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# Fundamental Phenomena in High Power $CO_2$ Laser Welding (Report I)[†]

## – Atmospheric Laser Welding –

**Yoshiaki ARATA*, Nobuyuki ABE** and Tatsuharu ODA*****

### Abstract

*Fundamental phenomena in high power $CO_2$ laser welding, including beam hole shape and peculiar plasma behavior, were observed dynamically using a transmission X-ray and high speed camera system. The effect of altering the flow rate of helium assist gas was also studied. It was found that the gas flow rate had a strong effect on the beam hole shape and plasma production, and the assist gas not only blowed away the laser plasma but also it enlarged the shape of the beam hole. Too high a flow rate of assist gas enlarged the beam hole too much to cause the failure of the wall focusing effect.*

*In order to avoid the interference effect of laser plasma, a new laser welding process, called "Laser Spike Seam Welding", was developed based on above study on fundamental phenomena. This process allowed considerably deeper penetration than conventional laser welding. The reasons for this superiority were also analyzed by the above high speed imaging method.*

**KEY WORDS:** (Laser Welding) (Beam Hole) (Laser Plasma) (Assist Gas) (Transmission X-ray)

## 1. Introduction

Dynamic observation during laser welding is a useful method not only for analyzing the mechanism of laser welding but also for developing new welding processes. Except for laser welding of glass by the authors[1, 2], however, very little research employing this method has been done.

The authors succeeded in observing the behavior of the beam hole in steel during high power $CO_2$ laser welding[3]. In this report, the shape of the beam hole and the peculiar motion of plasma are studied by direct observation with a transmission X-ray and high speed camera system. By analyzing the films obtained with this high speed imaging system, a clear basis is established in high power $CO_2$ laser welding and a role of assist gas. A new laser welding process: "Laser Spike Seam Welding" was developed under this basis and analyzed its characteristics with above high speed imaging system.

## 2. Experimental Condition and Apparatus

In order to reveal the fundamental phenomena in high power $CO_2$ laser welding, following observations were performed.

The phenomena of the shape and behavior of the beam hole were filmed by the transmission X-ray method[4–6]. A schematic drawing of the experimental apparatus is shown in **Fig. 1**(a). The transmission X-ray system consists of an industrial type X-ray tube (180 kVp, 3.6 mA), an X-ray image converter and a 16 mm high speed camera. X-rays emitted from the X-ray tube pass through a specimen during laser welding. They come into the input screen of the X-ray image converter where they are converted to visible images on the output screen. These visible images are filmed by the 16 mm high speed movie camera at 300 frames per second.

The phenomena of laser plasma were filmed directly by a high speed camera at 300 frames per second and 6000 frames per second (Fig. 1(b)).

In order to support the understanding of the phenomena in metal, laser welding of soda-lime glass was per-

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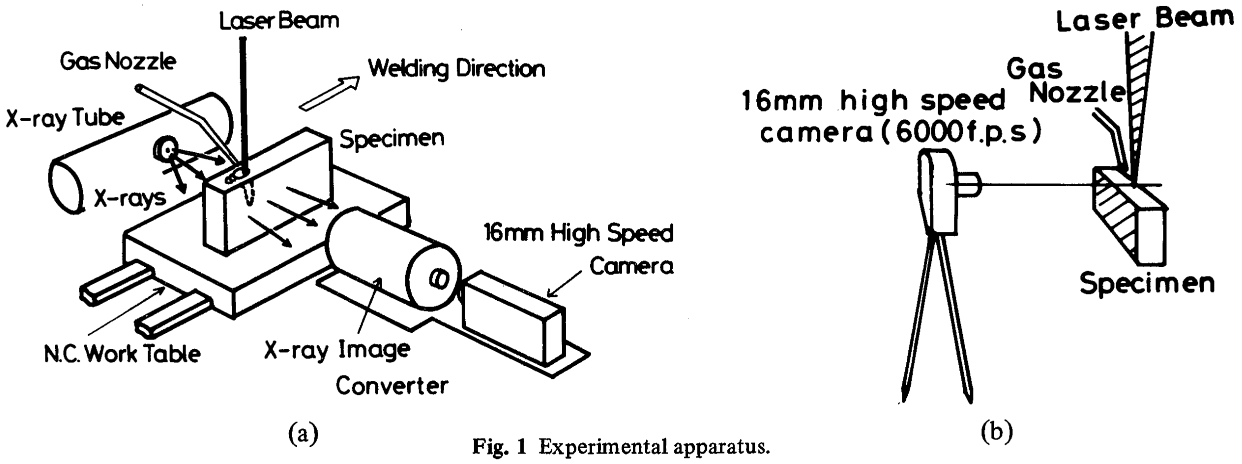


(a) (b)

Fig. 1 Experimental apparatus.

formed. The phenomena in laser welding of glass were filmed at 6000 frames per second (Fig. 1(b)).

All of the experiments were performed using a 15 kW $CO_2$ laser at our institute. Laser power of 7.5 kW and 9 kW with an $a_b$ value of 1.0 were used. Helium gas was used as assist gas, and was blown from the back of the laser beam at an angle of 60 degrees. The materials used were mild steel (SM41) and soda-lime glass. Their dimensions are 100 mm long, 10 mm wide and 50 mm thick. For easier X-ray penetration, narrow specimens about 10 mm wide were used in the experiments.

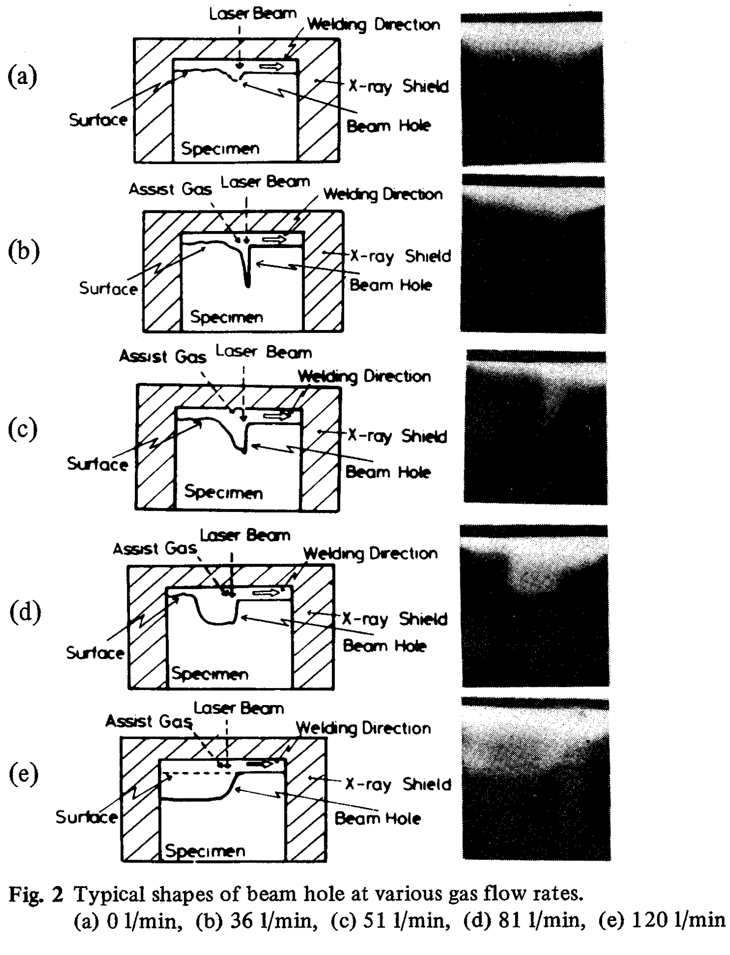


Fig. 2 Typical shapes of beam hole at various gas flow rates.
(a) 0 l/min, (b) 36 l/min, (c) 51 l/min, (d) 81 l/min, (e) 120 l/min

## 3. Results

### 3.1. Beam hole shape

**Figure 2** shows typical shapes of the beam hole at various gas flow rates. Schematic drawings of each photograph are also shown. When there is no assist gas, the beam hole is very unstable and shallow. Because the behavior of the beam hole is very violent, the beam hole cannot be seen clearly in this photograph even at a filming speed of 300 frames per second.

At an assist gas flow rate of 36 l/min, a narrow and deep wedge-type beam hole is formed. The beam hole still undergoes rapid fluctuation. When the gas flow rate is increased to 51 l/min, the upper part of the beam hole is enlarged by the assist gas, while the lower part of the beam hole is still wedge-type. The behavior of the beam hole is still unstable and the shape of the beam hole undergoes large changes. At 81 l/min, the beam hole opening becomes much larger, and the beam hole is no longer wedge-type. The behavior of the beam hole becomes more stable. As the gas flow rate increases, there is a large increase in the length of the beam hole opening, but no increase in depth is seen as in the case with a gas flow rate of 120 l/min. At 120 l/min, the assist gas pushes the molten metal backwards to such a degree that humping phenomena is observed behind the beam hole.

Thus it was recognized that the assist gas plays a very important effect on the beam hole shape and behavior in high power laser welding. When there is no assist gas, the behavior of the beam hole is quite violent. The assist gas flow increases the depth of the beam hole and stabilizes the behavior of the beam hole. There is, however, an optimum gas flow rate for maximizing the depth of the beam hole. Beyond this optimum value, the beam hole opening lengthens but the depth of the beam hole does not increase. When the maximum depth has been reached, a wedge shape appears at the bottom of the beam hole. The assist gas not only blow away the laser plasma to penetrate laser beam more deeply but also it enlarges the beam hole and decreases the wall focusing effect[7–9]. Therefore, too high a flow rate of assist gas cannot increase the depth of beam hole.

## 3.2. Laser plasma

When no assist gas is used, peculiar intense plasma is ejected perpendicularly from the beam hole at periodic intervals, as shown in the series of photographs in **Fig. 3**(a).

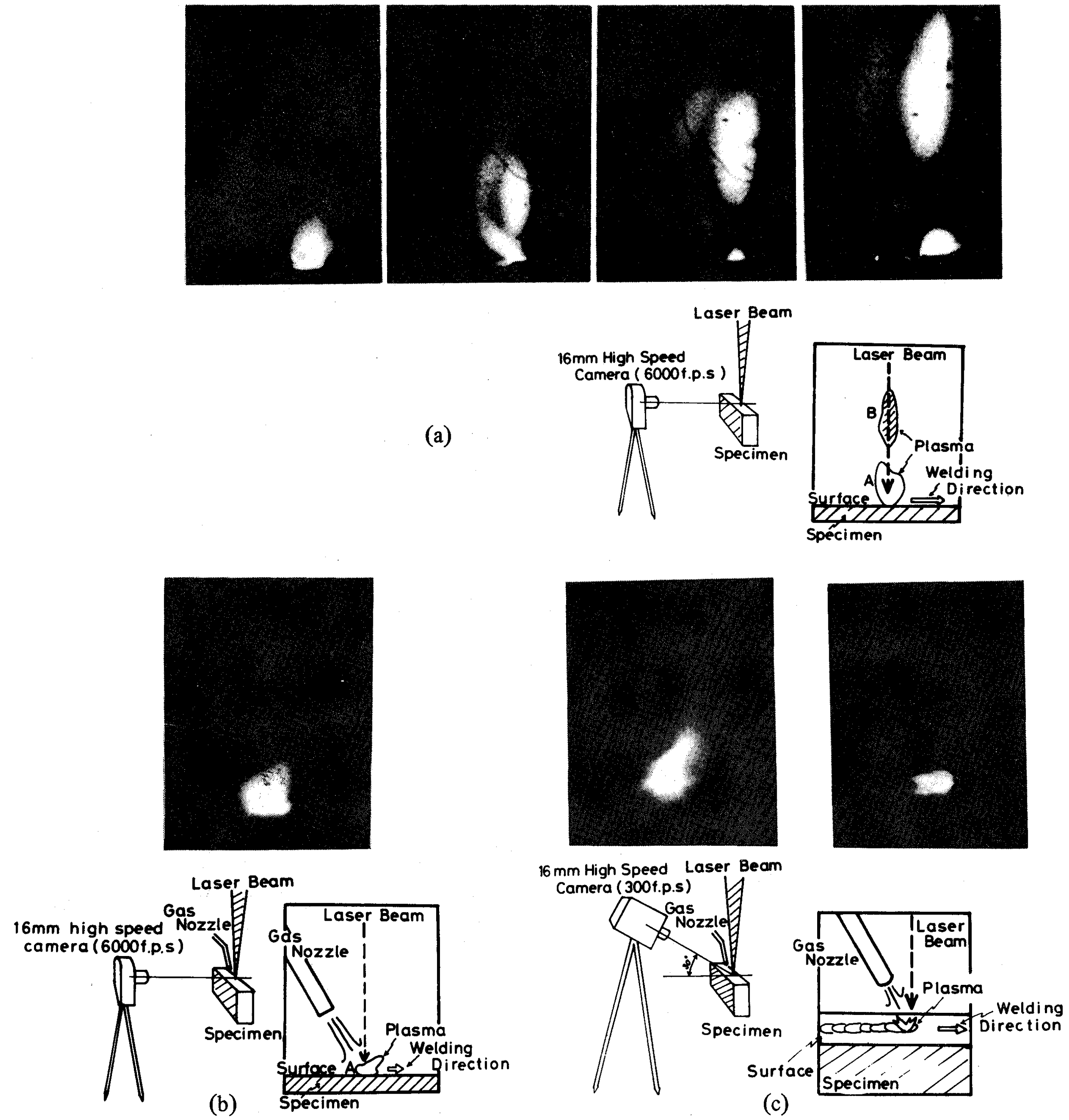


**Fig. 3** Laser plasma (a) 0 l/min, (b) 15 l/min, (c) left: 36 l/min, right: 51 l/min

These photographs were taken by a high speed camera at 6000 frames per second horizontally from the side of the specimen. Two kinds of plasma are seen. One is sky blue (A) and another is pink (B). The former stays near the specimen while the latter flies a further distance away from the surface. The pink plasma (B) is easily suppressed, even by a gas flow rate as low as 15 l/min as shown in Fig. 3(b). There is still, however, some plasma remaining in the beam hole and around the opening of the beam hole as shown in Fig. 3(c), even at flow rates of 36 l/min and 51 l/min. The photographs in Fig. 3(c) were taken from an angle of 30 degrees above the specimen, as shown in the schematic drawing in Fig. 3. This is the sky-blue plasma described before, which is never blown completely away by the assist gas.

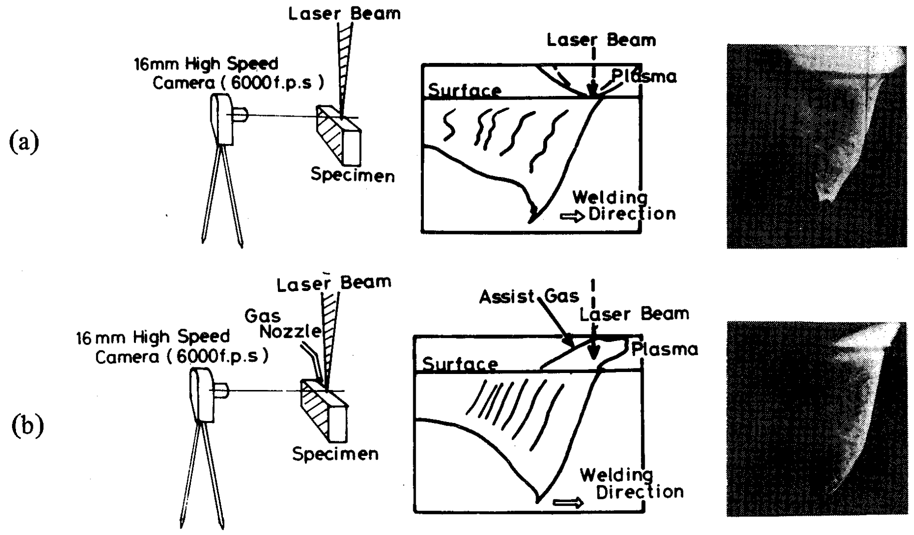


**Fig. 4** Side views of glass during laser welding.
(a) 0 l/min, (b) 7.5 l/min

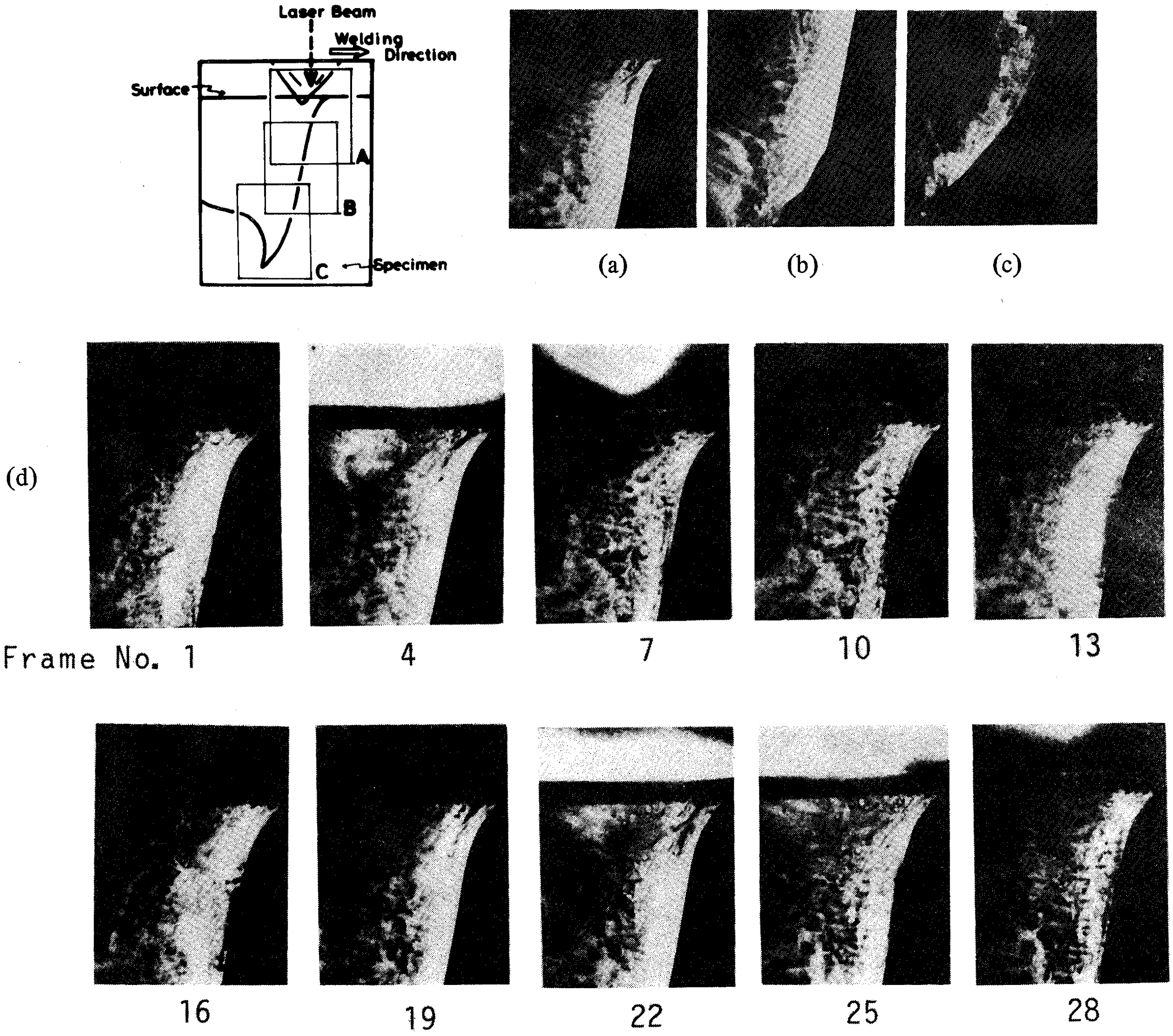


**Fig. 5** Close-ups of the upper, middle and lower parts of the beam hole.
(a) upper, (b) middle, (c) lower, (d) a periodic change at the upper part

### 3.3. Welding phenomena in glass

In order to support the understanding of the phenomena in steel, the beam hole and plasma phenomena were observed during laser welding in soda-lime glass, because both phenomena in glass are clearer and easier to observe at higher filming speeds at the same time than in steel.

**Figure** 4(a) shows a side view of glass during laser beam welding without assist gas. There is strong and periodic plasma production as in steel, and fast periodic horizontal flow is seen in conjunction with plasma production. However, an assist gas flow rate of only 7.5 l/min reduces the plasma sufficiently for the flow to become uniform (Fig. 4(b)).

In order to observe the phenomena more precisely, close-ups were taken of the upper, middle and lower parts of the beam hole along the front wall without assist gas as shown in **Fig. 5**. For the upper part of the beam hole, a series of pictures (Fig. 5(d)) was taken at high speed. They show the periodical movement of the irradiated zone of the laser, from the front wall to an area slightly away from the front wall. After strong impingement of the laser on the front wall, it happens that only a small amount of laser power can reach the front wall. These phenomena can be explained as follows (**Fig. 6**):

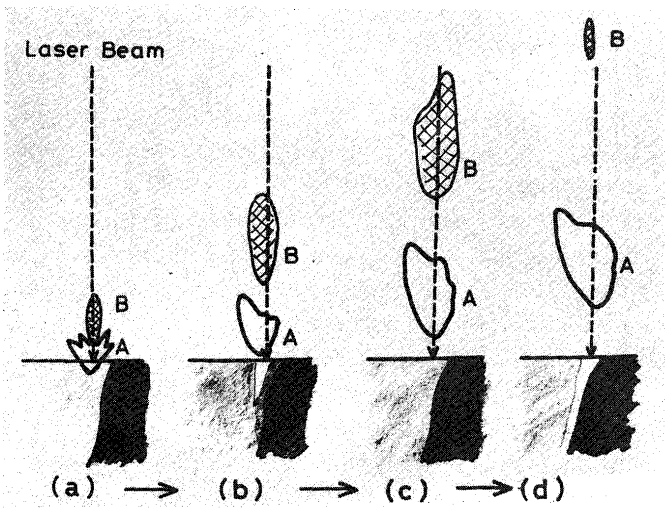


**Fig. 6** Laser welding phenomena in glass

a) When there is no plasma, the laser beam impinges directly on the front wall of the beam hole. (The front wall glows brightly.)
b) After strong impingement of the laser beam, intense laser plasma is produced and the laser beam is partially absorbed, reflected and/or scattered. (The front wall glows less brightly and the bright part moves a little inside the beam hole.)
c) This plasma is ejected upwards and the brightness of the beam hole is reduced.
d) When the plasma dissipates, the beam again intensely impinges on the front wall and this zone glows brightly.

Most of the drilling and melting occur only in the first stage, and strong flow is also associated with this stage. During this period, the laser beam rapidly melts the glass, producing a great deal of vapor and molten glass. In other stages, the plasma absorbs, reflects and/or scatters the laser beam although there is some difference in the degree to which these phenomena occur, thereby reducing the degree of vaporization and melting.

### 3.5. Laser Spike Seam Welding ("LSSW")

From the above analysis, it was found that the plasma produced during laser welding interrupts the laser beam and reduces its drilling ability. In order to remove or suppress the plasma, an assist gas is usually used. This assist gas, however, widens the beam hole, leading to failure of the "Wall Focusing Effect". Furthermore, it has been found that two kinds of plasma are produced, and that one of them can be suppressed by assist gas, but the other cannot be completely removed.

In order to overcome these difficulties, the authors utilized a new welding process: "Laser Spike Seam Welding" ("LSSW")[10]. In this process, the laser beam is oscillated so as to follow the movement of the specimen. The laser beam stops relative to the specimen for a certain period. It drills the specimen as a pulsed beam, then it quickly returns to its original position. In **Fig. 7**, the typical shapes of the beam hole in the continuous mode, pulsed mode and LSSW mode, respectively, are shown. Figure 7(a) shows the beam hole in laser welding of the conventional continuous mode. Figure 7(b) shows the

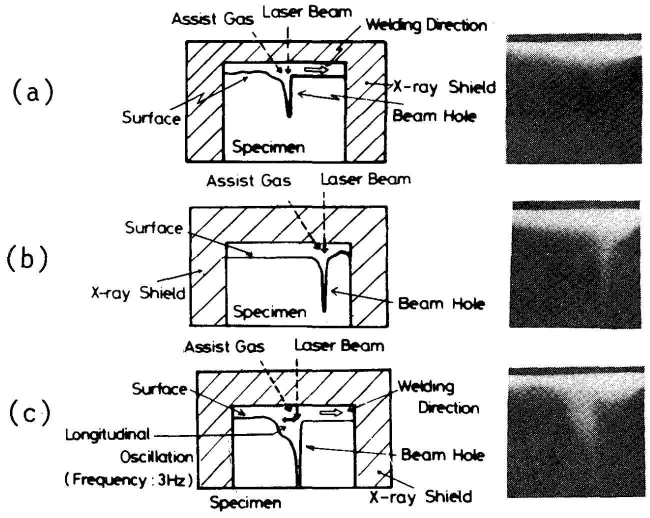
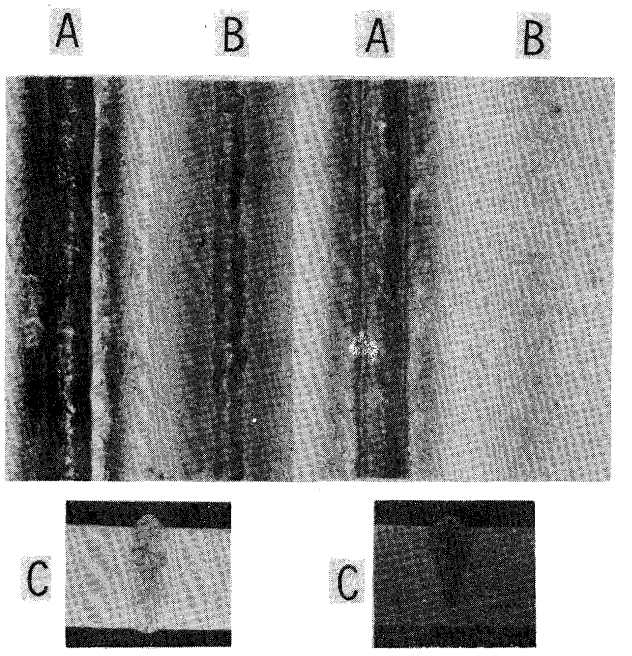


**Fig. 7** Typical photographs of beam hole in three different processes.
(a) continuous, (b) pulsed, (c) LSSW

drilling phenomena in laser welding of the pulsed mode. The pulse duration is the same as for the LSSW mode. It can be seen that the beam hole is deeper than in the conventional continuous mode. Figure 7(c) shows the shape of the beam hole during LSSW. The beam hole is deeper than above two modes. The shape of the beam hole in LSSW looks a combination of the continuous mode and pulsed mode. The upper part of the beam hole is bowl-typed, as in the continuous mode, and the lower part is wedge-shaped, as in the pulsed mode.



(a) (b)

**Fig. 8** Comparison of bead characteristics between LSSW and conventional type.

(a) LSSW, (b) Conventional
A: Front bead, B: Back bead, C: Cross section

**Figure 8** shows the comparison of bead appearance and cross section between LSSW and conventional laser welding under the same welding conditions of power and welding speed. It can be seen that LSSW process is superior in both the penetration depth and bead appearance.

The mechanism and the reasons why the LSSW process is superior are shown in **Fig. 9**. At the top of Fig. 9 is a series of high speed photographs of the beam hole in LSSW taken by the transmission X-ray method. The photographs at the bottom are the surface of the specimen which were taken at the same speed (300 frames per second) by conventional photography from 30 degrees above the specimen.

In the middle are schematic illustrations of these two kinds of photographs. The sequence of the LSSW process can be explained as follows:

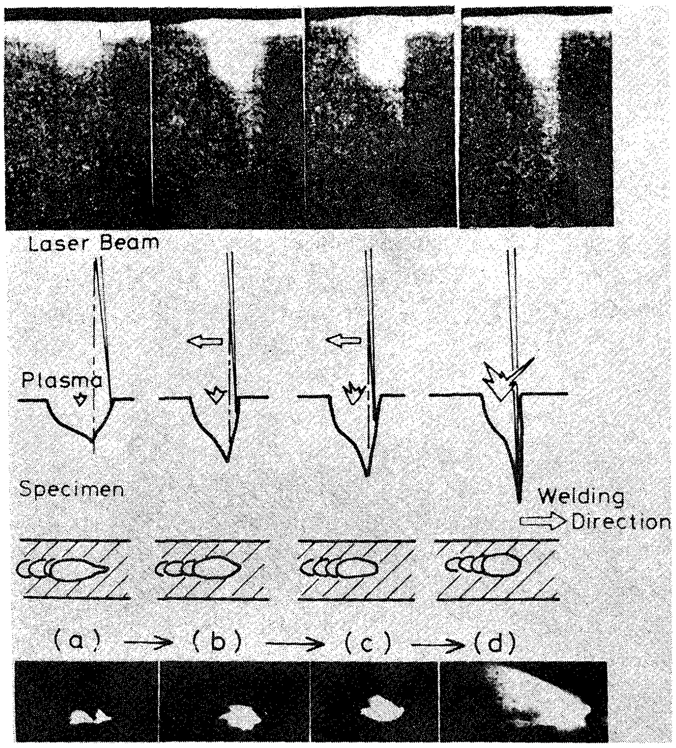


**Fig. 9** Welding mechanism of LSSW

a) When the laser beam is in its original position, the laser beam easily drills the specimen, because there is only a small amount of plasma.
b) The laser beam moves backwards along the specimen with the same speed as the worktable. It stops relative to the specimen, and quickly melts down the front wall.
c) As the laser beam drills the specimen, the amount of plasma produced gradually increases.
d) Just before a large amount of plasma is produced, the laser drills the specimen deeply.
e) Then the laser beam is quickly shifted forwards to its original position to avoid the plasma, and it again starts to drill the specimen.

In the top photographs, it can be seen that the gradient of the front wall changes during those stages. When the beam is in its original position (Stage (a)), the gradient of the front wall is gentle and the beam hole shape is bowl-typed. When the beam impinges perpendicularly (Stage (d)), however, the front wall becomes steep and the bottom of the beam hole becomes wedge-shaped. In the photographs on the bottom of Fig. 9, which show the beam hole from above, a small wedge can be seen at the front of the round beam hole opening (Stage (a)). It represents the shifting of the laser beam to its original position. With this periodic process, LSSW can avoid the plasma which reduces the penetration depth, thus allowing the laser beam to penetrate more deeply.

## 4. Conclusion

Fundamental phenomena during high power $CO_2$ laser welding in steel were observed dynamically. It was found that the laser plasma weakens the drilling force of the laser and this mechanism was shown in detail. Two kinds of laser plasma appear, one pink and the other sky blue, each showing characteristic behavior. Assist gas was effective in suppressing the pink plasma, but the sky-blue plasma could not be completely removed, even at high gas flow rates. The assist gas used for removing the laser plasma, however, also pushed away the molten metal and widened the beam hole. Therefore, too high a flow rate for the assist gas spoiled the "Wall Focusing Effect". This also caused a reduction in the penetration depth.

In order to solve these problems, "Laser Spike Seam Welding" was developed. This process can penetrate considerably deeper than conventional continuous welding by suitably avoiding the laser plasma.

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