Development of a Precision Wire Feeder for Small-Diameter Wire*

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ABSTRACT

At Sandia National Laboratories in Albuquerque, we designed and fabricated a precision wire feeder to be used with high energy density (electron beam and laser beam) welding for weld joints where filler wire might be needed to fill a gap or to adjust the chemical composition so that a crack-free weld could be made. The wire feeder incorporates a 25,000 step-per-revolution motor to power a urethane-coated drive roll. A microprocessor-based controller provides precise control of the motor and allows both continuous and pulsed feeding of the wire. A unidirectional 0.75-in.-dia ball bearing is used to press the wire against the drive roll. A slight constant backward tension is maintained on the wire spool by a Bodine torque motor. A Teflon tube is used to guide the wire from the drive roll to the vicinity of the weld, where a hypodermic needle is used to aim the wire into the weld pool. The operation of the wire feeder was demonstrated by feeding a 10-mil-dia, Type 304 stainless steel wire into a variety of CO₂ laser beam welds. The resulting welds are smooth and continuous, and the welds are considered to be completely satisfactory for a variety of applications:

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Introduction

The high-energy density welding (HEDW) processes (i.e., electron beam and laser beam) are normally used without filler metal (i.e., autogenously). There are several reasons for not adding filler wire: (1) The wire size required for an HEDW weld is necessarily limited to 10-mil-diameter or less, and commercial wire feeders are not presently available for feeding wire of less than 0.023-in.-diameter; (2) because space in the work stations is usually limited, adding a wire feeder may require other sacrifices; (3) the typical wire feeder usually adds mechanical and electronic complexity to a process; (4) the small weld pool of an HEDW presents a very small target and increases the necessary precision of positioning the wire; and (5) the heat in the small weld pool is inherently very low, which limits the amount of wire that can be added without "quenching" the molten pool. In addition, high energy density welds are inherently prone to weld defects caused by adsorbed contaminants on the weldment surfaces. Adding filler wire increases the percentage of surface area going into the weld zone and therefore may increase the propensity for weld defects.

There are, however, at least two reasons for adding a continuously fed filler wire that may sufficiently override the disadvantages noted: (1) the geometry of a weld joint and an inherent gap or mismatch at the joint may require use of a filler to adequately and reliably close a gap or provide the desired weld geometry, and (2) the chemistry of the base metal(s) may be such that a filler metal is necessary to adjust the chemical composition so that a crack-free weld can be made.

A wire feeder for feeding small-diameter wire could handle such "challenges" somewhat routinely. We, therefore, pursued the design and fabrication of a precision wire feeder for adding small diameter wire during electron beam and laser beam welding.

Design Criteria

The following factors were initially targeted for the development of a precision wire feeder:

- Capability of feeding 10-mil-dia wire
- Compact size—compatible with work station space; capable of being rotated around a laser nozzle
- Speed range of 0 to 600 ipm wire speed
- Guide tube to provide precise positioning of wire
- Positive, smooth wire feed motion; no slippage
- Programming capability; possible synchronization with laser on/off, pulsation, and workpiece motion
- Wire jamming sensor
First Generation PWF

The first generation model used a 24-VDC Globe motor to drive a 2-in.-dia, smooth-surface aluminum capstan driver, a Bodine KC1-26 torque motor to provide reverse tension on the wire spool, and a 20-gauge hypodermic needle to guide the wire after it exited the drive roll. The first wire feeder did operate, but numerous deficiencies were apparent that prevented a thorough evaluation of all the components. The following observations were made:

- The Globe 24-VDC motor used for driving the capstan had sufficient high-speed torque, but its low-speed torque was inadequate to smoothly overcome the static friction of the system. A stepper motor and controller were envisioned to improve low-speed torque. This substitution would also provide the capability of wire pulsing.

- The initial design allowed too much unsupported length of wire (~1 in.) from the exit of the capstan drive roll to the guide tube. The column strength of the wire was inadequate, and the wire tended to buckle if friction (in or after the guide tube) was excessive. This could be corrected by moving the guide tube closer to the drive roll.

- A 180° wire wrap around the capstan drive was apparently adequate; a 1½ wrap (540°) did not work.

- The frictional contact provided by the capstan drive was marginal and should be increased, possibly by adding a vee groove or a coating to the surface.

- For the wire guide, we first used a straight, 0.020-in.-ID hypodermic needle. The wire feeder worked well (at high speeds) with that arrangement, but the wire was not adequately guided. The wire wandered as it exited the end of the hypodermic needle. We then substituted a 0.0135-in.-ID hypodermic needle and bent it over a 2-in.-dia mandrel to an included angle of ~120° (which bent the wire ~60°). That added excessive drag to the wire causing (1) the motor to stall, (2) the wire to slip on the capstan, or (3) the wire to buckle between the capstan and the entry to the needle.

- The capstan drive concept seemed to work well.

Second Generation PWF

We then put together a second-generation model of a precision wire feeder and evaluated its performance, first on a bench test and then with the Photon Sources Model V-1200, 1000W CO₂ laser. This model incorporated a Compumotor Model A57-102 stepper motor, a urethane-coated, 2-in.-dia capstan drive roll, and a guide tube extension. The performance was much improved, and the deficiencies of the previous model were corrected. Following are comments and observations on the second-generation model:
- The Compumotor Model 57-102 stepper motor, rated at 120 in.-oz torque, provided adequate power. No stalling or speed variability was detected.

- The programmable acceleration and velocity features appeared to perform properly.

- Two types of controllers were used—a Compumotor Model 21 manual indexer, and a Compumotor Model 32 microprocessor terminal. The manual indexer contained controls for acceleration, velocity, number of indexing steps, direction of rotation, and continuous, or discrete, feeding. The microprocessor terminal was used to program these same variables, and it allowed pulsing the rotary motion. However, commands had to be reentered into the terminal each time the motor was run.

- The surface of the capstan was coated with ~ 1/8 in. of L-100 polyurethane. The coating was molded on a 1.85-in.-dia aluminum hub and then machined to a final 2-in.-dia. The surface was left smooth, and the wire was pressed against this surface by a unidirectional 3/4-in.-dia ball bearing. The radial force was ~ 90 oz. No wire slippage was observed with this design.

- We also briefly evaluated the use of a 2-in.-dia aluminum hub onto which regular heat-shrink tubing had been applied. This also appeared to provide adequate friction with the wire at the same 90-oz radial force.

- The wire-buckling problem encountered with the previous design was alleviated by using a phenolic extension between the drive roll and the hypodermic needle. That eliminated the unsupported length of wire.

- Two concentric Teflon guide tubes were employed. The inner tube provided guidance to the wire without undue friction, and the outer tube provided structural support to the smaller inner tube.

- The 20-gauge, 0.023-in.-ID hypodermic needle appeared to provide adequate precision for guiding the wire. The moderate 60° bend in the 2-in.-long needle did not impede the wire. A liner was necessary. The hypodermic needle concept provided a cheap, expendable wire guide tube.

- The Bodine Model KCI-26 torque motor applied an adjustable, constant reverse tension on the wire spool. In conjunction with the one-way ball bearing pressure roller, it served to keep the wire from unspooling. Approximately 4 oz of tension seemed to be satisfactory. (A friction brake is normally used in this application, but it does not eliminate wire slack and is not as easy to adjust.) The torque motor appears to be an excellent concept.

- No need for a wire straightener was observed. Even though the wire curved as it exited the guide tube, the curvature was compensated for by close placement to the weld spool.
- The wire spool was 2¾ in. OD by 1 in. wide, with a 1½-in.-dia hub. This compact size seemed appropriate for the anticipated wire usage and the light weight it offered.

Characterization Studies

We carried out a variety of welding tests to evaluate the wire feeder for feeding 10-mil-dia Type 308 stainless steel wire with our 1000 watt CO₂ laser beam welder. Both bead-on-plate and square-groove butt welds were made to evaluate the wire speeds and feeding techniques, to quantify the sizes of grooves that could be filled, and to determine the appropriate welding parameters and techniques required for gapped butt joints.

Early in the welding tests, we observed that two conditions must be met if satisfactory welds are to be made: (1) the wire needs to be aimed precisely into the weld pool without intercepting the beam, and (2) the weld pool needs to be sufficiently large to provide a target for the wire. To optimize these two conditions, we looked initially at the visual optics system and at a reliable method of achieving sharp focus.

The original visual optics system, i.e., a binocular eyepiece and a mirror/lens train, did not provide adequate viewing quality to precisely aim the wire. Consequently, we devised a CCD camera equipped with a 75 mm f1.3 zoom lens and a mirror/lens train for viewing coaxially with the beam. The resultant image provided the necessary magnification and clarity for aligning the weld path with the beam spot and the impingement of the wire tip in the weld pool. Unfortunately, the system cannot be used to view during welding.

We also experimented with techniques to maximize the weld pool size. The usual method of observing the beam spot while moving the z axis (lens-to-work distance) was not sufficiently precise. We found we could more reliably determine sharp focus by making a series of weld stripes at discrete focal distances. By incrementing the focal distance by 25 mils between weld stripes and then visually examining the width of the welds, we could quickly determine the z distance that gave the maximum weld size.

Wire Feeding Technique

In conventional cold wire feeding (CWF) with gas tungsten arc welding, the wire is fed into the leading edge of the weld pool. Further, the angle of elevation is fairly flat, ~30° from horizontal. Also, the wire is fed into the pool rather than into the arc. The advantages of these features are that visibility is maintained, and the resultant weld remains relatively smooth.

We made several B-O-P welds, using 10-mil-dia Type 308 stainless steel welding wire to resolve whether the conventional CWF techniques were appropriate. By traversing a square pattern and feeding the wire in from a fixed side, we were able to compare the effects of leading, trailing, and side approach of wire in a continuous weld. On successive welds, the elevation angle was fixed at 20°, 40°, and 50° above horizontal. We could thereby compare the effects of approach direction and angle in a single series of coupons.

At the welding parameters for these welds (600 W, 40 ipm travel speed, and 80 ipm wire speed using 10-mil-dia wire), we saw no significant difference between the approach direction (that is, leading edge, trailing edge, or from the side). Similarly, we saw no significant difference between wire elevation angles of 20, 40, and 50 degrees.
Bridging a Joint Gap

The objective of this phase of the experiment was to determine the dimensions of joint gaps that could be bridged, either autogenously or with filler wire added, and the approximate welding parameters required.

The base material (plate and plugs) used for this experiment was Type 304 stainless steel, 1/4 in. thick, and the welding wire was 10-mil-dia Type 308 stainless steel. We made a series of welds in 1-in.-dia stainless steel plug-in-plate coupons that had a range of gap widths and depths. The machined gaps were 10, 20, and 30 mils wide and 10, 20, 30, and 100 mils deep. (The 100-mil-deep gap was used to simulate a very deep gap and also a through gap.) The joint gap was rigidly maintained during welding.

An attempt was made to weld each joint combination (each width and each depth of groove), both with and without filler. The laser power, wire feed rate (WFR), travel speed, and number of passes were varied in attempting to achieve a satisfactory weld joint (a satisfactory weld joint was one that was completely bridged with a smooth or slightly convex surface). Also, it was a goal to use a minimum heat input to accomplish a satisfactory weld.

The wire approach was from a fixed side, that is, did not rotate around the weld path. The wire angle of elevation was fixed at 40° above horizontal. The only shielding gas was through the nozzle to provide protection to the focus lens and also moderate coverage to the weld. Since weld cleanliness was not a significant factor affecting the results, supplementary gas coverage was not used.

The smallest grooves (10 x 10 and 20 x 10 mils (width x depth)) were fused in one pass without adding filler; the largest grooves (30 x 100 mils) were not weldable within the parameters of this study (up to 860 watts and a travel speed of 40 ipm).

The deeper grooves were consistently more difficult to fuse, requiring more power, more passes, and more filler. The 100-mil-deep grooves that were wider than 10 mils could only be fused by making several passes and alternating the passes from side to side. The resultant welds exhibited a rough surface and only bridged the gap. We were not successful in filling a groove by building it up from the bottom.

The addition of filler allowed us to bridge an otherwise unweldable joint. Also, the wire significantly improved the quality (contour and soundness) of the welds.

The conclusions of the characterization and welding studies were:

- By using the precision wire feeder, satisfactory welding performance was demonstrated at travel speeds of 20, 30, and 40 in./min at a wire speed of 200 in./min.

- By making a square-pattern, bead-on-plate weld, the direction of feeding the wire into the weld pool was found to be insignificant.

- In the same manner, the angle of elevation of the wire guide tip was also insignificant in the range of 20° to 50° from horizontal.

- Alignment of the wire guide tip with the weld pool was critical, and improved optics were developed to aid in making that alignment.
Maximizing pool size (at a given set of welding parameters) by varying focal distance was required to present an adequate target and source of melting for the wire.

The wire must be melted by the weld pool; impinging the wire into the laser beam disrupts the smooth fusion of the wire and base metal.

The application of the precision wire feeder for filling joint gaps in stainless steel in the range of 10 to 30 mils wide and 10 to 100 mils deep was studied. Gaps as wide as 30 mils and as deep as 30 mils are readily filled. Gaps 100 mils deep could only be bridged (not filled). Bridging a deep gap required impinging the focused beam on the top surface near the gap and then adding wire to achieve a weld of adequate size to fuse the joint.

Specifically, a 10-mil-wide by 100-mil-deep gap was reliably bridged in one pass by adding 0.010 in. dia wire at a rate of 5 to 10 inches of wire per inch of weld. Laser parameters were 860 W, sharp focus on the top surface adjacent to the groove, and a travel speed of 40 in./min.

Addition of filler wire during laser welding increases the complexity of the process, and it should not be performed unless joint tolerances or materials compatibility concerns so dictate.

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