Relaxation of Thermal Residual Stresses in NiAl-AlN-Al_2O_3 Composites During Heating

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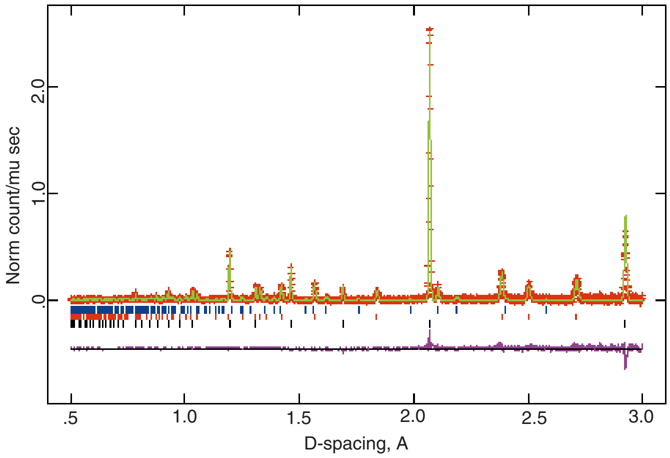
The nickel-aluminide-based composite containing both AlN dispersion particles and Al_2O_3 fibers shows good high-temperature strength and is a potential replacement for current nickel-base superalloys. To better understand the strengthening mechanisms of this composite, we characterized the thermal residual stresses as a function of temperature using the neutron powder diffractometer (NPD). Results show that the residual stresses developed during cooling from the processing temperature relax at around 1200 K upon reheating. Hence, we conclude that the mechanical properties of this composite are not directly affected by the thermal residual stress above this temperature.

The ordered intermetallic alloy nickel aluminide (NiAl) has potential advantages over current superalloys for use in high-temperature structural applications. These advantages include a high melting temperature (1922 K—about 300 K higher than the nickel-base superalloys); low density (5.9 g/cm^3— approximately 2/3 that of the superalloys); high thermal conductivity; and excellent oxidation resistance.[1] However, cast polycrystalline NiAl suffers from poor room temperature fracture toughness and poor creep resistance at intended service temperatures (1300–1400 K). Such inadequate mechanical properties pose a major challenge for the alloy designer who wishes to take advantage of those properties that are superior to current superalloys. To address these problems, we developed a hybrid NiAl composite containing both AlN dispersion particles and Al_2O_3 fibers.[2] We intended to achieve a synergistic improvement in mechanical properties, especially creep resistance, by combining the two different strengthening mechanisms: (1) fine AlN dispersion particles (typically less than 1 μm), distributed homogeneously both along grain boundaries and within grains, will inhibit dislocation movement, and (2) long fibers improve strength by load transfer and by constraining macroscopic flow over a wide strain rate range. Mechanical testing at 1300 K revealed that this composite is one of the strongest NiAl-based alloys developed to date, approaching the level of NASAIR 100, a first-generation Ni-base single-crystal superalloy.[2]

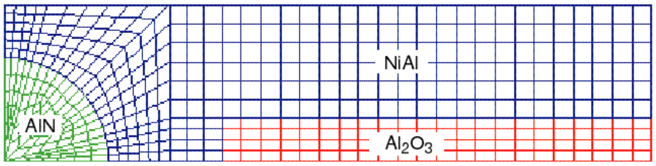
Most metal-matrix composites reinforced by a ceramic phase have a considerable difference in the coefficient of thermal expansion between the matrix (NiAl) and the reinforcements (both AlN and Al_2O_3). Thus, on cooling from the fabrication temperature (1473 K), thermal residual stresses develop as a result of differential thermal contractions of the three phases. These stresses are known to influence mechanical properties such as yield strength[3] and fatigue resistance.[4] Furthermore, since these composites are designed for high-temperature application (e.g., turbine blades), understanding the characteristics of thermal residual stresses at elevated temperatures and the effect on creep behavior is critical.

We characterized the thermal residual stresses in the NiAl-AlN-5%Al_2O_3 composite using NPD as a function of temperature. Figure 1 shows the diffraction pattern comprising raw data and Rietveld refinement. In the diffraction pattern, the crosses represent the data and the solid line overlapping the data points is the fit from the refinement. Tick marks identify the refined peak positions of the Al_2O_3 (rhombohedral), AlN (hexagonal), and NiAl (cubic) phases at the bottom of each graph, and the difference curve between measured data and refinement is shown below these. We measured each phase's lattice parameters as well as standards from room temperature to 1500 K and calculated the lattice strain and corresponding stress from the lattice parameter. We also estimated the residual stresses using a finite element model (FEM). Figure 2 shows the NiAl-AlN-5%Al_2O_3 composite mesh. We calculated the residual stress using ABAQUS,[5] assuming two-dimensional axisymmetry and a perfectly bonded matrix/reinforcement interface. We included plasticity and creep for the matrix but treated the AlN particles and Al_2O_3 fibers as purely elastic.

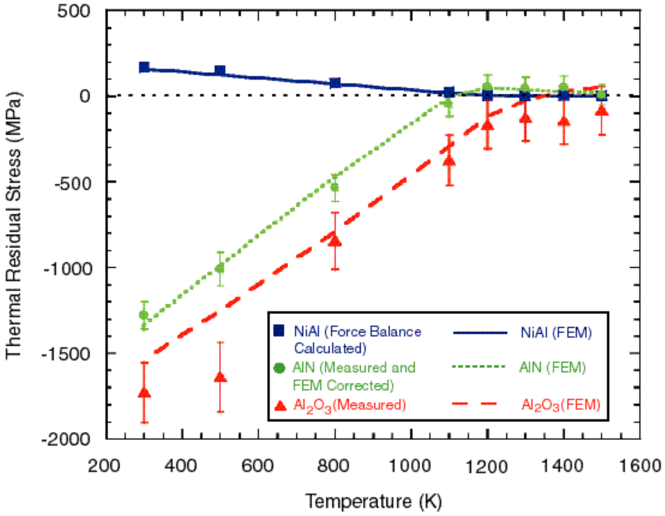


▲ **FIGURE 1.** *Time-of-flight neutron diffraction pattern of NiAl-AlN-5%Al_2O_3 composite.*

In Figure 3, the data points represent the thermal residual stresses in each phase in NiAl-AlN-5%Al_2O_3 measured with NPD as a function of temperature. The lines in Figure 3 represent the FEM results and are in good agreement with the experimental data. The tensile residual stress



▲ **FIGURE 2.** *Schematic of the finite element model showing the NiAl-AlN-5%Al_2O_3 composite mesh.*



▲ **FIGURE 3.** *Hydrostatic thermal residual stresses in NiAl, AlN, and Al_2O_3 phases in NiAl-AlN-5%Al_2O_3 composite.*

developed in the NiAl phase during cooling from the processing temperature decreased as the temperature increased and completely relaxed at around 1200 K, which is significantly lower than the processing temperature (1473 K). The magnitude of the compressive residual stress in the AlN phase decreased as the temperature increased and developed a small tensile stress above 1100 K. The relaxation temperature of Al_2O_3 phase is not quite clear due to uncertainty in the experimental data. However, the FEM result indicates that the residual stress relaxes at around 1300 K. Relaxation of the residual stress at temperatures below the processing temperature and the change of the sign in stress in AlN and Al_2O_3 are primarily due to the creep (either dislocation glide or diffusion) of the matrix during the heating cycle. At high temperatures where thermally activated process is important, the thermal residual stresses are known to relax by time-dependent deformation such as creep, which results in a dynamic evolution of the residual stress at high temperatures.

Considering the relaxation of thermal residual stress in the matrix above 1200 K, we conclude that the residual stress above this temperature will not directly affect this composite's creep properties. However, the thermal residual stresses will have some influence on the low and intermediate temperature mechanical properties such as strength and fracture toughness.

References

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