V-Bendability of Ultrahigh-Strength Low Alloy TRIP-Aided Steel Sheets with Bainitic Ferrite Matrix

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(Received on March 10, 2021; accepted on September 14, 2021; originally published in *Tetsu-to-Hagané*, Vol. 107, 2021, No. 2, pp. 165–174)

Effect of retained austenite characteristics on V-bending in ultrahigh-strength TRIP-aided steel sheets with bainitic ferrite matrix (TBF steel) was investigated for automotive applications. V-bending tests were performed on a servohydraulic testing machine at a processing speed of 1 mm/min using a 88-degree V-punch (2.0 mm in punch radius), 88-degree V-die (12 mm in die gap, 0.8 mm in die shoulder radius), and a rectangular specimen (50 mm in length, 5 mm in width, 1.2 mm in thickness). The results are summarized as follows.

(1) The 0.2C-1.5Si-1.5Mn (mass%) TBF steel sheets were able to perform V-bending by strain-induced martensitic transformation of TRIP effect. On the other hand, ferrite-martensite dual-phase (MDP0) steel sheet of 900 MPa grade was not able to perform 90-degree V-bending because of initiation of crack in tension area.

(2) The TBF375 steel sheet that produced by heat treatment of annealing at 1 173 K (900°C) for 1 200 s followed by austempering at 648 K (375°C) for 200 s, of 1 100 MPa grade was able to enable the 90-degree V-bending that considered an amount of springback ($\Delta\theta = \theta_1 - \theta_2$), in which the θ_1 and the θ_2 were a bending angle on loading and a bending angle after unloading respectively, of more than 2-degree by controlling a displacement of punch bottom dead center.

KEY WORDS: V-bending; TRIP steel sheet; springback; bending load; EBSD; residual stress; bainitic ferrite matrix.

1. Introduction

In recent years, 1 470 MPa grade hot stamped members¹⁾ have been widely used for pillars and bumper beams for the purpose of the weight reduction and the improvement of crash safety. These members will be manufactured by the cold press forming of the 1 470 MPa grade ultrahigh-strength steel sheets in the future. Therefore, it is necessary to consider the influence of springback when the V-bending^{2–4)} as a cold-forming of the 1 470 MPa grade ultrahigh-strength steel sheets are conducted. The low alloy TRIP⁵⁾-aided steel sheets using the transformation-induced plasticity (TRIP) of retained austenite (γ_R) can be expected to be applied for the

automotive structural parts, considering the cold-press formability and the crash safety.⁶⁾ In particular, the TRIP-aided bainitic ferrite steel (TBF steel) sheets⁷⁾ with bainitic ferrite matrix are expected as a next generation ultrahigh-strength steel sheets. The strain-induced martensitic transformation (SMT)⁶⁾ of the TRIP-aided dual-phase (TDP) steel sheet with polygonal ferrite matrix can be achieved by the carbon content of 0.4 mass% in the steel in order to achieve the tensile strength level of 1 100 MPa. In considering the weldability, it is desirable to reduce the amount of carbon to 0.2 mass% or less. However, for the low alloy TRIP steel sheets with carbon content of 0.2 mass% or less, there were few research reports on V-bending.^{8,9)}

Therefore, in this study, the V-bendability was investigated to clarify the formability of the 0.2C-1.5Si-1.5Mn

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(mass%) TBF steel sheets.

2. Experimental Procedure

Table 1 shows the chemical composition of steel sheets used. **Figures 1(a)** and 1(b) show the heat treatment diagrams of TBF steel and MDP0 steel, respectively.⁷⁾ In this study, a cold-rolled steel sheet (thickness 1.2 mm) with a chemical composition of 0.2C-1.5Si-1.5Mn (mass%) was used. The TBF steels were produced by the heat treatments of annealing at 1 173 K (900°C) for 1 200 s followed by austempering at 648 K (375°C) or 723 K (450°C) for 200 s, and quenching in oil. These TBF steels after the heat treatment were named as TBF375 and TBF450 steels. Here, the austempering temperatures were adopted as the temperatures below and above the martensite-start temperature (M_s). The M_s of the TBF steel was estimated at 693 K (420°C) using following Eq. (1).⁷⁾

$$M_s = 550 - 361 \times (\%C) - 39 \times (\%Mn) - 0 \times (\%Si) \dots (1) \\ + 30 \times (\%Al) - 5 \times (\%Mo)$$

For comparison, the TRIP-aided dual-phase (TDP1 - 4) steels with chemical composition of (0.1–0.4)C-1.5Si-1.5Mn (mass%) were prepared by intercritical annealing at 1 053 K (780°C) for 1 200 s followed by austempered at 673 K (400°C) for 1 000 s, and quenching in oil.⁸⁾ Moreover, the ferrite-martensite dual phase (MDP0) steel containing no γ_f with chemical composition of 0.14C-0.21Si-1.74Mn (mass%), was also prepared by intercritical annealing at 1 033 K (760°C) for 1 200 s, and quenching in oil (Fig.

Table 1. Chemical composition of steels used (mass%).

Steel	C	Si	Mn	P	S	Al
TBF375	0.20	1.51	1.51	0.015	0.0011	0.040
TBF450	0.20	1.51	1.51	0.015	0.0011	0.040
TDP1	0.10	1.49	1.50	0.015	0.0012	0.038
TDP2	0.20	1.51	1.51	0.015	0.0011	0.040
TDP3	0.29	1.49	1.50	0.014	0.0012	0.043
TDP4	0.40	1.49	1.50	0.015	0.0012	0.045
MDP0	0.14	0.21	1.74	0.013	0.0030	0.037

(a) Experimental apparatus for V-bending

1(b)).

Tensile tests were performed on an Instron type of tensile testing machine at a crosshead speed of 1 mm/min (strain rate: 2.8×10^{-4} /s) using JIS-13B-type tensile specimens.

V-bending tests were performed on a servohydraulic testing machine at a processing speed of 1 mm/min using a 88-degree V-punch (2.0 mm in punch tip radius), 88-degree V-die (12 mm in die gap (l), 0.8 mm in die shoulder radius), and a rectangular specimen along the normal direction (50 mm in length, 5 mm in width) produced by wire electrical discharge machining.^{2,3)} (**Fig. 2**). In the TDP2 steel as a base steel, a displacement of punch bottom dead center (S_{max}) of 10.6 mm^{8,9)} and holding time of 2 s were set by considering an amount of springback ($\Delta\theta = \theta_1 - \theta_2$) of 2-degree to achieve a bending angle during loading ($\theta_1 = 92$ -degree) and a bending angle after unloading ($\theta_2 = 90$ -degree).⁹⁾

The initial volume fraction of γ_f (f_{γ_0}) was quantified by

Fig. 1. Heat treatment diagrams of (a) TBF and (b) MDP0 steels, in which “O.Q.” and “R_T” represent quenching in oil and room temperature, respectively.

(b) V-bending tools

Fig. 2. Experimental apparatus for V-bending test. (Online version in color.)

(200)_α, (211)_α, (200)_γ, (220)_γ and (311)_γ diffraction peaks of MoK α radiation measured by means of X-ray diffractometry (five peak method¹¹). The initial carbon concentration in γ_R ($C_{\gamma 0}$, mass%) was estimated by following Eq. (2) using a lattice constant (a_γ , nm) measured from (220)_γ diffraction peak of CrK α radiation.¹²

$$C_{\gamma 0} = (a_\gamma - 0.35467) / 4.67 \times 10^{-3} \dots\dots\dots (2)$$

The microstructure of white regions etched by LePera reagent exhibited retained austenite (γ_R) or martensite and that of gray regions exhibited bainitic ferrite lath matrix, respectively. The volume fraction of martensite (f_{am}) was calculated from the difference of the second phase volume fraction measured from the white part using the line trace analysis and the initial volume fraction ($f_{\gamma 0}$) of retained austenite (γ_R) measured by the X-ray diffractometry.

Hardness tests were conducted using a dynamic ultra micro-Vickers hardness tester (load: 98.1 mN, holding time: 5 s, load speed: 1.42 mN/s). Vickers hardness (HV) was measured to obtain the distribution of hardness in thickness direction from punching side to outer side of V-bent part with $y = 0.1$ mm intervals.

The EBSD analysis sample was mounted in a thermosetting resin and then polished by # 320 and # 600 water-proof abrasive papers. After that, the mirror polishing was per-

formed by 9 μm and 3 μm single crystal diamond slurries and 0.05 μm colloidal silica. The EBSD analyses in an area of 40 $\mu\text{m} \times 40 \mu\text{m}$ with a beam step size of 0.2 μm , FEM analyses (Abaqus, Two-dimensional plane strain analyses) and the residual stress measurements (cos α method, α phase, 30 kV, 1.5 mA, Young's modulus $E = 206$ GPa, Poisson's ratio $\nu = 0.3$, X-ray incident angle of 35.0-degree, sample distance of 39.0 mm, μ -X360s, Pulstec Industrial Co., Ltd.) were conducted. For the FEM analysis, material properties were measured by the tensile tests at a crosshead speed of 10 mm/min using a JIS13B-type tensile specimen. True stress-true strain curve was estimated from engineering stress-engineering strain curve obtained by tensile test, and the strain hardening behavior was assumed by a Swift's equation.

3. Results and Discussion

3.1. Microstructure and Mechanical Properties

Figure 3 shows the microstructure of TBF steels. Figures 3(a) and 3(c) show the microstructure of TBF375 steel, and Figs. 3(b) and 3(d) show the microstructure of TBF450 steel. Figures 3(a) and 3(b) are band contrast images, and Figs. 3(c) and 3(d) are the microstructure etched by RePera reagent. Due to RePera reagent, the white part exhibited

Fig. 3. Band contrast maps and optical micrographs for TBF375 and TBF450 steels austempered at (a), (c) 648 K (375°C) or (b), (d) 723 K (450°C), in (c) and (d), white and gray regions represent retained austenite and/or martensite and bainitic ferrite matrix, respectively. (c) and (d): RePera etching.

Table 2. Retained austenite characteristics and mechanical properties.⁷⁾

Steel	T_A (°C)	f_{am}	$f_{\gamma 0}$	$C_{\gamma 0}$ (mass%)	$f_{\gamma 0} \times C_{\gamma 0}$ (mass%)	YS (MPa)	TS (MPa)	UEl (%)	TEl (%)	YR	TS $\times$ TEl (GPa%)
TBF375	375	0	0.089	1.16	0.103	971	1 154	4.4	7.8	0.84	9.0
TBF450	450	0.081	0.112	0.96	0.108	617	918	14.2	18.2	0.67	16.7
TDP1	400	0	0.049	1.31	0.064	429	651	27.8	37.2	0.66	24.2
TDP2	400	0	0.079	1.38	0.109	527	831	31.4	35.8	0.63	29.7
TDP3	400	0	0.132	1.41	0.186	562	895	28.6	32.2	0.63	28.8
TDP4	400	0	0.170	1.45	0.247	728	1 103	29.2	32.8	0.66	36.2
MDP0	—	0.329	—	—	—	434	923	9.3	11.3	0.47	10.4

T_A : austempering temperature, f_{am} : volume fraction of martensite, $f_{\gamma 0}$: initial volume fraction of retained austenite, $C_{\gamma 0}$: initial carbon concentration in retained austenite, $f_{\gamma 0} \times C_{\gamma 0}$: total carbon concentration of retained austenite, YS: yield stress or 0.2% offset proof stress, TS: tensile strength, UEl: uniform elongation, TEl: total elongation, YR: yield ratio (=YS/TS) and TS $\times$ TEl: strength-ductility balance.

retained austenite or martensite, and the gray part exhibited bainitic ferrite.

Table 2⁷⁾ shows the γ_R characteristics and mechanical properties of steel sheets used. From Fig. 3(a), the band contrast map of microstructure of the TBF375 steel subjected to austempering at 648 K (375°C) which is below the M_S temperature (693 K (420°C)) of the TBF steel mainly consisted of bainitic ferrite and γ_R , and most of γ_R existed as filmy shape.⁷⁾ On the other hand, in the TBF450 steel subjected to austempering treatment at 723 K (450°C), bainitic ferrite also existed as a matrix, and martensite was presented as the second phase in addition to γ_R ⁷⁾ (Fig. 3(b)). At this time, f_{γ_0} of the TBF450 steel increased compared to that of the TBF375 steel. In addition, the tensile strength (TS) was 1 100 MPa or more in the TBF375 steel, which was higher than that of the TBF450 steel (918 MPa) (Table 2). The total elongation (TEL) of the TBF375 steel was 7.8% and that of the TBF450 steel was 18.2%. The TEL of the TBF450 steel was larger than that of the TBF375 steel. It is clear that the microstructural morphology of TDP steel was defined as polygonal ferrite (α_f) matrix and network-like distributed second phase consisted of bainite (α_b) and γ_R ,^{8,9)} whereas the microstructure of the MDP0 steel consisted of polygonal ferrite matrix and martensite (α_m) as the second phase.⁷⁾ From Table 2, the initial volume fraction of γ_R (f_{γ_0}),¹¹⁾ carbon concentration (C_{γ_0})¹²⁾ and total carbon content ($f_{\gamma_0} \times C_{\gamma_0}$)¹³⁾ in γ_R increased with increasing the carbon content in the TDP1–TDP4 steels which exhibited the chemical composition of (0.1–0.4)C–1.5Si–1.5Mn (mass%). The TS of the TDP steels was in a range of 651 and 1 103 MPa, which tends to increase with carbon content. The TEL of the TDP steels was in a range of 32.2 and 37.2%, which was larger than that of the MDP0 steel.^{7–9)} The $TS \times TEL$ of the TDP steels was in a range of 24.2 and 36.2 GPa%, implying higher press formability than that of the MDP0 steel of more than 25 GPa%. In addition, the MDP0 steel possessed low yield ratio (YR) of less than 0.5.

3.2. Effect of Hardness Distribution in Bending Area on Bendability

Figures 4, 5 and 6 show the bending load (P)-punch stroke (S) curves for the TBF375 and TBF450 ($S_{\max}=10.6$ mm), TDP2, TDP4 and MDP0 ($S_{\max}=10.6$ mm),⁸⁾ and TBF ($S_{\max}=10.8$ mm, $\theta_2=90$ -degree) steels, respectively. **Figure**

Fig. 4. Bending load (P) – punch stroke (S) curves for TBF steels ($S_{\max}=10.6$ mm).

Fig. 5. Bending load (P) – punch stroke (S) curves for TDP2, MDP0 and MDP4 steels ($S_{\max}=10.6$ mm).⁸⁾ (Online version in color.)

Fig. 6. Bending load (P) – punch stroke (S) curves for TBF375 and TBF450 steels ($S_{\max}=10.8$ mm, $\theta_2=90$ -degree).

Fig. 7. Variation in bending angle after unloading (θ_2) with carbon content (C) for TBF375, TBF450, TDP1, TDP2, TDP3, and TDP4 steels, in which “ $\Delta\theta$ ” and “ θ_1 ” represent amount of springback and bending angle on loading respectively ((a) $S_{\max}=10.6$ mm, (b) $S_{\max}=10.8$ mm). (Online version in color.)

7 shows the relation between carbon content (C) and bending angle after unloading (θ_2) (TBF375, TBF450, TDP1 - TDP4 steels). Figures 7(a) and 7(b) show the $S_{\max} = 10.6$ mm and $S_{\max} = 10.8$ mm, respectively.

From Fig. 4, the region (O-A) corresponds to the pure bending deformation portion where the force required for bending is the load (P_1) at point A which is the transient force from elastic bending to plastic bending deformation.¹⁰⁾ On the other hand, the region (A-B) where the load is temporarily reduced is the load when the sheet slides into the die, corresponding to the load (P_2) at point B. The region (B-C) where the bending is completed is the load (P_3) at point C. In Fig. 5, the MDP0 steel could not obtain the typical bending load (P) – punch stroke (S) curve due to the occurrence of fracture before completing V-bending. On the other hand, similar bending load (P) – punch stroke (S) curves as those of TBF375 and TBF450 steels were exhibited in the TDP2 and TDP4 steels. In Fig. 6, the load (P) at point C was remarkably increased because of controlling the displacement of punch bottom dead center from $S_{\max} = 10.6$ mm to $S_{\max} = 10.8$ mm although load (P) of points A and B was hardly changed. The P_1 , P_2 and P_3 of TBF375 steel were higher than those of TBF450 steel.⁷⁻⁹⁾ This might be caused by the difference of tensile strength (TS) and yield stress (YS) (Table 2). In addition, the TBF steels exhibited the large amount of springback ($\Delta\theta$), and the bending angle after unloading (θ_2) was not able to form $\theta_2 = 90$ -degree at the displacement of punch bottom dead center $S_{\max} = 10.6$ mm but able to form it at $S_{\max} = 10.8$ mm (see Fig. 7). Therefore, the TBF steels enabled to conduct 90-degree V-bending by controlling the $S_{\max}$. Since the high carbon concentration provides the high TS and YS , θ_2 decreased with the increasing the carbon concentration. Since the elastic deformation region possessed the same modulus of elasticity, θ_2 decreased with increasing the carbon content. Resultantly, the amount of springback ($\Delta\theta$) increased due to the elastic recovery. In addition, the reasons that the TDP4 and TBF steels showed the same θ_2 were that the TS and YS were high in order of TBF 450, TDP4, and TBF 375 steels, and the yield ratio (YR) of the TBF 375 steel was high at 0.84 (Table 2). Moreover, it is considered that the microstructure such as matrix structures, retained austenite morphologies and stability of retained austenite also affected the θ_2 of the TRIP-aided steels.

Furthermore, the bending was not able to be completed for the MDP0 steel, as the crack occurred on the outer surface at the bending punch tip with a radius of 2 mm in the MDP0 steel. The maximum strain $\epsilon_{\max} = t/(2R_0)$ (thickness: t , radius of curvature for neutral surface: R_0)¹⁴⁾ in circumferential direction of about 23.1% with a bending punch tip radius of 2 mm occurred on the outer surface. Since the ductility of MDP0 steel originally possessed 23.1% or less, it was considered that the crack occurred with a plastic strain of 23.1% or more. On the other hand, it was considered that the TBF steels were applied with the ductility of 23.1% or more by the strain-induced martensitic transformation (SMT)¹³⁾ of retained austenite (γ_R), and the crack initiation was suppressed even with the plastic strain of 23.1%.

Figure 8 shows the V-bent specimen, and **Fig. 9** shows the Vickers hardness (HV) distributions in the radial direc-

Fig. 8. Specimen of cross-section after bending (TBF375 steel, $S_{\max} = 10.6$ mm). (Online version in color.)

Fig. 9. Variation in Vickers hardness (HV) with distance from inner surface (y) at cross-section after V-bending for TBF375, TBF450, and TDP2 steels ($S_{\max} = 10.6$ mm).

Fig. 10. Variation in residual stress (σ_R) with tensile strength (TS) on outer surface of V-bent specimen for TBF375, TBF450, TDP1, TDP2, TDP3, and TDP4 steels ($S_{\max} = 10.6$ mm). (Online version in color.)

tion (y) of the punch tip of thickness in the V-bending ($S_{\max} = 10.6$ mm). Here, $y = 0$ mm corresponds to the concave side of the V-bent portion. The Vickers hardness at outer and inner sides increased compared with that at the center in the TBF375 and TBF450 steels. The increase in the hardness at the outer and inner sides was attributed to not only the multiplication of dislocations but also the occurrence of martensitic transformation of retained austenite. Figure 9 suggested that the TBF375 and TBF450 steels enabled to conduct 90-degree V-bending considering

Fig. 11. Inverse pole figure (IPF) maps after V-bending for (a) undeformed region, (b) inside, (c) neutral surface, (d) outside of TB F375 steel ($S_{\max}=10.6$ mm). (Online version in color.)

Fig. 12. Phase maps of bcc and fcc after V-bending for (a) undeformed region, (b) inside, (c) neutral surface, (d) outside of TB F375 steel ($S_{\max}=10.6$ mm). (Online version in color.)

the springback due to the suppression of crack initiation at the outside of V-bent specimen which exhibited the tensile deformation like 900 MPa grade MDP0 steel because of the TRIP effect of γ_R since the inside and outside of deformation states of the V-bent portion of the TBF375 and TBF450 steels were plastically deformed⁸⁾ (Fig. 6). Furthermore, the hardness distributions of the TBF steel of 90-degree V-bent specimen with $S_{\max}=10.6$ mm and $S_{\max}=10.8$ mm exhibited similar trend (Fig. 9). It was noted that the HV on the tension side of TBF375 was the highest hardness, and the HV of TBF450 and TDP2 steels was the same hardness distribution.

Figure 10 shows the relationship between the residual stress (σ_R) and the TS of the TBF375, TBF450, TDP1 - TDP4 steels with $S_{\max} = 10.6$ mm. The σ_R in the longitudinal direction was measured at the plastic-deformed region on the outer surface of V-bent specimen (tensile side). It was noted that the compressive σ_R increased with increasing the TS . In this context, this σ_R was applied by the restraint of the specimen between 88-degree punch and die and bent back of the specimen. This might be caused by the increment of the amount of springback ($\Delta\theta$) over 2-degree (Fig. 7).

Figures 11 and 12 show the EBSD- inverse pole figure (IPF) and the EBSD-phase maps of the TBF375 steel. **Table 3** shows the area fraction of each phase for the TBF steels. **Figure 13** shows the kernel average misorientation (KAM) distribution maps for the TBF375 steel. **Figure 14** shows the frequency distribution of KAM values for the TBF

steels. The zero solution corresponded to a region where it could not be determined whether it was a fcc phase or a bcc phase (the region shown in black in Fig. 12). In this paper, the region of zero solution was determined to be the strain-induced martensite phase since the phase cannot be detected due to the large distortion of the crystal lattice. The area fraction of fcc phase was smaller than the volume fraction of retained austenite measured by X-ray diffraction. This was expected that the retained austenite transformed during sample preparation (polishing) and EBSD analysis could not detect the fcc phase because of the step size of $0.2 \mu\text{m}$ which was larger than retained austenite sizes.

Table 3. Area fractions of TBF steels analyzed by EBSD (area%).

Steel	position	fcc	bcc	zero solution	bcc + zero solution
TBF375	undeformed region	1.90	96.52	1.58	98.10
	inside	0.98	95.93	3.09	99.82
	neutral surface	1.33	96.11	2.57	98.68
	outside	0.32	93.24	6.44	99.68
TBF450	undeformed region	2.46	96.13	1.41	97.54
	inside	1.24	96.86	1.91	98.77
	neutral surface	1.02	97.67	1.31	98.98
	outside	1.35	97.28	2.37	99.65

Fig. 13. Kernel average misorientation (KAM) maps after V-bending for (a) undeformed region, (b) inside, (c) neutral surface, (d) outside of TBF375 steel ($S_{\max}=10.6$ mm). (Online version in color.)

Fig. 14. Variation in frequency with kernel average misorientation (KAM) values after V-bending for (a) TBF375 steel and (b) TBF450 steel. (Online version in color.)

In the cross section of the V-bent specimen in Figs. 11 and 12, (a), (b), (c) and (d) represent the undeformed region (base metal), the inner region of the V-bent part (compression side, $y = 0.1$ mm), the center region of the V-bent part (neutral surface, $y = 0.6$ mm) and the outer region of the V-bent part (tensile side, $y = 1.1$ mm), respectively. The blue and red parts indicate the bainitic ferrite matrix (bcc), and γ_R (fcc), respectively. The area fraction of γ_R drastically decreased from 1.90 area% to 0.32 area% as shown in Fig. 12(d) compared with Figs. 12(a) and 12(c) (Table 3). This was implied that the strain-induced transformation of γ_R into the martensite occurred during the bending deformation.

From Figs. 13 and 14, it could be seen that the V-bent neutral surface of the TBF375 steel was the elastic deformation region, and the TBF375 steel was deformed at the entire cross section which is different from the undeformed region of the V-bent neutral surface for the TBF450 and TDP4 steels.⁹⁾ The difference of KAM value distributions implied that the deformation mechanisms during V-bending were different between the TBF375 steel and the TBF450 and TDP4 steels.

It was considered that the HV at the inner region of V-bent specimen was higher than that at the undeformed region because of the multiplication of dislocation at the inner region of V-bent specimen which was resulted from the suppression of the volume expansion of around 3% during the martensitic phase transformation of γ_R , since the maximum tensile strain at convex side of V-bent region was applied, whereas the compression deformation at concave side of V-bent region was dominant (Table 3, Fig. 9). Therefore, it was concluded that the occurrence of strain-induced martensitic transformation of γ_R in 90-degree V-bending

Fig. 15. True stress (σ_T) – true strain (ϵ_T) curve using Swift equation for TBF375 steel.

Fig. 16. Geometry of V-bending test analysed by FEM. (Online version in color.)

for the TBF steels was supported by the results of the HV and the EBSD analysis of phase maps and distribution of KAM values.

Figures 15 and 16 show the true stress (σ_T) – true strain (ϵ_T) diagram of the TBF375 steel and the geometry of the V-bending test used for FEM analysis. The true stress (σ_T) – true strain (ϵ_T) curve of the TBF375 steel was approximated using Swift's equation. **Figures 17–19**, and **20** show the contour diagram of the equivalent plastic strain (ϵ_{eq}) distribution after the V-bending test for the TBF375 steel ($S_{max} = 10.6$ mm), the contour diagram of longitudinal stress (a) distribution in the longitudinal direction after the V-bending test for the TBF375 steel ($S_{max} = 10.6$ mm), the equivalent plastic strain (ϵ_{eq}) distribution on the outer surface of the V-bent specimen for the TBF375 steel ((a) $S_{max} = 10.6$ mm, (b) $S_{max} = 10.8$ mm), and the longitudinal stress (a) distribution on the outer surface of the V-bent specimen for the TBF375 steel ((a) $S_{max} = 10.6$ mm, (b) $S_{max} = 10.8$ mm). The equivalent plastic strain (ϵ_{eq}) distribution and the longitudinal stress (a) distribution were changed by the 90-degree V-bending at $S_{max} = 10.8$ mm (Figs. 19, 20). This was assumed that the bending deformation was simply applied at $S_{max} = 10.6$ mm, whereas the flanges of the V-bent

Fig. 17. Equivalent plastic strain distribution after V-bending test for TBF375 steel ($S_{\max}=10.6$ mm). (Online version in color.)

Fig. 18. Longitudinal stress distribution after V-bending test for TBF375 steel ($S_{\max}=10.6$ mm). (Online version in color.)

Fig. 19. Equivalent plastic strain (ϵ_{eq}) distribution on outer surface of V-bent specimen for (a) $S_{\max}=10.6$ mm and (b) $S_{\max}=10.8$ mm of TBF375 steel. (Online version in color.)

Fig. 20. Longitudinal stress (σ) distribution on outer surface of V-bent specimen for (a) $S_{\max}=10.6$ mm and (b) $S_{\max}=10.8$ mm of TBF375 steel. (Online version in color.)

specimen at $S_{\max} = 10.8$ mm were pressed by the punch and the die, and the thickness was reduced. Moreover, the longitudinal stress distribution of V-bent specimen might be caused by the application of the local plastic deformation at the vicinity of the top of the V-bent specimen. However, the effect of the longitudinal stress on the possibility of V-bending was small compared with that of the plastic strain because the large amount of plastic strain was applied at the convex side of the V-bent specimen.

It can be seen that the TBF375 steel possessed a larger strain on the neutral surface than the TBF450 steel (Fig. 14).

This was implied that the yield ratio (YR) of the TBF375 steel was extremely high at 0.84, with the plastic deformation over the entire cross section. The KAM value of the TBF450 steel tended to be the same as that of TDP2 steel.⁹⁾ In this context, it was considered that the deformation mechanism at the neutral surface of the V-bent part might be changed by the increment of the tensile strength of 1 100 MPa grade for TBF375 steel (Fig. 14, Table 2).

4. Conclusions

The effect of the retained austenite characteristics on V-bending in ultrahigh-strength TRIP-aided steel sheets with bainitic ferrite matrix (TBF steel) was investigated. The main results were as follows.

(1) The TBF steels with the chemical composition of 0.2C-1.5Si-1.5Mn (mass%) were able to perform the 90-degree V-bending, considering the springback, by the strain-induced martensitic transformation of retained austenite (γ_R) as the TRIP effect at the plastic deformation region of outside of the specimen whereas the ferrite-martensite dual-phase steel sheet (MDP0 steel) with 900 MPa grade occurred the crack at the tension region.

(2) The 1100 MPa grade TBF375 steel sheet with the chemical composition of 0.2C-1.5Si-1.5Mn (mass%) exhibiting the large amount of springback ($\Delta\theta$) of equal or more than 2-degree was able to conduct the 90-degree V-bending which was controlled by the displacement of punch bottom dead center.

(3) It was confirmed that the occurrence of strain-induced martensitic transformation of retained austenite (γ_R) by the 90-degree V-bending was supported due to the Vickers hardness (HV), the EBSD-phase maps and the strain distribution obtained by KAM values in the TBF steels with the chemical composition of 0.2C-1.5Si-1.5Mn (mass%).

Acknowledgments

Finally, the authors wish to thank the 2019 Joint Research Project at the Institute for Materials Research, Tohoku University Foundation (Subject No. 19K0032), Institute for Materials Research, Tohoku University and National

Institute of Technology (KOSEN), Nagano College Foundation for financial supports. We would also like to thank Yoshiaki Niwa of the Three-Dimensional Design Ability Association, Kazuhide Wada, Soma Kodama, Masami Komori, Hiroki Saito, Yuto Hirose, Takao Ichikawa, Yuya Okubo, and Takayuki Sato of National Institute of Technology (KOSEN), Nagano College.

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