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Effect of Retained Austenite on Formability of High Strength Sheet Steels

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Effects of retained austenite on press formability were investigated, using austempered 0.4C–Si–1.2Mn sheet steels with high tensile strength of more than 980 MPa.

The results showed plausible relationships between formability and initial volume fraction of retained austenite ($V_{\gamma 0}$). With an increase in $V_{\gamma 0}$, height of stretch forming increased linearly to its maximum at about $0.2V_{\gamma 0}$, and bending as well as expanding of a mechanically ground hole were gradually improved to the best at 0.15 to $0.2V_{\gamma 0}$. On the other hand, expanding of a punched hole was slightly deteriorated with increasing $V_{\gamma 0}$ in less than 0.15–$0.2V_{\gamma 0}$. These various types of formability were all extraordinarily deteriorated beyond $0.2V_{\gamma 0}$ in stretch forming and 0.15–$0.2V_{\gamma 0}$ in the others.

It was concluded that these effects of retained austenite on formability can be clearly understood in terms of $V_{\gamma 0}$ and k: a rate constant relating rate of deformation-induced transformation with uniaxial tensile strain, as a parameter showing stability of retained austenite in press forming.

KEY WORDS: high strength low alloy steel; cold rolled sheet steel; retained austenite; TRIP; deformation-induced transformation; stretch forming; bending; hole expanding; formability; austempering; intercritical heating.

1. Introduction

It is well known that transformation induced plasticity (TRIP) due to retained austenite (γ_R) makes elongation larger,[1–12] accompanied by improved strength and ductility combination expressed in TS (tensile strength) × El_t (total elongation).[5,6] These properties are requisites to high strength steel sheets for press forming. But it is also well known that γ_R has undesirable influences on fracture strain and complicated ones on toughness of steels.[13] In order to make TRIP applicable to press forming, therefore, it is needed both for steel manufacturers and for steel users, to clear how to use merits of enhanced elongation effectively, balanced with demerits of shortage of fracture strain.

There have been two troublesome problems to find genuine effects of γ_R on formability; first, it is difficult in these steels with mixed microstructures to distinguish the effects of γ_R of its own from those of the others. Secondly, effects of γ_R on formability should be expressed not only by amount of γ_R but by stability of γ_R, which generally consists of chemical stability and some other kinds of stabilizing effect. Amount of γ_R can easily be measured by X-ray diffraction or optical microscopic observation. But standardization to estimate stability of γ_R has not been established.

This report intends to clear up relations between γ_R and formability, using (1) intercritically heated and austempered 0.4C–1.2 to 2.0Si–1.2Mn steels with TS more than 980 MPa, (2) k, a rate constant relating deformation induced transformation rate with uniaxial tensile strain, as a parameter showing the stability of γ_R in press forming.[6,7]

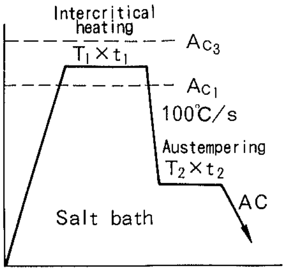
2. Experimental Procedure

Steels with chemical composition given in **Table 1** were hot-rolled (to 3.5 mm in thickness), cold-rolled (to 1.4 mm) and subsequently processed as shown in **Fig. 1**. Steels with the various amounts and stabilities of γ_R were obtained by changing Si content and isothermal holding conditions (T_2, t_2). Changing Si content with C content unchanged was to vary both the amounts and stability of γ_R without larger variation in TS. Intercritical heating conditions (T_1, t_1) in steels B1, B2 and B3 respectively were set to give 40% ferrite in the resulting final products. **Table 2** gives tensile properties and microstructures of used steels with the isothermal holding conditions. Tensile test was conducted at room temperature with a crosshead speed of 10 mm/min using JIS-5

Table 1. Chemical composition. (wt%)

Steel	C	Si	Mn	P	S	Sol.Al	T.N*
B1	0.392	1.16	1.20	<0.002	<0.001	0.045	0.0034
B2	0.383	1.46	1.20	<0.002	<0.001	0.045	0.0066
B3	0.391	1.99	1.20	<0.002	<0.001	0.045	0.0061

* Total nitrogen



steel	T_1(°C)	t_1(min)	T_2(°C)	t_2(min)
B1	770	5	375	1, 2, 5, 15, 40
B2	790		400	
B3	810		425	

Fig. 1. Sample preparation.

Table 2. Tensile properties, k (a parameter showing stability of γ_R) and microstructures of used steels.

Steel	T_2 (°C)	t_2 (min)	YP (MPa)	TS (MPa)	El_t (%)	El_u (%)	ε_f	k	V_γ (Xray)	V_α (O.M.)	V_B (O.M.)	V_M (O.M.)
*B1-1	400	1	696	1 200	25.3	20.1	0.42	96	0.231	0.33	0.44	0.03
B1-2	400	2	651	1 080	30.6	24.3	0.82	—	0.213	—	—	—
B1-3	400	5	731	1 000	30.0	21.6	0.99	26	0.155	0.37	0.50	0.00
B1-4	400	15	757	1 000	20.3	12.6	0.97	58	0.070	0.44	0.53	0.00
B1-5	400	40	848	1 000	15.5	9.2	0.92	—	0.007	—	—	—
B1-6	375	5	774	1 130	26.0	19.0	0.87	38	0.179	0.41	0.42	0.00
B1-7	375	15	821	1 060	23.8	15.0	0.96	33	0.128	0.32	0.52	0.00
B1-8	375	40	850	1 070	18.6	11.2	1.07	—	0.063	—	—	—
*²B2-1	425	1	526	980	29.3	22.2	0.73	103	0.144	0.38	0.43	0.02
*B2-2	400	1	764	1 320	23.4	18.2	0.40	51	0.215	0.42	0.26	0.09
B2-3	400	2	703	1 130	30.7	23.8	0.74	41	0.232	0.40	0.38	0.00
B2-4	400	5	737	1 030	34.5	26.6	0.89	22	0.197	0.36	0.41	0.00
B2-5	400	15	776	1 020	27.7	19.4	0.92	22	0.141	0.38	0.47	0.00
B2-6	400	40	852	1 040	16.8	9.9	0.88	100	0.032	0.40	0.57	0.00
B2-7	375	15	838	1 070	29.0	22.5	1.00	22	0.165	0.41	0.44	0.00
B2-8	375	40	848	1 070	26.5	16.3	1.00	—	0.135	—	—	—
*²B3-1	425	1	509	1 060	28.1	22.3	0.51	82	0.251	0.47	0.27	<0.02
*²B3-2	425	15	634	980	28.3	21.8	0.87	83	0.158	0.47	0.34	0.00
*B3-3	400	1	703	1 360	18.8	17.2	0.32	82	0.226	0.50	0.23	0.00
B3-4	400	5	680	1 090	35.5	29.0	0.73	31	0.234	0.47	0.32	0.00
B3-5	400	15	749	1 040	38.0	31.0	0.94	24	0.216	0.48	0.31	0.00
B3-6	400	40	764	1 050	33.4	26.1	0.93	—	0.187	—	—	—
*B3-7	375	5	782	1 220	28.7	22.0	0.76	50	0.220	—	—	—
B3-8	375	15	861	1 130	31.3	23.6	0.90	36	0.191	—	—	—

No marks: austempered at 375 and 400°C with TS of 980–1 130 MPa.
*: austempered at 375 and 400°C with TS > 1 130 MPa.
*²: austempered at 425°C.

type test pieces 25 mm wide with 50 mm gauge length, to obtain yield strength (YP), TS, El_t, uniform elongation (El_u) and fracture strain (ε_f).[14] Volume fraction of γ_R ($V_{\gamma 0}$) was measured by X-ray diffraction. Fractions of ferrite (V_F), bainite (V_B), and $V_{\gamma 0}$ + martensite (V_{M0}) were obtained from optical microstructures revealed by the tint etching method.[15] V_{M0} was estimated from the difference between $V_{\gamma 0}+V_{M0}$ from optical microstructures and $V_{\gamma 0}$ by X-ray diffractions.

The preliminary examination showed that the best of $TS \times El_t$ was obtained with isothermal holding at 375–400°C in 0.4C–Si–1.2Mn steels. Therefore, measurement of formability was conducted mainly using the steels held at 375 and 400°C (steels with no marks in Table 2). These have TS of 980–1 130 MPa with microstructures of 0–0.25 (0–25%) $V_{\gamma 0}$, 0.30–0.50 V_F, 0.30–0.60 V_B and less than 0.10 V_{M0}. The steels held at 375 and 400°C with TS > 1 130 MPa (*) and those held at 425°C (*²) were used if necessary. The size of γ_R grains decreased with increasing holding time, less than 5 μm for steel B2-2 (held at 400°C for 1 min) and less than 1.5 μm for the steel B2-6 (at 400°C for 40 min).

Forming test was conducted as follows.

(1) Stretch Forming

Steel sheets with 150 mm × 150 mm × (1.4 mm) in blank size were formed with a spherical punch of 100 mmϕ using a machine oil as lubricant. Forming height (H) at the beginning of fracture was measured to evaluate stretch formability.

(2) Bending

As sheared sheets with 35 mm × 70 mm × (1.4 mm) in size were bent with bending axis parallel to the rolling direction. The minimum bending radius (R_{min}) of the specimen without fracturing at sheared edges were examined to estimate bendability.

(3) Hole Expanding (A Mechanically Ground Hole and a Punched Hole)

Steel sheets of 80 mm × 80 mm × (1.4 mm) with a hole punched with a punch of 9.8 mmϕ and a die of 10.0 mmϕ as well as those with a mechanically ground hole of 10 mmϕ, were hole-expanded with the blank hold force of 1 ton using a conical punch with its top angle of 30 degrees, until the crack propagated through the thickness of sheets. Hole expanding ratio, either in a punched hole (λ_P) and in a mechanically ground hole (λ_M), is expressed by $(d-d_0)/d_0$, where d and d_0 are the diameter of the hole expanded and of the initial one respectively.

3. Experimental Results

3.1. Relation between Formability and Tensile Properties

In general, formability is estimated by tensile properties. Correlations between formability and tensile properties were examined preliminarily using Table 2. It was found that H depended linearly on El_t (El_u). R_{min}, λ_M, and λ_P were correlated with ε_f respectively. Comparing these results with those which have been examined in plain low carbon steels,[16] special features of γ_R containing steels were not recognized.

3.2. Plausible Relationships between Formability and $V_{\gamma 0}$

Figure 2(a) shows the relation between H and $V_{\gamma 0}$. H increases linearly with increasing $V_{\gamma 0}$ to its maximum at $V_{\gamma 0}=0.2$ and then decreases. That is, containing an optimum amount of $V_{\gamma 0}$ is required for the best stretch-formable steels.

Figures 2(b) and **2(c)** shows R_{min}, λ_M, and λ_P related to $V_{\gamma 0}$ respectively, where bendability is regarded as the better for the smaller R_{min}. The findings are: (1) R_{min} and λ_M tend to be improved while λ_P deteriorated gradually with increasing $V_{\gamma 0}$ to 0.15–0.20 $V_{\gamma 0}$. More than 0.15–0.20 $V_{\gamma 0}$, rapid deteriorating is found in all of R_{min}, λ_M, λ_P. The optimum (critical) amount of $V_{\gamma 0}$ seems to exist in each of R_{min}, λ_M and λ_P too, though slightly less than that in H. (2) The scattering of plots in R_{min} and λ_M at a constant $V_{\gamma 0}$ is larger than that in λ_P, suggesting that the formers depend not only on $V_{\gamma 0}$, while the latter depends strongly on $V_{\gamma 0}$.

Formability can plausibly be related to $V_{\gamma 0}$ as mentioned above. However, there remain some problems to be explained, such as the differences in optimum (critical) amount of $V_{\gamma 0}$ among types of formability and those in

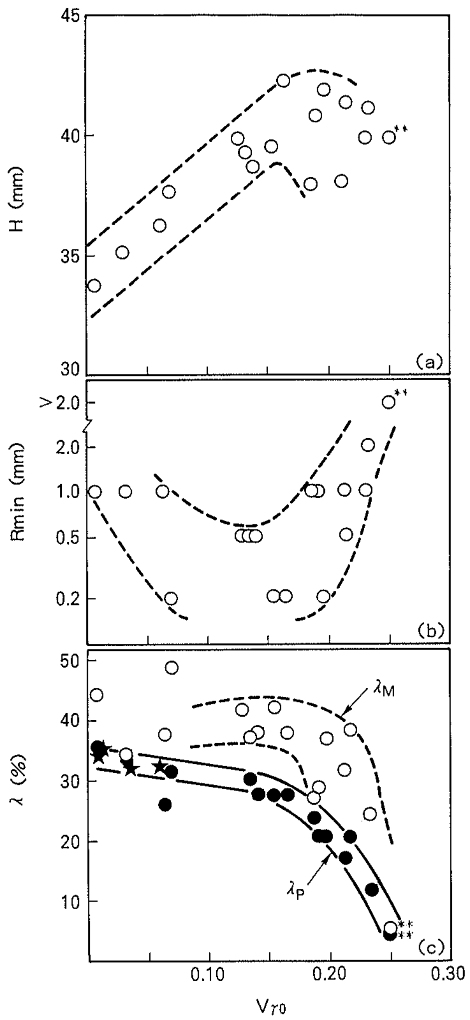


Fig. 2. Relation between initial volume fraction of retained austenite ($V_{\gamma 0}$) and formability: (a) H; forming height, (b) R_{min}; minimum bending radius, (c) λ_M; expanding ratio of a mechanically ground hole and λ_P; expanding ratio of a punched hole, using 0.4C–Si–1.2Mn steels intercritically heated and austempered at 375 and 400°C with TS of 980–1 130 MPa.
** Steels austempered at 425°C.
★ Commercially produced steels consisting of ferrite and bainite with TS of about 980 MPa.

variation of formability with $V_{\gamma 0}$ between the above and the below optimum (critical). To clear such details, they should be examined in terms not only of $V_{\gamma 0}$ but of stability of γ_R against deformation. From these points of view, the followings are discussed in the next chapter: (1) a parameter showing stability of γ_R in press forming, (2) anisotropy of TRIP and (3) based on (1), (2), the effects of $V_{\gamma 0}$ and stability of γ_R on formability.

4. Effects of $V_{\gamma 0}$ and Stability of γ_R on Formability

4.1. Stability of γ_R in Press Forming

Matsumura *et al.*[6,7] showed that enhancement of El_u or $TS \times El_t$ in austempered 0.4C–1.5Si–0.8Mn steels is caused by TRIP due to γ_R. They ascertained that increasing γ_R increases strain hardening coefficient ($d\sigma/d\varepsilon$) at the higher strain range with enhanced El_u, which is typical of TRIP.[17] Besides, they found that the variation of $d\sigma/d\varepsilon$ is related to that of deformation induced transformation rate $(-dV_\gamma/d\varepsilon)$*, where σ, ε are true stress, true strain in uniaxial tensile stretching and V_γ is fraction of γ_R after straining. They also tried to clear kinetics of deformation induced transformation using empirical equations of a modified Austin–Rickett type. The results indicated that the kinetics are expressed in the form of

$$-dV_\gamma/d\varepsilon = kV_\gamma^2 \quad \cdots\cdots (1)$$
$$V_\gamma = V_{\gamma 0}/(1+k\cdot V_{\gamma 0}\cdot\varepsilon),$$

where k is regarded as a constant showing mechanical stability of γ_R, and supposed to be mainly related to the solute C content in γ_R (C_γ) in austempered steels. It is deduced from Eq. (1) that El_u or $TS\times El_t$ depends on both $V_{\gamma 0}$ and k, and increases with decreasing k (increasing stability) at a constant $V_{\gamma 0}$ (Appendix).

However, as Eq. (1) is obtained from the results of uniaxial tensile stretching, it is not sure that k in Eq. (1) is also suitable for a stability parameter of γ_R in biaxial stress forming such as press forming. Moreover, planar anisotropy of used steels, if any, has to be checked crystallographically or mechanically. On the other hand, as mentioned in Sec. 3.1, H is related linearly to El_u (El_t). Therefore, the following experiments were conducted to clarify the propriety of k for a stability parameter of γ_R in biaxial stress forming.

Steel sheets with the chemical composition similar to steel B2, austempered for 5 min at 375°C, subsequently cooled into room temperature, and scribed with circles, were press-formed as described in **Fig. 3**. Variation of V_γ was examined by X-ray diffraction method with specimens cut from the frange (tension-compression) and ridge (tension-tension) of the formed product, while equivalent strain: $\varepsilon_{eq}=(2/3\cdot\sum\varepsilon_i^2)^{1/2}$ was calculated from changes in size of scribed circles before and after press forming. The results, as shown in Fig. 3, suggested that the deformation induced transformation in biaxial forming proceeded with increasing ε_{eq} at the same rate as that in uniaxial stretching. This implies that replacing ε with

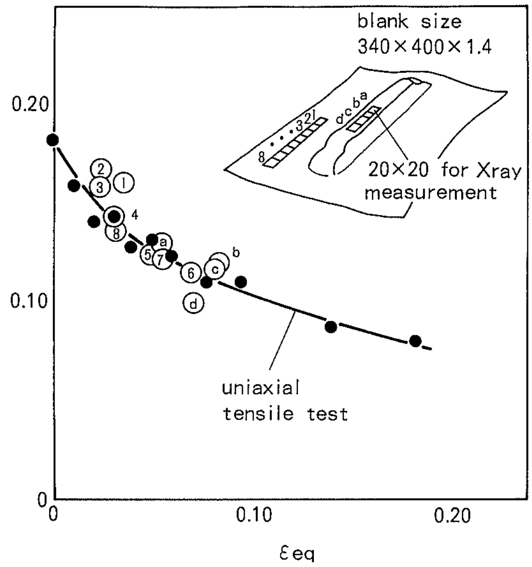


Fig. 3. Relation between fraction of retained austenite (V_γ) and equivalent strain (ε_{eq}) in biaxial stress forming compared with uniaxial tensile stretching, using austempered 0.36C–1.5Si–1.2Mn steels held at 375°C for 5 min with TS: 933 MPa and El_t: 31.5%.

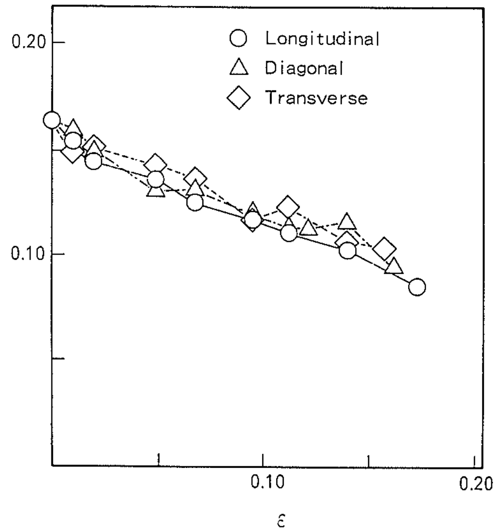


Fig. 4. Relation between fraction of retained austenite (V_γ) and strain (ε), uniaxially stretched in longitudinal, diagonal and transverse directions, using austempered 0.36C–1.5Si–1.2Mn steel held at 400°C for 5 min with TS: 834 MPa and El_t: 33.6%.

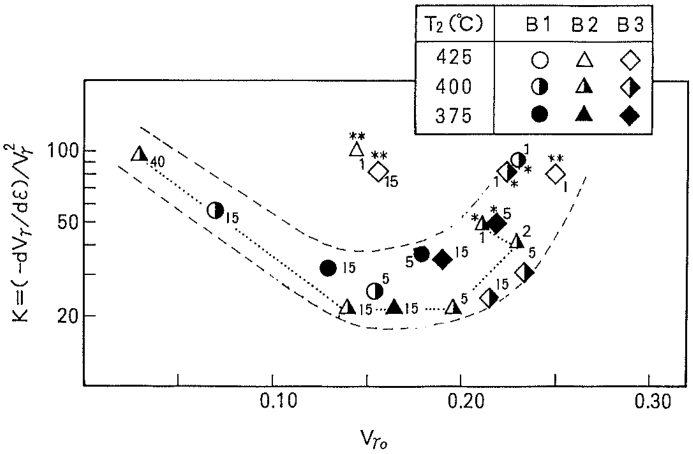


Fig. 5. Steels represented in terms of initial fraction of retained austenite $(V_{\gamma 0})$ and a stability parameter of retained austenite (k). Steels austempered at 375 and 400°C (no marks and *) are all in a zonal area between two dotted lines, while any steels austempered at 425°C (**) are not. Numbers attached to symbols show holding time.

* Empirically as $d\sigma/d\varepsilon \fallingdotseq 4700(-dV_\gamma/d\varepsilon)+500$ (MPa) in 0.4C–1.5Si–0.8Mn steel austemperd at 400°C except for at the smaller strain range.[7]

ε_{eq} in Eq. (1) brings about the same k value either for biaxial forming or for uniaxial stretching.

On the other hand, planar anisotropy of deformation induced transformation was examined by uniaxial stretching using steel sheets austempered for 5 min at 400°C. As shown in **Fig. 4**, the relations between V_γ and strain were nearly the same in all tensile directions, so the difference in k, if any, could be negligible. Thus, it was concluded that k obtained by uniaxial stretching could be regarded as a stability parameter of γ_R in press forming.

4.2. $V_{\gamma 0}$ and k in Used Steels

Steels with a variety of chemical compositions and heat treatments were selected to stretch to various amounts of strain respectively. k is determined from changes of V_γ with strain.[6,7] **Figure 5** shows the testing steels expressed in terms of $V_{\gamma 0}$ and k. Steels austempered at 375 and 400°C for various holding time are included in a zonal area outlined by two dotted lines. The zonal area is described to show the coordinates ($V_{\gamma 0}$, k) corresponding to the steels used in Fig. 2*2. Four examples exceeding 1 130 MPa in TS have larger k values in the area. They are obtained by the shorter period of austempering (followed by cooling to room temperature), containing unstable γ_R with co-existing martensite. Two examples of steels austempered at 425°C are positioned far above the zonal area at $V_{\gamma 0} \fallingdotseq 0.15$, which is consistent with the previously reported result that the maximum of C_γ in steels austempered above 425°C can essentially be less than that at 375–400°C.[19]

Making use of Fig. 5, mechanical properties of testing steels can easily be understood in terms of $V_{\gamma 0}$ and k. **Figure 6**, for example, shows the effect of $V_{\gamma 0}$ and k on $TS \times El_t$, which is plotted using Fig. 5 and Table 2. It is clearly found that $TS \times El_t$ becomes the largest at larger $V_{\gamma 0} \fallingdotseq 0.2$ and the smallest $k \fallingdotseq 20$ (the maximum in stability).

4.3. Effects of $V_{\gamma 0}$ and k on Formability

Presence of an optimum (critical) $V_{\gamma 0}$ for each types of formability as shown in Fig. 2, can not be explained in

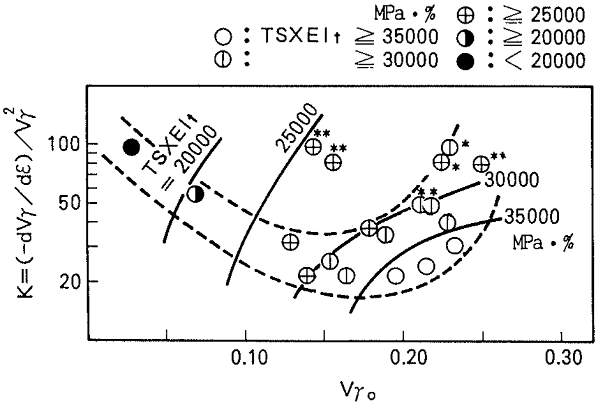


Fig. 6. Effects of initial fraction of retained austenite ($V_{\gamma 0}$) and the stability parameter (k) on $TS \times El_t$ (MPa · %). The marks (*, **) are the same as in Table 2.

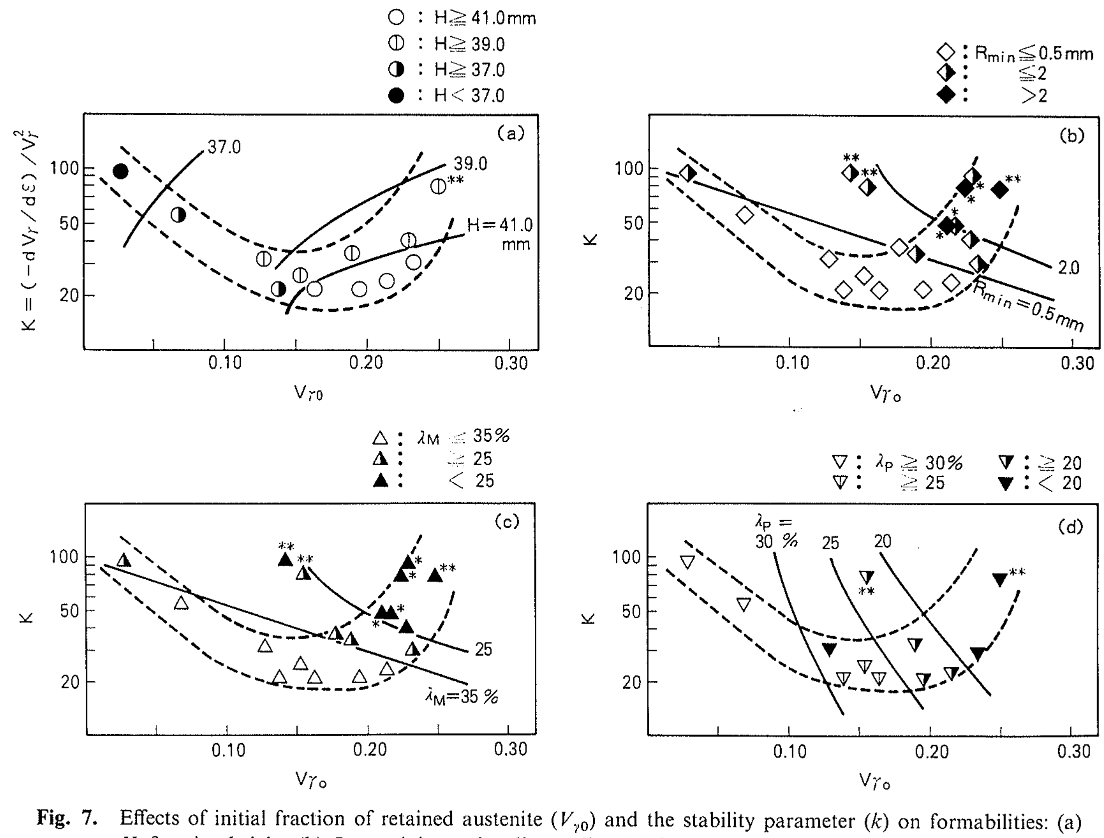


Fig. 7. Effects of initial fraction of retained austenite ($V_{\gamma 0}$) and the stability parameter (k) on formabilities: (a) H: forming height, (b) R_{min}: minimum bending radius, (c) λ_M: expanding ratio of a mechanically ground hole and (d) λ_P: expanding ratio of a punched hole. The marks (*, **) are the same as in Table 2.

*2 Bainite transformation proceeds from the right-hand side to the left along the zonal area, shifting with Si content (1.2–2.0%) and holding temperature (375–400°C).

term of $V_{\gamma 0}$ alone, but in terms of both $V_{\gamma 0}$ and k. **Fig. 7(a)** shows effects of $V_{\gamma 0}$ and k on H. Estimating from the slope of contour lines, H depends on both $V_{\gamma 0}$ and k, reaching its maximum at a coordinate ($V_{\gamma 0} \fallingdotseq 0.2$, $k \fallingdotseq 20$). The effects on H are similar to those on $TS \times El_t$ in Fig. 6. Thus, stretch forming is thought to be the best use of γ_R containing steels. **Figures 7(b)** and **7(c)** show effects of $V_{\gamma 0}$ and k on R_{min} and λ_M respectively. Different from H, these types of formability become good with decreasing both $V_{\gamma 0}$ and k. Estimating from the slope of contour lines, they depend strongly on k and not so much on $V_{\gamma 0}$. For them, the smallest $k \fallingdotseq 20$ with balancing $V_{\gamma 0} \fallingdotseq$ 0.15–0.20 is desired. **Figure 7(d)** shows effects of $V_{\gamma 0}$ and k on λ_P. λ_P is also improved with decreasing both $V_{\gamma 0}$ and k. Compared with R_{min} and λ_M, however, λ_P depends more on $V_{\gamma 0}$. That is, as for expanding of a punched hole, the presence of γ_R is obviously harmful, though stabilizing γ_R is favorable significantly.

The differences in formability *vs.* $V_{\gamma 0}$ curves in Fig. 2, which are attributed to forming modes, can also be explained by the site of a "zonal area" and the slope of contour lines in Fig. 7. This is shown schematically in **Fig. 8**. Figure 8(a) is reproduced partly from Fig. 7. Figure 8(b) is given by rewriting H and λ_M as ordinates, which are varied with ($V_{\gamma 0}$, k) along the zonal area in Fig. 8(a). Though Fig. 8(b) is changed a little with subtle scattering in drawing contour lines or a zonal area into Fig. 8(a), it reproduced well the plausible relationships between H or λ_M and $V_{\gamma 0}$ shown in Fig. 2. This is also true of R_{min} and λ_P.

It can be found that the relationships shown in Fig. 2 are plausible, because they vary with k of the testing steels. On the other hand, if the formability is expressed in terms of both $V_{\gamma 0}$ and k, the resulting contor lines shown in Fig. 7 may be unchanged with the steels used, so far as the genuine effects of γ_R are concerned. Thus, it is concluded that k is regarded as a parameter showing stability of γ_R in press forming, and that the effects of γ_R on formability can well be understood in terms of $V_{\gamma 0}$ and k. Needless to say, if k is thought to depend mainly on C_γ as in the present steels, the effects of γ_R can be explained also in terms of $V_{\gamma 0}$ and C_γ, which is not necessarily general and accurate.

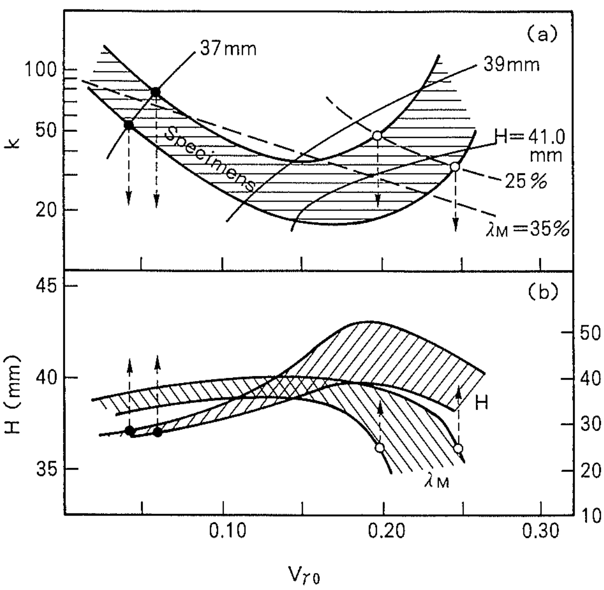


Fig. 8. Schematic view showing (a) effects of $V_{\gamma 0}$ and k on formability, reduced to (b) the plausible relationships between formability and $V_{\gamma 0}$ as in Fig. 2.

4.4. Formability of γ_R Containing Steels

For the purpose of making TRIP steels applicable to press forming, it is required to use merits of TRIP, the enhanced El_u (El_t) or $TS \times El_t$, with suppressing demerits caused by the shortage of ε_f. Stretch forming is of course the best use of TRIP. However, bendability and hole expandability are also improved with decreasing k, which may suggest TRIP or the other influences of stabilized γ_R are also effective even in these types of formability. Therefore, the problem for steel manufacturers is how to minimize k maintaining $V_{\gamma 0}$ suitably without increasing alloying elements (especially with regard to C). Clues to solve it may be found by clarifying the effects of Mn,[5,20] γ_R size[21] and microstructures adjacent to γ_R[12,22] on k.

5. Conclusion

The effects of γ_R on press formability were investigated using intercritically heated and austempered 0.4C–Si–1.2Mn steels with high tensile strength more than 980 MPa. The results were as follows.

(1) Plausible relationships between formability and initial fraction of retained austenite ($V_{\gamma 0}$) were obtained; with an increase in $V_{\gamma 0}$, stretch formability was improved linearly to its maximum at 0.2 $V_{\gamma 0}$, both bendability and expandability of a mechanically ground hole were gradually improved to their best at 0.15–0.20 $V_{\gamma 0}$, while expandability of a punched hole decreased slightly in less than 0.15–0.20 $V_{\gamma 0}$; these various types of formability are all deteriorated extraordinarily beyond 0.2 $V_{\gamma 0}$ in stretch forming and 0.15–0.20 $V_{\gamma 0}$ in the others.

(2) The effects of γ_R on formability, inclusive of the above plausible relationships with $V_{\gamma 0}$, can be clearly understood in terms of $V_{\gamma 0}$ and k, where k is a rate constant relating rate of deformation-induced transformation with uniaxial tensile strain, as a parameter showing stability of γ_R in press forming.

(3) To be made use of merits of TRIP, k must be minimized maintaining $V_{\gamma 0}$ suitably without increasing alloying elements.

Appendix

(1) Equation (1) involves the deformation on the iso-strain conditions which may be true of present steels but for in smaller strain range.[17,18]

(2) Deformation induced transformation in steels is generally expressed in an empirical form of $-dV_\gamma/d\varepsilon = k_p V_\gamma^2 \varepsilon^{p-1}$ or $-dV_\gamma/d\varepsilon = k_q V_\gamma^2 (V_{\gamma 0} - V_\gamma)^q$, where p and q are autocatalytic exponents and k_p and k_q are rate constants respectively.[6,7] Equation (1) can be derived as the special case with $p=1$ or $q=0$ in each equation. This means that the autocatalytic effect may be small or negligible in austempered steels, because it is suppressed by large amount of the other microstructures

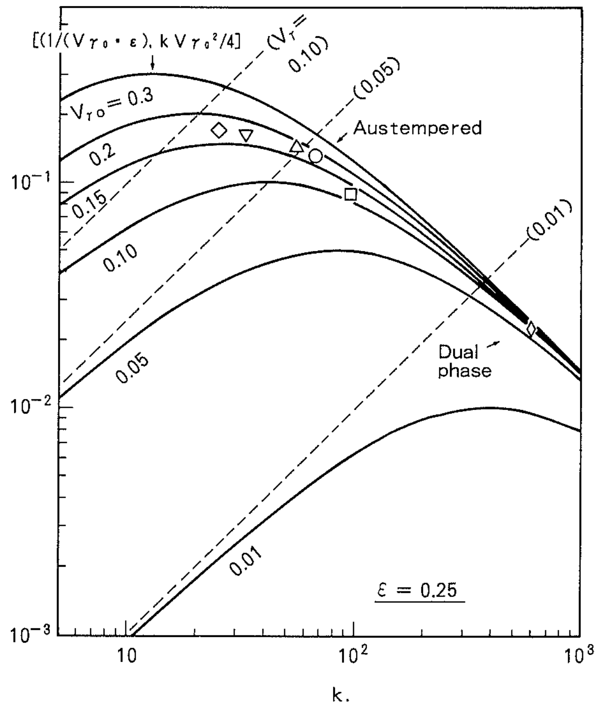


Fig. A. Variation of $-dV_\gamma/d\varepsilon$ with both k and $V_{\gamma0}$ at $\varepsilon=0.25$, in austempered 0.4C–1.5Si–0.8Mn steel held at 400°C for 1.5 min (○), 3 min (△), 6 min (▽), 15 min (◇), 30 min (□) and dual phase steel (◊),[6,7] where dotted lines show fraction of untransformed retained austenite (V_γ) at $\varepsilon=0.25$.

surrounding γ_R, which act as barriers against the autocatalytic propagation of transformation.

(3) **Figure A** shows variation of $-dV_\gamma/d\varepsilon$ with both k and $V_{\gamma0}$ at a higher fixed strain (0.25 for instance), using the previously reported results of 0.4C–1.5Si–0.8Mn steel.[6,7] At a constant $V_{\gamma0}$, $-dV_\gamma/d\varepsilon$ has its maximum $k_pV_{\gamma0}^2/4$ at $k=1/(V_{\gamma0}\varepsilon)$. The range of k is more than $1/(V_{\gamma0}\varepsilon)$, in which $-dV_\gamma/d\varepsilon$ increases with decreasing k (increasing stability). As a result, $d\sigma/d\varepsilon$ and El_u (or $TS\times El_t$) increases with decreasing k. This is also true of the present 0.4C–1.2 to 2.0Si–1.2Mn steels.

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