KAWASAKI STEEL TECHNICAL REPORT
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Mitsumasa Kurosawa, Susumu Satoh, Takashi Obara, Kozo Tsunoyama

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Age-hardening behavior of deep-drawable high strength steel has been investigated by measuring dent resistance in a model panel and yield strength change in a tensile test. Obtained results are as follows: (1) Bake-hardenability measured by the tensile test is in good agreement with the dent resistance of a pressed panel, (2) sufficient hardening effect is obtained even at a lower temperature aging, (3) once the sheet steel is deformed, age-hardening starts swiftly, (4) hardening is accelerated by increasing the strain and the amount of solute C.

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Age-Hardening Behavior and Dent Resistance of Bake-Hardenable and Extra Deep-Drawable High Strength Steel*


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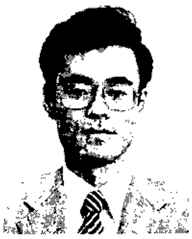
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Synopsis:

Age-hardening behavior of deep-drawable high strength steel has been investigated by measuring dent resistance in a model panel and yield strength change in a tensile test. Obtained results are as follows: (1) Bake-hardenability measured by the tensile test is in good agreement with the dent resistance of a pressed panel, (2) sufficient hardening effect is obtained even at a lower temperature aging, (3) once the sheet steel is deformed, age-hardening starts swiftly, (4) hardening is accelerated by increasing the strain and the amount of solute C.

1 Introduction

Adoption of high strength steels has made it possible to reduce the thickness of automotive sheets, thus contributing to the reduction of the total weight of automobiles. However, conventional high strength steels have a limit in pressing some outer panels such as a rear fender panel which requires excellent deep-drawability. Further, the reduction of sheet thicknesses tends to deteriorate the dent resistance of pressed panels.

To improve both formability and dent resistance in high strength sheet steels for automobile outer panels, bake-hardenable high strength steels have been developed[1, 2]. They are characterized by a low yield strength as supplied and a high yield strength after press-forming and subsequent baking during the coating process. The bake-hardening phenomenon results from age-hardening where solute C and/or N immobilize dislocations induced by deformation such as pressing.

The rimmed steels were widely used for automotive use in past decades. Since the rimmed sheet steel contains a lot of solute N, it exhibits high bake-hardenability. However, an excessive amount of solute N often causes the trouble called 'stretcher strain' at press-forming. On the other hand, N is stabilized as AlN in the Al-killed steels while C is stable as a form of Fe_3C in the case of box annealing production. Therefore, the Al-killed steels never provide bake-hardenability. For the new type bake-hardenable steels, the amount of solute C is controlled within an optimum range where the upper limit of solute C is determined by the resistance to a room temperature aging before pressing.

From the metallurgical viewpoint, the age-hardening behavior depends on deformation modes and aging conditions such as aging temperature. The ordinary simulation for baking is performed at 170°C for 20 min after prestraining. The baking temperature is required to decrease so as to save energy and meet the growing amount of automotive plastic parts.

This paper describes an improvement of dent resistance and age-hardening behavior when bake-harden-

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able sheet steel is used for automobile panels.

2 Materials

A Nb-added extra-low C steel (CHRX-BH) was continuously annealed to be used as a specimen for bake-hardenable and extra-deep drawing quality steel[2]. **Figure 1** compares the specimen's mechanical properties with the rephosphorized steel (REPHOS) where the tensile strength grade of both steels is 350 MPa. The material is characterized by high elongation and high Rankford-value (r value). Bake-hardenability (BH) was expressed by the flow stress difference (ΔYS) between pre-straining and straining after aging treatment at 170°C for 20 min. The schematic illustration of the method and the relationship between BH and WH (work-hardenability) are demonstrated in **Figs. 2** and **3**, respectively. In 1986, Japanese Industrial Standard (JIS-G3135 for "High strength cold-rolled sheet steel for automobiles") defined 2% as prestrain in measuring BH.

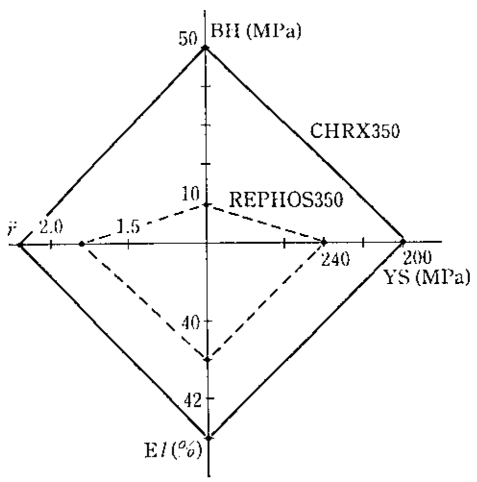

Fig. 1 Features of mechanical properties of CHRX-BH and rephosphorized high strength steel (TS grade: 350 MPa)

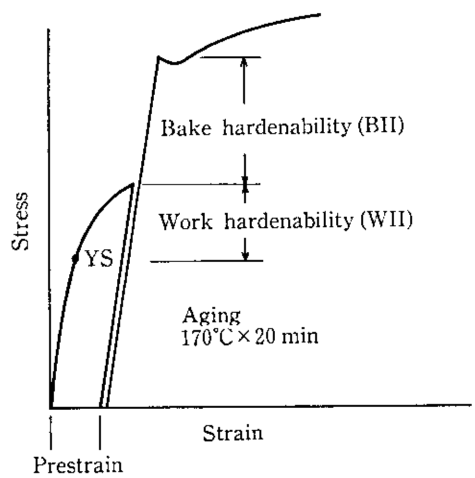

Fig. 2 Measuring method of bake-hardenability (BH) and work-hardenability (WH) by tensile test

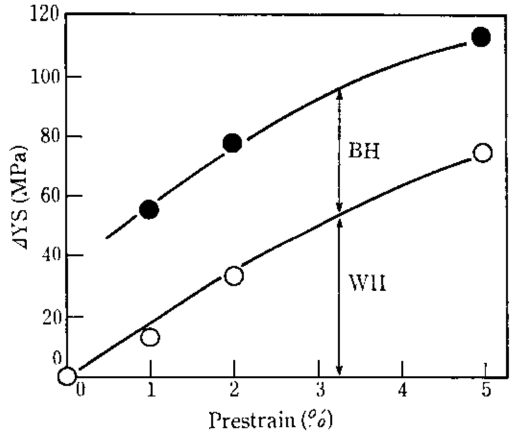

Fig. 3 Effect of tensile prestrain on work-hardening and bake-hardening after aging at 170°C for 20 min (Prestrain and tensile test were performed in the cross-rolling direction.)

Figure 4 shows schematically the producing process and the metallurgical principle of CHRX-BH. Dissolved NbC generates solute C after recrystallization at a continuous annealing process. The amount of solute C can be controlled by adjusting the ratio of Nb to C and the annealing conditions such as soaking temperature and cooling rate. This method provides both extra-deep drawability and bake-hardenability.

3 Dent Resistance

A static dent resistance test was conducted using a small D-shape panel pressed by a hydraulic press machine in the laboratory. The amount of plane prestrain was changed by the control of a blank holder force. The detailed experimental procedure and panel dimension are shown in **Fig. 5**. The dent resistance was evaluated by the depth when the hard steel ball was pushed under the load of 196 N on the panel.

The test was performed in just pressed panels and panels heated at 170°C for 20 min after pressing. The same test was given to panels held at a room temperature for 3 to 7 days after pressing. The relationship between the dent depth and the plane prestrain is shown in **Fig. 6**. The dent depth decreases with an increase of strain amount. This results from an increase of flow stress in panels due to work-hardening. Aging treatment provides a drastic improvement of dent resistance. This result proves that the bake-hardenability obtained in the tensile test shown in Fig. 3 corresponds to the improvement of dent resistance in actual pressed panels. It is very interesting that the dent resistance improvement in panels held at room temperature without aging is recog-

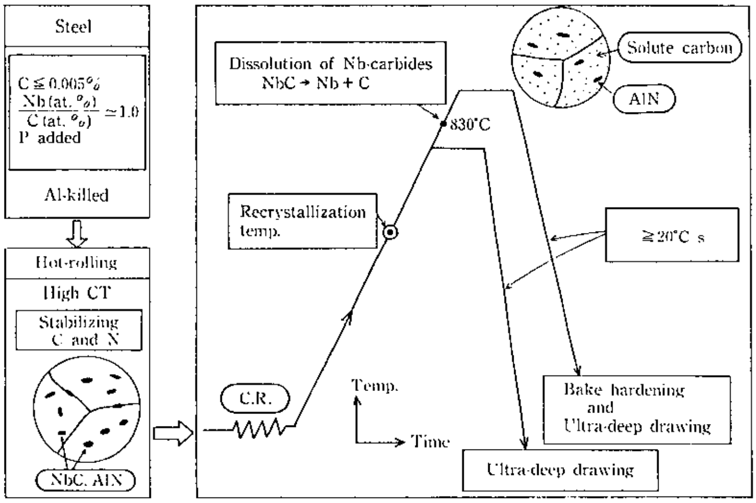

Fig. 4 Schematic illustration of metallurgical factors for producing CHRX-BH by a continuous annealing process

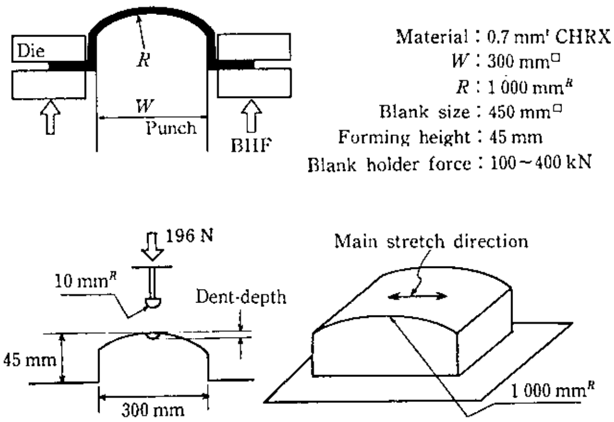

Fig. 5 Schematic illustration of static dent resistance test

nized and the panels strained at a high amount exhibit a dent resistance similar to that of heat-treated panels.

From the above results, it was found that the bake-hardenable sheet steel increases the dent resistance of pressed panels and that the effect is insensitive to baking conditions if the deformation is enough for strain aging.

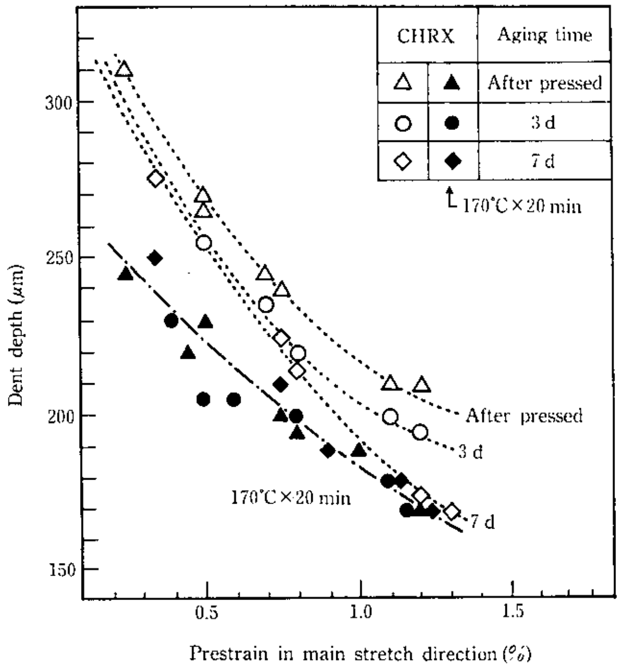

Fig. 6 Residual dent-depth plotted against plane pre-strain in the stretch direction of stamped panels (Aging treatment were carried out at 170°C for 20 min and room temperature, 30 to 40°C, for 3 to 7 days.)

4 Hardening Behavior of Bake-Hardenable Sheet Steel

The dislocation plays an important role in a plastic deformation of metals. It is defined as the line defect in the crystalline structure. The deformation proceeds with the nucleation and the propagation of dislocations. Work-hardening can be explained microscopically as follows. The necessary stress to move dislocations increases gradually due to a tangle of dislocations induced by plastic deformation. On the other hand, C and N in Fe exist as interstitial atoms which cause a strain field around themselves. Solute C and N diffuse fast in a steel and tend to relax the strain energy by moving adjacent to the core of dislocations, which also produces a strong strain field. The immobilized dislocations increase the flow stress when the steel is deformed. This phenomenon is called "strain aging" and the cause of stretcher strain which is detected as a high yield elongation in a tensile test. **Figure 7** illustrates schematically the process of strain aging.

Since the yield stress change was in good agreement

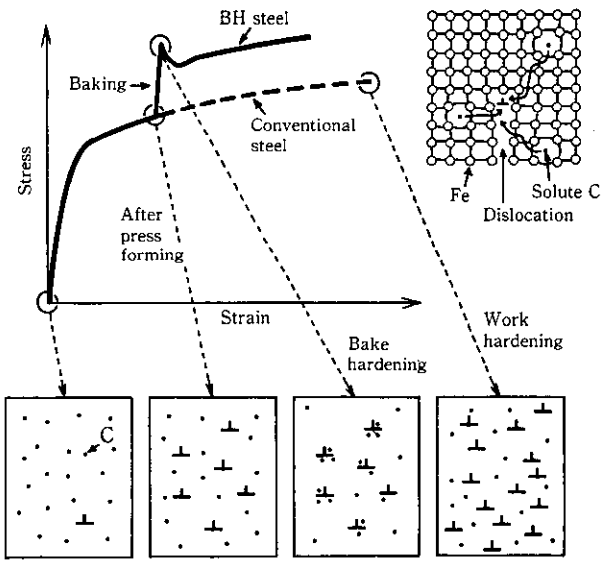

Fig. 7 Schematic illustration of a metallurgical principle of bake hardening

Table 1 Aging conditions

	Aging temperature and time	Tensile prestrain*
No. 1	70, 100, 130, 170°C × 20 min	0** & 1%
No. 2	70°C × 20 min→30°C × 1, 3, 7 day	0** & 1%
No. 3	30°C × 1, 3, 10, 24, 72, 168, 504 h	1, 2, 5, 10%

* Tensile test: 0.7 mm thick, JIS No. 5 specimen, crosshead speed 10 mm/min

** As temper rolled

with the dent resistance test results of actual pressed panels as shown in the previous chapter, the age-hardening behavior of CHRX-BH was investigated by the tensile test. The yield stress change was tested of two types of specimens heated to various temperatures for 20 min and then held at ambient temperature. One specimen was as-received and the other was followed by prestraining. The detailed conditions are shown in **Table 1**. The increment of yield stress (ΔYS) is obtained by the difference between the flow stress after prestrain, FS, and the upper yield stress after aging treatment, YS'.

$$\Delta YS = YS' - FS \quad \cdots\cdots(1)$$

The proof stress at 0.2% strain is defined as FS in as-temper rolled specimens. The tensile test was performed with the JIS Z 2201 No. 5 specimens acquired in the transverse direction against the rolling direction. The prestrained specimens were kept at −40°C to avoid the aging between prestraining and subsequent aging.

Figure 8 demonstrates the effect of aging temperature on the increment of yield stress after aging for 20 min. The age-hardening is accelerated with the increase of aging temperature since the diffusion of solute C

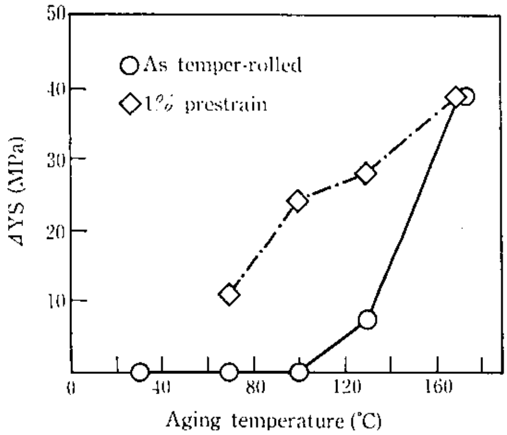

Fig. 8 Strain-aging effect of prestrained bake-hardenable steel aged at various temperature for 20 min (Specimens were in the cross-rolling direction)

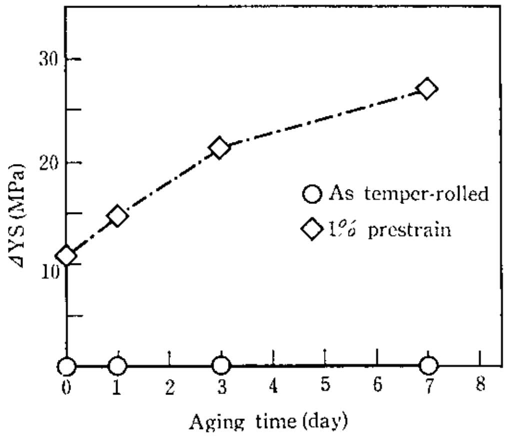

Fig. 9 Strain-aging effect of prestrained bake-hardenable steel aged at 30°C after aging treatment at 70°C for 20 min (Specimens were in the cross-rolling direction)

becomes fast. For prestrained specimens by a 1% strain, age-hardening was detected at 70°C, while as-received (as temper rolled) specimens never hardened at lower temperatures than 100°C. However, an increment of yield stress in both specimens heated at 170°C for 20 min reached the same value. This result clarifies that the prestraining process accelerates the age-hardening at the low temperature region.

The change of yield stress in specimens held at 30°C after aging at 70°C for 20 min is represented in **Fig. 9**. For the specimens prestrained by 1%, the hardening amount increased with increase in the aging time and after a week reached 80% of the hardening amount in the specimen heated at 170°C for 20 min when it was kept at 30°C. No change was recognized in the as-temper-rolled specimens after 1 week. Thus age-hardening

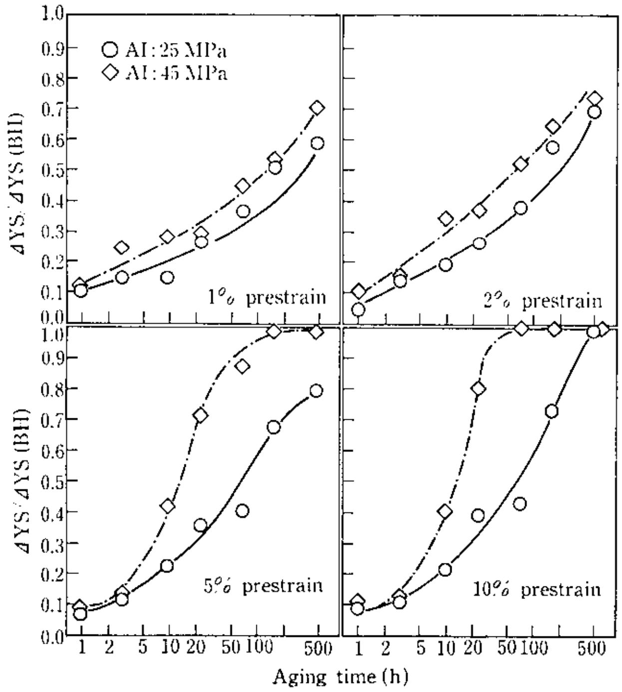

Fig. 10 Influence of aging index on strain-aging behavior of bake hardenable steel aged at 30°C after various amount of prestraining (Prestrained specimens were in the cross-rolling direction)

is detected even at ambient temperature when the bake-hardenable sheet steel is tensioned preliminarily.

Figure 10 illustrates the hardening ratio of the prestrained specimens plotted with the aging time where the hardening ratio denotes the normalized value with the hardening amount (BH) of specimens heated at 170°C for 20 min. Aging index (AI) exhibits the stress difference between the flow stress at 7.5% of prestrain and the lower yield stress after aging at 100°C for 30 min. The index is a convenient test for evaluating the amount of solute C and N. No serious problem occurs in pressing when AI value is controlled within 50 MPa. The figure includes two sheet steels with AI values of 25 and 45 MPa. The hardening ratio increased with an increase in the prestrain and the AI value. This result can be understood in the following mechanism. The higher the amount of solute C, the more frequently does solute C immobilize dislocations, with the result that age-hardening proceeds in a short time. In case of the heavily strained specimens, the necessary diffusion path length of solute C for pinning becomes short due to an increase of the dislocation density.

The above mentioned results and discussions are helpful to understand the fact that the dent resistance of bake-hardenable sheet steel was clearly improved by keeping the pressed panels even at ambient temperature, as shown in Fig. 6.

As for the difference between stretching and temper-rolling concerned with the age-hardening behavior, the amount of temper-rolling higher than 1% is more effective in avoiding age-hardening at ambient temperature[3]. This is realized as the essential difference between temper-rolling and a simple stretching. Temper-rolling has a strain mode unlike that of stretching or tensioning. In the case of temper-rolled specimens, the strain is localized near the surface in the thickness direction while the stretch and tension strains distribute homogeneously over the thickness. For the reason why temper-rolling is effective to restrain age-hardening, it is proposed that (1) a residual stress field induced by temper-rolling restricts the formation of the Cottrell atmosphere around the dislocation core and (2) some mobile dislocations located close to the surface with the high dislocation density are available for lowering the yield stress[4, 5].

In contrast with temper-rolling, stretching accelerates age-hardening even at a small strain. This may result from the relax of a residual stress field induced by temper-rolling and the homogeneous dislocation distribution which provides the shorter diffusion path for immobilization of dislocations by solute C.

5 Summary

Age-hardening behavior of deep-drawable high strength sheet steels has been investigated by measuring the dent resistance in a model panel and the yield strength change in a tensile test. Obtained results are as follows:

(1) With bake-hardenable sheet steels, the dent resistance of pressed panels is improved.
(2) Bake-hardenability measured by the tensile test is in good agreement with the dent resistance of the pressed panel.
(3) Sufficient hardening effect is obtained even at a lower temperature aging.
(4) Once the sheet steel is pressed or deformed, age-hardening starts swiftly even at room temperature.
(5) Hardening is accelerated by increasing the strain and the amount of solute C.

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