MECHANISM OF KEYHOLE FORMATION IN LASER WELDING

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Abstract – In order to perform the welding process, the minimum energy needed is of 106W/cm² where the diameter of the beamer represents 30% of the part thickness. The reflectivity of the metal is only important until the keyhole weld begins. After forming the first drop of melted metal, the level of absorbed energy increases because the metallic bath has a low reflection degree. As relative motion between the beam centerline and material occurs, the molten metal flows around from the front of the keyhole and solidifies at the back, forming a laser weld. The keyhole effect allows welding procedures with deep diffusion due to the fact that the laser beam heat is well absorbed in a steamy medium. The diameter of the laser beam used for the welding process generally varies between 0.1…1 mm, with a reference value of 0.3 mm. For the geometry of the elements, the lap joint is used, and only seldom the add-on material. Lap welds melt a lot of metal to produce a small connection, but they have a much larger tolerance on position than butt welds. The key process parameters for laser welding include laser power, focusing optics, and weld speed. All of these parameters are interactive. For a given focusing optic and material thickness, and assuming that full-penetration welds are desired, the higher the power, the faster the weld speed.

Key words – laser welding, keyhole, stainless steel.

1. Introduction

A laser beam can be positioned accurately, giving precise control over weld bead location. This enables dissimilar materials to be joined, since the beam can be positioned within one material and the energy transferred to the other by conduction. Welds can also be placed close to heat-sensitive components because of the limited HAZ. Parts can be redesigned located closer to one another, for example, since the beam can be guided into locations that would be inaccessible for a conventional welding torch [9].

The capital cost of a laser is several orders of magnitude higher than arc fusion welding equipment, and the running costs typically a factor of 5–10 higher. This cost penalty is offset by increased productivity, product quality and flexibility. Beam sharing or switching between workstations is often designed into a production line to maximize the beam-on time.

Laser welding can be automated easily, and is suitable for computer control, giving freedom from dependence on welder skill. Different welding configurations may be accommodated through changes in software, providing flexibility. The ease of automation enables adaptive control systems to be integrated into closed-loop production equipment.

Keyhole welding is a relatively clean process. Ionizing radiation is not produced by the interaction of a laser beam and engineering materials, and so screening for such is not required. The production of particulate fume and gases can be monitored and controlled. The laser beam is not deflected by magnetic fields. Processing can be carried out under normal atmospheric conditions.

The preparation of the workpiece prior to welding includes surface cleaning such as degreasing, pickling and wire brushing. Consistent welding results are obtained most easily if the surface condition of the workpiece does not vary along the joint line [10]. Oxide layers and coatings such as primers act to increase the absorptivity of the beam, but introduce instabilities if their properties change during welding.

2. Keyhole laser welding

The conduction-limited mode of laser welding, based on melting, was described. In the keyhole mode of laser welding, the beam is focused to produce an incident power density at the workpiece surface that is sufficient to initiate vaporization. A narrow, deeply penetrating vapour cavity, or keyhole, is then formed by multiple internal reflection of the beam. The keyhole is surrounded by molten material. By traversing the beam relative to the workpiece, a narrow weld bead is formed with a high aspect ratio (depth/width), illustrated in Fig.1 [6]. The keyhole is maintained during welding by...
equilibrium between the forces created by vapor pressure and those exerted by the surrounding molten material. In fully penetrating welds, the heat affected zone (HAZ) is narrow and parallel with the weld bead; in partially penetrating welds it resembles that of a conduction-limited weld.

Complex three dimensional parts are more easily welded using Nd:YAG laser light delivered via a robot-mounted fiber optic cable. A compact multi kilowatt diode laser head with a suitable focusing optic can be mounted on an articulated robot to create a highly flexible welding tool [1].

Fig. 1. Transverse section through a full penetration keyhole weld made in a carbon–manganese steel of thickness 6mm using an Nd:YAG laser beam.

Structural and stainless steels are particularly suitable for laser keyhole welding; their physical and chemical properties allow keyhole formation and dynamic weld bead stability. Laser keyhole welding is one of the few fusion joining processes able to deliver sufficient power to overcome high heat flow in alloys of high thermal conductivity. Light alloys of aluminum, magnesium and titanium are also laser welded, but measures must be taken to offset their high reflectivity to infrared radiation and the vaporization of volatile alloying elements.

Ceramics and glasses are poor candidates for laser welding because they are susceptible to cracking in high temperature gradients. Polymers absorb far infrared radiation well, but a stable keyhole is difficult to maintain – they are more suitable for conduction joining methods. Composite materials can be joined provided that steps are taken to avoid damage to the reinforcement, which is often non-metallic and absorbs the laser beam more readily than the matrix.

The data in Fig. 2 indicate that laser keyhole welding requires a power density in excess of \(10^5\text{Wmm}^{-2}\) (corresponding to the onset of surface vaporization) with a beam interaction time between 0.1 and 0.01 s (a compromise between maintaining the keyhole and an economical rate of welding). Simple relationships between incident beam power, traverse rate and penetration exist. A common rule of thumb for structural steels is that 1kWof power is needed per 1.5mm of steel to be penetrated at a welding speed of 1mmin\(^{-1}\). Analogous relationships are found with other materials. The objective of keyhole laser welding is to join materials as rapidly as possible, while meeting specified quality criteria.

Consider the reasons for the remarkable growth in the industrial application of laser beam keyhole welding. The principles of keyhole formation, weld bead solidification, and phase transformations in the HAZ of weldable engineering materials are described. The process characteristics are compared with those of conventional joining techniques, in order to identify materials and products for which laser welding has a competitive edge. Practical procedures for laser welding of carbon–manganese steels are described, together with the most common imperfections [7]. These are used as a baseline against which welding procedures for other engineering materials are contrasted. Laser welding diagrams are developed; these provide an overview of the process and can also be used to select processing parameters. The extent of industrial application is illustrated in a number of cases that highlight the advantages of keyhole welding and the opportunities that the process offers for novel design.

The power density available from an industrial laser beam spans many orders of magnitude, attaining \(10^5\text{Wmm}^{-2}\) in a high quality focused beam. However, such a high power density is difficult to control, and keyhole welding is normally carried out with a power density on the order of \(10^4\text{Wmm}^{-2}\). The surface of the material vaporizes at the point of interaction. The recoil force of vaporization from the liquid surface causes a surface depression, which develops into a deeply penetrating vapour cavity by multiple internal reflection of the beam, as illustrated in Fig.2 [6,12]. The diameter of the keyhole is approximately that of the beam diameter.

Energy is absorbed by the material through two mechanisms, which determine the overall energy transfer efficiency. Inverse Bremsstrahlung absorption (transfer of energy from photons to electrons) takes place in the partially ionized plasma formed in and above the keyhole; it is the dominant mechanism at low welding speeds. Fresnel absorption by multiple reflections at the walls of the keyhole dominates at high welding speeds, and is dependent on the polarization of the beam. Plasma (ionized vapour) and plume (vaporized material) facilitate energy transfer from the beam to the material, but they also defocus the laser beam, reducing its power density.
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**Fig. 2.** Principle of laser beam keyhole welding.

The vapor cavity is surrounded by molten material. The cavity is maintained through equilibrium between opening forces arising from material ablation and plasma formation, and forces caused by the surface tension and hydrostatic pressure of the molten pool, which act to close it.

As the beam and material move relative to one another, material is progressively melted at the leading edge of the molten pool and flows around the deep penetration cavity to the rear of the pool where it solidifies in a characteristic chevron pattern.

The requirement to maintain this balance leads to practical minimum and maximum traverse rates for keyhole welding – excessive speed causes the keyhole to collapse, whereas insufficient speed results in a wide weld bead that sags. The shape and size of the keyhole fluctuate during welding.

The molten pool temperature is considerably higher than that of a conventional arc weld. Heat is conducted into the surrounding material to produce a narrow HAZ. When the laser beam is turned off, several processes occur: the plasma inside the keyhole is extinguished; vaporization pressure decays; and the keyhole collapses through the effects of surface tension and gravity.

3. Regions of the welded zone

Keyhole welds exhibit two distinct regions: a fusion zone; and an HAZ. Within the HAZ, subregions can be identified; their extent depends on the material composition and the peak temperature attained during welding. The relationship between microstructure and peak temperature is illustrated for a structural steel weld in Fig.3 [6].

Each region has a specific composition, microstructure and set of properties. In the fusion zone, material is melted and solidified rapidly. Grains grow epitaxial with the adjacent HAZ grains in a columnar morphology.

Equiaxed grains may also be formed in the centre of the weld bead. The grain morphology depends on the welding speed: a high speed results in abrupt changes in grain orientation, causing parallel elongated grains to form along the weld centre line that are susceptible to solidification cracking. The weld bead microstructure and properties are essentially those of rapidly cooled cast material. Depending on the nature of the alloy and the composition of the weld metal, it might be possible to regain the properties of the base material through post-weld heat treatment.

**Fig. 3.** Schematic illustration of the regions of the heat affected zone in a laser beam keyhole weld in a 0.35wt% C structural steel

4. Characteristics of laser keyhole welding

The small focused spot has a high power density, which enables a deeply penetrating weld pool to be created and maintained during welding. Through-thickness welds can be made rapidly in a single pass [8]. However, small fit up tolerances are required to avoid sagging and other imperfections in the weld bead.

These may represent a high initial setup cost, but closer production tolerances have a positive effect on the complete fabrication philosophy: the requirements for modular assembly can be achieved more easily.

The energy input during laser welding is low. A narrow weld bead is produced, with a narrow HAZ. Distortion is limited and predictable, which minimizes the need for reworking and reduces material wastage.

Rapid solidification provides metallurgical advantages: segregation of embrittling elements such as sulphur and phosphorus can be reduced; and beneficial fine solidification microstructures are formed.

Ranges of power density and energy for various fusion welding processes are shown in Fig.4 [6]. The power density of laser welding is seen to be similar to electron beam welding, and is higher than gas and arc fusion processes (in which a keyhole is not formed). The energy input of laser welding is lower than conventional fusion processes, which is the origin of many of the advantages of the process.
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5. Joints

Close-fitting joints designed for conventional welding are suitable for laser welding. However, novel joints can be designed because of the accessibility of the beam. Groove preparation is not required unless the section thickness is greater than twice the maximum bead penetration. Figure 5 [6] shows a selection of joint designs used in laser welding. Alternatively, the weld may be made by fully penetrating the flange and partially penetrating the web to produce a stake, spike or spot weld (Fig. 5) [3].

6. Austenitic stainless steels

The material thickness plays a significant role in determining the most efficient welding process for a given joint, and dictates the processing parameters required. As mentioned earlier, a common rule of thumb for structural steels is that 1kW of power is needed per 1.5mm of steel to be penetrated at a welding speed of 1mm min⁻¹.

Stainless steels that solidify as primary austenite are normally more susceptible to solidification cracking than those which solidify in the primary ferrite mode, since harmful elements such as sulphur and phosphorus are less soluble in austenite than ferrite, and segregate more easily [11]. Constitution diagrams have been constructed to describe the mode of solidification and microstructure in terms of composition indices. The Schaeffler diagram displays the primary solidification mode of stainless steels using axes of chromium equivalent, $C_{eq}$ (abscissa), and nickel equivalent, $N_{eq}$ (ordinate), when welded using arc fusion processes [4,6]. The abscissa represents elements that promote the formation of ferrite, and is defined as

$$C_{eq} = Cr + Mo + 1.5 \times Ni + 0.5 \times Nb,$$

whereas the ordinate represents elements that promote austenite formation, defined by

$$N_{eq} = Ni + 30C + 0.5 \times Mn$$

where element symbols represent concentration (wt%). The diagram can be used to identify ranges of composition in which welds are susceptible to solidification cracking; for arc welding, a ferrite content of 3–8% gives a reasonable assurance of crack-free welds. A similar ferrite content can be expected to be desirable in the microstructure of laser welds, but the higher cooling rate of laser welds in comparison with arc welds influences the solidification mode, and hence the room temperature microstructure of stainless steel welds. The duplex region of low crack susceptibility in the Schaeffler diagram contracts, in comparison with arc fusion welds, as shown in Fig. 6 [6]. Thus a steel composition designed to produce a microstructure containing 3–8% ferrite after arc welding may solidify as a single phase during laser welding. Care must therefore be taken when using such diagrams with laser welding.

The Suutala diagram is constructed using an ordinate that represents the ratio of ferrite to austenite stabilizing elements, $Cr_{eq}/Ni_{eq}$, and an abscissa that indicates the concentration of elements associated with harmful grain boundary segregation. Crack-free welds are associated with a combined S+P concentration below 0.02wt%, or at higher concentrations a $Cr_{eq}/Ni_{eq}$ ratio greater than 1.5. The solidification cracking susceptibility of laser welds extends to a wider range of composition than arc welds, and so a higher concentration of ferrite stabilizing elements is required to prevent cracking in laser welds in stainless steels. Inhomogeneous mixing resulting from the high solidification rate may also contribute to the effect [5].
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Laser welding may reduce intermetallic phase formation because of the high cooling rate. Austenitic stainless steels can be welded by using a nickel-containing filler wire and post-weld heat treatment at 1100°C to obtain the desired balance of phases in the weld metal to avoid solidification cracking.

7. Laser keyhole welding diagrams

In its general form, Fig. 7 [6] may be used to describe a range of keyhole welding conditions for engineering materials within a particular class. But it can also be converted into a practical diagram with axes of principal process variables by substituting appropriate values for material properties.

Figure 7 is converted to a material-specific diagram by substituting appropriate thermal properties into the variables used as the axes. A focused beam radius of 0.3 mm is assumed. The positions of the contours are fixed through a single calibration, indicated by a star.

Figure 8 is based on the following calibration: a beam power of 8kW is required to fully penetrate a plate of thickness 8mm with a welding speed of 2 m min⁻¹. By using this data point in equation, the other contours of penetration shown in Fig. 8 [6] may be constructed. The model is unable to predict the loss of penetration with low beam power (irrespective of the welding speed), because this represents a change in the processing mechanism.

8. Summary and conclusions

Keyhole laser welding is now an established joining technique in many sectors of industry, and is being investigated actively in others. Most of the principles of keyhole formation are understood, and the formation and properties of the weld bead and HAZ can be established by adapting predictive methods that have been developed for conventional fusion welding processes. Most materials that can be welded by conventional fusion techniques are suitable for keyhole welding. Low alloy steels are particularly suitable, welds can be made rapidly in thin sections, and full penetration can be achieved in thicker sections in a single pass. Many variations of keyhole welding have been developed – hybrid arc–beam processes; multiple spot sources; filler wire welding, all of which exploit the advantages inherent in the individual techniques. The process can be modeled by using relatively simple analytical methods to obtain initial estimates for parameter selection in procedure development. To achieve the highest level of detail for practical use, models may be calibrated to known data points to produce a practical processing diagram.

The main benefits of laser keyhole welding become evident when it is used at the limits of its capability: high speed welding of sheet materials, or deep penetration joining in thick sections. As with all laser-based processes, the low energy input is the origin of many of the advantages over competing fusion joining processes, since distortion is low, productivity is high, quality is superior, and new materials may be considered. The accessibility of the beam enables new joints to be designed into products. The controllability of the beam allows dissimilar materials to be joined. Low distortion reduces the total number of manufacturing steps by removing post-weld straightening. However, the process is often not used to its fullest advantage because of a lack of understanding of the opportunities available at the design stage of a component. In addition, procedures for keyhole
welding and quality standards must be generated and approved by classification societies, particularly for thick section materials. Both are currently obstacles to greater application. Equipment for on-line process monitoring and quality control is continually being sophisticated. This will enable rugged systems to be made, which will increase process automation, and make the process more attractive to a wider range of industry sectors.

9. References