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QUASI-STATIC TENSILE TESTING OF HIGH-STRENGTH BALLISTIC STEEL USING DIGITAL IMAGE CORRELATION – PRELIMINARY STUDY

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1. Introduction

High-strength ballistic steels are widely used in protective structures, military vehicles, and safety equipment due to their superior strength, hardness, and energy absorption capabilities, which are essential for resisting high-velocity impacts and ensuring structural integrity [1]. While their primary application is in high-strain-rate conditions, understanding their quasi-static behavior is equally important, as it provides baseline mechanical properties for material modeling and structural performance predictions.

The mechanical response of high-strength steels is strongly influenced by factors such as microstructure, chemical composition, and strain rate. Investigations of strain localization phenomena under varying loading conditions have shown that these materials can exhibit complex deformation patterns, particularly when subjected to dynamic or quasi-static tensile loads [2].

In recent years, full-field optical measurement techniques, particularly Digital Image Correlation (DIC), have gained prominence in the characterization of metallic materials. DIC enables non-contact, high-resolution mapping of strain fields over the specimen surface, allowing for a more detailed understanding of deformation mechanisms compared to traditional measurement methods. A comprehensive review of DIC applications in laboratory structural tests confirms its versatility in evaluating mechanical behavior and identifying strain localization zones [3].

This study presents quasi-static tensile testing of a high-strength ballistic steel specimen with full-field strain measurements obtained using a Digital Image Correlation (DIC) system. The objective is to determine the material's key mechanical properties, visualize strain distribution during deformation, and provide experimental data suitable for validation of future numerical simulations.

2. Materials and Methods

The material is S1100QL, a quenched and tempered high-strength steel commonly used in protective/ballistic applications. It has a low-carbon alloyed composition with Cr–Mo–Ni additions, exhibiting typical room-temperature properties of approximately 1.1 GPa yield strength and 1.25–1.55 GPa ultimate tensile strength.

Axisymmetric threaded tensile specimens were machined from plate stock. The gauge was lightly polished, then coated with a matte white base and a fine black speckle for DIC, as shown in Fig. 1.

Fig. 1. Threaded tensile specimen (S1100QL) with DIC speckle applied to the gauge.

Tensile tests were performed on a universal Instron machine in displacement control at 0.001 mm/min, under laboratory conditions. Force and crosshead displacement were acquired and synchronized with imaging. At least five repeats were conducted to check repeatability.

Full-field strain was measured with MatchID using a monochrome industrial camera and macro lens with symmetric continuous LED lighting. DIC settings (subset/step) were kept constant across all tests and chosen according to speckle size.

Axial engineering strain was obtained from a virtual extensometer along the gauge; engineering stress was computed from the measured force and initial area. Yield strength was determined by the 0.2% offset method; localization and necking were assessed from DIC major-strain maps.

3. Experimental setup

Universal testing machine. Quasi-static tensile tests were performed on a universal Instron frame in displacement control at a very low crosshead rate (0.001 mm/min). Axial force was measured by the machine load cell; crosshead motion was used only for control.

Specimen mounting. Axisymmetric threaded specimens were gripped coaxially. A small seating load was applied before recording to remove slack and ensure alignment. The gauge section was lightly polished and prepared for optical measurements.

Digital Image Correlation (DIC). Full-field strain was measured with a MatchID system using a monochrome industrial camera and a macro lens. Four continuous LED lights were arranged symmetrically around the gauge to provide uniform, shadow-free illumination and minimize glare, as shown in Fig.2. The gauge was coated with a matte white base and a fine black speckle. Calibration was performed before testing; correlation parameters were kept constant across repeats. Axial strain for the stress–strain curves was obtained from a virtual extensometer along the gauge.

Fig.2. DIC arrangement with four continuous LED lights providing symmetric illumination of the gauge region – left; magnified - right

Synchronization and reduction. Force and images were time-aligned through the acquisition software. Engineering stress was computed from the measured force and initial cross-sectional area; the 0.2% offset method was used for yield strength. Localization and necking were assessed from DIC major-strain maps.

4. Results and Discussion

4.1 Quasi-static stress–strain response

The S1100QL exhibits a steep elastic segment followed by a short uniform-plastic regime and a pronounced post-UTS softening due to necking (Fig. 3). Five repeats overlap closely in the elastic and early plastic range, indicating stable alignment and repeatable measurement. Scatter around the peak stress is modest, and all curves show a similar transition to localization with substantial post-necking ductility. The strength levels and overall curve shape are consistent with the expected behavior of quenched-and-tempered high-strength steels tested at very low rates.

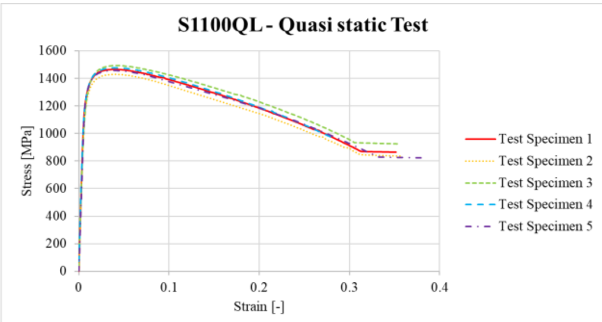

Fig. 3. Quasi-static engineering stress–strain curves for S1100QL

Fig. 3 shows the engineering stress–strain curves for S1100QL from five quasi-static tests. Strain was obtained with a DIC virtual extensometer in the gauge, and the curves are marked at the 0.2% proof stress, the UTS, and the onset of localization.

4.2 Full-field strain evolution (DIC)

DIC maps confirm a clear progression from homogeneous straining to a sharply confined neck (Fig. 4). At the start of loading, the field is essentially uniform. With the onset of plasticity, a faint axial band forms at mid-gauge and steadily intensifies. As the curve approaches UTS, this band evolves into a dominant localization zone; strain gradients steepen while the surrounding field remains comparatively low. In the last frame before fracture, the major-strain peak is strongly concentrated within a narrow region, consistent with the observed post-UTS softening on the engineering curve and with pronounced lateral contraction.

Fig. 4 presents the evolution of the DIC major-strain field at four representative instants – start of test, early plasticity (band nucleation), localization growth, and the final pre-fracture frame – plotted with a common color scale and field of view.

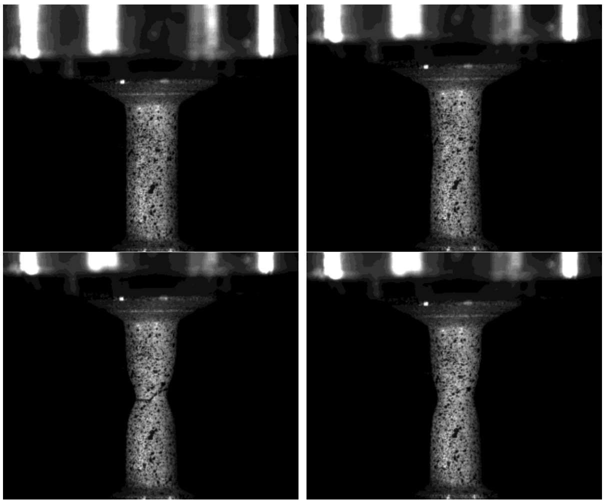

Fig. 4. DIC major-strain fields: baseline → band nucleation → localization growth → fracture (clockwise)

4.3 Necking and fracture appearance

Macroscopic inspection shows a single, centrally located neck with deformation confined to the gauge (Fig. 5). The overall appearance is consistent with ductile tensile failure controlled by localized necking typical of very high-strength Q&T steels.

Fig. 5 presents the fractured S1100QL specimen after a quasi-static test, indicating gauge-confined deformation and a single-neck failure mode.

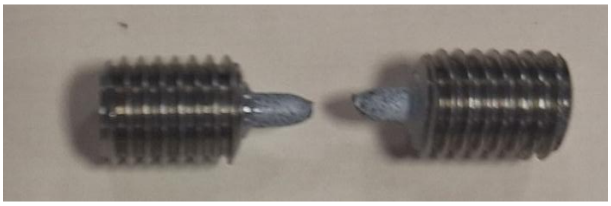

Fig. 5. Fractured S1100QL specimen; single neck centered in the gauge.

4.4 Implications for modeling

For parameter identification, the pre-necking segment of the true stress–strain curve (converted from engineering data using DIC-based strain) can be used, as it represents uniform deformation and yields robust rate-independent parameters. The onset of localization (from DIC) serves as a practical marker separating uniform from post-instability behavior. Because deformation becomes strongly confined after this point, model validation should prioritize field-level comparisons (major-strain maps and axial profiles) rather than relying on global elongation alone.

4.5 Measurement repeatability and uncertainty

Repeat tests show tight overlap in the elastic and early plastic range, and only modest scatter around the peak, indicating that the test alignment, gripping, and optical tracking were stable. Using identical DIC settings across repetitions minimized correlation-parameter bias, while four symmetric LED lights ensured uniform illumination and limited speckle glare. The remaining variability near UTS is consistent with specimen-to-specimen differences in the exact onset and sharpening of localization. Because global elongation can be biased by miniature threaded geometry, field-aware quantities (localization onset and local peak strain) together with classic strengths are emphasized.

4.6 Practical metrics for design and model calibration

For engineering use, three metrics are particularly informative and straightforward to extract from the present dataset:

- 0.2% proof stress – a conservative sizing parameter, directly read from the curves;
- UTS – an upper bound for load-carrying capacity before diffuse instability;
- Localization indicators from DIC – (i) global strain at localization onset, marking the transition from uniform to post-instability behavior, and (ii) the peak local major strain in the last frame, characterizing the severity of the neck.

In constitutive identification, the pre-necking true curve (converted using DIC-based axial strain) supports fitting rate-independent plasticity parameters (e.g., E, σ_y, and an isotropic hardening law K, n). The localization onset provides a practical delimiter for the fitting window, while the final DIC field offers a target for validating strain localization in finite-element simulations (e.g., comparison of major-strain maps and axial profiles rather than global elongation only).

5. Conclusions

Quasi-static tensile tests on S1100QL show a steep elastic response, a short uniform-plastic regime, and a rapid transition to localized necking. Full-field DIC confirmed the evolution from near-homogeneous straining to a single, centrally located neck with strongly confined major-strain just before fracture. Repeat curves overlapped closely, indicating stable alignment and measurement; the resulting strength levels and deformation pattern are consistent with the expected behavior of quenched-and-tempered high-strength steels at a very low rate. For engineering use and constitutive calibration, the pre-necking true stress–strain segment provides a reliable basis for rate-independent parameters, while DIC-based indicators – the global strain at localization onset and the peak local major strain – quantify the onset and severity of localization. These results establish a clean quasi-static baseline for S1100QL and a field-resolved reference for validating numerical simulations.

The present results are limited to very low loading rates and room temperature; as such, they establish a baseline for S1100QL under quasi-static conditions. Future work should pair these data with elevated strain-rate tests (e.g., tensile SHB) and temperature variations to cover the operating envelope used in protective applications. On the analysis side, reporting a work-to-fracture metric (area under the engineering curve up to the last frame) and a DIC-based neck width would add complementary measures of energy absorption and localization severity.

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