Physical Simulation of Marangoni Convection in Weld Pools

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Marangoni convection in the weld pool can affect its depth significantly, which is often critical in welding. Marangoni convection in the weld pool is induced by surface-tension gradients along the pool surface, which drive the liquid at the pool surface from where the surface tension is low to where it is high. The surface-tension gradients are induced by the temperature gradients along the pool surface. Arc heating makes the temperature of the pool surface significantly higher at the center than at the edge. In the absence of a surface-active agent, the surface tension decreases with increasing temperature, and so the melt at the pool surface flows outward from the center to the edge. In the presence of a surface-active agent, however, these phenomena can be reversed. Observation of Marangoni convection in a weld pool not only is limited to the pool surface because the melt is opaque, but also is difficult because the arc is too bright for convection to be seen clearly.

The objective of the present investigation is to understand Marangoni convection in weld pools by using transparent simulated weld pools and flow visualization.

The benefit of microgravity is that buoyancy convection is suppressed and thus will not interfere with the study of Marangoni convection. In the present investigation ground-based experiments are conducted in small, simulated weld pools where the effect of gravity is reduced so that Marangoni convection can dominate over buoyancy convection like in microgravity.

$NaNO_3$ was selected as the material for study because of its transparent melt, large temperature dependence of surface tension, and well documented physical properties. The apparatus for flow visualization consisted of:

1. an inner glass container holding an essentially hemispherical pool of $NaNO_3$ melt;
2. an outer glass container holding a molten $NaNO_3$ bath to keep the pool from freezing;
3. a heat source at center of the pool surface; and,
4. a light sheet of He-Ne laser passing through the meridian plane of the pool.

A laser light-cut technique for flow visualization was used. The laser light sheet was produced by a 20 mW He-Ne laser and optical lenses. Aluminum particles 20 μm in diameter was used as a tracer. Although the density of aluminum (2.7 g cm^{-3}) is greater than that of the $NaNO_3$ melt (1.9 g cm^{-3}), the settling velocity is much slower than Marangoni convection since the particles are very small in diameter. A certain amount of aluminum particles gradually settled to the pool bottom over extended periods of time.

In this preliminary stage of investigation, a hot wire touching the center of the pool surface was used as a tentative heat source to study Marangoni convection in the absence of a surface-active agent. Two different pool sizes were studied, 6 and 10 mm in diameter at the surface.

The flow pattern is described as follows for a 6 mm diameter pool with a surface temperature 45 °C higher at the center than at the edge. Essentially, the melt rose from the pool bottom along the axis of the pool to the pool surface. It continued to flow outward from the center of the pool surface, where the temperature was higher and the surface tension lower, toward the edge of the pool surface, where the temperature was lower and the surface tension higher. It went on to sink along

the container wall and returned to the pool bottom to start all over again. There were two stable and axisymmetric flow loops in the pool. The one on the right was clockwise and the one on the left counterclockwise. The vortexes of the flow loops were about 0.6 mm below the pool surface and 3.2 mm apart. Fluid flow was much faster near the pool surface, where the flow lines were much more closely spaced, than in the bulk pool or near the pool bottom, where the flow lines were much more widely spaced. This flow pattern is qualitatively consistent with those computed numerically in a stationary weld pool in the absence of a surface-active agent.

As the heater power was reduced to decrease the temperature difference between the center and the edge of the pool surface (e.g., to 25 °C), fluid flow in the pool slowed down but the flow pattern remained unchanged. When the temperature difference was further decreased, say to about 10 °C, however, fluid flow became too weak to sustain a stable and axisymmetric flow pattern.

The results of 10 mm diameter pools are very similar to those described above. With the surface temperature about 45 °C higher at the center than at the edge, the two flow loops were stable and axisymmetric. The vortexes of the flow loops were about 0.8 mm below the pool surface and 5.7 mm apart. When the temperature difference was reduced to about 10 - 15 °C, the two flow loops became unstable and asymmetric.

In the configuration of a weld pool, buoyancy convection is in the same direction as Marangoni convection. Therefore, it should be checked whether the convection observed is driven primarily by Marangoni convection or buoyancy convection. The dynamic Bond number is often used as an indication of the relative strength of buoyancy convection to Marangoni convection. It is defined as $Bo - \beta\rho g L^2 / (- \partial\gamma/\partial T)$, where β is the thermal expansion coefficient of the melt, ρ the density of the melt, g the gravitational acceleration, L the characteristic length of the pool, and $\partial\gamma/\partial T$ the temperature coefficient of surface tension of the melt. With the physical properties of the $NaNO_3$ melt and L taken as the radius of the pool surface, Bo is about 2 for the 6 mm diameter pool and 5 for the 10 mm diameter pool, respectively. Although $Bo > 1$ in both cases, the vortexes are very close to the pool surface. This suggests that Marangoni convection dominates in the melt in both cases. To further verify this, flight experiments are highly desirable.

In conclusion, Marangoni convection in weld pools can be simulated and observed in molten $NaNO_3$ pools by touching the center of the pool surface with a hot wire to raise its temperature above that at the edge of the pool surface. As shown in these ground-based experiments, the vortexes of the flow loops are very close to the pool surface, where fluid flow is much faster and the flow lines are much more closely spaced than in the bulk pool. This suggests that convection in these pools is dominated by Marangoni convection. When the temperature difference between the center of the pool surface and the edge is high, the flow loops are stable and axisymmetric. When the temperature difference is reduced beyond a certain point, however, convection weakens and the flow loops begin to lose stability and axisymmetry.