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# Crack driving force prediction in heterogeneous welds using Vickers hardness maps and hardness transfer functions

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ABSTRACT

Flawed welds often require an Engineering Critical Assessment (ECA) to judge on the necessity for weld repair. ECA is a fracture mechanics based prediction of the integrity of structural components with defects under operating conditions. Adding to the complexity of a weld ECA is the occurrence of local constitutive property variations in the weldment ('weld heterogeneity'). Their quantification allows for a more accurate assessment compared to common (standardized) practice, which assumes welds to be homogeneous. Hardness measurements allow to quantify weld strength heterogeneity given their theoretical relation with ultimate tensile strength. However, various standards and procedures report a wide variety of relations ('transfer functions') between hardness and strength, and recognize substantial scatter in hardness based predictions of strength. Within this context, this paper investigates the suitability of Vickers hardness mapping to perform an accurate weld ECA for high strength low alloy steel. To overcome the scatter associated with standardized transfer functions, this paper suggests an experimental calibration procedure based on all weld metal tensile tests. Finite Element (FE) analysis has been conducted on welds originating from steels to simulate their crack driving force response in Single-Edge notched Tension (SE(T)) specimens. Vickers hardness maps and hardness transfer functions are combined to assign element-specific constitutive properties to the model. The transfer function calibrated by all weld metal tensile tests yields a better agreement with experimental load-CTOD curves than transfer functions mentioned in standards and codes. Finally, a step-by-step procedure facilitates a practical adoption of the methodology.

## 1. Introduction

Engineering Critical Assessment (ECA) is a fracture mechanics based analysis of the integrity of a structure in presence of a defect. ECA involves the quantification of crack driving force (for instance expressed in terms of Crack Tip Opening Displacement – CTOD) on the basis of load, material, geometry and defect characteristics. Very often, ECA is applied to welds when detected flaws are rejected by rules of good workmanship. Standardized ECA procedures are for instance stipulated in BS 7910 [1,2], API 579 [3], R6 [4,5], SINTAP [6] and FITNET [7]. A main drawback common to all procedures is that they consider the defect to be surrounded by homogeneous material. Although this assumption is reasonably valid for a base metal, it involves an approximation for weld defects. In such case, local strength and toughness variations in weldments arise due to the application of numerous heat cycles (heating and cooling) during welding. The quantification of this heterogeneity is a challenge given its unique and distinct character for each weld

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**Nomenclature**

| | |
|---|---|
| $\sigma$ | true stress (MPa) |
| $\varepsilon$ | true strain (–) |
| $\sigma_y$ | true yield strength (MPa) |
| $\varepsilon_y$ | true yield strain (–) |
| $\alpha$ | yield offset (–) |
| $n$ | strain hardening exponent |
| $R_{p02}$ | 0.2% proof stress (MPa) |
| $R_{p02(AWMTT)}$ | 0.2% proof stress obtained from all weld metal tensile tests (MPa) |
| $R_m$ | ultimate tensile strength (MPa) |
| $R_{m(AWMTT)}$ | ultimate tensile strength obtained from all weld metal tensile tests (MPa) |
| $Y/T$ | yield to tensile ratio ($R_{p02}/R_m$) |
| $E$ | Young's modulus (MPa) |
| $P$ | tensile force (kN) |
| $HV$ | Vickers hardness |
| $HV_{AWMTT}$ | Vickers hardness obtained by averaging HV from the region of AWMTT extraction |
| $CTOD$ | crack tip opening displacement (mm) |
| $SE(T)$ | (clamped) Single-edge notched tension specimen |
| $AWMTT$ | all weld metal tensile test |
| $ECA$ | engineering critical assessment |

procedure.

The measurement of Vickers hardness (HV) is one of the most common techniques to evaluate local strength properties within a weld sample. Vickers hardness is known to relate to ultimate tensile strength $R_m$ and the equation expressing such relation is referred to as a *'hardness transfer function'* (or simply *'transfer function'* in this paper). Conceptually, transfer functions may also be constructed between hardness and yield strength (expressed here as 0.2% proof stress $R_{p02}$), and strain hardening, thus covering the entire stress-strain behaviour. The constitutive law of the weld material is represented by Ramberg-Osgood (RO) equation [8]:

$$\frac{\varepsilon}{\varepsilon_y} = \frac{\sigma}{\sigma_y} + \alpha\left(\frac{\sigma}{\sigma_y}\right)^n \tag{1}$$

Here, $\sigma$ and $\varepsilon$ represent true stress and strain while $\sigma_y$ and $\varepsilon_y$ represents yield strain (equal to $\sigma_y/E$, $E$ being Young's modulus). $\alpha$ is a yield offset parameter, where $\alpha\varepsilon_y = 0.002$ to set $\sigma_y$ as the 0.2% proof stress, and $n$ is the strain hardening exponent. Despite the availability of transfer functions for different materials and welds, a generic method to obtain material properties using HV values considering local constitutive property variations in weldments is lacking. Standards and procedures such as [7,9,10] provide equations for conversion of HV to material parameters ($R_{p02}$, $R_m$, etc.), which have been derived statistically from a large experimental database. Actual relations between hardness and strength are scattered and can substantially differ from the provided (average) relations.

In this research, we assess the ability of standard transfer functions to predict the crack driving force response of cracked specimens based on hardness information. The study focuses on welds connecting high strength low alloy steel. Along with this, we put forward a technique to bypass HV conversion using standardized ('average') transfer functions and instead propose an alternative method based on experimental calibration of the hardness transfer function. In order to evaluate the approach, numerical models of Single Edge notched Tensile (SE(T)) specimens are utilized and the model is validated by means of experiments.

The paper is structured as follows. In Section 2, a brief background on hardness transfer functions is given. Section 3 gives a detailed description of numerical and experimental techniques used in this work. This section also puts forward combinations of different transfer functions used to obtain material properties from HV values. Section 4 discusses the accuracy of SE(T) simulations assuming different hardness transfer functions, relative to experimental data. Section 5 concludes this research.

## 2. Background

The early work of Tabor [11] reported on relations between hardness and constitutive properties. Hardness was found to be in relation to the stress at a representative strain level, which is around 0.08 for a Vickers indenter. Given the typical ductility levels and strain hardening characteristics of high strength low alloy steel, this stress is close to the ultimate tensile strength $R_m$. Therefore, HV has very often been used to estimate $R_m$. As HV measurement fails to provide the full range of strain hardening behaviour, the approximate nature of these estimates is acknowledged and quantified in the standard ISO 18265 [9]. This standard contains tabulated conversion data between HV, $R_m$ and allows to construct scatter bands.

Another relevant international standard is ISO 15653 [10], which mentions $HV$ transfer functions for weld and base metal separately. Unlike ISO 18265, it also mentions relations between hardness and yield strength (additional to ultimate tensile strength). For instance, reported transfer functions for weld metal are:

$$R_{p02} = 2.35\,HV + 62 \tag{2}$$

$$R_m = 3.0\,HV + 22.1 \tag{3}$$

Researchers have independently constructed hardness transfer functions for their specific purposes. For instance, Hertelé et al. [12] termed hardness as a tool to produce realistic (but not necessarily the actual) local stress-strain properties of fusion welds with variable yield strength and strain hardening behaviour. They considered power law hardening according to the Ramberg-Osgood equation (Eq. (1)) and determined its parameters (yield strength $\sigma_y$, yield strain $\varepsilon_y$, strain hardening exponent $n$ and yield offset $\alpha$) as follows:

Ultimate tensile strength ($R_m$) was calculated using hardness values according to a linear regression fit of conversion data for steel