Comparison of Cold Formability of Cold Drawn Non-heat-treated Steels Having Similar Strength

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The cold formability of the drawn non-heat-treated steels, i.e. dual phase (DP) steel, low Si steel and ultra low carbon bainitic (ULCB) steel, was examined in terms of the deformation resistance and the forming limit. The present investigation was aimed at elucidating the effect of drawing on the cold formability of non-heat-treated steels which is directly affected by drawing since no heat treatment are involved during forming processes for them. A special care was taken for the present steels to exhibit the similar strength after drawing, so eliminating the strength effect. The present steels after drawing revealed the elastic-near perfect plastic behavior in compression. After drawing, the low Si steel exhibited the lowest deformation resistance estimated by the absorbed energy during deformation. In case of the forming limit in terms of the critical strain under which no cracking occurs during the upsetting test of the drawn steels, the low Si steel and the ULCB steel were better than the conventional heat-treated steel. Accordingly, among several non-heat-treated steels which can replace the conventional heat-treated steel as forging steels, the low Si steel seems to exhibit the best performance if they have the similar strength. The compressive deformation behavior of the present drawn non-heat-treated steels was discussed in association with the strain hardened state and the Bauschinger effect developed by drawing. In addition, their cold formability was explained by the plastic incompatibility between the constituent phases of each steel.

KEY WORDS: cold formability; drawing; non-heat treated steels; dual phase steel; low-Si steels; ultra low carbon bainitic steels; tensile and compression properties.

1. Introduction

Low or medium carbon steels used for machinery components are required to exhibit good formability for easiness of shaping (usually forging) and high static/dynamic strength for severe service conditions. To satisfy such two contradictory mechanical requirements, the fabrication of machinery components with low or medium carbon steels commonly consists of a spheroidization process before shaping and a combined process of quenching and tempering (QT) after shaping. The former process ensures affordable formability by decreasing the strength in association with modification of morphology of pearlitic cementite in their initial ferrite/pearlite microstructure. The latter process resulting in tempered martensite microstructure provides the desired combination of strength and toughness for the final products. However, a sequence of such heat treatments is the time-consuming and the non-cost-effective. In order to overcome these deficiencies, non-heat-treated steels for which spheroidization and QT are unnecessary have been developed since 1970’s by utilizing the various phases of the steel.1–3) The strong candidates for non-heat-treated steels are ferrite/martensite dual phase steel,4–6) low Si steel,7,8) ultra low carbon bainitic steel9,10) etc. The mechanical properties of non-heat-treated steels are manifested by low yield strength and high strain hardenability. That is, the relatively low tonnage shaping is possible by low yield strength, and the strength required to the final products can be achieved simultaneously during shaping by high strain hardenability.

In general, low or medium carbon steels for machinery components are produced in the form of wire rods and subjected to cold drawing to various sizes. In case of non-heat-treated steels, the mechanical properties of drawn steels directly influence the mechanical response of the steels during shaping as well as the resultant mechanical properties of the final product since no heat treatments are involved. Accordingly, it is essential to elucidate the effect of drawing on the formability of non-heat-treated steels for optimization of both their shaping process and the mechanical properties of the final products. In this study, three representative non-heat-treated steels having different microstructures were prepared. The three steels were low carbon ferrite/martensite dual phase (DP) steel, medium carbon low Si steel, and ultra low carbon bainitic (ULCB) steel. Then, after drawing to the predetermined true drawing strain of 0.22, their formability was examined in terms of the deformation resistance and the forming limit. A special care was taken on the control of their initial microstructures before drawing such that their strength after drawing be comparable each other to eliminate the effect of the strength difference on formability.
2. Experimental Procedures

Ingots of the three steels were prepared by vacuum induction melting and homogenized at 1250°C for 2 h: their chemical composition is listed in Table 1. After homogenization, ingots were size rolled at 1100°C and 900°C with each 30% reduction. For the DP steel, the slab was further hot-rolled at 780°C with 60% reduction and water-quenched (so-called step quenching). This step quenching resulted in the equiaxed ferrite grains and martensite islands of the linear intercept size of ~40 μm, and the martensite volume fraction of ~21% (Fig. 1(a)). The finish rolling for the low Si steel and the ULCB steel was carried out at 800°C and 830°C with 60% reduction respectively, and then air-cooled to room temperature. The microstructure of the low Si steel consisted of ferrite and pearlite with nearly equal volume fraction. The size of ferrite grains and pearlite colonies was about 20–25 μm (Fig. 1(b)). As typical, the ULCB steel consisted of granular bainite surrounded by equiaxed prior austenite grain boundaries (Fig. 1(c)). As will be seen later, the present hot rolling conditions resulted in the similar strength level of the present steels at the drawing strain of 0.22.

From the hot rolled slabs, rods of Ø12.6 mm were machined for drawing. Drawing was conducted on the draw bench with drawing speed of 3 m/min up to a true drawing strain of 0.22 by a single pass: a true drawing strain \( \epsilon = 2 \ln(d_o/d_f) \) where \( d_o \) and \( d_f \) are the diameter of rod before and after drawing, respectively. After machining the cylindrical samples for tensile (Ø4 mm and gage length of 20 mm) and compression tests (Ø10 mm and height of 15 mm) from the drawn rods, the quasi-static uniaxial tests were performed at constant crosshead speed with the initial strain rate of \( 5 \times 10^{-3} \text{s}^{-1} \): the 3–5 samples were tested for each test. Compression tests were conducted up to the true strain of 1.2 beyond which barreling became bothersome. During compression tests, the Teflon sheet of 0.254 mm thickness was used as a lubricant to minimize the undesired friction effect. In addition, compression tests were undertaken on the notched specimens to various strains to check the occurrence of the cracking at the notch tip. Formability was evaluated in terms of both the deformation resistance represented by the energy absorbed during deformation, i.e. the area under the true stress–strain curve obtained from the compression test, and the forming limit represented by the critical compressive strain revealing cracks at the notch tip.

3. Results and Discussion

3.1. Tensile Properties

The representative nominal tensile stress–strain curves of the present steels before and after drawing are presented in Figs. 2(a) and 2(b) respectively, and their average nominal tensile properties are listed in Table 2. Before drawing, all the steels (Fig. 2(a)) exhibited their characteristic curves; that is, (a) extensive strain hardening, (b) continuous yielding in the DP and ULCB steels due to a presence of mobile dislocations with high density associated with their own transformation accommodation characteristics, and (c) discontinuous yielding in the low Si steel. Although the absolute comparison of the tensile properties of the steels before drawing is less meaningful due to different chemistry and microstructures, it is worth noting that strain hardening of the low Si and ULCB steels was rapid from the onset of plastic deformation and quickly saturated while that of the DP steel occurred more gradually.

After drawing (Fig. 2(b)), all the nominal tensile stress–strain curves revealed no strain hardening and very small uniform elongation of ~3%, as typical in the severely cold
drawn steels. In addition, the strength of the three steels after drawing was almost the same, satisfying the intention of the present study described above. An inspection of Table 2 revealed that the strength increase by drawing was the most significant in the DP steel than other two steels. This is because that, as shown in Fig. 2(a), strain hardening of the low Si and ULCB steels was saturated quickly in spite of the initial rapid strain hardening, but strain hardening occurred gradually up to the high strain in the DP steel.

3.2. Compression Properties

Figures 3(a) and 3(b) show the true compressive stress–strain curves of the three steels before and after drawing respectively. All the steels before drawing (Fig. 3(a)), strain hardening of the low Si and ULCB steels was saturated quickly in spite of the initial rapid strain hardening, but strain hardening occurred gradually up to the high strain in the DP steel.

The effect of drawing on the compressive behavior can be more clearly seen in Fig. 4 where the stress–strain curves before and after drawing are superimposed for each steel. For all the steels, the compressive yield stress after drawing was higher than that before drawing. However, the crossover of the flow stress occurred at the early stage of plastic deformation in the low Si steel (Fig. 4(b)) and ULCB steel (Fig. 4(c)) such that the flow stress after drawing became lower than that before drawing. For the DP steel

| Table 2. Nominal tensile properties of the present steels before/after drawing. |
|----------------|----------------|-------------|-------------|-------------|
| grade               | YS*, MPa | UTS , MPa  | $\varepsilon_1$ | $\varepsilon_1$ | Yield ratio |
| DP                  | 353 / 709 | 537 / 720  | 0.28 / 0.03 | 0.38 / 0.14 | 0.66 / 0.98 |
| low Si              | 379** / 712 | 601 / 741  | 0.21 / 0.03 | 0.33 / 0.13 | 0.63 / 0.96 |
| ULCB                | 480 / 720  | 606 / 724  | 0.15 / 0.03 | 0.28 / 0.15 | 0.79 / 0.99 |

* 0.2 % proof stress, ** lower yield strength
such crossover was not observed up to the true strain of 1.2, but was expected to occur with further increasing of strain. The flow stress crossover or convergence before and after drawing can be explained in terms of the two combined effects of pre-straining by drawing and the Bauschinger effect during compression. As depicted in Fig. 5, the steels in the strain-hardened state by drawing exhibit the elastic-near perfect plastic behavior with high yield stress and nearly no strain hardening (curve II in Fig. 5). The high yield stress results from primarily the interaction between mobile glide dislocations and immobile forest dislocations: the density of both dislocations increases at the initial stage of plastic deformation (in this case, drawing). The near perfect plastic behavior is attributed to dynamic recovery associated with the limited dislocation mean free length and the accelerated rate of dislocation absorption at its sinks with high density generated by plastic deformation. Then, during subsequent compression, both yield and flow stresses decrease by the Bauschinger effect (curve III in Fig. 5). The main concept of the Bauschinger effect is that, when the loading direction is reversed, the yield stress for backward deformation is lower than that for forward deformation: in the present case, the forward deformation and the backward deformation are attributed to the tensile component of drawing and the compression test respectively. Resultantly, a crossover or convergence between the compressive stress–strain curves of steels before (curve I in Fig. 5) and after drawing (curve III in Fig. 5) inevitably occurs.

3.3. Cold Formability

For economic metal forming processes, the two aspects should be considered: (a) prolonged life of the machinery components, and (b) reduction of the inferior quality products. To ensure the former, it is desired to use materials to be formed with low deformation energy so that less impact damage is transferred to the machinery components. One of the representative causes of the inferior qualities during severe forming processes such as forging is the cracking. Accordingly, materials with high crack resistance are preferred. In this section, the cold formability of the present drawn steels is examined in terms of these two aspects.

3.3.1. Deformation Resistance

The energy needed for deformation, so-called absorbed energy, is easily estimated from the area under the stress–strain curves. The absorbed energy up to the true compressive strain of 0.3 of the present steels before and after drawing is compared in Fig. 6. Before drawing, the absorbed energy was low in the order of the DP steel, the low Si steel and the ULCB steel. The lowest absorbed energy of the DP steel was due to the lowest yield and flow stress among the steels (Fig. 3(a)). However, after drawing, the low Si steel
exhibited the lowest absorbed energy, and that of the DP steel and the ULCB steel was comparable. The lowest absorbed energy in the low Si steel would be attributed to the lower yield stress and flow stress in early plastic deformation stage than those of other steels after drawing, as seen in Fig. 3(b). It is of interest to note that the increase of the absorption energy in the DP steel after drawing, ~35%, was larger than that in other two steels, 4–6%. This can be justified by the difference of strain hardening characteristics of the steels as described in Sec. 3.1. For non-heat treated steels, the mechanical properties after drawing directly influence those of the final product after forming since no heat treatments are involved. Accordingly, in terms of deformation resistance, it can be concluded that, among the present steels having the comparable flow stress level after drawing, the use of the low Si steel is beneficial for enhancing the life of the machinery components.

3.3.2. Forming Limit

In the present investigation, the forming limit or the crack resistance of the drawn steels was evaluated by determining the critical strain (in terms of compressive reduction) under which no cracking occurs on the notched sample (Fig. 7) at the strain rate of $5 \times 10^{-2} \text{s}^{-1}$. For the purpose of comparison, the identical test was carried out on the reference steel, i.e., conventional heat-treated forging steel (SWRCH45F) after spheroidization. For replacement of the conventional forging steels with the non-heat-treated steels, the latter should exhibit the higher critical strain for cracking than that of the former. As summarized in Fig. 7, the critical strain of the ULCB steel and the low Si steel after drawing was higher than that of reference steel, but the DP steel exhibited the lower critical strain than the reference steel.

The crack initiation is primarily attributed to the plastic incompatibility causing non-uniform deformation. Therefore, the cracking in the single phase steel is relatively hard to occur compared to the multiphase steels: in the present case, the former is the ULCB steel and other steels including the reference steel belong to the latter. Accordingly, it is natural that the quasi-single phase ULCB steel revealed the highest critical strain. Since the plastic incompatibility in the DP steel consisting of soft ferrite and hard martensite is expected the most severe among the present steels including the reference steel, the critical strain of the DP steel appeared to be the lowest: in the present case, the hardness (Vikers HV scale) of ferrite and martensite of the DP steel was 195 and 430 respectively, and that of ferrite and pearlite of the low Si steel was 203 and 263.

4. Concluding Remarks

(1) The cold formability of the drawn non-heat-treated steels with the similar strength level after drawing, i.e., dual phase (DP) steel, low Si steel and ultra low carbon bainitic (ULCB) steel, was examined by the compression tests and the upsetting tests.

(2) All the drawn steels exhibited the elastic-near perfect plastic behavior in compression. The low Si steel exhibited the lowest deformation resistance (in terms of the absorbed energy estimated from the compressive stress–strain curves). The DP steel and the ULCB steel showed the comparable deformation resistance.

(3) In the upsetting tests with the notched samples, the forming limit (in terms of the critical strain under which no cracking occurs in upsetting) of the low Si steel and the ULCB steel was higher than that of the conventional heat-treated forging steels, but the opposite is true for the DP steel.

(4) Considering the deformation resistance and the forming limit, among several non-heat-treated steels which can replace the conventional heat-treated steel as forging steels, the low Si steel seems to exhibit the best performance if they have the similar strength.

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REFERENCES

1) M. Ueki, S. Horie and H. Tadahisa: Trans. Iron Steel Inst. Jpn., 27 (1987), 453.
2) G. Krauss and S. K. Banerji: Fundamentals of Microalloying Forging Steels, AIME, Warrendale, PA, (1987), 3.
3) D. J. Naylor: Ironmaking Steelmaking, 16 (1989), 246.
4) S. S. M. Tavares, P. D. Pedroza, J. R. Teodósio and T. Gurova: Scr. Mater., 40 (1999), 887.
5) N. J. Kim and G. Thomas: Metall. Trans. A, 12A (1981), 483.
6) H. G. Read: Scr. Mater., 37 (1997), 151.
7) G. Thomas and J. Y. Koo: Structure and Properties of Dual Phase
8) E. V. Pereloma and P. D. Hodgson: Mater. Sci. Eng. A, A251 (1998), 30.
9) R. Mendoza, J. Huante, M. Alanis, C. Gonzalez-Rivera and J. A. Juarez-Islas: Mater. Sci. Eng. A, A276 (2000), 203.
10) A. K. Lis, J. Lis and L. Jezierski: J. Mater. Process. Technol., 64 (1997), 255.
11) G. Krauss and S. W. Thompson: ISIJ Int., 35 (1995), 937.
12) J. D. Embury and R. M. Fisher: Acta Metall., 14 (1966), 147.
13) C. Biselli and D. G. Morris: Acta Mater., 44 (1996), 493.
14) S. N. Buckley and K. M. Eatwistle: Acta Metall., 4 (1956), 352.
15) D. Kim, M. G. Lee, C. Kim, M. L. Ernnt, R. H. Wagoner, F. Barlat, K. Chung, J. R. Youn and T. I. Kang: Met. Mater. Int., 9 (2003), 561.
16) L. P. Kubin and Y. Estrin: Acta Metall. Mater., 38 (1990), 697.
17) H. Conrad and J. Narayan: Acta Mater., 50 (2002), 5067.
18) H. Conrad: Mater. Sci. Eng. A, A341 (2003), 216.
19) R. Z. Valiev, Y. V. Ivanisenko, E. F. Rauch and B. Badelet: Acta Mater., 44 (1996), 4705.
20) B. Karlsson and B. O. Sundström: Mater. Sci. Eng., 16 (1974), 161.