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Tensile Shear Strength of Laser Welded Lap Joints

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Abstract

The dependency of fracture position and maximum load of laser welded lap joints on the weld-bead length and width was clarified through tensile shear test of joints, and a mechanical prediction model for the test results was developed. Joints showed the strength proportional to base metal tensile strength, which have the weld length over 60% of specimen width or the weld width of 2 times of sheet thickness. The developed model, which considers a joint dividing it into the base metal under uniaxial tensile stress, a portion R under stretch bending and the weld metal under shear stress, proved capable of qualitatively predicting the fracture behavior of laser welded lap joints of mild steel sheets at tensile shear test.

1. Introduction

Resistance spot welding has long been employed as a principal welding method for assembling automobile bodies, but some carmakers, mainly in Europe, recently use laser welding in place of resistance spot welding[1,2]. Laser welding is a non-contact welding method and capable of joining materials by one-side access. While the European carmakers reportedly find laser welding economically advantageous because the electrode wear of spot welding can be avoided, they do not seem to fully enjoy the benefits of laser welding such as easy connection of hydro-forming parts and other closed-section components and higher joint strength due to continuous welding. A reason for this is presumably that the application of laser welding is generally limited to those portions where spot welding can be used as a backup in the case of a trouble with laser welding, and another is that the advantages of continuous welding by laser are not very clear.

Furthermore, unlike spot-welding joints, laser-welding joints are not axisymmetric, and many variables such as weld length, bead width and welding direction affect the strength of a joint of laser welding, and for this reason, the withstand load of a laser-welding joint has not been clear. In view of this, the authors already proposed a method for estimating the strength of laser welded lap joints[3]. In the present study, the authors partially reviewed the regression analysis employed for the estimation, and attempted to express the relationship between the size of a weld bead and joint strength in a simplified manner.

2. Shear Strength of Laser Welded Lap Joints

2.1 Experimental procedure

An experimental examination was conducted on the tensile shear strength of laser welded lap joints. **Table 1** shows the mechanical properties of the steel sheets employed in this study; the sheet thickness was 1 mm and their tensile strength varied from 300 to 800 MPa. **Fig. 1** schematically shows the test piece for the tensile shear test. An Nd-YAG laser having a work-piece power of 1.6 kW was used for welding the test pieces. To examine the effects of the bead size on joint strength, the weld length and width were changed by welding across the whole width of the test pieces or partially (weld lengths L_b of 50 and 30 mm, respectively) and setting the welding speed at 1.6 and 0.7 m/min (weld widths W_b of 0.85 and 2 mm, respectively). **Table 2** summarizes the welding conditions.

Table 1 Mechanical properties of steels used

Steel	Thickness (mm)	YP (MPa)	TS (MPa)	Elongation (%)
A	1	142	301	49
B	1	339	472	34
C	1	392	629	33
D	1	435	794	24

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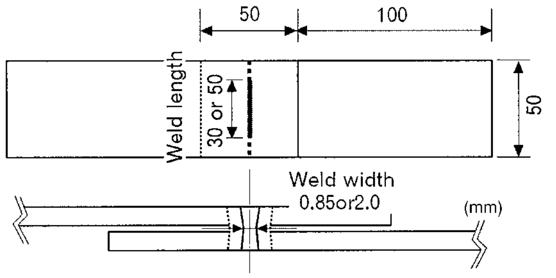

Fig. 1 Schematic diagram of laser lap joint for tensile shear test

Table 2 Welding conditions for tensile test specimens

Beam source	2kW Nd-YAG laser
Laser power at work (kW)	1.6
Focal position	Surface of upper sheet
Beam waist diameter (mm)	0.5
Welding speed (m/min)	0.7, 1.6
Weld width on sheets interface W_b (mm)	2, 0.85
Weld length L_b (mm)	30, 50

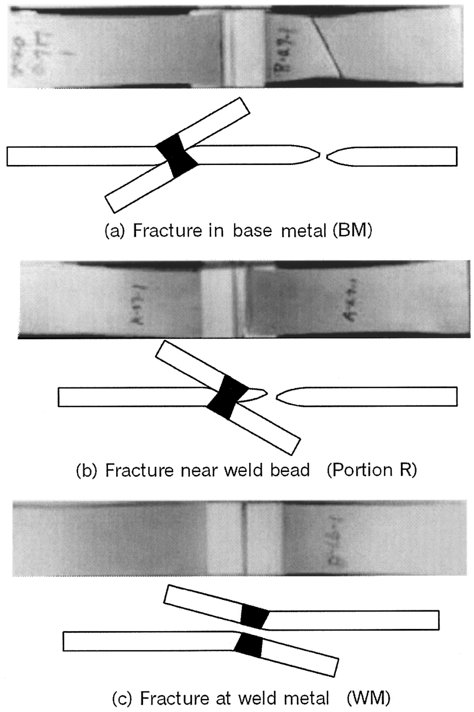

Fig. 2 Fracture mode of laser lap joint in tensile shear test

The tensile shear test was conducted at room temperature and at a constant tension speed of 10 mm/min, and the maximum withstand load of each weld joint was measured. To examine the deformation of the test pieces, some of them were loaded to withstand load, the load was removed before failure, and the deformation around the weld joint was recorded through sectional observation.

2.2 Tensile test results

In the tensile shear test of laser welded lap joints, fracture occurred at the base metal (BM), weld metal (WM) or portion adjacent to the weld joint (herein referred to as the portion R). **Fig. 2** shows the photographs of test pieces after fracture at different portions and schematic illustrations of the fracture portions, and **Fig. 3** shows the relationship between the maximum load that the lap joints withstood before fracture (hereinafter written as the joint strength) and the strength of the base metal. The dotted line of the graph shows the product of the tensile strength (TS) and sectional area of the base metal, namely the maximum withstand load of a joint in the case of fracture at the base metal (hereinafter written as the base-metal strength insofar as it is not confused with the tensile strength of the base metal).

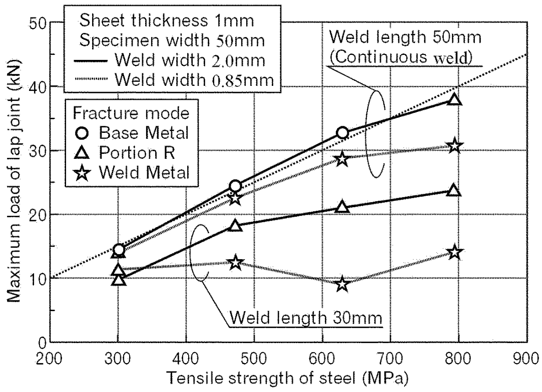

Fig. 3 Dependency of laser lap joint strength on tensile strength of steel

As Fig. 3 shows, when the weld width was 2.0 mm and the weld length was 50 mm across the whole width of the test piece, the fracture occurred at the base metal or portion R, and the joint strength was the same as the base-metal strength. In contrast, when the weld width was 0.85 mm and the weld length was 50 mm, the weld metal failed except for the test pieces of Steel A, the joint strength increased as the base-metal strength increased, and the joint strength did not decrease significantly below the base-metal strength. On the other hand, the test pieces of Steel A failed at the portion R, and the joint strength was equal to the base-metal strength.

When the bead width was 2.0 mm and its length was 30 mm, all the test pieces failed at portion R, and the joint strength increased as the base-metal strength increased. In contrast, when the bead width was 0.85 mm and the length was 30 mm, the weld metal failed except for the test pieces of Steel A, but different from the cases where the weld length was 50 mm, the joint strength was nearly the same, not depending on the base-metal strength. The test pieces of Steel A failed at the portion R even though the bead width was as small as 0.85 mm.

2.3 Deformation under load

Part (a) of **Fig. 4** shows a sectional view of a test piece deformed under a tensile load; the base metal is Steel A and the weld joint is 2.0 mm wide and 50 mm long. Before application of a tensile load, the thickness center planes of the two sheets were out of alignment from each other, but under a tensile load, the test piece underwent a torque about the weld metal. When the tensile load increased, the deformation increased such that the thickness center planes of the two sheets aligned with each other. On the other hand, the test piece shown in the lower frame of part (b) of Fig. 4, which had a weld width of 0.85 mm, failed at the weld metal before the thickness center planes of the two sheets were aligned with each other.

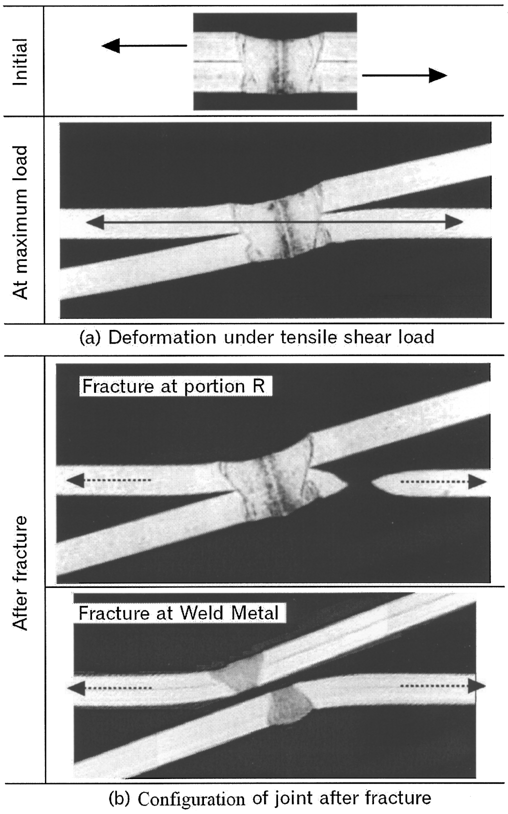

Fig. 4 Deformation of lap joint under tensile shear load and configuration after fracture, through cross-section of joint

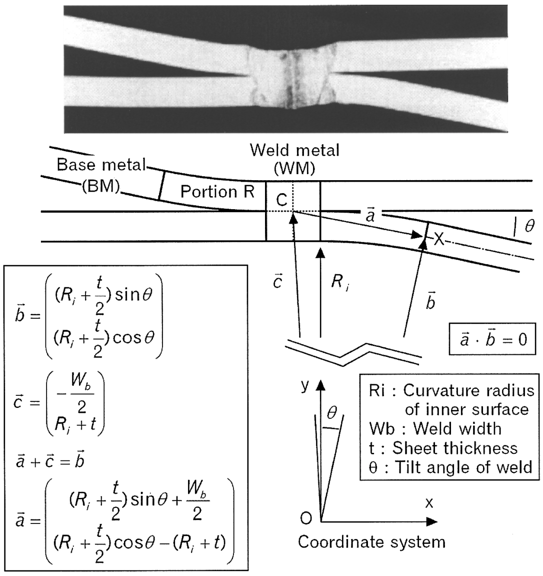

Fig. 5 Simplified model of joint and geometric demand for configuration

3. Mechanical Model of Stresses in Laser Welded Lap Joints under Tensile Shear Test

Although it is possible to experimentally determine the strength of joints having different weld lengths, weld widths and sheet widths, it is a tiresome and time-consuming business. In view of this, an attempt was made to construct a model to estimate the strength of a weld joint in consideration of the stress imposed on the joint by a tensile load.

3.1 Modeling of stresses at different portions of joint

The deformation of a joint shown in Fig. 4 (a) indicates that such a deformation can be studied dividing a joint under a tensile load into three portions: the weld metal, portion R and base metal shown in **Fig. 5**. The stress in each of these portions under a certain load can be estimated by studying it in a simple manner separated from that in the other portions.

3.1.1 Stress imposed on base metal

When the bead length and width are sufficiently large and the fracture occurs at a position away from the weld metal as shown in Fig. 2 (a), the base metal is considered to be under a uniaxial tensile stress just like a single-sheet test piece at tensile test. Under an outside force T, therefore, the stress imposed on the base metal σ_B can be estimated using the following equation:

$$\sigma_B = \frac{T}{W_s \cdot t} \qquad (1)$$

where, W_s is the width of the specimen, and t is its thickness.

We introduce a dimensionless parameter β according to Equation (2), which is the ratio between the stress on the base metal σ_B and the base metal strength TS_{BM}:

$$\beta = \sigma_B / TS_{BM} \qquad (2)$$

Here, the value of β changes from 0 to 1, and the joint fails at the base metal when the stress increases to $\beta = 1.0$.

Eliminating the stress σ_B from Equations (1) and (2), the outside force T can be expressed as follows using the dimensionless parameter β, which expresses the magnitude of the load:

$$T = \beta \cdot TS_{BM} \cdot W_s \cdot t \qquad (3)$$

3.1.2 Stress imposed on portion R

Here, let us simplify the portion R as being in a tension bending condition as shown in **Fig. 6**. This seems to be an adequate approximation as far as the center of the portion R is concerned,

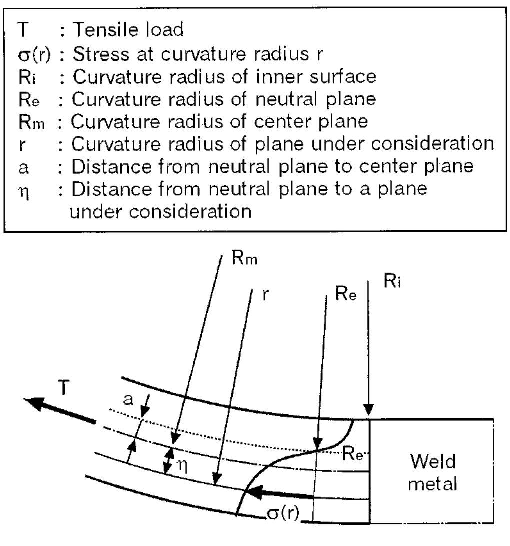

Fig. 6 Definition of parameters at portion R

excluding its interfaces with the base metal and weld metal. With respect to the case shown in the upper frame of Fig. 4 (b) where a joint fails at a position in the curved portion (portion R) a little away from the weld metal, this simplification would be adequate for a model for predicting the position of fracture.

Following a common analysis method of bending deformation, we suppose a neutral plane where there is no tension or compression: there is a compressive stress on the inner side of it and a tensile stress on the outer side.

Letting the curvature radius of the neutral plane be R_e, the circumferential strain $\varepsilon(r)$ at a plane away from the curvature center by a distance r is given as follows:

$$\varepsilon(r) = \frac{r \cdot \theta - R_e \cdot \theta}{R_e \cdot \theta} = \frac{r - R_e}{R_e} \tag{4}$$

In addition, the relationship between the curvature radius R_i of the inner surface of the portion R, the curvature radius R_e of the neutral plane and the distance a between the neutral plane and the thickness center shown in Fig. 6 is given by the following equation:

$$R_e = R_i + t/2 - a \tag{5}$$

Furthermore, using a relational expression frequently applied to the relationship between stress and strain, the relationship between the circumferential stress $\sigma(r)$ and strain $\varepsilon(r)$ is given as follows:

$$\sigma(r) = F \cdot \varepsilon^n(r) \tag{6}$$

where, F is the modulus of longitudinal elasticity, or Young's modulus, and n is a work hardening coefficient.

Based on the above and supposing that the integration of the circumferential stress in the portion R is equal to the tensile load T, the following equation can be obtained.

$$T = L_b \int_{R_i}^{R_i+t} \sigma(r)\, dr \tag{7}$$

where, L_b is the weld length. This integration is easily carried out by using Equations (4), (5) and (6), and the following equation is obtained:

$$T = \frac{L_b \cdot F}{n+1} \left(\frac{1}{R_e}\right)^n \left\{ \left(a + \frac{t}{2}\right)^{n+1} - \left|a - \frac{t}{2}\right|^{n+1} \right\} \tag{8}$$

Here, the thickness t was assumed not to change under the deformation.

The value of $\sigma(r)$ becomes largest at the outer surface, and the largest value σ_R is given as follows:

$$\sigma_R = F \cdot \left(\frac{t/2 + a}{R_i + t/2 - a}\right)^n \tag{9}$$

A joint is expected to fail at the portion R when the value of σ_R reaches the tensile strength TS_R determined by the material quality of the portion R.

3.1.3 Stress imposed on weld metal

In the case where a joint fails at the weld metal, as shown in Fig. 4 (b), the weld metal fails by shear fracture without significant deformation. The average shear stress τ imposed on the weld metal under a tensile load T is expressed by Equation (10) below.

$$\tau = \frac{T \cos\theta}{L_b \cdot W_b} \tag{10}$$

$$= \frac{\beta \cdot TS_{BM} \cdot W_s \cdot t}{L_b \cdot W_b} \cos\theta \tag{11}$$

where, θ is the tilt angle of the weld joint resulting from the tensile load shown in **Fig. 7**, and W_b is the weld width as measured between the two sheets. The dimensionless parameter β, which expresses the magnitude of the load in Equation (3), was used for the modification from Equation (10) to Equation (11).

While shear stress is estimated at $1/\sqrt{3}$ times tensile strength, tensile strength TS is known to be in good correlation with Vickers hardness Hv, and when stress is expressed in terms of MPa, the relationship between these two is expressed as $TS = Hv/3 \times 9.8$. Therefore, when the hardness of weld metal Hv_{WM} is given, it is possible to estimate the maximum shear stress τ_{max} that the weld metal can withstand by the following equation:

$$\tau_{max} = TS_{WM}/\sqrt{3} = \frac{Hv_{WM}/3 \times 9.8}{\sqrt{3}} = 1.9 \cdot Hv_{WM}\ (\mathrm{MPa}) \tag{12}$$

A joint is expected to fail by shear fracture of weld metal when the shear stress τ given by Equation (11) becomes equal to the maximum shear stress τ_{max} given by Equation (12).

To estimate the shear stress τ imposed on weld metal based on Equation (11), however, it is necessary to know the tilt angle θ.

3.1.4 Relationship between tensile load and tilt angle of test piece

Let us suppose that, in Fig. 5, the weld metal, portion R and base metal connect to each other smoothly, that is, the boundary lines between the portion R and base metal are perpendicular to the direction of the tensile load. Here, it is easy to calculate the vector $\vec{a}$ from the weld center C to the thickness center X on the boundary line between the portion R and base metal and the vector $\vec{b}$ from the curvature center O of the portion R to the point X. These two vectors are perpendicular to each other when the deformation is well advanced and the thickness centers of the two sheets are aligned with each other. This geometrical demand is expressed as follows using the vector $\vec{c}$ from the curvature center O to the weld center C:

$$\vec{a} \cdot \vec{b} = (\vec{b} - \vec{c}) \cdot \vec{b} = \left(R_i + \frac{t}{2}\right) \cdot \left\{(1 - \cos\theta) \cdot R_i + \frac{t}{2} + \frac{W_b}{2} \sin\theta - t\cos\theta\right\} = 0$$

Since $R_i + t/2$ is positive, the following equation is obtained:

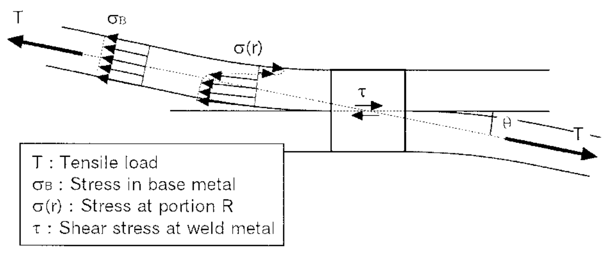

Fig. 7 Stress state at each part of joint

$$R_i = \frac{t\cos\theta - \frac{t}{2} - \frac{W_b}{2}\sin\theta}{1-\cos\theta} \tag{13}$$

As is clear from Equation (13), the larger the weld width W_b, the smaller the curvature radius R_i is expected, with the same tilt angle θ.

Laser welded lap joints of the steels shown in Table 1 were subjected to tensile test, applied a tensile load to cause a sufficiently large rotational deformation, removed the load, and measured R_i and θ through sectional observation. The relationship between these two is plotted in **Fig. 8**. The curves in the graph are the relationship between the two calculated from Equation (13). It is clear from the graph that the experimentally obtained relationship between R_i and θ agrees well with that calculated from Equation (13), which represents the geometric demand.

Next, it is necessary to calculate the relationship of the tensile load T with the curvature radius R_i or the tilt angle θ. Furusako et al. used the dimensionless parameter β for the tensile load and conducted regression analysis as follows[3]:

$$R_i = 147.84 - 147.93\beta \frac{W_s}{L_b W_b^{0.2}} \tag{14}$$

Here, it is impossible to obtain θ in the form of a function of R_i from Equation (13), and it will be rather troublesome to determine θ with respect to the value of R_i determined from Equation (14). In consideration of this, we attempted to directly determine θ as a function of the dimensionless parameter β, and determined the coefficient α using the equation below through a regression analysis.

$$\theta = \alpha \frac{\beta^{1.5}}{(L_b/W_s)^{1.5}(W_b/t)^{1.0}\,TS\,(\mathrm{MPa})^{1.25}} \tag{15}$$

Fig. 9 shows the relationship between the actually measured tilt angle θ shown in Fig. 8 and the regression estimate, obtained assuming that the value of α in Equation (15) is 45,000. One can see that the two are in reasonably good agreement.

3.1.5 Mechanical properties of portion R

Because the portion R includes a heat affected zone (hereinafter written as HAZ) caused by welding, its mechanical properties are inhomogeneous. The mechanical properties of HAZ are similar to those of the weld metal at a position adjacent to weld metal, and as the distance from the weld metal increases, they gradually change

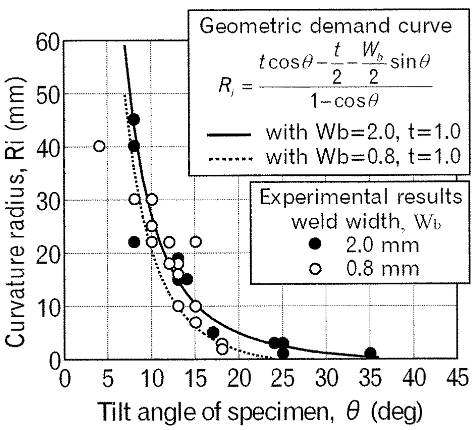

Fig. 8 Relationship between curvature radius R_i and tilt angle θ in tensile shear test

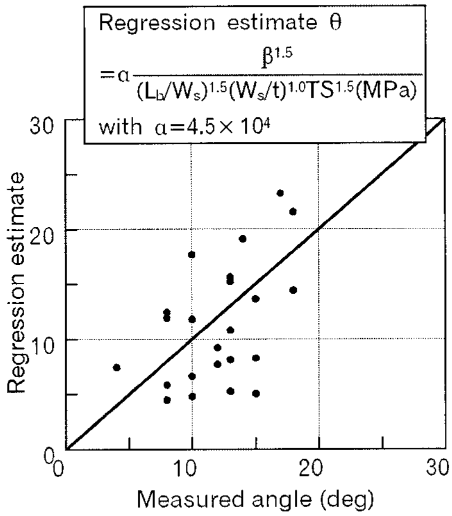

Fig. 9 Regression analysis of specimen tilt angle in tensile shear test

and become those of the base metal. As shown in Fig. 4, the fracture at the portion R does not occur close to the interface with the weld metal but at a position a little away from it because of weld metal's restriction on the plastic deformation of the portion R. In consideration of this, it was presumed that the mechanical properties of the fractured part were the average of those of the base metal and weld metal. Thus, the tensile strength TS_R and uniform elongation UE_R of the portion R were supposed, respectively, as follows:

$$TS_R = (TS_{BM} + TS_{WM})/2 \tag{16}$$

$$UE_R = (UE_{BM} + UE_{WM})/2 \tag{17}$$

Here, TS_{BM}, TS_{WM}, UE_{BM} and UE_{WM} are measured values.

When the tensile strength and uniform elongation of the portion R are given, then the modulus of longitudinal elasticity F and work hardening coefficient n are obtained using the following equations, and it becomes possible to use Equation (6) expressing the relationship between the stress and the strain in the portion R.

$$F = TS_R \cdot (e/n)^n \tag{18}$$

$$n = \ln(1 + UE_R) \tag{19}$$

Here, e is the base of natural logarithm.

3.2 Estimation of fracture position and joint strength

The following summarizes what has been described above. Two steel sheets, t in thickness and W_s in width each, are lap welded together by laser to form a bead W_b in width and L_b in length, and this joint is subjected to tensile shear test. Using a dimensionless parameter β (β = 0 to 1), one can estimate the state of stress and the conditions for fracture at different portions of a joint under a tensile load as described below.

Letting the tensile strength of the base metal be TS_{BM}, from Equation (2), the stress σ_B in the base metal portion is:

$$\sigma_B(\beta) = \beta \cdot TS_{BM} \tag{20}$$

The base metal fractures when $\beta = 1$, and at that time, σ_B satisfies the following equation:

$$\sigma_B(1) = TS_{BM} \tag{21}$$

When the modulus of longitudinal elasticity F, work hardening coefficient n and tensile strength TS_R of the portion R are obtained using Equations (16) to (19), the stress at the outer surface of the portion R can be determined by Equation (22) below, which is obtained from Equation (9).

$$\sigma_R(\beta) = F \cdot \left(\frac{t/2 + a(\beta)}{R_i(\beta) + t/2 - a(\beta)} \right)^n \tag{22}$$

Then, the tilt angle θ of the weld joint is calculated from Equation (15) as a function of β, and the curvature radius R_i at the inner surface of the portion R (see Fig. 5) from Equation (13), thus:

$$\theta(\beta) = \alpha \frac{\beta^{1.5}}{(L_b / W_s)^{1.5} (W_b / t)^{1.0} TS(\mathrm{MPa})^{1.25}} \tag{23}$$

$$R_i(\beta) = \frac{t \cos\theta(\beta) - \frac{t}{2} - \frac{W_b}{2} \sin\theta(\beta)}{1 - \cos\theta(\beta)} \tag{24}$$

On the other hand, the value of a is determined using Equation (25) below, which is given by substituting Equations (3) and (5) in Equation (8).

$$\beta = \frac{L_b \cdot F}{(n+1) \cdot TS_{BM} \cdot W_s \cdot t} \left(\frac{1}{R_i(\beta) + t/2 - a(\beta)} \right)^n \left\{ \left(a(\beta) + \frac{t}{2} \right)^{n+1} - \left| a(\beta) - \frac{t}{2} \right|^{n+1} \right\} \tag{25}$$

Inconveniently, a is not explicitly expressed as a function of β, but the value of a that satisfies Equation (25) can be obtained comparatively easily by using a spreadsheet.

The condition for fracture at the portion R is given as follows:

$$\sigma_R(\beta) = TS_R \tag{26}$$

The shear stress in the weld metal is, from Equation (11),

$$\tau(\beta) = \frac{\beta \cdot TS_{BM} \cdot W_s \cdot t}{L_b \cdot W_b} \cos\theta(\beta) \tag{27}$$

Letting the hardness of the weld metal be Hv_{WM}, the condition for fracture at the weld metal is given by Equation (12) as follows:

$$\tau(\beta) = 1.9 \cdot Hv_{WM} \tag{28}$$

To obtain the load T at the time of failure from the dimensionless parameter β, the following equation is used based on Equation (3):

$$T(\beta) = \beta \cdot TS_{BM} \cdot W_s \cdot t \tag{29}$$

When the test piece width W_s, weld length L_b and weld width W_b are given, the procedures for estimating the maximum tensile shear load that a laser welded lap joint can withstand and the position of fracture are as described below.

Fig. 10 shows an example of the estimation of the fracture position and load of test pieces, each made of mild steel sheets, 1.0 mm in thickness and 50 mm in width, lap welded by laser to form a weld bead 40 mm in length. The estimation was made on three different cases of weld widths: 0.5, 1.0 and 2.0 mm. The values of the variables necessary for the calculation are given in the graphs.

Increasing the value of β from 0 to 1 is the same as increasing the load in the tensile test. After determining the value of β, the stresses in the base metal and the outer surface of the portion R, and the shear stress in the weld metal are calculated using Equations (20), (22), and (27), respectively. Increasing the value of β gradually, and when the above stress value for each of the portions becomes equal to the values representing the failure conditions given by Equations (21), (26), or (28) at any one of them, then the joint is expected to fail at that portion. The joint strength at that time is given by substituting the value of β in Equation (29).

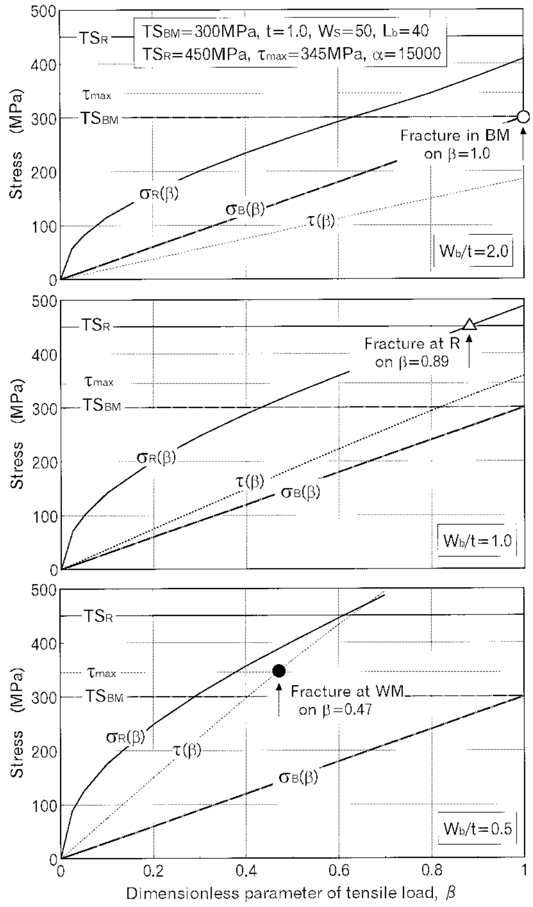

Fig. 10 Estimation procedure for fracture portion and maximum load

As Fig. 10 shows, when the weld width is as small as 0.5 mm, then the shear stress τ of the weld metal exceeds τ_{max} even with the smallest value of β, the test piece is expected to fracture at weld metal, and the value of β, namely the joint efficiency, is approximately 0.47. When the weld width is doubled to 1 mm, the shear stress τ of weld metal decreases accordingly, but the stress in the outer surface of the portion R does not decrease as much, and as a result, the test piece is expected to fail at the portion R, with an joint efficiency β = 0.89. When the weld width is as large as 2 mm, on the other hand, the value of β reaches 1.0 before the stress in the weld metal or portion R increases to the fracture limit, and the joint is expected to fail at the base metal.

3.3 Comparison of estimation results with test results

The authors verified how well the above method for estimating the fracture position and joint strength would reproduce test results. Test pieces were prepared by welding mild steel sheets 0.8, 1.0 and 1.2 mm in thickness and 40 and 50 mm in width by laser lap welding, and subjected these joints to tensile shear test. The results are plotted in **Fig. 11**; different plotting marks correspond to different fracture

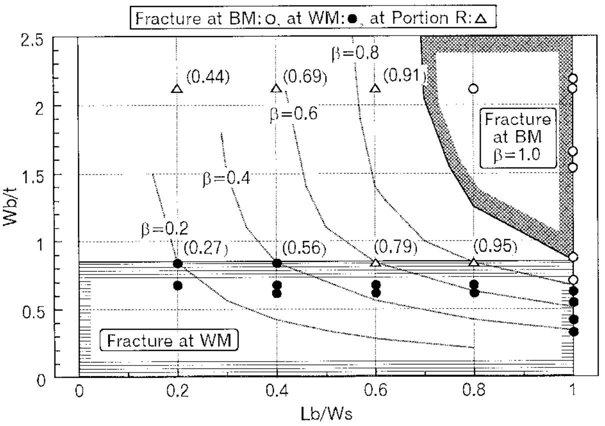

Fig. 11 Effect of weld length and weld width on fracture portion and joint strength in tensile shear test

positions and the figures between parentheses indicate the joint efficiency actually measured. The fracture position and joint strength were also estimated using the values shown in Fig. 10. It is understood from Fig. 10 that, in the case where $L_b / W_s = 0.8$, a test piece is expected to fail at the weld metal when $W_b/t = 0.5$, and at the portion R when $W_b / t = 1.0$. Similar operations using different values of W_b / t lead to an expectation that the fracture occurs at the weld metal when W_b / t is 0.85 or less, and at the portion R when W_b / t exceeds 0.85. The above operations were repeated using different values of L_b / W_s and W_b / t, and defined the ranges of L_b / W_s and W_b / t where the weld metal would fracture and those where the base metal would; the zones thus defined are also shown in Fig. 11. The curves in Fig. 11 show the relationship between L_b / W_s and W_b / t when the joint efficiency β is 0.2, 0.4, 0.6, 0.8 and 1.0. Fig. 11 demonstrates that the developed estimation method is capable of qualitatively reproducing the fracture position and joint efficiency actually obtained through test. Thus, the estimation model summarized in Sub-section 3.2 is regarded as capable of explaining the fracture behavior of laser welded lap joints at tensile shear test.

4. Closing

A model for estimating stresses in different portions of a laser welded lap joint under a tensile shear load was developed, and the developed model proved capable of predicting the portion of fracture and the maximum withstand load of the weld joint. This attempt is expected to constitute a foundation for better understanding of the strength and fracture behavior of a laser welded lap, contributing to further enhancing the passenger safety of automobile bodies.

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