Fundamental Research on Laser Welding of Structural Steel†

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Abstract

The laser weldability of structural steel was investigated along with the various fundamental characteristics of laser welding. The mechanical characteristics of the weld showed that laser welding could be practically applied to the welding of structural steel.

KEY WORDS: (Laser Welding) (Assist Gas) (Atmospheric Conditions) (Plasma Control) (Mechanical Properties)

1. Introduction

There is a great deal of laboratory data concerning laser welding, but there is less data on laser welding characteristics in practical applications. In this report, the effect of atmospheric gas and the problem of laser plasma control were taken up, and fundamental studies were performed regarding the practical application of laser welding to the welding of various types of structural steel.

2. Experimental Procedures

The chemical compositions of the materials used in this experiment are shown in **Table 1**. A 15 kW CO_2 laser with a beam diameter of about 1 mm at the focal point was employed. For 'laser welding in air' as shown in **Fig. 1**, the laser welding equipment consisted of an assist gas nozzle of Cu pipe with a 3 mm inner diameter, which blew the assist gas at various angles θ_N to the surface of the specimen. The work table was capable of moving in 3 directions along the X, Y and Z axes. An inert gas was used as the assist gas.

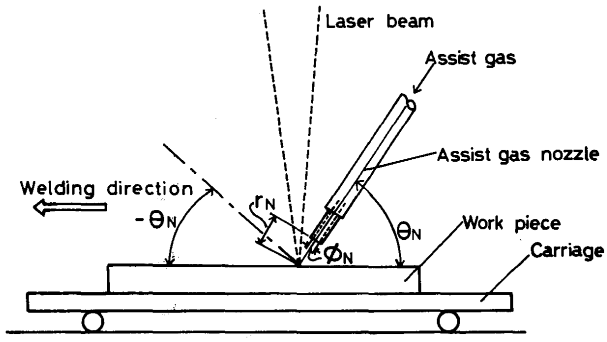

Fig. 1 Laser welding in air

'Laser welding in an enclosed gas atmosphere' was also performed. The same apparatus was used, but in this method the specimen was enclosed in a shield case, as shown in **Fig. 2**. The inside of the shield case was filled with shield gas and was kept at a pressure of at least one atmosphere. Laser welding was performed two ways, first without an assist gas and then using an assist gas.

Table 1 Chemical composition of materials used.

Material	Wt %					PPM	
	C	Si	Mn	P	S	N	O
1 40 Kilo class structural steel	.16	.21	.79	.017	.012	22	22
2 50 Kilo class structural steel	.15	.38	1.51	.027	.005	50	22
3 50 Kilo class rolled structural steel	.16	.18	.66	.017	.012	20	21

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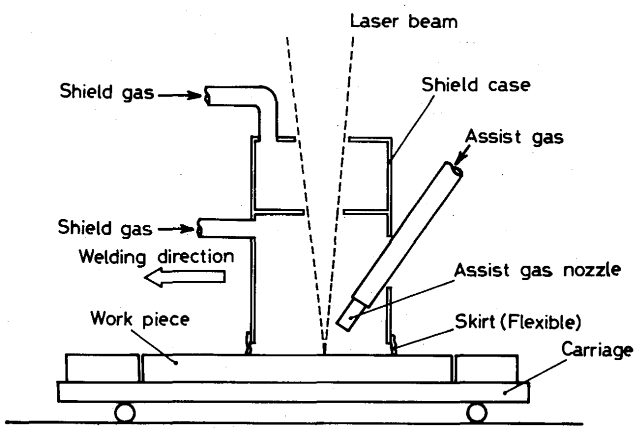

Fig. 2 Laser welding in an enclosed gas atmosphere

3. Experimental Results

First 'laser welding in an enclosed gas atmosphere' was performed without an assist gas, and the effect of the kind of shield gas on the penetration depth, h_p, and on the cross sectional area of the bead, S_m, was investigated. Four kinds of gas were used (He, Ar, CO_2 and air) under the same welding parameters. As shown in **Fig. 3**, the

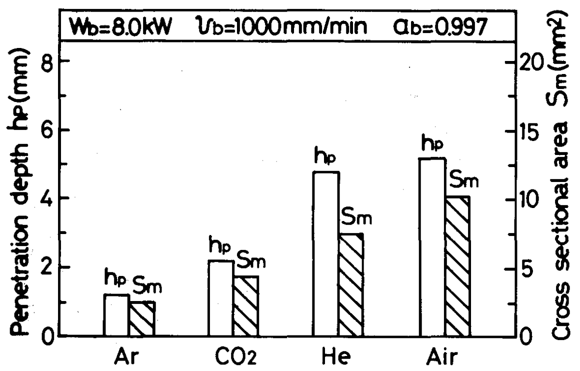

Fig. 3 Comparison of h_p, and S_m.

penetration depth and cross sectional area were largest when air was used. The next best results were achieved with He. The reasons for this are that in general, in order to transmit energy to the specimen, it is necessary that the laser beam not be absorbed before it arrives at the surface of the specimen, and that the laser energy be absorbed by the specimen without reflection. Since a CO_2 laser beam is easily absorbed by hot vapour and plasma, the best atmospheric gas is one which is not easily ionized. Furthermore, better results are achieved if the surface is covered by an insulator of high specific resistance (for instance, a layer of oxide). The absorption coefficient of the specimen's surface, Ab, is equal to $112\sqrt{\eta}$, assuming that the specific resistance is η. When these two parameters are large, the energy of the laser beam is easily transferred to the specimen and deep penetration results. Since among these 4 gases an insulating layer forms most easily on the surface in air, larger h_p and S_m values are thus obtained. Among the other 3 gases He has the highest ionizing coefficient and shows the most resistance to transforming into plasma. As a result it can more effectively transfer the laser energy to the surface of the specimen. In contrast, Ar turns into plasma most easily. The results shown in Fig. 3 can thus be easily understood.

For 'laser welding in air', He, CO_2 and Ar gas were used as an assist gas. Due to the different gas densities, for consistency the gas flow rate of He and CO_2 were converted to the equivalent gas flow rate for Ar. **Figure 4**

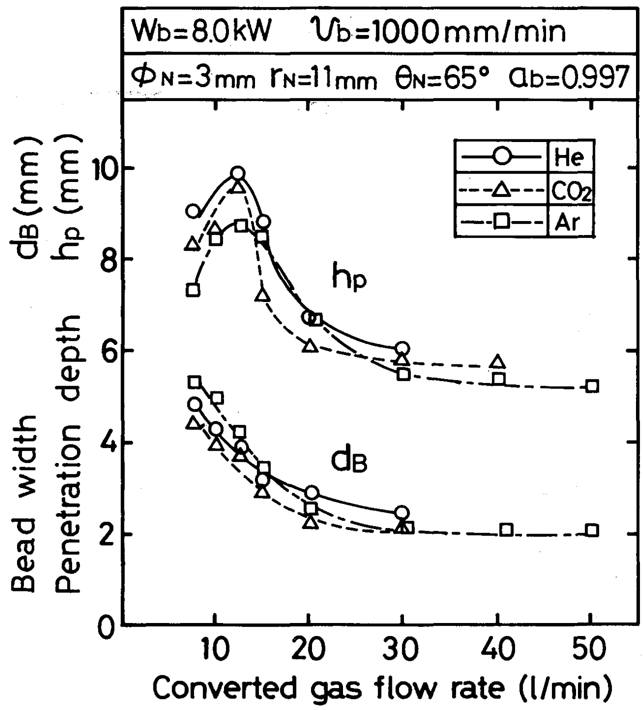

Fig. 4 Converted gas flow rate and penetration depth h_p.

shows the relation between h_p, d_B and the converted gas flow rate. The method of flow rate conversion was as follows: with Q_{Ar} as the indication of a flow meter measuring the flow of Ar gas, the flow rate of another gas, Q_1, which indicates the same value, is written as:

$$Q_1 = Q_{Ar} \times \sqrt{\frac{\rho_{Ar}}{\rho_1}}$$

ρ_{Ar}: standard gas density of Ar
ρ_1: density of another gas

Thus, the converted value Q_1* for a gas other than Ar, is obtained as follows.

$$Q_1^* = \frac{Q_1}{\sqrt{\frac{\rho_{Ar}}{\rho_1}}}$$

The formulae for converting the gas flow rate of He (Q_{He}) to Ar gas (Q_{He}^*) and the gas flow rate of CO_2 (Q_{CO_2}) to Ar gas ($Q_{CO_2}^*$) are thus written as follows:

$$Q_{He}^* = Q_{He}/\sqrt{\frac{\rho_{Ar}}{\rho_{He}}} = Q_{He}/3.16$$

$$Q_{CO_2}^* = Q_{CO_2}/\sqrt{\frac{\rho_{Ar}}{\rho_{CO_2}}} = Q_{CO_2}/0.95$$

When the data are corrected by this converted flow rate, the assist gas flow rates which can get maximum penetration are the same regardless of the kind of gas. The blowing pressure 'P' of these gases on the point irradiated by the laser is shown by the following equation.

$$P = k\rho v^2$$

v: gas speed from nozzle to surface of specimen
ρ: density of gas
k: constant

When the cross section of the nozzle is the same, the gas flow rate, Q, is proportional to the speed. This equation can then be rewritten as follows:

$$P = K\rho Q^2$$

K: constant

The equation for the gas flow rate is rewritten for He gas as follows:

$$Q_{He} = Q_{Ar} \times \sqrt{\frac{\rho_{Ar}}{\rho_{He}}}$$

Squaring and rearranging, this equation can then be rewritten as follows:

$$\rho_{He} Q_{He}^2 = \rho_{Ar} Q_{Ar}^2$$

Blowing pressure 'P' does not depend on whether the gas is Ar or He. Therefore, it is clear that the gas flow rate providing the maximum penetration depth is the same regardless of the type of gas[1].

The nozzle angle, θ_N, and the assist gas flow rate, Q_N, have important effects on the welding bead. The relation between these parameters and the penetration depth was studied in detail. The He gas flow rate, Q_N, and the bead cross section are shown in **Fig. 5**. When the nozzle angle θ_N was changed from +60° to +45°, +30°, −30°, −45° and −60°, little difference was found in the shape of the bead cross section at the different nozzle angles. Therefore, a nozzle angle of around +60° is recommended, as it requires the lowest flow rate and allows efficient handling.

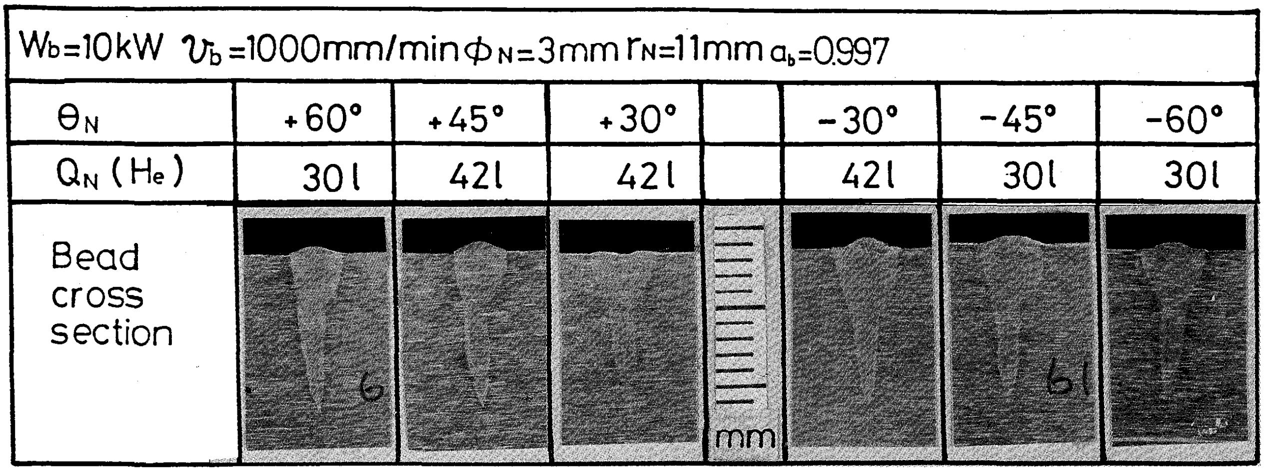

Fig. 5 Comparison between θ_N, Q_N, and bead cross section

The relation between h_p and Q_N and the welding speed, v_b is shown in **Fig. 6**. The gas flow rate which gives the maximum value for h_p increases with decreasing welding speed. **Figure 7** shows the bead cross section welded in air under constant welding conditions which maximized h_p against the gas flow rate, Q_N. With a deep penetration depth, it seems impossible to obtain a weld without spiking and root porosity regardless of the flow rate of the assist gas in laser welding in air. Therefore, it is necessary to diminish these defects by full penetration welding or by adopting proper beam oscillation.

A comparison of the welded bead obtained by 'welding in air' and 'welding in an enclosed gas atmosphere' using He as an assist gas is shown in **Fig. 8**. The penetration

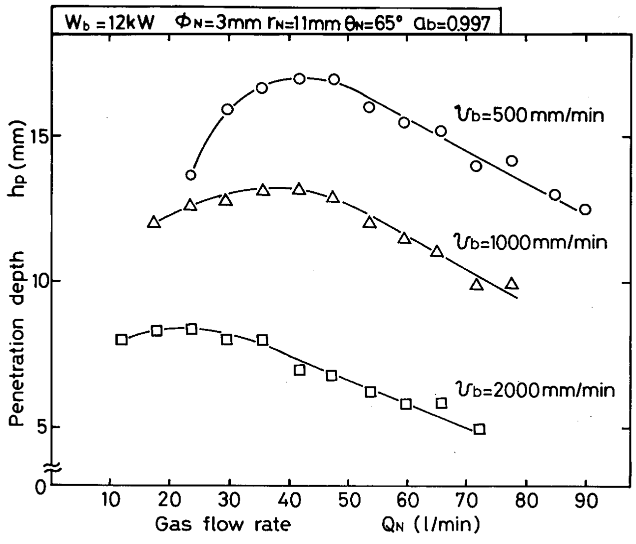

Fig. 6 Relation between h_p, v_b, and Q_N.

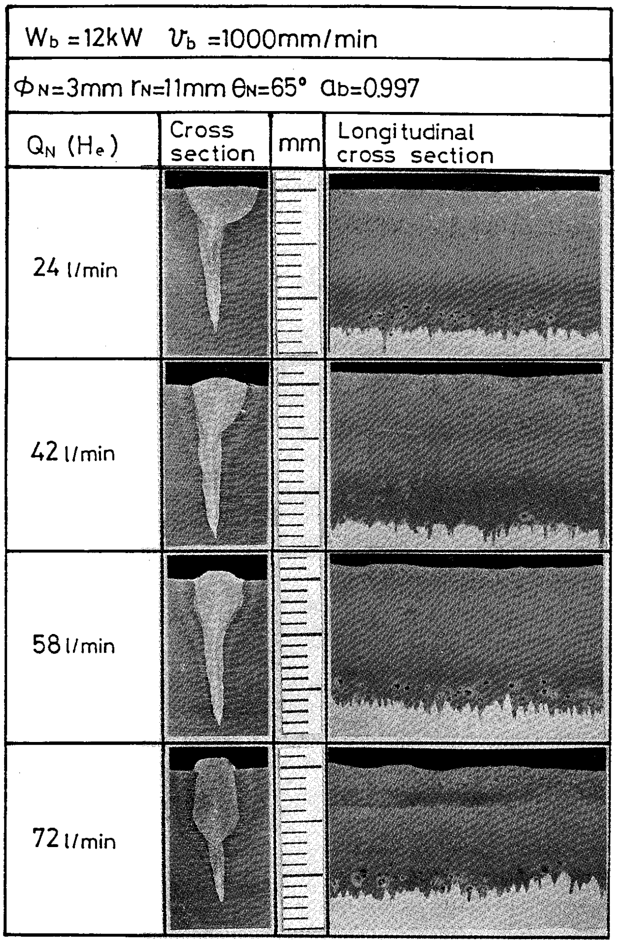

Fig. 7 Various welding conditions and bead cross sections

depth, the bead width and the cross sectional area of the weld in an Ar gas atmosphere were smaller than in the weld in air.

The relation between the surface condition of the specimen and the penetration depth was also investigated, as it is especially important in laser welding. **Figure 9** shows a comparison between two specimens, one with mill scale and the other without mill scale on the surface. Neither the penetration depth nor the cross sectional area were affected by the presence of mill scale. However, the bead width was narrower with the presence of mill scale than without.

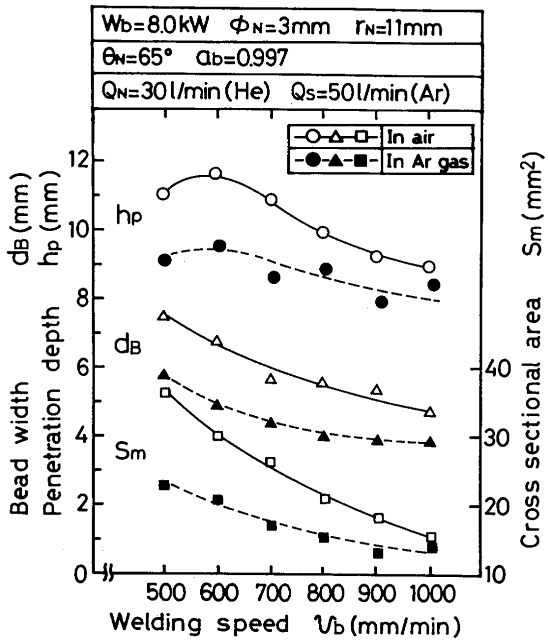

Fig. 8 Comparison of bead parameters between welding in air and in Ar gas.

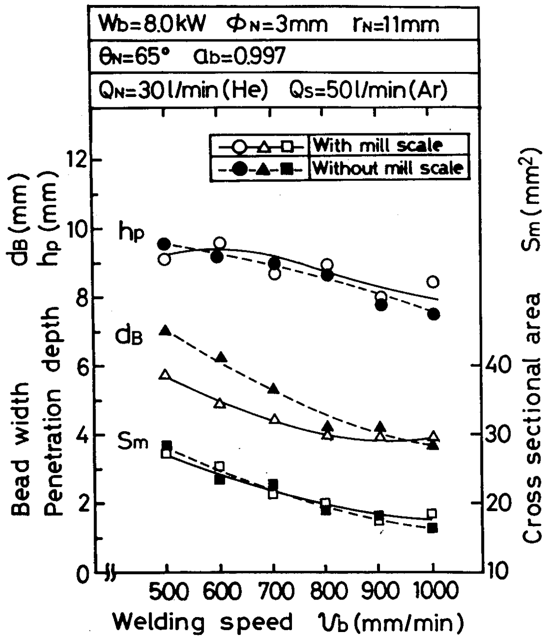

Fig. 9 Comparison of bead parameters between specimens with mill scale and without mill scale.

4. **Chemical Composition of the Weld Metal and its Mechanical Characteristics**

The chemical composition of the weld metal which was welded in air and welded in an Ar gas atmosphere are compared in **Table 2**. In the air weld, there is a markedly lower content of Si and Mn, but in the Ar gas weld, the chemical composition is almost the same as that of the base metal, except for a small decrease in Si and Mn.

The nitrogen content of the weld metal was investigated in relation to the input power. As shown in **Fig. 10**, a relatively small amount of nitrogen was absorbed into the molten metal under both of air and Ar gas conditions. The content rose to about 2 times that of the base metal. The oxygen content of the sample with mill scale was as much as 10 times that of the base metal. The weld metal obtained without mill scale in an Ar gas atmosphere had an O_2 content the same as that of the base metal, as shown in **Fig. 11**.

Table 2 Chemical composition of laser weld metal.

40 Kilo class structural steel	Wt %						PPM	
	C	Si	Mn	P	S	Al	O	N
Weld metal 1 (Welded in Air)	.16	.18	.70	.017	.014	.020	178	17
Weld metal 2 (Welded in Ar gas atom.)	.17	.20	.75	.018	.014	.019	91	19
Base metal (Reference)	.16	.21	.79	.017	.012	.025	22	22

Welding condition; $W_b = 8$ kW, $v_b = 500$ mm/min, $\phi_N = 3$ mm, $r_N = 11$ mm, $\theta_N = 60°$, $Q_N = 30$ l/min. (He), $Q_S = 50$ l/min. (Ar)

Material surface condition; with mill scale

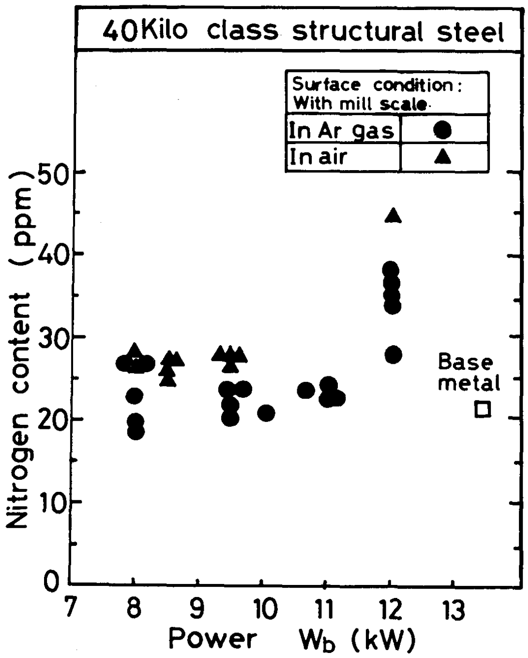

Fig. 10 Nitrogen content of weld metal

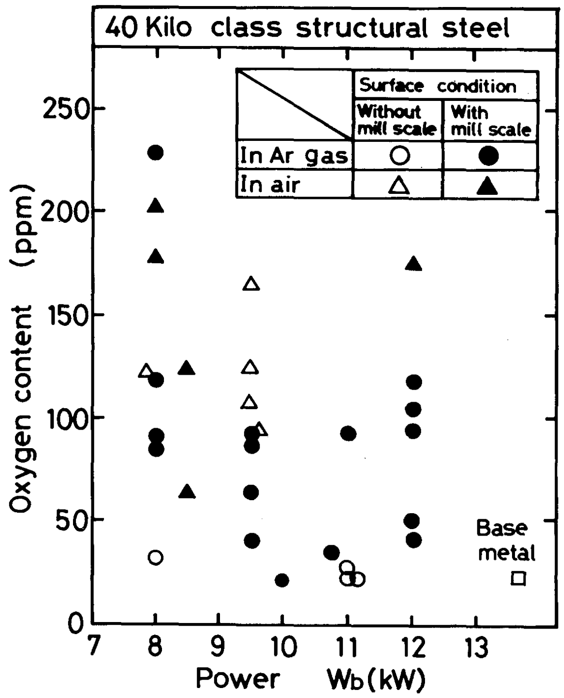

Fig. 11 Oxygen content of weld metal

The tensile strength of fully penetrated specimens, in which weld defects seldom appear, was measured. 50-kilo class structural steel and rolled structural steel 12 mm in thickness were used. A JIS #2 specimen was cut out of the center of the specimen in the normal direction of the bead. Full penetration welding was performed at various input powers in an Ar gas atmosphere and the specimen was cooled in air. The welding conditions are shown in **Table 3**. The place at which each specimen broke was in the base and not along the weld metal. The tensile strength and yielding point were the same as for the base metal, as shown in **Table 4**.

The tenacity of the weld metal was tested by using a Charpy test, also on a fully penetrated specimen. The position of the notch was at 1/2t as follows (see **Fig. 12**):

Table 3 Welding conditions

ϕ_N=3 mm, r_N=11 mm, θ_N=65°, a_b=0.997		
Q_N=30 l/min.(He), Q_S=50 l/min.(Ar)		
W_b (kW)	v_b (mm/min)	Heat input (kJ/cm)
8	300	16
9.5	400	14.3
11	500	13.2
12	600	12
12	800	9

Weld metal : Center of weld metal
Bond : Center of bond line
Haz : Center of the Haz

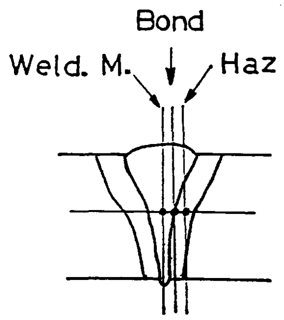

Fig. 12 Position of notch

Table 4 Tensile strength

Material		Base metal	Welded specimen
50 Kilo class structural steel	TS (kg/mm²)	57.5	58-59
	YP (u) (kg/mm²)	40.6	38-40
50 Kilo class rolled structural steel	TS (kg/mm²)	54.1	52-54
	YP (u) (kg/mm²)	41.0	38-40

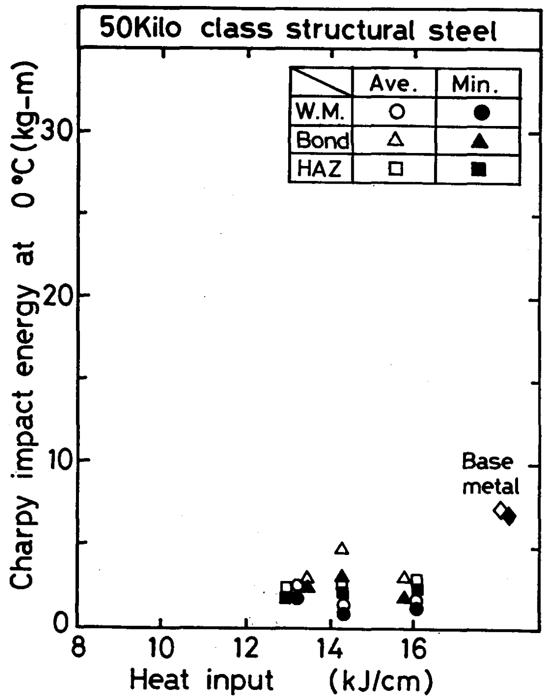

Fig. 13 Charpy results for weld metal of 50-kilo class structural steel

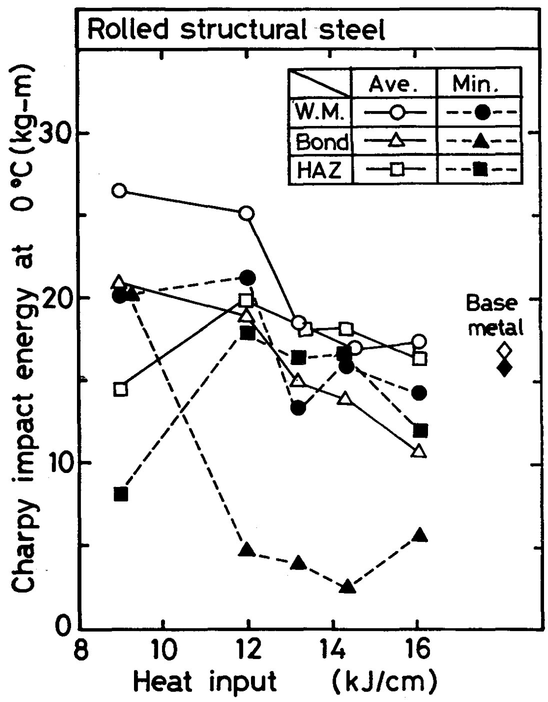

Fig. 14 Charpy results for weld metal of rolled structural steel

The tenacities of the weld metal, bond, and haz in the welded portion of 50-kilo class structural steel were all lower than in the base metal. The results of the Charpy test are shown in **Fig. 13**. In rolled structural steel, the result for the bond was slightly inferior to that for the base metal at a temperature of 0°C, as shown in **Fig. 14**.

The hardness of the weld was relatively high in 50-kilo class structural steel, but was comparatively low in rolled structural steel. This was because the rolled structural

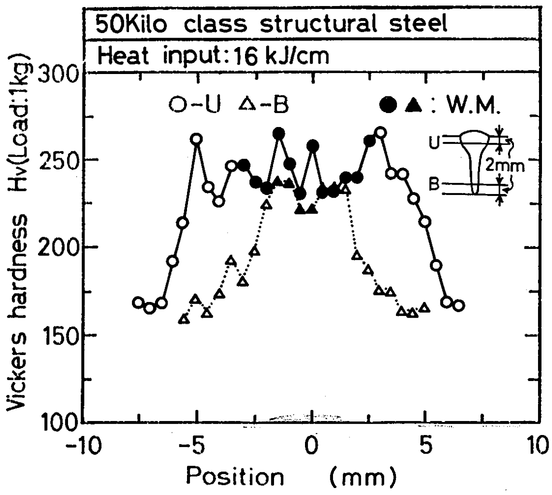

Fig. 15 Distribution of hardness of laser welds.

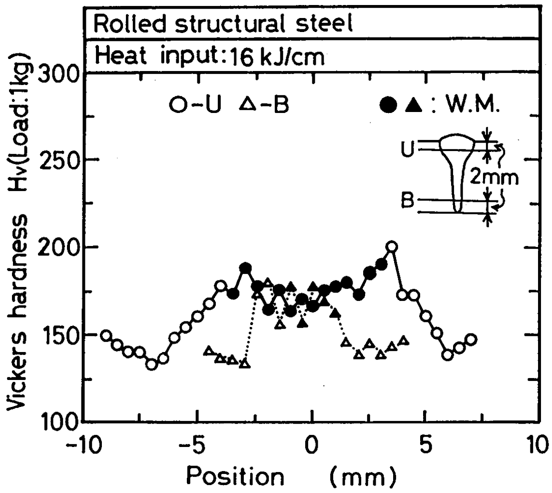

Fig. 16 Distribution of hardness of laser welds

steel had a relatively low content of Si and Mn, as shown in Table 1, and thus a low carbon equivalent, C_{eq}. The weldability of rolled structural steel was good compared with 50-kilo class structural steel. The hardness of the welded part was shown as in **Fig. 15** and **16**.

4. Conclusion

Laser welding of structural steel is suitable for practical welding applications through the use of a simple blow nozzle. In addition, Ar gas, which is cheaper than He, can be satisfactorily used as an assist gas. In this paper, only full penetration welding was discussed. The maximum thickness for full penetration welding of structural steel is limited to 14 mm. Beyond this thickness, backing plate is necessary to prevent the molten metal from dripping. By using the type of laser used in this experiment, which has a focussing diameter of about 1 mm, materials of above 20 mm in thickness are difficult to weld.

In laser welding in an air or in an enclosed gas atmosphere, the penetration depth does not increase with decreasing welding speed and increasing power. Also laser welding in a gas atmosphere has no effect on the bead appearance and the penetration depth. On the other hand, one major benefit is that there is no absorption of oxygen by the molten metal, this avoiding any change in chemical composition. In general, laser welding in air is suitable for welding structural steel. In order to prevent any change in the chemical composition of the weld metal, laser welding should be performed in a gas atmosphere without any mill scale.

Regarding the reduction in the tenacity of the welded part, further study is required to solve this problem, as it is a common problem in high speed and high power welding.

Reference

1) Y. Arata, T. Oda and R. Nishio: Trans. JWRI, 12-2 (1983), 1.