Numerical simulation of heat transfer and fluid flow in GTA/Laser hybrid welding

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In order to understand the temperature fields, cooling rates and mixing in the weld pool, a comprehensive, three-dimensional heat transfer and fluid flow model is developed and tested by comparing model predictions with two sets of experimental data. The first set of data was taken from the literature. The experiments varied the separation distance between the heat sources for three arc current levels at a constant laser power. The second set of experiments analysed the effect of varying laser power for a constant heat source separation distance. The results demonstrate that the distance between the two heat sources significantly affects the cooling rates. The calculated results showed that the hybrid weld pool was very well mixed with strong convection currents resulting from the interaction between the electromagnetic and Marangoni forces. The calculated and experimental results showed that hybrid welding increases the weld pool width and gap bridgability when compared with laser welding. The weld pool depth in hybrid welding was affected mainly by the characteristics of the laser beam. Hybrid weld pool penetration depth is maximised at an optimal distance between the arc electrode and laser beam. The cooling rate increases significantly when the heat sources are separated beyond a critical distance. At close separation between arc and laser, calculations show that the arc radius must be decreased to achieve the observed weld depths.

Keywords: Hybrid welding, Heat transfer and fluid flow, Laser beam, Gas tungsten arc, Modeling, Cooling rate, Keyhole

Introduction

Hybrid welding involves the joining of metals and alloys by a laser beam and electrical arc. The hybrid welding process incorporates the benefits of both laser and arc welding in order to overcome their individual problems.[1–6] Figure 1 is a schematic of the laser/GTAW hybrid welding process, which depicts the heat source separation distance and arc angle and length. The laser beam, with energy density greater than 10^9 W m^{-2}, provides relatively deep penetration at high welding velocities without the necessity of additional passes.[1–10] The hybrid welding process results in less residual stress and thermal distortion compared to arc welding. Gap tolerance is also increased due to the generation of a wide weld pool.[1–6] Experimental research has also shown that hybrid welding can reduce the propensity of cracking and presence of brittle phases due to relatively lower cooling rates.[11–14] Furthermore, keyhole stability increases, which reduces the amount of porosity due to unstable keyhole collapse.[12,15–18]

The experimentally observed benefits of hybrid welding are due to the interaction of the laser and arc heat sources.[1,2,4–6,19–21] When the arc and laser focal points are within close proximity, the heat sources may interact.[2,5,19,20] The interaction of the two heat sources during hybrid welding is explained by two phenomena. First, arc stability is enhanced due to the introduction of metal vapours into the arc plasma from the laser induced keyhole.[2,5,8–10,19,20,22–33] The metal vapours increase the electrical conductivity of the arc plasma.[2,5,19,20,22–24,26,27,32,33] In addition, the arc contracts, causing an increase in current density.[5,22,24,26,27,34] In the case of introducing copper vapours into a free burning arc, it was observed that the current density can increase by a factor of four.[26] Depending on the separation distance between the heat sources, the arc can bend towards the laser generated keyhole, rooting closer than the physical separation distance.[2,19,20,26]

Beyond a critical separation distance, the arc is unable to bend or root on the keyhole due to the lack of metal vapour introduced to the arc plasma, explaining why the effect decreases as the distance between the two heat sources increases.[2,5,19,20] Chen *et al.*[2] experimentally studied the hybrid welding of AISI 321 stainless steel and observed the laser–arc interaction. They did not accredit the observed effects to any particular phenomena, but described that a particular value of separation between the two heat sources resulted in a relatively small increase in the penetration of the weld pool. Chen

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