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Implications of Temperature Dependent Ferrite Arrest Toughness to an Invariant Master Curve Shape

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The toughness temperature $K_{IC}(T-T_0)$ curves of ferritic-martensitic steels may have a remarkably invariant master curve (MC) shape, where the reference temperature, $T_0$, depends on material and environmental/test conditions. For unirradiated alloys, with $T_0 < 0^\circ$C, an invariant MC shape is predicted by simple micromechanical models, assuming cleavage fracture occurs when an approximately temperature independent critical stress $\sigma^*$ contour encompasses a critical local volume $V_\ast$ of material in front of a crack. Finite element (FE) methods are used to determine the loading $(K_{IC})$ at cleavage as mediated by the alloy’s constitutive properties and local fracture properties, $\sigma^*$ and $V_\ast$. At low $T_0$, the shape of $K_{IC}(T)$ is governed almost entirely by the temperature dependence of $\sigma_\gamma(T)$. Irradiation hardening, $\Delta \sigma_\gamma$, increases $T_0$ ($\Delta T_0$). When $T_0$ is in the athermal $\sigma_\gamma$ regime, the assumption of a temperature independent $\sigma^*$ predicts changes (layovers) in the shape of $K_{IC}(T)$. This apparent contradiction with observation is resolved by assuming a mildly temperature dependent $\sigma^*(T)$ at higher temperatures. The temperature dependence is, in turn, controlled by the micro-arrest toughness of the material controlling the conditions for the propagation of microcracks formed at brittle trigger particles. Here we describe results of an independent study of the temperature dependent initiation ($K_{IC}$) and arrest toughness ($K_a$) for (100)[010] and (100)[011] Fe single crystals oriented for cleavage, using specially designed composite specimen test techniques. The $K_a(T)$ is weakly temperature dependent below about -100$^\circ$C, increasing from a minimum of 3.5 MPa$\sqrt{m}$, but rises more rapidly to 9 MPa$\sqrt{m}$ at higher temperatures near 0$^\circ$C. Static and dynamic $K_{IC}/d(T)$ curves were also measured over a wide range of loading rates from about 0.1 to 20,000 MPa$\sqrt{m}$/s. In all cases, the cleavage fracture dynamics were found to be controlled by nucleation of double kinks on screw dislocations, that also control the flow stress dynamics. When plotted on a strain rate compensated temperature, $T'$, the arrest and initiation data overlap to form a $K_a(T')$ master curve. The results were extended complex alloys by proposing that both the thermal and athermal contributions to $\sigma_\gamma$ combine to control $K_{IC}(T)$ as a fitted model $K_{IC}(T) = C(\sigma_\gamma)/\sigma_\gamma(T)$ with a minimum $K_e$ of about 3.5 MPa and where $C(\sigma_\gamma)$ is a weak function of $\sigma_\gamma$. Using these $K_{IC}(T) = C(\sigma_\gamma)/\sigma_\gamma(T)$ curves in the macroscopic $K_{IC}(T)$ model results in both approximate master curve shapes over a wide range of $T_0$ and the observed relation between irradiation induced $\Delta \sigma_\gamma$ and $\Delta T_0$. 

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