Laser welding in the pipeline industry

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Introduction

The construction of pipelines, in the plant or in the field, is an expensive process that requires reproducible high-quality welds because of the possible environmental and economic effects of weld defects, particularly those leading to breaks. This requirement has been accentuated by the shift to high-strength low-alloy (HSLA) steels for pipelines, with increasingly stringent demands on welding procedures. Rothwell et al.[1] report that "As new materials and design approaches for the pipeline construction industry are developed and economic pressures increase, methods which revolve around craft skills and arbitrary workmanship standards become less appropriate . . . given the intrinsically repetitive nature of cross-country pipeline welding, new, mechanized and automatic approaches will be sought, in which the quality of welds, and the way in which it is assessed, are related to prior engineering decision, rather than to individual craft performance in the field."

Many major pipeline companies have been investigating alternatives to the common shielded metal arc (SMAW) and automated gas metal arc welding (GMAW) procedures, in order to decrease costs. In the early 1980s, the forecast for very large pipeline construction jobs, in particular that from Prudhoe Bay in Alaska to the continental US, led to an examination of the need for high-speed, highly automated welding processes. Laser welding was considered worth investigating as a candidate process. Considerable effort has been spent investigating laser welding for high-strength steels used for pipelines and developing equipment to apply the technology to the field environment.

Laser welding is a keyhole, or deep-penetration, welding process, in which the focused power from the high-power laser forms a vaporized channel partially or completely through the thickness of the material. As the laser is scanned along a butt joint, material at the front of the beam is melted, flows around the side of the hole, and resolidifies at the rear of the hole. This forms an autogenous joint without the use of filler material.[2] Photo 1 compares the cross section of a laser weld (1a) to a double-pass submerged arc weld (1b) in 0.375-in. wall-thickness HSLA steel for pipeline applications. The submerged arc weld (SAW) is the spiral weld used to manufacture the pipe from a roll of steel.

Photo 1 clearly shows the narrow weld and heat-effected zone produced in the low-heat-input deep-penetration process. By comparison, in the SAW, a double-V groove-weld preparation is filled with large amounts of filler metal. Similar preparations are required for SMAW or GMAW. The principle advantage of laser welding is speed. It has been projected that laser welding has the capability of producing high-quality welds at a speed that will increase the overall production rate.

This article is a summary of past and present laser pipe-welding research. The development of the machines and procedures required for laser pipeline welding is described in the following section. The laser development program at Majestic Laser Systems Ltd. (Edmonton, Canada), with which the author is most familiar, is presented as a means of familiarizing the reader with details about a laser-welding system.

Field-welding pipelines

Majestic Laser Systems Ltd., founded in the early 1980s, intended to bring to the pipeline construction industry the PIE laser technology developed at the University of Alberta and described briefly in a following section. Engineering development of the pipeline laser-welding system was divided into three phases:

- Laser to generate a powerful beam of infrared radiation.
- Beam-delivery system, to deliver the beam to the pipe.
- A vehicle to transport the laser and the beam-delivery system to the pipeline right-of-way.

In addition, investigations were undertaken to determine the conditions for producing a reliable and reproducible weld in various thicknesses of modern HSLA steels.

Majestic Laser Systems ceased activity in July of 1985. The prime reason for the company's failure was the decrease in pipeline construction projects. When the company and its activities were initiated in 1981, the long and very expensive pipeline from Prudhoe Bay to the continental US was envisioned. But by 1985, all environmental concerns about the possibility of an Exxon Valdez-type disaster had been stifled and the much shorter pipeline from Prudhoe Bay to Valdez was constructed using conventional technology. In addition,

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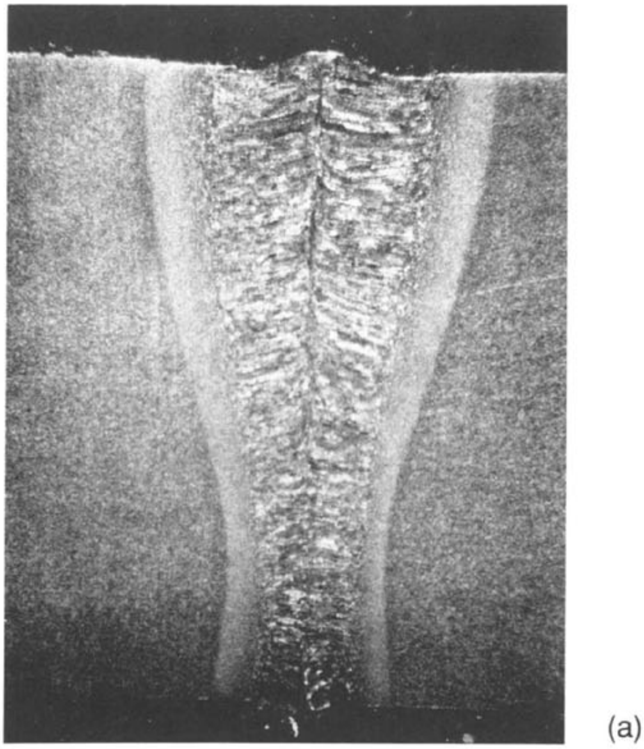
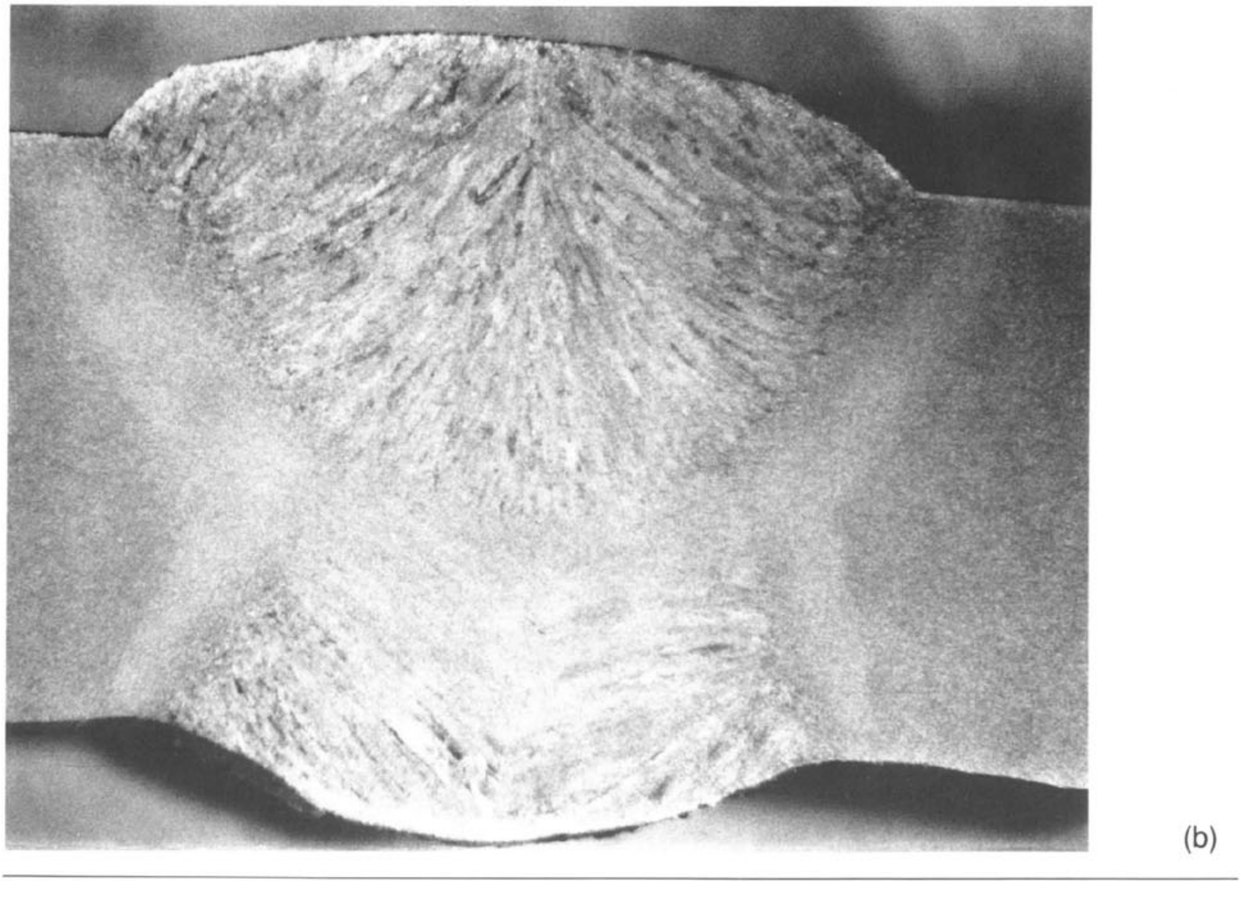
Photo 1. Comparison of (a) single-pass laser weld and (b) double-pass submerged arc weld in 0.375-in. wall-thickness pipe.





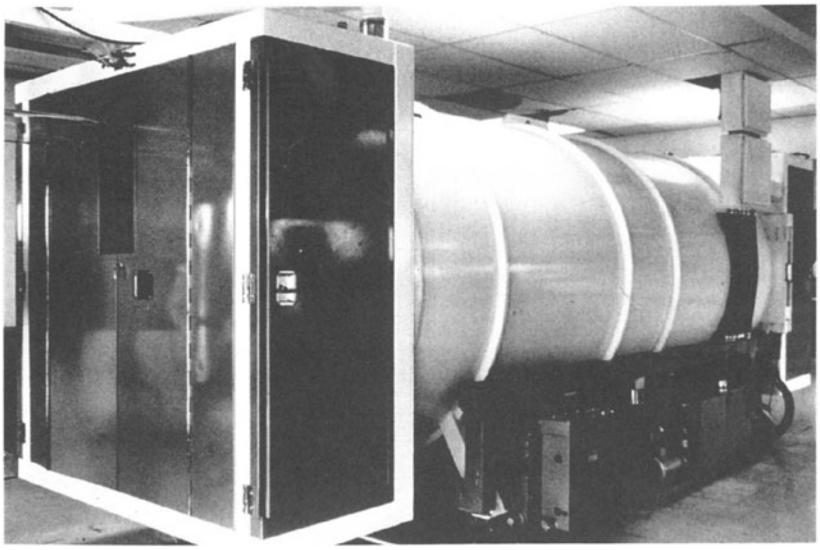


Photo 2. The 20-kW laser developed by Majestic Laser Systems Ltd. for incorporation into an off-road vehicle for pipeline welding in the field.

the price of oil had become very low, halting many oil-exploration projects and all pipeline-construction projects. When no pipelines were being built, no new pipeline welding processes were needed.

The following sections provide more detail of each of the development phases of the laser system developed by Majestic. Note that the beam-delivery system was only partially constructed at the time company activity was terminated, and construction of the vehicle had not commenced.

Laser development

The objective of the laser development phase of this project was the construction of a highly controllable, rugged, compact, 20-kW laser. Controllability was required to relieve the operator on the pipeline right-of-way of concerns about details of laser operations, such as mirror alignment and cooling-water temperature. The operator—a welder, not an engineer or laser specialist—would simply push a button to produce a laser beam to complete his job. All control and monitoring operations would have to be done remotely and automatically, without operator interaction.

The second requirement was for a rugged laser, of sufficient durability to withstand the jolting and jarring as it was moved across the crudely graded roads in the pipeline right-of-way. This motion would take place, in general, in a "ready-to-operate" mode as the laser was moved from one welding site to the next. It was anticipated that the laser would be used in an approximately 5-min-on, 5-min-off cycle. The laser would have to have the ability to produce a good-quality mode while operating with a considerable side-to-side or lengthways tilt due to uneven terrain.

A third requirement of the laser was compactness, since the laser system, including power supplies and cooler, had to be transported to the site in a vehicle. The overall vehicle length was limited to one-half the length of pipes being welded. Vehicle width was limited by regulations governing travel on public highways.

The power requirement for this project was for a 20-kW laser, due to the perceived need to weld 1-in. steel. Laser systems of this power rating were not commercially available at that time, though a laser design featuring lower power levels—known as photo-initiated impulsively enhanced electrically excited lasers (PIEs)—had been developed at the University of Alberta.[3,4] (The PIE acronym was in response to TEA and COFFEE—Transversely Excited Atmospheric lasers and Continuously Operating Fast Flowing Electrically Excited lasers, respectively.) The PIE lasers used a series of high-repetition rate pulses to preionize or condition the laser discharge region to absorb a large amount of power from a continuous power source. Specialized pulsed high-voltage circuits were developed to generate the pulses.[5] This technology was projected to be capable of meeting Majestic Laser Systems' requirements. Lasers with similar excitation schemes had been developed elsewhere.[6–8]

A PIE laser was designed by Majestic Laser Systems to fulfill the criteria of power, ruggedness, and compactness. Details about the laser (see Photo 2) as constructed at Majestic Laser Systems are presented in references 9 and 10.

Beam-delivery system

It was envisioned that the laser would be installed in a vehicle that would be driven up to the location of a joint and placed approximately parallel to the pipe. A motorized system of mirrors mounted on rails attached to a clamp would be extended from the vehicle and clamped onto the pipe. When the laser was turned on, the mirror system would move in such a way as to keep the circumference of the pipe (see Fig. 1). At the completion of the weld, the clamp would be released from the pipe and the system retracted into the vehicle.

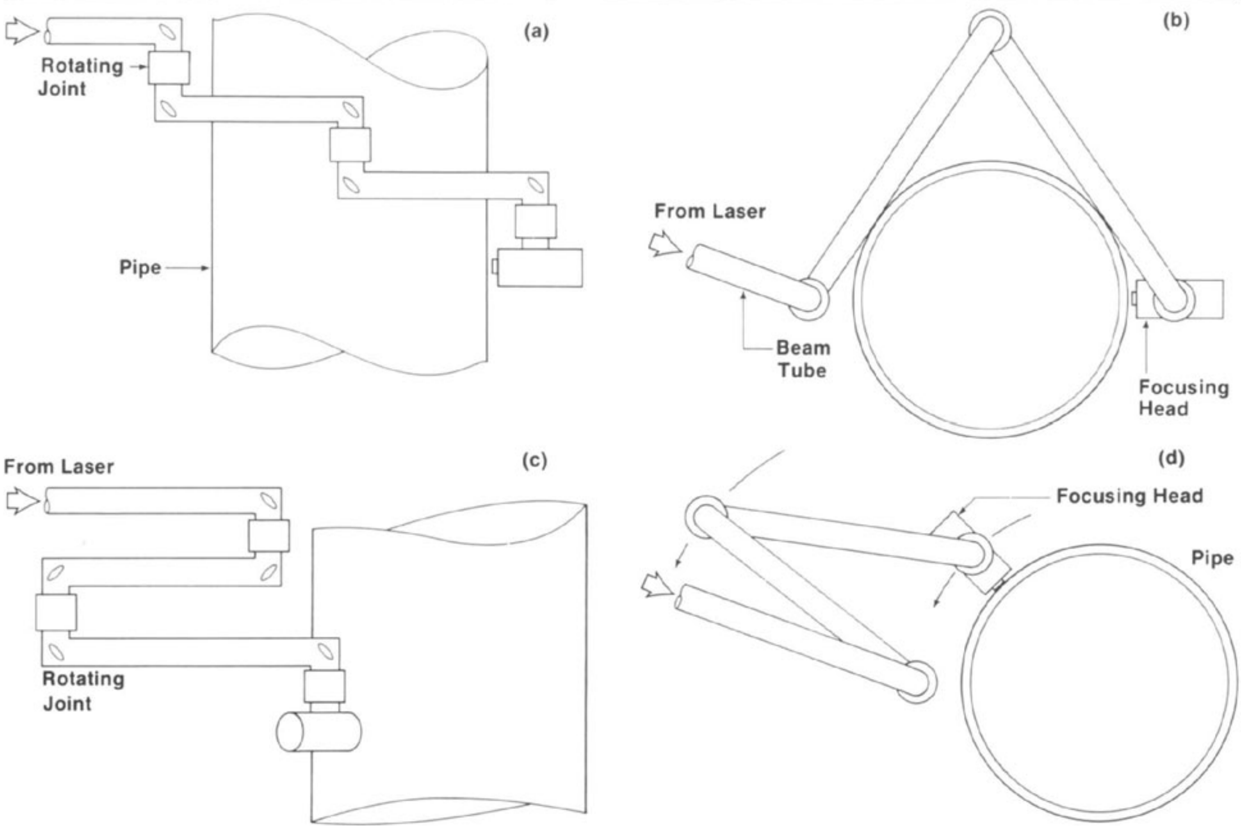


Figure 1. A proposed beam-delivery system for laser welding of a stationary pipeline from a stationary laser, using a moving beam system. (a) and (c) give top views; (b) and (d) end views. With the laser in the nine o'clock position, (a) and (b) show welding in the three o'clock position and (c) and (d) welding in the 11 o'clock position. Each joint consists of two mirrors; the upper joint is slaved to the motion of the welding head.

To accommodate the high laser power, all mirrors in the delivery system would be water-cooled. The delivery system would include the focusing head that would concentrate the laser power on the pipe seam; the gas shields required for plasma suppression and protection of the molten metal from atmospheric contamination during the welding process; and a commercial seam tracker to ensure that the beam hit the seam. Majestic Laser Systems designed and fabricated the focusing head and a compensating elbow mount. The focusing head contained a rotating joint and transverse slides that enabled the head to move longitudinally to follow the seam and radially to account for irregularities in the pipe. The compensating elbow, at the intersection of two beam tubes, adjusted the angle of the mirror to automatically bisect the angle between the beam tubes.

The beam-delivery system was envisioned to be contained inside a flexible, accordion-like tent that would be automatically extended and retracted simultaneously with the system itself. This cover was intended to ensure that the welding operation would be protected from the ambient environment, in particular from variations in temperature that may effect the accuracy of the system and from winds that would effect the gas shielding. Similar shields had been found to be necessary for successful implementation of automated GMAW.

The vehicle

A vehicle would be needed to move the laser along the pipeline right-of-way and to provide a controlled environment for the laser. The beam-delivery system would be contained inside the vehicle and would be deployed when needed. The vehicle would also carry the diesel electric power supply to generate the electricity required to operate the laser and accessories, and a closed-cycle refrigerator to dissipate the excess energy generated by the laser.

A commercially available off-road vehicle could be modified to carry the laser and associated equipment. Two personnel were expected to be involved, a driver and a welder-operator. The welder-operator would have to ensure alignment of the clamp and position of the welding head before the welding operation commenced. It was envisioned that conventional peripheral equipment would be used to the greatest extent possible, including preheat torches and the internal pipeline clamp. The welding procedure development would include an assessment of the ability of "end-prep" machines to prepare the ends of the pipes to sufficient accuracy for laser welding.

Welding procedure and development

For welding in the field, it had been envisioned that the laser would initially perform a tack weld with shallow penetration and subsequently a deep-penetration weld through the material thickness. Once the tack weld had been performed, the internal pipe clamp could be disengaged and used to prepare the next joint while the deep-penetration pass was being completed. This technique would lead to the fastest possible construction rate with a single-laser system.

After Majestic's laser was operational but before its operation and controls were optimized, a welding development program was initiated. Much of this work was bead-on-plate on a pipe rotating under a stationary beam; however, some work was on pipes with a gap or a mismatch at the joint. Focusing and gas-shielding conditions were found that allowed single-pass welding on 9.5-mm wall-thickness steel at 90 in./min. Some results of this welding development work have been published.[11] The development work was limited to welds on a rotating pipe and was not extended to circumferential welds on a stationary pipe in the duration of Majestic Laser Systems. The concept of tack welding was not verified.

Other laser pipe-welding developments

Offshore applications

Concurrently with the development of the laser pipeline welding machine for dry-land construction, several offshore construction companies had been investigating laser use for offshore construction using lay barges. Among these companies was Brown and Root (Houston, TX), which had been active in international offshore construction and was particularly interested in laser welding for the J-bend configuration in which only one welding station was practical. An engineering design study showed that the welding station should incorporate three lasers, one on either side of the pipe and one spare.

Contracts for welding development work were awarded to United Technology Research Center, which had 15-kW laser capability, and Culham Laboratories of the UK Atomic Energy Agency, where there was 10-kW capability. Much of the work was performed in the flat position, with the pipe rotating on a horizontal axis. However, toward the end of the project, some work was performed with a rotating mirror system. Welding procedures were developed to confine the liquid metal when laser welding in the overhead position, as required when performing a 360° weld on a horizontal pipe. Some of this work has now been published.[12,13]

In a benchmark publication,[12] it was concluded that in the flat and overhead welding positions, the stable welding limits are established by the maximum weight of molten material that can be supported by surface tension. The data presented in this paper lead to the conclusion that the maximum wall thickness of stationary pipe that could be welded by a continuously operated laser beam deflected by a mirror system around the pipe was about 13 mm. It might be possible to weld thicker pipes using a repetitively pulsed laser, in which case the metal would solidify before it would have time to move.[2] In other words, the liquid metal would be stabilized by inertial forces rather than primarily surface tension forces. This hypothesis has not been tested in practice, however.

Fairey Engineering, a UK firm, was contracted to design the beam-delivery system for the offshore environment. This company's design was similar in principle to that envisioned by Majestic Laser Systems.

Brown and Root apparently intended to use a laser on a lay barge in 1985. Their activity was approximately simultaneous with that at Majestic Laser Systems, but neither was aware of the other. Both activities were terminated in 1985, with the fall in the price of oil and in oil exploration activity.

Soviet pipe-welding activity

Since 1977, laser-welding activity has been ongoing at the All Union Scientific Research Institute of Pipeline Construction in Moscow.[14–17] As early as 1979, an investigation of laser welding pipeline steels was reported,[15] using powers up to 21 kW in a variety of welding positions. With a laser power of 21 kW, 15-mm wall-thickness steel was welded at speeds of 1.5 m/min. Few details of the welding results were given, but the publications indicated that the welds had a small reinforcement and contained undercutting to a depth of 0.5 mm, except those performed in the overhead position. Some contained defects, particularly micropores and pores with diameters 0.1 to 0.2 mm. Nevertheless, all bend-test specimens were reported to be deformed to 180° without fracture, and the majority of tensile test specimens failed in the parent material rather than the weld material. There are no reports, however, of this technology moving from the laboratory to field conditions.

Italian pipe-welding activity

In the 1970s, Italsider, an Italian manufacturer of pipeline steels, participated with United Technologies Research Corp. in a study of laser welding of pipeline steels.[18] Single-pass and dual-pass welds were performed in material of 12-mm and 26-mm thickness with powers of 10–15 kW. Initial results reported in the literature showed welds with poor visual, metallographic, and radiologic characteristics, specifically the presence of porosity, shrinkage cracks, and high hardness values.

Nevertheless, surprisingly good mechanical properties were observed with tensile strengths of many welds exceeding that of the base metal, and several welds with Charpy impact shelf energies above that of the base metal. The behavoir was attributed to fusion zone purification, a phenomenon previously noted in laser welding in which the beam preferentially vaporizes nonmetallic impurities that are generally present in the form of oxides and sulfides. The published study recommended improvements in cleaning and shielding practices, and use of alloys favorable to autogenous welding.

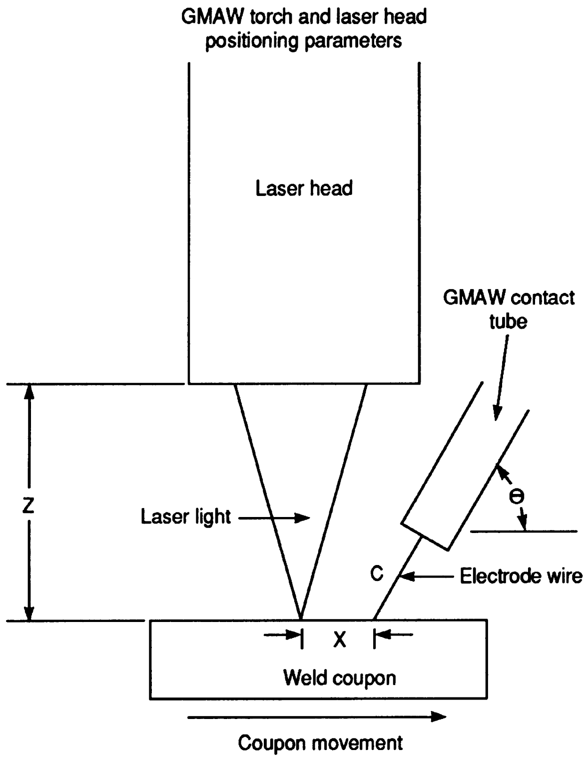


Figure 2. Schematic view of welding head used for laser-assisted arc welding, incorporating laser-focusing mechanism and GMAW torch.

New concepts in laser pipe welding

Laser-assisted arc welding

As already mentioned, laser welding is a keyhole, or deep-penetrating, welding process that produces joints at high speed and without the use of filler material. With lasers being installed in factories for pipe welding, the possibility of laser pipeline welding in the field or offshore is a topic that can be expected to be raised again. However, when this occurs, it may be appropriate to evaluate innovative processes such as laser-assisted gas metal arc welding (LAGMAW)[19] instead of simple laser welding. In laser-assisted arc welding, the relatively inexpensive power from an electric arc is combined with the expensive and highly controllable power from the laser, as shown schematically in Fig. 2.

The combined laser and arc process has several advantages over each process individually; some of these advantages would have potential benefit in pipe welding. The power from the laser serves to anchor the arc and prevent wandering. In thin materials, this would potentially allow welding at higher speeds than that achieved with the arc process alone. If the arc power is deposited in the keyhole produced by the laser, the combined welding process simulates the effect of a higher power laser and could weld thicker steel than that achieved by laser welding alone. The arc power can serve to preheat the steel and enhance welding in materials such as aluminum that are normally too reflective to be readily welded with a laser alone. Since a filler metal is used in the LAGMAW process, the tight fit-up requirements normally needed for laser welding are relaxed. The combined process can weld a given thickness of steel with a lower heat input than can each process individually. This may have metallurgical and mechanical advantages such as greater impact strength.

Moreover, it is expected that the laser power will anchor the arc to the bottom of the groove, which may allow welding with a groove far narrower than that possible with gas metal arc welding alone. Because the groove is narrower, less filler metal and less welding time is required and dramatic increases in productivity over that obtained with gas metal arc welding may result. However, further research is needed to confirm these expectations and to ensure that use of the narrow groove does not result in defects such as lack of fusion.

For a given thickness of steel, the combined laser-arc process may lower the laser-power requirements and hence capital cost of a welding project, as compared to the cost to be incurred using laser welding alone. If it is confirmed that a narrower groove and less filler metal can be used to produce high-quality welds, the combined laser-arc process may increase the productivity of a welding project as compared to that when using arc welding alone. However, the process is not sufficiently developed for field application at the present time.

Laser-assisted electric resistance welding

Another new concept in pipe welding, applicable to plant applications, is laser-assisted electric resistance welding (ERW).[20] In ERW, a high current flows between two electrodes, one mounted on either side of a butt joint. The higher resistance at the butt causes melting and fusion of the two pieces of material. However, the current flows preferentially at the metal surface, rather than being equally distributed throughout the material thickness. Thus the butt joint has a wider fusion zone at both the upper and lower parts of the seam, as shown in Fig. 3.

In experimental trials, this situation was rectified by directing a laser between the two pieces of metal as they were shaped into a butt (Fig. 4) and positioning the electrodes close to the point where the laser energy was absorbed. This re-

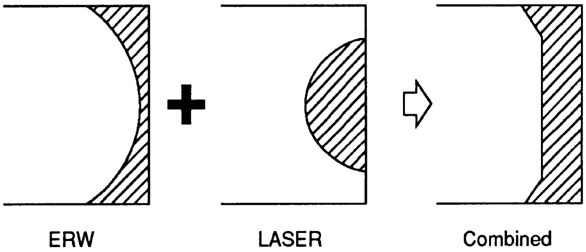


Figure 3. The concept of uniform heating produced by laser-assisted electric resistance welding.

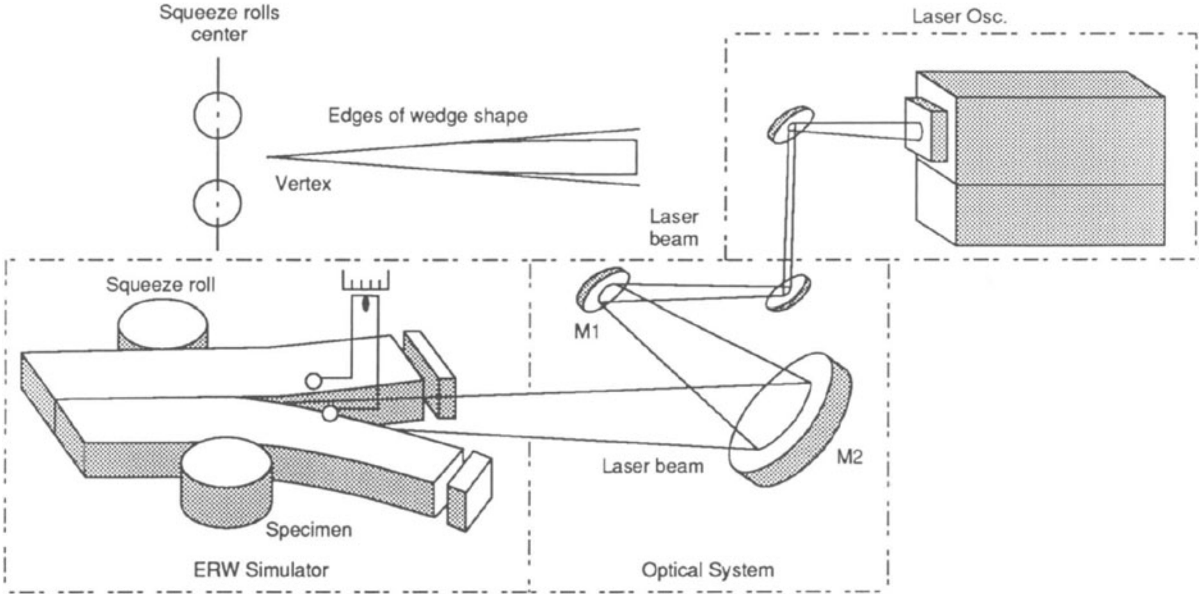


Figure 4. Schematic view of welding configuration used in laser-assisted electric resistance welding.

sulted in a melt zone of relatively uniform thickness over the thickness of the pipe, as shown in Fig. 3. Morever, the occurrence of lack-of-fusion defects was reduced. Notice this effect was caused by relatively low laser powers, for example 3.5 kW, as compared to the power in the electric current, which was 207 kVA.

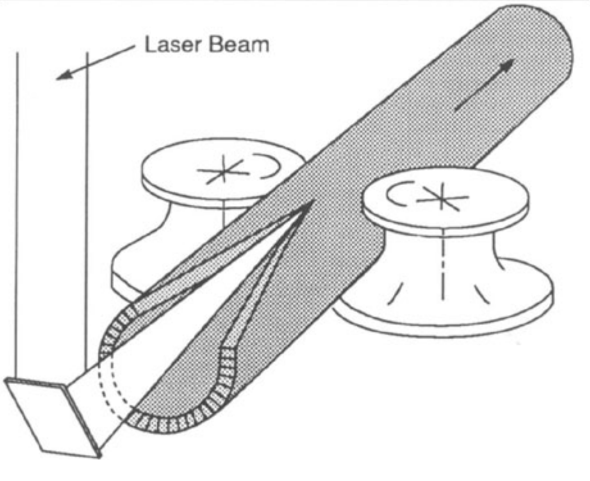


Figure 5. Set up for high-speed laser welding of pipe, with focusing of the beam into the wedge formed by shaping of pipe from sheet metal. Welding plated pipes is possible.

Welding with polarization-enhanced absorption

Another departure from the keyhole welding process using lasers has been investigated by Beyer et al.[21] at the Fraunhofer Institute. In this case, the laser was also focused into the convex-shaped "funnel" or wedge formed when a piece of steel is being formed into pipes (Fig. 5). The laser was used without an auxiliary power source.

It is well-known that absorption of optical radiation striking a metal surface at a glancing angle is a function of laser polarization. In this case, the polarization of the laser was chosen so that the laser energy was absorbed in the seam at the apex of the wedge. The power of the laser was high enough (20 kW) that both metal surfaces melted. The forming operation causes a joint to form by squeezing the two molten pieces of metal together. Solidification takes place immediately, since the beam can no longer continue to heat the metal at that location. This process is claimed to be considerably faster than the keyhole process, relatively insensitive to misalignment of the beam and potentially useful for producing pipe from preplated steel. This laser-welding process is to be used in the Hoesch Rohr AG pipe mill[22] beginning in 1992.

Conclusion

The task of developing a laser pipeline-welding system remains to be completed. While lasers have demonstrated hundreds of thousands of hours of production operation for a variety of difficult applications in factories, laser operation in the rough-and-ready oil-patch environment is another matter. Have current lasers demonstrated reliability to withstand the rigors of cross-country or maritime environments, where downtime might cost a million dollars a day? Can laser mirrors that direct the laser beam to the workpiece remain functional in the muddy and windy environment of a pipeline right-of-way, the greasy and salt-laden atmosphere of an offshore lay-barge, or the thermal gradients close to a large mass of steel preheated to welding temperature? Can the mirrors of the complicated beam-delivery system remain aligned in a nonstop production environment? These questions must be answered.

This article has described in some detail one attempt to produce a laser pipe-welding system, along with several other projects in lesser detail. Variations on the laser-welding process potentially useful for pipe manufacture and joining have been described. While the impetus for pipe-welding machines largely disappeared with the collapse of the pipe market accompanying the fall of oil prices in 1985, the impetus for developing laser pipe-welding processes and the potential financial savings that can be made on repetitive fabrication processes still exists. The next few years will see a number of laser installations in the more friendly factory environment. These installations will provide valuable experience.

Acknowledgments

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References

1. A.B. Rothwell, D.V. Dorling, and A.G. Glover, "Welding Metallurgy And Process Development Research for The Gas Pipeline Industry," *Advanced Joining Technologies, proceedings of the International Institute of Welding Congress-Joining Research July 1990*, T.H. North, ed., Chapman and Hall, London, pp. 175–192 (1990).
2. C.M. Banas, "High Power Laser Welding," *The Industrial Laser Annual Handbook*, M. Levitt and D. Belforte, eds., PennWell Press, Tulsa OK (1985).
3. K.H. Nam, H.J.J. Seguin, and J. Tulip, "Operational Characteristics of a PIE CO_2 Laser," *IEEE Journal of Quantum Electronics QE-15*, 1, pp. 44–50 (Jan. 1979).
4. S.K. Nikumb, H.J.J. Seguin, V.A. Seguin, and H. Reshef, "Gain and Saturation Parameters of a Multikillowatt PIE CO_2 Laser," *J. Phys.E: Sci. Instrum 20*, pp. 911–916 (1987).
5. V.E. Merchant, H.J.J. Seguin, and J. Dow, "A High-power, High-Repetition Rate Pulser for Photo-Impulse Ionized Lasers," *Review of Scientific Instruments 49*, p. 1631 (1978).
6. N.A. Generalov, V.P. Zimalov, V.D. Kosynkin, Yu. P. Raiser, and D.I. Roitenburg, "Steady Externally Sustained Discharge with Electrodeless Pulsed Ionization in a Closed Loop Laser," *Fizika Plazmy 3*, pp. 626–643 (1977).
7. A.E. Hill, "Continuous Uniform Excitation of Medium-Pressure CO_2 Laser Plasmas by Means of Controlled Avalanche Ionization," *App. Phys. Lett. 22*, pp. 670–673 (1973).
8. J.P. Reilly, "Pulser/Sustainer Electric-Discharge Laser," *J. Appl. Phys. 43*, p. 3411 (1972).
9. V.E. Merchant, "Development of a New 20 kW CO_2 Laser," *Laser Focus* (May 1985).
10. V.E. Merchant, M.R. Cervenan, and H.J.J. Seguin, "An Industrial Quality 20 kW Infrared Laser," Lasers '85 Conference, Las Vegas (Dec. 1985).
11. V.E. Merchant, M.R. Cervenan, and H.J.J. Seguin, "New Developments in High-Power Laser Welding," *Welding for Challenging Environments*, Proceedings of an October 1985 conference published by The Welding Institute of Canada.
12. J.H.P.C. Megaw, M. Hill, and S.J. Osborne, "Girth Welding of X-60 Pipeline with a 10 kW Laser," Culham Laboratories Preprint #CLM-P773, Culham Laboratory, Abington, Oxfordshire (1986).
13. J.S. Foley and C.M. Banas, "Laser Welding Stability Limits," *Proc. ICALEO '87, Focus on Laser Materials Processing*, S.L. Ream, ed., IGS Publication.
14. A.M. Belen'kii et al, "Laser Beam Welding with Dagger-shaped Penetration," *Svar. Proizs. 1977*, 11, pp. 23–24; translated in *Welding Production 1977 24*, 11, pp. 9–10.
15. I.A. Shmeleva et al, "The Properties of Welded Joints Produced with a High-power Laser Beam," *Svar. Proiz. 1977*, 11, pp. 13–15; translated in *Welding Production 1979 26*, 11, pp. 1720.
16. E.S. Lur'e, I.A. Shmeleva, and V.S. Smirnov, "Thermophysical Processes in Laser Welding Pipeline Steels," *Svar. Proiz 1986*, 7, pp. 31-35; translated in *Welding Production 1986*, 7.
17. I.A. Smeleva and E.S. Lur'e, "Effect of the Parameters on the Penetration Depth in Laser Welding Pipe Steels," *Avtomaticheskaya Svarka 1987 40*, 8, pp. 61–62; translated in *Welding International 1988*, 7, pp. 594–595.
18. C. Parrini, C. Banas, and A. DeVito, "Laser Welding of Pipeline Steels," *Welding of HSLA (microalloyed) Structural Steels* (1976).
19. K.H. Magee, V.E. Merchant, and C.V. Hyatt, "Laser-Assisted Gas Metal Arc Weld Characteristics," presented at the 1990 International Symposium on Applications of Lasers and Electro-Optics (ICALEO '90) and to be published in the conference proceedings.
20. K. Minamida, H. Takafuji, N. Hamada, H. Haga, and N. Mizuhashi, "Wedge shape welding with multiple reflecting effect of high-power CO_2 laser beam," *The Changing Frontiers of Laser Materials Processing, Proc. of ICALEO '86*, C.M. Banas and G.L. Whitney, eds., Springer Verlag IFS Publications Ltd., UK, in association with the Laser Institute of America, pp. 97–104.
21. K. Behler, E. Beyer, G. Herziger, and O. Welsing, "Using the Beam Polarization to Enhance the Energy Coupling in Laser Beam Welding," *Laser Materials Processing, Proc. of ICALEO '88*, G. Bruck, ed., Springer Verlag IFS Publications Ltd., UK, in association with the Laser Institute of America, pp. 98–105.
22. "Is Laser Pipe Welding Coming Soon?" *Industrial Laser Review 3*, 9, p. 21 (Feb. 1989).