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Influence of Microstructural Anisotropy on the Quasi-static and Dynamic Fracture of 1080 Eutectoid Steel

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The influence of crystallographic texture on elastic and plastic constitutive response has seen extensive investigation in recent years. In contrast, the influence of anisotropy on the fracture of engineering materials remains less explored. In particular, the influence of anisotropy, both crystallographic and morphological, on the dynamic fracture behavior of materials remains largely unquantified. In this study, the quasi-static and dynamic fracture of 1080-steel has been studied as a function of microstructural morphological anisotropy. Previous research has shown how crystallographic anisotropy can control ductile damage evolution. In this study, the role of microstructural anisotropy, due to the presence of elongated MnS stringers, resident within a crystallographically isotropic eutectoid steel was investigated. The quasi-static and dynamic fracture response of a fully-pearlitic 1080 steel was found to be dominated by the heterogeneous nucleation of damage normal and orthogonal to the MnS stringers. Delamination between the matrix pearlitic microstructure and the MnS stringers was seen to lead to significantly lower quasi-static and dynamic tensile strains to failure during transverse loading compared to loading parallel to the stringer axis. The constitutive and damage behavior of a 1080 eutectoid steel as a function of loading direction, stress state, and temperature is discussed with reference to the influence of morphological anisotropy on void nucleation and growth.

1. INTRODUCTION

While the influence of crystallographic texture on metal plasticity has seen in-depth investigation over the last four decades [1, 2], the role of texture effects on fracture remains less extensively quantified [3, 4]. Texture effects on fracture can be: 1) atomistic in nature on a single-crystal level, such as the role of crystallographic orientation on cleavage[5], 2) microscopic due to the influence of anisotropy (either texture or microstructural anisotropy-induced[6, 7]), 3) elastic and plastic anisotropy in damage initiation and growth in a polycrystal[8, 9], or 4) macroscopic due to complex long-range microstructural constructs such as those in functionally-graded polycrystals and/or continuous- or laminate-based composites[10].

Strong crystallographic texture, commensurate

with pronounced anisotropic yielding behavior, has been shown in high-purity zirconium to lead to anisotropic plasticity during tensile loading resulting in ellipsoidal-shaped ductile dimples following isotropic damage nucleation[4, 11]. Conversely, anisotropic damage evolution due to second-phase initiation sites, such as MnS inclusions, in structural steels has been shown to lead to pronounced anisotropy in quasi-static fracture response and ballistic impact resistance[6, 7].

Engineering implementation of materials in structural applications requires, in addition to its constitutive behavior, understanding of the dominant micromechanisms controlling damage evolution and fracture in a material and its linkage to microstructure and therefore material processing. The development of physically-based damage-evolution and fracture models therefore requires a

detailed understanding of the synergistic effects between microstructure and anisotropy (crystallographic and microstructural) because many engineered materials are not isotropic. The ductile fracture and fracture toughness of structural steels has been shown to be strongly influenced by inclusion distribution [12]. Further, experimental and modeling studies of anisotropic ductile fracture of steel plates containing elongated inclusions has been shown to be promoted by both the dilatational growth of voids and the coalescence processes [13]. Coalescence processes are known to be strongly influenced by void shape and interparticle spacing [13].

The goal of this study was to quantify the influence of microstructural anisotropy, specifically anisotropically-oriented MnS stringers, in a crystallographically isotropic material on the constitutive behavior, quasi-static and dynamic tensile response, and dynamic fracture behavior of a structural material. The material selected for this study was 1080 eutectoid rail steel.

2. EXPERIMENTAL TECHNIQUES

The material used for this investigation was a hot-rolled rail steel made by U.S. Steel and supplied by the Association of American Railroads[14]. The chemical composition (wt. pct.) was analyzed to be: 0.80 carbon, 0.17 silicon, 0.84 manganese, 0.013 sulfur, and 0.018 phosphorus (conforming to AISI 1080 steel). The rail steel studied possesses a fully pearlitic

microstructure with pronounced MnS stringers elongated along the rail axis formed during hot rolling as seen in Figure 1. The crystallographic texture of the rail steel was measured using X-ray diffraction. As seen in Figure 2, the texture of the rail steel investigated was quantified to be nearly purely random in nature as reflected by the average texture value of 1.02.

To examine the influence of loading orientation, and thereby microstructural anisotropy, on the constitutive and fracture response of the rail steel, compression and tensile samples, for both quasi-static and dynamic testing, were sectioned from the longitudinal and transverse directions relative to the rail axis. Quasi-static compression and tensile tests were conducted at a strain rate of 0.001 s^{-1} . Samples for low and high-strain rate uniaxial compression were nominally 6.35 mm in diameter and had a 1:1 length-to-diameter (l:d) aspect ratio. Prior to compression testing, specimen loading faces were lubricated with molybdenum disulfide.

The quasi-static tensile samples are 60 mm long round samples with a 25.4 mm gauge length and 5-mm gauge diameter. Dynamic compression and tensile tests were conducted as a function of strain rate, utilizing a compression and tensile Split-Hopkinson Pressure Bar(SHPB)[15], respectively. The inherent oscillations in the dynamic stress-strain curves and the lack of stress equilibrium in the specimens at low strains make the determination of yield inaccurate at high strain rates.

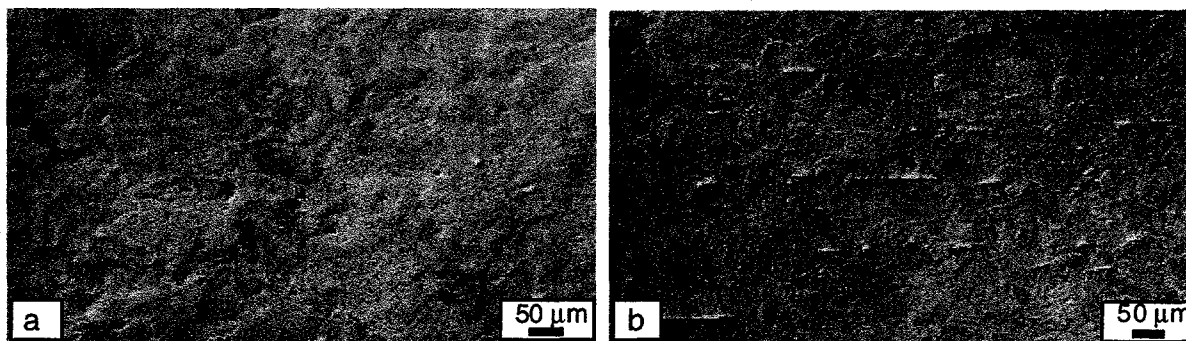


Figure 1: Optical metallography of 1080 Rail steel as a function of orientation showing the morphology of MnS stringers in the fully pearlitic microstructure: a) longitudinal to the rail axis, and b) transverse to the rail axis (note the elongated MnS stringers).

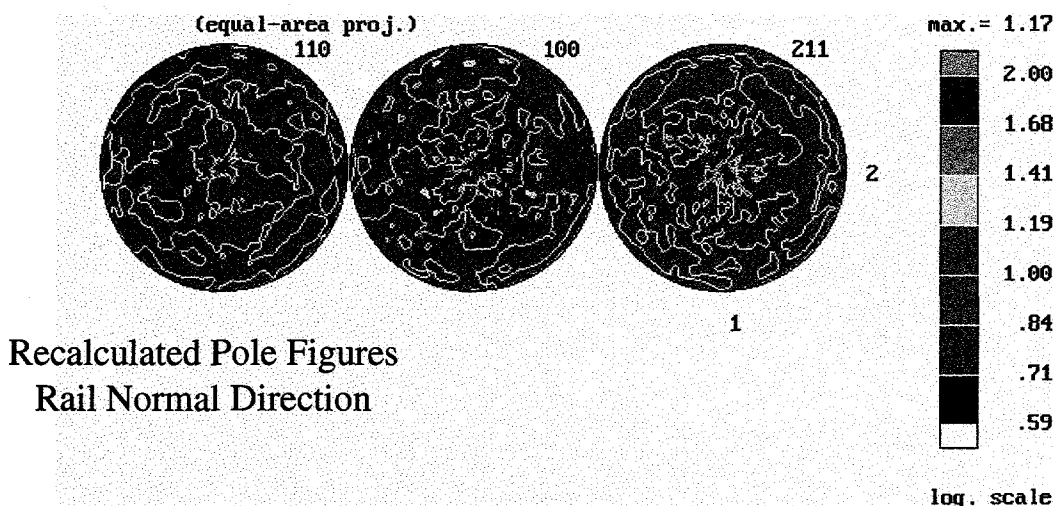


Figure 2: Plot of recalculated pole figures measured in the rail normal direction. The average texture strength was measured to be 1.02. (Note that a texture of 1.00 is fully random).

The tensile SHPB samples used were round threaded samples with a uniform 11.43-mm gauge length and 3.81-mm gauge diameter. The transmitted tensile pulse and the reflected compression pulse are captured in momentum traps located at the free ends of the transmission bar and the incident bar, respectively[16]. Thus, the tensile SHPB sample is loaded by a single, well defined, tensile pulse.

Specimens for optical metallography were sectioned, parallel and transverse to the rail axis, from the as-received rail steel and from fracture tensile samples. Analysis of the influence of microstructural anisotropy on damage evolution as a function of loading orientation was evaluated by sectioning fractured tensile samples. Samples for optical metallographic examination were polished conventionally and etched using Nital (95% methanol + 5% nitric acid).

3. RESULTS AND DISCUSSION

3.1 Compressive Constitutive Behavior

Preferred texture in polycrystals has been shown to correlate with orientation-dependent constitutive

properties [17] and also affect damage evolution and fracture mechanisms [3]. The compressive true-stress true-strain response of the 1080 rail steel as a function of loading orientation and strain rate is given in Figure 3. The compressive stress-strain response is observed to be essentially identical for samples loaded parallel to the rail axis (longitudinal) and perpendicular to the rail axis (transverse) independent of the strain rate. Increasing strain rate is seen to lead to a pronounced increase in the flow strength of the 1080 rail steel while displaying parallel strain-hardening behavior at both strain rates. The rate sensitive nature of the flow strength and rate insensitive hardening response is typical of many body-centered-cubic (bcc) metals due to a pronounced Peierls stress[18]. The isotropic nature of the stress-strain behavior (longitudinal vs. transverse) is consistent with the nearly purely random crystallographic texture measured for the 1080 rail steel. The anisotropic distribution of MnS stringers is seen to exhibit no measurable affect on the compressive stress-strain behavior of the 1080 rail steel.

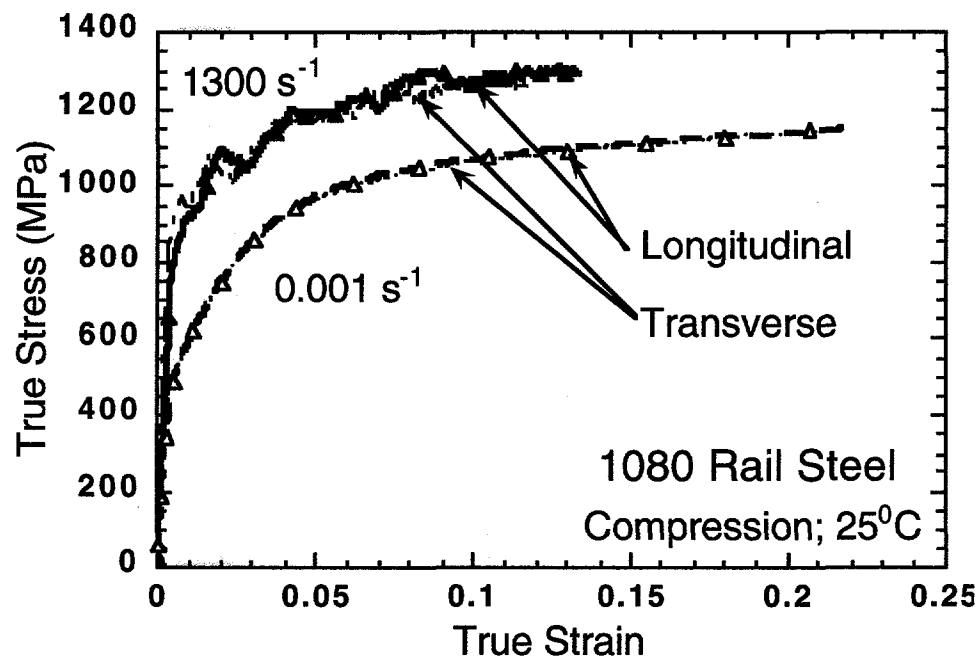


Figure 3: Comparison of compression stress-strain behavior of 1080 Rail steel as a function of loading orientation and strain rate.

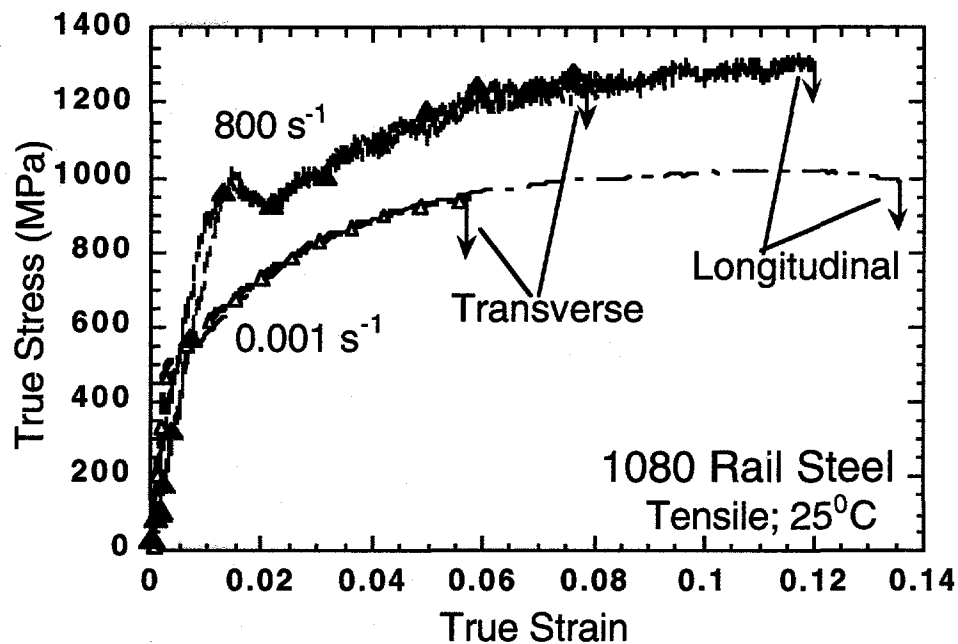


Figure 4: Comparison of tensile stress-strain response of 1080 Rail steel as a function of loading orientation and strain rate.

3.2 Tensile Constitutive Response

The tensile true-stress true-strain response of the 1080 rail steel as a function of loading orientation and strain rate is given in Figure 4. The tensile stress-strain response, similar to the compressive behavior, is observed to exhibit identical flow stresses and strain-hardening behavior when loaded parallel and perpendicular to the rail axis independent of the strain rate. The strain-hardening behavior of the 1080 rail steel when tested in tension is similarly seen to exhibit essentially identical response when loaded at 0.001 and 800 s^{-1} . However contrary to the compressive properties, the anisotropic distribution and orientation of the

MnS stringers is seen to lead to a pronounced difference in the strain to failure during tensile testing at quasi-static and dynamic loading rates. The transverse-oriented tensile samples display drastically reduced strains to failure compared to the longitudinal-oriented samples. The transverse SHPB tensile samples exhibited a reduction in strain to failure from ~ 0.12 to 0.08 while the quasi-static tensile sample strain to failure decreased from 0.14 for the longitudinal sample to 0.055 . The pronounced decrease in the strain to failure relative to the MnS stringer orientation is similar to that documented in a number of structural materials including HY-100 steel[7] and a $0.29\text{C}-3.2\text{Ni}-1.3\text{Cr}$ armor steel[6].

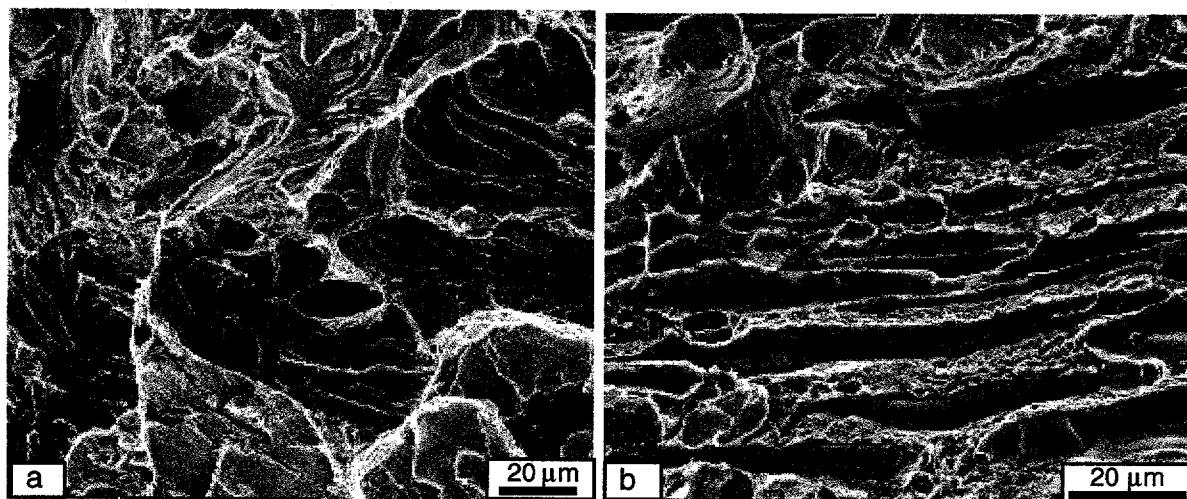


Figure 5: Scanning electron micrograph showing the fracture morphology of tensile SHPB samples as a function of loading orientation: a) loading longitudinal to rail axis showing end-on fracture of stringers intermixed with transgranular cleavage fracture, and b) loading transverse to rail axis showing fracture / delamination along MnS stringers intermixed with ductile dimples, ductile tearing, and transgranular cleavage fracture.

3.3 Damage Evolution and Fracture Behavior

The damage evolution and fracture behavior in the 1080 rail steel studied as a function of loading orientation was evaluated through metallographic examination of cross-sectioned failed tensile samples and scanning-electron microscopic (SEM) examination of the fractured samples. Figure 5 shows that the primary fracture mode during

dynamic deformation for both the longitudinal and transverse-oriented samples deformed in tension is transgranular cleavage. The primary fracture mode during quasi-static loading was transgranular ductile tearing[19].

The details of the fracture mode, independent of the strain rate of loading, as a function of loading orientation were found to be significantly different between the tensile samples loaded parallel and

perpendicular to the rail axis. As seen in Figure 5a, tensile loading parallel to the rail axis, and therefore the MnS stringers, exhibits delamination around the stringers. Conversely, loading transverse to the rail axis and therefore the MnS stringers displays a pronounced change in fracture initiation. Decohesion and delamination of the pearlitic microstructure from the MnS stringers is seen to alter the fracture path revealing the elongated stringers within the matrix as seen in Figure 5b. The low cohesive strength of the pearlitic microstructure with the stringers leads to early crack nucleation along the stringers and promotes crack growth and final fracture at significantly reduced tensile strains compared to loading longitudinal to the stringers.

The pronounced influence of the MnS stringers on the fracture morphology in the 1080 steel is observed to be similar under both low and high-rate tensile loading although the difference in fracture strains is larger at low rate. While the transverse-oriented tensile samples exhibit significantly reduced strains to failure at both low and high-strain rate, the difference is less pronounced at high rate due to the transition to cleavage as the primary fracture mode within the pearlitic microstructure. The more ductile nature of the transgranular ductile tearing observed during quasi-static tension failure leads to a more pronounced difference in the tensile strains to failure between the longitudinal and transverse loaded samples.

The damage evolution within the 1080 rail steel tensile samples loaded dynamically was examined by sectioning the fracture samples and examining the microstructure behind the fracture surface. Figure 6 shows details of the damage processes behind the fracture surface for the longitudinally and transverse-loaded tensile samples. Figure 6a shows that loading parallel to the MnS stringers leads to decohesion of the stringer/matrix interface and cracking of the elongated stringers perpendicular to the stringer axis. Loading across the stringers, as seen in the transverse samples, exhibits decohesion between the stringer/matrix interface as well as cracks linking the stringers.

The results of the current study illustrate the significant role that anisotropic damage evolution can have on the fracture of a crystallographically isotropic structural material. This result is in contrast to the situation in a strongly crystallographically texture material like Zr where due to its high purity damage evolution is an essentially isotropic process[4, 11]. This study offers a sequential experimental step toward systematically isolating the various and synergistic influences of anisotropy (crystallographic and microstructural) on constitutive behavior, damage evolution, and fracture. Coupling both anisotropic elastic and plastic response (due to texture) with anisotropic damage initiation processes is the next obvious step toward the goal of understanding complex engineering materials such as composites.

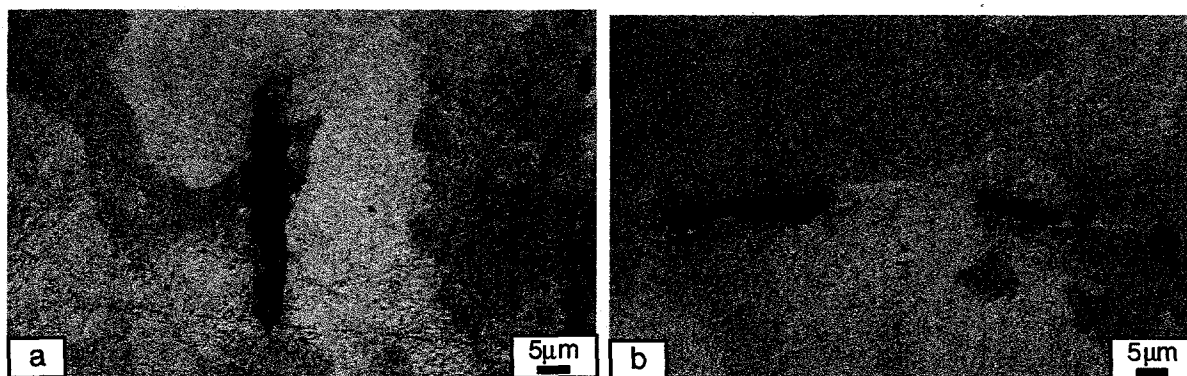


Figure 6: Optical metallography of damage below the fracture surface of tensile SHPB samples as a function of loading orientation: a) loading longitudinal to the rail axis showing MnS stringers cracked normal to their axis, and b) loading transverse to the rail axis showing decohesion around MnS stringers and cracks emanating from and between the stringers.

4. SUMMARY AND CONCLUSIONS

The effect of microstructural anisotropy on the quasi-static and dynamic constitutive and fracture behavior of 1080 eutectoid rail steel was studied using compression and tensile testing and post-mortem analysis of fractured tensile samples. The crystallographic isotropy of the rail steel leads to isotropic quasi-static and dynamic stress-strain response during both compressive and tensile loading. Microstructural anisotropy in 1080 rail steel was found to exhibit a strong influence on the strain to fracture under both quasi-static and dynamic tensile loading related to the role of MnS stringers on damage evolution. The influence of microstructural anisotropy on the fracture of 1080 rail steel is shown to be consistent with the orientational dependency of the damage evolution in this steel adjacent to MnS stringers under both low- and high-rate tensile loading.

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