EFFECT OF YAG LASER CUTTING ON STRETCH-FLANGEABILITY OF 0.1-0.6%C TRIP SHEET STEELS

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ABSTRACT

The **tr**ansformation-**i**nduced **p**lasticity (**TRIP**) of retained austenite is very useful to enhance the press formability of ultra high strength sheet steels. The TRIP steels with different matrix structure and different retained austenite morphology have been developed for weight reduction and shock safety up to now. The conventional TRIP-aided dual-phase steel or "TRIP-aided polygonal ferrite (PF) steel" composing of polygonal ferrite matrix and blocky retained austenite plus bainite second phase possessd an excellent stretch-formability and deep drawability. We have recently developed new type of TRIP steel or "TRIP-aided annealed martensitic (AM) steel" composing of bainitic ferrite matrix by annealed martensite matrix, and "TRIP-aided bainitic ferrite (BF) steel" composing of bainitic ferrite matrix and interlath retained austenite films. It is supposed that carbon addition is effective to rise the tensile strength of TRIP steel. So, in the present study the effect of YAG laser cutting on the stretch-flangeability of 0.1-0.6%C TRIP steels was investigated.The strength-stretch-flangeability balance ($TS \times \lambda$) of holes obtained by either laser cutting and hole-punching decreased with increasing carbon content in PF, AM and BF steels. When the carbon content of 0.3 mass% or higher, the λ value in the case of laser cutting decreased to a level comparable to that in the case of hole-punching in PF steels. On the other hand, we demonstrated that YAG laser cutting contributes to the improvement of the stretch-flangeability of 1200 MPa class BF steels with 0.4 mass% .

KEYWORDS

Stretch-flangeability, Retained Austenite, Transformation-induced Plasticity, YAG Laser Cutting, TRIP Steel

INTRODUCTION

Among high-strength sheet steels that have recently been developed with the aim of weight reduction and improvement in the shock safety of automobiles, transformation-induced plasticity (TRIP)[1] sheet steels, in which the TRIP of retained austenite (γ_R) is effectively utilized, have excellent press formability.[2-10] To date, aiming at improving press formability, Shirasawa et al.[11] and Hayashi et al.[12] have reported on the stretch flangeability of sheet steels as affected by CO_2 laser cutting.
However, there are only a few reports on TRIP steel and YAG laser, and they mainly deal with C-Si-Mn TRIP steels (PF steels) that form a polygonal ferrite matrix; no reports have been published regarding TRIP-aided annealed martensitic (AM) steels and TRIP-aided bainitic ferrite (BF) steels in which superior stretch-flangeability can be expected.
In this study, we investigated the effect of YAG laser cutting on the stretch– flangeability of C-Si-Mn TRIP steels with a controlled matrix structure.

1. EXPERIMENTAL PROCEDURE

As steel specimens, we used five types of cold-rolled sheet steel (sheet thickness: 1.2 mm) having the chemical compositions listed in Table 1. We set the amounts of Si and Mn added to be almost constant, whereas that of C added to be varied between 0.1-0.6 mass%. These steels were heat-treated as shown in Table 2, and three types of sheet steel were prepared: PF steel, AM steel and BF steel.[7]

For tensile tests, JIS-13B specimens were used with a crosshead speed of 1 mm/min. For stretch-flangeability tests, we used disk-shaped specimens of 50 mm diameter that were subjected to laser cutting or punching of a 5-mm-diameter initial hole, and then formed into a flat-bottom punch (Fig. 1). Here, we used a YAG laser (maximum average output: 350 W, maximum peak output: 4.5 kW) for cutting. The laser processing conditions are as follows: pulse energy of 4 J/P, pulse width of 2 ms, pulse frequency of 25 Hz, and feed speed of 0.1 m/min. Oxygen gas was used as an assist gas (0.5 MPa). The laser cutting was performed at an angle of 45° to the rolling direction.

The stretch-flangeability was evaluated using the hole-expanding ratio (λ) expressed as Eq. (1) .

$$\lambda = (d_f - d_0) / d_0 \times 100\ \% \cdots (1)$$

where d_0 and d_f represent the initial diameter of holes and the diameter at which cracks occur, respectively.

Volume fraction of the retained austenite was determined by X-ray diffractometry using Mo-Kα radiation. To minimize the effect of texture, the volume fraction was calculated on the basis of integrated intensity of (200)α, (211)α, (200)γ, (220)γ, and (311)γ diffraction peaks.[13]

An initial carbon concentration of the retained austenite $C_{\gamma 0}$ (mass%) was estimated from lattice parameter $a_{\gamma 0}$ (nm) measured from (220)γ diffraction peak of Cr-Kα radiation using Eq. (2).[14]

$$a_{\gamma 0} = 0.34567 + 0.00467 \times C_{\gamma 0} \cdots (2)$$

where the effect of silicon and manganese concentrations on the lattice parameter was ignored because these effects were much smaller than that of the carbon concentration.

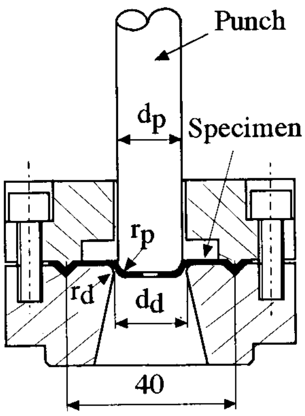
Table 1. Chemical composition (mass%) of steels.

steel	C	Si	Mn	P	S	Al
0.1C	0.10	1.49	1.50	0.015	0.001	0.038
0.2C	0.20	1.51	1.51	0.015	0.001	0.040
0.3C	0.29	1.46	1.50	0.014	0.001	0.043
0.4C	0.40	1.49	1.50	0.015	0.001	0.045
0.6C	0.61	1.50	1.53	0.015	0.001	0.041

Table 2. Heat treatment conditions of AM, PF and BF steels.

steel		$T_{\alpha+\gamma}$ or T_γ (°C)	$t_{\alpha+\gamma}$ or t_γ (s)	T_A (°C)	t_A (s)
AM & PF	0.1C - 0.6C	780	1200	400	1000
	0.1C			450	100
	0.2C			425	200
BF	0.3C	950	1200	400	300
	0.4C			375	500
	0.6C			350	3000

$T_{\alpha+\gamma}$ or T_γ (°C): annealing temperature, $t_{\alpha+\gamma}$ or t_γ (s): annealing time, T_A: austempering temperature, t_A: austempering time.



(d_p=17.4 mm, r_p=3.0 mm, d_d=22 mm, r_d=1 mm)

Fig. 1. Experimental apparatus for hole-expanding.

2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1 STRUCTURE AND TENSILE PROPERTY

Figure 2 shows SEM images of the TRIP steel structures. Retained austenite is present in particle, acicular, and interlath retained austenite films in the PF, AM and BF steels, respectively.
Figure 3 shows the relationship between the initial volume ratio ($f_{\gamma 0}$) of the retained austenite (γ_R) and the initial carbon content ($C_{\gamma 0}$) in γ_R with respect to the carbon content of the TRIP steels.
In each type of steel, $f_{\gamma 0}$ and $C_{\gamma 0}$ increase with carbon content.
Figure 4 shows the relationship between total elongation (*TEl*) and tensile strength (*TS*). The PF and AM steels show a particularly large total elongation.

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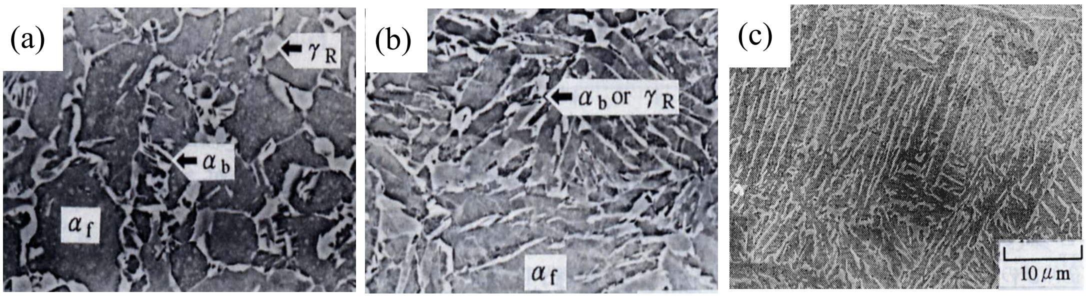

Fig. 2. Microstructure of PF steel (a), AM steel (b) and BF steel (c) morphology, "α_{pf}", "α_{am}", "α_b" and "γ_R" represent porigonal ferrite, annealed martensite, bainite and retained austenite, respectively.

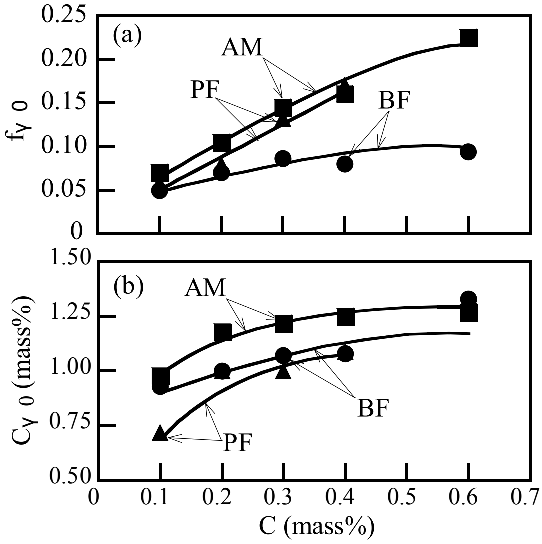

Fig. 3 Variations in (a) initial volume fraction ($f_{\gamma 0}$) and (b) initial carbon concentration ($C_{\gamma 0}$) of retained austenite as a function of carbon content (C) in TRIP steels.

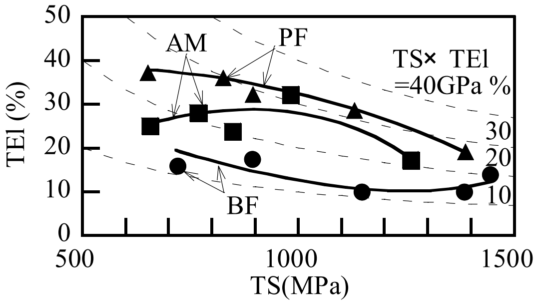

Fig. 4 Total elongation (TEl) as a function of tensile strength (TS) in TRIP steels.

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2.2 STRETCH-FLANGEABILITY

Figure 5 shows the relationship between the hole-expanding ratio (λ) and tensile strength (*TS*) of the TRIP steels. Here, contour lines represent the strength–stretch-flangeability balance ($TS\times\lambda$), and $\Delta\lambda$ is the improvement percentage, i.e., the difference between λ of a laser-cut hole (solid mark) and λ of a punched hole (open mark). For the PF steel with a carbon content of 0.3 mass% (PF0.3C steel) and *TS*=900 MPa or higher, λ of the laser-cut hole with $\Delta\lambda$ of 15% or higher decreases to a level similar to that of the punched hole (Fig. 5(a)). For the AM steels, $\Delta\lambda$ becomes maximum at a carbon content of 0.3 mass% (AM0.3C steel), and the improvement in λ by laser cutting is obtained up to *TS* = 1000 MPa for the AM0.4C steel (Fig. 5(b)). In addition, the improvement percentage obtained by laser cutting in the BF steels was not as high as those obtained in the AM and PF steels, but the improvement can be expected up to *TS* values higher than 1200 MPa (Fig. 5(c)). The reason for this is that the $TS\times\lambda$ limit for metal-mold shapes that can be improved by laser cutting is predicted to be approximately 60 GPa%.

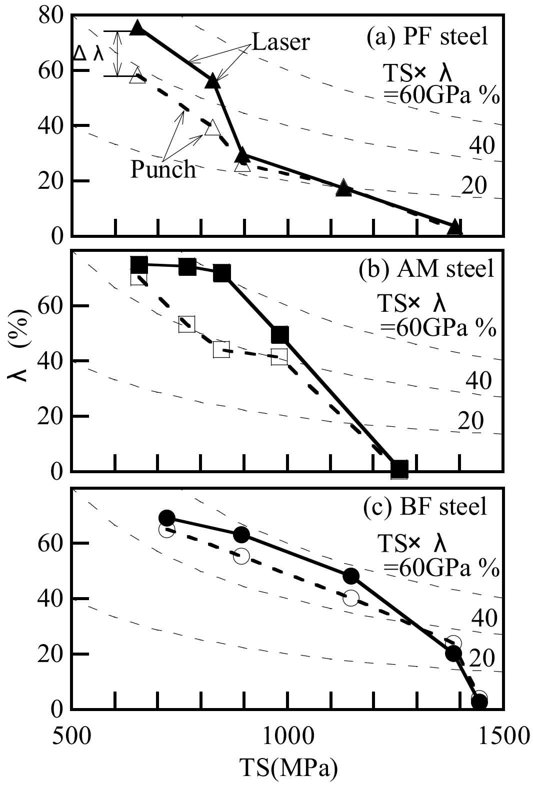

Fig. 5 Comparison of hole-expanding ratio (λ) as a function of tensile strength (*TS*), in which marks represent punching (open marks) and laser cutting (solid marks), respectively.

2.3 MECHANISM OF IMPROVEMENT OF STRETCH-FLANGEABILITY BY LASER PROCESSING

Figure 6 shows the relationship between strength–stretch- flangeability balance ($TS\times\lambda$) and carbon equivalent (C_{eq}). Here, C_{eq} is obtained using using Eq. (3).[15]

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C_{eq}=[C]+1/6[Mn]+1/24[Si] ・・・(3)

Since a negative correlation is observed in Fig. 6, C_{eq} is suggested to be one of the causes of the decrease in stretch flangeability. Assuming that TS×λ =50 GPa% or higher, that is, an excellent strength–stretch-flangeability balance, we can consider that laser cutting positively affects the stretch-flangeability of TRIP steels of 980 MPa class (C_{eq}=0.6 mass% or higher) in which annealed martensite and bainitic ferrite are used as the matrix structures of the AM0.4C and BF0.3C steels, respectively.

Figure 7 shows the distribution of Vickers hardness of the steel plate immediately under the laser-cut plane. From Fig. 7(a), we can see that no laser-hardened layer is present in the PF0.1C steel; from Fig. 7(b), a hardened layer of approximately 250μ m thickness is present in the PF0.4C steel.

Figure 8 shows SEM images of the layer immediately under the laser-cut plane. In Fig. 8(a), no effect of laser cutting is confirmed in the PF0.1C steel, whereas the presence of cracks accompanied by the generation of a hardened layer is confirmed in the PF0.4C steel (Fig. 8(b)).

The hardened layer of the PF0.4C steel is composed of part of the fused portion, part of the heat affected zone called HAZ and part of the base metal. Therefore, we applied the concept of welding, and found that as carbon content increases, the hardness of the martensite increases, which may enhance the effects of carbon addition on the sensitivity of steels to low-temperature cracks. Thus, an increase in C_{eq} (Fig. 6) may lead to the generation of and increase in the thickness of hardening layers, which could induce crack generation in an early time.

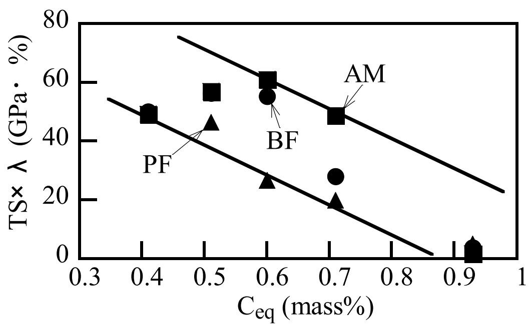

Fig. 6 Correlation between strength - stretch-flangeability balance (TS×λ) and carbon equivalent (C_{eq}) in TRIP steels.

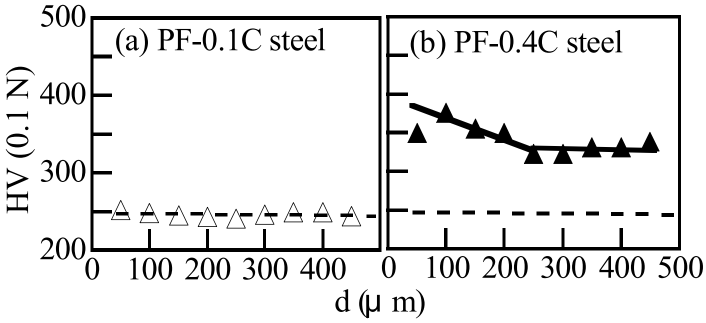

Fig. 7 Variation in Vickers hardness (HV) at the cross section of distance of laser cutting in (a) PF0.1C and (b) PF0.4C steels.

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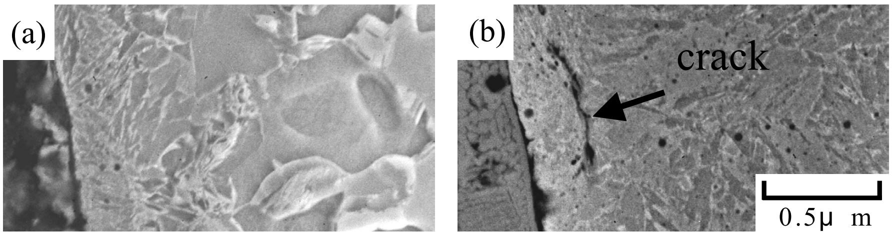

Fig. 8. Scanning electron micrographs showing cross section of laser hole surface in (a) PF0.1C and (b) PF0.4C steels.

3. CONCLUSIONS

We investigated the stretch-flangeability of TRIP sheet steels comprising 0.1-0.6 mass% carbon and cut by a YAG laser; we obtained the following results.
1) The stretch-flangeability of TRIP sheet steels comprising (0.1-0.4)C-1.5Si-1.5Mn was improved by laser cutting.
2) The stretch-flangeability of ultrahigh-tensile-strength steels, particularly that of TRIP steels made of annealed martensite or bainitic ferrite as the matrix structure, was effectively improved by laser cutting.
3) An increase in C_{eq} induces the generation of and the increase in the thicknessof hardening layers; this is considered to induce crack generation in an early time.

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