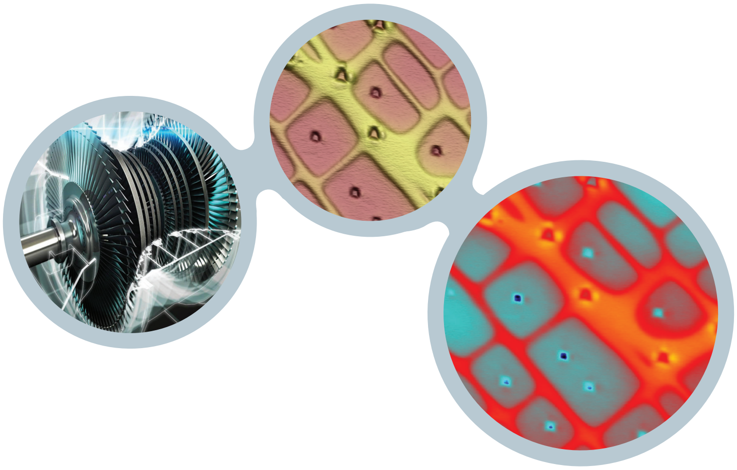

Application Note #1527

Strength Engineering in a Nickel-Base Superalloy

Materials used for production of gas turbine blades are subjected to very harsh operating conditions. The blades must withstand centripetal forces during long periods of operation at temperatures of 700°C to 1100°C. Dimensional tolerances in the turbine require a material that does not creep, and the materials must also endure a highly corrosive environment. Because higher operating temperatures improve turbine efficiency, development of superalloys that can perform at higher and higher temperatures is an ongoing area of research requiring further advances in the design of the alloys. Nickel-base superalloys are complex alloys often containing more than ten elements. Alloying with an increasing amount of refractory elements is one way to improve high-temperature capability and creep resistance. Re and Ru are two such alloying elements, with Re being used to promote the alloy's creep resistance, and Ru being used to reduce the formation of topologically close-packed phases. A detailed understanding of hardening mechanisms in the alloy and the effect of alloying elements on the γ matrix and γ′ precipitates is important in designing alloys with improved properties. This application note combines nanoindentation with SPM imaging to directly measure the properties of the individual phases.

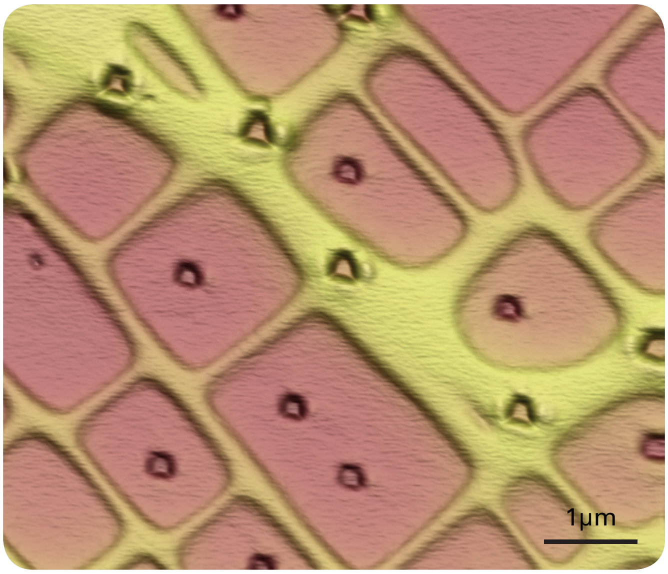

Figure 1. In-situ SPM image of indentations on the Ni-base alloy showing tests positioned on specific phases.

Experimental

One control alloy based on CMSX-6 (wt.%: Al 4.9, Ti 3.9, Cr 8.2, Co 4.1, Mo 2.5, Ta 0.6, Ni 74.8) and three alloys containing 3 wt.% Re, 3% Ru, and 3% of Re and Ru, were directionally solidified in a Bridgman furnace. After annealing, the samples were cut along the {001} crystallographic plane of the γ matrix (perpendicular to the solidification direction) and polished with SiO_2 to a roughness less than 2nm. Figure 1 shows that, when polished in this orientation, the cuboidal γ′ precipitates are clearly visible as rectangular areas separated by thin channels of γ matrix. The alloy with 3% Re and 3% Ru had the smallest precipitates, and for that sample, the average γ′ size was 790nm and the γ channel width was 250nm. The γ′ precipitates were slightly recessed due to the polishing procedure, which is a typical effect from polishing with SiO_2. Several nanoindentation tests were performed with a Hysitron® TriboIndenter® on the different phases using a diamond cube corner indenter probe and a maximum load of 250µN. Figure 2 compares a load-displacement curve from an indent on a precipitate to an indent on the matrix. The "pop-in" events, visible in both curves, indicate the onset of plastic deformation during the indentation test. The similarity between the curves prior to the pop-in indicates that the elastic properties of the phases were similar, and the force required to generate the pop-in shows that the γ material yielded well before the γ′ precipitates.

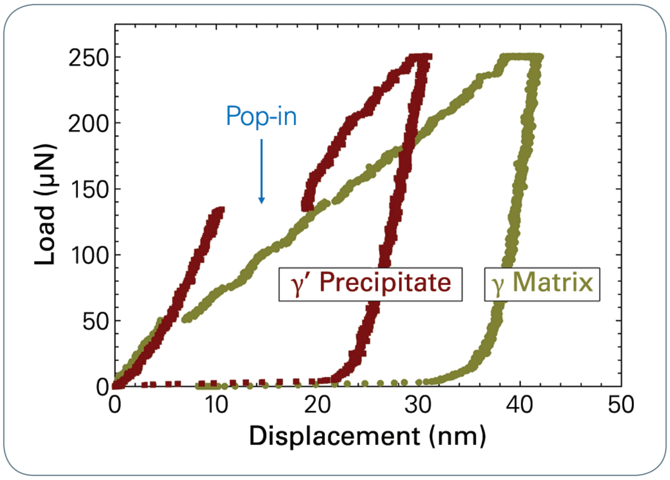

Figure 2. Load-displacement curves on alloy Re with nominal 3 wt.% Re.

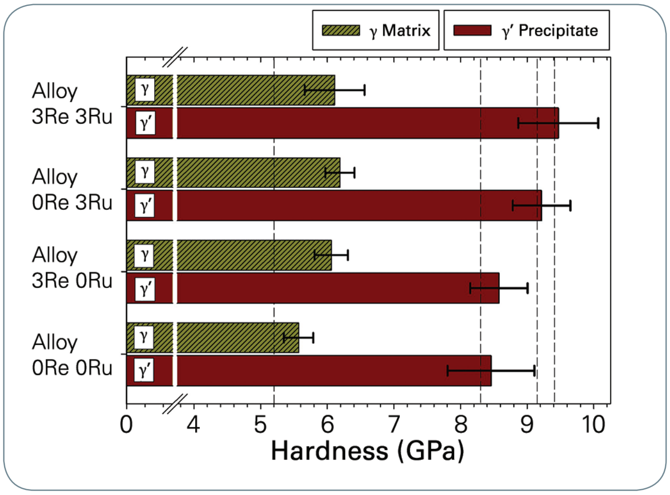

Figure 3. Hardness of the γ-matrix and γ′-precipitates for the different alloys.

Results

The hardness tests on the alloys revealed that the γ matrix and γ′ precipitates were affected differently by the addition of Re and Ru. Figure 3 summarizes the results from tests on the four alloys. The addition of Re led to a significant increase in the hardness of the matrix, while the Ru increased the hardness of both phases. Adding both elements increased the hardness of the precipitates slightly more than adding Ru alone. In all cases, the hardness increase was due to a solution strengthening mechanism. To understand the change in hardness of the respective phases in the different alloys, the partitioning behavior of the alloying elements Re and Ru must be considered [1]. Energy dispersive X-ray spectroscopy (EDS) measurements performed on the alloys in a transmission electron microscope (TEM) revealed that the alloying elements were not evenly distributed. Re was present mainly in the matrix, while Ru was more equally distributed between both phases. The partitioning behavior of the two elements can qualitatively explain the trends in hardness observed in Figure 3; however, it is also important to note that the distribution of other elements in the alloy is affected by the presence of both Re and Ru [1].

Conclusions

The combination of hardness testing and local chemical analysis allows for investigating the effect of a single alloying element on various parts of the microstructure in nickel-base superalloys. The large number of elements used for these high-performance alloys requires detailed study to understand the complex interactions between the alloy's many components. This study demonstrated that mechanical measurements with high-spatial resolution and in-situ SPM imaging are key to understanding the underlying principles affecting the overall performance of the material. With this improved understanding, future alloy design will allow development of materials that can operate under increasingly demanding conditions.

References

1. S. Neumeier, F. Pyczak, M. Göken (2011): Influence of rhenium and ruthenium on the local mechanical properties of the γ and γ' phases in nickel-base superalloys, *Philosophical Magazine*, 91:33, 4187-4199.

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