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ESTIMATION OF LOW-CYCLE FATIGUE CURVES OF HIGH-STRENGTH AND WELDED STEEL 10CrNi3MoV

ODHAD NÍZKOCYKLOVÝCH KRIVIEK ÚNAVOVEJ ŽIVOTNOSTI VYSOKOPEVNOSTNEJ A ZVÁRANEJ OCELE 10CrNi3MoV

Abstract

In this work is tested applicability of the extended uniform material law for high-strength steel on 10CrNi3MoV steel and its weld. Predicted low-cycle fatigue curves differ significantly from the measurements. Despite the reported scientific effort to predict fatigue properties numerically, results show that strain controlled fatigue tests must be conducted for determination of fatigue properties in the praxis.

Abstrakt

V tejto práci je testovaná využiteľnosť rozšíreného zjednocujúceho pravidla pre vysokopevnostnú oceľ 10CrNi3MoV a jej zvarok. Predpovedané nízkocyklové krivky únavovej životnosti sa líšia podstatne od meraní. Napriek zdokumentovanému vedeckému úsiliu pri predikcii únavových charakteristík výpočtovo, výsledky ukazujú, že deformačne riadené únavové skúšky sa musia vykonať pre stanovenie únavových charakteristík v praxi.

Keywords

low-cycle fatigue, high-strength steel, undermatched weld, extended uniform material law, fatigue properties prediction.

1 INTRODUCTION

Low-cycle prediction is based on strain-based fatigue analysis and it is based usually on uniaxial tests [1]. However, these tests are time and cost expensive [1-2]. The situation is even more complicated in case of multiaxial [1] and non-proportional loading [3]. Hence, there was an effort to estimate fatigue properties from simple tensile data by developing methods like the four-point method, universal slope method, the uniform material law (UML) or four-point correction method - summarization can be found for instance in [4]. Recently, there was an attempt to estimate multiaxial life prediction in absence of any fatigue properties [5] or in a fact statistical evaluation of cyclic-stress strain parameters from monotonic properties of steel [2] that have influence on estimation of fatigue properties as it will be shown further in the paper.

Undermatched welds are welds with lower yield strength or ultimate strength than base material [6-7]. Undermatched welds are usually used as joints with high-strength steel in order to minimize hydrogen cracking tendency and reduce or even exclude preheating operation [7].

It seems to be lack of the information about the fatigue behaviour of high-strength steel and its undermatched weld or an effort to estimate their fatigue properties numerically. Therefore, the aim of

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the paper is an estimation of the fatigue properties of high-strength steel 10CrNiMoV and its undermatched weld numerically by extended uniform material law for high-strength steel (E-UML).

The novelty of the paper can be viewed from the practical (engineering) point of view. According to the author experiences, finite element analysis is nowadays spread also in the relatively small companies. Such small "computational" or production companies can lack of material testing facilities and overestimate design by using high safety factors. This paper shows clearly a necessity of proper material testing procedure despite the developed computational schemes.

Material is introduced in Chapter 2. Chapter 3 is devoted to E-UML and Chapter 4 presents results and discussion.

2 MATERIAL

Material data is taken from [8] where 16 mm high strength rolled, quenched and tempered steel plate of 10CrNi3MoV was examined. Undermatched weld was produced on fatigue specimens by the gas metal arc welding with multiple passages of the (undermatched) electrodes [8]. Low-cycle fatigue tests were conducted according to ASTM E606 standard in the referenced paper [8].

Tab. 1 shows the chemical composition of 10CrNi3MoV and undermatched weld according to [8]. Tab. 2 shows welding conditions applied on the fatigue specimens [8].

Tab. 1 Chemical composition (in %) of 10CrNi3MoV and undermatched weld. [8]

	C	Si	Mn	Cr	Mo	Ni	Cu	V	S	P
10CrNi3MoV	0.09	0.29	0.48	0.94	0.4	2.88	-	0.06	0.005	0.011
Undermatched Weld	0.027	0.243	1.3	0.051	-	1.09	0.05	-	0.0073	0.011

Tab. 2 Welding conditions applied on the fatigue specimens. [8]

Current[A]	Voltage [V]	Welding speed [mm/s]	Electrode diameter [mm]	Shielding Gas 80%Ar-20%CO_2 [L/min.]	Heat input [KJ/mm]	Interpass temperature [°C]
140-190	24-28	4.5.5.3	1.2	20	0.7-0.85	<80

Basic mechanical properties can be obtained from Fig. 1 and the reader is for more details referred to [8].

3 EXTENDED UNIFORM MATERIAL LAW FOR HIGH-STRENGTH STEEL

UML has been extended about high strength steel (E-UML) [9] and later about cast iron (UMCLI)[10]. Parameters, constants and coefficients are in E-UML defined as [9-10]:

$$\Psi = 0.5\{\cos(\pi)[(R_m - 400)/2200] + 1\}, \tag{1}$$

$$\sigma_f^{/} = R_m(1 + \Psi), \tag{2}$$

$$\varepsilon_f^{/} = 0.58\Psi + 0.01, \tag{3}$$

$$\sigma_E = R_m(0.32 + \Psi/6), \tag{4}$$

$$b = -\log\left(\sigma_f^{/} / \sigma_E\right) / 6, \tag{5}$$

$$c = -0.58, \tag{6}$$

$$n^{/} = b / c, \tag{7}$$

$$K^{/} = \sigma_f^{/} / \left(\varepsilon_f^{/}\right)^{n^{/}}, \tag{8}$$

where:

Ψ – cosinusoidal function $[\text{-}]$,

R_m – ultimate tensile strength $[\text{MPa}]$,

$\sigma_f^{/}$ – fatigue strength coefficient $[\text{MPa}]$,

$\varepsilon_f^{/}$ – fatigue ductility coefficient $[\text{-}]$,

σ_E – endurance stress $[\text{MPa}]$,

b – fatigue strength exponent $[\text{-}]$,

c – fatigue ductility exponent $[\text{-}]$,

$n^{/}$ – cyclic strain hardening exponent $[\text{-}]$,

$K^{/}$ – cyclic strength coefficient $[\text{MPa}]$.

Above equations were implemented in Python programming language. Computed values are compared for $R_m = 800$ MPa with the literature [9]. Results are summarised in Tab. 3.

Tab. 3 Verification of the Python implementation ($R_m = 800$ MPa). Computed results are exactly same as the literature [9] assuming same rounding of the number.

Source	Ψ [-]	$\sigma_f^{/}$ [MPa]	$\varepsilon_f^{/}$ [-]	σ_E [MPa]	b [-]	c [-]	$n^{/}$ [-]	$K^{/}$ [MPa]
[9]	0.92063	1537	0.544	379	-0.10136	-0.58	0.175	1709
Current	0.92063	1537	0.544	379	-0.10136	-0.58	0.175	1709

4 RESULTS AND DISCUSSION

Fig. 1 shows engineering monotonic and cyclic stress-strain curves. Fig. 1a shows results for steel 10CrNi3MoV and Fig. 1b shows results for its undermatched weld. Lit. Data represents measured data up necking point from the tensile test published in [8], Monotonic represents curve fitting by the least square minimization algorithm used in the python library scipy.optimize. Following function has been used for the fitting:

$$y = ax^b . \tag{9}$$

Lit. Monotonic represents fitting done by same function in [8] (see coefficients in Tab. 4 for the equation (9) in the form of $\sigma_a = K^* \varepsilon_a^{n^*}$). Cyclic represents calculated cyclic stress-strain curve by E-UML. Lit. Cyclic represents fitted curve from stable hysteresis curve peaks presented in [8] (see coefficients in Tab. 4 for the equation (9) in the form of $\sigma_a = K^{/} \varepsilon_a^{n^{/}}$).

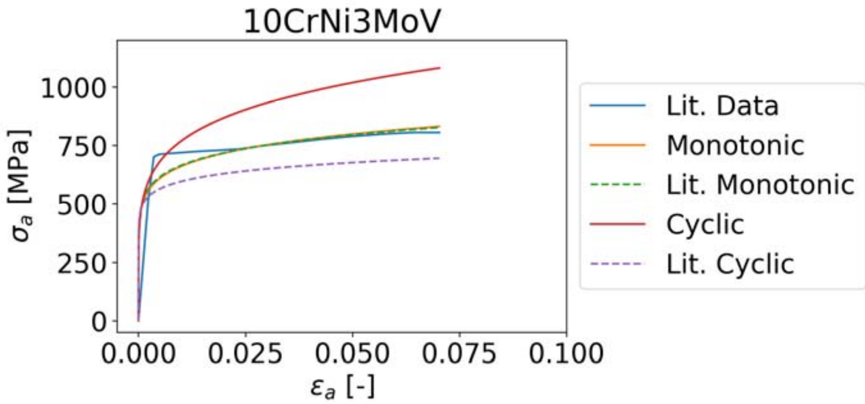

Fig 1a Engineering stress-strain monotonic and cyclic stress-strain curves of 10CrNi3MoV steel. Literature data ("Lit. Data") is taken from [8]. "Lit. Monotonic" and "Lit. Cyclic" are computed using the coefficients from [8] (see Tab. 4).

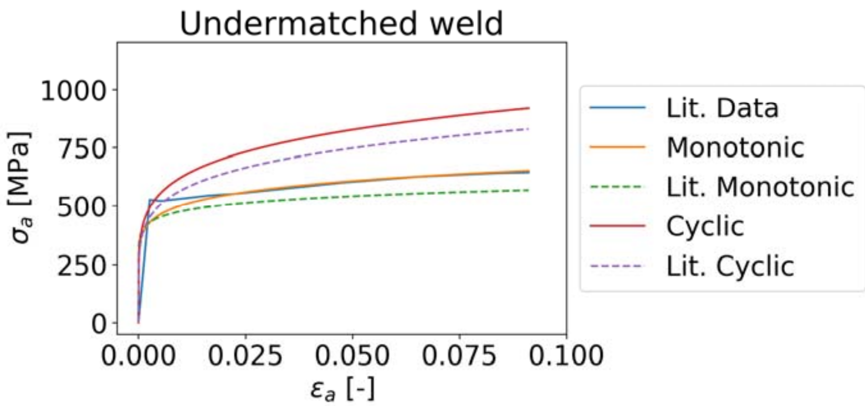

Fig 1b Engineering stress-strain monotonic and cyclic stress-strain curves of undermatched weld. Literature data ("Lit. Data") is taken from [8]. "Lit. Monotonic" and "Lit. Cyclic" are computed using the coefficients from [8] (see Tab. 4).

Monotonic fitting is very well done in Fig. 1a and Fig. 1b. The literature fitting underestimates measured curve in Fig 1b. The cyclic curve computed by E-UML is wrongly predicted in Fig. 1. The error is lower in Fig. 2b than in Fig. 2a. 10CrNi3MoV steel is cyclically softened in the reality but E-UML predicts cyclic hardening, Fig 1a. Cyclic hardening is predicted correctly for Undermatched weld, Fig. 1b. It can be concluded that E-UML is very sensitive on the data and predicts cyclic curve wrongly. Fitting and computed coefficients are summarized in Tab. 4. No coefficient of determination R^2 is evaluated.

Tab. 4 Fitting and computed coefficients of monotonic and cyclic engineering stress-strain curves. Monotonic coefficients K^* and n^* are in "Current" computed by the curve fitting, see equation (9) and cyclic coefficients $K^{/}$ and $n^{/}$ are computed by E-UML.

Source	10CrNi3MoV				Undermatched weld			
	K^* [MPa]	n^* [-]	$K^{/}$ [MPa]	$n^{/}$ [-]	K^* [MPa]	n^* [-]	$K^{/}$ [MPa]	$n^{/}$ [-]

[8]	1113	0.112	857.16	0.079	685.99	0.079	1251.8	0.172
Current	1135	0.117	1719.21	0.175	863.75	0.118	1399.3	0.178

Fig. 2 shows low-cycle fatigue curves. Fig. 2a shows results for steel 10CrNi3MoV and Fig. 2b shows results for its undermatched weld. Low-cycle fatigue curves are computed following [2,4,8] as:

$$\varepsilon_a = \varepsilon_{el} + \varepsilon_{pl} = \frac{\sigma_f^{/}}{E}\left(2N_f\right)^b + \varepsilon_f^{/}(2N_f)^c \,, \tag{10}$$

where:

ε_a – half of the total strain range [-],

ε_{el} – half of the elastic strain range [-],

ε_{pl} – half of the plastic strain range [-],

E – Young's modulus $[\mathrm{MPa}]$; 10CrNi3MoV = 205 000 MPa, undermatched weld = 195 000 MPa,

$2N_f$ – number of reversal to failure.

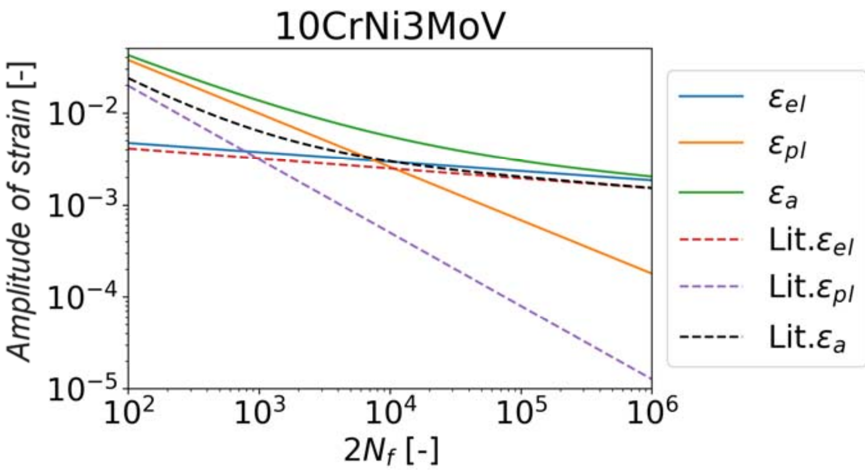

Fig 2a Low-cycle fatigue curves of 10CrNi3MoV steel. Literature data ("Lit. ε_{el}"; "Lit. ε_{pl}"; "Lit. ε_a") is taken from [8].

Low fatigue curves are wrongly estimated in Fig 2. E-UML overestimates significantly half of the plastic strain range ε_{pl} for 10CrNi3MoV steel as well as for undermatched weld, Fig. 2. Differences are bigger for 10rNi3MoV steel (Fig. 2a) than for undermatched weld (Fig. 2b). Half of the elastic strain range ε_{el} and resulting half of the total strain range ε_a is also wrongly predicted. Resulting coefficients are listed in Tab. 5.

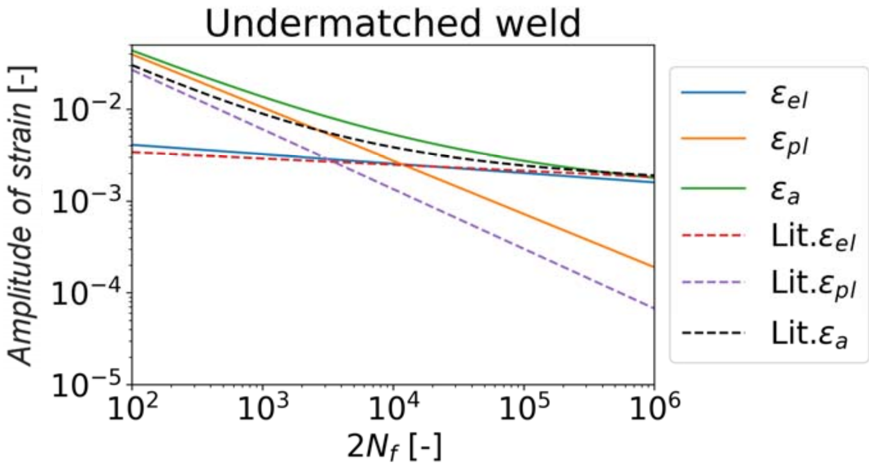

Fig. 2b Low-cycle fatigue curves undermatched weld. Literature data ("Lit. ε_{el}"; "Lit. ε_{pl}"; "Lit. ε_a") is taken from [8].

Tab. 5 Fitting and by E-UML computed coefficients low-cycle fatigue curves

Source	10CrNi3MoV				Undermatched weld			
	$\sigma_f^{/}$ [MPa]	b [-]	$\varepsilon_f^{/}$ [-]	c [-]	$\sigma_f^{/}$ [MPa]	b [-]	$\varepsilon_f^{/}$ [-]	c [-]
[8]	1386.4	-0.108	0.779	-0.798	896.9	-0.067	0.5351	-0.65
E-UML	1545.1	-0.101	0.543	-0.58	1268.6	-0.102	0.573	-0.58

The measured and predicted results differ significantly, Fig. 2 and Tab 4.and 5. Differences can be assumed because the production technologies affect the fatigue life [11-15]. However, it is assumed that the high-strength steel 10CrNi3MoV from [8] lies as a base material outside the heat affected zone (HAZ). Nevertheless, low-fatigue curves are wrongly predicted by E-UML Additionally, cyclic softening is wrongly for base material 10CrNi3MoV. E-UML takes for calculation of cyclic and fatigue properties into account only the ultimate tensile strength. Fatigue ductility exponent is constant value -0.58. For comparison, UML and modified universal slope method gives very similar value -0.58, -0.56 respectively for other types of steel [1]. In [2] was shown that dividing materials to the groups (unalloyed, low-alloyed, high-alloyed) can at least bring correct estimation of the cyclic properties. Similar conclusion was drawn for ferritic steel in [16]. Current results do not support those statements and it seems to be no valid method for estimation of cyclic and fatigue properties. Hence, the experimental results as they are presented for instance in [3] or [17] are inevitable in order to predict fatigue life of the loaded components in the praxis.

5 CONCLUSIONS

Applicability of the extended uniform material law for high strength steel (E-UML) is evaluated on high strength steel 10CrNi3MoV and its undermatched weld. Stress-strain and fatigue curves predicted by E-UML differ substantially from the literature measurements. Prediction of the fatigue characteristics must be conducted hand on hand with strain controlled fatigue tests in the praxis.

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