Fracture Analysis of an Embrittled Low Alloy Steel Rotor Blade from an Operating Steam Turbine

A public utility company had several steam turbine electrical generation systems that had been in service for nearly three decades. A catastrophic brittle failure occurred in the rotor section of one of the turbines. Auger Electron Spectroscopy (AES) analysis with a PHI Scanning Auger Nanoprobe examined specimens removed from the failed rotor to ascertain the cause of the failure and to examine the possibility of recovering similar rotors that remained in service.

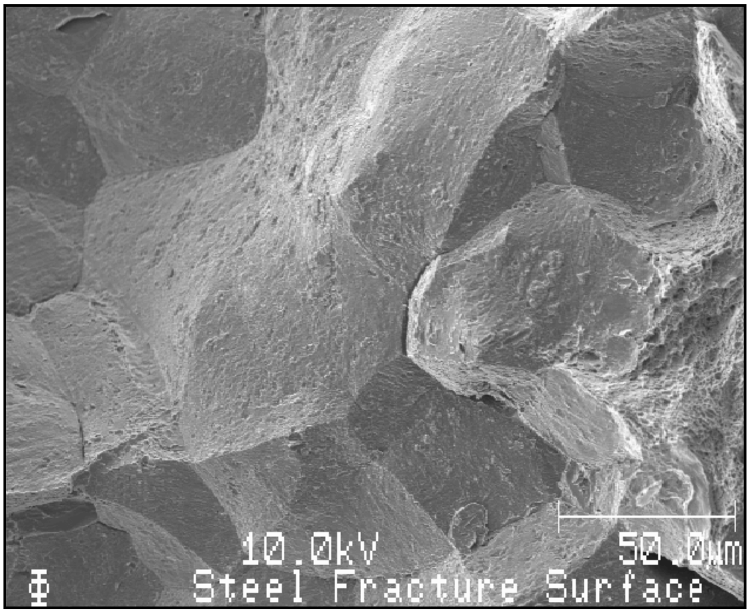
Element	Weight %
Ni	0.025%
Cr	0.97%
Mo	1.01%
V	0.17%
Mn	0.76%
Cu	0.10%
Si	0.32%
Fe	Balance

Samples were taken from the failed rotor and analyzed with AES using a PHI 680 scanning Auger nanoprobe. The samples were cooled *in vacuo* with liquid nitrogen to enhance brittle fracture, then fractured at a pressure of 1.2 x 10-10 torr to prevent contamination of the newly-exposed surfaces. AES analysis revealed predominantly brittle intergranular fractures, as shown in the secondary electron image. Analysis results also indicated that some ductile rupture was present and that the grain boundary surfaces were not smooth, but highly textured.

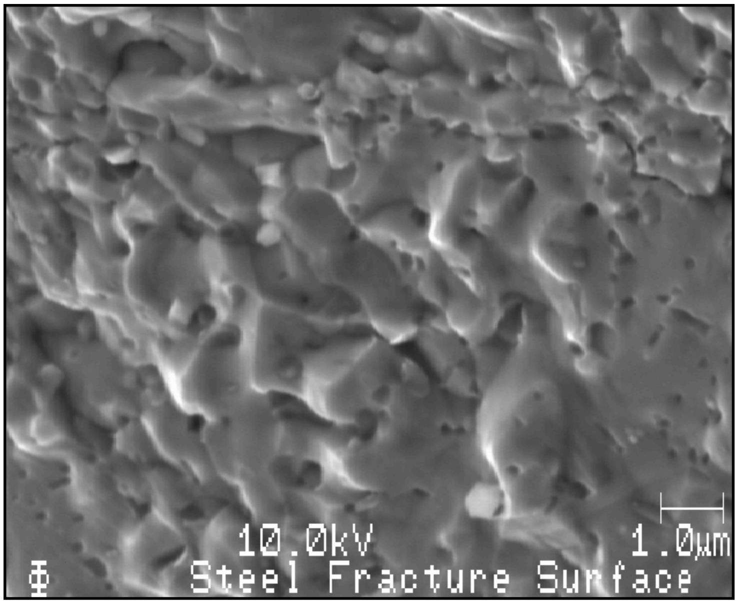
Metallurgical examination of the failed rotor showed a bainitic microstructure and a predominantly intergranular failure along prior austenite grain boundaries. Bulk chemical composition is shown in the table. All impurities were found to be at parts-per-million (ppm) levels.

The rotor had experienced about 27 years of nearly continuous operation at an average temperature of 450º C. Laboratory testing of additional samples cut from the rotor revealed primarily intergranular brittle fracture under both tensile and impact testing.

Long-term exposures to temperatures in the range of 450º C are known to cause temper embrittlement in low-alloy steels. Temper embrittlement occurs when grain boundaries are weakened by the cosegregation of tramp impurities (such as Sn, Sb or As) with metal alloying elements (such as Ni or Mn).



Secondary electron image of the rotor blade showing the brittle fracture surface.

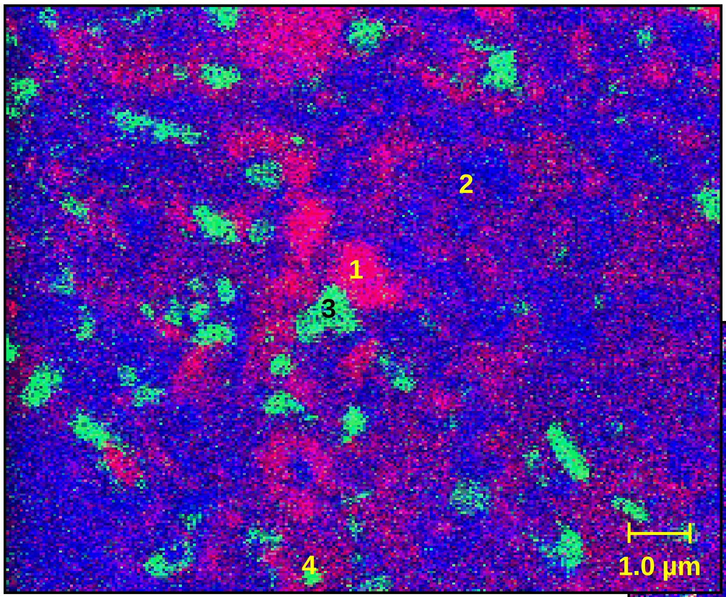


High magnification secondary electron image of the fractured rotor blade

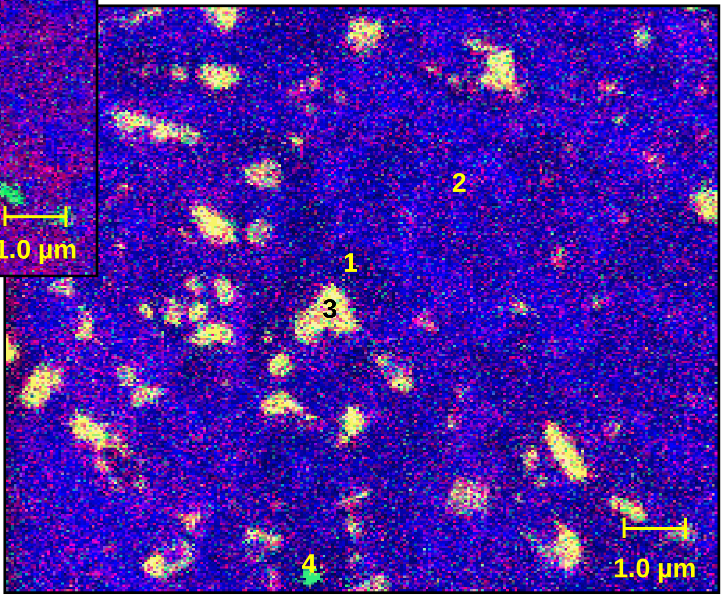
At high magnification, the texture of the grain boundary surface is very evident. Auger analysis of the area shown detected alloying elements Fe, Cr, Ni and C and impurity elements S and Sb. The detection limits for Auger are about 1 part-per-thousand (ppt) under optimum conditions and were greater than 1ppt under the conditions used for this experiment. S and Sb were present in the bulk at only ppm levels, suggesting grain boundary segregation of these elements. Ion sputter etching to remove about 50 Å of material from the grain boundaries eliminated all traces of Sb. Some S remained, providing good physical evidence of Sb segregation to the grain boundaries.

Auger elemental images were collected before sputter etching for all detected elements. Color overlays of the Auger maps show elemental distributions across the grain boundary. Four locations for Auger point analysis, which were chosen to represent high local concentrations of particular elements, are shown on the overlays. Auger survey spectra were taken at each selected point.

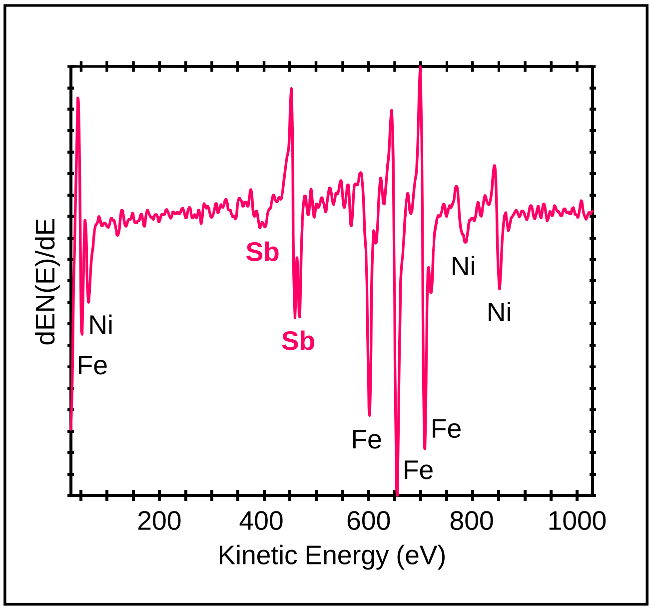
By comparing the Auger images with the secondary electron image, it is evident that the elemental distributions correspond with morphology changes. The PHI scanning Auger nanoprobes utilize a Cylindrical Mirror Analyzer (CMA) that is coaxial with the electron beam, virtually eliminating surface morphology effects on Auger signal intensity. This allows the Auger elemental images to be used with confidence to model surface chemistry variations.



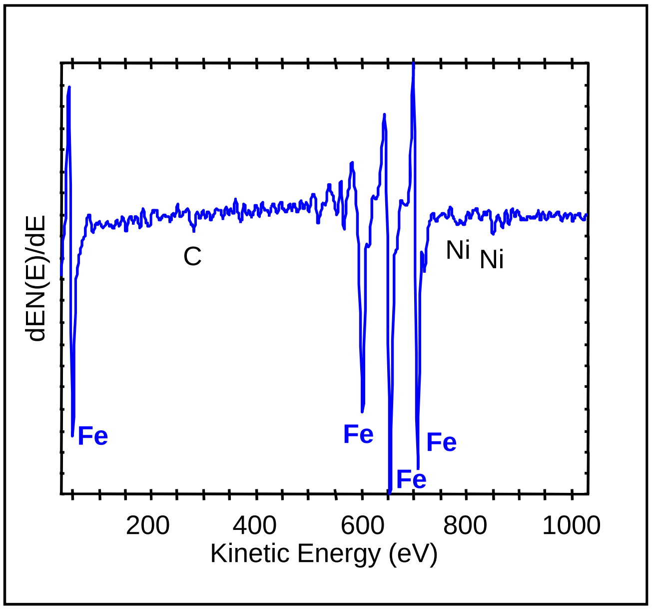
Color overlay of Auger elemental images: Blue = Fe, Red = Sb, Green = Cr.



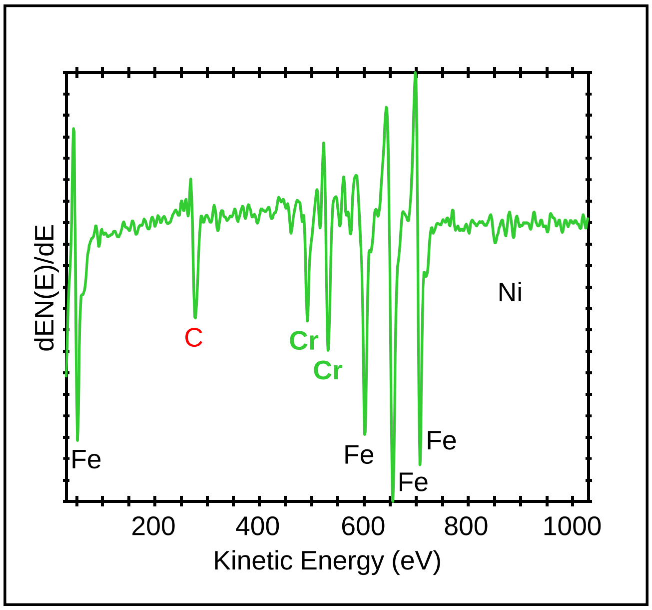
Color overlay of Auger elemental images: Blue = Fe, Red = C, Green = Cr, Yellow = Cr + C.



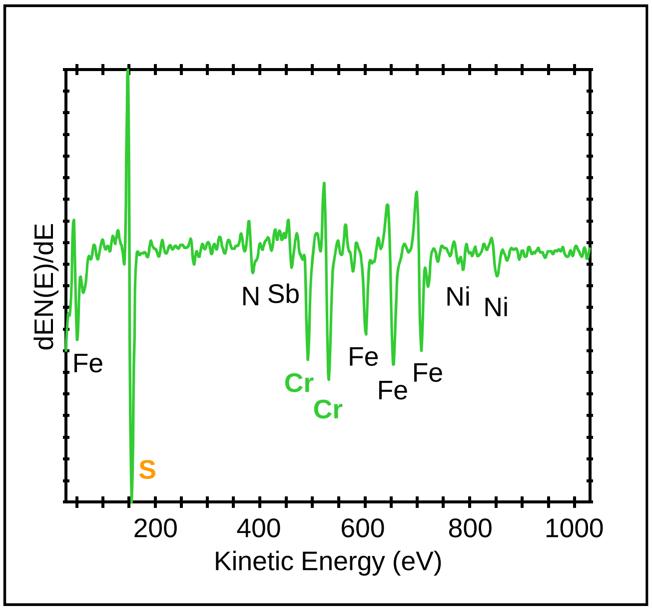
Point 1: high in Sb and Ni



Point 2: steel matrix



Point 3: high in Cr and C



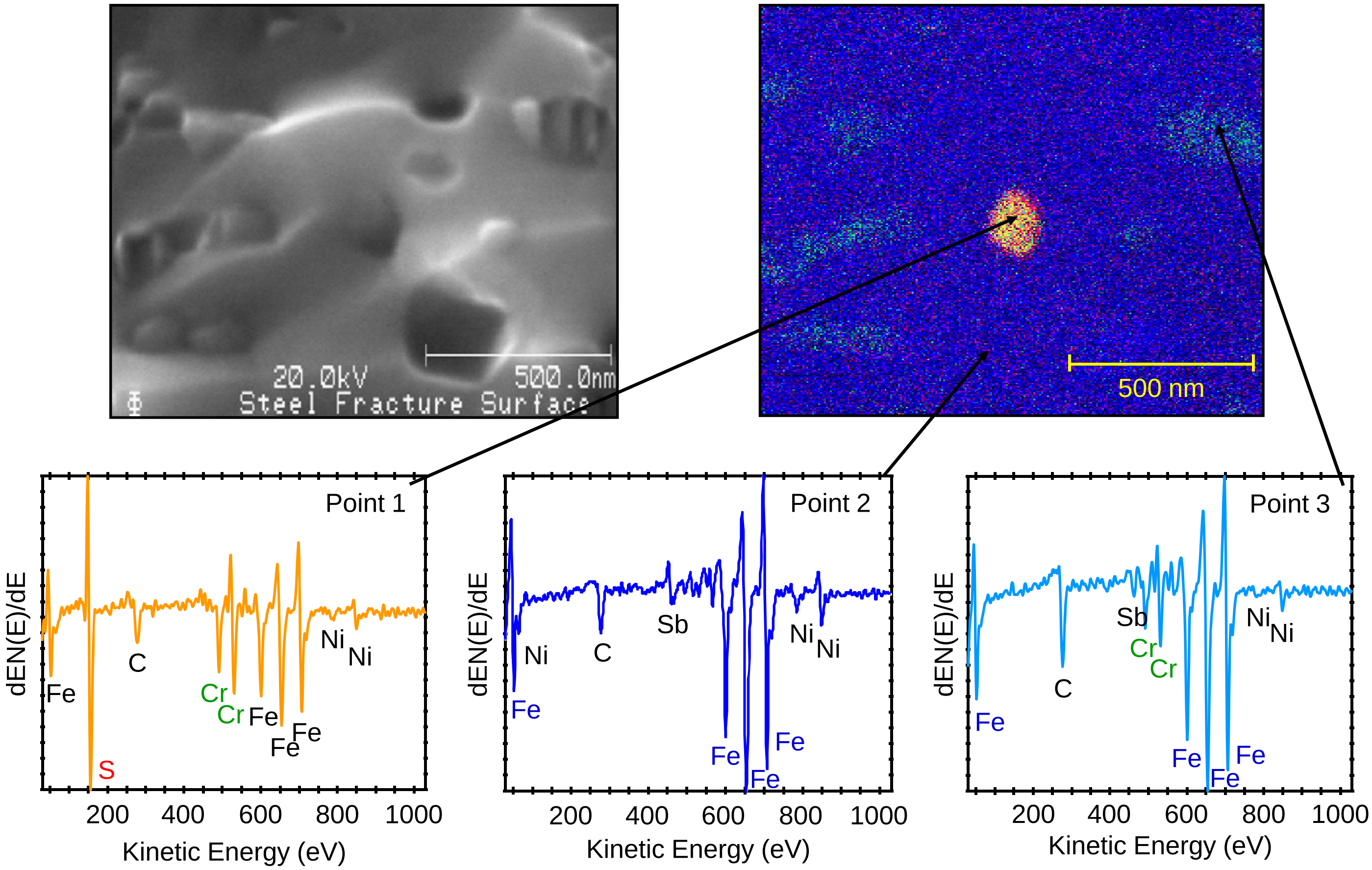
Point 4: high in Cr and S

The analysis shows clear evidence for segregation of Sb to the grain boundaries. Individual elements are not uniformly distributed across the grain boundary surface, but are localized. Point 1 is an area that is high in Sb and also quite high in Ni, an alloying element. This cosegregation is consistent with temper embrittlement.

From these analysis results, it can be surmised that Sb is a primary cause of the observed embrittlement. Point 3 is high in Cr and C, and the C peak shape indicates Chromium-Carbide (CrC). At Point 4, the Cr is associated with S, most likely indicating Chromium-Sulfide (CrS). The CrC and CrS are very small grain boundary precipitates or inclusions that may have little effect on the brittle nature of the sample. This is important, because a general segregation of S to the grain boundaries where it is not chemically bound into a sulfide can also cause embrittlement.

Secondary electron image of rotor blade at higher magnification showing inclusions

Color overlay of Auger elemental images: Blue = Fe, Red = S, Green = Cr, Yellow = Cr + S



These discrete inclusions lend themselves to further analysis at higher magnification. An area with several inclusions was examined at very high magnification and analyzed with a similar sequence. The secondary electron image, as well as the color overlay Auger elemental maps and Auger point spectra detail a very small, 1000 Å diameter CrS inclusion (Point 1), general Sb and Ni segregation to a smooth area of the grain boundary (Point 2), and a CrC inclusion (Point 3).

The segregation of Sb and Ni to the grain boundaries of the low-alloy steel rotor blade was shown to be the primary cause of the catastrophic failure. It is known that temper embrittlement is a reversible effect. The public utility is undertaking heat-treating experiments to determine if the non-failed rotors can be salvaged by reversing the segregation. If this is possible, it will save several million dollars for each turbine.

The PHI Scanning Auger Nanoprobes have proven to be an effective tool for characterizing the elemental composition and elemental distribution of highly-topographic surfaces such as the grain boundaries, and for analyzing extremely small particles.

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