Dynamic Bake Hardening of Interstitial-Free Steels

K. DEHGHANI and J.J. JONAS

Two types of dynamic strain aging (DSA) strengthening methods were investigated to determine their potentials for industrial use. They are referred to here as dynamic-static bake hardening (DSBH) and dynamic bake hardening (DBH). For this purpose, a 0.06 pct Ti interstitial-free (IF) steel was reheated to 900 °C and cooled at 12 °C/s to room temperature. It was then dynamically bake hardened in the temperature range 100 °C to 250 °C to strains of 2 to 8 pct at a strain rate of 10^{-3} s^{-1}. The tensile properties were determined before and after these treatments. It was found that the occurrence of DSA during dynamic baking led to significant increases in work-hardening rate as well as in the final strength. The results indicate that, for a given solute carbon level, the dynamically and then statically aged samples have higher strengths than those that are bake hardened in the conventional way.

I. INTRODUCTION

TWO important objectives being pursued by the automobile industry are a decrease in car weight and improvements in safety. To realize these requirements, reductions in sheet thickness, higher strength, and improvements in press formability are generally demanded for automobile body panels.[1,2,3] Bake-hardenable high-strength steels are an interesting solution that can satisfy all these requirements. This property provides a capacity for a strength increase of approximately 20[4] to 30 pct[5] (i.e. 30 to 60 MPa) from the initial yield strength.[6] The method employed to measure the amount of static (conventional) bake hardening (SBH) by means of tensile testing is illustrated in Figure 1. Target bake-hardening values for the increase in flow stress range from about 40 to 60 MPa and require solute carbon levels between about 10 and 20 ppm.[7]

The procedure employed to assess the SBH is the following:

(1) the specimen is strained 2 pct at room temperature,
(2) the sample is aged at 170 °C for 20 minutes, and
(3) the specimen is tensile tested at room temperature.

The amount of bake hardening is determined by subtracting the flow stress after the 2 pct prestrain from the lower yield strength after baking. Although a 2 pct prestrain and aging at 170 °C for 20 minutes are typical values employed to cause bake hardening in steels, some workers have used other prestrains, temperatures, and times.[8,9]

A. *Effect of the Amount of Carbon in Solution*

Bake-hardenable steels must contain a certain minimum amount of solute carbon. This interstitial element is responsible for the strength increment,[6] as bake hardening occurs by static strain aging as a result of interstitial atom segregation to dislocations. In the initial stages of strain aging, strengthening is accomplished solely by the formation of solute atmospheres.[6,9,10] During atmosphere formation, carbon segregates to dislocations and strengthening arises from the additional force needed to separate the dislocations from their atmospheres.[6,7,9]

When the solute carbon level is too low, the bake-hardening values are also low. On the other hand, excessive amounts of carbon in solution lead to room-temperature aging. In order to have sufficient susceptibility for bake hardening, different required amounts of solute carbon have been reported: 5,[6] 10,[11] and 5 to 15 ppm.[12] These amounts of solute carbon at room temperature can be produced by employing a suitable cooling rate after the annealing of low, extra-low, or ultra-low carbon steel. As for N, most bake-hardenable steels contain sufficient aluminum to remove the dissolved nitrogen and rely solely on carbon to provide the bake hardenability.[6,10]

Bake-hardenable steels can be produced by both conventional batch-annealing and continuous-annealing processes.

B. *Batch Annealing*

In the case of batch annealing, in which very low carbon, <0.01 pct,[10] steel is frequently used, the precipitation of Fe_3C is suppressed because of the sparseness of nucleation sites. This results in some amount of carbon remaining in solution, even after the use of relatively slow cooling rates.[6,7,9,10] This process was not investigated in the present simulations.

C. *Continuous Annealing*

With regard to continuous annealing, a high annealing temperature, about 900 °C,[8,9,10,13] is required in order to produce bake hardenability in interstitial-free (IF) steels. The cooling rate from the soaking temperature should also be high so as to provide enough carbon in solution at room temperature. This cooling rate normally ranges from 20 to 30 °C/s,[10] through 70 °C/s,[6] to 100 °C/s.[14] In the present work, a cooling rate of 12 °C/s was used.

The higher the Ti*/C (Ti* = total Ti-3.42N-1.5S) or Nb/C atomic ratio, the higher the annealing temperature that must be used during continuous annealing (and *vice versa*). For a fixed annealing temperature, the lower the Ti*/C or Nb/C atomic ratio, the higher the bake hardenability.[10]

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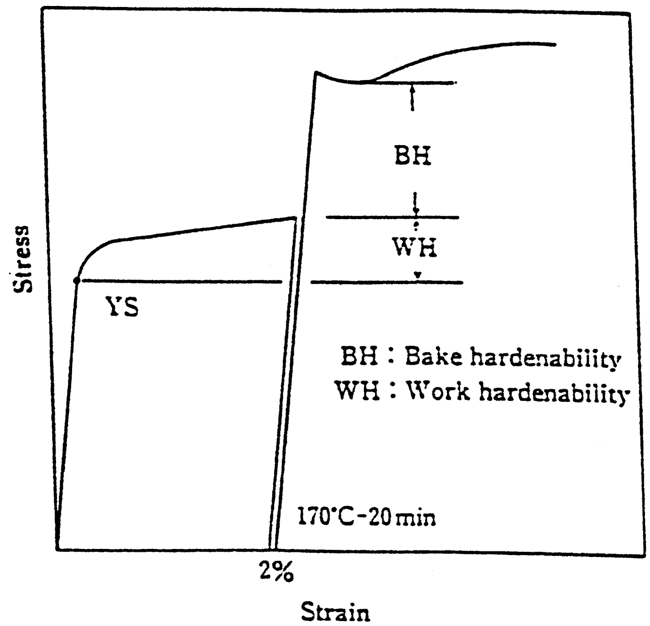


Fig. 1—Measuring method for assessment of bake hardenability in a tensile test.

D. *The Link between Dynamic Strain Aging and Bake Hardening*

The aim of the present work was to establish a link between bake hardenability and dynamic strain aging (DSA) in IF steels for which the occurrence of DSA has been already shown.[15,16,17] Based on this link, two novel methods, referred to as dynamic bake hardening (DBH) and dynamic-static bake hardening (DSBH), are introduced here. These have advantages and disadvantages compared to SBH. The possibility of an industrial application is therefore discussed.

II. EXPERIMENTAL TECHNIQUES

A. *Material*

Samples for laboratory testing were taken from strip mill transfer bars that had been rolled down to a thickness of approximately 26 mm. The original 240-mm-thick slab was reheated to about 1260 °C before rolling and the last roughing pass was carried out at about 1140 °C. The composition of the IF grade studied is listed in Table I, and an example of an industrial rolling schedule employed to process this material is given in Table II.

B. *Tension Tests*

For the tensile testing at elevated temperature, standard ASTM specimens with threaded ends were prepared,[18] with their longitudinal axes parallel to the rolling direction. Their dimensions are shown in Figure 2. The use of threaded shoulders for gripping the specimens enables aging phenomena, such as the propagation of Luders bands, serrated flow, increases in flow stress, and decreases in ductility, to be observed clearly.[19] All samples were cleaned with alcohol before carrying out the tests, in order to remove stains that could possibly lead to stress concentrations at elevated temperatures.

The tensile tests were carried out using a computer-controlled MTS machine. A microprocessor-controlled tungsten-lamp radiant furnace mounted on the machine frame was used to heat the specimen to the desired elevated temperature. The heat generated by the four tungsten-filament lamps is reflected to the center of the furnace, where the specimen is located, by four mirror-finished, elliptical reflectors of aluminum. The specimen was heated at 1 °C/s and held at the testing temperature for 5 minutes prior to testing. A type K (chromel-alumel) thermocouple attached to the center of the specimen gage length was used to measure the temperature, and its deviations were found not to

Table II. The Industrial Rolling Schedule Employed on the Present Material

Pass Number	Exit Thickness (mm)	Temperature (°C)	Interpass Time (s)
1	215	1260	10.9
2	195	1255	10.5
3	175	1250	12.0
4	155	1245	12.1
5	130	1239	14.8
6	100	1231	15.8
7	70	1219	22.0
8	45	1195	22.1
9	26	1139	—

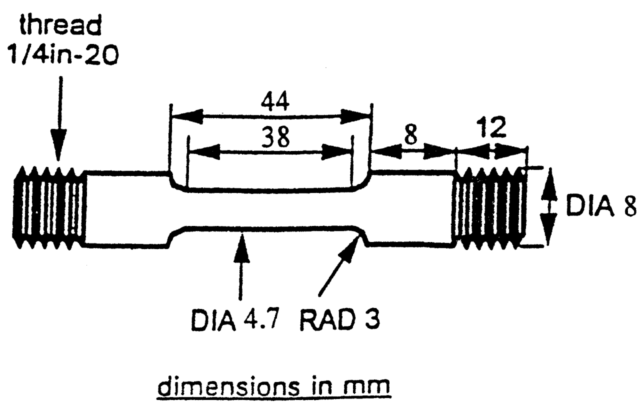


Fig. 2—Geometry of tension sample.

Table I. Chemical Composition of the Experimental Steel (Weight Percent)

C	N	Ti	Nb	S	P	Mn	Ti_{exc}	$(Ti^*_C + Nb)/C$	Ti^*_S/S
0.0023	0.0032	0.06	0.005	0.023	0.011	0.16	0.005	1.58	1.43

Ti^*_S is the amount of Ti available to combine with S after all the N is tied up as TiN.
Ti^*_C is the amount of Ti available to tie up the C after the formation of TiN and TiS.
Ti_{exc} is the amount of Ti remaining in solution after the precipitation of TiN, TiS, and TiC.

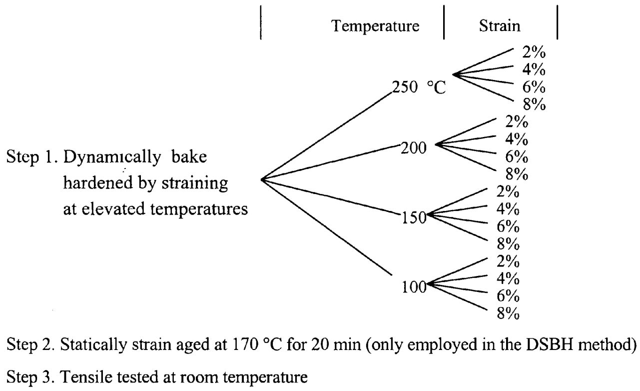


Fig. 3—Schematic diagram of the DBH (steps 1 and 3) and DSBH (steps 1 through 3) methods. Steps 1 and 3 are common to both techniques, while step 2 is only employed in the DSBH method.

exceed ±1 °C. To make sure that the distribution of temperature was uniform along the gage length, another type K (chromel-alumel) thermocouple was placed against the shoulder of the specimen for some of the tests. Temperature variations between the two thermocouple measurements were found to be within ±2 °C. The specimen and grips were enclosed in a quartz tube and argon gas was passed through it to minimize oxidation for testing temperatures of 200 °C and 250 °C. The gripping bars were water cooled to prevent oxidation.

C. *Bake Hardening Methods*

All samples were reheated to 900 °C,[20] held for 60 seconds, and then cooled to room temperature at 12 °C/s. The aim was to ensure that enough solute carbon was present to produce bake hardening. All the tensile tests were then carried out at a strain rate of 10^{-3} s^{-1}.

The reheat temperature was also chosen by considering the following solubility products for TiC and $Ti_4C_2S_2$:[21]

$$\log\,[\mathrm{Ti}][\mathrm{C}]^{0.5}[\mathrm{S}]^{0;5} = -17{,}045/T + 7.9 \qquad [1]$$

$$\log\,[\mathrm{Ti}][\mathrm{C}] = -10{,}800/T + 5.02 \qquad [2]$$

For example, the TiC dissolution temperature obtained for the present steel is about 864 °C. As for C and N, their solubilities in α-iron can be calculated using the following equations:[22,23,24]

$$\log\,[\mathrm{C}]_{\mathrm{ppm}} = 6.38 - (4040/T) \qquad [3]$$

$$\mathrm{C\ (wt\ pct)} = 2.55\ \exp\,(-4850/T) \qquad [4]$$

$$\mathrm{N\ (wt\ pct)} = 12.3\ \exp\,(-4177/T) \qquad [5]$$

1. *DBH method*

According to this new method, samples were strained 2, 4, 6, and 8 pct while being held at 100 °C, 150 °C, 200 °C, and 250 °C (*i.e.*, they were bake hardened "dynamically"). After cooling in still air, they were tensile tested at room temperature. This procedure is illustrated in Figure 3. The yield strengths before and after baking, and therefore the bake-hardening values, were then obtained from the tensile test results. The yield strength after baking is usually used to judge the dent resistance of metals.[6,25]

2. *SBH method*

This method is exactly the procedure normally used to assess the bake hardenability of steels. Samples were prestrained 2, 4, 6, and 8 pct in tension and at room temperature. They were then aged for 20 minutes at 100 °C and 150 °C in air and at 200 °C and 250 °C in argon. Following this step, further tensile tests were carried out at room temperature. These steps were summarized in Figure 1.

3. *DSBH method*

This method is another new technique for producing bake hardening. As in the DBH process, in the DSBH method, samples were also dynamically bake hardened by straining 2, 4, 6, and 8 pct at 100 °C, 150 °C, 200 °C and 250 °C, Some tests were also carried out at 170 °C; these results were reported in Reference 17. The only difference between the DBH and DSBH procedures is that, in the DSBH technique, the samples are subjected to another aging process: static strain aging at 170 °C for 20 minutes (this step is usually employed for the simulation of conventional bake hardening). After this treatment, they are pulled to fracture at room temperature. This method (DSBH) is thus a combination of the DBH and SBH techniques, as presented in Figure 3.

III. RESULTS

To estimate the amounts of solute carbon available for bake hardening, aging-index tests were carried out. An average value of 26 MPa was obtained, corresponding to about 4 ppm carbon in solution, as described in Reference 15. The maximum and minimum bake-hardening values obtained with this amount of solute carbon were about 55 (DSBH method) and 3 (SBH method) MPa, respectively. This means that, for a given solute carbon level, the dynamically and then statically aged samples have much more capacity for hardening than those that are bake hardened in the conventional way.

A. *DBH Method*

The effects of strain and temperature on (a) the increase in stress due to bake hardening and (b) the yield strength after the DBH process are presented in Figure 4. Figure 4(a) illustrates how the DBH depends on temperature. The amount of the increase reaches a maximum at around 170 °C, a position that does not change with strain. With respect to strain, the samples strained 2 pct under DBH conditions exhibited the greatest hardening or strength increase (Table III). The yield strength before straining was 95 MPa. After DBH, this was again measured at room temperature. It increased with the DBH strain, reaching a plateau at the higher temperatures, as illustrated in Figure 4(b).

B. *SBH Method*

The effects of prestrain and temperature on (a) the amount of bake hardening and (b) the yield strength after this treatment are illustrated in Figure 5. It is evident from Figure 5(a) that the maximum in the SBH value *vs* prestrain curve shifts to lower prestrains as the temperature is increased; this is in agreement with previous work.[8,9] At intermediate temperatures (150 °C and 200 °C), three different behaviors

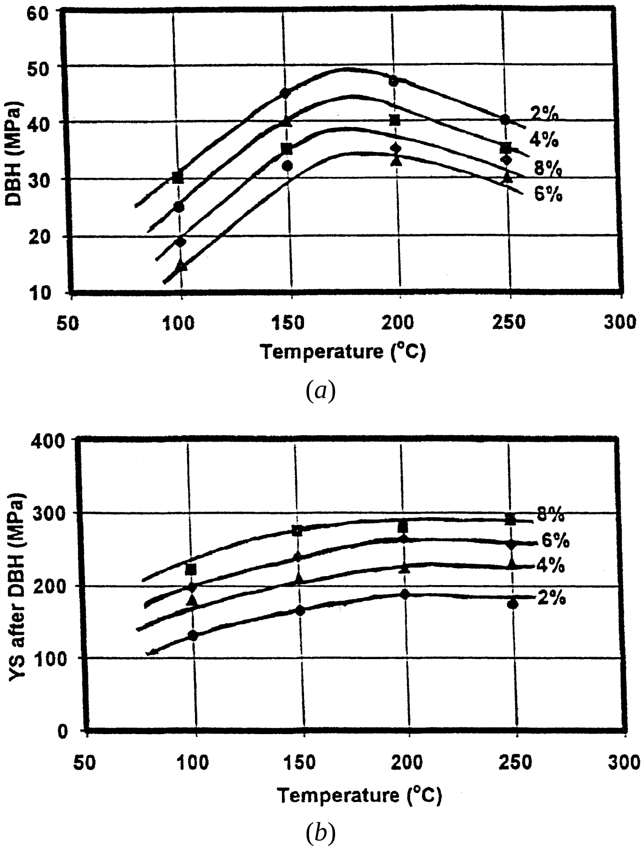


Fig. 4—(*a*) Effect of temperature and strain on the DBH values and (*b*) dependence of the room-temperature yield strength after DBH on temperature.

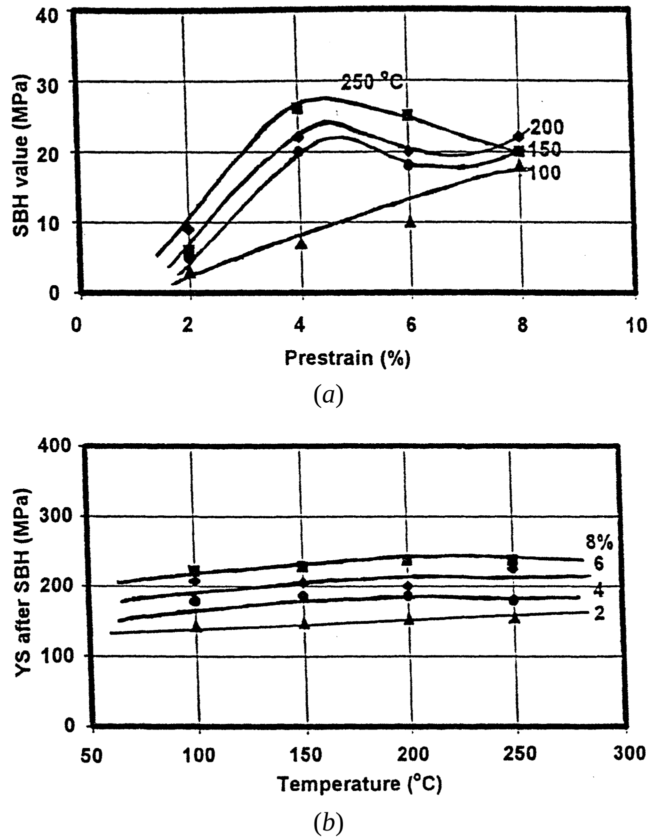


Fig. 5—(*a*) Effect of temperature and strain on the SBH values and (*b*) dependence of the room-temperature yield strength after SBH on temperature.

Table III. Comparison of the Characteristics of SBH, DBH, and DSBH

Characteristic	SBH	DBH	DSBH
Amount of BH	low	high (up to 8× SBH)	high (up to 15× SBH)
Luders strain	yes	no	no
Yield drop during straining	yes	no	no
Yield drop during subsequent room-temperature testing	—	rare	significant
Yield strength at test temperature	high (about 150 MPa)	about 45 MPa lower	about 45 MPa lower
Work-hardening rate	low	high	high
YS/UTS ratio	low	high	high

are observed: (1) at low prestrains, the bake-hardening values increase with increasing prestrain; (2) less bake hardening is observed with further increases in prestrain; and (3) larger prestrains result in a plateau, or in a slight increase, in the hardening value. This is in good agreement with the findings of other investigators.[5,8] The maximum and minimum amounts of static bake hardening (26 and 3 MPa) were obtained in the cases of 4 and 2 pct prestrain followed by baking at 250 °C and 100 °C, respectively.

Prestraining followed by baking led to an increase in the subsequent yield strength until the latter essentially reached a plateau. This occurred in the range between 200 °C and 250 °C (Figure 5(b)), again in agreement with the results of past workers.[5,26–28] Note that the initial yield strength before straining is about 140 MPa, which is about 45 MPa higher than in the two cases of dynamic (elevated temperature) straining.

C. *DSBH Method*

The effects of strain and temperature on (a) the amount of bake hardening and (b) the yield strength at room temperature after use of this technique are depicted in Figure 6. Two different behaviors were observed in the former case (Figure 6(a)). When the subsequent static-aging temperature (170 °C) was higher than the temperature of dynamic aging (*e.g.*, 100 °C and 150 °C), the influence of dynamic aging was diminished. In this case, the effect of strain on the amount of bake hardening was almost the same as that produced by the SBH method at 150 °C and 200 °C. By contrast, when

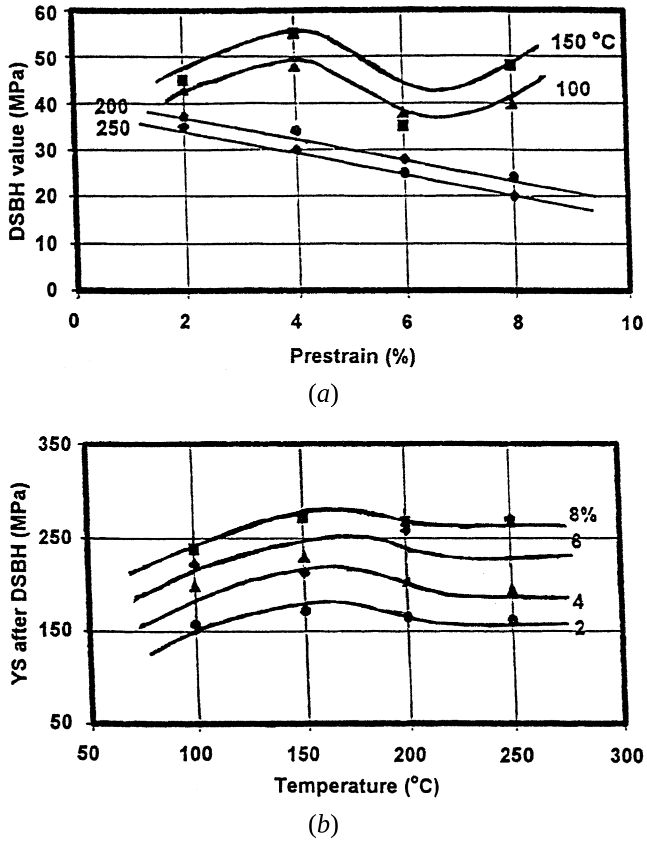


Fig. 6—(*a*) Effect of temperature and strain on the DSBH values and (*b*) dependence of the room-temperature yield strength after DSBH on temperature.

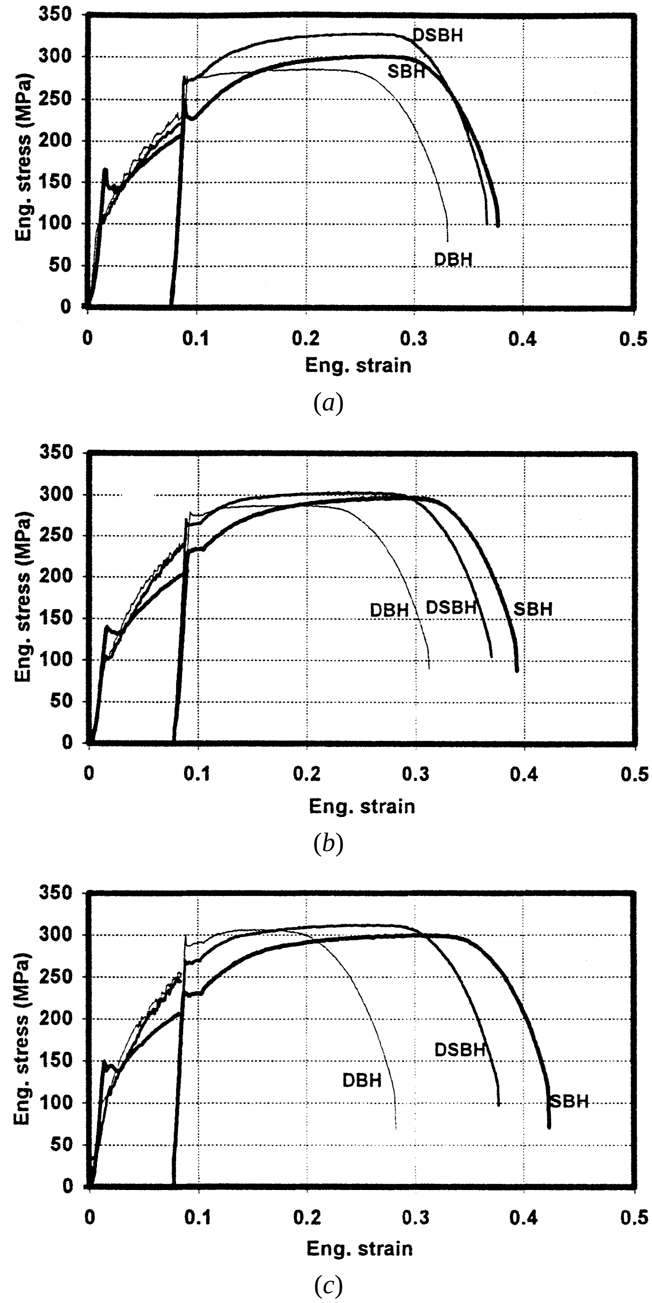


Fig. 7—Comparison of DBH and DSBH values after applying a strain of 8 pct at (*a*) 150 °C, (*b*) 200 °C, and (*c*) 250 °C. The SBH curve is included for reference purposes.

the former temperature was lower than the latter, the amount of bake hardening decreased with the strain. The maximum and minimum amounts of bake hardening (55 and 20 MPa) obtained with this method corresponded to straining to 4 and 8 pct at 150 °C and 250 °C, respectively.

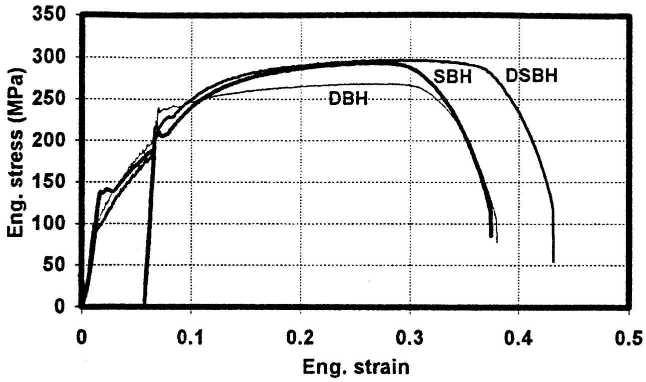
As in the DBH method, the elevated-temperature yield strength before employing the DSBH process was approximately constant at about 95 MPa. By contrast, the room-temperature yield strength after treatment increased with the amount of strain and essentially reached a plateau. The latter began somewhere between 150 °C and 200 °C, *i.e.*, at approximately 170 °C (Figure 6(b)).

D. *Comparison of the DBH, SBH, and DSBH Methods*

The three methods of bake hardening the present steel are compared in Figures 7 through 11. It is evident that the highest BH values are produced in the dynamically-aged specimens (*i.e.*, by the DBH and DSBH methods). These also lead to more pronounced work-hardening rates, reduced Luders strains, lower yield strengths before prestraining, and significant increases in yield strength after baking. These factors can help to prevent buckling and wrinkling, necking in expanded zones, and stretcher strains and should therefore lead to higher dent resistance after baking.

To avoid the aforementioned defects in press forming, the yield strength should be as low as possible, the Luders strain should be almost zero, and the work-hardening rate as high as possible. In addition, high yield strengths after baking confer high dent resistance. Referring to Figures 7 through 11, all these properties can be improved by using a dynamic aging process. In general, the increases in stress due to bake hardening in the cases of DSBH and DBH are much higher than those produced by the SBH method. For example, in the case of a 2 pct strain at 100 °C, the amounts produced by the DSBH and DBH methods are about 15 and 8 times the SBH value, respectively.

The minimum bake-hardening value is about 3 MPa (2 pct prestrain at 100 °C with the SBH method) and the maximum value is about 55 MPa (a strain of 4 pct at 150 °C with the DSBH method). Generally speaking, the lowest bake-hardening values were obtained in the case of SBH. Conversely, the highest amounts were observed in the case



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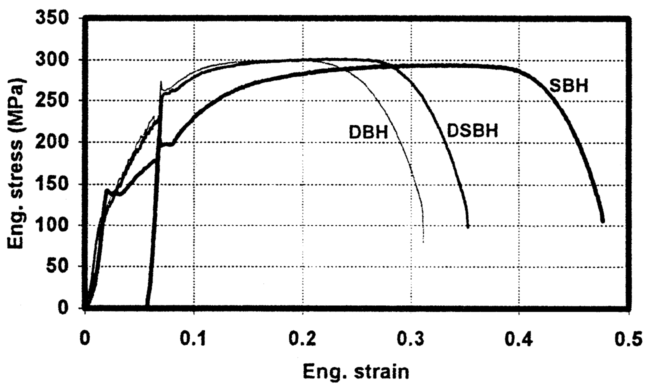

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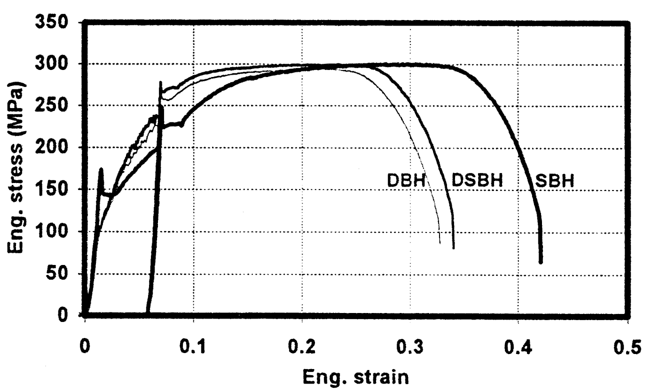

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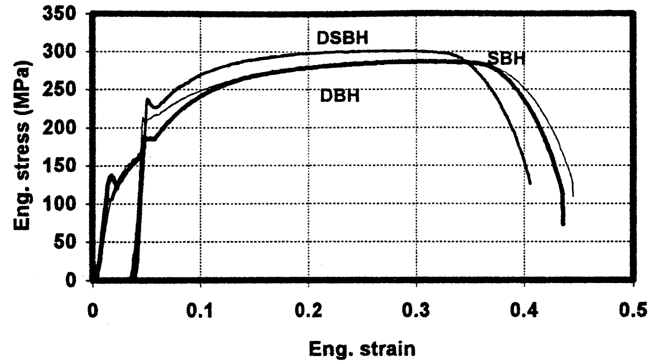
Fig. 8—Comparison of DBH and DSBH values after applying a strain of 6 pct at (*a*) 150 °C, (*b*) 200 °C, and (*c*) 250 °C. The SBH curve is included for reference purposes.



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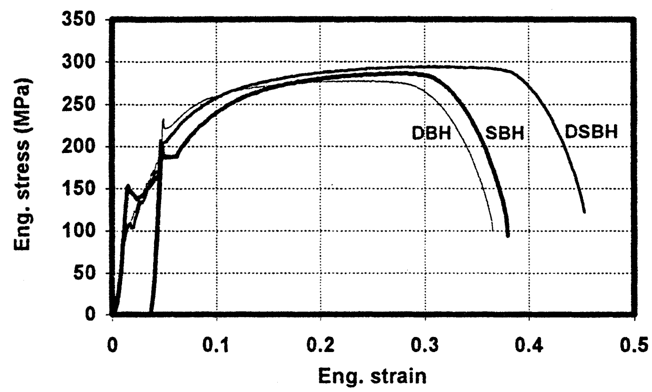

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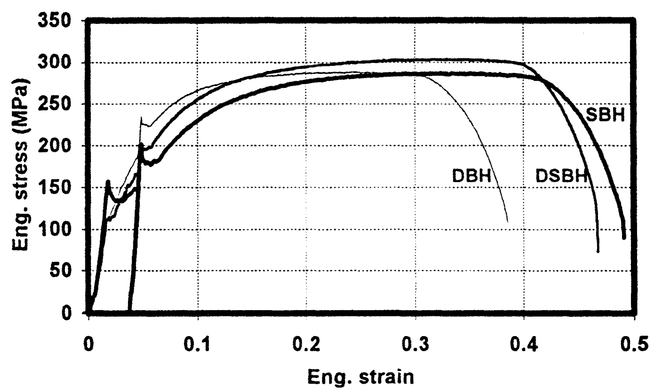

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Fig. 9—Comparison of DBH and DSBH values after applying a strain of 4 pct at (*a*) 150 °C, (*b*) 200 °C, and (*c*) 250 °C. The SBH curve is included for reference purposes.

of the DSBH method when the temperatures of dynamic aging (100 °C and 150 °C) were lower than the temperature of subsequent static aging (170 °C). In the other cases, the DBH method exhibited the higher values.

The characteristics described previously are listed and compared in Table III.

IV. DISCUSSION

A. *Effects of Prestrain and Temperature*

As was illustrated in Figure 5(a) three different behaviors are observed when the SBH method is employed on the present type of IF steel. At low prestrains, the amount of bake hardening increases with the prestrain until it reaches a maximum. When the prestrain is further increased, the bake hardening decreases because the carbon concentration/dislocation ratio decreases. In the third stage, the bake hardening increases slightly or approaches a plateau. Some workers[8] have shown that, in the Nb IF steel, the increase in the third stage begins at about 4 pct prestrain. By contrast, others[4] have observed no significant increase after a 5 pct prestrain in a low-carbon Al-killed steel and report that the third stage corresponds to a plateau. This may arise because no significant increase in dislocation density occurs after a 5 pct prestrain.[29] The present results correspond mostly to the latter case, in which no pronounced increase was observed after a 4 pct prestrain.

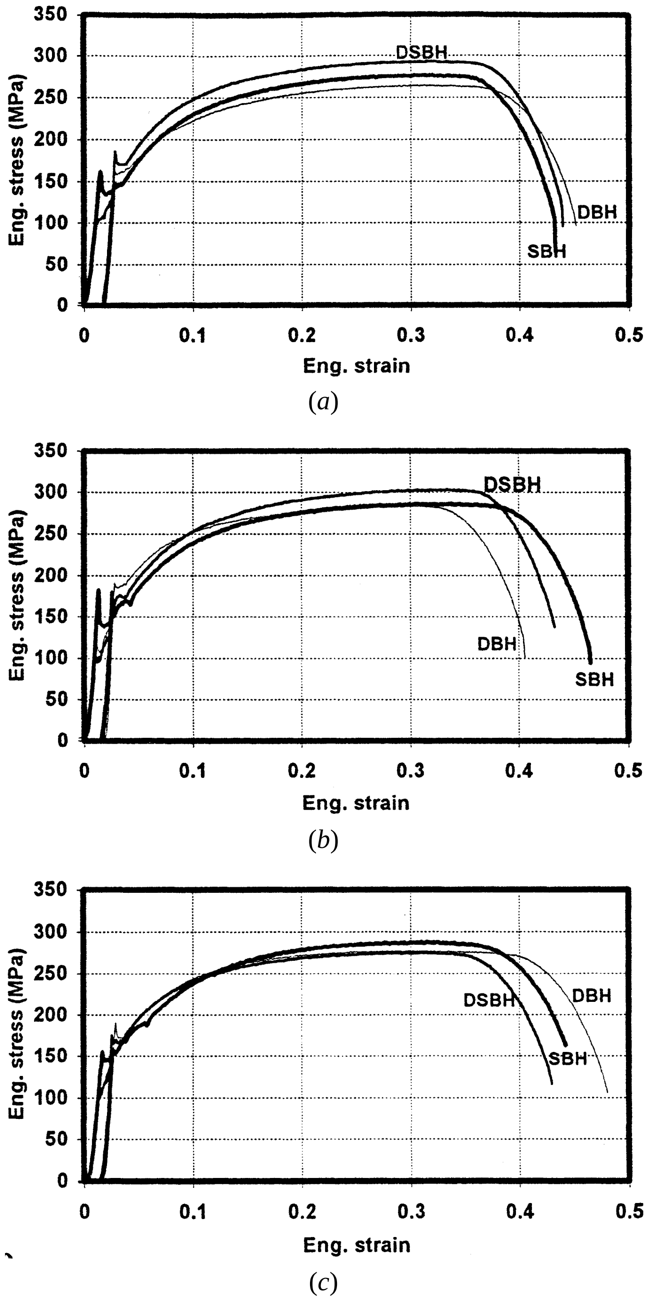

Fig. 10—Comparison of DBH and DSBH values after applying a strain of 2 pct at (*a*) 150 °C, (*b*) 200 °C, and (*c*) 250 °C. The SBH curve is included for reference purposes.

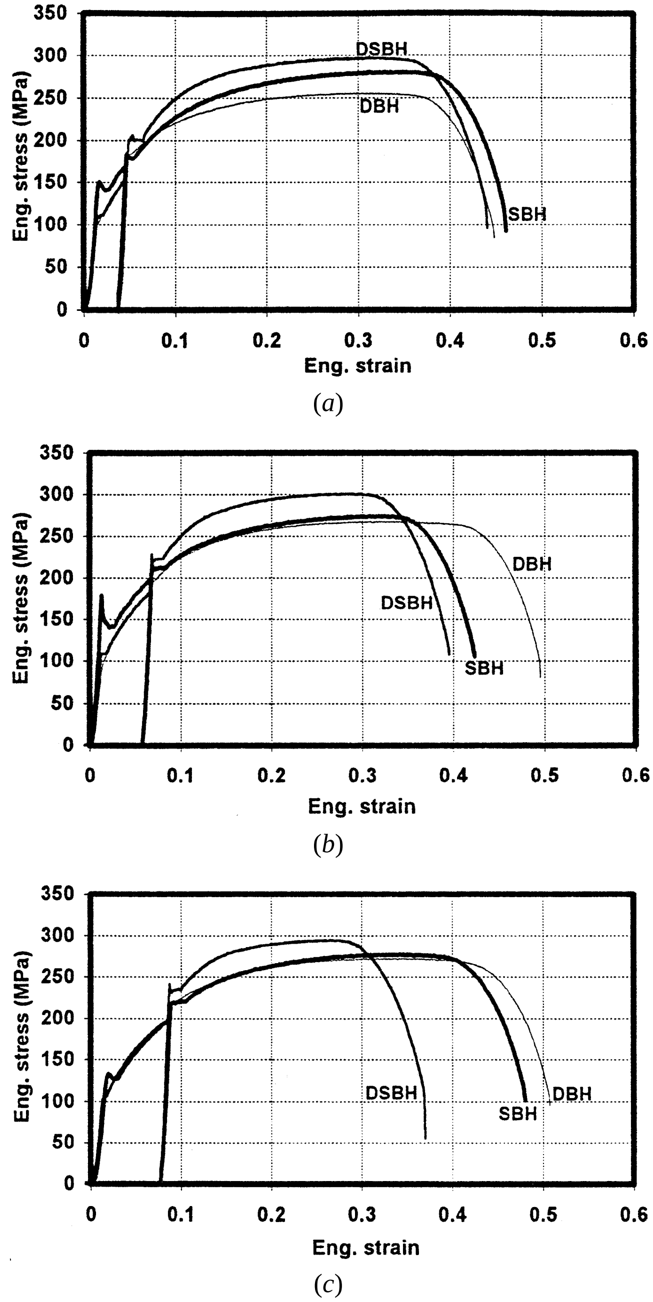

Fig. 11—Comparison of DBH and DSBH values after straining at 100 °C to (*a*) 4 pct, (*b*) 6 pct, and (*c*) 8 pct. The SBH curve is included for reference purposes.

The situation is a little different in the case of baking at 100 °C and 250 °C. At 100 °C, the bake hardening increased continuously with the prestrain. At this relatively low temperature, maximum pinning corresponded to higher prestrains or longer aging times. Elsen and Hougardy[30] did their study on an ultra-low carbon steel and reported similar results at the same solute carbon level, 5 ppm. They observed that, in samples prestrained to 1, 2, and 5 pct, the increase in yield strength and, therefore, the bake hardening at low temperatures depended on the time. To produce a 40 MPa increase in yield stress after a prestrain of 2 pct, they had to increase the aging time (30 minutes) by a factor of 20 when the temperature was decreased from 180 °C to 150 °C. Kurosawa *et al.*[31] also reported that, for 1 and 2 pct prestraining, the bake hardening increased continuously with both aging temperature and time in a Nb-added extra-low carbon steel. After 2 pct prestraining, the plateau in the bake-hardening value was not reached even after 1000 minutes of aging at 150 °C in a low-carbon Al-killed steel.[29]

Similar behavior was observed for the yield stress, which reached a plateau after baking at 200 °C (except for the case of 2 pct prestraining, Figure 5(b)). As discussed subsequently, it appears that, after holding at about 200 °C, the mechanism of aging starts to change and overaging begins. For this reason, the yield point approaches a plateau at this temperature, Figure 5(b). Furthermore, overaging becomes more pronounced at around or above 250 °C, leading to a drop in yield strength. (In the case of DSBH, the room-temperature yield-strength values are to some extent variable due to the complexity of this process. In general, behaviors similar to those produced by the SBH technique are observed (Figure 6(b)).)

With regard to the DBH process, the maximum in bake hardenability was observed at about 200 °C, with the highest level for 2 pct prestraining at this temperature (Figure 4(a)). This is in agreement with the findings of Li *et al.*[32,33] On studying the effects of DSA on the subsequent mechanical properties of low-carbon steels, they reported that the maximum strength was obtained after about 5 pct prestraining at 200 °C.

In the case of the DSBH method, two different behaviors were observed (Figure 6(a)). For prestraining at 100 °C and 150 °C, the results resemble those mentioned previously for the SBH technique. In this case, since the aging temperature (170 °C) is above the prestraining temperatures (100 °C and 150 °C), the structure produced by DSA is modified. In the second situation, when the aging temperature (170 °C) is below the prestraining temperatures (200 °C and 250 °C), it appears that the relatively high temperatures of straining lead to overaging, caused by coalescence of the precipitates. This topic is discussed in detail in References 6, 13, and 34 through 40.

B. *Effect of Strain Rate*

The tests described previously were all carried out at 10^{-3} s^{-1}. However, with regard to the employment of the methods outlined here in industrial forming processes, considerably higher strain rates, *e.g.*, 1 s^{-1}, are of interest. For this reason, tests were also carried out at strain rates of 10^{-4}, 10^{-2}, and 10^{-1} s^{-1}. Examples of the results obtained are presented in Figure 12.[41] Significant DSA effects are readily observed at 10^{-1}, s^{-1}, including higher work-hardening rates than at room temperature and the absence of a yield drop at elevated temperatures of testing. Similar results were obtained on three other IF steels.[41]

The minimum strain rate at which the serrations of Figure 12 are likely to appear is given by the following expression:[41]

$$\dot{\varepsilon} \cong 10^8 \exp\left(-Q/\mathrm{R}T\right) \qquad [6]$$

where R is the gas constant and T is the absolute temperature. Thus, even though experiments were not carried out at higher strain rates, due to the limitations of the testing equipment, it seems reasonable that the present behavior would extend to 1 s^{-1} or even higher.

C. *Possible Industrial Applications of the DBH and DSBH Methods*

To prevent surface defects in press forming, a low yield-strength and high work-hardening rate are recommended.[42–45] Comparing two steels with different yield strengths and hardening rates, the one that has the lower yield strength and higher hardening rate will provide better quality after press forming. In addition, the near absence of yield-point elongation during forming and a high yield strength in the finished part are required.[25]

In the present work, the increase in yield strength produced by various forms of baking was studied with the aim of

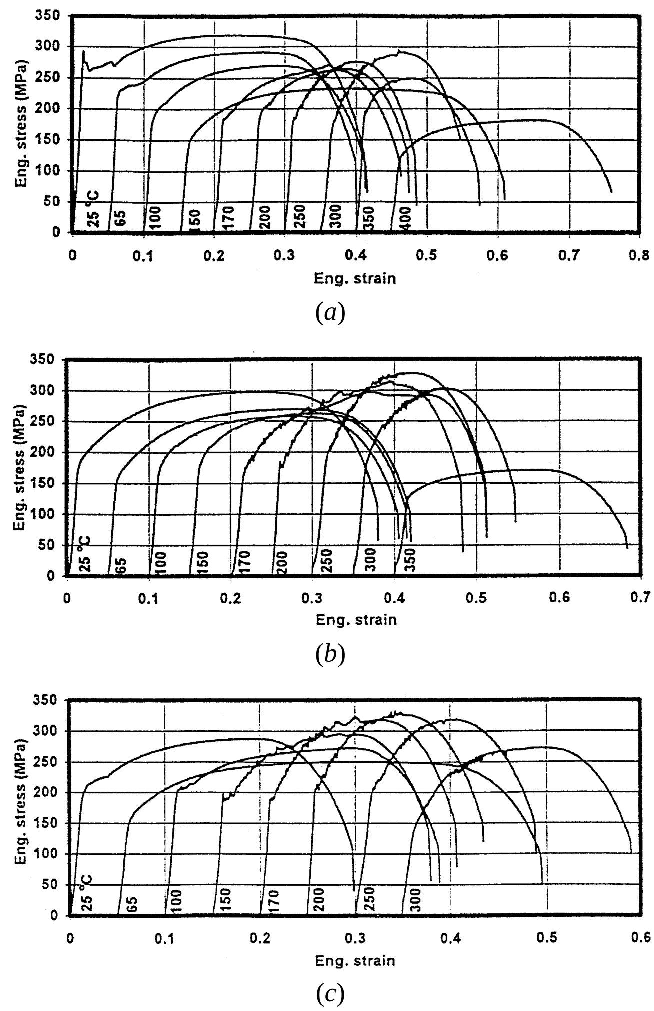

Fig. 12—Stress/strain curves of specimens tensile tested at different temperatures and strain rates of (*a*) 10^{-1}, (*b*) 10^{-2}, and (*c*) 10^{-3} s^{-1}.

attaining minimum yield strengths of 210[12] or 240 to 255 MPa.[25] Note that such values can also be reached with the aid of solution strengthening or the use of much higher cooling rates to raise the solute C levels, although the latter does not apply to conventional IF steels with only about 4 ppm of solute C. In a Ti-Nb IF steel with 0.055 pct P and 0.023 pct Si, for example, a yield strength of 190 MPa was reached.[46] This value was increased to 289 MPa when the alloying-element levels were raised to 0.07 pct P, 0.6 pct Si, and 1.07 pct Mn. By contrast, the yield strength for a conventional Ti-Nb IF steel, after cooling at 20 °C/s from 900 °C, is 175 MPa.[46] In the case of the present DBH method applied to the steel of Table I, the yield strength produced by strain of 2 pct at 200 °C is about 200 MPa. (Three other IF steels were also studied, leading to qualitatively similar results.[41] These are not reproduced here to conserve space.)

With reference to the present DBH and DSBH methods, all the general requirements discussed previously can be satisfied by the use of these techniques. Furthermore, because they do not produce any yield-point elongation, no temper rolling is required prior to forming.

Lou and Northwood[47,48,49] introduced a new criterion for the work-hardening rate, namely, the difference between the yield stress (YS) and ultimate tensile strength (UTS). This

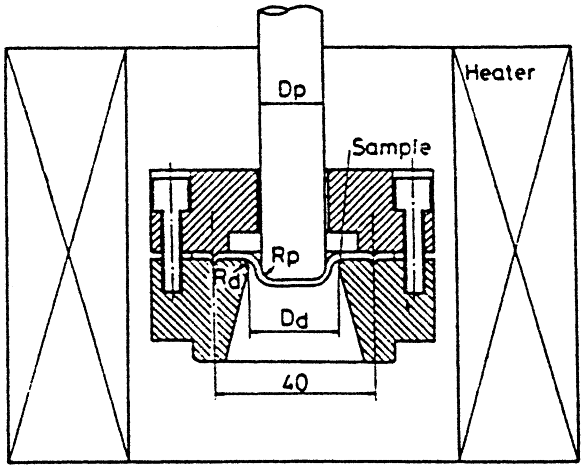

Fig. 13—An apparatus for warm press forming.

parameter takes higher values when press forming is carried out at elevated temperatures, as in the DBH and DSBH methods. Of course, high work-hardening rates are associated with good quality during forming.[38,44]

In terms of warm forming, Sugimoto and Kobayashi[50] invented an apparatus that can be used exactly for this purpose (*i.e.*, for the warm pressing of automotive structural parts). A sketch of their equipment is reproduced here in Figure 13. Their aim was to study the effect of forming temperatures up to 400 °C on the mechanical properties caused by the presence of retained austenite. The operation resembles a compression-testing machine with equipment available to control the forming speed. A graphite-suspension-type lubricant was used. However, only cups of moderate size were formed.

When comparing the DBH and DSBH techniques, there is one more advantage to be listed for the DBH method; this is the elimination of one step, namely, conventional bake hardening (2 pct prestrain). On the other hand, if it were possible to paint or to bake the paint before forming (*i.e.*, during the soaking time before forming) then again a one-step process could be used. Clearly, this is a point that requires further investigation.

In terms of industrial applications, the energy needed to heat each tonne of steel up to, for example, 200 °C is

$$Q = m \times c \times \Delta T \qquad [7]$$

$$Q = 1000 \text{ kg} \times 460 \text{ J/kg °C} \times 175 \text{ °C} = 80.5 \times 10^6 \text{ J}$$

If the cost of energy for 1 kWh is taken as \$0.05, the cost of heating is \$1.1/tonne.

By comparison, the saving in alloying costs can be significant. For example, to make 1000 kg of steel containing 0.03 pct Nb, each 100 ppm of Nb (*i.e.*, each 0.01 pct Nb) costs about \$4 (a total of \$12 for 0.03 pct Nb). Thus, strengthening by DSA could become an economic and attractive alternative to the addition of alloying elements. Similar remarks apply to the cost of adding Mn, P, Si, or Ti.

V. CONCLUSIONS

Two new methods for bake hardening, dynamic bake hardening (DBH) and dynamic-static bake hardening (DSBH) were introduced here. They have the following characteristics.

1. The DSBH and DBH methods lead to more bake hardening than does SBH (the conventional method). For example, in the case of a 2 pct strain at 100 °C, the amounts produced by the DSBH and DBH methods are about 15 and 8 times the SBH value, respectively. The minimum amount of bake hardening is about 3 MPa (2 pct room-temperature prestrain followed by baking at 100 °C with the SBH method) and the maximum value is about 55 MPa (4 pct strain at 150 °C followed by static-strain aging at 170 °C for 20 minutes with the DSBH method). Generally speaking, the lowest bake hardening values are produced by SBH. Conversely, the highest amounts result from the DSBH method when the temperature of dynamic aging (100 °C or 150 °C) is lower than that of subsequent static aging (170 °C). In the other cases, the DBH method exhibited the highest values.
2. There is no Luders strain during elevated temperature straining in the cases of the DBH and DSBH methods, nor is there a sharp yield point or yield drop.
3. The yield stress during elevated temperature straining by the DBH and DSBH procedures is about 45 MPa lower than the room temperature one associated with the SBH technique.
4. Because of DSA, the work-hardening rate is much higher in the DBH and DSBH methods than in the SBH process. By contrast, the rate of work hardening is much lower when straining is carried out at room temperature. As a result, the yield strength after elevated-temperature deformation is much higher in the DBH and DSBH methods.
5. With increasing elevated-temperature deformation, the room-temperature yield/tensile strength ratio increases until it attains a value of almost unity in some cases of the DBH technique.
6. Although a sharp yield point and the Luders strain are rarely observed when straining at room temperature after employing the DBH procedure, they are more significant after prior application of the DSBH process.
7. A bake-hardening value of about 55 MPa (a strain of 4 pct at 150 °C with the DSBH method) is obtained with the aid of only 4 ppm solute C in the case of the Ti IF steel.
8. The yield strengths produced by all three methods reach a plateau after either straining or baking at about 200 °C. It appears that overaging takes place above this temperature and is responsible for a drop in yield stress.

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