire after wire drawing with an area reduction of 30% were SA-treated in the temperature range between 700°C–730°C and the different microstructures were developed. The relationship between the microstructure and the reduction of area was investigated. The relationship between the average ferrite grain size developed by the SA and the reduction of area obtained in this research is shown in **Fig. 3**.

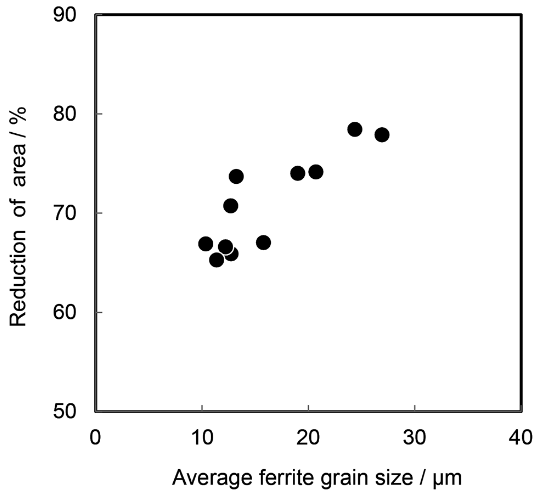

Fig. 3 Effects of average ferrite grain size on reduction of area after spheroidizing annealing

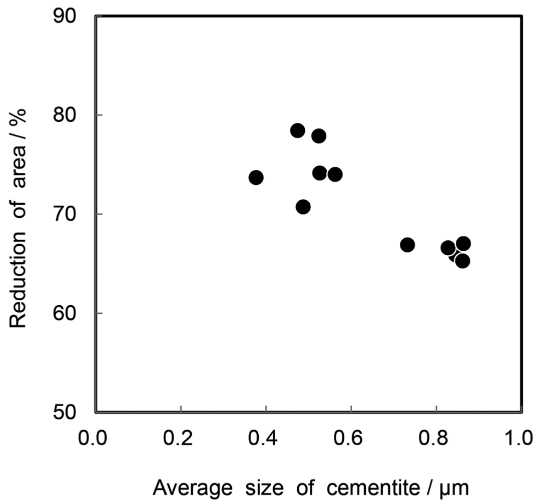

Fig. 4 Effects of average size of cementite on reduction of area after spheroidizing annealing

Along with the growth of ferrite grain size, there is a noticeable trend of the reduction of area increasing, exhibiting a trend different from past findings. Similarly in **Fig. 4**, the relationship between the average cementite size and the reduction of area is shown. Along with the growth of the average cementite size, reduction of area became smaller. It is reported that, in the process of ductile fracturing, the larger the cementite size, the more frequently voids are produced by small plastic strain[8]. The result of this research shows that the average cementite size is more influential than that of the ferrite grain size as the void is generated by the stress concentration preferentially around the coarse cementite at the boundary of the coarse cementite and ferrite. Based on the above, this research also confirmed that the reduction of area after SA increases along with further refinement of the average cementite.

3. Utilization of Isothermal Transformation Treatment for Controlling Material of Medium Carbon Steel Wire Rod

3.1 Concept of controlling microstructure

To improve the formability in cold heading, it is effective to soften the material (to lower strength) and to improve ductility. As presented hereunder, a method was studied that furnishes a medium carbon steel material with lower strength and higher ductility by controlling the ferrite grain size, cementite size and so forth of the microstructure.

As stated in 2.1 and 2.2, the following relationship is established between the mechanical properties and the microstructure of steel with dispersed spherical cementite.

(1) Tensile strength lowers as the interparticle spacing of cementite and the ferrite grain size grow larger.
(2) Reduction of area increases along with the refining of cementite.

Accordingly, to lower the strength of medium carbon steel and to improve ductility, a microstructure with larger ferrite grain size and smaller cementite size is to be developed.

Next, the method of obtaining the abovementioned microstructure was studied. Generally, in the case of precipitates dispersed randomly, the radius R of the grain of a steel including grains of the second phase can be expressed by the following Zener's formula using the radius r and the volumetric fraction f of the precipitates[9].

$$R = \frac{4}{3}\frac{r}{f} \tag{2}$$

This means that the smaller the size of the precipitates, the smaller the grain becomes. However, in practically used medium carbon steel, cementite is scarcely dispersed randomly; rather, it tends to be distributed unevenly and exists more at the grain boundary and/or in the area of prior pearlite before SA. It is reported that in the case that the precipitates are distributed unevenly and exist more at the grain boundary, the radius of the grain R is expressed in Φ by the following formula, where Φ is the ratio of precipitates unevenly distributed at the grain boundary[10].

$$R = \frac{2}{\Phi^{1/2}}\frac{r}{f^{1/2}} \tag{3}$$

Formula (3) suggests that when there are more precipitates at the grain boundary, growth of grain is suppressed. This means that in the case of cementite size and volume fraction being fixed, in the steel wherein cementite is dispersed evenly, ferrite grain size increases more than in the steel wherein cementite is distributed unevenly and exists more at the grain boundary. Accordingly, by dispersing cementite evenly, ferrite grain can be coarsened even if cementite size remains fine, and consequently, low strength and high ductility can coexist.

3.2 Microstructure of medium carbon wire rod after isothermal transformation treatment

As stated in 3.1, the state of the dispersion of cementite influences the ferrite grain size. To reinforce this matter, microstructures of medium carbon steel wire rods after SA, each having a different state of cementite dispersion, were investigated. By applying different cooling processes to medium carbon wire rods with a carbon content of 0.43 mass% after hot-rolling, wire rods having different pearlite distribution were prepared. **Figure 5** shows the cooling processes schematically[5]. The DLP process is a cooling process in which wire rods are isothermally transformed directly immediately after hot rolling by retaining at the pearlite transforming temperature region in the molten salt bath cooling equipment (Direct in-Line Patenting: DLP)[11] built after the rolling mill. The STM process is a process of continuously air-cooling the hot-rolled wire rods by using the Stelmor equipment[12]. Hereafter, the medium carbon steel wire rod processed by the DLP process is called 43C-DLP and the wire rod processed by the STM process is called 43C-STM.

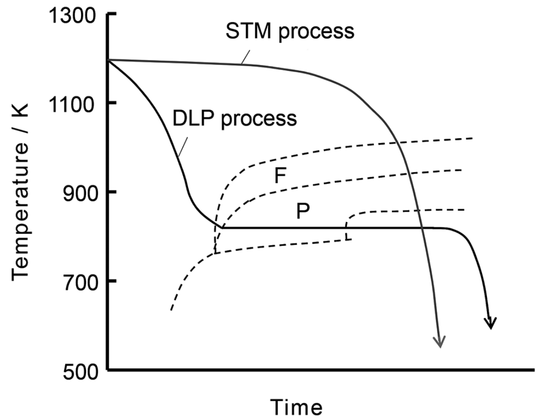

Fig. 5 Schematic diagram of cooling processes after hot rolling[5]
DLP process employs isothermal transformation by quenching into salt bath and STM process employs continuous cooling. F and P designate ferrite and pearlite, respectively.

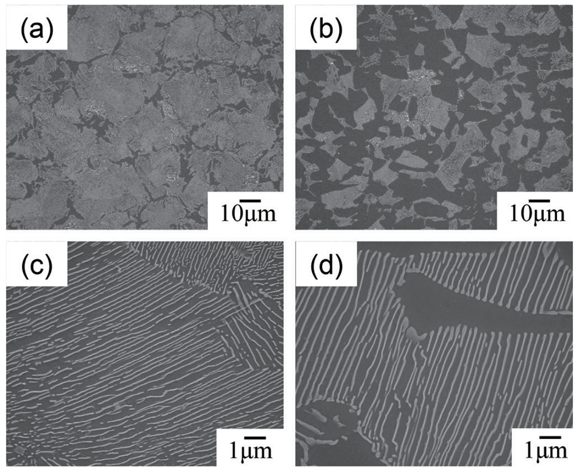

Fig. 6 SEM images showing microstructures prepared by different cooling processes after hot rolling
(a) Pearlite microstructure prepared by isothermal transformation treatment (DLP process), (b) Ferrite-pearlite microstructure prepared by continuous cooling (STM process), (c) Magnified image of (a), (d) Magnified image of (b).

As **Fig. 6**(a) shows, the isothermally transformed 43C-DLP exhibits microstructure similar to a pearlite single phase microstructure with remarkably reduced ferrite. The microstructure of 43C-STM continuously cooled by the Stelmor equipment has become a ferrite/pearlite microstructure as shown in Fig. 6(b). Furthermore, the lameller spacing of the pearlite of 43C-DLP (Fig. 6(c)) was smaller than that of 43C-STM (Fig. 6(d)). Thus, the medium carbon wire rod produced by isothermal treatment has microstructure similar to the pearlite single phase with refined pearlite lamellar spacing.

Figure 7 shows the microstructures of 43C-DLP and 43C-STM after wire drawing and SA immediately below the A_1 point. As Fig. 7(a) shows, in the microstructure of 43C-DLP, cementite is dispersed almost evenly. However, as Fig. 7(b) shows, in the microstructure of 43C-STM, cementite is distributed unevenly and exists more in the prior pearlite area before SA. Furthermore, the average cementite sizes of 43C-DLP and 43C-STM after SA are 0.47 μm and 0.53 μm, respectively. 43C-STM cementite is coarser than that of

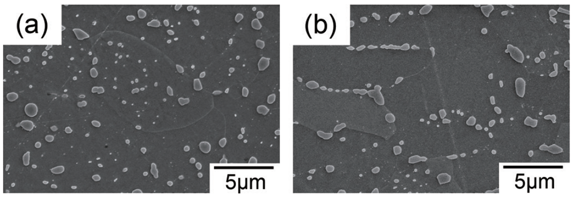

Fig. 7 SEM images showing microstructures after spheroidizing annealing
(a) 43C-DLP, (b) 43C-STM

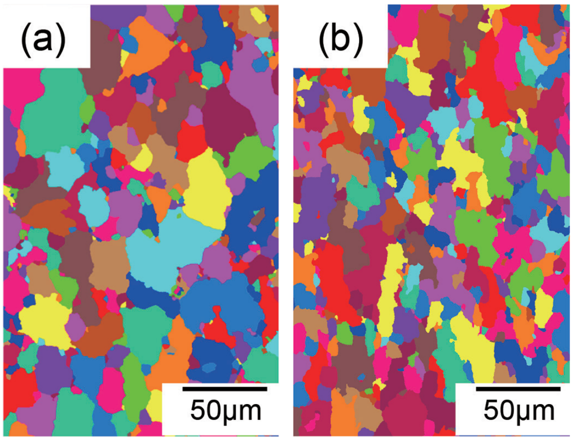

Fig. 8 EBSD images showing ferrite grain of (a) 43C-DLP and (b) 43C-STM after spheroidizing annealing

43C-DLP, and less spherical and more heterotypic in shape.

Thus, after SA, cementite was more evenly dispersed and the cementite size became smaller in the pearlite microstructure developed by the isothermal transformation treatment as compared to those in the ferrite/pearlite microstructure developed by continuous cooling. In the pearlite microstructure, as cementite is dispersed evenly, the volume of cementite unevenly distributed and distributed more at the ferrite grain boundary reduced. **Figure 8** shows the ferrite grain after SA measured by the electron back scatter diffraction method (EBSD). The ferrite grain size of 43C-DLP and 43C-STM after SA is 20μm and 17μm respectively, and the ferrite grain size of 43C-DLP was larger than that of 43C-STM.

From the measured average cementite size and the average ferrite grain size, ratio Φ of the cementite unevenly distributed at the ferrite boundary (hereinafter referred to as the uneven distribution ratio) was sought. Assuming the uneven distribution ratio Φ, average cementite size r, average ferrite grain size R of 43C-DLP and 43C-STM as Φ_{DLP}, Φ_{STM}, r_{DLP}, r_{STM}, R_{DLP}, and R_{STM}, from formula (3), the ratio of the uneven distribution ratio of 43C-STM vs. 43C-DLP is expressed by the equation (4) below.

$$\frac{\Phi_{STM}}{\Phi_{DLP}} = \left(\frac{r_{STM}}{r_{DLP}}\right)^2 \left(\frac{R_{DLP}}{R_{STM}}\right)^2 \qquad (4)$$

With the actually measured values of the average cementite size and the ferrite grain size inserted into equation (4), Φ_{STM}/Φ_{DLP} became 1.8. This value agreed mostly with the value actually measured from the microstructure photograph of Fig. 7. Thus, by taking into consideration the uneven distribution ratio, the difference in ferrite grain size after SA between those of 43C-DLP and 43C-STM can be well defined. In medium carbon steel with isothermal transformation treatment, the ferrite grain became coarse and the cementite size became smaller due to evenly dispersed cementite after SA. Accordingly, lower strength and higher ductility were realized and formability could be improved in cold heading.

4. Material Properties of Developed Steel

4.1 Production method of developed steel

Based upon the above hypothesis, a medium carbon steel wire rod for cold heading was produced based on JIS SWRCH40K that is widely used for mechanical parts such as bolts (hereinafter referred to as CH40K). **Figure 9** shows the production process of the trial steel wire rod. The developed steel (hereinafter referred to as CH40K-DLP) was hot-rolled, underwent isothermal transformation treatment through DLP equipment and then cooled. As stated in 3.2, in the medium carbon steel wire rod produced through DLP equipment, as cementite becomes fine and ferrite grain becomes coarse after SA, the strength lowers and the ductility increases. Therefore, the SA process before wire drawing was omitted and the wire was produced by wire drawing and the subsequent SA process. The conventional steel wire (hereinafter referred to as CH40K-STM) produced for comparison purposes was hot-rolled, air-cooled through the general wire-rod cooling equipment of Stelmor equipment, SA-treated and wire-drawn, and again SA-treated.

4.2 Microstructure and mechanical properties

Figure 10 shows the microstructures after SA. Unlike CH40K-DLP wherein cementite is refined and dispersed evenly, in the CH40K-STM microstructure, cementite coarse and heterotypic in shape is dispersed unevenly and more at the ferrite grain boundary and in the area of prior pearlite. Furthermore, the ferrite grain size of CH40K-DLP tended to be larger than that of CH40K-STM.

Figure 11 shows the tensile strength and the reduction of area after SA. Tensile strengths of CH40K-DLP and CH40K-STM after SA were almost equal. On the other hand, the reduction of area of CH40K-DLP after SA was higher than that of CH40K-STM.

As stated in 2.1, tensile strength is influenced by the average ferrite grain size and the average cementite spacing. Although the average cementite spacing of CH40K-DLP is small as the cementite is fine, the strength of CH40K-DLP is almost equal to that of CH40K-STM because of the larger average ferrite grain size. On the other hand, as stated in 2.2, the reduction of area is influenced by the average cementite size. The cementite size of CH40K-DLP after SA

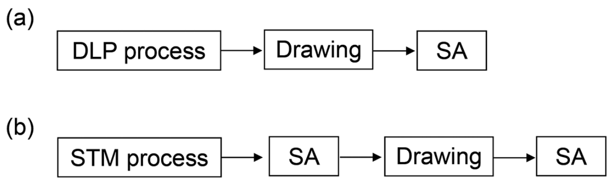

Fig. 9 Manufacturing process of tested steels
(a) CH40K-DLP, (b) CH40K-STM

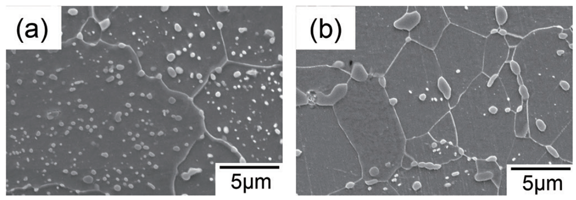

Fig. 10 SEM images showing microstructures after spheroidizing annealing
(a) CH40K- DLP, (b) CH40K-STM

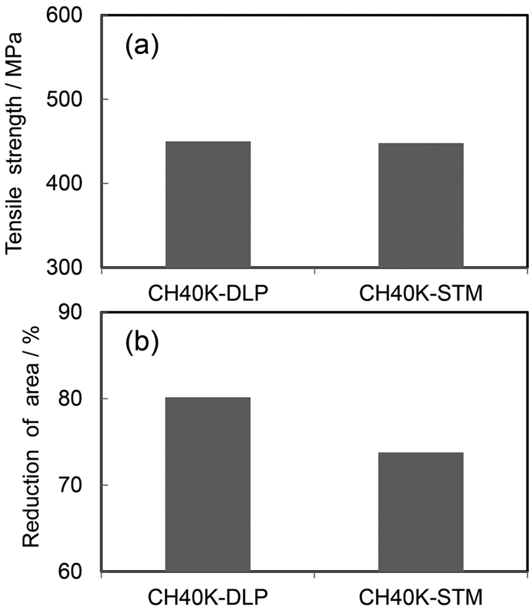

Fig. 11 Mechanical properties obtained by tensile tests of CH40K-DLP and CH40K-STM samples after spheroidizing annealing (a) Tensile strength, (b) Reduction of area

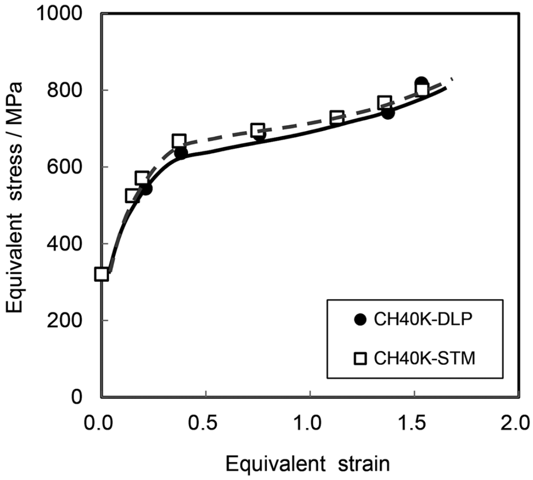

Fig. 12 Stress - strain curves obtained by upsetting tests of CH40K-DLP and CH40K-STM

was finer than that of CH40K-STM as shown in Fig. 10. Accordingly, the reduction of area of CH40K-DLP became higher than that of CH40K-STM.

4.3 Formability in cold heading

To evaluate the formability in cold heading, the compressive deformation resistance and the critical upsetting ratio at which point working cracks occur (hereinafter referred to as critical upsetting ratio) were obtained by an upsetting test with grooved platens[13]. **Figure 12** shows the stress-strain curve obtained from the upsetting test. Despite the SA process prior to wire drawing being omitted and SA-treated only once, CH40K-DLP exhibited the same deformation curve as that of CH40K-STM which was SA-treated twice. Based on the result, the deformation resistances of the two wires were almost equal.

In **Fig. 13**, the critical upsetting ratios of CH40K-DLP and CH40K-STM are shown. The working crack was evaluated in the following manner. A test specimen with a notch groove of a depth of 0.8 mm, an angle of 30° and with a radius of notch bottom curvature of 0.15 mm processed in the longitudinal direction was used, and when a crack of 0.5 mm or wider was observed, it was judged as a working crack. The critical upsetting ratio e was sought from the following formula wherein the initial height of the test piece is taken as h_0 and the height when the working crack was observed as h.

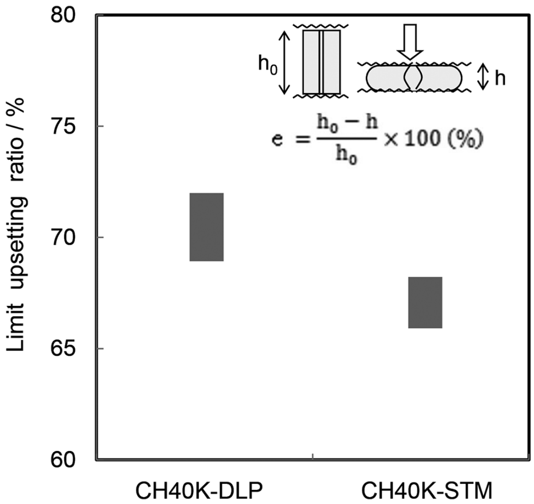

Fig. 13 Limit upsetting ratio e of CH40K-DLP and CH40K-STM

$$e = \frac{h_0 - h}{h_0} \times 100\,(\%) \tag{5}$$

The critical upsetting ratio of CH40K-DLP was higher than that of CH40K-STM. This result suggests that CH40K-DLP has the ability to suppress the generation of working cracks to a higher degree in terms of strain as compared to CH40K-STM. This is due to the small size of spherical cementite that suppresses the generation of cracks at the cementite and ferrite grain boundary.

5. Conclusion

The tensile strength of the SA-treated medium carbon steel deteriorated along with the growth of the average ferrite grain size and the average interparticle spacing of cementite. The reduction of area was improved by the average refined cementite size. This result indicates that in the microstructure wherein ferrite grain size is large and cementite is fine, lower strength and higher ductility are compatible and the formability is improved thereby. To obtain this type of microstructure, it is effective to apply isothermal transformation treatment to medium carbon steel, develop pearlite microstructure therein and apply the SA process.

As compared to the twice-SA-treated conventional steel wire rod, the developed medium carbon wire rod for cold heading exhibited, in spite of the one-time only treatment of SA, almost equivalent high mechanical properties of deformation resistance, and a higher critical upsetting ratio regarding the generation of cracks. Due to the mechanical properties thus obtained, reduction in heat treatment cost was realized by the omission of SA prior to wire drawing, suppression of the generation of working cracks in the cold heading process was enabled and furthermore, forming of parts with a more complicated configuration by cold heading may become possible.

The developed medium carbon steel wire rod for cold heading contributes to the improvement in productivity and energy saving in the manufacturing of mechanical parts such as bolts to lower the manufacturing cost, and to the enhancement of the configuration complexity of mechanical parts to further sophisticate their function.

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