Compact Forced Simple-Shear Sample for Studying Shear Localization in Materials

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Abstract

A new specimen geometry, the compact forced-simple-shear specimen (CFSS), has been developed as a means to achieve simple shear testing of materials over a range of temperatures and strain rates. The stress and strain state in the gage section is designed to produce essentially “pure” simple shear, mode II in-plane shear, in a compact-sample geometry. The 2-D plane of shear can be directly aligned along specified directional aspects of a material’s microstructure of interest; i.e., systematic shear loading parallel, at 45 degrees, and orthogonal to anisotropic microstructural features in a material such as the pancake-shaped grains typical in many rolled structural metals, or to specified directions in fiber-reinforced composites. The shear-stress shear-strain response and the damage evolution parallel and orthogonal to the pancake grain morphology in 7039-Al are shown to vary significantly as a function of orientation to the microstructure.

Keywords: Shear Localization, anisotropy, microstructure, sample geometry

1. Introduction

Unstable deformation of ductile metals and alloys subjected to complex loading paths and/or high strain rates is frequently associated with shear rupture (shear localization or shear bands) when the failure surface in the material is close to the plane of maximum shear stress, as opposed to void nucleation, growth, and coalescence. The development of predictive constitutive descriptions of strength, and thereafter damage-evolution and fracture models, requires a detailed understanding of the correlated effects among microstructure, loading conditions, and finally anisotropy, as many engineered materials possess orientation-dependent mechanical properties. The stability of plastic deformation in a given metal alloy, which depends on physical (heat capacity, thermal conductivity, thermal softening) mechanical (stress state, temperature, strain rate) and material/microstructural factors (e.g., crystallographic texture, grain morphology and shape, dislocation density and distribution, microstructural and phase stability) affect the ability of a material to deform homogeneously versus exhibiting a propensity toward inhomogeneous shear localization, has been the subject of numerous reviews and archival research studies over the past 6 decades [1-36]. The majority this research has focused on thermally-assisted mechanisms driving shear localization, i.e., adiabatic shear localization, of relevance to ballistic penetration [1, 37, 38], impact [2], and crashworthiness [2], high speed machining [2], and forming and manufacturing mechanics [2]. Accordingly, research emphasis has been placed on quantifying the mechanical and metallurgical characterization of shear bands, such as local strain, temperature, hardness distribution, and products inside shear bands [25, 36].

A wide spectrum of test techniques and test sample geometries have been developed to examine and quantify the shear propensity of materials [39]. An in-depth description of the advantages and disadvantages of the various techniques is given in the book “Adiabatic Shear Localization” by Dodd and Bai [39]. Developed shear-loading techniques for metallic materials include: 1) torsion testing [40], 2) hat-shaped samples [12, 41], 3) dynamic compression testing [42], 4) compression/shear testing [43], 5) cylinder expansion and collapse testing [44-46], 6) punch testing [47], 7) indentation testing [48], 8) double-shear specimen testing [49, 50], 9) single-edge and double-edge specimens [51], 10) shear-compression testing [52], 11) simple-shear testing – a modification of ASTM B831 for sheet materials [53, 54], and the eccentric notch shear specimen [55].

Given the propensity for adiabatic shear band formation during high-strain-rate loading, several experimental studies have particularly centered on the development of techniques to obtain compact sample geometries that can be readily loaded in high-strain-rate loading equipment such as split-Hopkinson Pressure/Kolsky Bars, impact testing, drop-weight tests, and high-speed servo-hydraulic platforms. It is also of interest to have these dynamic loading tests conducted over a range of temperatures, and in a manner by which temporal shear-stress/shear-strain quantitative data can be obtained [39]. To achieve high shear rates under dynamic and/or impact loading conditions, several of the above mentioned specimen geometries have been devised such that linear displacement applied to the sample exterior boundary is transitioned into local “principle shear deformation” within a gage section of the specimen. One such forced shear sample, termed the “top-hat” specimen was originated by Hartman, Kunze, and Meyer [41] and Meyer and Manwaring [12] and thereafter further developed by several investigators [23, 25, 56]. This sample design has seen wide application due to its compact geometry making it readily

amenable to testing on quasi-static, intermediate strain-rate testing platforms, and using split-Hopkinson/Kolsky Pressure Bars [57, 58]. In addition, the ‘top-hat’ sample design has been modeled using finite-element methods, where the modeling results have been shown to positively compare with experimental results [58, 59].

The small, compact nature of the ‘top-hat’ design has the advantages of: 1) readily facilitating testing at various temperatures within different testing platforms, 2) enabling studying shearing propensity in “small” cross-sections of material, such as through-thickness loading in the wall of cylindrical pipes or thin plates, and 3) through modification of the sample dimensions facilitate systematic variation of the magnitude of the compressive and shear loading components experienced within the cylindrical shearing section [60]. The “top-hat” design incorporates a slight overlap between the hat section and the cylindrical ‘brim’ portion that results in a mixed loading stress state within the cylindrical shear loading zone, combining both shear and compressive stresses. This design helps to restrain Mode I crack initiation along the shear localization zone.

However, several significant issues regarding the ‘top-hat’ sample geometry remain unresolved. First, due to the overlapping nature of the shear region in the sample design, during testing the shearing surface rotates during testing. In addition, there is a reduction of the shear conical area during the shear deformation making quantitative determination of the shear stress in the shear section difficult or impossible to achieve.

The second complexity with the ‘top-hat’ sample design is the radial expansion of the ‘brim’ portion of the hat-shaped specimen during testing. The inclined-shearing zone in the ‘top-hat’ sample is subjected to both compressive and shear loading components. While assumptions can be made to estimate the magnitude of the compressive stress on the shear stress behavior, and although the sample does allow examination of shear band formation in the absence of tensile failure, there remains no definitive way to both completely remove the bending moment within the sample nor quantify the shear strain evolution during the forced shear loading [23, 59]. In estimating the shear stress, both the reduction of the shear area and the rotation of the shear direction were considered in the decomposition of the total force [23]. The estimation takes into account the fact that the overlapping shear region of the hat-shaped specimens leads to an additional hoop expansion of the cylindrical ‘brim’ that impedes a correct estimation of the load applied for the real shear deformation. Due to this fact, a fraction of the total input energy is allocated to expand the cylindrical ‘brim’, and this fraction varies as a function of the displacement in the estimation [23]. The qualitative estimation of the shear stress is further complicated if the metal or alloy is crystallographically textured as the yielding and work-hardening behavior around the circular shearing zone varies.

Third, due to the cylindrical or toroidal shear section being loaded in a “top-hat” specimen, systematic investigation of the shear response and/or shear band evolution correlated in crystallographically or morphologically anisotropic materials is not possible as isolated direct alignment of a planar shearing section in the specimen to a specific planar direction aligned to the microstructure cannot be achieved [61]. This is analogous to easy shearing of wood parallel to its grain compared to orthogonal to the grain (much harder to do) versus punching out a round plug in the same piece of wood, which represents an average shearing response akin to that

obtained using a “top-hat” sample in metallic materials.

Additional forced shear loading techniques have been developed by Klepaczko using a modified double-shear specimen [50, 62], direct impact-loaded pre-notched plate specimens by the Cal Tech group [63], and pressure-shear impact testing developed by Clifton *et al.* [64]. The double-shear specimen design subjects a material to a complex stress-state across the shearing zone surface as well as also lacking the ability to tie the shearing zone directly to a specific 2D loading plane within a material microstructure as discussed for the “top-hat” sample design due to its cylindrical shearing zone. The direct shock plate impact geometry facilitates a direct means to Mode II loading, but relies on impact loading to achieve this, and is therefore not amenable to testing across a spectrum of strain rates. This sample requires a significantly larger (200x100x6mm) sample size making it impractical for testing many material product forms, and cannot be readily aligned with small-scale microstructural features.

The pressure-shear impact test is designed to obtain shear waves in symmetric plate impact experiments [64]. Limitations include, as with other wave propagation experiments, that: 1) the constitutive relations between stress, strain, and strain rate is not obtained directly, but must be inferred by comparison of the recorded wave profiles with those predicted for various constitutive models, 2) the testing is limited to fine-grained materials because the grain size must be small compared to specimen thickness to ensure that a representative average polycrystalline response is measured, 3) the experiments are lengthy and expensive because of the time required for sample preparation, and 4) the sample should be soft compared to the anvil plate material used to impose the deformation so that the anvil will remain elastic under the impact loading conditions of the experiment [65].

Rittel *et al.* developed an alternate shear-loading specimen geometry by which a shear dominant field is applied to a gage section through compression loading, either quasi-statically or dynamically, termed the shear compression specimen (SCS) [52, 66-69]. An approximation of the stress state within the shearing zone of the SCS sample design has been modeled analytically [67] and simulated using finite-element modeling [52, 66]. This sample design also offers a compact geometry that can be utilized in studying shear localization over a spectrum of strain rates and temperatures if desired. However, this geometry does possess several complications. First, the SCS sample design does not constitute a “simple” shear loading stress state within the gage section, but is rather a three-dimensional stress state [52, 66, 68]. Second, potential bending moments are possible in the sample due to lateral frictional constraint in the motion of the loading faces in contact with the loading platform, which are a concern. An assumption of no lateral frictional constraint on the loading faces, such as in the case of high-rate loading in a split-Hopkinson Pressure Bar, remains problematic at best. Finally, during loading, this geometry brings the added complication of radial inertial effects of the sample motion under dynamic loading.

While each of the four shear sample designs discussed in detail above offers the possibility of subjecting a material to a predominantly shear dominant deformation mode, each is far from loading the gage section in an ideal pure Mode II loading stress state, or more realistically simple shear, in addition to each sample design possessing various caveats as to: 1) the exact stress-state of the “shearing zone” and how it evolves with plastic strain, 2) the degree of quantification of

the shear stress-shear strain response that can be extracted from the test data either directly, analytically, or requiring numerical finite-element simulation, 3) the applicability, or lack thereof, for each design to be used over a range of strain rates and temperatures, 4) sample size requirements determining the material form and thickness from which a sample can be fabricated, and 5) whether the sample geometry allows systematic alignment and direct indexing of the local shearing zone with the crystallographic texture and/or specific morphological features within the microstructure of the material under investigation.

The objective of this paper is to present results of the development and application of a new compact-forced-simple-shear (CFSS) specimen geometry to investigate the large strain constitutive behavior, damage evolution, and failure of 7039-Al tested in shear systematically as a function of shear loading versus microstructural orientation. The paper is divided into four sections. First, we detail the design of the CFSS sample. Second, we present a study of the influence of microstructural anisotropy on the shear localization propensity in 7039-Al (an armor material). The unique design of the CFSS sample facilitates “simple” shear testing exactly parallel and orthogonal to the elongated pancake grain morphology, in both the thru-thickness and in-plane orientations, typical of this rolled Al-armor plate material. This sample design is shown to uniquely allow systematic quantification of the effect of morphological or crystallographic anisotropy on the shear-stress shear-strain response and damage evolution of a material over a range of temperatures and strain rates unlike sample designs like the ‘top-hat’ or compression-shear geometries. The next section of the paper presents a discussion of the shear loading results using the CFSS sample geometry on 7039-Al, as a function of shear-loading orientation, and discusses the shear-loading data and microstructural observations in the context of previous integrated ballistic impact studies illustrating microstructural effects on ballistic-induced shear localization and damage evolution processes. The final section presents concluding remarks summarizing the results of this study and thoughts on future directions of research and testing applications afforded by the CFSS sample design.

2. Experimental Procedure

A. The Compact Forced-Simple-Shear (CFSS) Sample Design

The compact forced-simple-shear sample design is schematically depicted in Figure 1. The sample geometry is designed to align a single plane of shear parallel to the loading direction of the sample. The CFSS sample as shown is machined in a cylindrical geometry although an overall rectangular-shaped sample geometry is also possible albeit requiring more complex machining steps to manufacture the sample. Utilizing the cylindrical overall geometry was selected as the easiest to machine using two channels cut across the sample clocked on opposite sides of the cylinder, machined using an end-mill cutter, and then orthogonal side V-notches clocked on either side of the sample. Fabrication of the sample can be readily produced from material bar stock or cylindrical cores taken from a larger product form. The design allows positioning of a single narrow plane to be subjected to simple shear on the sample’s compression axis. Machining samples with the shear plane as a function of position within a material possessing microstructural or crystallographic anisotropy can be utilized to systematically probe

shearing mechanical response as well as the damage evolution directly correlated to specific orientations within a material. The sample drawing dimensions, as presented, have been utilized for shear testing on a number of materials possessing modest yield strengths and shear-banding propensity, such as Ta and the 7039-Al to be presented in detail in the results section of this paper. Figure 2 presents photographs of tantalum CFSS samples before and following quasi-static loading illustrating the overall response of the sample. It should be noted that the specific CFSS dimensions presented in Figure 1 were sized to the materials of interest in this study. The specific area of the shearing plane needs to be sized so as to minimize or totally avoid macroscopic bending of the sample to assure a simple pure shear stress state on the shearing plane within a sample. Accordingly, low yield strength materials will require a reduced shear plane area to avoid bending of the sample versus allowing a larger shear plane area for a material possessing higher yield strength. The extent of work hardening prior to strain localization can also influence the selection of the area of the shear plane in the sample.

The selection of the total shear area of the sample should be determined so that the anticipated maximum force produced within the shear plane (e.g. anticipated maximum shear stress times shear area) does not cause plastic flow in the adjacent shoulder region. Short of performing a full finite-element simulation of the sample, this can be approximated by using the following expression for the stress achieved within the inner section of the shoulder region due to both bending (first term) and normal (second term) stress,

$$\sigma_{InnerShoulder} = \frac{4608}{9\sqrt{3}\pi(9\pi^2 - 64)} \frac{\sigma_y A_s}{d^2} + \frac{4}{\sqrt{3}\pi \left(\frac{1}{2}d^2 - r_c^2\right)} \frac{\sigma_y A_s}{d^2} = 3.79 \frac{\sigma_y A_s}{d^2} + 0.735 \frac{\sigma_y A_s}{\left(\frac{1}{2}d^2 - r_c^2\right)},$$

where $\sigma_{InnerShoulder}$ is the approximate stress in the inner portion of the shoulder region, σ_y is the tensile yield stress, A_s is the shear region surface area, d is the bar diameter, and r_c is the cut-out radius. For the current case of 7039Al, using the measured yield strength of 350 MPa and the sample design dimensions in Figure 1, the inner shoulder stress is calculated to be 248 MPa. Consistent with the experimental observations detailed in this paper, the selected shear area facilitated simple shear loading for the 7039Al alloy without any visible bending in the hinge section of the CFSS sample.

However, the authors point out to the reader that in order to assure “simple” shear loading in the CFSS sample, it is suggested that one simulate using finite-element techniques their own test material and testing configuration prior to manufacturing specimens. The above-mentioned expression provides only a qualitative starting point from which to design the dimensions of the CFSS sample for a given material. Variation of loading strain rate and temperature for example, may significantly influence the yield strength and shear response for the material of interest. In addition, the anisotropic nature of both the constitutive response of the material, as well as the directional dependency of the operative damage mechanism in the shearing region, requires careful consideration in selecting the sample dimensions. A significant directional dependency of the material shear response, for which the CFSS sample was uniquely designed to allow systematic quantification, could well require several different sample configurations if the shear localization propensity varies widely as a function of microstructure.

Additionally, shear loading to a fixed magnitude of shear strain can be attained with the insertion of fixed dimension wedges in the two side slots of the sample or placing the sample in a non-constraining cylinder surrounding the sample to limit the total level of shear applied to the sample. Finally, the compact nature of the CFSS sample readily facilitates testing on platforms spanning a wide range of temperatures and strain rates including the split-Hopkinson Pressure Bar.

Figure 1 – Schematic representation of the compact-forced-simple-shear specimen. All dimensions are in mm.

Figure 2 – Photograph of a high-purity tantalum CFSS sample: a) as machined/undeformed, and b) following quasi-static deformation.

B. Material / Mechanical Testing

The experimental portion of this study focused on systematically quantifying the orientation-dependent shear and damage-evolution response of the aluminum alloy 7039. The 7039-Al alloy was received in the form of 25.4 mm thick plate. The nominal chemical composition (in wt. %) of the 7039 alloy was 0.40 max Fe, 0.15-0.25 Cr, 0.30 max Si, 0.10 max Cu, 0.10-0.40 Mn, 2.3-3.3 Mg, 3.5-4.4 Zn, 0.10 max Ti, others max 0.15, balance Al. The microstructure of the 7039-Al alloy is characterized by elongated “pancake-shaped” grains orientated along the rolling direction of the plate, typical of rolled 7000 series Al-alloys. EBSD quantification of the starting 7039-Al plate material was performed in all three directions of the plate. An EBSD map of the elongated microstructure of the 7039-Al is shown in Figure 3. The material exhibits a strong through thickness texture of 9.7 times random, indicated by a large number of grains oriented with $\langle 101 \rangle$ parallel to the through thickness direction. However, due to the pancaked microstructure, the area where the EBSD analysis was performed may be insufficient to reflect the overall texture of the plate. Shear testing samples, using the CFSS geometry, were machined from the 7039-Al plate in five orientations as shown in Figure 4. Samples were fabricated in the thru-thickness plate orientation parallel and perpendicular to the elongated grains, and from the in-plane plate direction, samples were sectioned orientating the shearing plane parallel, perpendicular, and at a 45 degree angle to the plate thickness. The CFSS samples in the five orientations were loaded quasi-statically at a strain rate of 0.001/sec for the shear gage section at an ambient temperature of 25°C. Multiple samples of each orientation were tested to ascertain a statistically reproducible response.

Figure 3: EBSD map of the top-surface the 7039-Al plate material showing the elongated grain microstructure and overall texture of the plate material.

Figure 4 – Optical Metallography of 7039-Al showing the pancake-elongated grain structure typical of this rolled Al-alloy and showing the test sample orientations aligning the shearing section to a parallel, perpendicular, and at a 45 degree orientation to the microstructure of the plate.

C. Post-Mortem Metallographic Analysis

Following testing, the CFSS specimens were sectioned through the shear zone, as seen in Figure 5, orthogonal to the plane of shear, along the indicated direction of the plate, and metallographically prepared using conventional methods. Electron backscatter diffraction (EBSD)[70] and light optical microscopy (LOM) were utilized to investigate the cross-sections of the specimens (highlighted in Figure 5). Sample preparation consisted of grinding on SiC paper with increasingly finer grit, followed by mechanical polishing with 0.3 μ m alpha alumina slurry and then a mixture of 5:1 by volume of 0.04 μ m colloidal silica and hydrogen peroxide. In preparation for EBSD analysis, the samples were chemically polished by dipping in a solution of 6g of sodium hydroxide in 50ml of water for 20 seconds, then another 30 seconds in a mixture of 3 drops hydrofluoric acid in 50ml of water. Due to the elongated microstructure of the 7039-Al material, EBSD analysis was performed with a step size of 0.25 μ m on a Phillips XL30 FEG SEM, using the TSL Data Collection and Analysis software. EBSD analysis[70] was followed by a quick etch using the Keller's reagent in preparation for optical microscopy. The EBSD data collected for individual tested specimens, as presented in the results/discussion section of this study, were rotated so that the maps reflect crystal directions aligned with the TT direction.

Figure 5 – Sectioned view of CFSS sample shear zone utilized for optical metallographic and EBSD study.

3. Results and Discussion:

A. Mechanical Response

The load-displacement behavior for the 7039-Al, using the CFSS geometry, was found to be very reproducible for the five orientations studied. Typical load versus displacement responses of the five different orientations for the samples sectioned following testing are presented in Figure 6. The load displacement responses of the differently oriented shear samples was found to be nominally similar in magnitude of maximum load response for all five orientations, while the plastic deformation response of the material microstructure to shear loading and the damage evolution was seen to vary significantly. The CFSS sample design in this example demonstrates the unique ability to systematically isolate the effects of microstructural anisotropy on shear behavior in contrast to the widely utilized “top-hat” or compression-shear sample geometries that cannot readily be oriented to specific planes within a test material. The one difference noted in the mechanical response was the two sample orientations loaded parallel to the elongated grains (C-direction and B-direction). These two loading directions were seen to retain a higher peak loads to a greater level of sample shear displacement (labeled arrow 1 in Figure 6) than the two

orientations perpendicular to the elongated grain directions as well as the sample loaded at a 45° angle to the in-plane plate direction (arrow 2 in Figure 6). The two orientations loaded parallel to the elongated grains are seen to not only retain a higher load to a substantially higher shear strain but also exhibit a significantly different local damage evolution behavior as is discussed in the next section.

Figure 6 – Load versus displacement response of the 7039-Al CFSS samples for the five different testing orientations (designated as samples “A” through “E” as shown in Figure 4).

B. Microstructural / EBSD Examination of Sheared Regions

The plastic deformation due to shear loading and local damage evolution of the 7039-Al microstructure subjected to shear loading using the CFSS sample geometry as a function of 5 loading orientations is presented in Figures 7-11. Consistent with previous investigations of the high-strain-rate compressive and dynamic projectile penetration response of 7039-Al [37, 38, 71, 72], the current results show that 7039-Al displays a pronounced propensity to strain localization upon intense compressive shear loading.

The shear responses of the 7039-Al is seen in optical micrographs in Figures 7-11 to display differing degrees of plastic deformation via grain rotation and damage evolution along grain boundaries prior to cracking along the shearing zone for the five different loading orientations. Shearing perpendicular to the elongated grain structure, as seen in Figures 7a, 8a, and 10a, whether in the thru-thickness plate direction or in-plane plate direction, is observed to lead to significant grain rotation and localized plastic flow in the direction of shear. In addition to the plasticity accompanying grain rotation adjacent to the sheared regions, void nucleation and cracking at and between inclusions primarily located along the grain boundaries is observed for all of the 7039-Al shear samples. Figure 8c details an example of cracking and void formation at inclusions lying along grain boundaries. The current observation of cracking at inclusions in 7039-Al during shear loading is similar to the research of Woodward [37] who noted that void formation initiated at inclusions located along grain boundaries in 7039-Al significantly affected plastic shearing at the plug/target interface leading to shear fracture during ballistic penetration loading. The previous research carried this observation further and demonstrated the potency of the effect of the inclusions in shear localization by ballistic testing of low-inclusion content pure aluminum [37]. Their results clearly suggest that reducing inclusion content in thick section Al-alloys should lead to an improvement in ductility during armor penetration loading [37].

Shear loading parallel to the elongated grains is observed to display not only an increased resistance to shear localization, as evidenced by a higher shear strain prior to a load drop as seen in Figure 6, but also a significantly altered local damage evolution. Loading parallel

to the grains as seen in Figures 9a and 11a displays much less evidence of a shear band, minimal macroscopic grain rotation, and evidence of voids forming along the elongated grains with some coalescing into a “necklace” appearance. Intragranular voids are also discernible in some of the large grains in the parallel-loaded grains. Damage in the parallel-loaded grains appears to have formed at the boundaries before localization occurs. Shearing parallel to the grains for the in-plane sample, Figure 11a, additionally displays no readily discernible shear band but rather only a slightly deformed microstructure and a difficulty distinguishing voids from the inclusions on the grain boundaries.

EBSD analysis results on the CFSS samples from the 5 orientations is also presented in Figures 7-11. The EBSD maps clearly show a well-formed shear band of approximately 200 microns wide in the A and B-direction samples (Figure 7b and 8b) and a well-defined shear band of 150-200 microns in width in the D-direction sample (Figure 10b). The deformation affected regions adjacent to the shear band is more diffuse and slightly wider in the A and D-direction samples than in the case of the B-direction sample, as indicated by the crystal direction maps. Texture measurements extracted from EBSD data shown in Figures 7-11 are observed to vary from 2.8 to 5.2 times random, and such variations are not considered significant. It is typical that in rolled materials texture may be anisotropically distributed in the plate. As specimens were machined from slightly different portions of the plate, texture differences may also reflect local texture properties from these locations. In addition, texture variations for the scans presented in Figures 7-11 can be attributed not only to slight local texture variations, but also to lattice rotations caused by shear. Crystal rotations are observed in the vicinity of the shear region in all the specimens investigated as indicated by the gradual color change inside grains in the crystal direction maps. These lattice rotations were quantified to be up to 10-15 degrees for specimens A and D (shearing perpendicular to the pancake-shaped grains) and up to 25 degrees for specimen orientations B, C, and E (sheared parallel and at an angle of 45 degrees to the pancake-shaped grains, respectively).

(a) (b)

Figure 7 – Shear zone aligned with the A-direction (Thru-thickness –transverse to pancake grains), a) optical micrograph, and b) EBSD crystal direction map .

(a) (b)

(c)

Figure 8 – Shear zone aligned with the B-direction (oriented shear plane parallel to longitudinal pancake grains – shearing thru-thickness direction, a) optical micrograph, b) EBSD crystal direction map, and c) optical micrograph showing details of cracking at inclusions along grain boundaries.

(a)

(b)

Figure 9 – Shear zone aligned with the C-direction, a) optical micrograph, and b) EBSD crystal direction map.

(a)

(b)

Figure 10 – Shear zone aligned with the D-direction, a) optical micrograph, and b) EBSD crystal direction map.

(a)

(b)

Figure 11 – Shear zone aligned with the E-direction, a) optical micrograph, and b) EBSD crystal direction map.

C. Ramifications and Future Directions:

The overall observations of a strong dependency of shear localization propensity on orientation relative to microstructural anisotropy during shear loading is pertinent to the observation of differences in ballistic penetration response of anisotropic microstructures. Research on rolled steel plates, exhibiting strong microstructural banding in the form of elongated grains and elongated sulfide stringers aligned with the rolling direction, were found to correlate with reductions in fracture toughness and tensile ductility in the through-thickness direction [73]. Thereafter, thick sections of steel plate were tested as a function of angle of attack to the microstructural directionality in the plate to study the effect on ballistic performance and the mode of failure. In these studies, Leach and Woodward [73] noted a strong influence of microstructural anisotropy on the mode of plate failure and ballistic performance during projectile impact using ogive-shaped projectiles. The mode of failure was found to develop with multiple shear bands with the initiation of the shear bands strongly dependent on the orientation of the original rolled structure [73]. This observation, coupled with the previously discussed research on 7039-Al quantifying how inclusions promoted shear localization during ballistic testing [37], demonstrates the importance of being able to quantify the systematic effects of microstructural anisotropy on shear behavior.

These research findings illustrate one potent application of the new CFSS sample design to facilitating the systematic quantification of the orientation dependent shear-stress/shear-strain response of an anisotropic microstructure. Additionally, the CFSS offers the possibility of systematically quantifying the influence of crystallographic anisotropy within a material to its shear behavior. One example is research specifically focused on the quantification of the influence of crystallographic texture and/or correlating textural effects with how shear localization is manifested in Ti and Ti-alloys [74-77]. These studies very specifically focused on the quantification and identification of the links between

texture and the mechanisms for shear band formation in Ti and Ti-alloys and thereafter a search for any correlation with ballistic performance was operative. The results of this study found a higher propensity of adiabatic shear bands in annealed CP-Ti loaded along the rolling direction due to a preferred prismatic slip texture [74]. Further, Woodward [75] observed directionality of the ballistic performance in 50mm thick Ti-6Al-4V blocks was directly associated with anisotropy in the microstructure and the flow stress response demonstrating the importance of both texture and microstructural variations. Recently additional experimental and numerical simulation studies of shear localization in Ti-6Al-4V showed that when $\langle a \rangle$ slip is aligned with the principle direction of shearing, soft mode responses dominate and energy absorption by the microstructure decreases, and therefore the ballistic limit velocity is decreased (plugging in ballistics) [76, 77]. Future systematic investigations quantifying the influence of crystallographic anisotropy in polycrystalline metals and alloys, in addition to microstructurally-anisotropic structural metals and composites, using the CFSS sample geometry will be presented.

Finally, while the compressive shear-stress/shear-strain response of materials is paramount and dominant in many complex engineering applications, alternate loading stress states may prevail and are therefore of interest as well. Figure 12 presents a natural extension of the CFSS to a global tensile loading stress state. In this design, the solid cylindrical end portions of the CFSS geometry are extended and threaded to facilitate loading the sample in uniaxial tension. Similar to the compressive CFSS design, the modification to tensile loading on a plane section of the sample will subject the shear plane to simple pure shear along the sample axis. Just as in the compressive CFSS design, the sample can be machined to orient the shear plane along specific directions within a microstructurally or crystallographically anisotropic material. This same threaded CFSS design allows for stress reversal shear localization testing, as well as low cycle fatigue testing in Mode II or simple shear.

Figure 12 – The addition of threads to the two ends of the CFSS sample design to facilitate shear loading in tension

4. Summary and Conclusions:

A new specimen geometry, the compact forced-simple-shear specimen (CFSS), has been developed as a means to achieve simple shear testing of materials over a range of temperatures and strain rates. The stress and strain state in the gage section is designed to produce essentially “pure” simple shear, mode II in-plane shear, in a compact-sample geometry.

The CFSS geometry sample provides a sample configuration that:

- 1) is readily and reproducibly machined,
- 2) provides a state of essentially pure shear stress in the shear region,
- 3) is a compact geometry allowing testing over a range of strain rates and temperatures,

- 4) upon addition of threads on the sample ends, the same compact-simple shear sample design concept is adapted to tensile shear loading and stress reversal loading,
- 5) provides a straightforward relation between the measured force and axial sample displacement, thus allowing extraction of the local shear stress-shear strain response in the shear region,
- 6) provides minimal effect of boundary conditions on the shear stress and shear strain in the planar shear region,
- 7) facilitates alignment of the planar shear region to specific directions within a materials microstructure thereby allowing systematic investigation of shear response in crystallographically or morphologically anisotropic materials, and
- 8) The sample can be configured to allow either compressive or tensile loading of the shear plane of interest.

As an illustration of the CFSS sample utility and unique advantages, the shear-stress shear-strain response and the damage evolution parallel and orthogonal to the pancake grain morphology in 7039-Al is shown to vary significantly as a function of the orientation of shear loading to the anisotropic microstructural morphology. Quantification of the 2-D plane of shear directly aligned parallel, orthogonal, and at a 45-degree angle to the pancake grains in this alloy revealed significantly different shear-stress shear-strain mechanical response and operative damage evolution processes. Shear loading directly aligned parallel to the elongated grain boundaries is seen to exhibit a higher resistance to shear localization.

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Figure 8

Figure 1

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Figure)

Figure 4U

Figure 7b

Figure 8a

Figure 8b

Figure 8c

Figure 9a

Figure 9b

Figure 10a

Figure 10b

Figure 11a

Figure 11b

Figure 12