Dual Beam Laser Welding

An experiment in which a high-power CO_2 laser beam was split into two equal-power beams that were then used as a welding heat source indicated the dual-beam laser could significantly improve weld quality

BY J. XIE

ABSTRACT. In recent years, laser beam welding using two laser beams, or dual-beam laser welding, has become an emerging welding technique. Previous studies demonstrated use of dual-beam laser processing can delay humping onset to higher speeds and slow down cooling rates. In this study, a detailed investigation was performed to quantify the benefits of dual-beam laser processing and to understand the mechanism for improving weld quality. A 6-kW CO_2 laser beam was split into two equal-power beams and the dual beams were located in tandem (one beam follows another) during welding. Experimental results indicated the dual-beam laser could significantly improve weld quality. For steel, surface quality was improved with fewer surface defects such as undercut, surface roughness, spatter, and underfill. Weld hardness and centerline cracking susceptibility were also reduced. In aluminum, quality improvements were in the form of smooth weld surfaces and fewer weld defects such as porosity, surface holes, and undercut. A high-speed camera investigation of welding vapor plumes above a workpiece showed plume height and size changed dramatically in conventional single-beam laser welding and the average fluctuation frequency was 1.2 kHz for steel. As the plume fluctuation was associated with keyhole instability, unstable vapor plume indicated the process was unstable and would result in poor welds. The vapor plumes in dual-beam laser welding were found to fluctuate at a certain frequency range, but the plume size changed only slightly during welding. The stabilized process contributed to improved weld quality in dual-beam laser welding.

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Introduction

Laser welding has been widely used in the automotive, aerospace, electronic, and heavy manufacturing industries to join a variety of materials. In the automotive industry, high-power lasers are used to weld many components such as transmissions, mufflers, catalytic converters, exhaust systems, and tailor-welded blanks. It was reported about 70 million tailor-welded blanks were produced in 2000, a number predicted to be 95 million in 2001 (Ref. 1).

However, a number of defects, such as porosity, surface holes, irregular beads, undercuts, humping, and solidification cracking, are often found in laser welds. Industrial laser users are always looking for economical methods to improve weld quality and relax the strict fitup requirement for workpieces. A welding technique that combines two high-energy beam sources (either electron beams or laser beams), called "dual-beam welding," has been investigated in recent years. Initial experimental studies showed the dual-beam process offered several advantages over the conventional single-beam process. An early electron beam (EB) welding experiment performed by Arata *et al*., who used dual electron beams during welding, demonstrated a trailing beam impinging on a molten pool could increase the welding speed at which humping occurred up to 50% (Ref. 2). In dual-beam laser processing, the dual beams can be arranged either side by side (Fig. 1A) or in tandem — Fig. 1B. Conrad Banas (Ref. 3) used a bendable mirror to split a laser beam into two beams that were then arranged side by side during welding to increase the fitup tolerance of workpieces — Fig. 1A. A study on using side-by-side laser beams for improved fitup tolerance has been reported in welding tailored blanks (Ref. 4). The rule of thumb is that the air gap between two workpieces should be less than 10% of the sheet thickness for butt joints and 25% for lap joints in conventional single-beam laser welding. Use of the side-by-side dual-beam lasers could substantially increase the fitup tolerance in welding tailored blanks (Ref. 4).

KEY WORDS

Laser Welding
Beam Splitting
Dual Beam
Weld Quality
Defect
Steel
Aluminum
Vapor Plume
Fluctuation
Keyhole Instability

Dual laser beams arranged in tandem (Fig. 1B) have been reported to provide benefits over conventional single-beam laser welding such as improved weld quality (Refs. 5–11). The current study focused on the tandem dual-beam laser welding process and its impact on weld quality. In this paper, unless specified, dual-beam laser welding means two laser beams are arranged in tandem, as shown in Fig. 1B.

One of the possible benefits of using the dual-beam laser was to decrease cooling rates in laser welding of high-carbon steel (Refs. 5, 6). It was said cooling time between 800 and 500°C could be extended from 3.8 up to 7 s by enlarging the distance between the two beams (interbeam spacing), where two 5-kW CO_2 lasers were combined (Ref. 5). A dual-beam laser welding experiment on AISI 4140 steels was performed by Liu and Kannatey-Asibu in which the leading laser beam was focused on the surface of a workpiece and the trailing beam was defocused on the weld bead at an interbeam space of 10 mm (Ref. 6). The dual-beam process resulted in lower cooling rates, reduced hardness,

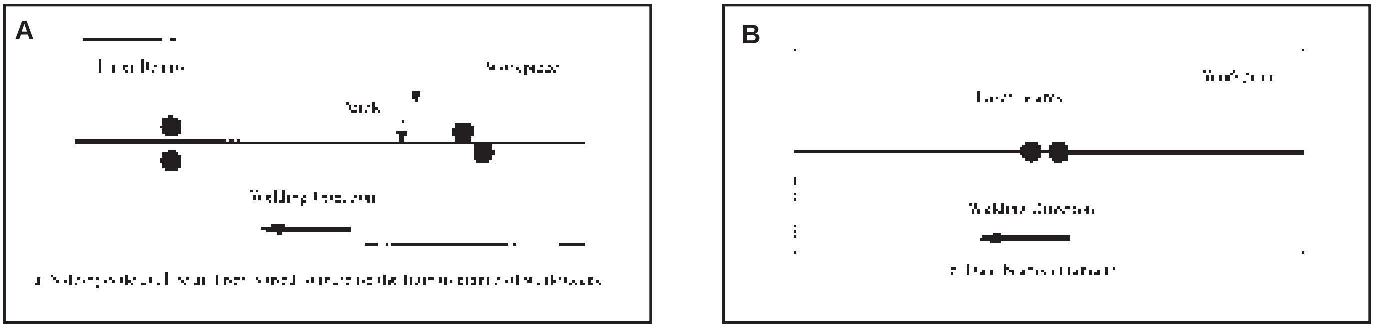

Fig. 1 — Setup of dual laser beams. A — Side-by-side dual-beam laser is used to increase the fitup tolerance of workpieces; B — dual beams in tandem.

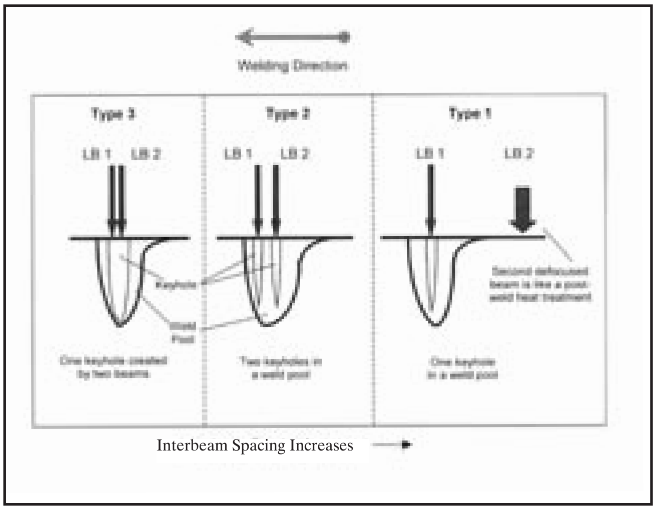

Fig. 2 — Welding mechanism at various interbeam spaces in parallel dual-beam laser welding.

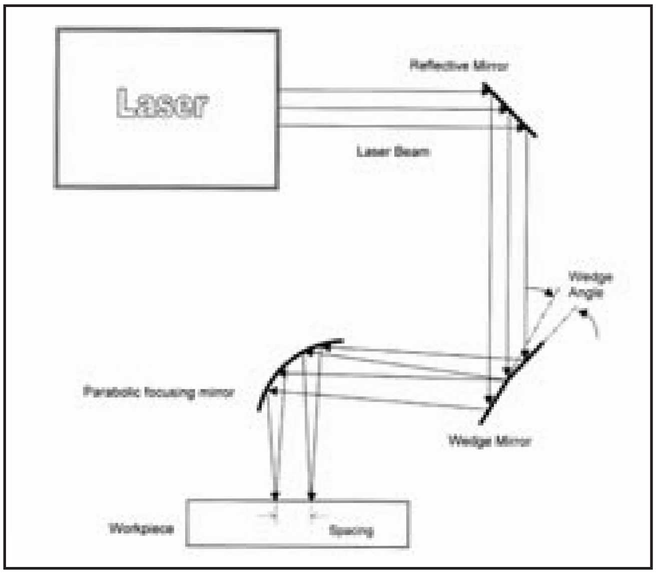

Fig. 3 — Beam splitting system for a high-power CO_2 laser.

and a smaller volume percentage of martensite in the 4140 steel welds when compared to single-beam laser welds. Similar results were obtained in welding thin, high-carbon steel sheet (0.85% carbon content) using two combined pulsed Nd:YAG lasers (Ref. 7). Several mathematical models on the cooling rates in dual-beam laser welding were developed by Kannatey-Asibu *et al.* (Refs. 8, 9). These theoretical analyses showed the cooling rates at the weld centerline were reduced from 1004°C/s in the single-beam process to 570°C/s in the dual-beam process while the laser power and interbeam spaces were 1.8 kW and 10 mm, respectively (Ref. 9).

Dual-beam laser processing was also reported to help reduce porosity and prevent cracking in laser welding of aluminum alloys. Porosity in weld metal could be significantly reduced when the leading laser beam was focused at the workpiece surface and the trailing beam was defocused at 2 mm above the workpiece (Ref. 5). In this experiment, two 5-kW CO_2 lasers were combined with an angle of 30 deg between two beams and an interbeam space of 3 mm. Using a dual-beam laser system that combined a continuous wave Nd:YAG (200 W) and a pulsed Nd:YAG (410 W), microcracking could be prevented in welding 1-mm-thick A5052 aluminum sheets (Ref. 10). A similar experiment using two pulsed Nd:YAG lasers indicated porosity and cracking were reduced when welding 0.8-mm A5005 aluminum plates (Ref. 11). In this experiment, the leading beam was focused on the surface at an incline angle of 10 deg and the trailing beam focused down at an angle of 45 deg. It was found porosity- and crack-free welds could be produced at interbeam spaces of 0.2 and 0.4 mm only, while other processing parameters were 10-Hz pulse frequency, 3-ms pulse width, 140-mm/min travel speed, 18-J pulse energy for the leading beam, and 9 J for the trailing beam. As interbeam spacing was increased to greater than 0.6 mm, the effects of reducing porosity and cracking no longer existed in the experiments (Ref. 11).

Changes in weld depth in dual-beam laser welding were investigated in some studies (Refs. 5, 12). An experiment studying the influence of interbeam spacing and power ratio of dual laser beams on weld depth and width was reported by Glumann *et al.* (Ref. 5). In the experiment, the angle between the two CO_2 laser beams was 30 deg and the laser power combinations were 400/3500, 3500/1700, and 3500/900 W, respectively. The experimental results showed changes in weld depth and width were small at spaces of 1, 10, and 20 mm (Ref. 5). Further investigation indicated weld depths produced by both single- and dual-beam lasers were almost the same if the dual beams were focused on a common spot (Ref. 5). Another welding experiment, in which a 1-kW pulsed and a 2-kW CW Nd:YAG laser beams impinged at the same spot on a 304 stainless steel plate, showed weld depth

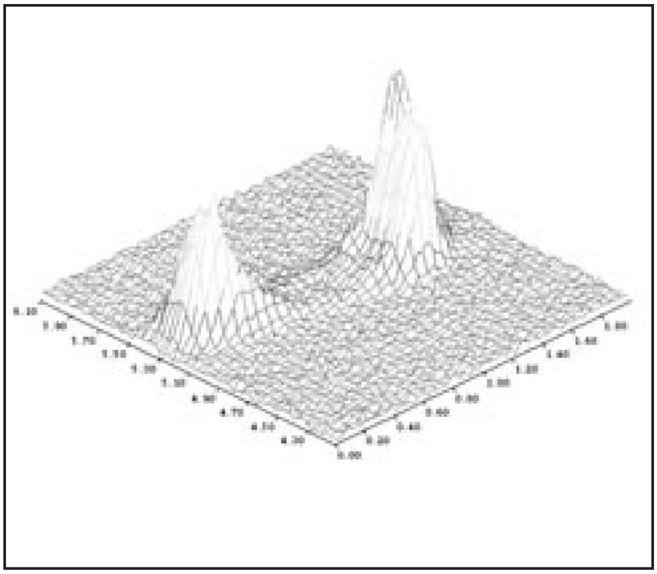

Fig. 4 — Dual-beam laser power density distribution at focus position.

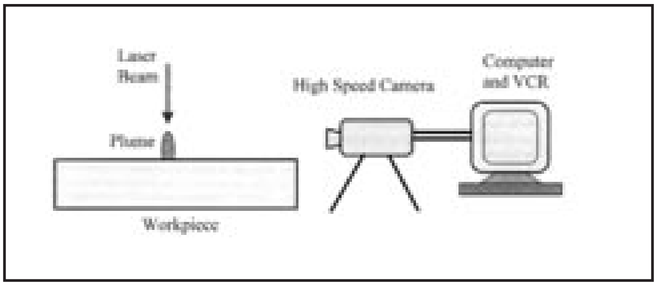

Fig. 5 — Experimental setup for investigating vapor plumes during laser welding.

varied from 5 to 7 mm at various angles between the two beams (Ref. 12). Since the previously mentioned results were obtained at different experimental conditions, it was not easy to conclude the impact of dual laser beams on weld morphology.

In most reported experiments, the term "dual beam" means two laser beams were used during welding. However, the lasers used in these experiments changed dramatically from low-power CW/pulsed Nd:YAG lasers to high-power CW CO_2 lasers, and the setup of the two laser beams was different, such as interbeam spacing, angles between two beams, focusing positions, and laser power ratios. Essentially, the dual-beam laser systems could be built by either combining two lasers with an angle between two beams (Refs. 5, 10–12) or splitting a laser beam into two parallel beams with an optical splitter (Ref. 6). Among the reported dual-beam systems, many were the combination of two Nd:YAG lasers because of easy manipulation by using two focus heads with fiber optics (Refs. 10–12). It was possible to combine CO_2 lasers by using a special optic device as well (Ref. 5). The combined dual-beam laser systems were more flexible in changing interbeam spacing and the power ratio of dual laser beams. However, the split dual laser beams were almost parallel and had the same planes of polarization (coherent) as many lasers produced polarized beams. Based on the arrangements of the two laser beams, the dual-beam process can basically be divided into two types, angled and parallel. Most of the reported dual-beam systems were angled and a small interbeam spacing could easily be achieved in these systems. In the parallel dual-beam systems, spacing was usually large and they were often used for reducing cooling rates (Refs. 6, 7). In such systems with a large interbeam spacing, two Nd:YAG laser heads could simply be put together by a common holding fixture (Refs. 7, 11, 12), or a transmissive beam splitter was inserted in a CO_2 laser beam path if the laser power was not high (<2 kW) (Ref. 6). The welding mechanisms and impact on laser welds are believed to be slightly different between the angled and parallel dual-beam processes and, also, the welding mechanism changed with variations in interbeam spacing in both the angled and parallel beam systems.

Generally, there might be three types of welding mechanisms in parallel dual-beam laser welding, depending on interbeam spacing, as shown in Fig. 2. The first type is the dual-beam process with large interbeam spacing in which one of the two beams creates a keyhole and the other acts as a heat source for heat treating the laser beam weld. The second is the two laser beams generate two keyholes in a common weld pool and the mass flow pattern of the molten metals is changed. In Type 3 of the parallel dual-beam process, interbeam spacing is small and the two beams interact with materials in a common keyhole. In the angled dual-beam process, the mechanism is also believed to be changed at various interbeam spacings similar to the parallel dual-beam process.

When interbeam spacing in the parallel dual-beam process is large (Type 1), the leading beam usually acts as a welding heat source to create a keyhole on the workpiece, and the trailing beam is usually defocused or has a lower laser power to do heat treating on the laser weld. In this case, the cooling rate is reduced and this feature can benefit some crack-sensitive materials such as high-carbon or alloyed steels. Additionally, the amount of the bainitic structure is increased in the weld metal and heat-affected zone (HAZ), and improved toughness is expected for the welds. This benefit has been verified by a number of experiments and was well analyzed by mathematical modeling (Refs. 5–9).

As interbeam spacing is reduced to a certain degree, the welding mechanism switches to Type 2, in which two laser beams interact in a common weld pool but the dual laser beams create two separate keyholes, as shown in Fig. 2. In an early work on dual EB welding (Refs. 2, 16), the influence of interbeam spacing on mass flow of liquid metal in a weld pool and the formation of humping and undercut were discussed; the tested interbeam spaces were 4, 7, and 16 mm, respectively. It was found humping and irregular welds could only be prevented at the 7-mm space because of the change in the flow direction of molten metal in the weld pool. However, humping and some surface defects were present at the 4- and 16-mm spaces. In the experiment, two separate keyholes were generated by two electron beams in a common weld pool (Ref. 2). When interbeam spacing is reduced further to the Type 3 mechanism, the two laser beams are close enough to create one common keyhole in the weld pool. Few welding experiments have been reported for such a parallel dual-beam process with small spaces.

In angled dual-beam laser welding, the welding mechanism could be slightly different from that in parallel dual-beam laser welding. It was reported a funnel-shaped keyhole was produced by combining two high-power CO_2 lasers at a 30-deg angle and 1- to 2-mm spaces (Refs. 5, 15). The keyhole created by angled dual beams was enlarged; thereby, the keyhole might not be easy to collapse. Therefore, the angled dual beams enhanced the keyhole stability and weld quality was improved (Refs. 13, 15). In this dual-beam CO_2 laser system, a special optical device was designed to combine the two high-power CO_2 lasers (Ref. 5).

Although dual-beam laser processing

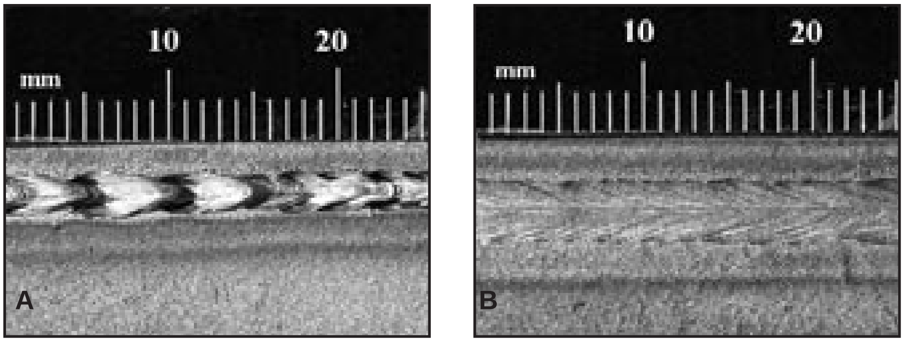

Fig. 6 — Complete-penetration butt-joint welds of steel (1045 steel, 6.35 mm, complete joint penetration, CO_2 laser, 6 kW, welding speed of 1.25 m/min). A — Irregular butt-joint weld produced by a conventional single-beam laser; B — smooth butt-joint weld made by a dual-beam laser.

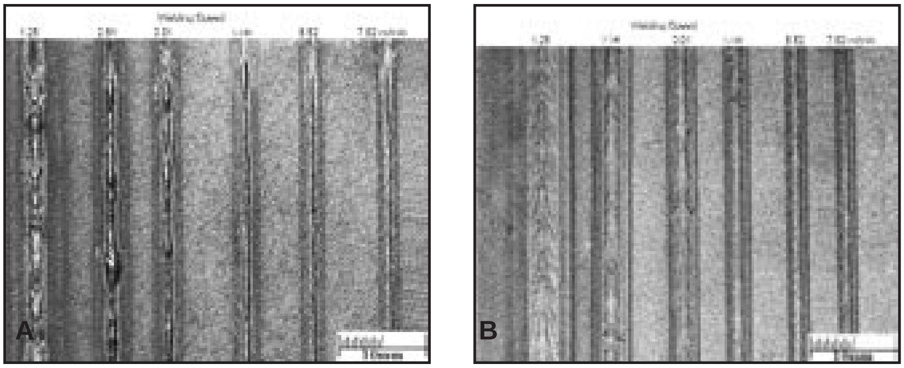

Fig. 7 — Partial-penetration, bead-on-plate steel welds (1045 steel, CO_2 laser, 6 kW, welding speeds of 1.25 to 7.62 m/min). A — Single-beam laser welds; B — dual-beam laser welds.

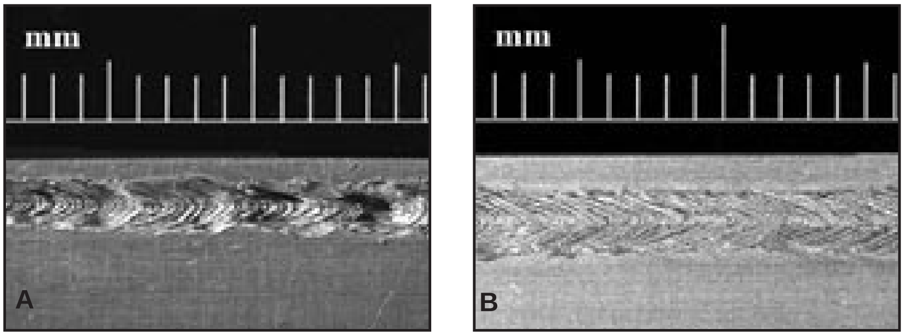

Fig. 8 — Complete-penetration butt-joint welds of aluminum (5083 aluminum alloy, 3 mm, CO_2 laser, 3.81 m/min). A — Single-beam laser weld (laser power: 3 kW); B — smooth, dual-beam laser weld (laser power: 4.5 kW).

has been investigated in some studies, many issues, such as welding mechanisms and influences on weld morphology, are still poorly understood. To better understand the process and properly use the emerging technique in industries, a comprehensive study on the dual-beam laser welding process was carried out in the current investigation. A high-power CO_2 laser beam was split into two equal-power beams by a wedge mirror and the split beams, when focused on workpieces, were almost parallel. The dual-beam CO_2 laser was used to weld steel and aluminum plates and conventional single-beam laser welding was also performed as a baseline. Weld characteristics such as surface quality, weld morphology, cracking susceptibility, weld hardness, and defects were analyzed and the dynamic behavior of vapor plumes was investigated using a high-speed camera.

Experiments

In this study, a 6-kW, parallel dual-beam CO_2 laser system with a small interbeam space was investigated. A flat mirror ahead of the focusing mirror was replaced with a wedge mirror to split the incoming laser beam into two equal powered and parallel beams, as shown in Fig. 3. The power density distribution of the split laser beams measured by a Primes beam analyzer is shown in Fig. 4. Dimensions of the laser beams, interbeam spacing, and power density could accordingly be obtained from the test results. The diameter of the dual laser beams and the interbeam spaces were found to be 0.4 and 1.2 mm, respectively, at the focal length of 200 mm. Interbeam spacing was determined by both the wedge mirror and focal length. In the study, a fixed interbeam space was used for all welding experiments, and the current setup (6-kW laser power and 1.2-mm space) should create a common keyhole in most welding conditions that were defined as the Type 3 mechanism in Fig. 2. Conventional single-beam laser welding was performed as well using the 6-kW CO_2 laser.

The welding experiments included bead-on-plate and butt-joint welding of steel and aluminum plates. In the bead-on-plate experiments, 6.25-mm-thick AISI 1045 steels and 6.0-mm-thick 5052 aluminum alloys (2.2–2.8% Mg) were used. Laser power was kept at 6 kW and travel speeds varied from 0.625 to 7.62 m/min. The laser beams were focused on the surface of the workpieces using a 200-mm parabolic focusing mirror. Helium was used as the shielding gas delivered to the welding area by a side jet at a flow rate of 20 L/min.

In complete-penetration butt-joint welding, 6.25-mm-thick 1045 steel plates and 3-mm-thick 5083 aluminum alloy sheets were used. These sheets were shear cut and no machining was prepared for the edges to be welded. The laser power and travel speed for welding 1045 steel plates were 6 kW and 1.25 m/min, respectively. In the butt-joint welding of 3-mm 5083 aluminum sheets, laser powers were 3 kW in the single-beam process and 4.5 kW in the dual-beam process while travel speed was kept at 3.81 m/min. Back shielding with helium gas was used in laser butt-joint welding of aluminum plates.

Welds produced by the single- and dual-beam CO_2 laser were visually inspected and the welded plates were checked using X-ray radiography to detect cracking and porosity in the welds. Hardness distributions in the base metal, HAZ, and fusion zone were measured.

To understand the laser/material interaction mechanism in dual-beam laser welding, a high-speed camera was used to investigate the dynamic behavior of the vapor plumes above the workpiece by performing bead-on-plate welding on 6.35-mm-thick 1045 steel plates. The experimental setup is shown in Fig. 5. The camera used was a high-speed motion analyzer Model 4540 made by Eastman Kodak Co. and run at a speed of 9000 frames/s.

Results and Discussion

Laser Welds

Complete-penetration butt-joint welds of 1045 steel produced by both single and dual laser beams are shown in Fig. 6. The weld made by the dual-beam process was smooth but the single-beam laser weld was rough and irregular. The bead-on-plate welding results on 1045 steel plates in which travel speed was varied from 1.25 to 7.62 m/min and laser power was kept constant at 6.0 kW are shown in Fig. 7. Among the single-beam laser welds, appearance of the shallow beads produced at high speeds was acceptable, but the deep welds made at low speeds presented some surface defects and the welds were irregular. However, the dual-beam laser welds were always smooth and no defects were found for the welds made with the same welding parameters. This implies dual-beam laser welding is a stable process and good welds were achieved over the range of process parameters investigated.

Aluminum alloys are well known to be difficult to laser weld because of their high reflectivity, high thermal conductivity, and volatilization of low boiling point constituents. Weld defects such as surface holes, undercut, porosity, and irregular beads are often observed. A complete penetration weld was made using the dual-beam CO_2 laser and the weld surface was quite smooth; the single-beam laser weld was irregular with some spatter — Fig. 8. Partial-penetration, bead-on-plate aluminum welds produced by the single- and dual-beam lasers are shown in Fig. 9. As expected, dual-beam laser welds had much fewer defects than the single-beam laser welds. Generally, Nd:YAG lasers, instead of CO_2 lasers, have to be used to make acceptable aluminum welds due to the short wavelength (1.06 mm for Nd:YAG vs. 10.6 mm for CO_2 lasers) that improves laser energy absorption for aluminum workpieces. The current experiment implies it is possible to use CO_2 lasers to produce acceptable aluminum welds by using dual-beam laser processing.

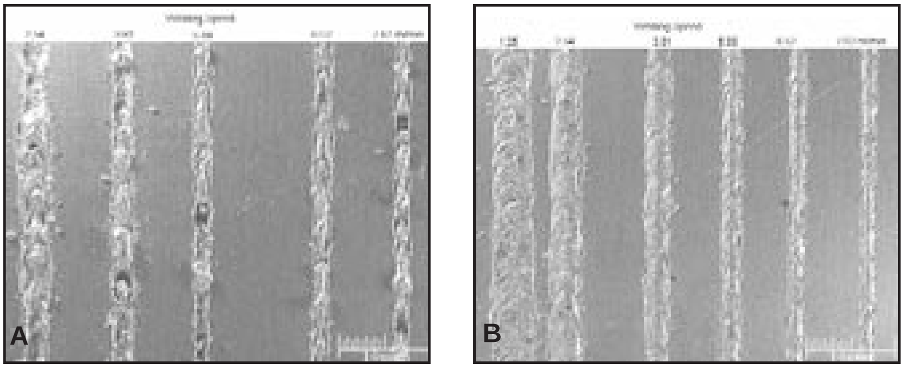

Fig. 9 — Partial-penetration, bead-on-plate aluminum welds (5052 aluminum alloy, CO_2 laser, welding speed: 1.25 to 7.62 m/min). A — Single beam; B — dual beam.

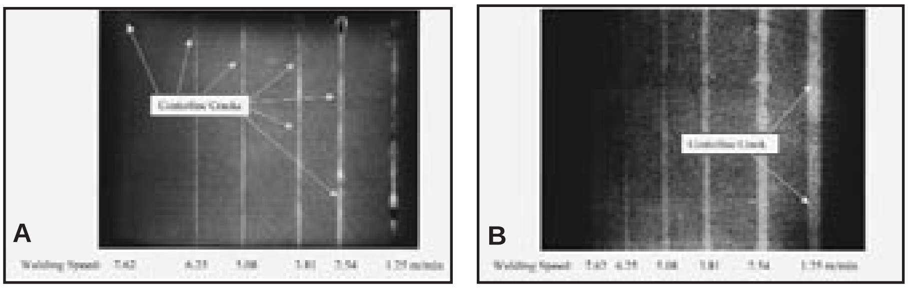

Fig. 10 — X-ray radiographs indicating centerline cracking in laser welds (1045 steel, bead-on-plate, 6.35 mm, CO_2 laser, 6 kW, welding speed of 1.25 to 7.62 m/min). A — Single-beam laser welds; B — dual-beam laser welds.

Centerline Cracking and Hardness

Centerline cracking was found in both the single- and dual-beam laser welds of 1045 steel plates, as shown in Fig. 10. A typical centerline crack found in the 1045 steel welds is also shown in Fig. 11. Since 1045 steel is a medium-carbon steel with a carbon content of 0.45%, the material is sensitive to solidification cracking in welding. Centerline cracking is a type of solidification crack usually found in medium/high-carbon steel, some alloyed steels, and aluminum alloys. While cracking was found in some of the dual-beam laser welds, it was found in almost every single-beam laser weld for the process conditions investigated. Centerline cracking susceptibility, which was defined as the ratio of the accumulated crack length over total weld length, was plotted against the travel speeds for both processes in Fig. 12. Centerline cracking was present in a wide speed range in single-beam laser processing and it was detected only over a small range in dual-beam laser welding. This result implies dual-beam laser welding may have less cracking susceptibility than conventional laser welding.

Weld hardness was tested at the location 1.5 mm below the weld surfaces as shown in Fig. 13. Average hardness of the single- and dual-beam laser welds was Hv 640 and Hv 590, respectively. This result indicates dual-beam laser welds might have better toughness than single-beam laser welds due to lower hardness.

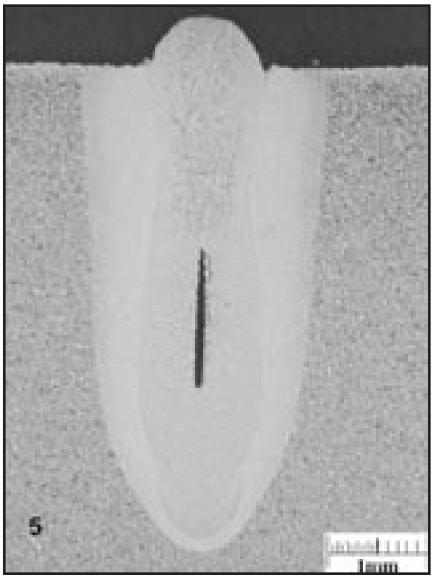

Fig. 11 — A typical centerline crack in laser welds (1045 steel, CO_2 laser, 6 kW, 2.5 m/min).

Since the materials/welding parameters used in the single- and dual-beam processes were exactly the same, the differences in cracking susceptibility and weld hardness should be contributed by the change in heat flows during welding. In the dual-beam process, the keyhole

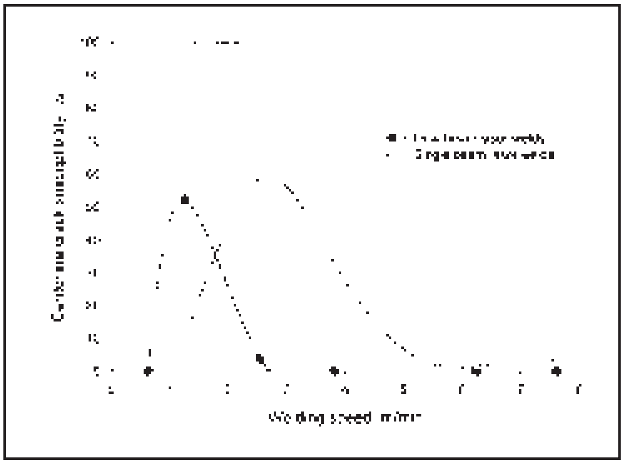

Fig. 12 — Centerline cracking susceptibility in laser welding of 1045 steel.

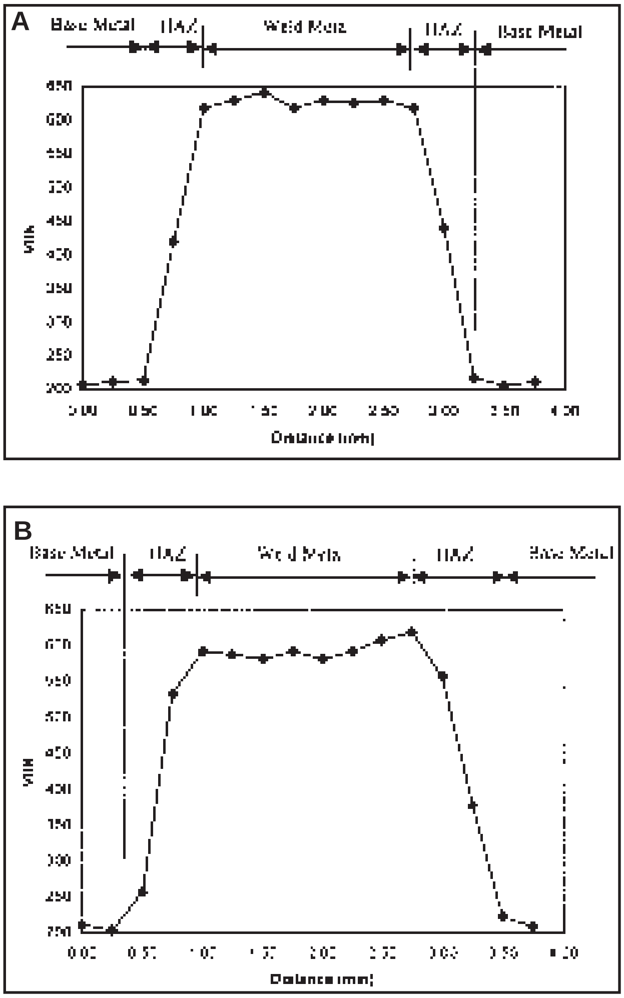

Fig. 13 — Hardness distributions in steel welds (1045 steel, bead on plate, CO_2 laser, 6 kW, 2.54 in./min). A — Single beam laser welds; B — dual beam laser welds.

shape would be elongated along the welding direction due to the interbeam spacing. As a result, the temperature distribution around the weld pool was changed, which may have resulted in the change in mechanical restraint around the pool and the cooling rate of molten metal. In dual-beam laser welding, the mechanical restraint might be reduced somewhat, thereby reducing cracking susceptibility. The temperature gradient in the transverse direction could be flattened because of heat conduction loss along the transverse direction. The cooling rate of the molten metal was therefore reduced, leading to lower hardness. A detailed analysis of heat flow and its impact on welds in dual-beam laser welding will be addressed in another paper.

Fluctuation of Vapor Plumes

Welding experiments indicated weld quality could be substantially improved using dual-beam laser welding technology. It was interesting to understand how the dual beams interact with materials and why weld quality was improved in dual-beam laser welding. The laser/material interaction in dual-beam laser welding with a small space was studied by investigating the dynamic behavior of vapor plumes (or plasma plumes in some literature) using a high-speed camera, as shown in Fig. 5.

The vapor plume was found to fluctuate in height under the high-speed camera in single-beam laser welding of steel. The typical cycles of the vapor plume fluctuation are shown in Fig. 14. The plume grew to a maximum height, then decreased with respect to time. When the plume was small enough, it grew up again to start another fluctuation cycle. Occasionally, the vapor plume completely disappeared, as shown in the picture at t = 1.10 ms in Fig. 14. In the single-beam laser welding of steel experiment, the plume fluctuated in the frequency range from 0.9 to 1.5 kHz, and the average fluctuation frequency was 1.2 kHz at the travel speed of 1.25 m/min. In other words, cycle time of each plume fluctuation was in the range of 0.66 to 1.1 ms and the average cycle time was 0.83 ms in CO_2 laser welding of steel.

When welding speed was increased from 1.25 to 7.62 m/min with the laser power kept at 6 kW, keyhole depth decreased accordingly. The plume fluctuation was still observed, but the change in plume height was less and the phenomena of complete disappearance of the plume (t = 1.10 ms in Fig. 14) was no longer observed. In other words, the plumes were more stable at high speeds due to shallow keyholes, and the stabilized plumes represented acceptable welds with fewer defects. The average fluctuation frequency at 7.62 m/min was almost the same as that at 1.25 m/min, which was 1.2 kHz. The frequency of plume fluctuation in laser welding might be related to material properties and laser wavelength instead of welding parameters.

Plume fluctuation in high-power laser welding is typically related to the keyhole instability experimentally observed in both laser and electron beam (EB) welding using X-ray transmission techniques (Refs. 17, 18). The keyhole instability was strongly affected by the irregular mass flow of molten metal in a keyhole (Ref. 17). A detailed discussion on plume fluctuation, irregular mass flow, and keyhole instability could be found in Ref. 19.

In single-beam laser welding, the surface of a workpiece is heated up to the boiling point in a short time (an order of milliseconds) by high-power laser beams (Refs. 20, 21). The material is vaporized to create a keyhole in the workpiece and then portions of the metal vapor and shielding gas are ionized by the laser beam, forming a hot and high-pressure plume in the keyhole. The plumes are called “vapor plumes” or “plasma plumes” in some of the literature. When the keyhole is completely open, the vapor plume can easily escape from the keyhole and a portion of the escaped plume can be observed above the workpiece. Since the keyhole is usually unstable during welding due to irregular mass flow of molten metal (Refs. 17, 18), the keyhole opening contracts at a certain frequency range. The keyhole is occasionally closed or collapsed. When the keyhole opening decreases in size or contracts, it limits the escape of the plume from the keyhole and, therefore, the plume above the workpiece becomes smaller. Meanwhile, plume pressure increases in the key-

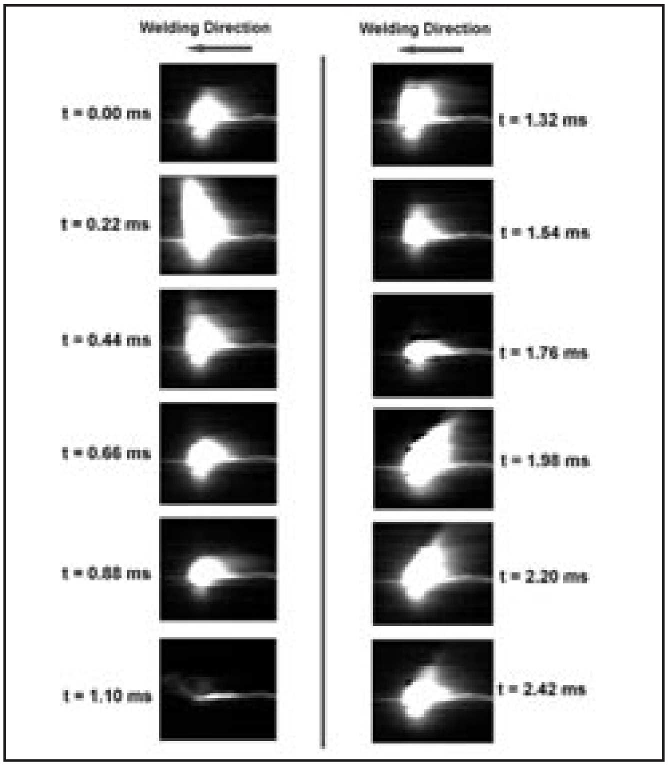

Fig. 14 — Size of vapor plumes dramatically changed in single-beam laser welding (1045 steel, bead on plate, CO_2 laser, 6 kW, 1.25 m/min, helium).

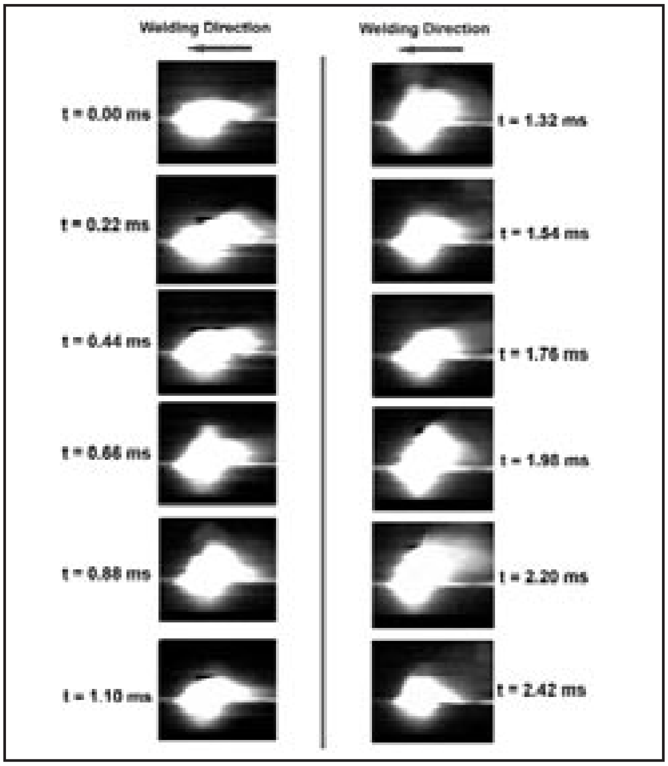

Fig. 15 — Vapor plume size varied slightly in dual-beam laser welding (1045 steel, bead on plate, 1045 steel, CO_2 laser, 6 kW, 1.25 m/min, helium).

hole by continuous irradiation of the laser beam. When the plume pressure in the keyhole is high enough, the plume erupts out of the keyhole and the plume size is thereby increased. The plume eruption brings some liquid metal out of the keyhole in the form of spatter (Ref. 19) and results in a cavity in the bead. If insufficient liquid metal fills back to the cavity, the weld appearance will be rough and irregular. In laser welding of aluminum, this situation becomes worse because the high thermal conductivity gives a very short solidification time for liquid metal to refill the cavity. This could be the reason weld defects such as surface holes, undercut, porosity, and irregular beads are often found in aluminum welds. As a result, the eruption of vapor plumes during welding might be responsible for the spatter and some weld defects in single-beam laser welding.

In dual-beam laser welding, plume fluctuation was observed, but the variation in plume size was much smaller, as shown in Fig. 15. Under certain conditions, the plume was completely stable and the plume size changed very little. The stable vapor plume might indicate the keyhole was always open during dual-beam laser welding and plumes could continuously come out of the keyhole. The stabilized and open keyhole, which was elongated by two close laser beams (dual beams), allowed the metal vapor and plasma inside to continuously escape and the pressure of the plume inside the keyhole was kept at a low level. Thus, big plume eruptions could be suppressed by the stable and open keyhole. Little plume eruption could lead to smooth welds and little spatter, as shown in Figs. 6–9. In addition, the plumes in dual-beam laser welding appeared larger and the maximum height was smaller when compared to conventional single-beam laser welding, because the dual beam kept the elongated keyhole open most times and suppressed vapor plume eruption.

Fluctuation frequency of vapor plumes in single- and dual-beam laser welding of steel is summarized in Fig. 16. Average fluctuation frequency was found to be 1.4 kHz in dual-beam laser welding, which was slightly higher than the 1.2 kHz of single-beam laser welding. The increased fluctuation frequency of the vapor plume meant smaller amounts of plume escaped per eruption.

However, it was occasionally found there were two vapor plumes at a high welding speed of 7.62 m/min, as shown in Fig. 17. This implies two keyholes might be created at a high speed with the current dual-beam setup and one plume was found only at speeds lower than 7.62 m/min. In other words, it was the Type 3 welding mechanism (one keyhole in one weld pool) at speeds less than 7.62 m/min and then it switched to the Type 2 mechanism (two keyholes in one pool) at a higher speed. Generally, the welding mechanism would change to Type 2 in Fig. 2 if interbeam spacing and welding speed increased or laser power decreased. Some industrial applications of the dual-beam laser welding technique were discussed in Refs. 22 and 23. It was found use of dual-beam Nd:YAG lasers could make high-quality aluminum welds (Ref. 22).

Conclusions

A 6-kW CO_2 laser beam was split into two equal-power beams with small spacing by a wedge mirror and then the split laser beams or dual beams were used to weld steel and aluminum plates. Welding results were analyzed and the dual-beam laser process was investigated using a high-speed camera to better understand the impact of dual laser beams on weld quality. The following conclusions were obtained:

1) Weld surface quality was significantly improved for both steel and aluminum using the dual-beam laser welding technique. Weld spatter, weld hardness, and centerline cracking susceptibility were reduced in steel welds. Porosity, irregular beads, and spatter were substantially decreased in aluminum welds. Using the dual-beam technique, it is possible to use CO_2 lasers to achieve acceptable aluminum welds.

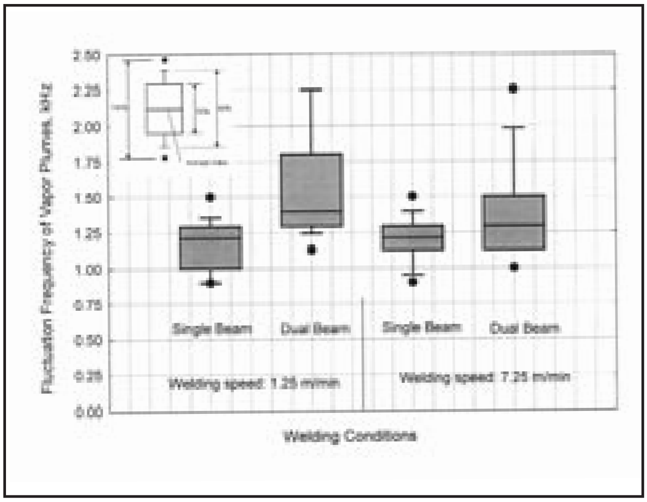

Fig. 16 — Statistical fluctuation frequencies of vapor plumes (1045 steel, bead on plate, CO_2 laser, 6 kW, helium).

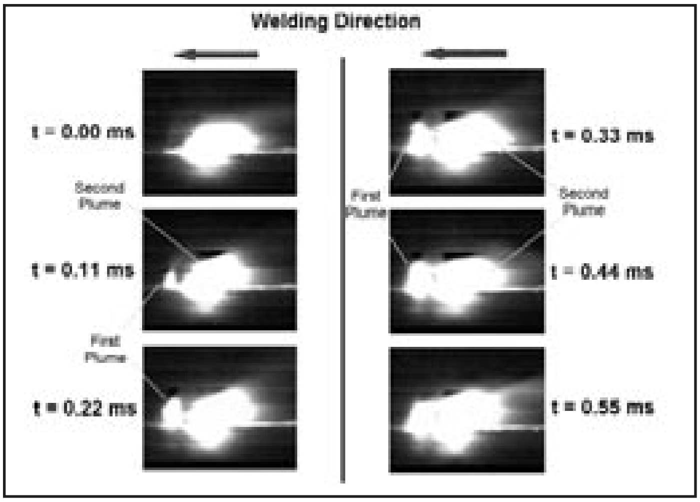

Fig. 17 — Two vapor plumes were found at a high welding speed of 7.62 m/min (1045 steel, bead on plate, CO_2 laser, 6 kW, helium).

2) Using a high-speed camera, the vapor plumes above the workpiece were found to be unstable and the height and volume of the plumes fluctuated dramatically in single-beam laser welding of steel. The average fluctuation frequency was 1.2 kHz. Unstable plumes might result in weld defects such as surface holes, irregular beads, and spatter.

3) Vapor plume fluctuation was found to be suppressed in dual-beam laser welding. Fluctuation still was found, but the height and volume of the plumes varied slightly. The stabilized vapor plume implies the dual laser beams could keep the elongated keyhole open, which suppresses eruption of plumes during welding. The increased process stability would result in improved weld quality.

4) In the current experimental setup with two parallel laser beams with a small interbeam spacing, one common keyhole in a weld pool was created in most welding conditions. The welding mechanism may switch to two keyholes in a weld pool with an increase in interbeam spacing and welding speed or a decrease in laser power.

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