

Alternating ductile and brittle cracking mode in medium manganese steel sheets

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Abstract

Medium manganese steel sheets exhibit an unusual alternating failure mode transition involving an arrowhead fracture pattern under various loading conditions. Tests were performed using an Arcan setup with different shear-to-tension ratios and specimen orientations to explore the failure mechanisms and unravel the root causes of the transition. The fracture surfaces, characterized by optical and electron microscopy, show a periodic switchover from ductile damage to quasi-cleavage, organized into repeating arrowhead zones pointing towards the crack propagation direction. The step-by-step crack propagation leaves a signature on the load-displacement curve matching the discontinuous cracking events found on the fracture surfaces. A reduction of the stress-intensity factor due to sudden crack advance and associated load drop causes the brittle crack to arrest. Periodic porosity clusters under the fracture surface indicate re-blunting after each cycle of stable/unstable fracture.

Keywords: austenitic steels, ultrafine grained microstructure, brittle-to-ductile transition, fracture, Arcan test

Thin steel sheets are extensively used in the automotive industry for excellent combination of strength and ductility at low manufacturing costs. The development of the third generation of advanced high strength steels (3G AHSS), such as medium manganese (MMn) and quenching & partitioning (Q&P) grades, leads to superior tensile strength around 1200 MPa with adequate total elongation around 25% [1, 2]. However, the fracture toughness is limited and sometimes induces problems during forming operations, notably edge cracking [3, 4].

Furthermore, these steel grades suffer from failure mode competitions, raising concerns about crash performance. 3G AHSS exhibit both traditional ductile fracture dominated by void growth and coalescence and other failure modes such as macroscopic plastic localization [5]. A recent study by Xiong et al. [6] on Q&P steel, indicated a failure mode transition from ductile damage under uniaxial tension to intergranular brittle fracture at higher stress triaxiality, highlighting a sensitivity to local stress state. Older

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literature reports cracking mechanisms alternating from ductile damage to brittle quasi-cleavage in martensitic pipeline steel sections such as X100, X80 and X70 [7, 8, 9, 10]. This unusual alternating failure mode leaves distinctive arrowhead marks on the fracture surface, pointing towards the crack propagation direction. An interpretation of this phenomenon was proposed by Sowards et al. [11] and more detailed analysis was pursued by Hashemi [12]. Still, the underlying failure micro-mechanisms and the fundamental reasons for the failure mode transition, which could lead to catastrophic failure of structural components, are not fully understood.

Here, a wide range of loading conditions have been investigated to assess the dependency of the failure mechanisms and fracture mode transition on the stress state. In particular, the influence of the Lode parameter is explored together with stress triaxiality. Arcan cracking tests have been carried out [13, 14], involving the propagation of cracks into modified single edge notched tensile (SENT) specimens, in which the initial notch direction is varied with respect to the tensile direction. One aim is to discriminate the influence of shear stress at fixed stress triaxiality on crack initiation and propagation. The unexpected fracture process is characterized by fractography and porosity quantification to unveil the dependencies on intrinsic microstructural and micro-mechanical parameters.

A medium manganese steel of composition Fe-0.20C-3.90Mn-1.49Si-0.82Al (wt %) is processed from the as-received state (cold rolled, 50% reduction) through intercritical annealing at 700°C for 15 min, using a fluidized bed furnace, and followed by water quenching. The sheet thickness is equal to 1.35 mm. Figure 1a shows the microstructure etched with 5% nital solution and a schematic of the thermal treatment. The microstructure is composed of ultrafine-grained ferrite and 30% of retained austenite (RA), measured by image analysis [15]. The rolling texture is removed through the dual phase nucleation and globularization in the intercritical domain but some acicular RA grains remain.

The mechanical response under uniaxial tension is shown in Figure 1b, for the longitudinal (L) and transverse (T) direction (EN10002-1 standard), with gauge length $L_0 = 28$ mm. The metastable RA is responsible for transformation-induced plasticity (TRIP) during deformation resulting in significant strain hardening. The metallography and kinetics of the TRIP effect for similar medium manganese steels can be found in the literature [16, 15, 17, 18, 19]. Static and dynamic strain ageing are taking place at room temperature with a Lüders plateau and serrated flow, indicating a Portevin-Le Chatelier (PLC) mechanism [18].

Arcan SENT specimens, shown in Figure 2a-c, are produced by electrical discharge machining (EDM) in L and T directions, with a notch width of 350 μm . The ligament length is equal to 17.5 mm, allowing for the development of a steady state cracking process. Two loading angles are imposed: $\theta = 0^\circ$ (pure mode I) and $\theta = 45^\circ$ (mixed modes I & II) as well as three loading rates equal to 0.1, 1 and 10 mm/min under displacement control. The specimens are identified by loading direction, loading angle and loading rate, respectively (e.g. specimen L0-01 is loaded in the longitudinal direction with 0° of tilt at 0.1 mm/min).

The fractography study relies on optical microscopy (OM) and on higher magnification scanning electron microscopy (SEM). The characterization of the fracture surfaces involves image treatment to identify specific features by combining contrast enhancement, filtering and edge detection methods (Figure Supp. I). Some in-plane cross-sections are polished, etched and characterized by SEM to determine the porosity content and distribution under the fracture surface.

The Arcan load-displacement curves are displayed in Figure 2d, exhibiting four distinct stages: (i) an elastoplastic regime during which the initial notch undergoes significant blunting; (ii) cracking initiation as identified by a clear maximum load; (iii) crack propagation associated to crisp cracking sounds and marked by sharp drops in the load-displacement response. These discontinuities translate as peaks in the derivative plot of the loading curves. The number of discontinuities, N_d , is counted for each specimen. (iv) An increasing hump due to compressive stresses building up in the final ligament as the sample rotates in the late stage of the tearing process, as also confirmed by digital image correlation.

Optical micrographs of the fracture surfaces are presented in Figure 3a showing three zones. (a) The first crack advance is orthogonal to the loading axis under pure mode I and corresponds to a flat triangular plane, extending for about one to three times the sheet thickness. (b) Subsequently, the crack switches into a slant mixed mode I and III. In this zone, all test specimens show well-defined arrowhead markings (AHMs) pointing towards the crack propagation direction, regardless of loading direction, loading angle and loading rate. This is the main unexpected results of this study. The flat-to-slant transition occurs later in some specimens, such as in specimen T45-1, in which the fracture surface is flat over the first 10 mm, displaying large voids (10 to 50 μm) along the center line and accompanied with shear lips. Some faint or incomplete AHMs can be observed in these shear lips as well as close to the faces of other specimens. (c) The final region is characterized by micron-sized dimples on the last millimeters. Figure 3b-e shows SEM fractography details of specimen L0-1. At the microscopic scale, AHMs consist of a combination of dimples and sharper quasi-cleavage type facets separated by fully ductile areas with micron-sized dimples.

Figure 4a-b shows that the number of arrowhead markings, N_{AHM} , perfectly matches with the number of load discontinuities, N_d , for all loading conditions (except for sample T45-1) and increases with increasing loading rate. Under high loading rate, the load signal acquisition frequency is not sufficient to accurately capture the fast and discontinuous events, leading to larger uncertainty on N_d .

The arrowhead markings are identified by image treatment and defined by an unstable quasi-cleavage length, L_u , and preceding stable ductile spacing, L_s , measured at mid-thickness, as reported in Figure 3b. The frontiers are parabolic with similar curvature for all specimens but tend to become straighter if preceded by a larger L_s . The AHMs length and spacing both range from 80 to 700 μm , with the smaller values obtained at higher loading rates. Small ductile gaps are followed by small arrowhead markings while larger gaps lead to larger arrowhead markings. Figure 4c indicates a linear correlation between the AHMs quasi-cleavage length and preceding ductile spacing

for all loading conditions grouped together ($R^2 = 0.73$). Figure 4d shows that loading in the longitudinal direction results in twice larger mean ductile spacing (400 μm) compared to transverse loading direction (220 μm).

Figure 5a presents the topography profile of sample L0-1 extracted from SEM cross-sections. The corrugated topography of the fracture surface corresponds to the alternating fracture mode embodied by the arrowhead markings pattern. The amplitude of this first order oscillation ranges from 40 to 80 μm . Figure 5c shows that damage originates from micro-voids nucleation by decohesion of adjacent martensite grains or ferrite/martensite interfaces. No cracking of martensite grain is found. Quantitative analysis of the porosity distribution in Figure 5b indicates significant clusters located after each quasi-cleavage failure mode.

The sequence of events leading to the formation of arrowhead markings alternates stable ductile tearing and unstable brittle advances. Consequently, three fundamental questions arise:

1. What are the microstructural and micro-mechanical parameters conditioning the switch from ductile tearing to brittle quasi-cleavage?
2. Once initiated, why does the brittle crack arrest?
3. Once arrested, what is the crack re-initiating mechanism?

In order to answer the first question, the ductile damage process is further investigated in the light of the literature on ductile/brittle transition. As the crack tip blunts, plastic deformation accumulates ahead of the crack tip, damage develops and the crack slowly extends by void growth and coalescence. Preferential void nucleation by interface decohesion is common in duplex and multi-phased steels [20, 19, 18]. During propagation, the magnitude of the maximum principal stress (MPS) ahead of the crack tip increases [21]. Eventually, the MPS reaches a threshold value that triggers a brittle mechanism. This brittle mechanism can initiate on different types of sites [22]. For instance, in X100 steel, the occurrence of arrowhead markings has been attributed to hardness heterogeneities, acting as local brittle zones (LBZ) [11]. Third generation AHSS involve the formation of brittle fresh martensite during deformation associated to the TRIP effect [16]. The closely packed martensite with already damaged interfaces acts as a LBZ and fail in a zipper fashion, propagating splits and leaving quasi-cleavage features on the fracture surface.

The correlation between the cracking lengths of both stable and unstable fracture modes suggests that the energy accumulated to drive the brittle mode is proportional to the stress built up during ductile tearing. The various loading configurations applied are expected to directly influence this increase of the maximum principal stress ahead of the crack tip and thus impact the number, size and morphology of the resulting arrowhead markings. However, the strain fields experienced at the crack tip, generated by digital image correlation and available in Figure Supp. II, reveal very similar strain intensity and distribution, regardless of the loading angle. Cracking under mode I is largely

promoted, both at initiation and during propagation, with a crack path orthogonal to the loading angle. Therefore, the proportion of shear stress is not a controlling factor for this alternating ductile and brittle cracking mode. Still, two parameters clearly influence the AHMs geometry : the loading direction and the loading rate. Indeed, specimens loaded in the T direction (i.e. when the crack propagates parallel to the rolling direction) show a larger number of more closely packed AHMs than their L counterparts, suggesting that the activation stress level for brittle initiation is reduced when encountering aligned martensite necklaces. Such sensitivity of arrowhead markings to morphological anisotropy has also been found in duplex steels for which the LBZ comprises non-metallic inclusions [7]. Similarly, deformation rate has a direct impact on the AHMs geometry. Higher loading rates lead to a larger number of AHMs, that are both smaller and more closely spaced, indicating a lowered activation threshold. In the literature, results on AHMs have been reported for quasi-static displacement rates up to dynamic and full burst loading rates [11, 23], although quantitative data on their number and geometry is an original contribution of this study.

The medium manganese steel follows the usual trend found in thin sheet fracture of high strength metals with a slant mode (modes I & III at 45°) preceded by a flat triangular plane in front of the initial notch [24]. This slant fracture mode appears to be a necessary condition, though not sufficient, to the development of the arrowhead markings. Indeed, both phenomena are always reported together [11, 10, 7, 8, 9, 25] and this is true here as well. In particular, similar observations of partial arrowhead markings have also been reported in the shear lips of specimens displaying flat fracture [9]. The fundamental reason for the relationship between the slant mode and the arrowhead alternating failure mode is yet to be fully elucidated.

Regarding the second question, crack arrest implies that the criterion $K_I \geq K_{Ic}$ is no longer satisfied. Two reasons can be invoked : (1) the current stress-intensity factor K_I decreases with crack advance below the critical value or (2) the critical stress-intensity factor K_{Ic} increases with crack advance. The latter option could occur if the crack tip would suddenly encounter a microstructural region with higher fracture toughness, such as retained austenite instead of fresh martensite. However, earlier studies have shown that the fracture process zone (FPZ) in similar TRIP-aided steels is embedded inside a zone where martensitic transformation is complete [20, 15]. Electron backscattered diffraction and micro-hardness measurements, not presented here, confirm the complete transformation of austenite in an area larger than 500 μm around the crack tip.

Fracture toughness is also strain rate dependent, usually increasing for metals with increasing crack velocity [26]. Moreover, strain rate dependent mechanisms, such as the PLC behavior, can be hindered or deactivated at higher loading rate and decrease K_{Ic} [27, 28, 17]. Nevertheless, these effects appear not to prevail here.

The matching between the number of load discontinuities and arrowhead markings supports the hypothesis that these discontinuities constitute the macroscopic signature of the brittle type micro-mechanism. These pop-ins [29, 30] are associated to discrete events of brittle crack propagation and arrest in the main cracking plane or sometimes perpendicular to it [29]. The change in stress-intensity factor ΔK_I associated to a

sudden crack advance, Δa , during a pop-in, can be estimated for SENT-like geometries from [31] :

$$K_I = Y \frac{F(a)}{S} \sqrt{a}, \quad (1)$$

$$\frac{\Delta K_I}{\Delta a} = Y \frac{F(a)}{S} \frac{1}{2\sqrt{a}} + Y \frac{1}{S} \sqrt{a} \frac{\Delta F}{\Delta a}, \quad (2)$$

with Y a geometry-dependent function, F the load applied on an area S and a the crack length. Using the measured load drops $\Delta F = [-600; -100]$ N and corresponding crack jumps $\Delta a = [0.1; 0.7]$ mm results in negative values of ΔK_I ($\Delta K_I/K_I = [-20; -10]\%$), effectively decreasing the current stress-intensity factor below K_{Ic} and leading to crack arrest.

As for the third question, once arrested, the crack tip requires additional blunting and damage accumulation to re-initiate the ductile tearing and repeat the cycle. This is supported by the presence of porosity clusters located right after the quasi-cleavage zones.

In conclusion, Arcan crack propagation tests on medium manganese steel sheets show an unusual alternating ductile and brittle cracking mode, involving an arrowhead pattern on the fracture surfaces. Different loading angles, loading directions and loading rates produce this pattern. This is, to our knowledge, the first time that such an alternating ductile-to-brittle failure mode is reported and explored in medium manganese steel sheets, and more generally for 3G AHSS. The underlying failure mechanism alternates between stable ductile crack propagation, dominated by void growth and coalescence, and unstable quasi-cleavage. The correlation between the cracking lengths of both stable and unstable fracture modes indicates that the activation energy accumulated to drive the brittle mode is proportional to the stress built up during ductile tearing. The morphological anisotropy of the rolled sheets and higher deformation rate reduce this activation energy, leading to an increased number of arrowhead markings. Slant fracture mode appears to be a necessary condition to the development of the arrowhead pattern. Crack arrest is caused by a local decrease of the stress-intensity factor. Crack re-blunting is necessary to re-initiate the ductile propagation. This unusual combination of fracture modes raises important questions regarding the cracking resistance of such alloys and the impact that such transitions could have on structural integrity.

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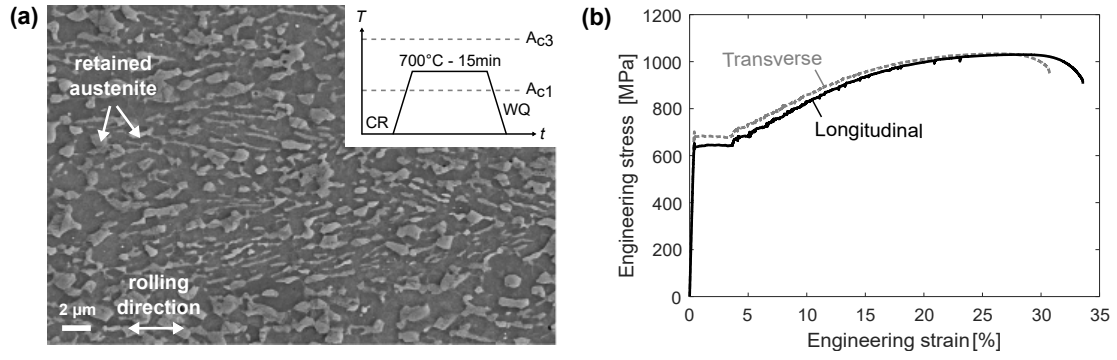


Figure 1: (a) SEM micrograph of the microstructure after intercritical annealing with a schematic of the heat treatment and (b) engineering stress-strain curve of the medium manganese steel sheet under uniaxial tension along the longitudinal and transverse direction.

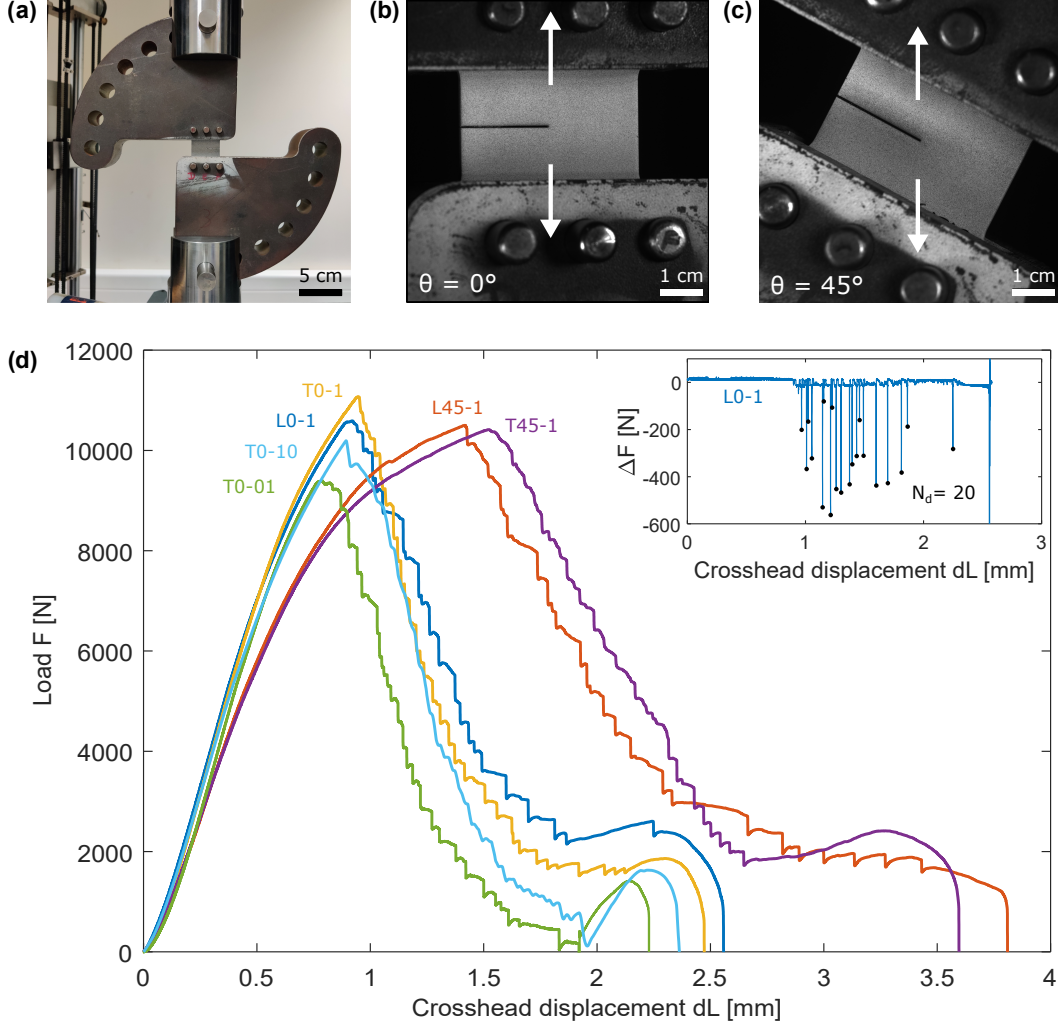


Figure 2: (a) Arcan loading setup (b) in pure mode I and (c) mixed modes I + II. (d) Load-displacement curves of Arcan specimens under various loading directions (L,T), loading angles (0° , 45°) and loading rates (0.1, 1, 10 mm/min). The insert shows the magnitude of the discontinuities in the loading response of sample L0-1.

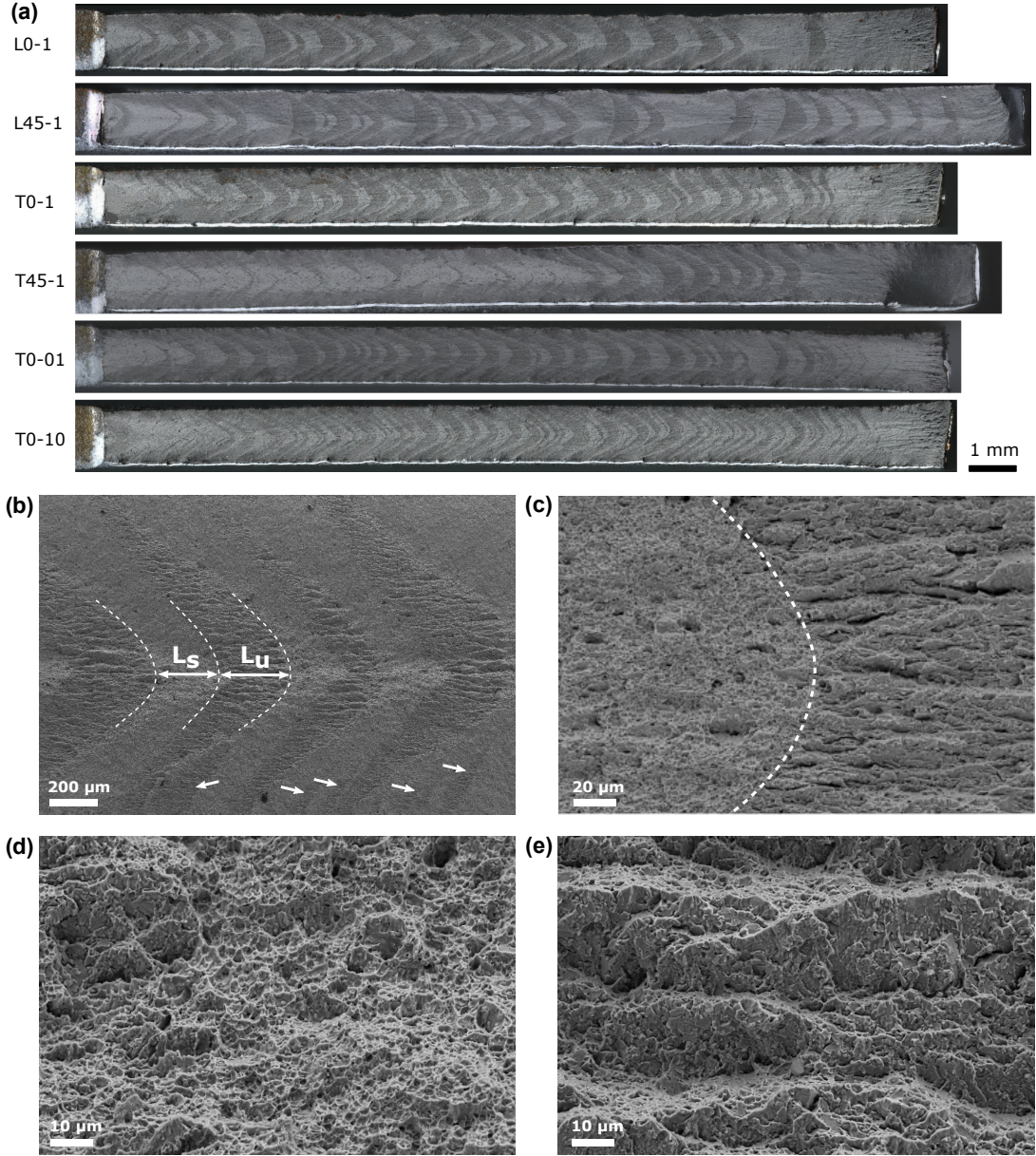


Figure 3: (a) OM of Arcan fracture surfaces under various loading configurations showing arrowhead marking patterns. SEM micrographs of sample L0-1 (b) defining the stable, L_s , and unstable, L_u , cracking lengths with arrows indicating partial arrowhead markings. (c) Contrasting fractographic features including (d) micron-sized dimples and (e) quasi-cleavage facets.

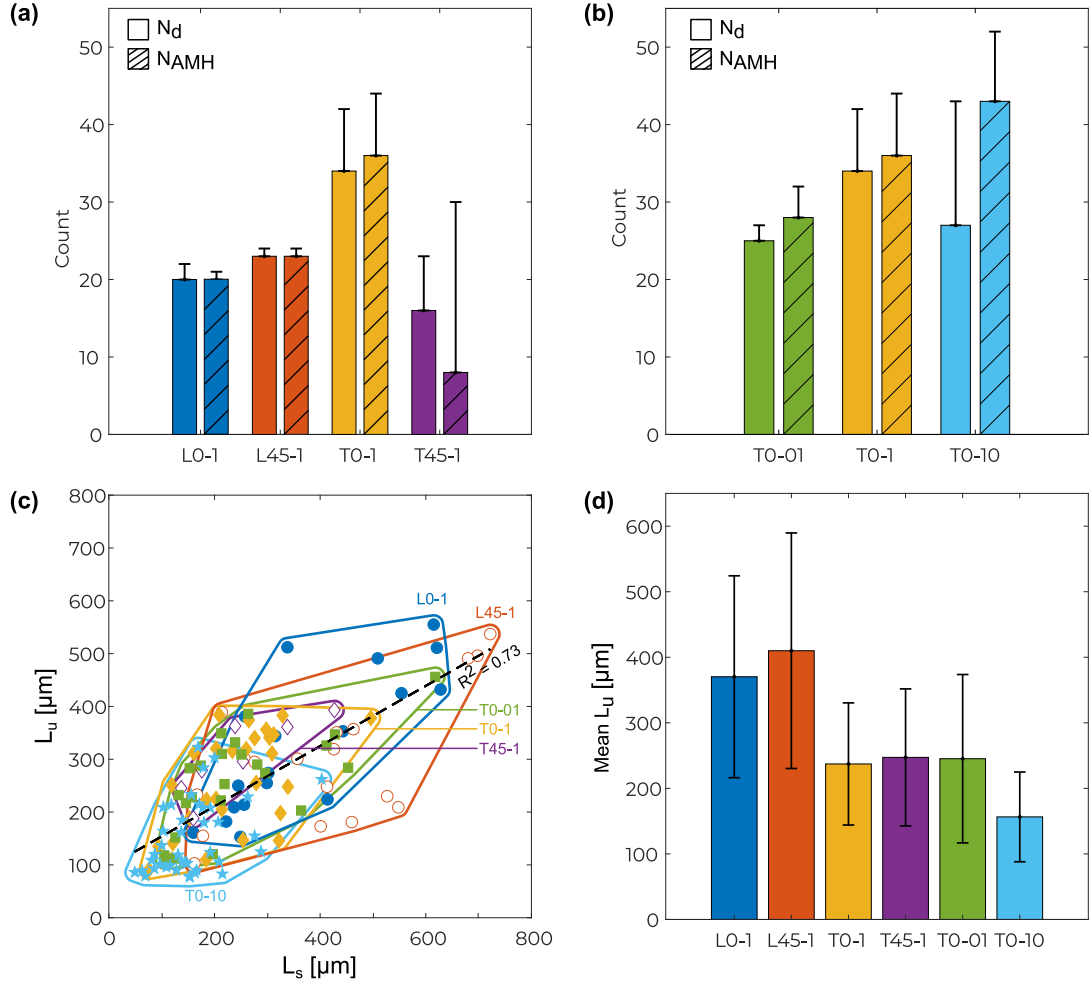


Figure 4: Number of load discontinuities, N_d , and arrowhead markings, N_{AHM} , as a function of (a) loading direction and angle, and (b) loading rate. (c) Correlation between stable ductile spacing, L_s , and unstable brittle advance, L_u , for all loading configurations, and (d) mean ductile spacing between AHM.

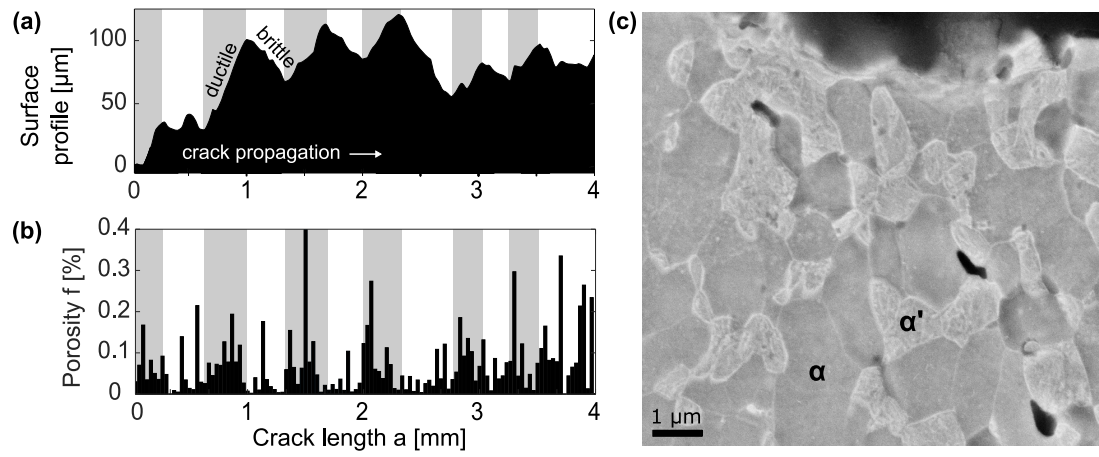


Figure 5: (a) In-plane fracture surface profile of specimen L0-01, (b) associated porosity distribution and (c) SEM micrograph of damage nucleation sites under the fracture surface.

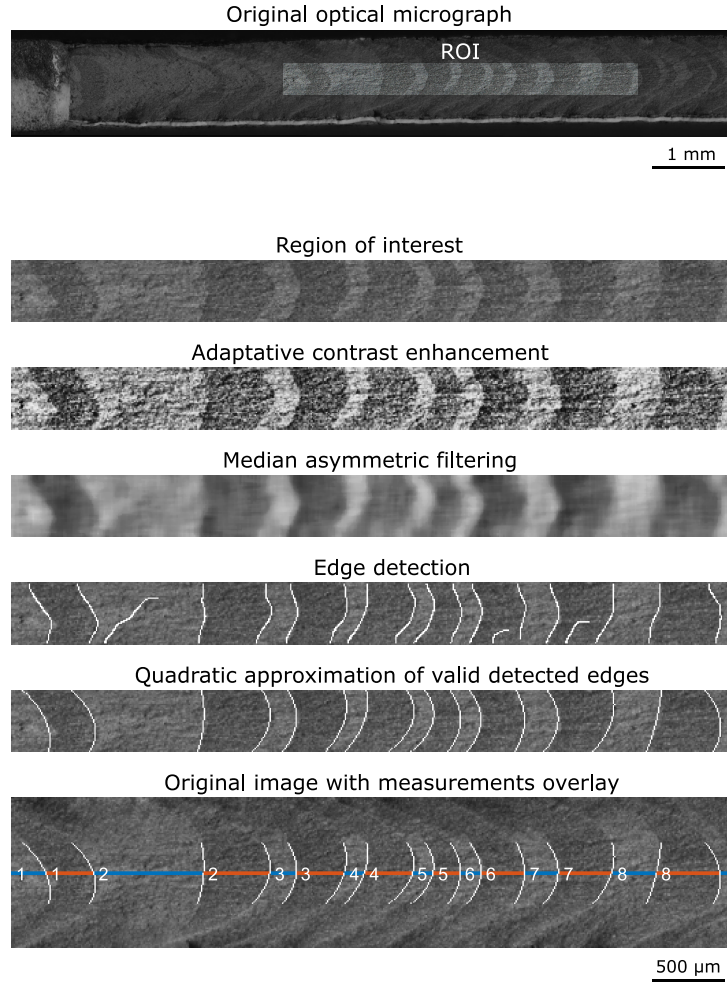


Figure Supp. I: Image treatment algorithm for the identification and measurement of the arrowhead markings. In blue, the stable ductile spacing, L_s , and in red, the unstable brittle advance, L_u .

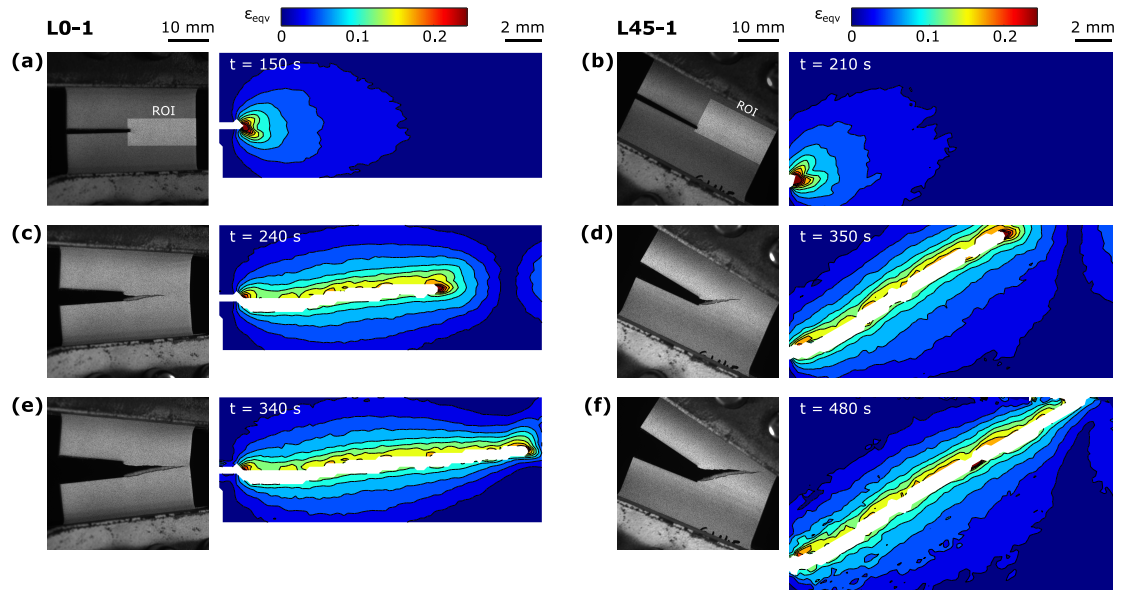


Figure Supp. II: Strain fields generated by digital image correlation at crack initiation, mid-propagation and final tearing under Arcan testing with loading angle of 0° (a, c, e) and 45° (b, d, f) for a fixed loading rate of 1 mm/min along the longitudinal direction.