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# Fracture mechanism maps in unirradiated and irradiated metals and alloys

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**Abstract**

This paper presents a methodology for computing a fracture mechanism map in two-dimensional space of tensile stress and temperature using physically-based constitutive equations. Four principal fracture mechanisms were considered: cleavage fracture, low temperature ductile fracture, transgranular creep fracture, and intergranular creep fracture. The methodology was applied to calculate fracture mechanism maps for several selected reactor materials, CuCrZr, 316 type stainless steel, F82H ferritic–martensitic steel, V4Cr4Ti and Mo. The calculated fracture maps are in good agreement with empirical maps obtained from experimental observations. The fracture mechanism maps of unirradiated metals and alloys were modified to include radiation hardening effects on cleavage fracture and high temperature helium embrittlement. Future refinement of fracture mechanism maps is discussed.


## 1. Introduction

The deformation and fracture behavior of metals and alloys can be significantly modified by neutron irradiation. Professor Monroe S. Wechsler has made significant contributions to our understanding of deformation and fracture mechanisms in irradiated metals and alloys. As reviewed in his seminal paper on dislocation channeling [1], plastic deformation in irradiated metals and alloys can be quite inhomogeneous as opposed to uniform deformation that occurs in annealed materials. Irradiation-induced defect clusters such as black dots, dislocation loops, and stacking fault tetrahedra can be removed by glide dislocations, resulting in the formation of cleared channels (dislocation channels). Dislocation channeling is observed in a number of irradiated face-centered cubic (fcc), body-centered cubic (bcc) and hexagonal close-packed (hcp) metals and alloys during mechanical testing. The phenomenon of dislocation channeling has led to the recognition that this inhomogeneous deformation may play a significant role in radiation embrittlement, plastic instability, and radiation-assisted stress corrosion cracking.

The fracture issues in irradiated metals and alloys, particularly at low temperatures were also thoroughly reviewed by Wechsler [2]. The phenomenon of 'radiation embrittlement' in ductile metals (loss of uniform elongation) is characterized by the premature onset of plastic instability at low

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tensile elongation values, and dislocation channeling seems to be largely responsible for the dramatic ductility loss. Metals that experience distinct ductile-to-brittle transition temperatures (DBTT) associated with a transition from cleavage to ductile fracture can experience radiation embrittlement with an increased DBTT following irradiation. Wechsler [2] also pointed out that radiation embrittlement is likely associated with changes in plastic properties particularly with inhomogeneous plastic deformation rather than changes in inherent fracture processes.

The understanding of deformation and fracture behavior of irradiated materials requires a knowledge of deformation and fracture mechanisms in unirradiated conditions. It is well-recognized that Ashby-type deformation mechanism maps [3–6] can provide an overview of the deformation behavior of a material in response to stress and temperature. Deformation mechanism maps describe the dominant deformation mode at a given temperature, stress or strain rate condition. They are constructed by physically-based constitutive equations for various operative deformation mechanisms in the shear modulus-normalized stress and the melting point normalized-temperature coordinates. The maps provide useful guidance in identifying deformation mechanisms, defining operating conditions and developing new alloys. Our previous work has also shown that the deformation behavior of irradiated metals can be conveniently represented by irradiation-modified Ashby deformation mechanism maps [5,6]. Radiation hardening and radiation-enhanced softening can be incorporated into deformation maps by modifying the dislocation glide flow stress and the dislocation creep frictional stress. Dislocation channeling can be considered as a specialized case of the normal dislocation glide deformation mechanism. Irradiation creep represents a new deformation mechanism, whereas helium embrittlement at high temperature may be considered similar to diffusional creep [5]. With the success of 'deformation mechanism maps', it is worthwhile to examine how fracture mechanisms may be quantified in a similar convenient map formulation.

The idea of 'fracture mechanism maps' was first proposed by Wray [7] in 1969 and studied in detail by Ashby et al. [8–12]. Ashby et al. developed a methodology to construct fracture mechanism maps and plotted the maps for a number of fcc and bcc metals. Unlike deformation mechanism maps that were computed from model-based constitutive equations, these fracture mechanism maps were generated based on experimental observations. The maps were constructed by compiling experimental data and drawing field boundaries that bound blocks of data having a given fracture mode. Few attempts have been made in the past to calculate the fracture mechanism maps using mechanistically-derived constitutive equations [13,14]. The difficulties of doing so are primarily due to the fact that the model-based constitutive equations for fracture mechanisms are not well-established. The construction of fracture mechanism maps is also complicated by stress state, notch effects, deformation rate, mechanical constraint, etc.

The fracture behavior of irradiated metals and alloys is not well understood from a mechanistic viewpoint. The problem stems from complexity of fracture in unirradiated materials and irradiation-induced changes in many intrinsic and extrinsic properties that confound the complex situation. However, it is clearly valuable for irradiation-modified fracture behavior to be modeled on a physical basis, and the fracture behavior of irradiated materials thereby predicted on a constitutive level.

In this paper, we explore the physical models for several common fracture mechanisms, and apply the model-based constitutive equations to compute the fracture mechanism maps for selected nuclear reactor materials such as CuCrZr (Cu–0.8wt%Cr–0.1wt%Zr), 316 type stainless steel, V4Cr4Ti (V–4wt%Cr–4wt%Ti), F82H (Fe–8wt%Cr–2wt%WVTa) ferritic–martensitic steel and pure Mo. We also attempt to include the impact of radiation effects in fracture mechanism maps with the emphasis on low temperature cleavage fracture and high temperature intergranular creep due to helium embrittlement.

## 2. Fracture mechanisms and physical models

In the present work we focus on the fracture of fcc and bcc metals and alloys. For the purpose of constructing fracture mechanism maps, seven fracture mechanisms have been distinguished, i.e. fracture at the ideal strength, low temperature brittle fracture (cleavage), low temperature ductile fracture, high temperature transgranular creep fracture, high temperature intergranular creep fracture, rupture and dynamic fracture [9,10]. Only the first five fracture mechanisms are considered here, and their physical models are discussed below.