Measuring Stress Relief in Electron Beam Weld Joints of Superalloys

Single-crystal turbine blades are the pinnacle of a decade-long development and refinement of nickel-based superalloys. By eliminating creep along grain boundaries as the main failure mechanism of polycrystals at high temperatures, the use of single crystal turbine blades has allowed a rise in temperature in the "hot zone" by more than 100 K, thus substantially increasing thermodynamic efficiency of jet engines. The complete turbine blade, including the mounting base and the cooling channels, is grown from the melt in a single process and represents a considerable investment. In order to protect this investment, electron beam welding (see Fig. 1) is used to repair minor structural damage of failed components.

The weld process creates very high residual stresses that make the extended weld region prone to cracking. Cracks are sometimes found parallel to the weld especially in the *z*-direction, so that an additional heat treatment must be applied for stress relief. The standard heat treatment is 2 h at 1423 K for homogenizing (solution) and a subsequent aging treatment. In this investigation neutron diffraction is used to compare the stresses before and after heat treatment in the single crystal side of the weld joint.

Usually a polycrystalline alloy of comparable composition is chosen as a replacement material. The typical grain size of the polycrystal is approximately one millimeter, which is about the size of the incident neutron beam. Thus, stress measurements are not feasible for this side of the weld. Compared to a measurement on a fine-grained polycrystal, the measurement procedure is rather difficult because all small angle grain boundaries (Fig. 2) have to be brought into reflection and averaged over the rocking angle ω in the data reduction.

Additionally, both the welding and the heat treatment produce position-dependent chemical gradients that affect the unstressed lattice parameters. Their measurement would have required cutting the specimen into little pieces for complete stress relief. We chose an alternative approach of applying mechanical boundary conditions at the surface. The results obtained from this procedure are shown in Fig. 3.

The effect of the heat treatment is dramatic. Both the strong tensile stresses in the heat-affected zone (5 mm from the weld center) and the strong gradients at the interface between weld and heat affected zones are removed. Stress relief in the *z*-direction is especially important because it removes the driving force for crack opening parallel to the weld in the heat-affected zone.

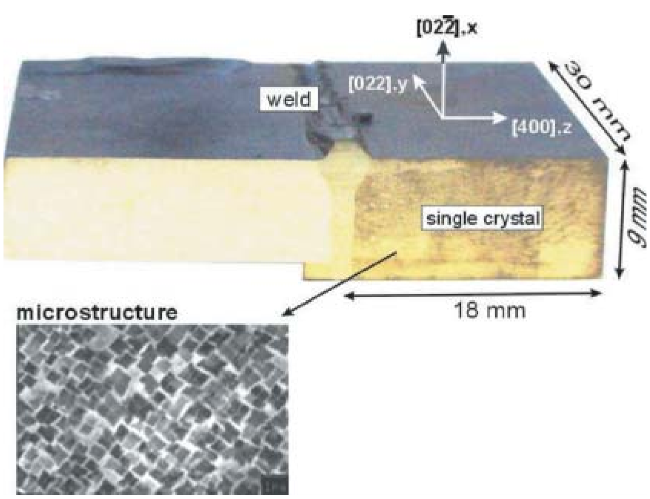

FIGURE 1. Test specimen of a weld joining a Rene N5 single crystal and a polycrystal. The three different regions, polycrystal, weld, and single crystal, appear in different colors after etching which indicates different chemical compositions. The microstructure shows typical features: 60 % cuboidal γ'-precipitates and unimodal size distribution.

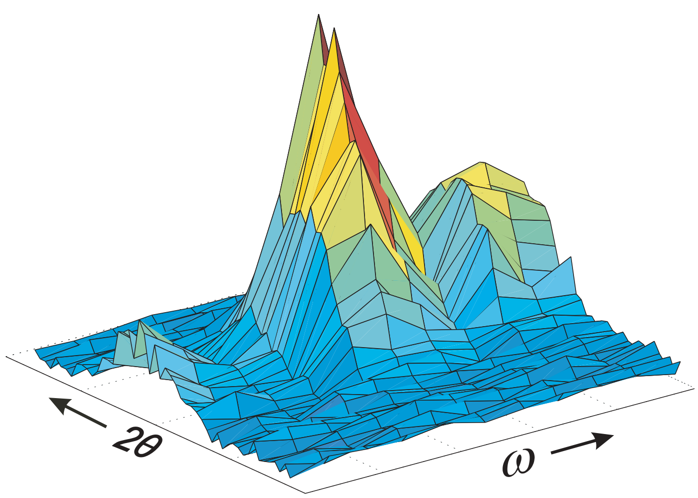

FIGURE 2. Q_x-intensity map for the as-welded sample (reciprocal space) plotted vs. 2θ and the rocking angle ω. Small angle grain boundaries as indicated by the presence of several maxima are characteristic for superalloy single crystals. The existence of two maxima in 2θ (equivalent to two *d*-spacings) indicates the γ-matrix and the γ'-precipitates whose lattice parameters are close to each other.

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Remarkable features in Fig. 4 are the strong compressive stresses after heat treatment in the middle (4 mm depth) both for the *z*-direction and the *y*-direction. There is evidence that solidification partitioning can lead to a different γ/γ'-microstructure in the weld zone, thus affecting the mean lattice parameter measured by diffraction. The immediate results are apparent stresses caused by changes in the unstressed *d*-spacing. This effect can be removed with some confidence only for the measurements close to the surface (= 1 mm depth) by using mechanical equilibrium conditions. Further investigations are under way to clarify this effect for larger depths.

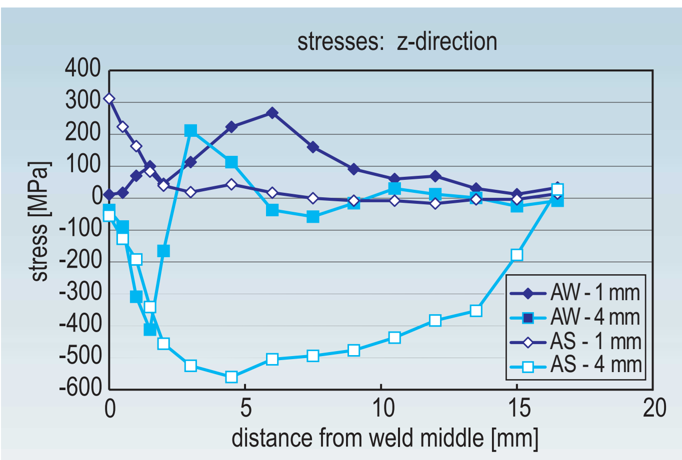

FIGURE 3. Residual stresses σ_{zz} before and after the heat treatment for two different depths from the upper surface. AW stands for "As Welded"; AS stands for "Heat Treated." The uncertainties are of the order of the size of the data points.

The stresses parallel to the weld (Fig. 4) are usually the highest and the most dangerous stresses because they reach the yield limit (around 600 MPa). If the weld direction is oriented such that the weld line is parallel to the main stress axis – i.e., radially for a rotating blade – then further loading would exceed the flow stress and cause a dangerous local weakening of the turbine blade. Here, the effect of the heat treatment is most beneficial because almost complete stress relief is achieved.

The stress relief effect of the heat treatment extends also to the microstresses between sub-grains by removing the dislocations created by the plastic deformation in the weld region. While direct observations of dislocations are not available, we can use the full width at half maximum (FWHM) of the measured integrated strain distributions as a measure for the dislocation density (see Fig. 5).

Figure 5 shows clearly that substantial plastic deformation exists only in the weld itself (0…1.0 mm) and within a very narrow zone of about 0.5 …1.0 mm in the base material. This effect vanishes completely after the heat treatment. These results demonstrate that a heat treatment after welding is essential for avoiding detrimental effects to the mechanical properties of the turbine blade.

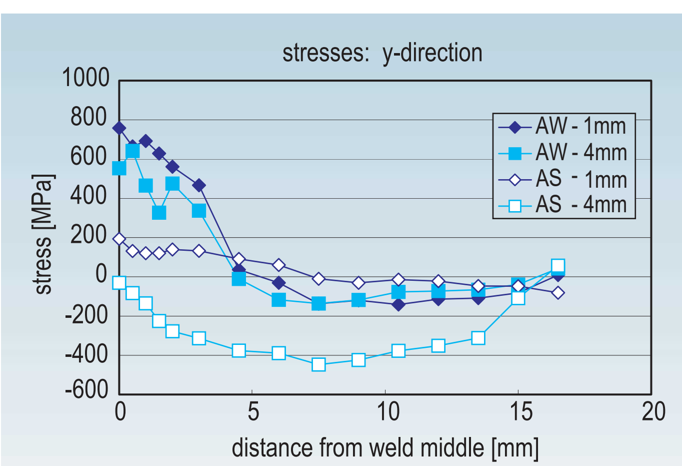

FIGURE 4. Residual stresses σ_{yy} (parallel to the weld) before and after the heat treatment.

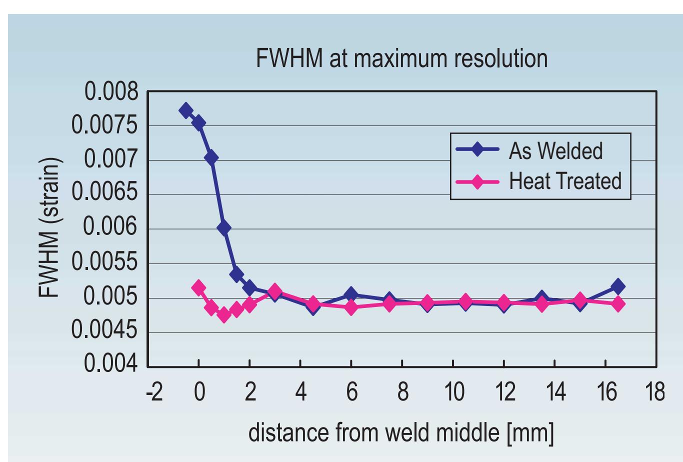

FIGURE 5. FWHM at the best instrument resolution before and after heat treatment. These results are representative for all measured depths.