Bendability of Weld Metal —Development of Application Technology of Tailor-Welded Blanks 1st Report—*¹

Masahiro Saito^{1,*2}, Yoshiaki Nakazawa², Kenichiro Otsuka¹, Masanori Yasuyama²,
 Masatoshi Tokunaga² and Tohru Yoshida³

¹Nippon Steel Corporation, Tokai 476-8686, Japan

²Nippon Steel Corporation, Futtsu 293-8511, Japan

³Nippon Steel Corporation, Amagasaki 660-0891, Japan

To decrease car body weight and improve crash safety, tailor-welded blanks are often used for the car body materials. In the past, little research has been conducted on the formability of the weld metal (WM). This study focuses on the bendability of the WM and evaluates it by the bending test. The main results are as follows. (1) The bendability of the laser-welded specimens was better than that of the plasma-welded specimens. (2) The bendability of the weld line (WL) was related to the homogeneity of the WM structure, and it increased with increasing homogeneity. (3) The surface roughness of the WL has no effect on the bendability of the WL. (4) The deformation of the bent surface of the WL changed with the WL width, and the bendability increased as the WL narrowed because the bent surface showed increasing uniaxial stretching deformation. [[doi:10.2320/matertrans.P-M2019836](https://doi.org/10.2320/matertrans.P-M2019836)]

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1. Introduction

In the automobile industry, reducing CO₂ emissions required increasingly necessary in the context of global environmental protection.¹⁾ The gas mileage of cars is correlation to car body weight,²⁾ and development of technology to lighten car bodies is a pressing issue. Furthermore, in the area of crash safety, because the safety regulation has grown stricter every year, improvement of car body strength is necessary. As a technology to solve these issues, in recent years, the use of Tailor-Welded Blanks (hereafter referred to as TWBs) in car bodies is proceeding.²⁾ TWBs are a technological means on joining raw sheets with different material species and/or thickness together, or forming by joined sheets, and the TWBs techniques can give the interior of a part with distributed strength and plate thickness, differing from products from a sheet of homogeneous quality. Parts fabrication using TWBs has an advantage that functions of the parts can be improved through arranging the right material in the right place. Regarding the previously studies on TWBs, many papers reported³⁻¹⁰⁾ the mechanical properties and formability from the tensile properties, bulging properties and deep drawing properties in portions of specimen that affected by Weld Line (hereafter WL). On the other hand, the properties of the Weld Metal (hereafter WM) have been studied to the effect of different welding methods on hardness,^{3,4)} and there are fewer studies focusing on the formability of the WM. In general, the hardness of WM by welding is greater than the Base Metal (hereafter BM), so the WM possible crack even under strain conditions in which the BM can be still formable. In particular, cracking in the WL is high risk, because bending provides large strain on the bending surface.

In this report, the bendability of the WL in a V bending at a right angle was examined with TWBs prepared using high tensile strength steel sheet, which is increasingly used for car bodies. Used raw sheets with different material species and/or thickness are frequently used for TWBs; however, in this report, for a basic study excluding the impacts due to combining different raw sheets, the TWBs were made from steel sheets of the same material species and thickness. Bending specimens were prepared by two welding methods, and the factors improving the bendability of the WM were investigated from result of experimental measurement of the distributed hardness of the WM and numerical analysis.

2. Experimental Procedure

2.1 Base materials

As base materials, steel sheet with four kinds of strengths were prepared. The tensile properties of the base materials in accordance with JIS No. 5 specimens are shown in Table 1. And carbon equivalent¹⁰⁾ (hereafter Ceq) of base materials shown at same table. The thickness of all sheets was 1.6 mm.

2.2 Conditions for bending specimens and measurement of hardness distribution

Same steel grade sheets were butt-welded for the bending test. Two types of welding methods were employed: plasma

Table 1 Chemical composition and mechanical properties of the specimens (R.D.).

Steel	Carbon equivalent (Ceq) /%	TS /MPa	EL /%
A	0.028	312	44.0
B	0.168	449	37.3
C	0.187	815	20.4
D	0.211	1014	17.0

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*²Corresponding author, E-mail: saito.dz5.masahiro@jp.nipponsteel.com

Table 2 Welding conditions.

Conditions	Plasma	Fiber Laser
Current /A	145–180	-
Output /kW	-	4.8
Welding speed /m min ⁻¹	0.7–0.9	8.0
Sealing gas	Ar100%	Ar100%
Flow speed of sealing gas /l min ⁻¹	10	10
Plasma gas	Ar + H ₂ 5%	-
Flow speed of plasma gas /l min ⁻¹	2.0	-

(a) Plasma-welded specimen (63 points)

(b) Laser-welded specimen (15 points)

Fig. 1 Measurement positions in the hardness test (Steel C).

welding and laser welding. The conditions for each welding method are shown in Table 2. In order to analyze the impact of WM hardness on bendability, the hardness distribution in WM was measured in the vicinity of the back face of the welded portions, that situated on the outside of the bend. The measurement sites are shown in Fig. 1. In total, 63 points for the plasma welded specimens, and 15 points for the laser welded specimens were measured. A Vickers hardness tester running with an indentation weight of 300 g was used for measuring the hardness distribution. In addition, laser welded specimens remarkably more under fillings were generated than plasma welded specimens, as shown at UF in Fig. 1(b). To examine the effects due to the surface configuration of the WM, specimens that were ground to a plate thickness of 1.1 mm with both surfaces flattened were prepared, and compared with as-welded specimens by bending test.

2.3 Bending test conditions

The dimension of the die for the bending test is shown in Fig. 2. A specimen dimension was 30 mm width and 50 mm length. The WL in TWBs is often used in structures having the bend in the direction perpendicular to the WL. In this test also, the WL was placed at perpendicular to the bending ridge line of the punch. As shown in Fig. 1, because the WL had a different width between the front and back of the specimens, the all bending tests were conducted with back side at the time of welding faced to the die-side. The 13 kinds of bending punch were prepared for bending test. Test was conducted three times for each bending radiuses R_p of the

Fig. 2 Model of the bending test.

Table 3 Specimens and bending test conditions.

Materials	Steel A, B, C and D
Surface treatment	As-welded and Surface-milled
Welding method	Plasma and Fiber Laser
Punch radius R_p /mm	0, 0.2, 0.5, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 6.0, 8.0, 15 and 20

Fig. 3 Stress-strain curves for the FEM analysis (Steel C).

punch ridge line. The specimens and bending test conditions are shown in Table 3.

2.4 Conditions for numerical analysis

The impacts of the WL width on bendability were verified by numerical analysis. The FEM code LS-DYNA of the dynamic explicit method was used for the analysis. The J₂F model for the plastic flow rule and Hill's 1948 anisotropic yield function assuming planar isotropy were adopted for material models. The flow curve of the BM was approximated the Swift type work hardening law from tensile test results of the BM. The flow curves of the WL was approximated the Swift type work hardening law from small tensile test of laser welded specimens.¹¹⁾ The flow curves are shown in Fig. 3 for the BM and WM of steel grade C used in the numerical analysis.

Coulomb's friction was assumed to occur between the specimen models and tools at a frictional coefficient of 0.10. The mesh size of specimen model was 0.5 mm. The specimen model had solid element of a hexahedron with 8 nodes. The number of division in the plane thickness direction was three. Each model of the laser welded specimens and plasma welded specimens had a WL width of 1 mm and 3 mm,

Fig. 4 Results of the bending test (As-welded).

(a) Plasma-welded metal (Steel B)

(b) Laser-welded metal (Steel B)

Fig. 5 Fractures in the WM.

respectively. The overall dimension of a specimen was decided to be 30 mm in width and 50 mm in length match with the experimental conditions. Please note that numerical analysis was performed under bending conditions without cracks in the experiments, and formability was evaluated in terms of the strain on the superficial layer.

3. Results

3.1 Bending test results

The bending test results are shown in Fig. 4. The impact of Ceq on bendability was compared. The vertical axis is the ratio of the minimum radius R_p at the tip of the bending punch that allowed forming without crack to the sheet thickness t of WL. The horizontal axis is the Ceq of the specimens. For steel grade A with a Ceq of 0.028%, bending at $R_p = 0$ was succeeded for both welding methods, and bendability decreased as Ceq increased. In particular, this trend remarkably appeared in the case of plasma welding. The formation of cracks in the laser welded specimens and plasma welded specimens with steel grade B is shown Fig. 5. All cracks were generated in the WM.

3.2 Measurement results of the hardness distribution

In steels with Ceq of 0.16 (steel grades B, C, and D) or more, there was a difference in the hardness distribution between the plasma welded specimens and laser welded

specimens. The hardness distribution in the WL of steel grades B, C, and D is shown in Fig. 6. The plasma welded specimens show a large dispersion in hardness distribution, and the higher the Ceq, the larger the average hardness. On the other hand, the laser welded specimens have less dispersion in hardness distribution. There is little difference in average hardness by Ceq.

3.3 Effects of surface configuration

The specimens of high Ceq steel grades C and D indicated a difference in the bendability by the welding method. Figure 7 is shown the appearance bending specimens “as-weld” and “Surface-milled”. Figure 8 is shown the impacts of the superficial behavior on the bendability. Because grinding sheet was varied thickness, the bendability was evaluated the strain on the outer superficial layer of the bend that using uniform bending theory. In all of the steel grades, the bendability was almost invariant irrespective of surface treatment, and no impacts of surface configuration were confirmed for bendability.

4. Discussions

4.1 Impacts due to the homogeneity of the WM texture

According to Yamazaki *et al.*,¹²⁾ the standard deviation of hardness can be used as an index of homogeneity of the texture of steel plates. In the case of lower the standard deviation in hardness, the higher the homogeneity of texture and bendability. For this reason, the standard deviation of the hardness of the WM was regarded as the indicator of homogeneity of the WM texture, and the correlation with the bendability of the WM was examined. The relationship between the bendability in steel grades B, C and D and average hardness of the WM, and that between the bendability and standard deviation of hardness are shown in Figs. 9 and 10, respectively. The higher the Ceq, the smaller the difference in average hardness between the plasma welded specimens and laser welded specimens. When paying attention to the plasma welded specimens alone, lower average hardness and larger standard deviation of hardness in the case of better bendability. In general, steel texture with lower Ceq is harder to transform into martensite. Thus, the textures other than martensite were considered that has ductility of WM. Therefore, in the case of lower Ceq, because WM has hard texture and ductility texture, the standard deviation of hardness is predicted higher. However, from the results of laser welded specimens, there was small difference in the average hardness between the steel grades, and no impacts of the average hardness on bendability were observed. There was small difference in the average hardness between the steel grades, and no impacts of the average hardness on bendability were observed. In past study,³⁾ the relationship between the hardness and texture of the WM by the similar laser welding conditions of this study has indicated. Martensite textures have identified even in the WM softer than that of steel grades B, C, and D. Accordingly, it is considered that the WM on the welding of steel grade B, C and D in this study would have transformed into martensite with irrespective of the carbon equivalent. When seeing for each steel grade, the average hardness of the laser welded

(a) Plasma welding (Steel B)

(b) Laser welding (Steel B)

(c) Plasma welding (Steel C)

(d) Laser welding (Steel C)

(e) Plasma welding (Steel D)

(f) Laser welding (Steel D)

Fig. 6 Hardness distribution of the WM.

Fig. 7 Specimens for evaluation of the surface conditions (Steel C).

Fig. 8 Effect of the surface condition on bendability.

specimens is larger or equal to that of the plasma welded specimens, and no evident relationship can be identified between bendability and average hardness. The standard

Fig. 9 Relationship between the average hardness and the ratio of bending radius to WM thickness.

deviation of hardness in the laser welded specimens is smaller than that in the plasma welded specimens, and the specimens with smaller standard deviation of hardness showed better bendability in all steel grades. From this, it was thought that how the texture of the WM affects bendability is primarily depend on the standard deviation of hardness rather than by the average hardness of the WM.

In order to clear influence of the mechanical properties of the WM by each welding methods, the total elongation and reduction of area obtained from the micro tensile tests¹¹⁾ of the WM for each welding method in steel grade D were compared. The results are shown in Fig. 11. The micro tensile tests were performed three times each WM specimens.

Fig. 10 Relationship between the standard deviation of hardness and the ratio of bending radius to WM thickness.

Fig. 11 Total elongation and reduction in the small-scale tensile test.

Both the total elongation and reduction of area of the laser welded specimens showed a higher average value and a lower scattering. Because it can be surmised that high drawing of the laser welded specimens resulted from the homogeneity of the WM textures, and thus, this would be a factor that enhances bendability.

4.2 Impacts of the WL width

In a sheet bending, when the ratio of width to thickness is high, the bended portion is close to plane strain state. On the contrary, when the ratio is low, it is close to plane stress state. In this study, WL width of laser welded specimen was about 0.7 mm, and that of plasma welded specimen was about 3.0 mm. The deformation state of the WL surface depended on the WL width, because the WL width affected the bendability. Accordingly, in order to examine the impacts of the WL width on bendability, the strain distribution in the longitudinal direction and the strain distribution in the width direction on bending surface of the WL were compared by numerical analysis. Material properties of the WL part of numerical analysis used result of micro tensile tests of the laser welded specimens. Laser welded specimens and plasma welded specimens of steel grade C were simulated under the condition with a radius of curvature of 8 mm on the punch ridge line, which allowed forming without any cracks in all of the welding conditions. The analysis results of FEM simulation are shown in Fig. 12. Note that magnified figures of WL alone in the neighborhood of the respective vertexes of bending is shown as “Top of bent weld line”. The strain

(a) Model of the laser-welded specimen

(b) Model of the plasma-welded specimen

Fig. 12 Strain distribution at the top of bent weld line determined by FEM.

distributions in the longitudinal direction were similar regardless of welding method. On the other hand, the strain in the width direction of the laser model with a narrow WL width that simulated the laser welded specimens lower value than that of plasma model with a wide WL width.

The strain distribution in the bending superficial layer of an element close to a bending vertex is shown in Fig. 13. Only the plots near the vertex of the bent elements in the outer superficial layer of bending marked with the white squares for the models in the figure were extracted.

The maximum major principal strain ε_1 was about 0.068 in both models. On the other hand, the strain ratio of the plasma model exhibited a strain ratio that is closer to the plane strain than that of the laser model. A Hill's local necking limit line obtained from the material properties of the WM in the laser welded specimens used for the analysis, it is drawn in Fig. 13. When seeing the relation to the Hill's local necking limit line, the strain status of the plasma model is closer to the limit line than that of the laser model. Assuming that Hill's local necking limit line is the fracture limit during forming, when the variation in the maximum principal strain amount before reaching the Hill's local necking limit line is compared, it can be seen that the plasma model has an allowance of 0.005 and the laser model has an allowance of 0.010. The difference between both models is 0.005, it is considered to be extremely minor compared to the difference in the bendability (R_p/t) between the plasma welded

Fig. 13 Difference in strain distribution of the bending surface between the laser-welded specimen (narrow WL) and plasma-welded specimen (wide WL).

specimens and the laser welded specimens of steel grade C in Fig. 4.

5. Conclusions

Bending tests were performed in order to investigate the bendability of TWB that welded by leaser welding or plasma welding, factors improving bendability were researched from WL conditions, and the following conclusions were obtained.

- (1) Laser welded members have better bendability than plasma welded members.
- (2) The bendability of the WL in TWB was affected by the homogeneity of the WM textures and width of the WL, and it was found that higher homogeneity of the WM textures resulted in better bendability.
- (3) The impacts of the superficial behavior in the bend superficial layer of the WL on the bendability were small.
- (4) It was suggested that the strain status in the bent superficial layer depends on the WL width, and thus, the narrower the WL width, the better the bendability.

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