Effect of Aluminum and Nitrogen on Ductility of Steels in the Temperature Range Brought into by Cold Work*

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Synopsis

In order to investigate the effect of Al and N on workability at elevated temperatures attained by cold working, ductility of steels with varying Al/N ratios was examined by tensile test conducted at R. T.  250 °C for low carbon steels (JIS S15C) and case hardening steels (JIS SCR420). In the low carbon steels, the ductility at those elevated temperatures was reduced markedly for lower Al/N ratios than 1.2, but did not decrease so much for higher Al/N ratios than 3.3. On the other hand, in the case hardening steels, the reduction of ductility at the same elevated temperature range was smaller and did not depend on Al/N ratio.

It appeared that the ductility of steels at those elevated temperatures is affected by the content of nitrogen in solution, which in turn depends on Al/N ratio, cooling rate from austenite, and content of other alloy elements.

I. Introduction

During cold forging with high speed and high forging ratio, the temperature of worked steel ascends to nearly 200 °C. For example, in cold extrusion of Disc Piston Cup (inner diameter: 64 mmφ, outer diameter: 79 mmφ, height: 48.5 mm) out of low carbon steel at a forging rate of 25 pieces/min by a 1,000 t mechanical press, the temperature of the specimen rose to more than 130 °C just after cold working. Another example is the experimental investigation by Tozawa et al. on the upsetting of steel: when a steel specimen of 11.2 mmφ and 16.8 mm long was upset to an upsetting ratio of 69.4 % by a mechanical press, the temperature of the specimen rose to more than 150 °C after 100 m·sec from the start of upsetting.

Therefore, the properties especially the ductility of a steel at those elevated temperatures are important for its workability, e.g., deformability without fracturing.

It is known that soluble nitrogen in steel has a strong influence on the ductility at elevated temperatures. In steels for cold forging, nitrogen in solid solution is usually fixed as AIN by addition of aluminum, but a considerable amount of nitrogen in solution may remain depending on the balance of aluminum and nitrogen contents. Consequently, Al/N ratio in steel may be an important parameter for the ductility of steel at elevated temperatures.

In the present note, two grades of steels frequently offered to cold forging—JIS S15C low carbon steel and JIS SCR420 case hardening steel—were taken up, and the effect of the ratio of aluminum and nitrogen on the ductility of these steels at elevated temperatures was investigated.

II. Test Method

1. Tested Steels

Six JIS S15C low carbon steels (Al: 0.001~0.031 %, N: 0.0042~0.0073 %, Al/N: 0.1~7.0) and six JIS SCR420 case hardening steels (Al: 0.005~0.036 %, N: 0.0040~0.0090 %, Al/N: 0.8~5.2) were supplied to tensile test.

They were melted in a 30 kg vacuum furnace and the content of nitrogen was changed by controlling the holding time under an atomosphere of 10⁻²~10⁻³ Torr and by addition of nitrogen by means of manganese nitride. Chemical compositions and Al/N ratios of tested steels are shown in Table 1.

Melted steels were poured into a number of 15 kg molds, and ingots were forged into bars of 15 mmφ at 1,200 °C. Then they were heat-treated and machined to test pieces of 8 mmφ and 60 mm long.

For heat treatment, normalizing and full annealing were performed in order to investigate the effect of cooling rate. Conditions of heat treatment are shown in Table 2.

2. Method of Tensile Test

Tensile tests were performed at temperatures from room temperature to 250 °C by a 10 t hard machine, and tensile strength and reduction of area were examined. Test pieces for 100~250 °C were heated in an electric furnace equipped in situ, kept at the designated temperature for about 15 min, then stretched. The crosshead speed was 3 mm/min.

III. Results and Discussion

Tensile strength and reduction of area at each temperature are shown in Fig. 1 (S15C) and Fig. 2 (SCR420).

In the low carbon steels of lower Al/N ratios than 1.2 (steels Nos. 35, 31, and 36), tensile strength increased and reduction of area decreased markedly at temperatures of 150 °C and 250 °C in normalizing and full-annealing conditions. On the other hand, in low carbon steels of higher Al/N ratios than 3.3 (steels Nos. 32, 33, and 34), tensile strength and reduction of area did not vary so much as the former at temperatures from R.T. to 250 °C. Moreover, extensive serration was recognized in the tensile curves obtained at 150 and 200 °C of Nos. 35, 31, and 36 in the two heat treatment conditions, but they were not recognized in the curves obtained at 150 °C.

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In the case hardening steels containing about 1% Cr, tensile strength of all steels varied in nearly the same pattern with increase of the testing temperature in either heat treatment condition, and reduction of area also did so. The differences in tensile strength and in reduction of area between at 250 °C and at room temperature are shown in Fig. 3 for S15C and in Fig. 4 for SCR420.

As clearly shown in Fig. 3, in low carbon steels, there exists a marked embrittlement with decreasing AlN ratio, and stronger tendency to embrittlement is found in normalizing than in full annealing. Further, the decrease in ductility at 250 °C seems to associate with Al/N ratios lower than about 2 for full annealing and those lower than about 3.5 for normalizing, and these losses in ductility due to low Al/N ratio seem to be caused by nitrogen remained in solution after cooling.

Equilibrium constant (solubility product) of aluminum and nitrogen in ferrite can be estimated to be about 1/10 of that in austenite, and so nitrogen in ferrite may be combined 100% as AlN when it coexists with much aluminum. But this conclusion is only obtained supposing that equilibrium among aluminum, nitrogen, and AlN is maintained always during cooling. However, it has been shown that the precipitation of AlN is so slow during cooling that AlN scarcely precipitates in comparatively rapid cooling after normalizing. It is therefore that the cooling rate from austenite will influence strongly the precipitation of AlN, reversely the content of nitrogen remained in solution after cooling.

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Figure 5 is an estimated result of the content of nitrogen in solution when steel is cooled from austenite at 900 °C in which AlN coexists with aluminum and nitrogen in solution. The calculation was made by selecting Leslie's solubility product among several reported data. In rapid cooling, nitrogen in solution equilibrated with AlN in austenite may stay uncombined, but in slow cooling, nitrogen in solution may be reduced with the precipitation of AlN and may be combined wholly as AlN in the case of the
stoichiometric composition.

In the case hardening steels, it is seen in Fig. 4 that the decrease in ductility at 250 °C is almost independent of Al/N ratio. The decrease in ductility at 250 °C for full annealing is slight over the whole range of Al/N ratio, while that for normalizing is considerably large. It seems that chromium of about 1 % in tested steels have probably influenced the solubility of nitrogen9 in these steels.

IV. Summary

(1) In the low carbon steel of S15C class with a low Al/N ratio, decrease in reduction of area and increase in tensile strength occurs at 150~250 °C, the temperature range the steel may be brought into during cold working.

(2) For low carbon steels with a low Al/N ratio, the normalized ones are more susceptible to this kind of embrittlement than the full-annealed ones.

(3) In the case hardening steel of SCR420 class, clear Al/N ratio dependent embrittlement does not appear.

REFERENCES


3) J. Glen: JISI, 186 (1957), 21.


