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# Study of local mechanical properties and deformation mechanisms of the soft zone of welded joints of high-strength steels

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**Abstract:** High-strength steels (*HSS*) are crucial in the production of lightweight structures. Their welding creates a distinct heterogeneous heat-affected zone (*HAZ*) in which a softened zone with locally lower mechanical properties forms. This critical zone acts as a weak point, concentrates strain, and can initiate failure, thereby compromising the structural integrity of the welded joint. Detailed understanding of the local behaviour of this zone is insufficiently investigated. Standard tests provide only basic data, which limits the reliability of simulations and the integrity assessment of steel structures. The article deals with the characterization of the local mechanical properties and deformation behaviour of the *HAZ* softened zone using the *DIC* (*Digital Image Correlation*) and nanoindentation techniques. The combined approach enables a comprehensive understanding of the mechanical properties of the *HAZ* subzones, crucial for assessing the reliability and integrity of welded structures.

**Keywords:** DIC analysis, nanoindentation, *HAZ*, soft zone, *HSLA* steel.

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## INTRODUCTION

Fusion welding, a widely employed technique in the manufacturing of critical engineering components, introduces significant microstructural and mechanical inhomogeneity within the *heat-affected zone (HAZ)* of welded joints. This localized region, situated adjacent to the weld fusion zone, experiences complex thermal cycles that induce variations in grain size, phase transformations, and residual stresses. A thorough understanding of the local changes in mechanical properties within the *HAZ* is essential for ensuring the reliability and integrity of welded structures, as its properties often govern the joint's overall performance and failure resistance. The performance of welded joints is of particular concern in high-strength steels (*HSS*), which are increasingly used in critical applications such as pipelines, bridges, and vehicle construction due to their high strength-to-weight ratio and improved toughness. However, the welding process can significantly alter the mechanical

properties of the *HAZ* in these steels, leading to potential weaknesses and creating initiation sites for failure.

## 1 DIGITAL IMAGE CORRELATION (DIC) ANALYSIS

*Digital Image Correlation (DIC)* is a non-contact optical technique that tracks the deformation of a material surface by comparing digital images of the surface before and after deformation. *DIC*'s ability to characterize local deformation and correlate it with microstructures makes it particularly suitable for analyzing welded joints with inhomogeneous microstructures. The heterogeneity of the *Heat-Affected Zone (HAZ)* in welded joints necessitates the use of techniques that can accurately measure local variations in mechanical properties. Traditional methods, such as tensile testing, provide average properties over a relatively large gauge length, failing to capture the localized variations within the *HAZ*

subzones. This limitation highlights the need for more refined techniques capable of characterizing the mechanical behavior at smaller length scales [1-8].

The fundamental principle of *DIC* analysis involves applying a random pattern of small spots (a speckle pattern) onto the sample's surface. This pattern is precisely monitored by a high-resolution camera during a tensile test. The first image, referred to as the reference image, is divided into small, overlapping subsets. The *DIC* algorithm then searches for the corresponding location of each subset in the subsequent deformed images. By tracking the movement of these subsets and comparing their new positions to their original ones, the *DIC* software calculates a displacement field [1-3].

There are two primary configurations of *DIC* analysis, each suitable for samples of different geometries. The first is *2D DIC*, which uses a single camera oriented perpendicular to the sample surface. This approach is suitable for planar samples, e.g., metal or plastic sheets. The second is *3D DIC*, which uses two cameras positioned to view the sample from different angles. This configuration is necessary for non-planar (e.g., curved) or complex-shaped samples. These two configurations are illustrated in Fig. 1.

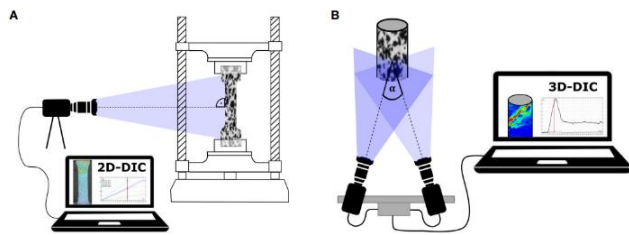


Fig. 1. Types of *DIC* analysis, a) *2D* analysis, b) *3D* analysis [13]

The usefulness of *DIC* for analysing welded joints is based on its capability to determine local strain fields, local strain rates, and to precisely localize the zone of plastic deformation onset. Furthermore, it is possible to track how the initiation and evolution of plastic deformation depend on the loading rate and the type of load applied to the sample.

Mohsen Amraei *et al.* [14] investigated the influence of heat input on the mechanical properties of butt-welded *high-strength steel* (HSS) and ultra-high-strength steel (UHSS) plates. Both *GMAW* and laser welding were employed. Figure 2 shows the stress distribution on an HSS weld sample at the point of failure, as measured by *3D DIC*. Failure of the weldment occurred in the *base material* (BM), characterized by the localization of shear bands at a 30° fracture angle.

*DIC* data can also validate numerical models of welded structures by comparing measured strain and displacement fields with model predictions, thereby assessing the accuracy of the models. The technique

is also suitable for high-temperature applications, allowing for the study of welded joint behavior under elevated temperature conditions, relevant in industries such as power generation and aerospace.

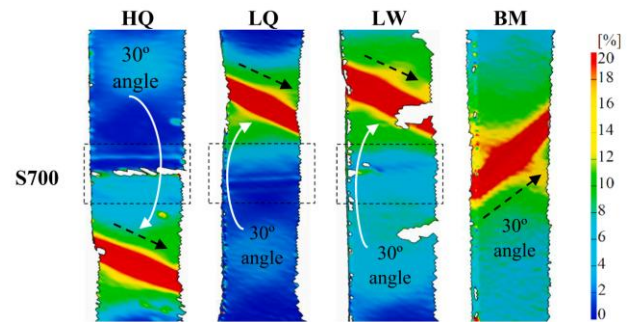


Fig. 2. *DIC* optical measurements showing distribution of strains across the specimens of weld joint of HSLA steel at the time of failure: HQ - *GMAW* with lower heat input, LQ - *GMAW* with higher heat input, LW - laser beam welding, BM - base material, dashed box - welded area [14]

## 2 NANOINDENTATION TECHNIQUE

In addition to *DIC*, nanoindentation is a technique used to evaluate localized mechanical properties at the micro- and nanoscale. Unlike traditional mechanical testing methods, which assess the bulk response of a material, nanoindentation allows for the determination of properties such as hardness and Young's modulus. This is achieved by pressing an indenter tip into the material under a controlled load while continuously measuring the resulting penetration depth. The process typically uses a diamond *Berkovich indenter*, and the displacement is precisely measured by a three-plate capacitive transducer. This technique is particularly valuable for characterizing inhomogeneous materials, thin films, and hard materials [9-12].

The basic nanoindentation process is divided into three stages:

- *approach and loading*,
- *hold*,
- *unloading*.

The process consists of three stages: loading, holding (or hold phase), and unloading (Fig. 3). During the loading stage, the indenter tip approaches the sample. Once the tip makes contact with the surface, a controlled load is applied until it reaches a predetermined maximum value. The hold phase then begins, during which the maximum load is maintained for a set period while the material may continue to deform (creep) and the displacement is measured. Finally, during the unloading stage, the load is gradually removed, and the tip is moved to the next measurement location.

The previously described load-hold-unload cycle is just one common testing procedure in nanoindentation. Other methods are also employed,

such as partial unloading, *XPM*, or roughness mapping. Each method has its specific applications.

The intended use of nanoindentation on welded joints is to determine the precise boundaries of each heat-affected zone (*HAZ*), identify its mechanical properties, and precisely localize the "soft zone". The "soft zone" in the welds of high-strength steel (*HSS*) is a region within the *HAZ* that experiences a reduction in hardness and strength compared to the base metal and the weld metal. This localized softening arises from the thermal cycle of the welding process, which induces microstructural changes in the *HAZ*.

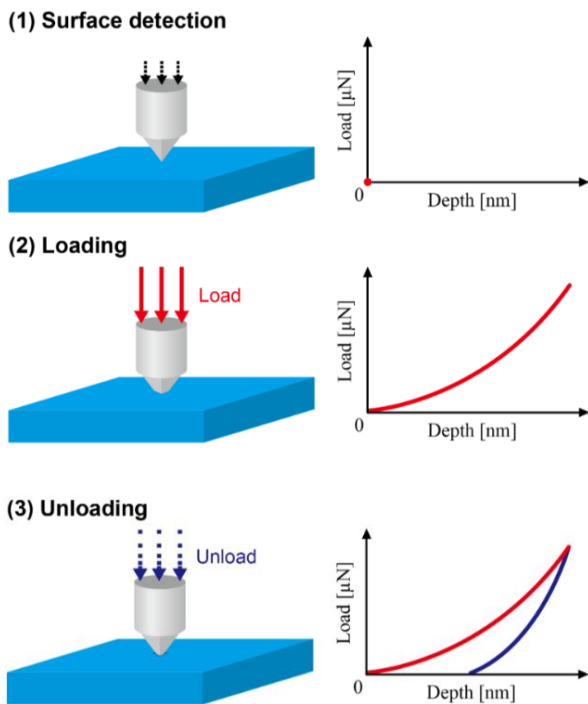


Fig. 3. Principle of nanoindentation testing [15]

The presence of a soft zone is significant, especially in the highest grades of *HSS* steels, because it can act as the weak link, reducing the overall strength of the welded joint, particularly under transverse loading. Failure is consequently more likely to initiate in this region. The width of the soft zone is influenced by welding parameters like heat input and cooling rate; higher heat input generally widens the soft zone and increases softening. The relative thickness of the soft zone compared to the base material is also a critical consideration. When the soft zone is sufficiently narrow, constraint effects from the surrounding stronger material can make it mechanically insignificant, causing the joint to behave as if the soft zone were not present.

GAO et al. [16] used nanoindentation methods to determine the *Young's modulus*, yield strength, and strain hardening exponent of individual zones in the welded joint. Nanoindentation test was performed at room temperature using the *iMicro nanoindenter* of

*KLA* company, which has a diamond *Berkovich indenter* with an elastic modulus of 1141 GPa and *Poisson's ratio* of 0.07. In all indentation tests, the fixed maximum load is 25 mN with a constant indentation strain rate of 0.2 /s, and the maximum depth is about 500 nm. Taking into account the inhomogeneity of the local mechanical properties in the welded joint, three sets of indentation tests (labelled Zone 1, Zone 2 and Zone 3) were carried out in the base metal, the heat-affected zone and the molten pool, respectively, each set of which consisted of 5×5 indenting points matrix (Fig. 4).

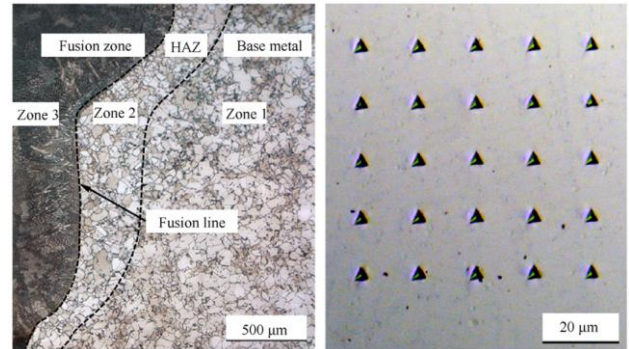


Fig. 4. Subdivided zones in a welded joint and expected indent positions on the sample surface (left), 5×5 indenting points matrix in the Zone 1 (right) [16]

The distribution of the average nanohardness value in individual weld zones is shown in Fig. 5. The lowest nanohardness value is achieved in the weld metal.

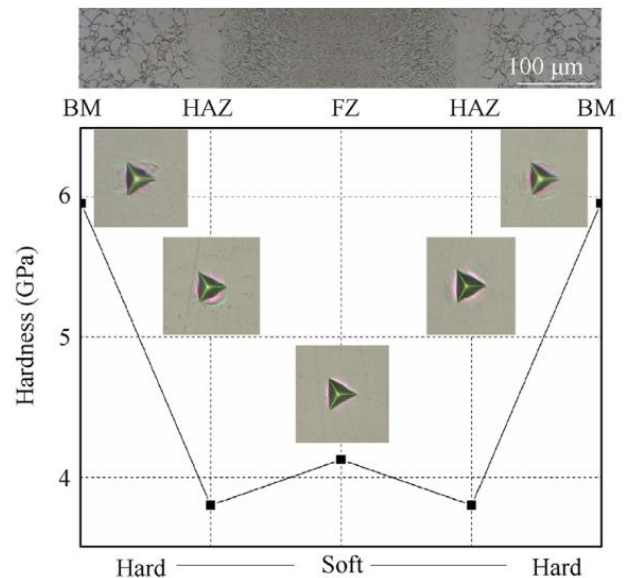


Fig. 5. Distribution of the average nanohardness value in individual weld zones [16]

## CONCLUSION

Combining *DIC* with nanoindentation provides valuable information about the behaviour of the sub-zones within the *HAZ*, especially the soft zone, which is crucial for the application of *HSS* steels. The sub-zones can be defined more precisely, and their

dependence on factors like heat input and cooling rates can be studied at the micro- and nanoscale. This understanding facilitates the optimization of welding cycles, aiming to produce welds with mechanical properties that match those of the base material.

The conclusions can be stated as follows:

- DIC can be used to determine local strain fields, local strain rates, and to precisely localize the zone of plastic deformation onset, providing key information about the mechanical properties of the sub-zones,
- DIC analysis makes it possible to track stress concentrations, identify the precise initiation point of plastic deformation, and monitor the entire deformation process,
- the use of nanoindentation on welded joints allows for the determination of precise boundaries of each heat-affected zone, the identification of its mechanical properties, and a more precise localization of the "soft zone".

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