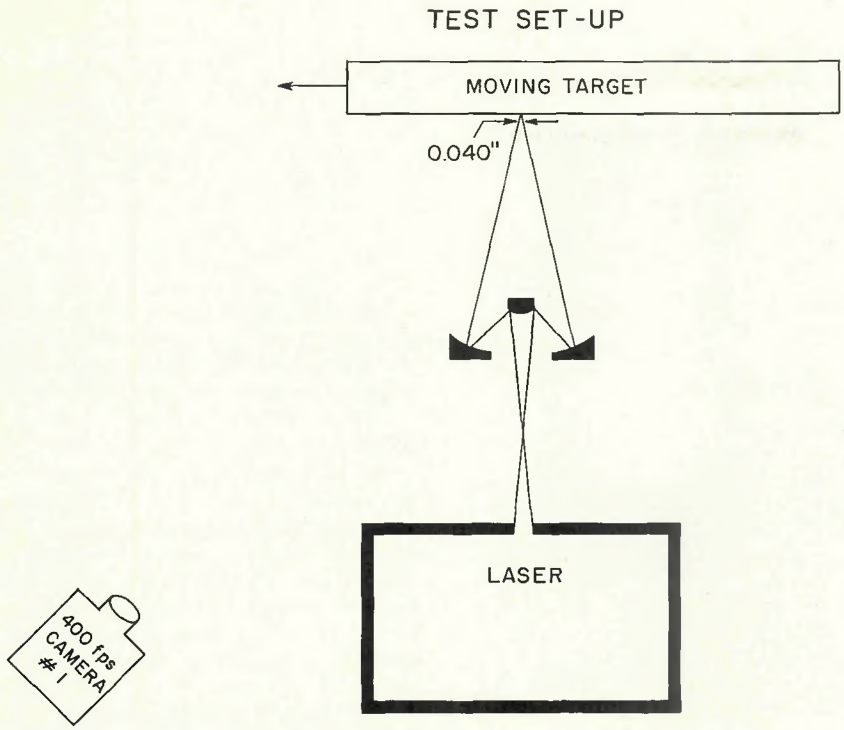

Fig. 1—Schematic of laser welding set-up

Deep Penetration Welding With High Power CO_2 Lasers

In type 304 stainless steel a penetration of 1/2 in. has been achieved at a rate of 100 ipm with a 20 kw power level

BY
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ABSTRACT. Experiments performed over the past year have involved the use of near diffraction limited lasers at power levels up to 20 kw for welding applications. This is a substantially higher power level than used in all previously reported experiments. As a result of the higher powers, significantly deeper penetration has been achieved. The optical cavity for the lasers was an unstable oscillator, producing a near diffraction limited output with an obscuration of approximately 50%. The measured penetration for these tests is in reasonably good agreement with established correlations for vacuum electron beam welding data, indicating a strong similarity between the two types of welding. It is shown that a power of 2 to 4 kilowatts is needed to produce thermally efficient welds in low thermal diffusivity plate materials such as 1/2 in. stainless steel and that higher powers are needed for the more highly conducting metals.

Introduction

The advent of high power CW lasers opens the door to metal working applications previously reserved for the more conventional high flux heat sources such as reacting gas jets, electric discharges, plasma arcs and electron beams. This paper is directed toward the applications of high power CO_2 lasers to such applications and in particular to rapid and deep penetration welding. Such welds were obtained at laser power levels of 8 kw and 20 kw. The results of these welding tests and other tests are correlated in a manner similar to that previously described for electron beam welding. Also, some quantitative estimates of the efficiency of these welds are presented. Finally, a brief summary will be given of some cutting tests performed with these lasers.

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Description of Apparatus

A schematic of the experimental set-up is shown in Fig. 1. For both of the lasers used, the beam emerged from the laser as a converging f/18 beam which reached a primary focal point just outside of the laser device itself. This primary focal point was reimaged by a Cassegrain optical system onto the workpiece which was transported by a conventional translational table through the secondary focal point. Due to a substantial degree of astigmatism in one of the external mirrors in this optical system, the resulting focal point size on the moving workpiece at the secondary focal point was approximately 0.040 in.

The characteristics of the two lasers is shown in Table 1. The gasdynamic laser delivered a power of 20 kw.[1] The optical cavity for this device is an unstable oscillator of the type described by Siegman which operated with an output coupling of 60%.[2, 3] The resulting beam was, therefore, an annular beam with the missing area in the center representing 40% of the total area of the beam. Independent measurements of the beam quality of this device obtained by focal point scans indicated a beam divergence quite close to the diffraction limit.[4]

The second laser was an electric discharge laser. While this unit has recently operated at a power of 14 kw, experiments were performed at an output power of 8 kw. This EDL was a closed cycle CW device with a total electric efficiency of approximately 14%. The optical cavity for this device was very similar to that in the previously described gasdynamic laser. It also operated with an unstable oscillator; however, for this device a coupling was only 40%. Therefore, the annular output beam had an obscuration of 60%. No quantitative measurements of the beam quality for this device were made but some qualitative measurements indicated that the beam quality was comparable to that of the gasdynamic laser mentioned earlier.

Experimental Results

Shown in Fig. 2 are photomicrographs of etched cross sections of welds made with the 20 kw gasdynamic laser on type 304 stainless steel. On the left side of Fig. 2 is shown a bead on plate weld with a penetration of approximately 3/4 in. and with approximately a 6 to 1 depth to width ratio. This weld was made at a speed of 50 in. per min (ipm). Also shown in Fig. 2 is a weld made with the same device at 100 ipm with a penetration

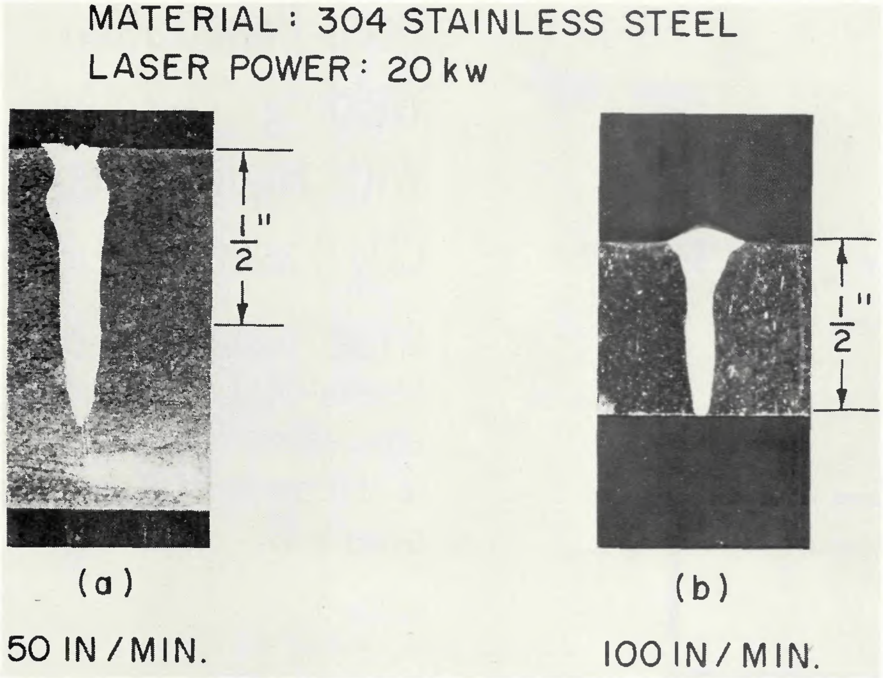

Fig. 2—20 kw laser welding cross sections

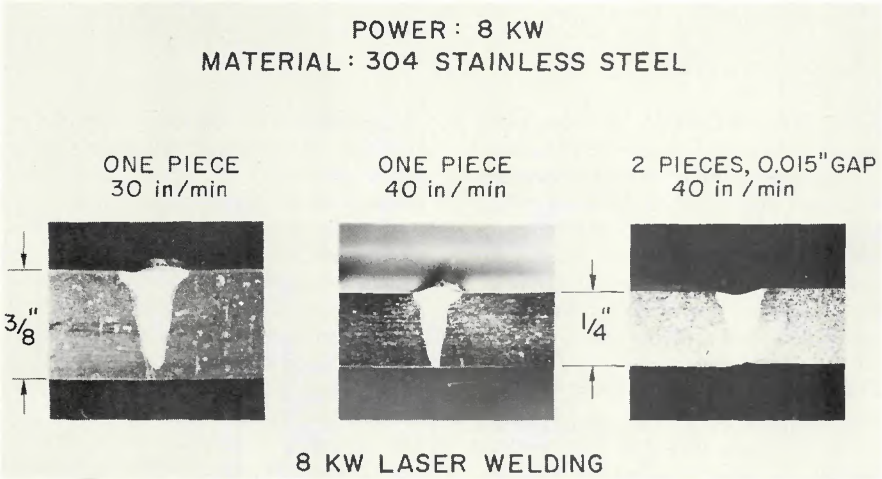

Fig. 3—8 kw laser welding cross sections

of $^1/_2$ in. While this photo shows full penetration to the $^1/_2$ in. thickness, the bead was made in a thicker plate which was subsequently milled down to $^1/_2$ in. The $^3/_4$ in. penetration weld shown in Fig. 2 was less regular and uniform along the weld length than the $^1/_2$ in. penetration weld. The reasons for this will be discussed later and are connected with the assist gas that was used.

In Fig. 3 are shown two bead on plate welds as well as a butt weld made at the 8 kw power level. At the left side of the figure is shown a bead on plate weld with nearly full penetration at 30 ipm in $^3/_8$ in. thick 304 stainless steel. In the middle of Fig. 3 is a bead on plate weld with full penetration at 40 ipm in a piece of $^1/_4$ in. stainless steel. Shown at the right is a butt weld between two pieces of $^1/_4$ in. stainless steel with commercially sheared edges which were separated by 0.015 in. before welding. Since the maximum average irregularity of the sheared edges was measured to be $\pm$ 0.005 in. the average gap was 0.020 in. The resulting fusion zone is slightly depressed as a result of this gap but it is seen that full penetration was still achieved. The significance of this is as follows: While very high depth-to-width ratios are desirable because of the structural characteristics of such a weld, it is frequently experienced that the minimum gap spacing requirement necessary to make such a weld render the process very uneconomical. It is for this reason that the degree to which this accurate edge fit-up is required will be an important consideration in laser welding. Results shown on the righthand side of Fig. 3 are therefore encouraging because they indicate that a fit-up requirement of slightly less than $^1/_{10}$ the thickness is still sufficiently good to obtain a good full penetration weld. For all of the welds shown in Fig. 3 the aspect ratio is approximately 3 to 1.

The results of these tests, as well as other tests reported in Ref. 5, are correlated in Fig. 4. In this figure, the normalized welding speed is plotted as a function of the normalized laser power. The power is normalized with respect to the power conducted into the parent material and the welding speed is normalized with respect to the speed of the characteristic isotherm as heat is conducted into the adjacent material. The solid line is a correlation obtained for E-beam welding data.[6] This correlation has been shown to be accurate over many orders of magnitude in these two normalized parameters.

At values of $P/\theta tk$ greater than 100, heat conduction is unimportant and the welding speed is a linear function of the power. However, at powers below 100 θth, heat conduction becomes important and the welding speed drops with the square of the power. Hence for any particular weld, the ratio of the actual power needed to the power needed without any heat conduction is a measure of the efficiency. It is seen that for the fastest welds obtained in our test of 20 kw, an efficiency of approximately 45% was obtained. At the lower power levels of 8 kw, the experimentally obtained efficiency was about 28%. For the United Aircraft Research Laboratory welding at 3.8 kw, the efficiency was about 22%.

If an efficiency of 30% is arbitrarily defined as the minimum efficiency for reasonable laser welds, a plot of power required to achieve this efficiency as a function of material thickness for different materials can be plotted. Such a plot is shown in Fig. 5 for stainless steel, low carbon steel, 6061 aluminum and copper. It is seen that a power of approximately 4 kw is needed for penetration of 1 cm in stainless steel, 14 kw in low carbon steel, 16 kw in aluminum and over 60 kw for pure copper. It is interesting to note that the efficiency is independent of the width of the weld zone and depends only on the product of weld velocity times width of the weld.

It should be pointed out that deep penetration welds can be obtained at much lower powers but with correspondingly low efficiencies. For example, E-beam welds in 0.5 cm copper have been obtained at 4 kw, where the efficiency is only 1%.

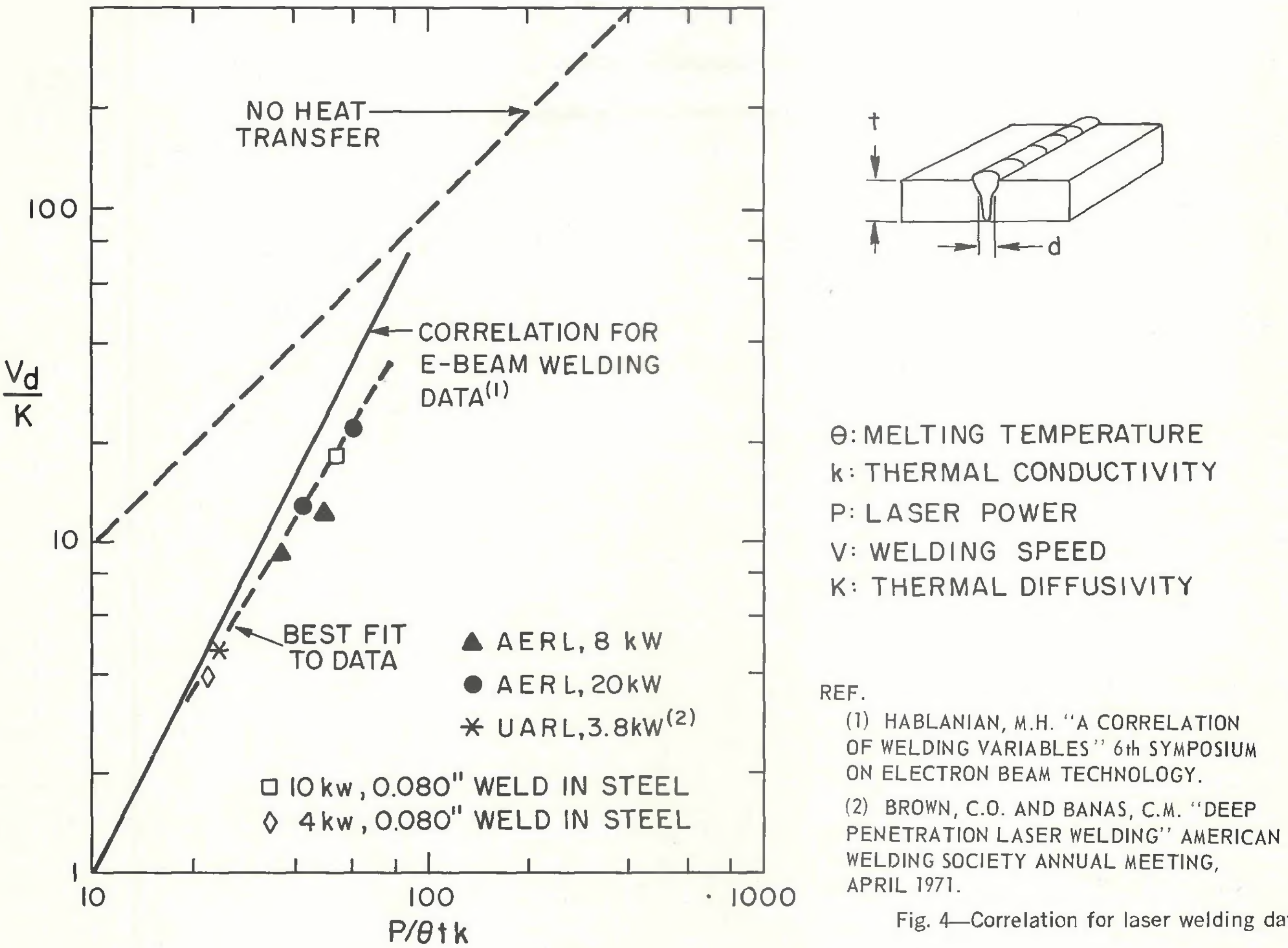

Fig. 4—Correlation for laser welding data

To perform the welds described in Figs. 2 and 3, an assist gas was used. Several configurations of gas assist were tried and are shown schematically in Fig. 6. In the gas assist shown schematically as type 1, a low mass flow jet of argon was directed at the interaction point. In the type 2 assist, the gas was directed parallel to the workpiece and slightly offset from the piece to be welded.

Photographs of the laser workpiece interaction point with the various types of assist gases just described are shown in Fig. 7. The resulting cross sections of the welds made with each of these gas assist types are also shown.

With the type 1 gas assist, penetration was the deepest. However, the weld was not uniform and had less penetration at some locations along the length of the weld. In addition, the head of the weld was blown off because of the dynamic pressure exerted on the molten metal by the gas assist. With the type 2 gas assist there is a considerably greater degree of luminosity at the interaction point. However, from the resulting weld it is obvious that most of the laser beam penetrated through to the material to be welded. This type of weld in which the gas assist was displaced slightly off the surface resulted in a very smooth continuous weld with uniform properties along the length.

On the righthand side of Fig. 7 is shown the type of interaction resulting from the tests in which no gas assist was used. It is seen that the interaction point of the laser beam with the workpiece is only slightly incandescent. However, a region of very high luminosity is seen to be located in the laser beam but displaced well away from the workpiece. Apparently, a significant amount of metal is vaporized at this interaction point, ejected backward into the incoming laser beam, and ionized by the laser beam. This standing ionization cloud then radiates away the incident laser radiation and only allows enough of the laser beam to penetrate to the workpiece to maintain the vaporization.

This phenomena of a standing ionization cloud with no gas assist and the difference in types of welds depending on the type of gas assist used clearly demonstrates the significance of a proper gas assist for laser welding. At powers below 8 kw, no ionization was observed. However, at powers above that value precautions must be taken to prevent the formation of this ionization cloud for laser welding. For the gas assist to be successful (prevent the formation of the ionization cloud) it must "blow away" the metal vapor ejected from the interaction point. Quite clearly, there are other mechanisms which can more easily prevent the formation of this ionization cloud—such as the use of gases which inhibit ionization.

In addition to the welding experiments previously described, a limited number of laser cutting experiments were performed with different types of materials. A summary of these tests is shown in Table 2. No gas assist was

Table 1—Laser Characteristics

Gas Dynamic Laser

Power: 15–20 kw
Optical cavity: unstable oscillator, 60% coupling
Beam quality: near diffraction limited

Electric Discharge Laser

Power: 8–14 kw
Optical cavity: unstable oscillator, 40% coupling

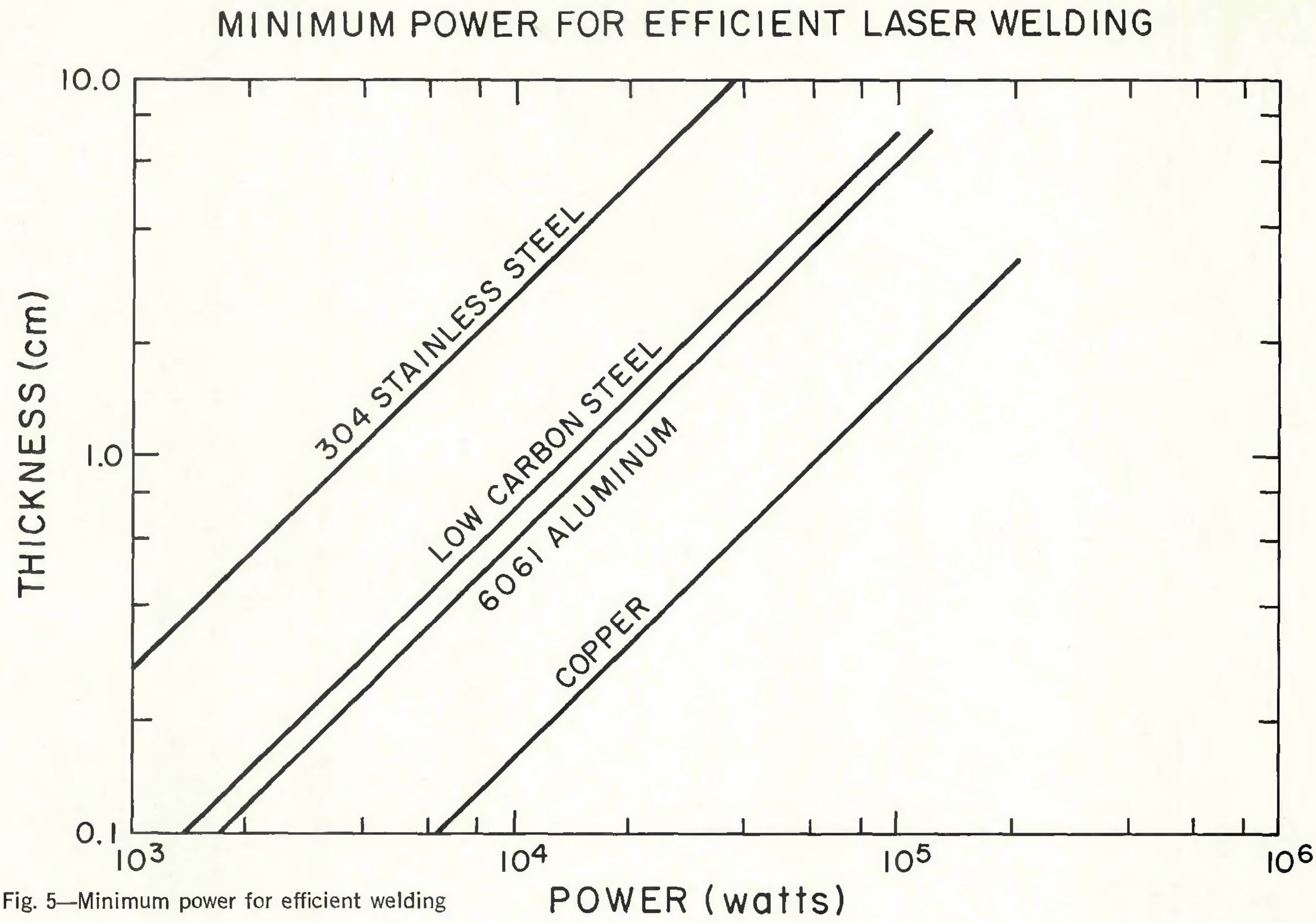

Fig. 5—Minimum power for efficient welding

used for these tests. Cutting rates of up to nearly 200 ipm were obtained at 20 kw in 0.5 in. thick fiberglass epoxy. In this material, as well as the boron epoxy composite, heat affected zones of up to 0.080 in. were measured. It is likely that a properly designed blanket of inert gas would substantially reduce this heat affected zone (HAZ). Rates of 50 to 100 ipm in 0.187 to 0.5 in. metals including aluminum, steel and stainless steel were attained with HAZ less than 0.010 in. but with edge curvatures of up to 0.010 in. Again in this case, a properly designed gas assist jet would very likely result in straighter sided cuts with a smaller HAZ.

Table 2—Summary of Laser Cutting and Welding Experiments

Material	Application	Thickness in.	Rate in./min	Kerf	Power
Aluminum	Cutting	0.5	90	0.040	15,000
Carbon Steel	Cutting	0.25	90	0.040	15,000
Stainless steel, type 304	Cutting	0.187	50	0.080	20,000
Boron epoxy composite	Cutting	0.32	65	0.040	15,000
Fiberglass epoxy composite	Cutting	0.5	180	0.025	20,000
Plywood	Cutting	1.0	60	0.060	8,000
Plexiglass	Cutting	1.0	60	0.060	8,000
Glass	Cutting	0.375	60	0.040	20,000
Concrete	Cutting	1.5	2	0.250	8,000
Stainless steel, type 304	Welding	0.8	50	0.130	20,000
Stainless steel, type 304	Welding	0.5	100	0.090	20,000
Stainless steel, type 304	Welding	0.35	30	0.090	8,000

Conclusion

Experiments involving deep penetration laser welding have been discussed. These experiments were performed at power levels of 8 kw and 20 kw with near diffraction limited laser beams. The resulting welds have deeper penetration and higher speed than any previously reported laser welding. Penetration of $^1/_2$ in. has been achieved at a rate of 100 ipm in a 5 to 1 depth to average width fusion zone in 304 stainless steel at a 20 kw power level. These experiments were made on a gasdynamic CO_2 laser. Penetration of nearly $^3/_8$ in. in a 3:1 aspect ratio fusion zone was achieved at 8 kw with a recently completed closed cycle EDL which has produced an output of up to 14 kw. In one experiment at the 8 kw level, two pieces of $^1/_4$ in. stainless steel with commercially sheared edges and spaced 0.015 in. apart were joined with nearly full thickness fusion zone of 0.080 in. average width.

In addition to the reporting of these experimental results, correlation of the laser welds have been achieved using the same correlation parameters successfully used in deep penetration E-beam welding data.

An interesting phenomenon that can occur at these very high power levels was observed. This phenomenon which became evident at about 8 kw results in a generation of a well concentrated ionization cloud in the laser beam which appears to be fed by ejecting metal vapor from the material to be welded. This plasma appears to absorb most of the incident laser radiation and unless blown away prevents most of the laser radiation from reaching the metal target. While this standing plasma must be eliminated in one way or another to accomplish

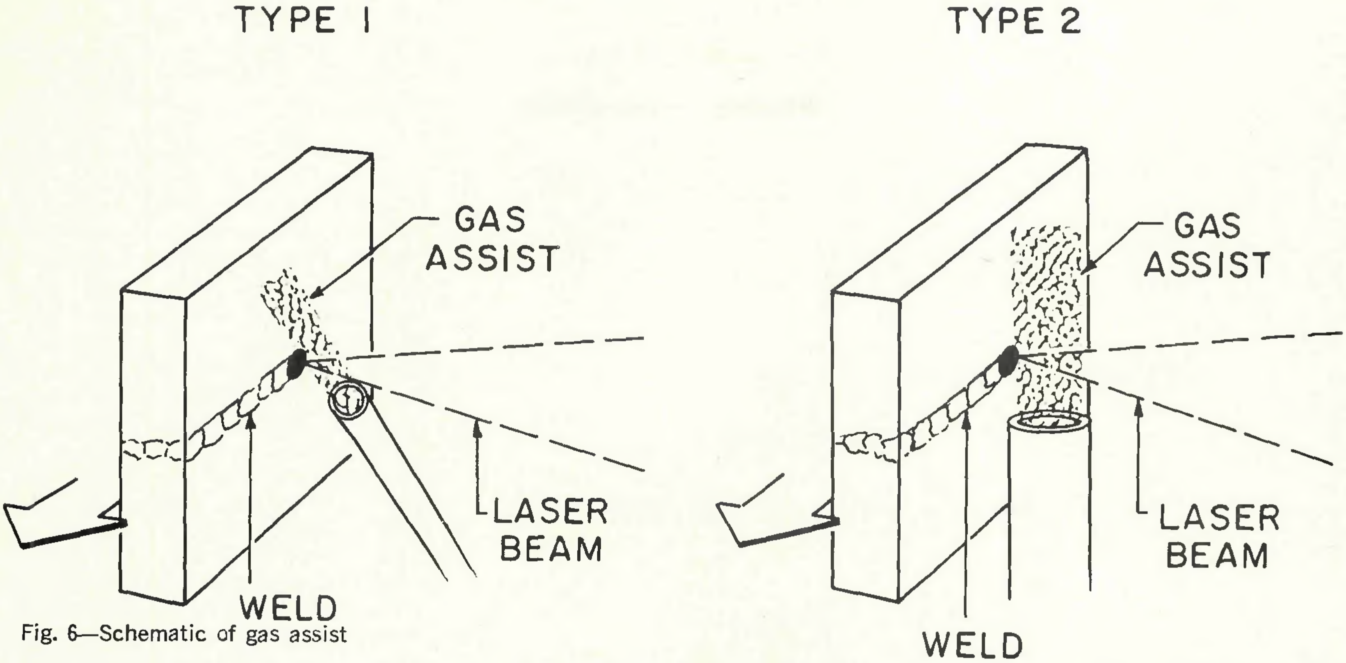

Fig. 6—Schematic of gas assist

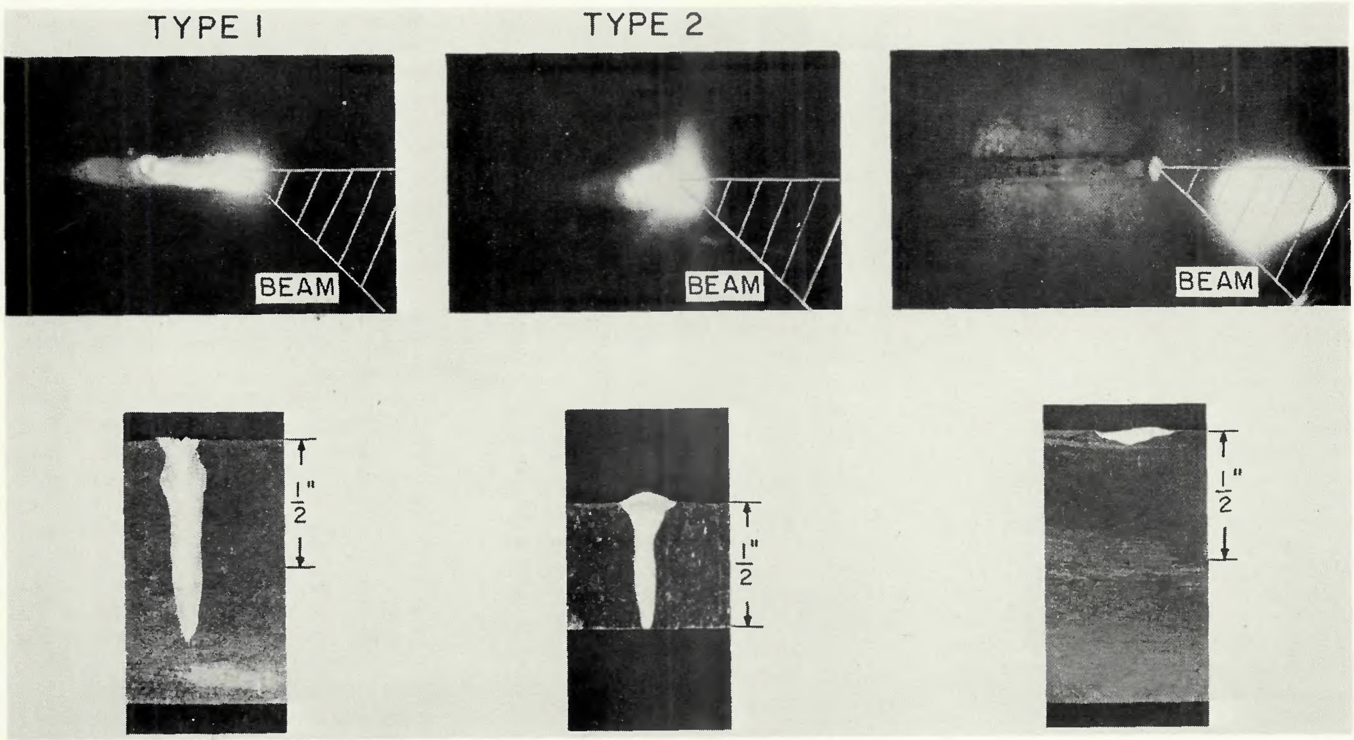

Fig. 7—Photographs of laser material interaction

successful welds at high powers, its presence may be the basis of a series of very interesting applications for high power lasers due to the peculiar and unique characteristics of this standing plasma cloud.

Acknowledgement

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