

## **C. Gleeble Simulation of Ferrite Formation in 21-6-9 Inertia Welds**

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### **Introduction**

Given their generally superior resistance to hydrogen-assisted fracture, austenitic stainless steels are often favored over ferritic or martensitic stainless steels for use in hydrogen environments. However, recent microstructural investigations into the application of inertia welding to components fabricated of 21Cr-6Ni-9Mn, a nitrogen-strengthened austenitic alloy, have revealed the formation and retention of large quantities of ferrite at the weld interface. To better understand the mechanism and conditions under which ferrite forms, rapid thermal cycle Gleeble simulations have been coupled with applied plastic shear strains typical of those prevalent at the interface during inertia welding.

### **Technical Approach**

Cylindrical samples of 21-6-9 were instrumented with thermocouples and inertia welded using a wide range of axial forces and kinetic energies. The measured thermal cycles were then used for experimental simulations of the welding cycle. Various heats of 21-6-9 containing from 0 to 2% ferrite were used in this study. Thermodynamic calculations showed that the measured peak temperatures were well within the ( $\delta + \gamma$ ) two-phase region. Thermal cycle simulations, as well as coupled thermal cycle / shear strain simulations were performed in a Gleeble thermal-mechanical simulator. The resulting microstructures were examined by both optical and scanning electron microscopy.

### **Results/Discussion**

Thermal cycles were measured from inertia welded samples of 21-6-9 material using thermocouples spot welded to the outside of the stationary cylinder. The thermal cycles were found to be strongly influenced by the choice of the inertia weld processing parameters. Specifically, the measured peak temperatures were found to be inversely related to the axial stress that was applied to the specimens. Furthermore, for a given kinetic energy, the weld cycle time, and consequently the thermal cycle time, was also found to be inversely related to the axial stress. These thermal measurements were then analyzed to obtain estimates of the thermal cycle in the weld interface zone, and can be used in empirical descriptions of the relationships between thermal conditions and process parameters. In all cases, ferrite was observed to form and be retained at the weld interface after inertia welding.

Thermal simulations were performed that duplicated typical thermal cycles determined from the measurements. It was found that the thermal cycle alone was insufficient to alter the initial ferrite in the microstructure. Furthermore, in the case of materials that had undetectable amounts of starting ferrite, and even though inertia welding produced appreciable amounts of ferrite, no ferrite was observed either via dilatometry during testing or during subsequent microscopic examinations. Simulations of thermal cycles with imposed strains were then conducted. For the relatively short thermal cycles that were typically observed in inertia welding the cylindrical specimens, large strains were a necessary component to obtain ferrite at the interface. From these results it is possible to develop processing maps describing the thermal, strain, and composition conditions under which ferrite develops. These processing maps, though

difficult to relate quantitatively to processing conditions, can be used in conjunction with the empirical thermal relationships to guide inertia weld process selection toward minimizing the ferrite levels.

### **Conclusion**

Inertia welding was used to join 21-6-9 weld samples while the thermal cycles were experimentally measured. An inverse relationship was determined between the applied axial stress and both the measured peak temperatures and weld cycle times at specific kinetic energies. All welds contained ferrite contents much greater than those of the base material, although the ferrite levels were found to be parameter dependent. Thermal cycle simulations alone did not increase ferrite content. Rather, large strains typical of those seen at the inertia weld interface in conjunction with the rapid thermal cycles were required for ferrite formation.