Laser Weldability of High Strength Steel Sheets in Fabrication of Tailor Welded Blanks

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A TWB (Tailor Welded Blank) consists of materials different in thickness, tensile strength, and other properties, and is now widely used for fabricating automotive bodies. TWBs are used not only to save materials and reduce cost in stamping and assembling, but also to improve fuel efficiency by reducing the weight of automobile bodies and to improve the stiffness. This report presents the results of an investigation for optimizing the quality of welds in differential thickness TWBs composed of 590 MPa class high strength steel sheets with large thickness ratios. The mechanical and fatigue properties and press formability of high strength steel TWBs are also reported.

1. Introduction

A TWB (Tailor Welded Blank) is composed of two or more sheets welded together, each of which may have different thickness, material properties, and surface treatment. The blank is subsequently stamped into various shapes. The use of TWBs at a mass production level was started in Europe (Germany) in the early 1980s, and thereafter the practical use expanded rapidly all over the world[1),2)].

Initially, TWBs were used mainly to reduce material consumption and cost. For example, several pieces of stamping scrap are jointed together, stamped again and reused as a new part for reducing material consumption. In the conventional parts manufacturing process, two or more stamped parts are spot-welded together to form a part. In the TWB stamping process, sheets are first welded together, and then integrally stamped into a part; in this way, the numbers of parts, welding steps, and press dies are reduced, and costs are reduced accordingly.

In recent years, demand is rising for lighter, stiffer automobile bodies to meet stricter environmental and safety regulations. Accordingly, the purpose of using TWBs is changing. In addition to the use of high strength steel sheets having the strength exceeding 590 MPa, a differential thickness TWB that has a thickness ratio as high as three has begun to be used.

At present, ISO and North American ASP (Auto-Steel Partnership) specify the TWB quality standards. These standards are for TWBs that use mild steel sheets and have relatively low thickness ratios. Currently, there are no quality standards for differential thickness TWBs that use high strength steel sheets.

This report presents the conditions required at welds of TWBs composed of high strength steel sheets with high thickness ratios. Further, from the viewpoint of material properties, basic characteristics such as mechanical and fatigue properties and press formability of TWBs having a tensile strength of 590 MPa or more were clarified.

2. Butt welding technology

Since material sheets joined by welding are stamped and used as automotive panels and parts, welds must satisfy the following requirements[2)].

(1) The weld has a uniform configuration as close to the base metal as possible.
(2) The weld strength exceeds that of the base metal.
(3) The press formability is close to that of the base metal.

Welded joint samples were fabricated by butt-welding two steel sheets with a gap between them to determine the conditions required of the weld from the viewpoint of the weld configuration, weld defects, and joint strength.

2.1 Experimental method

The materials used in the experiment are 270 and 590 MPa class steel sheets with a thickness of 0.8 to 2.9 mm. **Table 1** gives the chemical composition and mechanical properties of each steel sheet. **Table 2** lists the welding conditions.

Table 1 Chemical compositions and mechanical properties of materials used

TP no.	Thickness (mm)	C	Si	Mn	YS (MPa)	TS (MPa)	El (%)
CR270	0.8～2.9	0.001	0.01	0.17	171	296	53.8
CR590	1.2～2.3	0.072	0.02	1.61	383	630	28.5

Table 2 Laser welding conditions

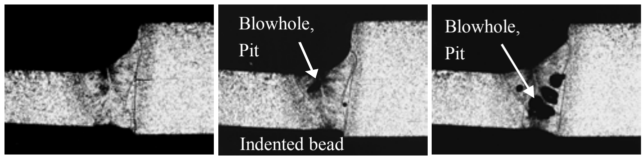
Kind of laser	CO_2 laser
Laser power	3kW
Welding speed	4m/min
Shieding gas	Ar 20 l/min

Welding was performed by irradiating the steel sheets with a CO_2 laser concentrated to about 0.6 mm by a ZnSe lens with a focal length of 254 mm. The CO_2 laser output and welding speed were set constant at 3 kW (working point output) and 4 m/min, respectively. Differential thickness butt-welded samples with thickness ratios of 1.0, 2.0 and 2.9 were fabricated with different gap widths of 0.1 to 0.4 mm between two sheets.

The quality of the welds was evaluated as follows. The uniformity of the weld width, and the surface quality such as the presence of underfill and pits (blowholes), were evaluated visually. The strength of a welded joint was evaluated by using JIS No.5 test pieces in which the weld line was positioned perpendicular to the load direction. Whether a weld had sufficient strength was judged from the fracture position. A longitudinal cross section was cut from a weld, and the appearance of the weld (bead irregularities), the presence of blowholes, and the Vickers hardness were examined. The Vickers hardness was determined by measuring the hardness of a weld at seven arbitrary points with a load of 100 gf, and obtaining the mean value.

2.2 Experimental results

Photo 1 shows some examples of weld cross sections evaluated in this experiment. When the gap width between two sheets was 0.1 mm, the weld exhibited good quality; there were no defects such as indentation, pits, or blowholes. When the gap width was set at 0.2 mm or wider, the amount of molten metal was insufficient, and the weld surface became indented. Weld defects such as blowholes and pits began to appear as well.



Gap width= 0.1mm Gap width=0.2mm Gap width=0.3mm

1mm

Photo 1 Cross section of laser weld of differential thickness TWB

Table 3 summarizes the results of evaluation. For example, in the case where the thickness of the thinner sheet is 1.0 mm and the thickness ratio is 1.0, the weld quality is good up to the gap width of 0.1 mm. When the gap width is wider than 0.1 mm, weld defects are produced. When the gap width is 0.3 mm, meltdown occurs, making welding impossible.

The limit of the gap width that provides a good-quality weld tends to increase with increasing sheet thickness and thickness ratio. This is because the amount of molten metal increases with the increase in sheet thickness and thickness ratio. The result of the 590 MPa class material is the same as that of the 270 MPa class material. Thus, material properties did not appear to have an influence in the range of this experiment.

Table 3 Quality of laser welds

Tensile strength of base metal, MPa	Thinner gauge, mm	Thickness ratio	Gap width, mm 0.1	0.2	0.3	0.4
270	0.8	1.0	Good	No good (Fracture in WM and pits in WM)	No good (melt down)	No good (melt down)
		2.0	Good	No good (Fracture in WM and pits in WM)	No good (Fracture in WM and pits in WM)	No good (melt down)
		2.9	Good	Good	No good (Fracture in BM and pits in WM)	No good (Fracture in WM and pits in WM)
	1.0	1.0	Good	No good (Fracture in BM and pits in WM)	No good (melt down)	No good (melt down)
		2.0	Good	No good (Fracture in BM and pits in WM)	No good (Fracture in WM and pits in WM)	No good (melt down)
		2.9	Good	Good	No good (Fracture in WM and pits in WM)	No good (Fracture in WM and pits in WM)
	1.2	1.0	Good	No good (Fracture in BM and pits in WM)	No good (melt down)	No good (melt down)
		1.9	Good	Good	No good (Fracture in BM and pits in WM)	No good (Fracture in WM and pits in WM)
590	1.2	1.0	Good	No good (Fracture in BM and pits in WM)	No good (melt down)	No good (melt down)
		1.9	Good	Good	No good (Fracture in BM and pits in WM)	No good (Fracture in WM and pits in WM)

Good (Fracture in BM and no pits in WM)
No good (Fracture in BM and pits in WM)
No good (Fracture in WM and pits in WM)
No good (melt down)
* BM : Base metal, WM : Weld metal

Fig.1 shows the relation between the gap width (G) and weld thickness ratio (T_w/T_1). The plotted marks indicate whether the weld quality is good (open marks) or not (solid marks). T_{av} designates the average sheet thickness in a differential thickness welded joint. The figure indicates that the weld thickness ratio decreases with increasing gap width. When the weld thickness ratio is about 0.8 or higher, no defect is produced, and a weld having a higher strength than that of the base metal is obtained regardless of the average sheet thickness and material properties.

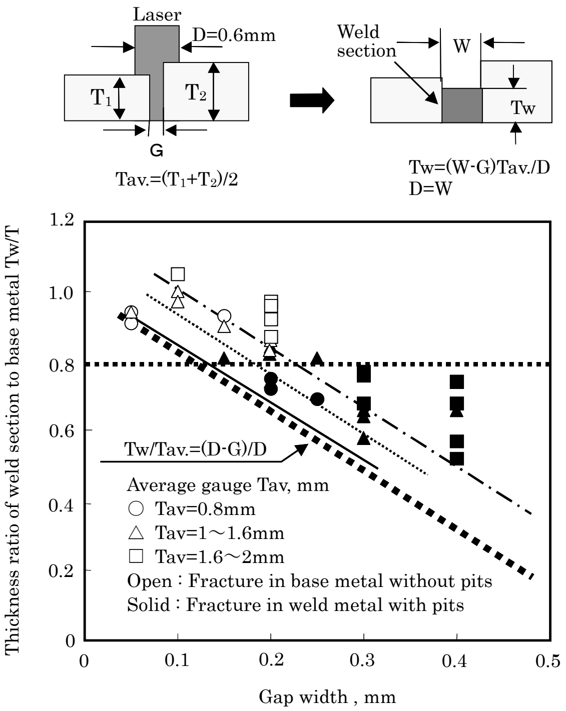


Fig.1 Relation between laser welding configuration and weld quality

3. Laser weldability of high strength steel sheets

3.1 Experimental method

3.1.1 Specimen and welding conditions

The 270, 590, 780 and 980 MPa class high strength steel sheets were used as specimens for evaluating the laser weldability of high strength steel sheets. **Table 4** shows the chemical composition and mechanical properties of each specimen. **Table 5** gives the welding conditions. Welding was performed by irradiating steel sheets with a CO_2 laser concentrated to about 0.7 mm by a copper parabolic mirror with a focal length of 254 mm. In the standard condition, the CO_2 laser output and welding speed were set constant at 6 kW (working point output) and 7 m/min, respectively. Additional samples were fabricated by laser welding under the comparative conditions of a CO_2 laser output of 3 kW (working point output) and a welding speed of 4 m/min. Further, additional samples were fabricated by mash seam welding.

Table 4 Chemical compositions and mechanical properties of materials used

TP no.	Thickness (mm)	C	Si	Mn	YS (MPa)	TS (MPa)	El (%)
CR270	0.97	0.001	0.01	0.17	171	296	53.8
CR590	1.40	0.072	0.02	1.61	383	630	28.5
GA780	1.21	0.055	0.207	2.45	584	891	18.0
CR980	0.99	0.110	1.320	1.90	848	1037	15.5

Table 5 Laser welding conditions

Kind of laser	CO_2 laser
Laser power	6kW
Welding speed	7m/min
Shieding gas	Ar 20 l/min

Comparative examples : CO_2 laser 3kW-4m/min and mash seam welding

3.1.2 Evaluation method

The hardness distribution in the vicinity of welds was examined by the same method as the hardness measurement described in Section **2.1**.

The mechanical properties of welds were examined by conducting a uniaxial tensile test using JIS No.5 test pieces. The weld lines were set parallel and perpendicular to the tension direction (hereinafter referred to as "parallel tension" and "perpendicular tension"). The fatigue properties of welded joints were evaluated by applying perpendicular tension to JIS No.5 tensile test pieces. An electro-hydraulic servo fatigue-testing machine was employed for this fatigue test. Load-controlled pulsating tension (stress ratio R < 0.1) was applied at a frequency of 20 Hz. The formability of welded joints was evaluated by fracture position and fracture height in plane stretch forming by a hemispherical punch of 100 mm in diameter.

3.2 Experimental results

3.2.1 Hardness of welds

Fig.2 shows the hardness distribution in the vicinity of welds. A material having a higher tensile strength has a higher hardness in the weld because it contains larger amounts of alloying elements such as carbon, silicon, and manganese.

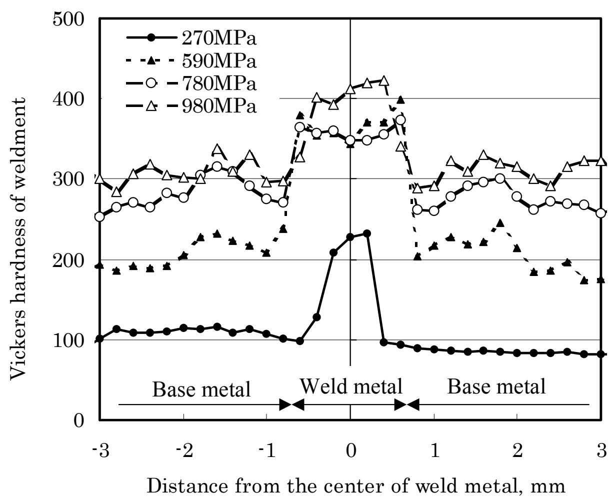


Fig.2 Vickers hardness distributions of laser welded joints (laser power: 6 kW, welding speed: 7 m/min)

Fig.3 shows the hardness distribution in the vicinity of welds of samples fabricated using the 980 MPa class material by laser welding under the comparative conditions of 3 kW and 4 m/min and by mash seam welding. Comparing the results obtained under the standard condition (6 kW, 7 m/min) with those under the comparative condition (3 kW, 4 m/min), the widths of welds and HAZ (Heat-Affected Zones) are apparently wider under the comparative condition than under the standard condition. This result suggests that the weld heat input is higher under the comparative condition. The weld heat input Q (cal/min) is the heat input per unit length of a weld line, and is defined by $Q = P/v$, where P is the laser output and v is the welding speed.

According to this definition, the standard condition and comparative condition would provide a heat input of the same level. However, the heat input is not necessarily equal to $Q = P/v$ in laser welding. This is probably because laser welding progresses while the laser beam penetrates through the sheet thickness, therefore, laser energy is lost from the rear side of the sheet. Rather, in laser welding, the weld heat input is inversely proportional to the welding speed. The 980 MPa class material is composed of ferrite and martensite, and martensite is softened by the weld heat cycle in the vicinity of the weld.

The weld heat input becomes progressively higher in order from standard condition laser welding, to comparative condition laser welding, and to mash seam welding. Accordingly, the softened amount becomes larger, and thus the softened region becomes wider in this order.

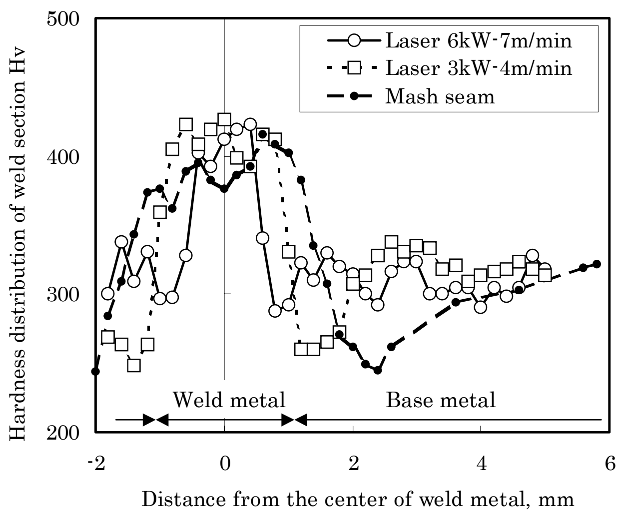


Fig.3 Vickers hardness distributions of laser and mash seam welded joints

The strength and elongation of welded joints are closely related to the hardness of welds. Therefore, in order to control the hardness of laser welds, the carbon equivalent Ceq(laser)[3] for laser welding was obtained by regression analysis.

$$\text{Ceq (laser)} = C + Si/50 + (Mn + Cr)/25 + P/2 \quad \cdots\cdots(1)$$

Fig.4 shows the relation between Ceq (laser) and the hardness of laser welds. This figure verifies that the hardness of laser welds is estimated accurately by Ceq (laser).

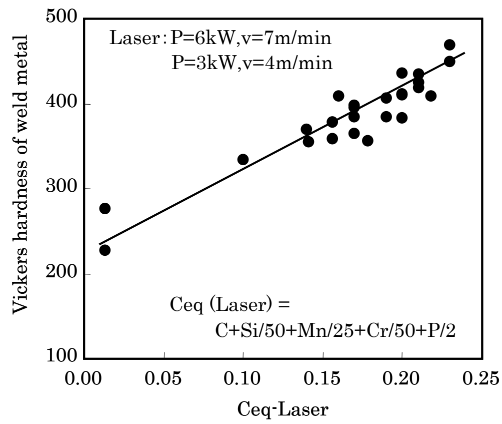


Fig.4 Relation between Ceq (laser) and Vickers hardness of laser welds

3.2.2 Mechanical properties of welded joints

Fig.5 shows the relation between the tensile strength of base metal and the total elongation of welded joints when perpendicular tension is applied. As the tensile strength of base metal increases, the total elongation of base metal decreases. The total elongation of welded joints becomes lower than that of the base metal. The elongation of welded joints decreases because the deformation in the width direction is restrained by the significantly increased hardness of welds. For materials having a tensile strength of up to 780 MPa, the decrease in the elongation of welded joints is approximately equal regardless of welding conditions. For materials having a tensile strength of 980 MPa, the elongation of welded joints decreases more under the comparative conditions (3 kW, 4 m/min) than under the standard conditions (6 kW, 7 m/min). This is because the heat-affected zone is softened, so that deformation (strain) concentrates in this zone, therefore the elongation decreases.

Mash seam welding provides higher weld heat input than laser welding. Therefore, the heat-affected zone is softened even in the 590 MPa class material, and the elongation of welded joints decreases. The elongation of welded joints further decreases in the 980 MPa class material.

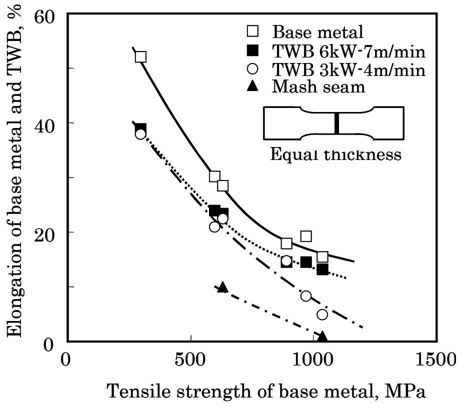


Fig.5 Relation between tensile strength of base metal and elongation of TWB

Fig.6 shows the relation between the sum of weld metal hardness and base metal hardness and the total elongation of welded joints when parallel tension is applied. It is apparent that the total elongation under parallel tension and the sum of weld metal hardness and base metal hardness is are related.[4)] The reason is thought to be as follows. A crack starts from the weld that is harder than the base metal and propagates to the base metal, so generally, the elongation of welded joints is determined by the hardness of the weld. However, the width of a laser weld is so narrow that the elongation of welded joints is affected not only by the weld hardness but also by the base metal hardness.

For differential thickness welded joints, the deformation of the weld over the step between two sheets is also restrained by the restraint on the deformation of the thicker sheet, so the decrease in elongation is relaxed in some cases.

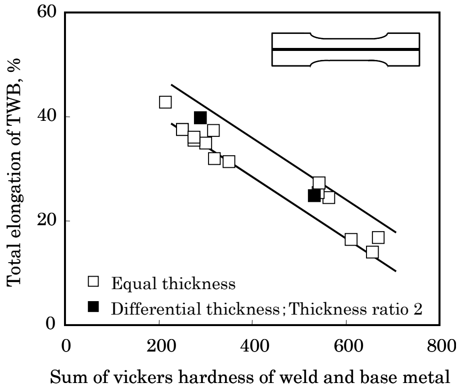


Fig.6 Relation between hardness of weld and base metal, and elongation of TWB

3.2.3 Fatigue properties of welded joints

Fig.7 is a $\Delta\sigma$-Nf diagram for equal thickness and differential thickness joints when perpendicular tension is applied. The fatigue strength of the equal thickness and differential thickness joints is lower than that of the base metal. This tendency is more noticeable as the thickness ratio increases, and also in a long fatigue life region where the number of cycles to fracture is 10^6 or larger. For the differential thickness joint, fracture occurred in the weld on the thinner sheet side without exception. In this case as well, because the strength of the weld increases, the fatigue deformation concentrates in the base metal on the thinner sheet side that has lower strength and hardness. Thus, a significant stress concentration takes place in the stepped weld area, leading to fracture in this region. This is thought to be the reason why differential thickness joints have lower fatigue strength than equal thickness joints[4)].

Mash seam welded joints have lower fatigue strength than laser welded joints. A crack started from the edge of the lapped area and propagated in the sheet thickness direction. It is apparent that the fatigue strength decreases because of the stress concentration at the edge of the lapped area.

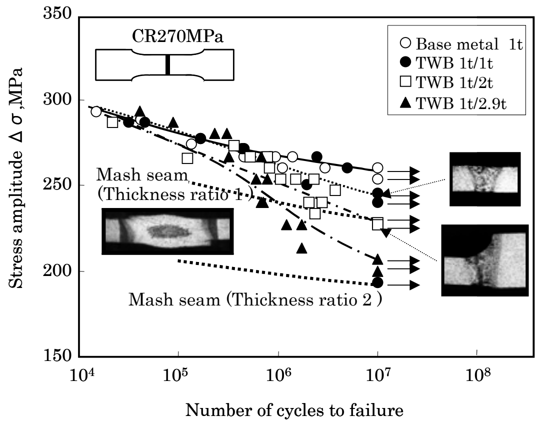
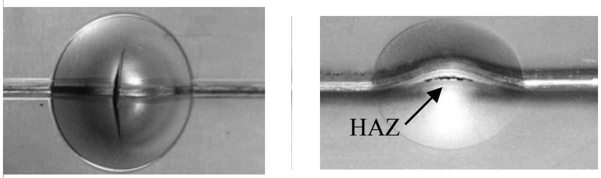


Fig.7 S-N diagram for differential thickness TWB and base metal

3.2.4 Press formability of welded joints

Photo 2 shows fracture positions obtained by Erichsen tests on welded joints of the 980 MPa class material. Under the standard conditions (6 kW, 7 m/min), a crack started from the weld and propagated to the base metal. In contrast, under the comparative conditions (3 kW, 4 m/min), a crack started from the heat-affected zone. This is because, in the 980 MPa class material, the high weld heat input softens the heat-affected zone as shown in **Fig.3**, and strains concentrate there, leading to fracture. Since the 590 MPa and 780 MPa class materials are not softened at the heat-affected zone under either the standard condition or comparative condition, none of their test pieces fractured at the heat-affected zone.



P=6kW,v=7m/min P=3kW,v=4m/min
CR980MPa 1.0t

Photo 2 Erichsen stretch test results of high strength TWB

4. Conclusions

With regard to mild steel sheets and high strength steel sheets, conditions required at welds of differential thickness joints (thickness ratio up to three) and basic characteristics such as mechanical and fatigue properties and press formability of welded joints were clarified. The main conclusions obtained are as follows:

(1) Conditions required at welds

The weld thickness ratio T_w/T_1 must be kept at 0.8 or higher regardless of material properties and sheet thickness ratios, where T_w is the thickness of the weld, and T_1 is the thickness of the thinner base metal.

(2) Laser weldability of high strength steel sheets

The hardness of laser welds is estimated accurately by the carbon equivalent formula for laser welding.

$$Ceq\ (laser) = C + Si/50 + (Mn + Cr)/25 + P/2$$

The elongation of welded joints under perpendicular tension becomes lower than that of the base metal because the deformation is restrained by the increased hardness of welds. When the weld heat input is high and thus the heat-affected zone is softened, strain concentrates in the softened zone, and the elongation significantly decreases.

The strength of welded joints under parallel tension becomes higher than that of the base metal, but the elongation thereof becomes lower because the weld is harder than the base metal. The elongation of weld joints is estimated systematically by the sum of weld metal hardness and base metal hardness.

The fatigue strength of welded joints is lower than that of base metal regardless of equal thickness or differential thickness welded joint. Also, as the thickness ratio increases for the differential thickness joints, the fatigue strength becomes low.

The formability of welded joints is inferior to that of the base metal because the weld is hard. When the weld heat input is high and thus the heat-affected zone is softened, the formability decreases further.

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