Gravity Effects on the Microstructural Behavior and the Development of Weld-Pool

Jogender Singh - Principal Investigator
Applied Research Laboratory
Pennsylvania State University

Co-Investigators:
Nam Hyun Kang, Applied Research Laboratory/Pennsylvania State University
Samuel George Lambrakos, Naval Research Laboratory
Steven Paul Marsh, Naval Research Laboratory

Objective

Welding process in space needs a better understanding of many interacting phenomena during melting and solidification. The objective of the investigation is to study the effect of heat/mass transfer on the weld-pool shape and microstructure under solidification conditions varying 0.01 g to 1.8 g. Three major driving forces for convection in laser welding are buoyancy (gravity driven), thermocapillary (surface tension gradient driven) and thermosolutal (concentration gradient driven) flows. Lorenz flow driven by electromagnetic force must be considered for convection in GTA weld-pool. In normal earth gravity, surface tension gradient driven flow was determined to be the dominant force. The scientific and technological benefits of the investigation are to clarify welding phenomena and to optimize future application in building a space station.

Approach

To achieve the stated goal, the following parallel efforts are in the process or planned:

(i) Ground-based experiment;

(ii) Mathematical modeling; and,

(iii) Microgravity experiment.

Ground-based experiments are composed of Gas Tungsten Arc (GTA) and laser welding of Fe 15% Cr-15% Ni alloy and Fe-18% Cr-8% Ni alloy. The shape of weld-pool and microstructural evolution will be studied to obtain better understanding of welding interactions. These experiments are also conducted to compare with microgravity welding results.

Similar welding investigations are conducted on Ni-Ag alloys. Significantly different ionic radii (Ni = 0.7 and Ag = 1.26) and different melting temperatures (Ni = 1453 and Ag = 960.8 °C) have been known to make this alloy immiscible even in liquid state. If the effect of different densities (Ni = 8.9 and Ag = 10.49 gm/cm^3) is more significant than the other effects of the ionic radius and the melting temperature difference, this alloy will have indication of partly or completely homogeneous microstructure in microgravity welding.

Another welding experiment with tracer elements will be conducted on Ni-Al alloys. This alloy has been selected because both solute atoms have significantly different densities (Ni = 8.9 and Al = 2.7 gm/cm^3). This alloy system is an ideal candidate for investigating the effect of gravitational force during solidification. The difference in component densities will emphasize the effect of gravity-driven buoyancy flow, and it will cause variation of solidification microstructure.

The first level of modeling involves the macroscopic simulation of the transport processes that occur in the region of the weld and within the weld pool. Three-dimensional temperature histories will be calculated for the two classes of weld data by means of an inversion procedure. Comparison of simulations with measurements on actual welds under various gravity conditions permits the refinement of the physical models in the simulations, thus leading to optimization of critical operating variables in the laser welding process.

NASA's KC-135 aircraft experiment was conducted on Fe-18% Cr-8% Ni alloy to produce various gravity conditions. The effects of gravity was studied on the shape of the weld pool and the resulting changes to the heat transfer conditions. Temperature distribution within the weld-pool and the circulation of the melt within the pool will affect the final weld microstructure and composition. Since stainless steel has a strong negative surface tension temperature coefficient, heat from the GTA welding will be transported to the edges of the pool across the surface. Natural convection due to buoyancy effects contributes to heat transfer when a gravity field is present. Buoyancy driven flow adds to the surface tension driven flow if the temperature coefficient of surface tension is negative. This flow mechanism is non-existent in a microgravity environment, even though Lorenz force still exists within the pool. Changes in the flows caused by gravity variation need to be studied through all metallographic and pool-size examinations.

Results and Future Plans

Recent statistical analysis on Fe-18% Cr-8% Ni welds demonstrated that the weld-pool geometry changes considerably depending on gravity. The width of the weld-pool was observed of 10% increase at 1.8 g compared with the width at ~1.2 g. However, in microgravity environments, inconsistent results were observed as high fluctuation of the weld-pool width. The emphasis in this analysis was to determine a general estimate of the sensitivity of the weld structure to variation of gravity and to attempt a filter of experimental artifacts or structures due to the influence of gravity on other features of the welding process. Even though the gravity effect was not revealed quantitatively on the size of the weld-pool, qualitative change of the pool was proved under different gravity.

Based on the experimental measurements, basic modeling reproduced the shape of the weld-pool and temperature distribution within the pool were constructed. The fraction of the weld data for which the influence of changes in gravity was found to be statistically significant was classified into two classes: welds corresponding to low gravity (near 0 g) and welds corresponding to high gravity (above 1 g). The goal of this classification and the subsequent qualitative analysis was to determine a general bound estimate of the gravity variations on the temperature history of the welds. The results of these calculation indicated that changes in gravity did result in a non-negligible change in temperature history of the workpieces.

The rippling on the free surface was also observed to connect gravity effects to the resulting convection within the pool or to the recoil pressure between the liquid and the gas phases. Scanning transmission electron microscope (STEM) was employed to measure the concentration gradient of alloying elements. This technique will establish a better understanding of microstructural evolution and mass transport within the pool under different gravitational solidification conditions (0.01 ~ 1.8 g).

A more quantitative correlation between weld structure and actual values of the gravitational force was purposely avoided in this analysis at this point. Before a quantitative analysis is undertaken, several tasks must be completed (which are now underway). These are:

(i) Filtering of the weld data must be undertaken in order to extract weld structure corresponding to quasi-steady-state conditions. This must be performed for the different

fraction of the gravitational force in order that a quantitative analysis by inversion can be effected.

(ii) The KC-135 flight data must be calibrated against ground-based experiments corresponding to the exact same weld process parameters. A suggested range of values of the gravitational force is $g(\cos\Omega)$ where $0<\Omega<360$. This calibration should provide a basis for filtering of experimental artifacts associated with the influence of changes in gravity on other aspects of the weld process (e.g., heat source). These ground-based data should provide extension of the data set for a more complete quantitative analysis.

Ground-based experiment on Ni-Ag alloy was conducted to provide fundamental results on welding microstructure of immiscible monotectic alloy system. GTA welding and laser welding/cladding techniques were employed to produce homogeneous microstructure within the pool. However, dispersed Ag particles in Ni matrix or dispersed Ni particles in Ag matrix were observed instead of homogeneous microstructure.

To achieve better understanding on gravitational effects, more specific experimental efforts on microstructural behavior and more fundamental studies on gravitational effects are needed with the parallel efforts of mathematical modeling and simulation. X-ray diffraction (XRD) and STEM measurements will be employed or continued for measuring the amount of retained ferrite and the concentration gradient of alloying elements, respectively. These approaches will provide clarification of microstructural behavior, directly on heat/mass transport within the pool or indirectly on the gravity effects. Ground-based experiment will be conducted on Fe-18% Cr-8% Ni alloy to compare with the flight experiment and on Ni-Al alloy. The long-term plan based on this research effort is to carry out KC-135 or DC-9 low gravity experiments in order to provide a basis for the development of a series of solidification experiments with laser welding for future development on the Space Station fabrication.