Fundamental Phenomena in High Power CO_2 Laser (Report II)[†]

— Vacuum Laser Welding —

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Abstract

Laser welding under vacuum conditions (760 Torr — 10^{-5} Torr) was performed. The fundamental phenomena during Vacuum Laser Welding were dynamically observed, including the behavior of laser plasma, the molten pool and the beam hole. Observation was performed with a high speed camera and by the transmission X-ray method. It was found that Vacuum Laser Welding can almost completely suppress laser plasma and that this allows deep penetration at a very slow welding speed. Under these conditions, the shape and behavior of the beam hole during welding were very similar to electron beam welding.

The fundamental characteristics of Vacuum Laser Welding were also studied, including the effect of gas pressure and the welding speed on the penetration depth. The penetration depth increased with decreasing pressure and welding speed. A penetration depth of over 40 mm was achieved at a power of 11 kW, a pressure of 10^{-3} Torr, and a speed of 10 cm/min.

Vacuum Laser Welding using an aerodynamic window was proposed for practical applications. A penetration of over 25 mm was subsequently achieved, even at a pressure of 50 Torr.

KEY WORDS: (Vacuum Laser Welding) (Laser Plasma) (Beam Hole) (Molten Pool)

1. Introduction

Laser beams, electron beams, ion beams and special plasma beams are generally classified as "High Energy Density Beam (HEDB)". The most important feature of HEDB welding is the deep penetration depth. This is due to the presence of a deep beam hole, which results from the violent melting and evaporation phenomena caused by the high energy density[1].

However, compared with the considerably deep penetration of vacuum electron beam welding, it was difficult to achieve such deep penetration in atmospheric laser welding. This is due to the fact that laser welding in an atmosphere produces a great amount of laser plasma, which strongly interferes with a CO_2 laser beam[2]. An assist gas can easily suppresses such laser plasma and thus increases the penetration depth. However, an assist gas also affects the shape and behavior of the beam hole. When the flow rate of the assist gas is low, it has a very beneficial effect, but too high a flow rate of assist gas enlarges the upper part of the beam hole. This causes failure of the wall focusing effect and the beam hole becomes shallow.

In order to solve this problem, one of the authors developed a new welding method, "Laser Spike Seam Welding (LSSW)". In this method, the laser beam stops relative to a specimen for a short period of time in order to drill more deeply. Just before an overabundance of plasma is produced, the laser beam is quickly shifted forwards to keep it away from the strong plasma. Thus, LSSW can penetrate more deeply than conventional laser welding at the same power and welding speed. However, the penetration depth is still shallower than can be achieved with an electron beam of the same power[2].

Another solution to this laser plasma problem, Vacuum Laser Welding, is described in this report. In order to completely suppress the laser plasma, laser welding was performed inside a vacuum chamber such as is usually used for electron beam welding. The fundamental phenomena during Vacuum Laser Welding were dynamically observed,

and the fundamental characteristics were also studied.

2. Experimental Apparatus

A sketch of the experimental apparatus is shown in Fig. 1. It consists of a vacuum welding chamber, a vacuum pump system, a beam transport system and a work table. A 6″ diffusion pump system can make a pressure of from one atmosphere to 10^{-5} Torr inside the vacuum chamber. A 15 kW CO_2 laser apparatus was used at an a_b value of 0.998. The laser beam enters through a ZnSe window and a transport system which protects the ZnSe window from vapor and/or laser plasma. Mild steel, stainless steel and high tension steel were used as the specimen.
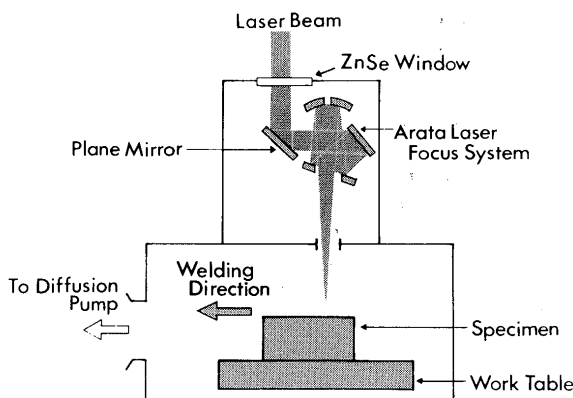

Fig. 1 Sketch of experimental apparatus.

3. Results and Discussion

3.1 Laser plasma

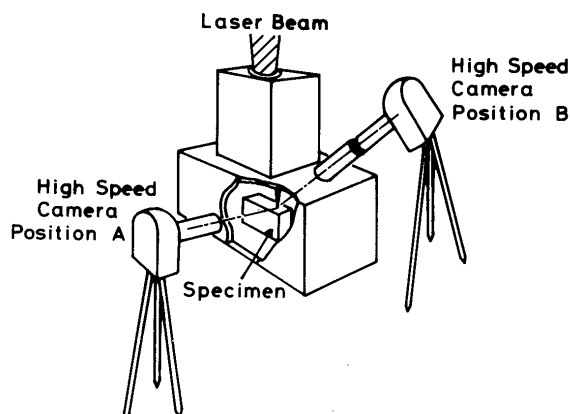The laser plasma produced by 9 kW laser beam at a

Fig. 2 High speed camera positions.

constant welding speed of 30 cm/min and at various pressures of from 200 Torr to 10^{-4} Torr was filmed with a high speed camera at a film speed of 3000 frames per second. The camera was placed at a side observation window of the vacuum chamber horizontally to the specimen as shown in Fig. 2. Several typical examples of the laser plasma produced at different pressures are shown in Fig. 3. When the pressure is 200 Torr, although there is no strong upward emission of plasma as under atmospheric conditions[2], a large amount of plasma is nevertheless produced. As shown in Fig. 3, the amount of laser plasma decreases with pressure. Below 5 Torr, the laser plasma is almost completely suppressed and only a minute amount of plasma can occasionally be seen. In this pressure range there is only a slight change in the amount of laser plasma as the pressure decreases further, even at a laser power of 11 kW.

To observe the phenomena on the surface of the molten pool in more detail, the phenomena were filmed from the upper observation window with the camera at position B, as shown in Fig. 2. Typical examples observed at a constant welding speed of 30 cm/min and a power of 9 kW are shown in Fig. 4. At a pressure of 50 Torr, some laser plasma still remains. The molten pool width is very wide, and the beam hole is positioned a little apart from the front wall. With decreasing pressure, the laser plasma inside the beam hole is suppressed. The molten pool width becomes narrower, and the beam hole moves near the front wall. The molten center line of the front wall and the solid wall on each side of the center line was sometimes seen. Below a pressure of 5 Torr, there is very little change in the molten pool width and in the beam hole position.

3.2 Beam hole

In order to observe the behavior of the beam hole inside the specimen, the dynamic X-ray observation method[3] was employed, as shown in Fig. 5. An X-ray tube was set at the side window of the vacuum chamber, and the glass in the side window was replaced with a thin sheet of aluminum. The X-rays emitted from the X-ray tube enter through the aluminum window of the vacuum chamber and irradiate the specimen. The X-ray image of the beam hole is converted to a visible image by an X-ray image converter placed opposite the X-ray tube. The
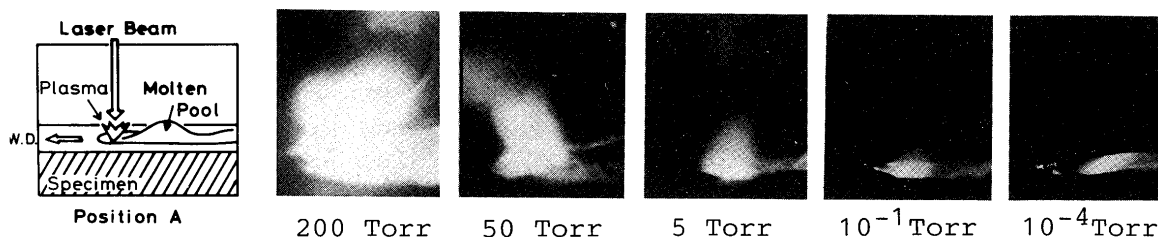

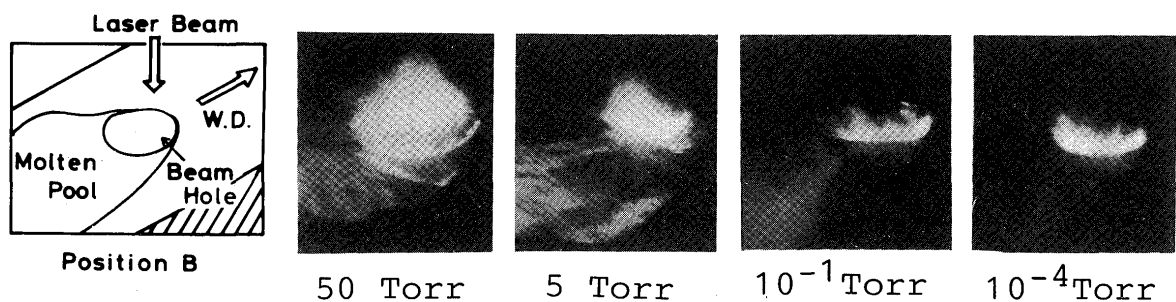Fig. 3 Typical photographs of laser plasma at different pressures.

Fig. 4 Typical photographs of laser plasma and the molten pool observed from upper observation window.
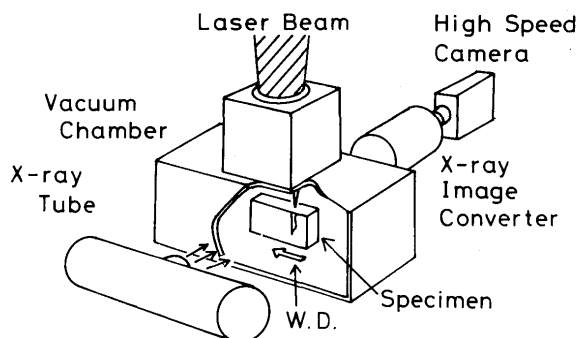

Fig. 5 Experimental setup of transmission X-ray method.

image is then filmed by a high speed camera at a film speed of 300 frames per second. Typical photographs of the beam hole at pressures of 5, 10^{-1} and 10^{-4} Torr and at a constant welding speed of 30 cm/min are shown with explanatory drawings in Fig. 6. It can be clearly seen that below a pressure of 5 Torr, at which point laser plasma is seldom apparent, there is little change in the beam hole shape and size. The behavior of the beam hole at a pressure of 10^{-3} Torr, a welding speed of 30 cm/min and a power of 9 kW is shown in Fig. 7. A bulge first appears at the bottom of the beam hole, then it moves smoothly upwards with a strong effect on the motion of the molten pool. The shape and behavior of these beam holes are similar to that in electron beam welding already re-
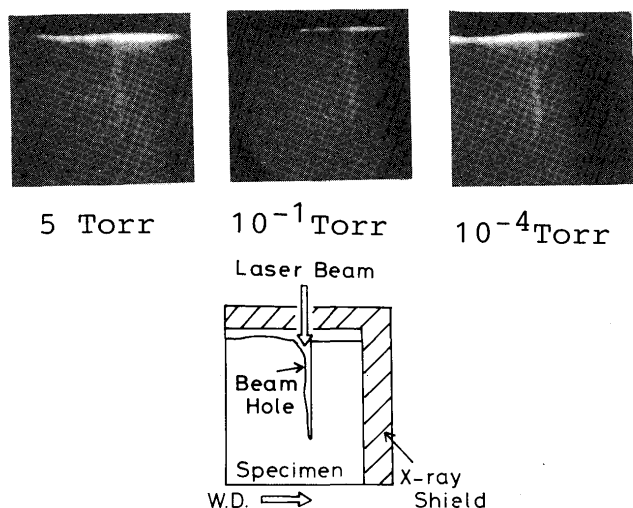

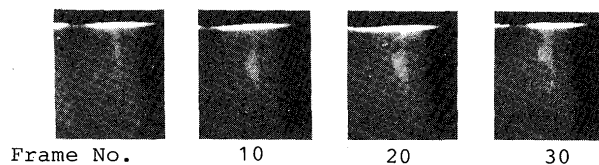**Fig. 6** Typical photographs of the beam hole at different pressures.

Fig. 7 Typical sequence of the motion of the beam hole. Numerical numbers represent frame numbers.

ported[3].

3.3 Penetration depth

Figure 8 shows the pressure dependence of the penetration depth at a constant welding speed of 30 cm/min and at a constant laser power of 9 kW. It is clear that the penetration depth increases with decreasing pressure down to the level of a few Torr, below which little increase in depth is seen. This pressure dependence of the penetration depth shows great similarity to that already reported for electron beam welding[4].

Figure 9 shows the dependence of the penetration depth on the welding speed, at a constant pressure of 10^{-3} Torr and at a constant power of 9 kW. The penetration depth also increases with decreasing welding speed
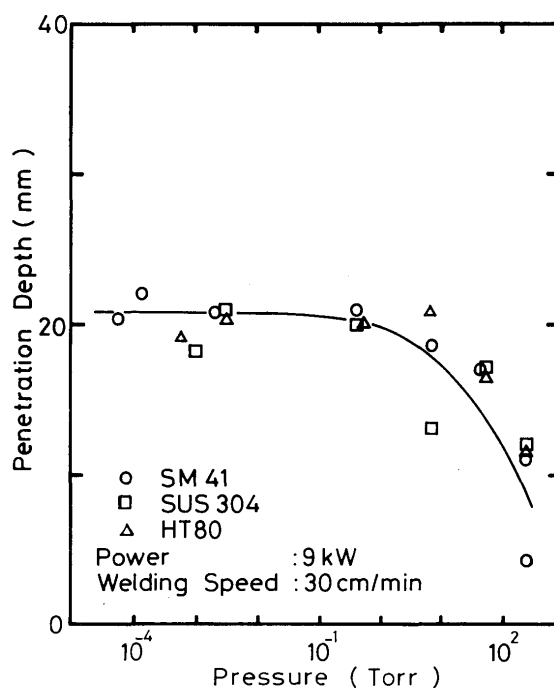

Fig. 8 Pressure dependence of the penetration depth.

Fig. 9 Welding speed dependence of the penetration depth.

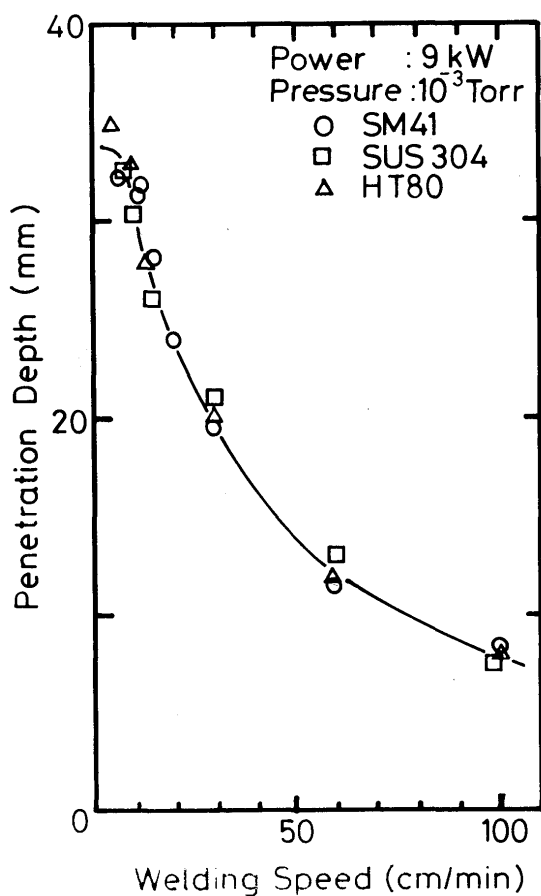Fig. 10 Power and welding speed dependence of the penetration depth.

and reaches a maximum value at about 10 cm/min. It also increases with power, as shown in Fig. 10. Even at a power of 11 kW and a speed of 10 cm/min, a penetration depth of 40 mm was achieved. The bead cross section welded under these conditions is also shown in Fig. 10.

Figures 11 − 13 show the phenomena when the pressure is kept at 10^{-3} Torr and the welding speed is reduced from 100 to 15 cm/min. Figure 11 shows a side view of the laser plasma. Even at a welding speed of 15 cm/min, there is no increase in laser plasma production. Figure 12 shows a top view of the specimen's surface from the upper observation window with the high speed camera at position B. When the welding speed is high, the molten pool is very narrow and the beam hole opening is at the very front of the molten pool. At a very slow speed, the molten pool becomes much wider and the beam hole
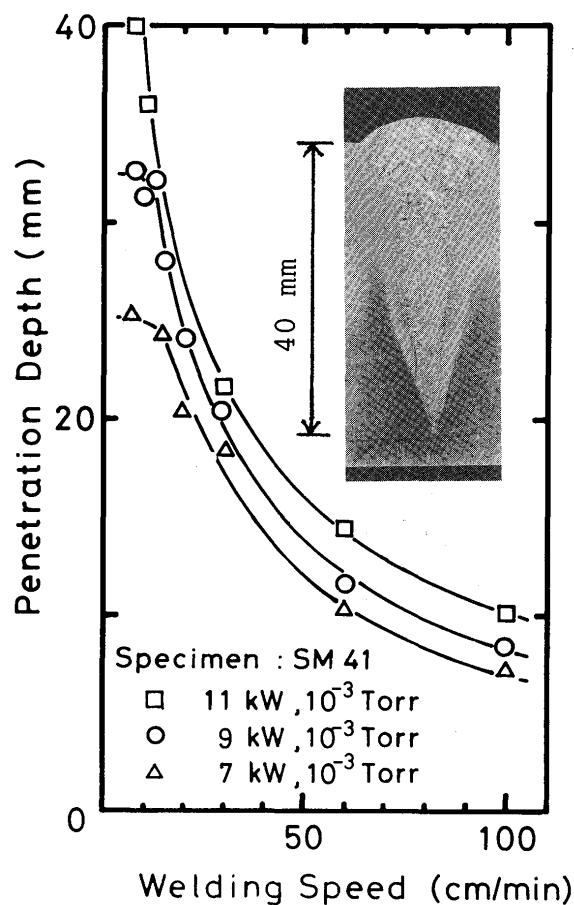
opening is positioned a little apart from the front of the molten pool. Figure 13 shows the beam hole as imaged by the transmission X-ray method. At a speed of 100 cm/min, the beam hole is shallow and inclined, and appears as a sock-like shape with a large bottom. In contrast, at a low speed of 30 cm/min, the beam hole does not yet have a sock-like shape, and is instead similar to that produced by electron beam welding.

It is found that in Vacuum Laser Welding, laser plasma, which is a fundamental problem in atmospheric laser welding, is almost totally suppressed. This enables very low welding speed and deep penetration can thus be achieved. Even at a laser power of 11 kW, deep penetration of over 40 mm was achieved at a welding speed of 10 cm/min. Under these conditions, the beam holes in
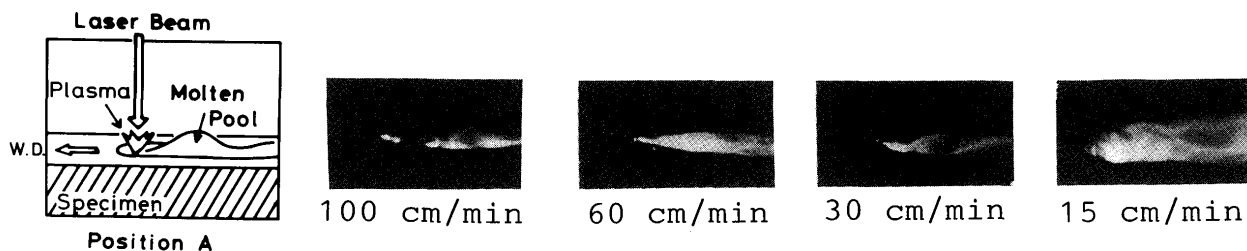

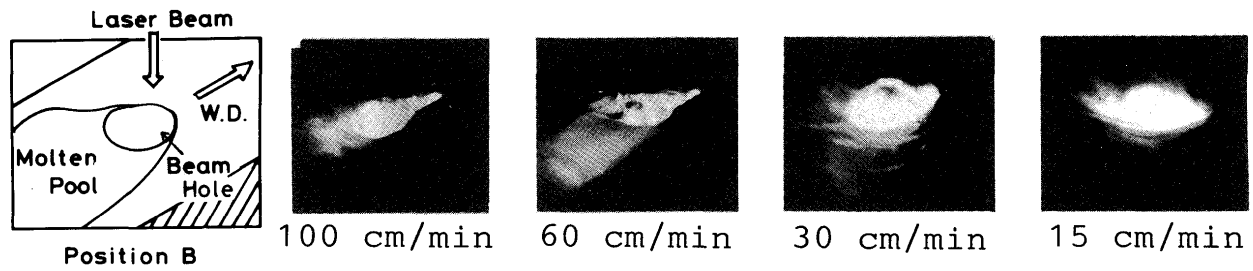Fig. 11 Laser plasma at different welding speeds.

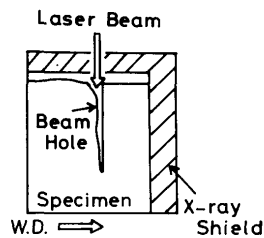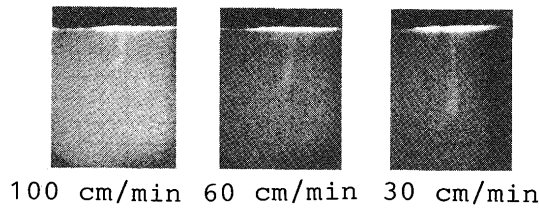Fig. 12 Laser plasma and molten pool observed from the upper observation window at different welding speeds.

Fig. 13 Beam holes at different welding speeds.

both laser beam welding and electron beam welding display a very similar shape and behavior.

4. Vacuum Laser Welding with Aerodynamic Window

Compared to an electron beam, which is essentially well-suited for welding in a high vacuum, a high power laser beam is not easy to handle under high vacuum conditions. The authors therefore would like to propose a new method of vacuum laser welding for practical applications. Figure 14 shows a prototype incorporating a low vacuum welding chamber with no ZnSe or KCl window for laser beam transmission. Instead, it has only a simple hole which functions as an aerodynamic window, thus avoiding the problem of laser power limitation and vapor damage to the window or mirrors. Furthermore, by varying the pressure of the welding chamber and upper vacu-
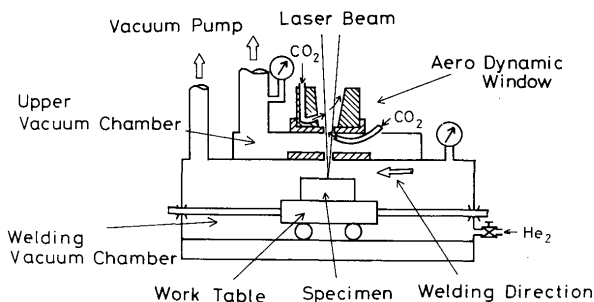

Fig. 14 Experimental apparatus of Vacuum Laser Welding with aerodynamic window.

um chamber, a dynamic pressure can be generated from the upper chamber to the welding chamber. This dynamic pressure serves the same function as an assist gas in atmospheric laser welding. Typical photographs of laser plasma at a constant welding pressure of 50 Torr and at different dynamic pressures are shown in Fig. 15. Above a dynamic pressure of 8 Torr, the laser plasma is visibly suppressed. However, as the dynamic pressure increases the upper part of the beam hole enlarges and the depth of the beam hole is reduced, as shown in Fig. 16. The gas flow caused by this dynamic pressure has the same effect on the beam hole as an assist gas in atmospheric laser welding already reported[2]. There is also an optimum value for deep penetration. At the optimum dynamic pressure, even under a pressure of 50 Torr, deep penetration of over 25 mm was achieved at a power of 11 kW and a speed of 25 cm/min, as shown in Fig. 17.

5. Conclusion

The laser plasma problem, which is the most severe problem in atmospheric laser welding, was completely solved by Vacuum Laser Welding. The fundamental phenomena during Vacuum Laser Welding were studied. Dynamic observation of the laser plasma with a high speed camera showed that laser plasma production decreased with pressure. Below a few Torr, laser plasma was almost completely suppressed, even at a welding speed of 15 cm/min. Dynamic observation of the beam hole with a transmission X-Ray method showed that the beam hole at
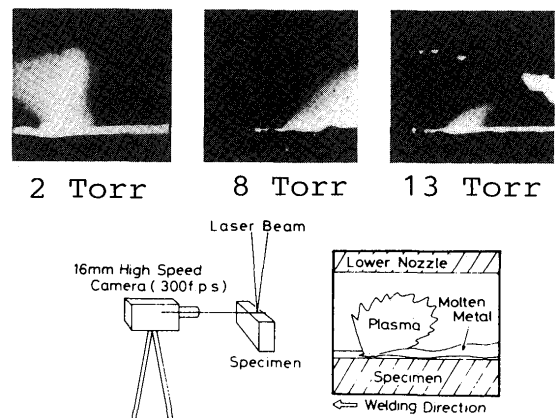

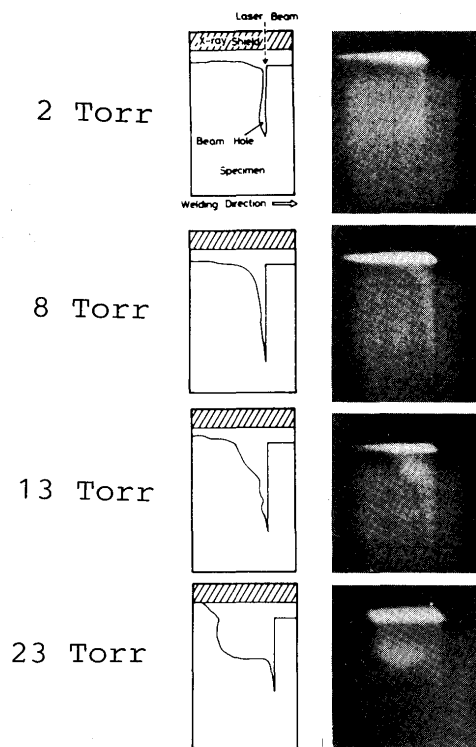Fig. 15 Laser plasma at different dynamic pressures.

Fig. 16 Beam holes at different dynamic pressures.

Fig. 17 Typical example of bead cross section of vacuum laser welding with aerodynamic window.

this low pressure is very similar to that of electron beam welding.

The fundamental characteristics of Vacuum Laser Welding were also studied, and it was found that the penetration depth increased with decreasing pressure at a constant welding speed and power. It also increased as the welding speed decreased, down to a speed of 10 cm/min under constant pressure and power. Under optimum conditions, a penetration depth of over 40 mm was achieved even at a power of 11 kW. It can be concluded that in Vacuum Laser Welding, laser plasma can be almost com-
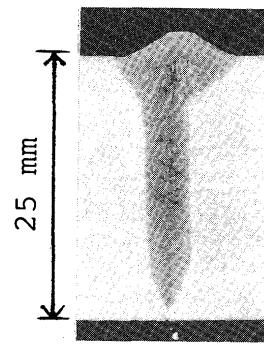
pletely suppressed. This enables very low welding speed which provides such deep penetration.

Furthermove, Vacuum Laser Welding with aerodynamic window is proposed for practical applications of Vacuum Laser Welding, and it has the potential to allow much high laser powers to be employed compared with other method under relatively low vacuum conditions of a few Torr to a few tens of Torr. Even at a pressure of 50 Torr, penetration depth of over 25 mm was achieved at a laser power of 11 kW.

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