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Porosity formation in laser-beam materials processing

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One of the principal defects encountered in high-power laser-beam welding is the formation of porosities [1–5]. When the deep-penetration keyhole is formed by a laser beam under certain conditions, plasma plume is produced on the metal surface and some porosities are found in the weld pool. The formation of porosity is closely related to the plasma density and the gas pressure on the metal surface in high-power laser-beam processing. As the operating gas pressure increases, usually the porosities increase by exerting excessive pressure on the molten pool. There are several ways to decrease the number of porosities in the molten zone; for example, plasma control on the weld pool surface by inert gas, reduction of the laser power and a slow cooling rate, etc. In particular, it is important to avoid the formation of porosities in laser surface alloying treatment of tool steel for die and moulds, where high impact strength and hardness are necessary. During the bead-on-plate laser welding of mild steel with a 2 kW CO_2 laser, porosities were always observed on the root of molten pool when the scanning speed was near 8 mm s^{-1} under He shielding gas as shown in Fig. 1. This scanning speed was the value between that which gave a dense plasma cloud on the metal surface and that which gave the deepest penetration of molten pool. Therefore, one of the porosity formation mechanisms was investigated in the high-power laser beam processing of steel.

If the laser intensity is set equivalent to the minimum required for deep penetration welding ($I = 5 \times 10^5$ W cm^{-1}), then an equivalent temperature of 17 000 °C is obtained [1]. Pressure on the surface is strongly enhanced due to the recoil of the expanding hot gas and plasma. Because of the temperature increase in the plasma due to the absorption of the laser beam and the presence of the metal surface, a pressure wave is generated and propagates along the laser beam axis. In the limit of laser-supported detonation, the pressure can reach local values up to 1 MPa and results in an uncontrollable expulsion of molten metal [6]. The plasma coupling can reach around 50% of the incident laser energy and the expanding plasma moves away from the surface [7]. As the plasma continues to absorb incident laser energy and the temperature increases, its energy begins to spread to the surrounding region via radiation. Plasma is undesirable in laser-beam welding, because it can absorb a significant fraction of the laser energy and prevent effective laser energy transfer to the substrate. Furthermore, in addition to the absorption of laser energy, the plasma can degrade the welding efficiency by distorting the optical characteristics of the laser beam and reducing focusability.

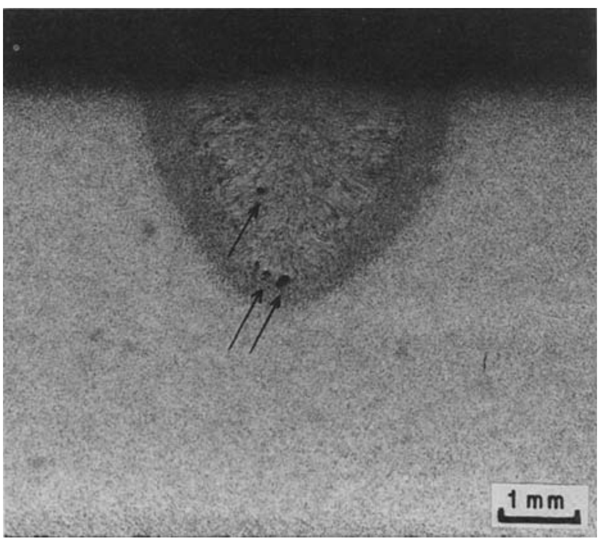

Figure 1 Cross-section of the mild steel after bead-on-plate welding with a CO_2 laser. Arrows indicate porosities on the root of keyhole. He shielding gas, scanning speed 8 mm s^{-1}, laser power 2 kW.

In laser-beam welding, melting takes place at the leading edge of the molten pool and the liquid metal flows back around the keyhole and then resolidifies. The recoil force of evaporated gas is the driving force for maintaining a cavity in the liquid [8]. The absorption of laser energy on the metal surface is dependent on the laser scanning speed under the same laser power density and focusing condition. Thus, the shape of the molten pool changes, depending on the scanning speed at same power level.

When the laser scanning speed was set to 2 mm s^{-1} in bead-on-plate welding of mild steel, the laser energy density was so strong that an optically dense plasma plume was formed and it effectively shielded the substrate surface. As a result the substrate no longer received the direct laser beam and the hot plasma led to the heating of metal surface. Consequently, penetration was not deep enough and a bowl-shaped melting pool was produced by radiant energy from the plasma ball hovering over the weld pool, and porosities were not observed. When the laser scanning speed was increased to 32 mm s^{-1} the laser energy density was lower and the plasma coupling was also reduced. If there was little plasma on the surface, the laser beam would pass through the plasma to the metallic surface. Thus, the laser beam penetrated into the

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cavity without attenuation or redirection by the plasma, and deep-penetration welding could be obtained. The deep-penetration welding keyhole is stable only under dynamic conditions, where the balance between the hydrostatic force of liquid metal surrounding the keyhole and the vapour pressure within this is important. In the centre of the keyhole the vapour pressure would be higher than that of the outside rim of molten pool, due to having a higher temperature and the confining effect of expanding vapour by the keyhole wall. Thus, the expanding vapour is expected to move vertically towards the beam axis out of the cavity. However, since the scanning speed was rapid and the back-trail acted like a conduit of vapour, no accumulation of pressure would result in the cavity. Then the gravitational force and surface tension of molten metal would cause a back-flow of molten metal along the wall, and it would fill the cavity without porosities.

When the laser scanning speed was $8\ \mathrm{mm\,s^{-1}}$, which was intermediate between the two above values, the laser energy density was strong enough to ionize the ejected vapour from the cavity. However, the plasma was not so dense that a portion of the laser beam could penetrate into the cavity. Therefore, the upper part of cavity would be filled with more plasma, and the lower part would be filled with more vapour. Since the temperature of the upper part was higher than that of the lower part, the expanding gas pressure in the upper region would exceed the recoil pressure of vapour out of the cavity and it would temporarily maintain a net counter-pressure toward the root of cavity as shown in Fig. 2. Also, the coaxial assit-gas which was blown towards the keyhole would help to increase the counter-pressure by pushing plasma into the cavity. In this case, since the scanning speed was not so rapid, the back-trail could not act as an efficient conduit of vapour. Then the escape of metal vapour would be effectively arrested by the cavity wall, and it would be trapped on the root cavity, where the conduit of high-pressure gas was not provided.

Generally, the keyhole stability decreases as the welding speed is reduced below a certain level. At lower speed the volume of molten metal generated becomes relatively large in accordance with the increase in specific energy deposition. Although the excessive vapour pressure pushes out most molten metal surrounding the cavity, the vapour pressure becomes inadequate to counteract the fluid force and surface tension of the melt flowing in to fill the cavity. If the scanning speed was chosen to be $8\ \mathrm{mm\,s^{-1}}$ in this experiment, it gave the condition that the net counter-pressure due to expanding gas in the upper region would temporarily keep the pore of vapour on the root of the cavity while the keyhole collapsed due to flowing molten metal. Since the molten metal resolidified before it could float to the surface and escape from the fusion zone, porosities were trapped on the root of the cavity. Therefore, there exists a minimum welding speed below which a stable keyhole can no longer be maintained and porosities are produced on the root of keyhole as shown on Fig. 1, which shows the overlapping of the keyhole effect and the heating effect by plasma.

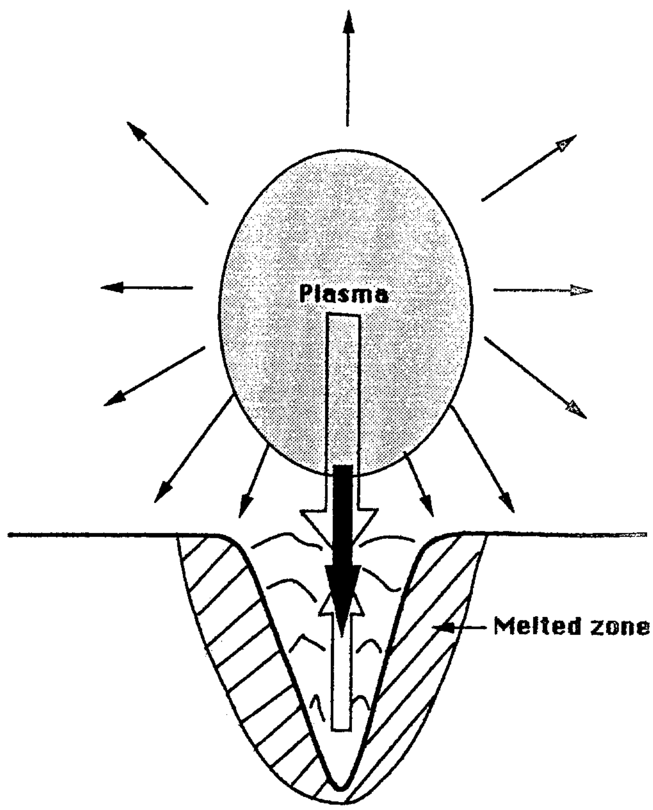

Figure 2 Illustration of trapping of porosities. The temperature of the plasma in the upper region is higher than that of vapour in the lower keyhole. Thus, the direction of net pressure is towards the root of keyhole. Since the keyhole wall prohibits leakage of pressure, the pores are trapped on the root while the keyhole is collapsed by flow-in of molten metal.

As full penetration was achieved on the bead-on-plate laser welding, the formation of porosity was suppressed [4]. The reason is believed to be that a conduit of high-pressure vapour was provided through the bottom hole. If this is accepted, the formation of porosity can be reduced or suppressed in butt welding and lap welding by proper welding design, no matter what laser power and scanning speed are selected, because the high vapour pressure would be reduced on the root of the cavity due to the passage of gas through the clearance between two pieces which acts as a conduit of high-pressure vapour. However, in order to avoid the formation of porosities in bead-on-plate laser processing, the laser scanning speed should be chosen not to give the higher counter-pressure in the keyhole which would maintain porosities on the root of the cavity before resolidification.

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