Omega: A material parameter for quantifying fracture in sheet materials

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The Omega parameter offers a novel approach to quantifying line pipe steels' fracture resistance through a post-processing 3D scanning and slicing technique. Unlike traditional parameters such as the Crack Tip Opening Angle (CTOA), Omega reduces testing costs and subjectivity and remains unaffected by the geometrical configuration of the test setup. It provides a comprehensive evaluation of the fracture process, including tensile-dominant initiation, steady-state shear propagation, and the transition between these modes. This study explores Omega's application to widely used sheet materials (DP600, DP1000, and Al7075) using Single Edge Notched Tensile (SENT) tests. Findings demonstrate Omega's capability to accurately capture fracture behaviour across various stress triaxiality states and fracture modes. This highlights Omega's potential to become a standardized test for analysing fracture failure in the sheet metal forming industry, where a wide range of stress states during forming is often observed.

Keywords: Omega; Fracture Modes; Stress Triaxiality; Sheet Materials.

1. Introduction of Omega Concept

The concept of Omega as a fracture-related material parameter was introduced in 2021 [1], based on the philosophy that the fracture surface of an object is a static manifestation of the dynamic fracture propagation process, and Omega brings this static manifestation back to dynamic analysis. Omega offers lower testing costs and reduced subjectivity compared to established parameters like CTOA (Crack Tip Opening Angle). It was also observed that Omega's quantification is not affected by the geometrical configuration of the testing setup, unlike CTOA [2]. Omega enables a comprehensive evaluation of the fracture process, including quantitative descriptions of fracture initiation under a tensile-dominant mode and steady-state fracture propagation under a shear-dominated mode [1]. Moreover, Omega provides detailed information on the transition between these two modes, as experimentally observed across a wide range of testing configurations [1, 2].

Understanding fracture failure modes is crucial in the metal-forming industry [3, 4]. Formed parts experience a wide range of stress/strain states and histories and inevitably contain some level of damage that must be optimized to enhance product serviceability [3]. Fracture modes are influenced by stress states (stress triaxiality), which can be varied by adjusting the geometrical configuration of testing samples to cover a range of stress triaxialities [5, 6]. Different stress states induce different microscopic fracture mechanisms, which manifest in various ways at the macroscopic level [3, 7]. This is particularly relevant

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in metal forming, where complex and evolving stress states are inherent in the operation [3, 4].

In experimental tests, stress triaxiality variation is achieved by altering the sample's geometrical configurations. Typically, each configuration yields a single-valued stress triaxiality by obtaining an average value [6, 8]. Omega offers an opportunity to correlate a range of critical stress states (a range of stress triaxiality) – from tensile mode to steady-state shear fracture modes, including the transition phase. This work serves as an introductory step and focuses on Omega's applicability to three commonly used sheet materials (DP600, DP1000, and Al7075). It quantitatively analyzes their resistance to fracture failures using Single Edge Notched Tensile (SENT) tests. The potential of Omega to accurately capture critical stress/strain states and transitions was demonstrated and discussed.

2. Methodology

The SENT tests were conducted using an Instron 5967 with a 30 kN load cell and a test speed of 0.08 mm/s. The specimen geometry schematically demonstrated in Fig. 1 was determined to maximize the likelihood of transitioning to steady-state fracture propagation. A 1.5 mm straight line notch was created using wire cutting. The sheet materials DP600, DP1000, and Al7075, each with a thickness of 2 mm, were chosen for the analysis. Additionally, normal tensile tests (based on the specimen configuration in Fig. 1 but without a notch) were also performed on the three materials to assess their general mechanical responses. These responses were used as references for the subsequent discussion section.

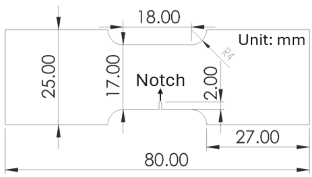


Fig. 1: SENT specimen geometrical configuration.

The Omega parameter was obtained post-testing using a handheld 3D laser scanner (Creaform HandySCAN 700) on the broken SENT specimen. Minor debris and gap scan errors were corrected using Autodesk Meshmixer's "Make Solid" function (see Fig. 2a). The repaired file was imported into Autodesk Netfabb to isolate the Volume of Interest from the unaffected volume using the pre-cut notch plane (see Fig. 1) and to conduct slicing. In Fig. 2b, a horizontal slicing plane intersected the Volume of Interest, capturing 2D profiles of the intersection areas. Starting from position 1, the slicing plane moved in 0.015 mm increments to position 2 and continued to subsequent positions to the end, producing a sequence of slices that illustrate the whole fracturing process.

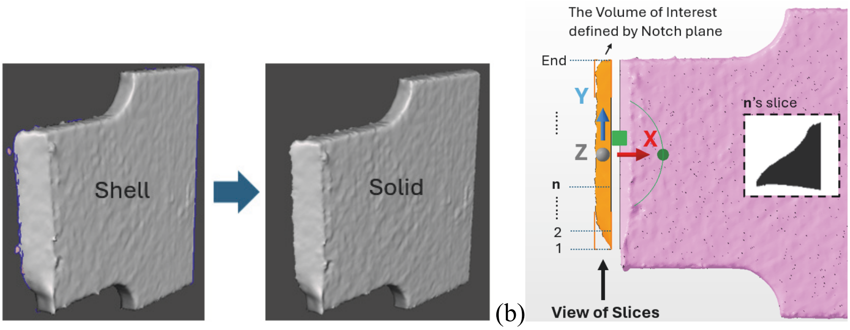


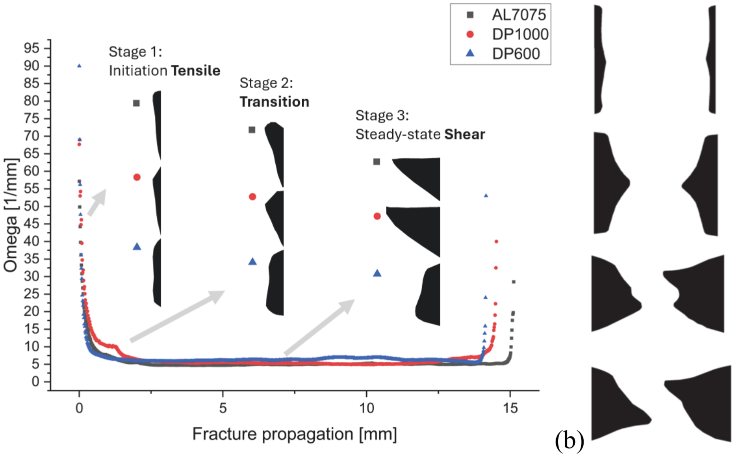
Fig. 2: (a) Sample scanning and repairing after SENT tests; (b) Defining Volume of Interest using notch plane.

The 2D profile of slice position n in Fig. 2b exemplifies such an intersection area, viewed in the direction indicated in the figure. Omega is calculated using $\Omega = L_{con}n/A_{con}n$, where L_{con} and A_{con} are the contour length and area of the 2D slice (black profile in Fig. 2b), respectively, and n is the slicing step increment, 0.015 mm for the current work.

3. Results and discussions

The Omega values covering the entire fracture process are plotted against fracture propagation in Fig. 3a, using grey squares for Al7075, red circles for DP1000, and blue triangles for DP600. For all materials, Omega values are significantly higher (in the range of 50 to 90 1/mm) at the initiation stage and then rapidly transition to a steady state shear (in the range of 5 to 7 1/mm), indicated by stable Omega values within the 2.5 to 12.5 mm fracture propagation range. The fracture process concerning different stages (tensile initiation, transition, and shear) is reflected by the evolution of 2D slice geometry. As shown in Fig. 3b, at the initiation stage (stage 1), all three materials show a "flat" tensile profile, which then enters into an intermediate phase (stage 2) where a slant shear 2D profile is forming, that finally transitions to a steady-state "slant" shear fracture propagation, as of stage 3.

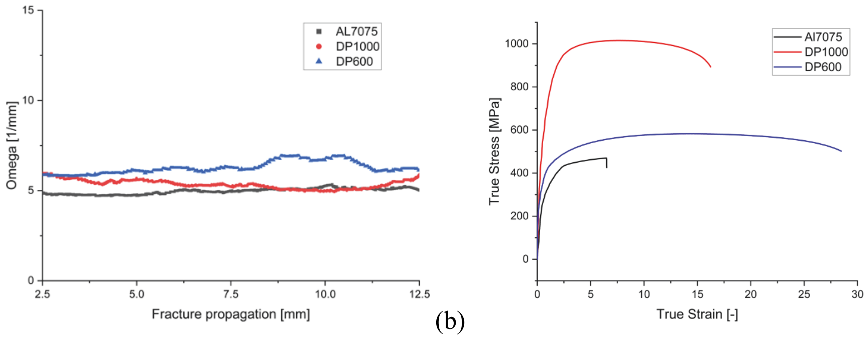
The change in fracture mode corresponds to a systemic change in stress triaxiality states, meaning that in a controlled manner, the Omega parameter could quantify fracture with respect to a wide range of critical stress triaxiality states within one test, covering both fracture initiation and propagation. This tensile-to-shear transition was also observed under dynamic conditions using SENT tests at crosshead speeds up to 20 m/s [1], see Fig. 3b.



(a) (b)

Fig. 3: (a) Omega values of Al7075, DP1000, and DP600, across the whole fracture process and their corresponding characteristic 2D profiles from tensile to shear; (b) Tensile to shear transition observed in a dynamic SENT test of line pipe steels [1].

Omega can capture the different responses of the three materials at various fracture stages. Al7075 (grey square) tends to reach stage 3 (steady-state shear) without a noticeable tensile mode (see Fig. 3a), resulting in the lowest Omega value during steady-state fracture propagation as shown in Fig. 4a. In contrast, DP600 (blue triangle) shows a dominant tensile mode in stage 2 and a mixed mode of tensile and slant shear during steady-state fracture propagation (see Fig. 3a), leading to a higher Omega value in this stage (see Fig. 4a). DP1000's response lies between these two extremes. The differences in fracture response could be correlated to the materials' general tensile behaviors shown in Fig. 4b: DP600 exhibits the highest ductility, while Al7075 shows very limited ductility. However, the correlation between tensile ductility and Omega remains qualitative in this work and is largely unexplored, suggesting an area for future research.



(a) (b)

Fig. 4: Al7075, DP1000, and DP600's (a) Omega results for steady-state fracture propagation from 2.5 to 12.5 mm. (b) Tensile stress-strain behavior without notch for reference.

4. Conclusion

This study introduced and validated the Omega parameter for assessing fracture resistance in sheet materials like DP600, DP1000, and Al7075. SENT tests demonstrated Omega's capability to capture the complete fracture process from initiation to steady-state shear propagation.

Omega covers a broad range of fracture stress states within a single test. While its quantitative relationship with stress triaxiality remains unexplored, this could be a valuable research path as highlighted in [9].

These findings underscore Omega's potential as a reliable tool for evaluating fracture resistance across various materials and stress conditions, suggesting broader applications in metal forming and sheet material assessments.

Acknowledgments

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