Melting as an extreme deformation mechanism at high strain rates

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Abstract

Deformation, especially plastic deformation involving shock and impact in crystalline metal and alloy systems, begins as nonlinear dislocation phenomena which in the extreme deformation regime involving high strains and high-strain-rates leads variously to shear phenomena involving twinning and microband formation, dynamic recrystallization either as localized shear instabilities in shear bands or large volume solid-state flow, and finally localized melting. These mechanisms can be viewed as "deformation state" changes within some pressure-temperature regimes. In this work, we present examples of deformation-induced melting, especially in association with dynamic recrystallization (DRX). These examples include partial melting in explosive weld-wave vortex structures in connection with DRX in several dissimilar metal and alloy (explosive welded) systems, as well as projectile-target interactions for W single crystal rods and W rods clad with Inconel 718 (53% Ni, 17% Fe, 20% Cr) penetrating RHA steel targets at impact velocities ranging from 1.2 to 1.4 km/s.

Keywords: dynamic recrystallization, melting, projectile-target interactions, shear bands, microstructures.

1 Introduction

There are numerous examples of melting in deformation or melting especially as a consequence of extreme deformation. These include the so-called mach stem zones along the central axis of cylindrical shock regimes [1,2], melting zones

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along the jet fragment or slug centreline of shaped charge regimes [3,4], and weld wave vortex melting in explosive welding [5]. Even on a geological sale, large displacements on faults can trigger so-called decompression melting [6]. Grady and Assay [7] describe thermal trapping leading to inhomogeneous heating as a melt precursor arising through a critical strain rate condition, and more generally localized deformation heating such as that occurring in shear localization in a shear band can be generalized as $\Delta T \alpha(\varepsilon)\left(\dot{\varepsilon}\right)$, where ε is an extreme strain and $\dot{\varepsilon}$ denotes a high strain rate ($\dot{\varepsilon} \geq 10^4 s^{-1}$). Shock heating can also lead to localized heat generation and melting at excessive pressure-induced deformation.

While the melt regime associated with extreme deformation is not directly observable, characteristic, melt-related microstructures such as dendritic or microdendritic features as a consequence of melt solidification provide unambiguous evidence of melt. Figure 1 illustrates this feature for a weld-wave vortex zone in explosively welded copper and aluminium. This high-pressure vortex creates localized melt from the dynamically recrystallized (DRX) copper and aluminium flow zones. DRX is often a precursor to melting since grain boundaries tend to melt preferentially [8], and a large volume fraction of boundaries in DRX induces a propensity for melting. This is especially true for various shear zones (as in fig. 1) or shear bands composed of DRX grains, which provide deformation-induced flow of the material in the solid state [9]. However, for deformation exceeding either a critical strain-rate [7] or some critical product: $(\varepsilon)\left(\dot{\varepsilon}\right)$, ΔT can equal or exceed the melting point. Critical pressure regimes associated with melting can also be rationalized through the dynamic strain: $\varepsilon = 1.33 \ln (V/V_o)$, where V and V_o are related to the volume change in the shock front (or the shock Hugoniot) [10].

In this paper we revisit recent studies involving the penetration of single-crystal [001] W rods and [001] W rods clad with Inconel 718 into rolled homogeneous armour (RHA) steel targets [11]. The DRX-induced flow of the penetrating rods interacting with the DRX-induced flow of the steel targets produces complex DRX mixing in shear structures (including shear bands) where zones of melting also occur.

2 Experimental issues

CVD [001] single-crystal W rods and these same rods clad with ~140 μm of Inconel 718 (53% Ni, 17% Fe, 20% Cr, and 10% micro-alloying elements) with a length/diameter ratio of 15 (4 mm diameter) were launched into RHA (MIL-A-12560) steel targets at nominal velocities of ~1.3 km/s from a 40 mm smoothbore gun positioned 3 m in front of the targets. Penetrator-in-target half sections were then ground, polished and etched. The W penetrators were etched with equal amounts of H_2O, 3% H_2O_2, and NH_4OH while the steel targets were etched with 0.5% Nital. The target/rod/clad material regime was etched with 5 g $FeCl_3$ in 2 mL HCL and 100 mL ethanol. Microstructures were observed in a

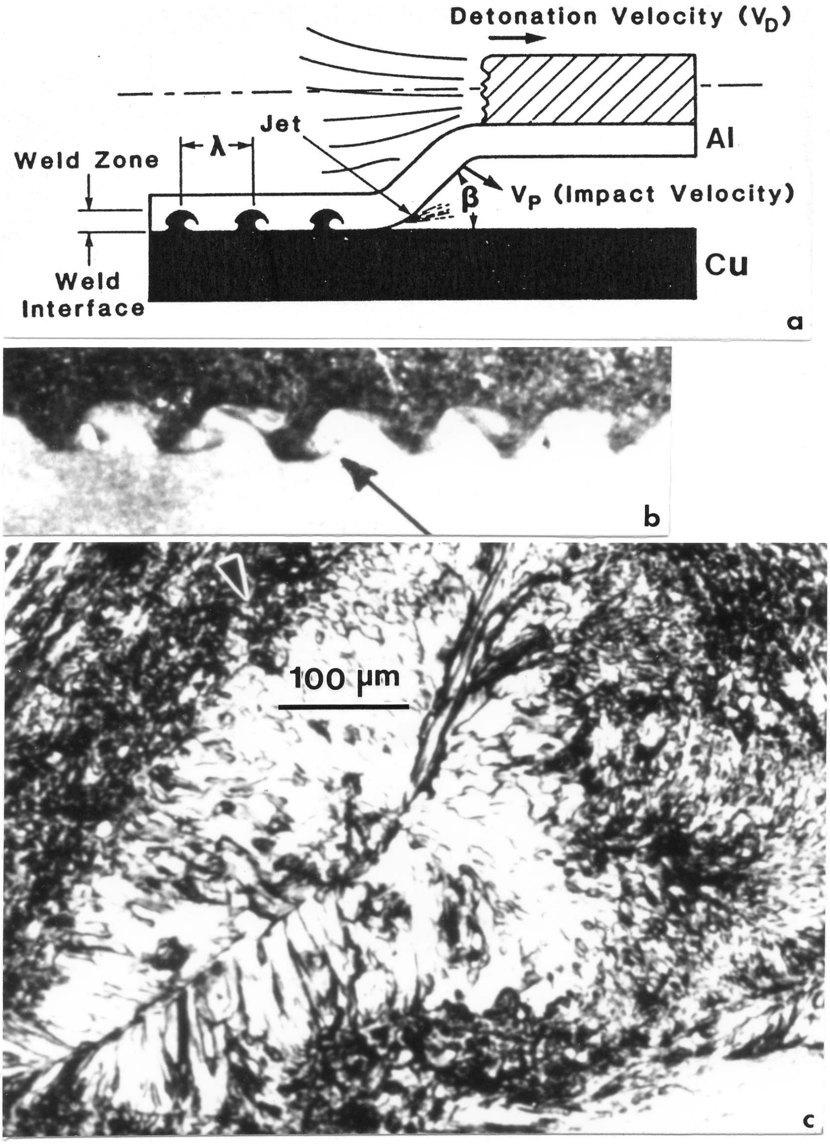

Figure 1: Explosive welding arrangement and solidification dendrite structure (arrow) in an aluminium/copper weld wave surrounded by DRX grain flow regimes. (a) Explosive welding schematic. (b) Aluminum/copper weld wave structure. (c) Magnified view showing dendritic weld wave vortex structure (arrow).

Reichert MEF4 A/M optical metallograph as well as an ISI-DS-130 scanning electron microscope (SEM) operating at 20 kV. Selective sections made from the original W penetrator rods and erosion fragments within the penetration channels were also prepared for transmission electron microscopy (TEM) as described in Pizaña, *et al* [11]; and will not be included in this study.

Figure 2 illustrates the penetration regimes, which include the erosion/flow of the penetrating rod to form a so-called rod erosion tube (RET) within the penetration channel, a corresponding target erosion tube (TET), and more complex mixing regimes between these tube zones, including the Ni-Fe rich clad regime for the Inconel 718 clad penetrating W rods.

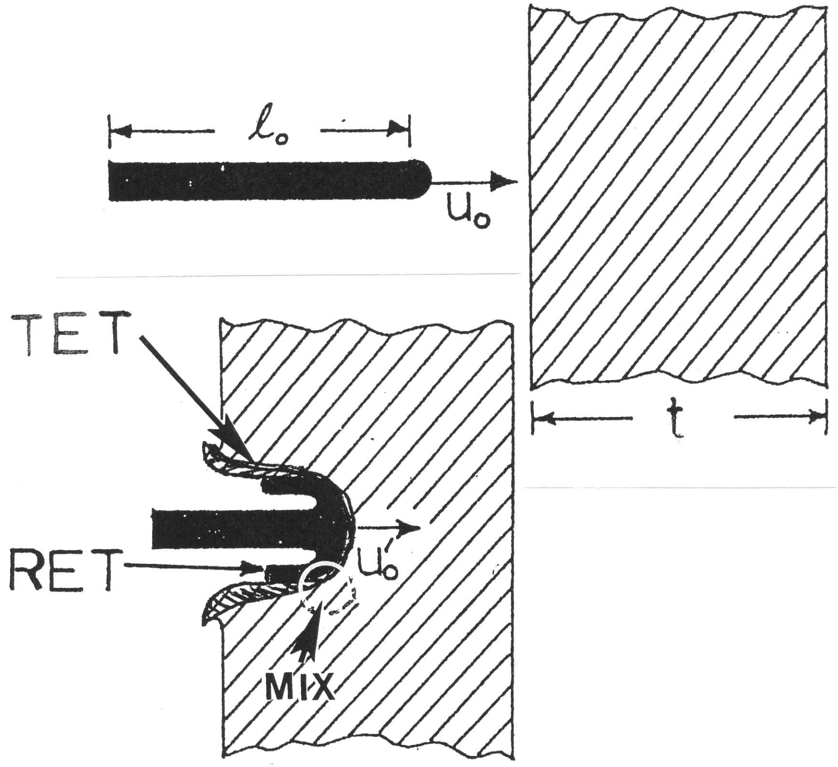

Figure 2: Schematic views of rod penetration into steel (RHA) targets showing the erosion (flow) regimes.

3 Results and discussion

Figure 3 shows a portion of a cross-section view for a W [001] rod that has penetrated an RHA target at an initial velocity of 1.35 km/s. Essentially the entire rod has been eroded during penetration since only a small head remnant

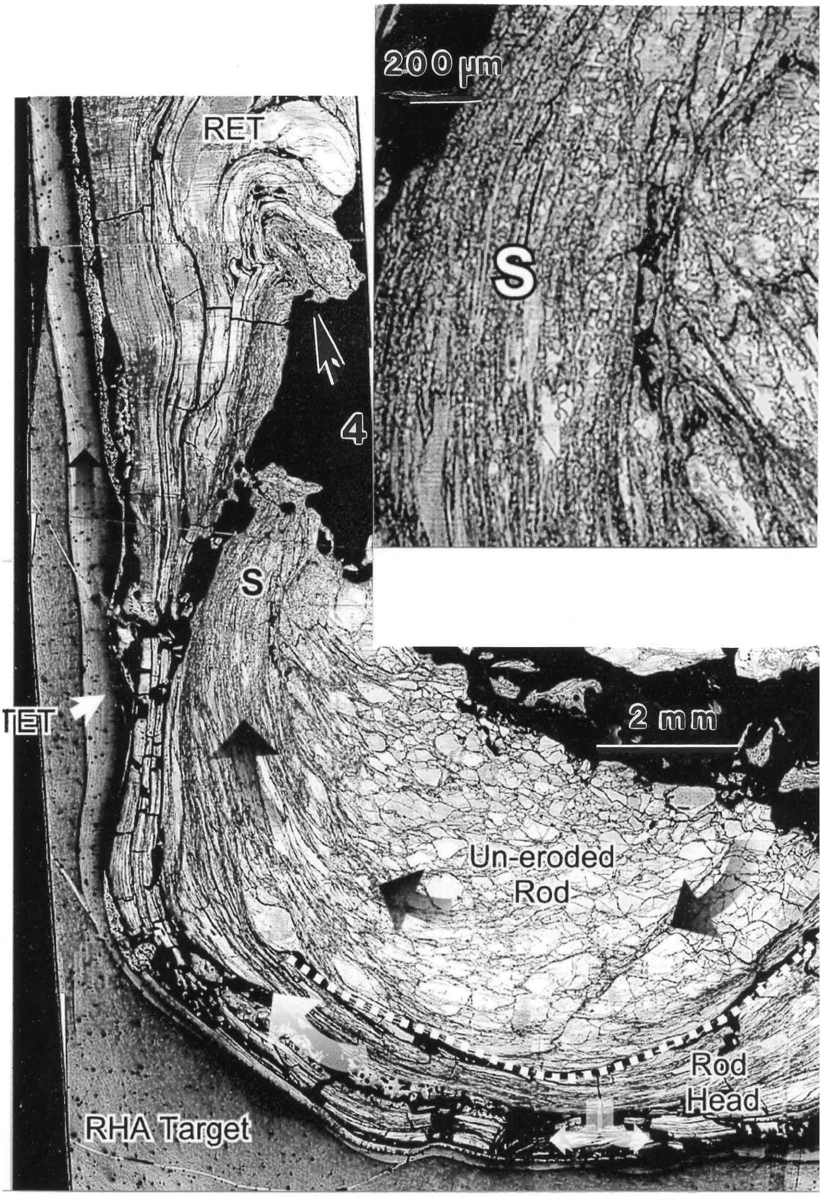

Figure 3: Optical micrograph composite showing a residual [001] W rod remnant in RHA. Large arrows show solid-state flow. Insert shows magnified view of shear zone (S).

remains, which is recrystallized and the grains have grown to sizes averaging 100 μm. The DRX flow regime marked "S" at the base of the left RET is shown in the enlarged insert where DRX grains <5 μm diameter characterize the shear flow regime. Figure 4 shows a magnified view of the vortex-like flow characterizing the RET section shown by the arrow at the left and above "S" in fig. 3. The magnified insert in fig. 4 also shows a DRX zone with grain diameters ≥ 1 μm. This DRX regime represents mostly dynamic grain growth, which can be compared to the much larger grain growth in the rod head (fig. 3).

Figure 5 shows examples of isolated shear bands or shear zones in an un-clad W [001] rod (fig. 5a) and an Inconel 718 clad W [001] rod (fig. 5b). Figure 5b

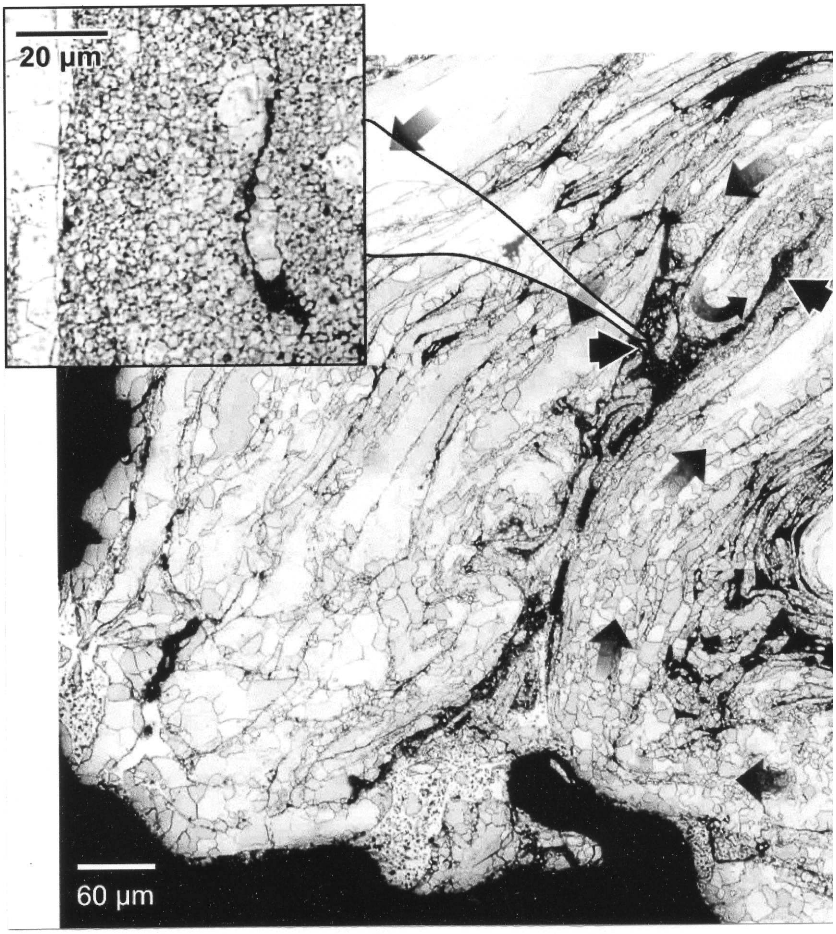

Figure 4: Magnified view of RET zone marked at arrow (4) in fig. 3. The insert shows a magnified view of DRX zone. Note the image is reversed from fig. 3.

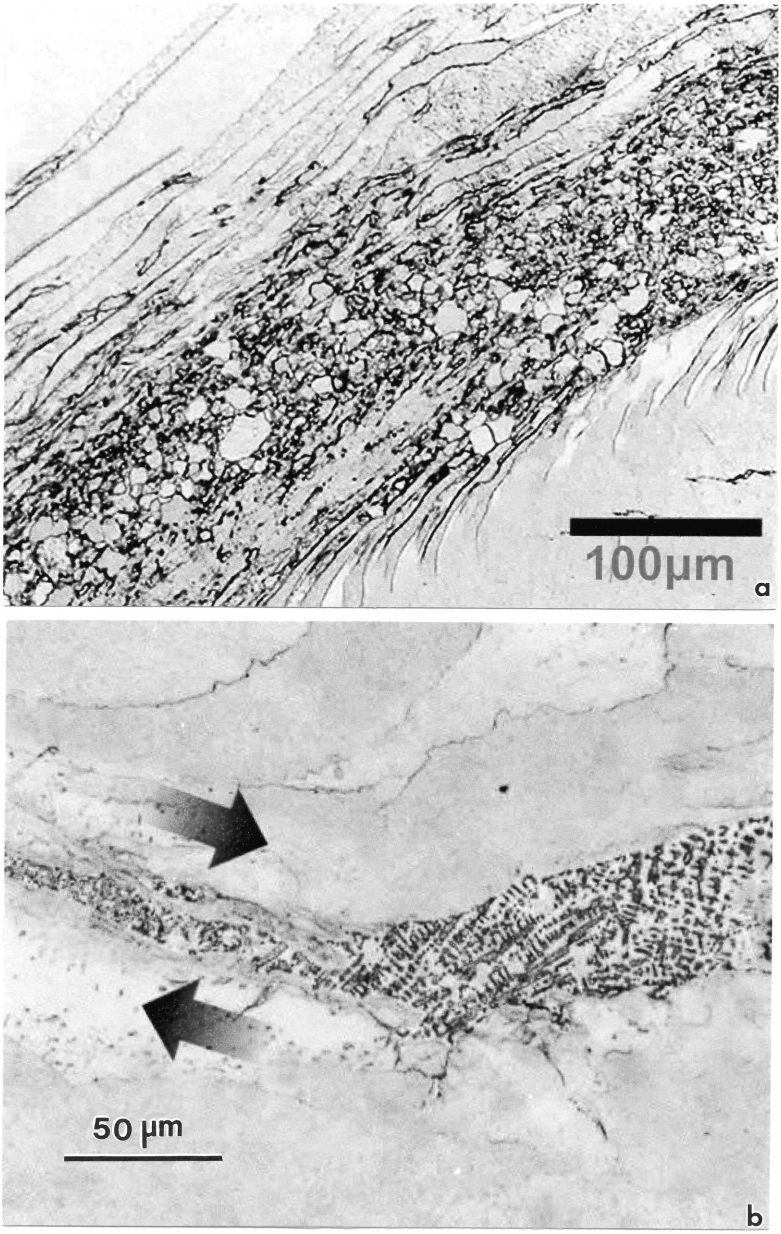

Figure 5: Shear bands in W penetrator rods. (a) DRX structure in unclad W rod in RHA (1.25 km/s). (b) Dendritic structure in clad W rod in RHA (1.32 km(s).

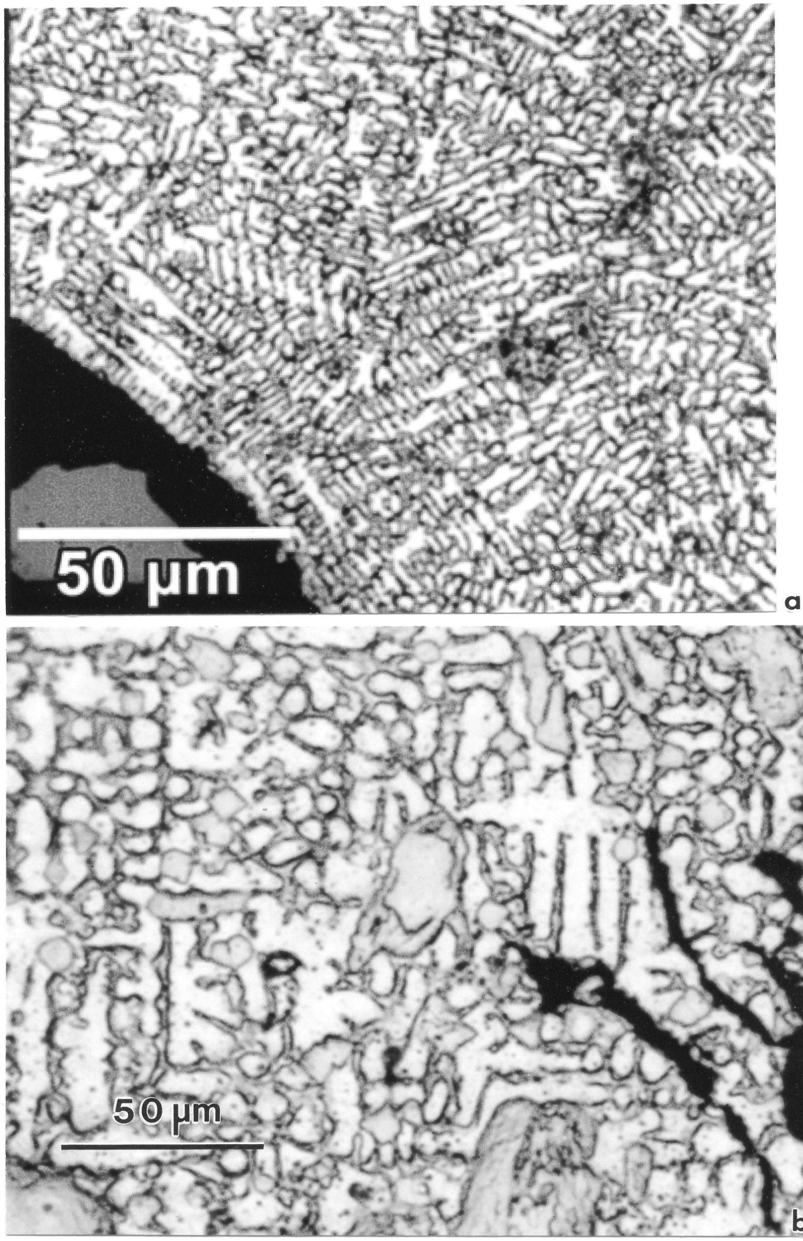

Figure 6: Examples of residual microdendrite structure in the mixed zone (fig. 2) for W/RHA (a), and W/cladding/RHA (b).

shows a mostly microdendritic structure characteristic of solidification from the melt which we assume was a solid/liquid transformation from a precursor mix of DRX grains composing the shear band as in fig. 5a.

Similarly, fig. 6 shows two examples of microdendritic structures in a mixture of W rod DRX grains and Fe target DRX grains (fig. 6a), and a more complex mix of W, Ni-Fe, and Fe DRX grains in a clad W[001] penetrator/RHA target regime (fig. 6b) (see Fig. 2). Figures 5b and 6 suggest that melting is a deformation-driven solid/liquid transition which may also depend upon high pressure-temperature-composition thermodynamics, especially in the W/Fe DRX and W/Ni-Fe/Fe DRX mixing zones where the RET/TET regimes flow together at correspondingly high strain and strain rates. These melt regimes can accommodate much larger strains, and are therefore a deformation mode beyond DRX. In the case of extreme deformation, $(\varepsilon)(\dot{\varepsilon})$ large, deformation commences through dislocation generation and interaction, leading to deformation twinning and DRX in localized shear zones (shear bands). The DRX regimes facilitate solid-state flow, which can lead to localized melting to accommodate the residual, large strains. Deformation therefore begins within the realm of the stress-strain-strain rate paradigm, then transforms to the DRX regime, and finally deformation induced solid-state flow transforms to the liquid state.

Melting, as noted earlier, generally occurs preferentially at interfaces and is energetically favored in DRX regimes [8]. Kuhlmann-Wilsdorf [12] has also discussed melting in general in crystalline solids on the basis of lattice dislocations which implies that defects, including the grain boundary region, or defect structures, are phenomenologically important in the induction of melting, culminating in the loss of shear strength and the absorption of latent heat.

4 Conclusion

Melting can be considered the terminus in extreme deformation, especially where stain (or shear) localization occurs.

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