Development of Light Beam Welding Process[†]

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Abstract

A light beam can be used as one of excellent welding energy sources to improve weld quality.

In this report, in order to realize a practical use of a light beam welding process, investigations for improvement of concentration efficiency of the light beam and charactor of the high power lamp for special heat source were performed. As a result, the energy density of the light beam was able to reach a very high level never before obtained (2.6 KW/cm^2 at 5 KW lamp) by the successful utilization of the direct light concentration method with an elliptical reflector having an extremely small ratio of the focal distances, and by a lamp that tube structure and gas pressure were especially designed. Moreover, the necessary conditions on the energy density of the light beam as a heat source were clarified. By means of this process, it was possible to obtain good results as to the welding of sheet metal, such as mild and stainless steel, and the brazing of large size silver contactors, as compared with conventional welding processes. This newly developed welding process can be used widely as a useful method in practical.

1. Introduction

The method of fusing metalic materials by converging light energy has been known from old time[1]. The solar farnace using sunbeam is one such example and has been tested by many people.

In recent years, lamps of various kinds have been developed, and an image furnace using high power lamp was also developed for usage in the zone refining process[2].

Although theoretically known for a long time, it was only in the early 1970s that light energy was first used as a heat source for welding purposes[3].

Among various kind heat sources for welding use, the source using light beams is ranked relativly low from the stand point of energy density. However this heat source has come to be studied seriously for a following reasons.

1) Quite different from cases where flams or arcs are used, material can be heated free from chemically active atmosphere.
2) It is possible to apply heat to material without direct contact from heat source.
3) It is possible to apply heat to material without affecting the electromagnetic nature.

These advantages of the light beam method will result in an expanded scope of welding applications and facilitate high quality welding.

However in the light beam method, losses in electricity-to-light conversion and losses in light reflection on the surface of the material to be welded can not be avoided and this lowers considarably the heat efficiency, therefore it is vitally important to obtain effectively high energy converged light beam. According to the references[4], it was reported that an energy density is relatively low and it is being used only a heat source for heat treatment as an industrial-purpose. Under these circumstances the authors[5] have studied utilization of light beam for welding use, thereby developing a more efficient converging method of converging light beam and a lamp for heat generation purpose.

2. Development of Converging Method

2.1 The Lamp Used for This Study

Xenon discharge lamp and halogen lamp are typical of high power lamps that are able to operate continuously. Specially xenon discharge lamp is well known as a point light source[6]. **Fig. 1** shows relative brightness distribution of a xenon arc lamp, and **Fig. 2** shows its spectral energy distribution that has relatively high energy on infrared zone.
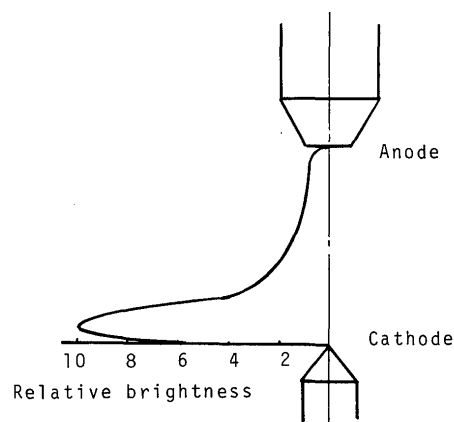

Fig. 1. Relative brightness distribution of xenon arc lamp.
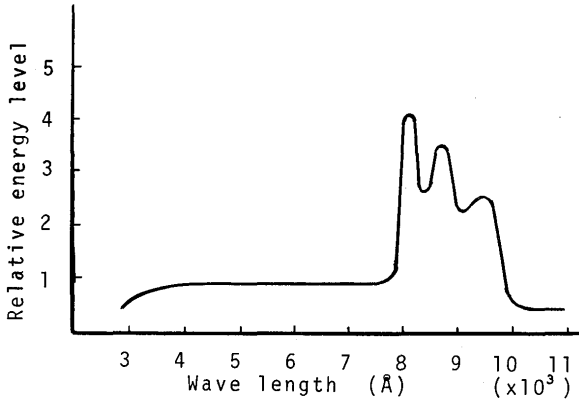
Fig. 2. Spectral energy distribution of xenon arc lamp.

From the above reason the xenon arc lamp is expected as to suitable heat source. For this converging study the light source used was an illumination purpose high voltage short-arc type xenon discharge lamp which is commonly found on market.

2.2 Method of Convergence Using Lens

The basic element used for convergence is an elliptical reflector. **Fig. 3** shows the outline configuration of the converging method. When the point light source is placed at the first focus of the elliptical reflector, its image is formed at the second focus without aberration shown in Fig. 3.
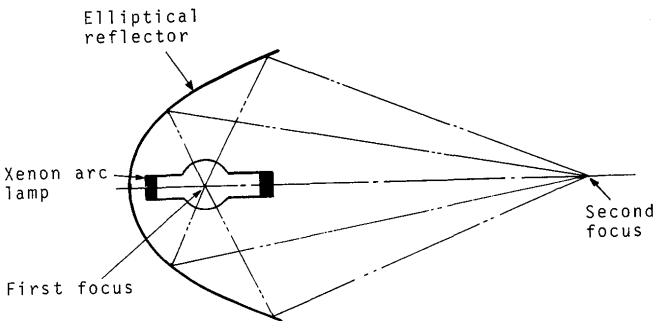

Fig. 3. Elliptical reflector.

The focal distance ratio of the elliptical reflector being commonly installed in the conventional movie projector is relatively large, so that the image of the light source obtained at second focus is large and consequent, the energy density of light beam is low. Therefore, in order to obtain a high energy density light beam of sharp convergence as a welding heat source, the converging system using the lens together with conventional elliptical reflector was studied. This converging system illustrated in **Fig. 4**.

The focal distance ratio of this method is as follows:

$$m = \frac{b}{a} \cdot \frac{1}{1+(c/D_F)} \quad\text{------------------------------(1)}$$
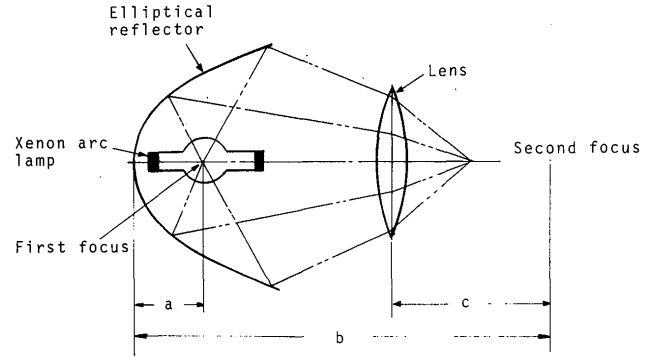

Fig. 4. Illustration of the lens converging system.

where   a : First focal distance of elliptical reflector.
             b : Second focal distance of elliptical reflector.
             c : Distance between lens and second focus.
             D_F : Focal distance of lens.

From this equation, in order to make the focal distance ratio smaller, the short focal distance lens is required and/or this lens has to be placed so near to the first focus of the elliptical reflector. But, generally, the heat resisting lens is difficult to make so large in its diameter than the length of its focal distance. Consequently there are some limit of focal distance ratio in the method of converging with a single lens. It was studied how the focal distance ratio affects on the surface melting time (i. e. the time from the light beam starting to the begining of surface melting of a mild steel sheet having 0.5 mm thickness.) This results are shown in **Fig. 5**.

Fig. 5 shows the surface melting time reduces in proportion to decreasing the focal distance ratio, and the losses in converging are minimum when the single lens is used.

Then, the energy density distribution on the plain prependicular to light beam axis at the focal point, was measured about the converge method using a piece of lens together with elliptical reflector. The specifications of the reflector and lens are as follows:
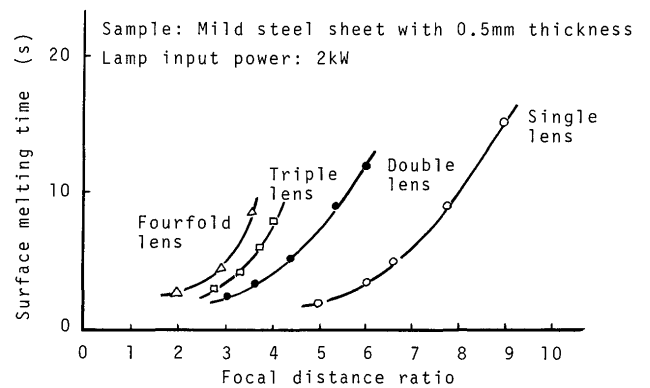

Fig. 5. Influence of focal distance ratio on the surface melting time.

The elliptical reflector:

    The focal distance ratio: 12

    Aperture diameter: 400 mm.

The lens:

    Focal distance: 230 mm.

    Lens diameter: 200 mm.

The focal distance ratio of this coverge system is 4.5. The energy distribution is shown in **Fig. 6.**
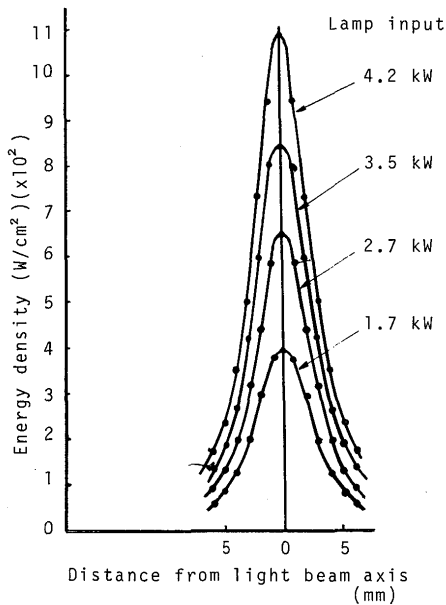

Fig. 6. Energy distribution. (converging system using lens.)

The energy density was measured by the calorie meter with a calibrated ballistic thermo-pile being provided with slit of 2 mm diameter. **Fig. 7** shows this measurement installation.
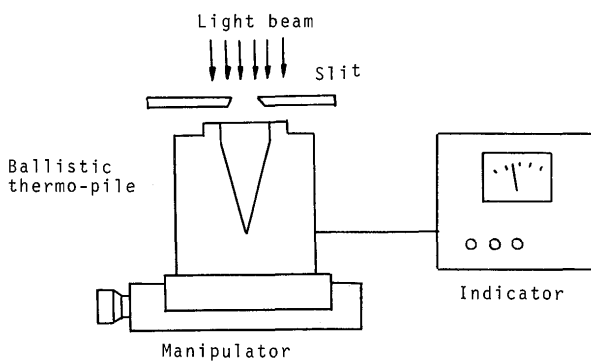

Fig. 7. Measurement installation of the energy density distribution.

This distribution can be approximated by the Gauss distribution and, therefore, this distribution is expressed by the following formula:

$$w(r) = w_{max} \exp\{-(\alpha r)^2\} \hspace{2cm} (2)$$

where $w(r)$ the energy density at distance r from the light axis.

w_{max} : maximum energy density

    α : constant number

Total energy W of the light beam is expressed by the following formula:

$$W = 2\pi \int_0^\infty w(r) \cdot r dr = \frac{\pi}{\alpha^2} w_{max} \hspace{1cm} (3)$$

The efficiency of condensed light beam power vs input power of the lamp is shown as follows:

$$\eta = \frac{W}{W_{in}} \times 100 \, (\%) \hspace{2cm} (4)$$

where W_{in} : Electrical input power of lamp.

When the maximum energy density is indicated w_{max} and the distance r where the energy density decrease to w_{max}/e is also r_e equations (3) and (4) become:

$$W = \pi r_e^2 w_{max} \hspace{2cm} (5)$$

$$\eta = \pi r_e^2 w_{max}/W_{in} \hspace{2cm} (6)$$

When the lamp is excited at input power 4.5 KW, the energy density distribution of condensed light beam is shown as:

$$w(r) = 1090 \exp\{-(2.8r)^2\} \, (W/cm^2) \hspace{1cm} (7)$$

The maximum energy density, the total energy and the efficiency of this system are shown in **Fig. 8.**
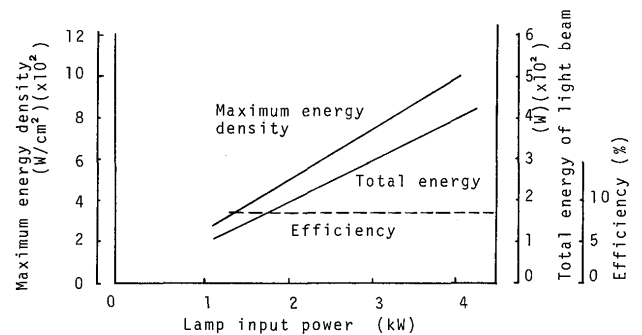

Fig. 8. Characteristic of light beam (converging system using lens.)

2.3 Energy Density Required for Welding

In order to ascertain the minimum value of the energy density required for welding use, the following experiment was carried out.

The experiment was aimed at ascertaining the relation between the surface melting time of a mild steel plate measuring 50 mm × 50 mm and maximum energy density of the light beam to be applied.

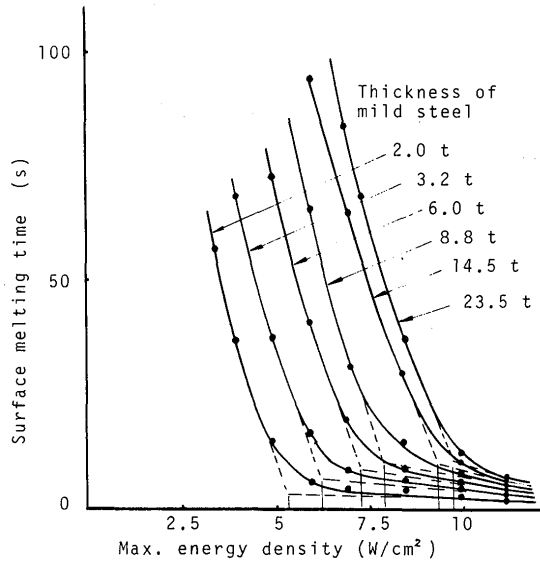The measurement result for various thickness

Fig. 9. Influence of the maximum energy density on the surface melting time (mild steel).

plates, each having different thickness, is shown in **Fig. 9.**

In Fig. 9 each curved line can be substituted for the doted refracted line respectively. When the energy density becomes lower than the value of each refraction point, the surface melting time sharply increases.

Fig. 10 shows the relation between the energy density at refraction point and the plate thickness.
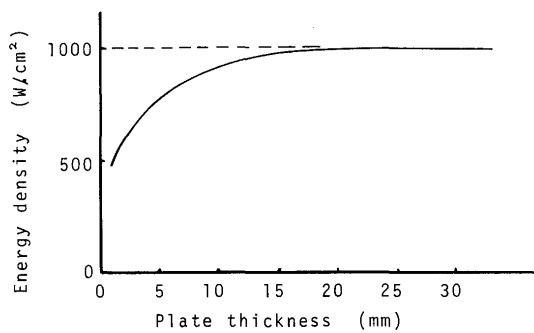

Fig. 10. Energy density of refraction point vs. thickness of mild steel.

In the light beam are converged into an energy density of over 1000 W/cm², the surface of the mild steel plate can be melted in a very short time, regardless of plate thickness.

In actual welding process, fixed jig being heat sink is used, especially in case of thin material welding. Therefore, thin, material has to be considered as thick material.

It can be concluded that for welding of metals, light beam must be converging into a energy density of about 1000 W/cm² or more.

This boundary value of energy density is determined by not only thermal characteristic of welding materials but, in case of light beam method, of course,

light beam absorbability on the surface of material.

Since the light beam absorbability is affected by mechanical roughness of the material surface, it is difficult to understand quantatively.

2.4 Discussion to the Lens Converging Method

In the case of converging method with lens, the energy losses in the lens are fatal to obtain a high energy density light beam.

These losses are described mainly as:

1) Reflection loss on the lens surface.

It is well known that the light beam reflects on the boundary between two materials having different refractive index. When light beam is transmitted from a material having high refractive index to the low one, there is much losses on the boundary between two materials.

2) Losses in the lens substance

Light beam having wave length of about 1μ is absorbed in the lens substance existence of ions of Fe^{2+}, Co^{2+} and Ni^{2+}.

Besides the above losses, the aberation of the lens prevent light beam from being converged.

From these reason, the energy density at the focal point of lens converging method is limited relatively low.

2.5 Direct Converging Method

The light beam can not be converged sufficient enough to an energy density of boundary value for welding by lens converging method.

For the sake of converging the light beam into higher energy density effectively. The direct converging method employing elliptical reflector only, was studied.

The smaller the focus distance ratio of the converging system, the light beam can be converged the more effectively.

The elliptical reflactor having smaller focal distance ratio (1:4) than conventional one was designed for experimental use.

This reflactor have large aperture and deep depth enough to catch the light beam from lamp.

The energy distributions, at the second focus point, on the plain perpendicular to the light beam axis are shown in **Fig. 11.**

The energy distribution at lamp input power 4.5 KW. is expressed as following formula.

$$w(r) = 1960 \exp. \left\{ -(3.6r)^2 \right\} (W/cm^2) \quad\text{----------------(7)}$$

Relations between lamp input power, and maximum energy density, the total energy and the converging efficiency are shown in **Fig. 12.**

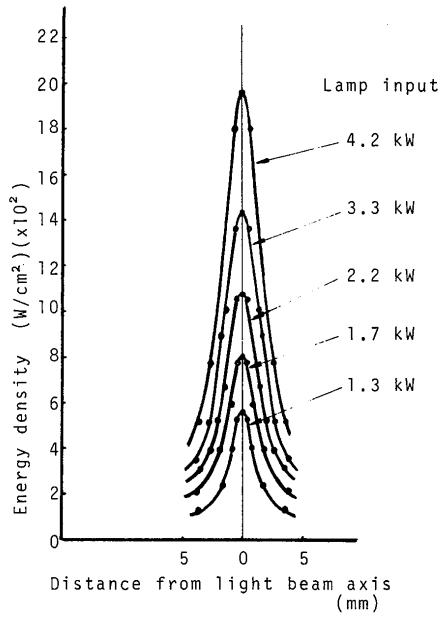The converging efficiency is increased to the value

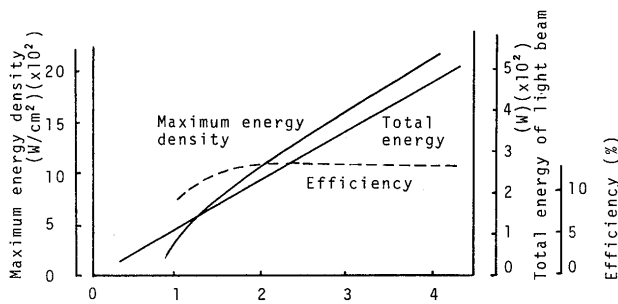Fig. 11. Energy density distribution (Direct converging system).

Fig. 12. Characteristic of light beam (Direct converging system).

of 13 %.

2.6 Comparison Between the Lens Converging Method and the Direct Converging Method

The advantages of the direct converging method in comparison with the lens converging method are as follows:

1) The maximum energy density increases two times greater than that of lens method.

2) The constant α, shown formula (2), relating to expansion of energy density distribution become 3.6 (cm^{-1}) from 2.8 (cm^{-1}), this means that the energy distribution becomes sharp. Moreover the efficiency increases to 13 % from 8.9 %.

As a result, the direct converge method is indispensable to obtain the high energy density light beam that is enough to practical welding use.

3. Development of the Lamp Specially Designed for Heat Source

A lamp to be specifically used as the heat source

for light beam welding purposes has been developed, based on the following ideas.

1) The shape of the anode has been changed, the distance between both electrodes altered, and the light emitting angle from the cathode spot has been enlarged so that the lamp out put can be increased.

2) The lamp tube has been made spherical and the cathode spot being placed at the center, in this way, the light reflection loss and the double image eliminated and consequently the light convergence improved.

3) Composition of the enclosed gases added to xenon has been selected adequatly, the gas pressure increased and the expansion of the cathode bright spot has been reduced.

The maximum energy density distribution available by this newly developed lamp and the direct convergence system is shown in **Fig. 13.**

The energy density comparision of specially designed lamp with conventional lamp is shown in **Fig. 14.**
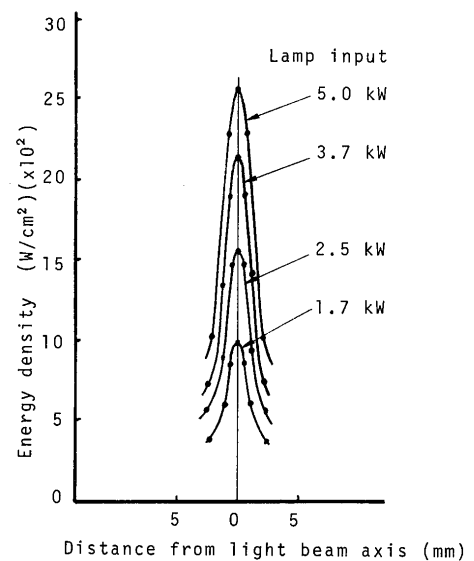

Fig. 13. Energy density distribution (Newly developed lamp and direct converging system).
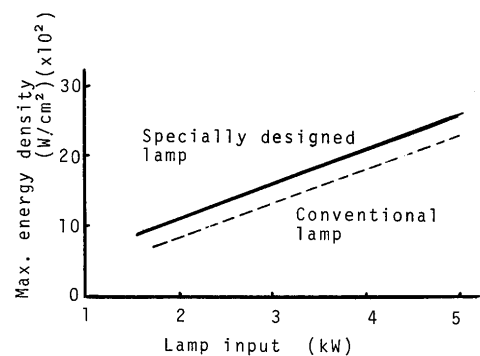

Fig. 14. Comparison of specially designed lamp with conventional lamp.

The maximum energy density of 2600 Watt/cm^2 and the distance $r_e = 2.2$ mm. are obtained by newly developed lamp.

The quantative effects. of the above mentioned items regarding the lamp is not clear yet and now be - ing studied.

Also the behavior of the high-voltage short-arc type discharge lamp at its cathode spot has not yet been elucidated.

4. Proto-type Light Beam Welding Machine

The Proto-type light beam welding machine is illustrated in **Fig. 15.**
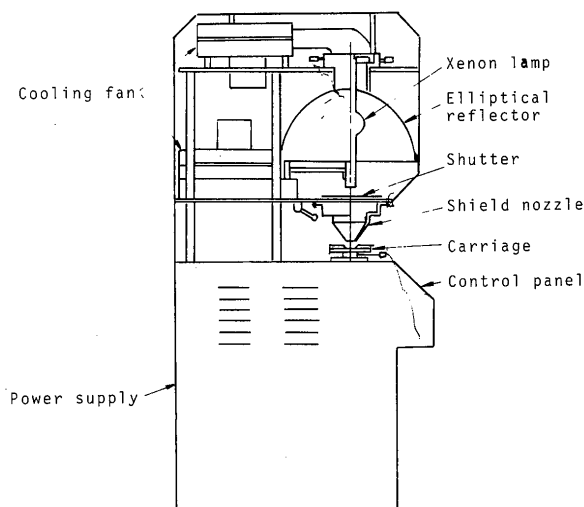

Fig. 15. Structure of proto-type light beam welding apparatus.

4.1 Lamp

The newly developed xenon arc lamp is used and its rating shows as follows:

Maximum rated input power: 6 KW.
Maximum lamp current: 150 (A)
            lamp voltage: 40 (V)

4.2 Reflector

Specially designed elliptical reflector is employed and its specifications is as follows:

The first focal distance   : 100 mm.
The second focal distance: 400 mm.
The aperture diameter   : 400 mm.

4.3 Power Supply

The constant current characteristic is required for xenon arc lamp power supply.

The output current has been stabilized from input voltage fluctuations of 10 %. The ripple voltage has been reduced to less than 5 % of output voltage, and the lamp output power is stabilized.

4.4 Shielding Gas Nozzle for Welding Zone

Shielding gas nozzle being installed on this proto-type machine is illustrated in **Fig. 16.**

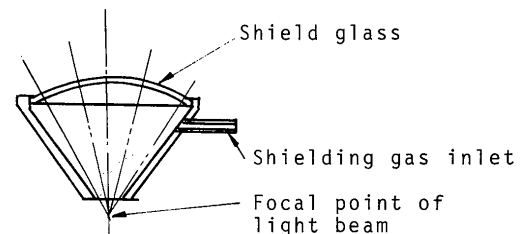Another shielding gas nozzle shown in **Fig. 17** is also available.

Fig. 16. Illustration of shield gas nozzle.

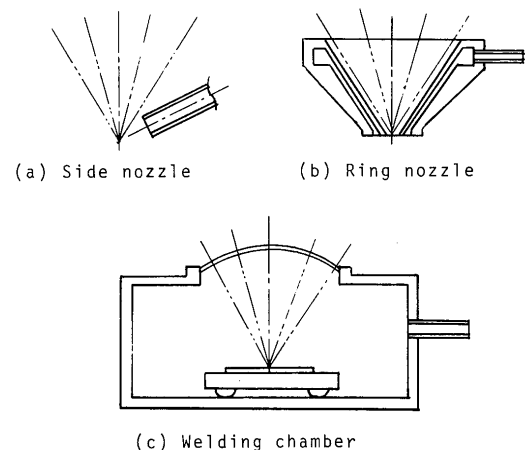(a) Side nozzle   (b) Ring nozzle

(c) Welding chamber

Fig. 17. Methods of gas shield.

4.5 Carriage

Carriage with fixture of weldment also equipped and its specifications is as follows:

Carriage speed: 45 cm/min.
Fixture size   : 100 mm × 100 mm

5. Welding Using Proto-type Welding Machine

5.1 Weldment Set Up

This study is proceeded about butt joint.

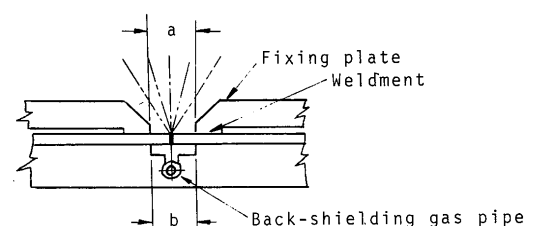The weldment is fixed to welding jig as shown in **Fig. 18.**

Fig. 18. Fixing of weldment.

Dimensions of fixing weldment is shown in **Table 1.**

Table 1. Dimensions of fixing of welding sample.

Thickness (mm)	Space (a) (mm)	Groove (b) (mm)
1.0	13 ± 1	8
0.5~0.4	11 ± 1	8
0.3~0.2	5 ± 0.5	4

5.2 Welding of Sheet Metals

As examples of welding using light beam, butt joint welding samples are indicated in **Table 2.**

Table 2. Typical conditions of the light beam welding.

Materials	Thickness (mm)	Max. energy density (W/cm²)	Welding speed (cm/min.)
Mild steel	1.0	2,600	15
	0.5	2,000	40
	0.3	2,000	45
Stainless steel	1.0	2,600	26
	0.5	2,600	45
	0.2	1,200	40
	0.03	850	40
Titanium	1.0	2,600	28
	0.5	2,200	45
	0.2	1,200	28

On the spot where light beam is irradiated the movement of molten metal is observed, and the welding process is considered to proceed by convection of the molten metal. Regard as the metallurgical property of weld metal, the same tendency is observed in conventional TIG welding, the detail elucidation of which depends on further study and experiment.

Comparision of light beam welding and TIG welding in welding speed is shown in **Table 3** and the appearance of weld bead comparison of light beam welding and TIG welding is shown in **Photo. 1.**

As shown in **Fig. 19,** the welded bead of this method has a beautiful appearance.

Fig. 19 shows the relation between the maximum welding speed and the maximum energy density of the light beam, in a stainless steel plate having a thickness of 1.0 mm.
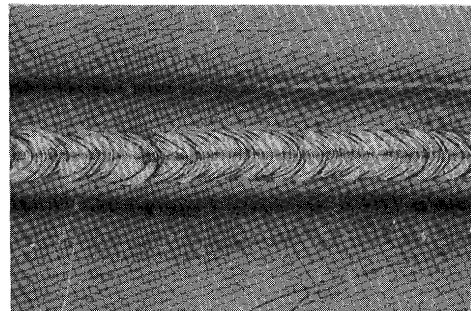
From these welding study, it is cleared that the new developed welding method using light beam is available for practical use.

Table 3. Comparison of light beam welding and TIG welding (stainless steel).

Thickness (mm)	Welding speed (cm/min.)		
	Light beam welding	TIG welding	
		Manual welding	Automatic welding
1.0	20	25	75
0.5	40	30	100
0.2	45	-	-
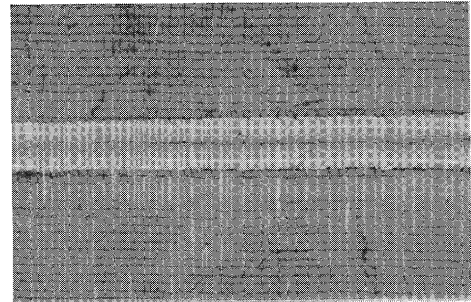
Light beam welding

TIG welding

Photo. 1. Appearance of welding samples comparison of TIG and light beam welding (stainless steel having 1.0 mm thickness).
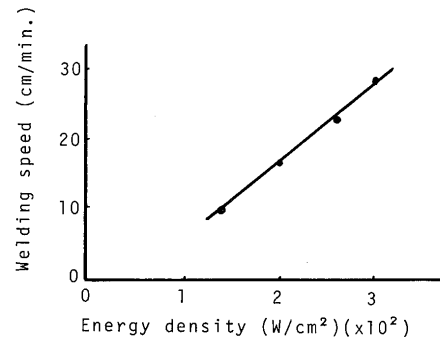

Fig. 19. Influence of maximum energy density on the welding speed (stainless 1 mm).

5.3 Practical Examples of Light Beam Welding

The practical examples of the welding are shown in **Fig. 20.**

In the figure, a) shows overlapping rim joint welding, b) shows edge joint welding of filter mesh, c) shows seal welding of small pipe end and d) shows spot welding of sheathed thermocouple.

In the case of b) ——c) welding was impossible to perform by conventional method. This is a significant examples of the use of non-contact type heat source from light beam.
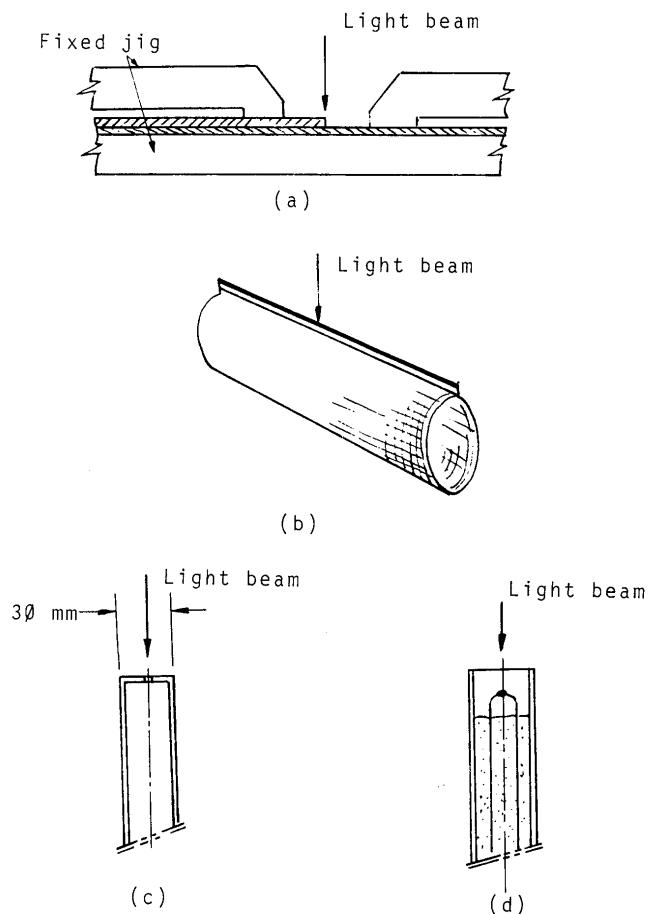
Fig. 20. Some applications of light beam welding.

5.4 Application Fields

The expected application fields of this new light beam welding method are seemed to be followings:

1) Automatic welding of small parts.

   The light beam is stable heat source and its power can be controlled easily.

2) High quality weld.

   Since the light beam is possible to apply heat to material without direct contact from heat source, the desirable welding atmosphere can be selected.

3) Automatic brazing and soldering

   The converged light beam make material to heat effectively. The brazing and soldering can be made with good appearance.

As shown the above, the light beam welding method can be expected to use in the new welding and heating field.

6. Conclusion

The following results are obtained through this development of light beam welding process.

1) The light beam must be converged into the energy density of about 1000 W/cm^2 or more for welding of mild steel sheet.

2) The energy density at the focal point of lens converging method is limited relatively low and it is not sufficient enough to welding.

3) The energy density at the focal point of direct converging method is 2200 W/cm^2 at the 5 KW, input with the conventional xenon lamp.

4) The newly developed lamp for heat source is installed on the direct converging system, and the energy density of the converged light beam become 2600 W/cm^2 at 5 KW lamp input.

5) From welding study of mild and stainless steel sheet, the newly developed light beam welding method is available for practical use, as well as conventional TIG welding process with various special features.

References

1) C. G. Abbot: The Sun of the Welfare of Man (Smithsonian Scientific Series) 2, chap 9 (1934).

2) M. R. Null and W. W. Lozier: Carbon arc image furnace. Rev. Sci. Instr. 29, 163 (1958).

3) Raymond Shah: Light beams, micro-plasma and friction mark gains in welding. Iron Age Metal. Inster. October. 28 (1970).

4) G. D. Nikiforov: Using focused beams from powerful xenon lamps for welding and brazing metals. Welding Production 9, 1 (1969).

5) Y. Arata, T. Oku, Y. Matsumoto and S. Yoshizumi: IIW, Doc. IV-150-74 (1974).

6) P. Shultz: Edelgasbogen Reich Sherichte fur Physik, 1, 147 (1944).