Grain Boundary Engineering for Improved Resistance to Intergranular Degradation

Peter Lin
Integran Technologies Inc., Toronto Canada

Stuart Wright
EDAX-TSL, Draper, UT 84020

Introduction

Intergranular degradation processes such as intergranular-cracking, -corrosion, and –creep cavitation have plagued numerous plant components in the nuclear, oil and gas, transportation, chemical and food processing industries. The occurrence of these degradation processes often leads to costly outages; protracted regulatory proceedings for system re-start, and reduced overall plant life. One solution to overcoming these challenges is to optimize microstructures of the materials used in the critical components. An approach that has proven effective in improving the resistance of material to intergranular degradation is grain boundary engineering.

Grain Boundaries

It has long been recognized that grain boundaries in polycrystalline materials can possess distinct structures [1]. It is possible to describe these distinct grain boundary structures using the so-called Concident Site Lattice (CSL) model [2]. This model is based upon the misorientation of adjoining crystals, whereby at specific orientation relationships, a 3-dimensional sub-lattice, with points common to both adjoining crystals can be achieved. The unit volume of this coincident site lattice relative to that of the unit cell of the single crystal lattice is described by the parameter Σ; increasing values of Σ correspond to a greater degree of disorder at the interface.

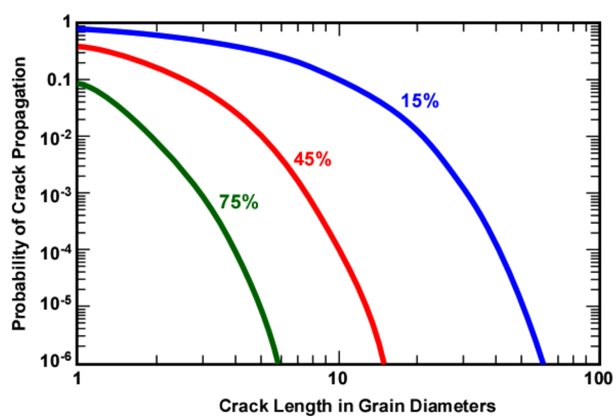

Figure 1 - The effect of low Σ boundary frequency on the probability of continued intergranular crack propagation in components based on microstructural modeling [5].

Numerous studies [3,4] have shown that low Σ CSL grain boundaries (usually $\Sigma \leq 29$) can possess "special" chemical, mechanical, electronic, kinetic, and energetic properties. Of particular relevance to industrial materials, these "special" grain boundaries have been shown to display a high resistance, and in many cases immunity to:

(1) sliding, cavitation and fracture, (2) corrosion and stress corrosion cracking, (3) sensitization, and (4) solute segregation. Models have been developed to predict the effect of the special boundary population on these various properties. An example is shown in Figure 1.

"Special" low Σ CSL grain boundaries are found to naturally occur in all materials; their frequency of occurrence being strongly dependent upon the processing history of the material (e.g., casting, deformation, recrystallization heat treatment, etc.). Figure 2 shows an OIM map where the low Σ CSL boundaries are highlighted in color along with a plot showing the distribution of the special boundaries. Generally, materials processing is undertaken without regard to resultant "grain boundary structure distributions", thus producing component materials with highly variable populations of "special" grain boundaries (≤25%).

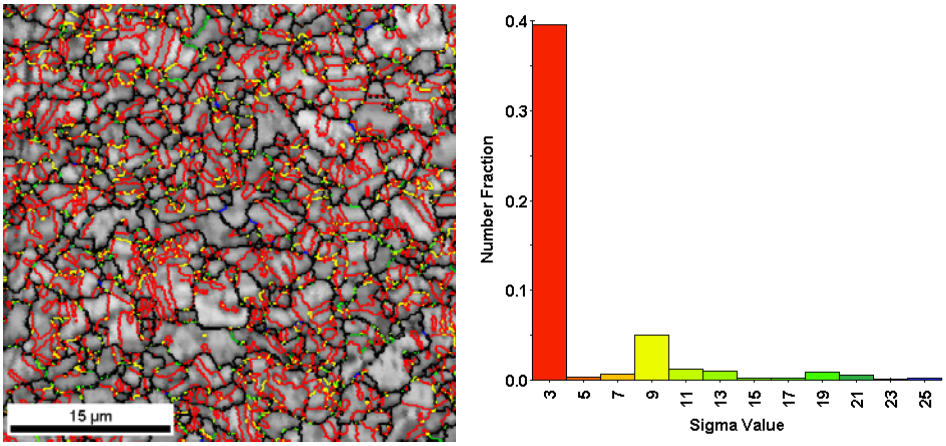

Figure 2 – Extract of a map showing CSL boundaries and the corresponding distribution in a copper thin film.

Grain Boundary Engineering

Grain Boundary Engineering GBE®[1] is a technique for optimizing the population of "special" boundaries in an effort to improve component material performance. The steps used in the general application of grain boundary engineering are two-fold.

First, identify the effect of various thermomechanical processing steps used to make a component material on the "special" grain boundary population. OIM is the ideal tool for the statistical characterizations of grain boundary character necessary for this procedure. It can effectively measure the fraction of special boundaries in materials.

Second, from the insights gained, modify the thermomechanical processing route to produce materials with high "special" boundary populations. Materials can then be qualified by their "special" boundary population.

Several successful examples showing the improvements achieved through grain boundary engineering are shown in Figures 3 through 7.

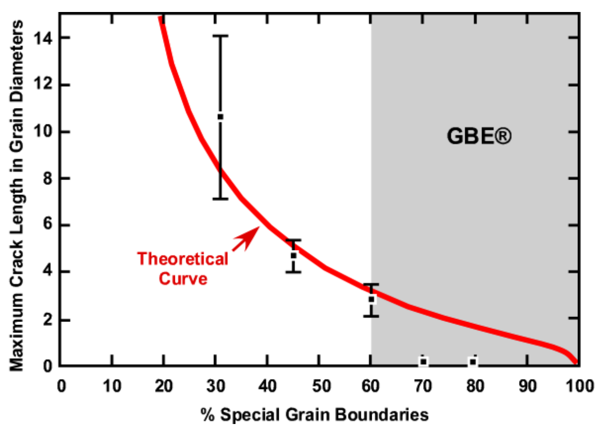

Figure 3 – Integranular cracking susceptibility in alloy 600 - a common nuclear steam generator tubing alloy. Samples stressed in 10% NaOH at 350°C for 3000 hours [6].

[1] GBE® is a registered trademark of Integran Technologies Inc., Toronto, Canada.

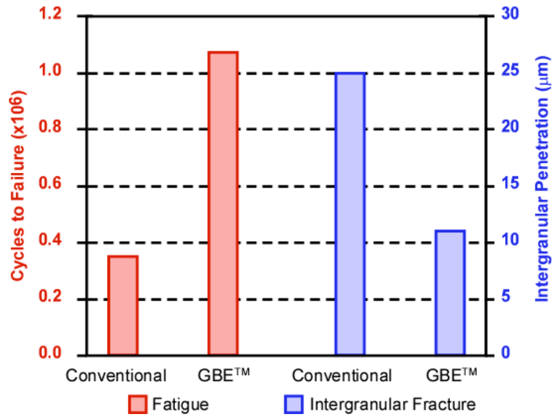

Figure 4 – Intergranular penetration depth after 500 hours exposure to Na_2So_4 at 850°C and improvement in room temperature fatigue resistance in alloy 738 – an advanced aerospace material.

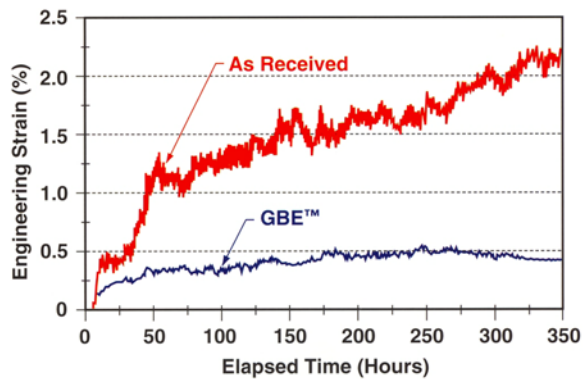

Figure 5 – Creep resistance in alloy 625 – a super alloy used in gas turbine components. Samples creep tested under a 5 ksi tensile stress applied at 700°C.

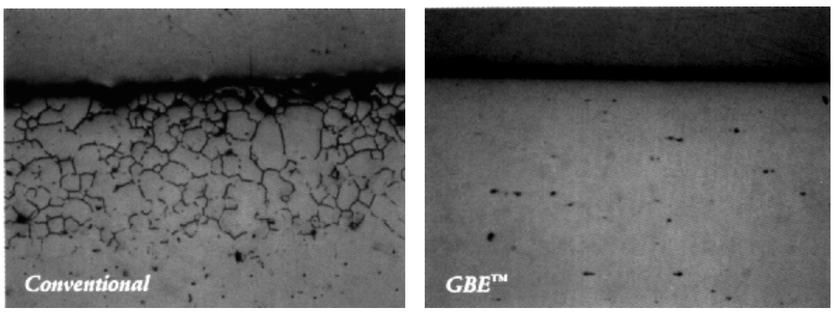

Figure 6 – Stress corrosion cracking in alloy 800, a nickel based superalloy. Cross sections were sensitized for 1 hour at 600°C and exposed to a boiling solution of ferric sulphate-sulphuric acid for 120 hours.

Conclusions

The goal of materials engineering is to identify the effect of materials forming processes on microstructure and in turn identify the role microstructure plays on the properties of a material. Grain boundary engineering is a good example of this process. It is a very effective approach for tailoring the thermomechanical processing used to form materials to optimize their performance for applications where prevention of intergranular degradation is a critical performance parameter.

OIM is an enabling technology for grain boundary engineering. With the automation of EBSD, statistically relevant distributions of grain boundaries can be practically measured.

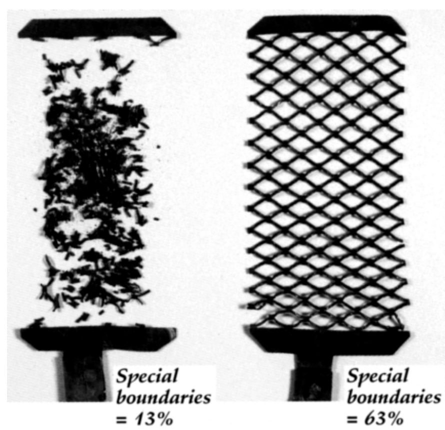

Figure 7 – Conventional and GBE® PbCaSn battery grids after 40 charge-discharge cycles (0 to 1.781 Vdc) in 1.28 s.g. H_2SO_4 at 70°C.

Bibliography

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