

Experimental Investigation of High-Strength Structural Steel Welds

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Material toughness becomes more significant material mechanical property, as well as design variable with recent advances of fracture mechanics understanding. Also, toughness is a particularly important parameter for novel structural materials such as high-strength steels. Furthermore, due to the fact that high-strength steels are mainly used in various welded structures, evaluation of welded joint mismatched properties, including toughness, become particularly important. Therefore, the following paper presents investigation results of impact and quasi-static toughness distribution and mismatch on high-strength steels welds. Welded joint's characteristic heterogeneous zones are obtained by mean of real welding and welding simulation. Finally, relation terms between various mechanical properties, including toughness, for further simplified engineering prediction are provided.

Keywords: toughness, fracture mechanics, high-strength steel, welds, mismatch.

0 INTRODUCTION

Benefits of high-strength steels, HSS, are well known. However, to meet the necessary design and exploitation requirements for various steel structures, a number of factors must be considered when selecting HSS. These factors should include at least a reduced deformability, weldability and demanding toughness. Moreover, due to the unfavourable yield stress to tensile strength ratio, Y/T , and reduced ductility, those steels are mostly not allowed for use for some demanding steel structures due to the limitations set in design codes [1] to [4]. Development of novel structural integrity assessment procedures based on fracture mechanics, such as the international FITNET procedure [5], a more reliable and confident assessment is possible for various types of structures. Here, the important property of materials, particularly of welded joints, the presence of material flaws, such as cracks, as well as material toughness and components stress state are required to assess particular component for a level of integrity. Moreover, there is a trend in national specifications, and in some international design codes for a particular type of structures, to apply fracture mechanics methods already in a design phase [6] and [7]. Furthermore, there is a trend that conventional qualification of welding procedures may require additional testing of fracture mechanics parameters on test coupons [5] to [7]. Never the less, a general toughness of high-strength structural steel present particular issue. However, toughness should be considered from the point of predicted or design loads. Therefore, according to fracture mechanics

principles, at least the following toughness parameters should be considered [5] and [8]:

- Quasi-static toughness, represented by elasto-plastic fracture mechanics, *EPFM*, resistance curves, e.g. $J-\Delta a$ or $CTOD-\Delta a$; where J is J -integral in $[kJ/m^2]$, $CTOD$ is crack tip opening displacement in $[mm]$ and Δa is crack growth in $[mm]$; and characteristic initiation or materials critical values, e.g. J_{Ic} $[kJ/m^2]$, $CTOD_{Ic}$ $[mm]$; as well as linear-elastic fracture mechanic parameter, *LEFM*, fracture toughness, K_{Ic} $[MPa \cdot m^{0.5}]$.
- Impact toughness, represented by resistance curves, $KV-T$ or $DL-T$; where KV is total impact absorbed energy in $[J]$, DL is percentage of shear fracture in $[\%]$, and T is testing temperature in $[^{\circ}C]$; and therefore characteristic transition temperatures (depending on applied criteria), T_T in $[^{\circ}C]$. In addition, KV , may be evaluated for its parts, the so called crack initiation energy, KV_i $[J]$ and crack propagation energy, KV_p $[J]$. Determination of KV_i and KV_p are also based on one kind of resistance curve, e.g. $F-t$, where F is impact force in $[N]$ and t is time in $[s]$ [4].

Furthermore, from the point of fracture mechanics and structural assessment procedures [5] to [10], a higher confidence and less conservatism may be achieved if material resistance properties, as well as applied stress condition are better known. Here, another problem arises: Can sophisticated experimental evaluation of various fracture mechanics parameters, as well as stress state be performed? Therefore, from the point of the fracture mechanics parameters evaluation, novel assessment procedures

recognize approximation or relationship terms to evaluate rather “complicated” parameters, on basis of “simplified” ones. Even this paper does not deal with evaluation of stress state; various analytical and numerical approaches for evaluation of stress state are known.

It is not an intention of this paper to underestimate other general material toughness parameters, such as those related to dynamic-cyclic loads, e.g. material fatigue resistance, and corresponding fatigue resistance curves and appropriate critical values represented in known $da/dN - \Delta K$ format, where da/dN is fatigue crack growth rate, e.g. da in [mm] and dN in [cycles] are crack growth and number of cycles, respectively, and ΔK [$\text{MPa}\cdot\text{m}^{0.5}$] is stress intensity factor.

Furthermore, because HSS are mainly used for the manufacturing of welded structures, welded joints resistance properties become particularly important. Here, well known microstructural heterogeneity and mismatch of mechanical properties of a complete joint must be carefully considered and evaluated. In addition, because welded joint presents typical structural joints with generated micro and macro faults (considered as cracks), the need for the application of fracture mechanics arises.

Therefore, this paper shows approach and experience on selected toughness properties investigation of HSS welds.

1 EXPERIMENTAL PROCEDURE

Similarity to the tests in [11] and [12], which have evaluated the hardness of quenched and tempered (QT) steels for particular machine elements, related to cooling time $t_{8/5}$ [13], as well as research work of structural steels in [1], this research has also considered and investigated two HSS QT steels: S690QL and S890QL according to EN 10025-6 (Q for quenched and tempered delivery condition; L for the required impact toughness of 27 J at -40°C). On each steel, pairs of test coupons are butt welded, in PA (flat) position, using gas metal arc welding, GMAW, process and 82% Ar + 18% CO_2 shielding gas. Generally, described welding conditions are shown in Table 1. Filler materials (FM), delivered in accordance to EN 12534 [14], were G 69 5 M Mn3Ni1CrMo for S690QL, and G 89 6 M Mn4Ni2CrMo for S890QL, of 1.2 mm diameter, are selected on the basis of recommendation of a respective manufacturer. In fact, the FM was of a similar class (chemical composition and weld metal mechanical properties [2] and [14])

as the base materials (represented with carbon equivalent, CET, as shown in Table 1).

Table 1. Welding conditions

steel	thickness	preheat	Q	$t_{8/5}$	CET_{BM}
S690QL	30 mm	200 °C	1.4 to 1.8 kJ/m	6 to 8 s	0.306
S890QL	20 mm	150 °C			0.350

In Addition to specimens with an initial crack in the base, BM, and weld metal, WM, for evaluation of quasi-static toughness, an additional set of specimens for the evaluation of impact toughness is prepared with an initial notch in the base and weld metal, as well as in a heat affected zone, HAZ. The selection of welding parameters was made on the basis of good engineering experiences and a general recommendation given in EN 1011-2 [1], [4] and [13], as well as on the basis of steel manufacturer recommendation, based on the optimum cooling time concept, e.g. $t_{8/5}$, in range of 5 to 15 s. Typical specimen sampling plan is shown in Fig. 1.

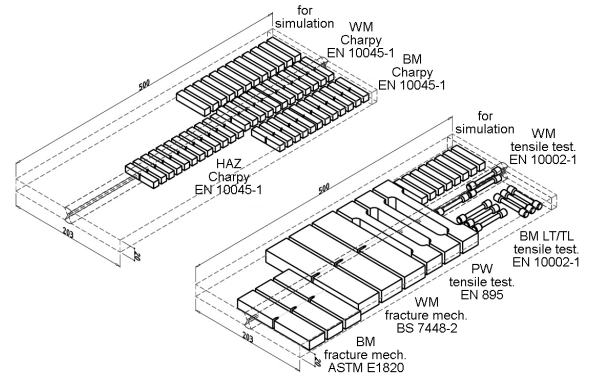


Fig. 1. Example of specimen sampling plan for the pairs of welded test coupons on steel S890QL

Due to the fact that a well known weakest weld zone within coarse-grain heat affected zone, CG-HAZ, cannot be evaluated from real welds; additional specimens for welding simulation, and further impact toughness testing were prepared. Welding simulation was performed on thermo-mechanical simulator SmithWeld, in a condition similar than for real welding, e.g. for CG-HAZ with $T_{max} = 1300^\circ\text{C}$, and $t_{8/5}$ in range of 6 to 7 s (as shown for real welding on Table 1). In fact, the welding simulation correspond to the determined input thermo-cycle (T_{max} , $t_{8/5}$) [4]. Fig. 2 shows the applied thermo cycle for the welding simulation, as well as representative specimen during simulation.

Necessary initial testing consisting of chemical composition testing, hardness distribution testing and

tensile testing were also performed. In addition, even if it is not a subject of this paper, the microstructural evaluation of complete weld joints was performed. Briefly, base metal consists of tempered martensitic microstructure; weld metal consists of dendrite low carbon martensitic microstructure, while HAZ consist of a mixture of martensitic-ferite-bainite microstructure. Appropriate weld joint hardness distribution is shown in Fig. 3. Therefore hardness mismatch, MM, or exactly the undermatching, UM, between weld and base metal, WM/BM, was in the range of $MM_{HV} = UM_{HV} = 0.97$ to 0.99 . for both steel's welded joints.

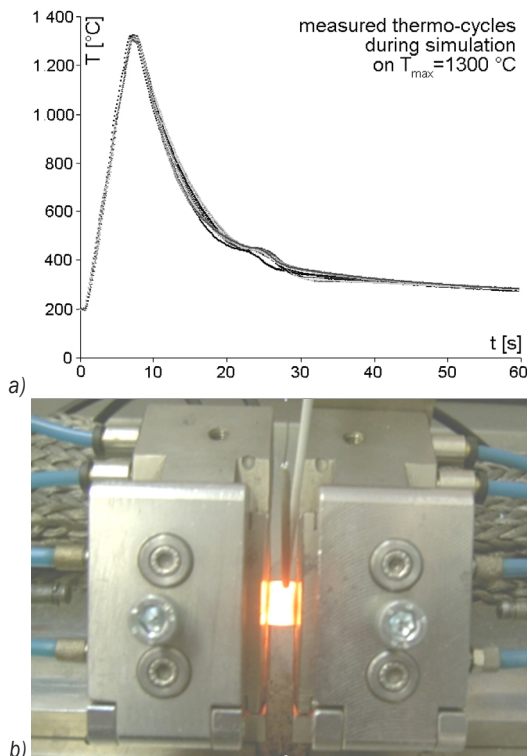


Fig. 2. a) Applied (measured) thermo cycles and b) typical specimen during welding simulation

In addition, results of tensile testing Fig. 4. show the following mismatch of strength and ductility, between weld and base metal, for both steel's weld joints:

- for yield stress, $MM_{R_{p0.2}} = 0.89$ to 0.96 ,
- for tensile strength, $MM_{R_m} = 0.93$ to 0.95 ,
- for cross-section contraction, $MM_z = 0.85$ to 0.92 .

Moreover, the general range of yield stress to tensile strength ratio, for both steel, for BM and WM, was found to be in the range of $Y/T = 0.89$ to 0.96 .

Welded joints macro sections as well as corresponding hardness distribution, tested in accordance to EN 1043-1 [15] are shown in Fig. 3.

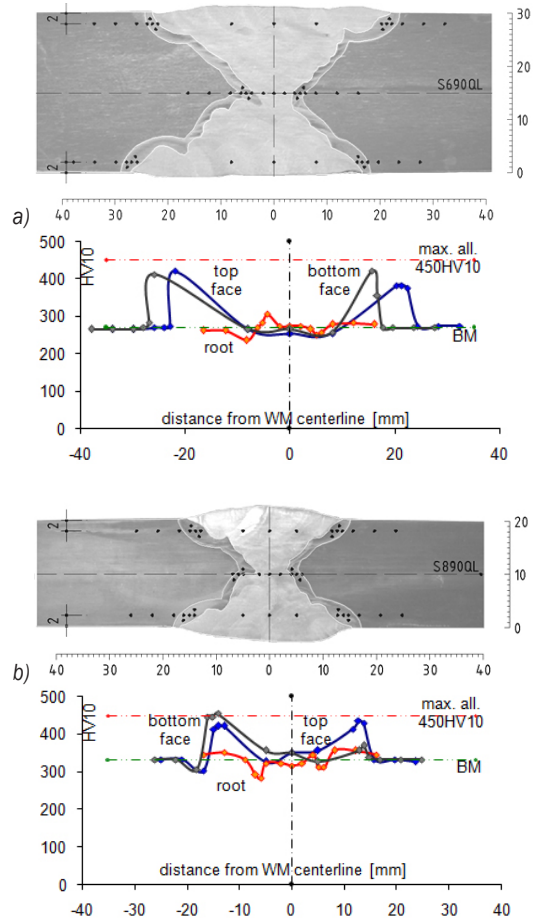


Fig. 3. Welded joints macro section and hardness distribution; a) welded joint on S690QL, b) welded joint on S890QL

The resistance stress-strain curves, $R-A$ Fig. 4, designated as PW present the results for specimen sampled perpendicular to the line of the welded joint. Testing of such specimen is common for the welding procedure qualification.

2 RESULTS OF TOUGHNESS TESTING

Typical resistance curves, $F-t$, of impact toughness testing using instrumented Charpy pendulum are shown in Fig. 5. The corresponding results of impact toughness testing on various testing temperatures are shown in Fig. 6.

The impact toughness testing were done in acc. to EN 10045-1 [16], while EPFM parameter testing was done in acc. to ASTM E1820 [9] and BS 7448-2 [10]. Each impact toughness specimen testing has provided

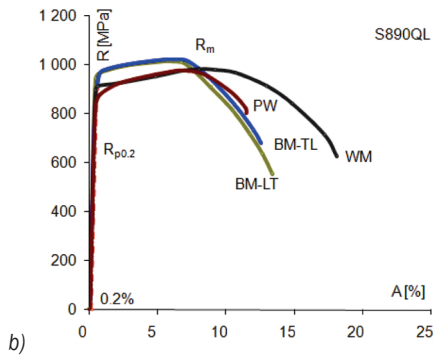
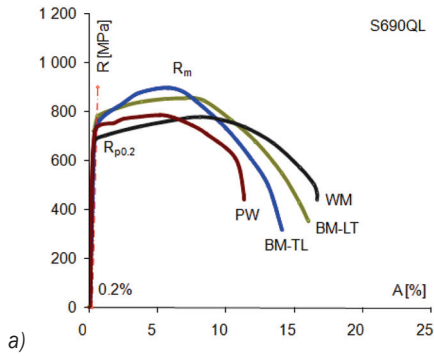


Fig. 4. Typical results of tensile testing (resistance curves) of real welded joint specimens; a) welded joint on S690QL, b) welded joint on S890QL

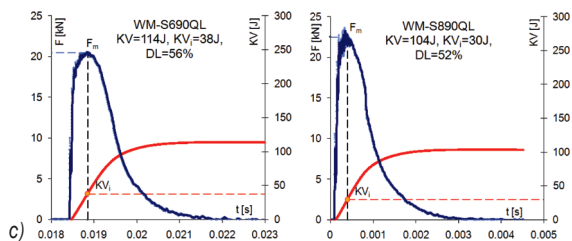
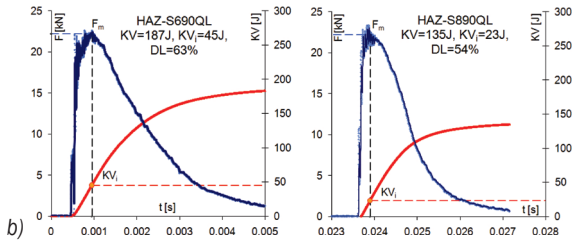
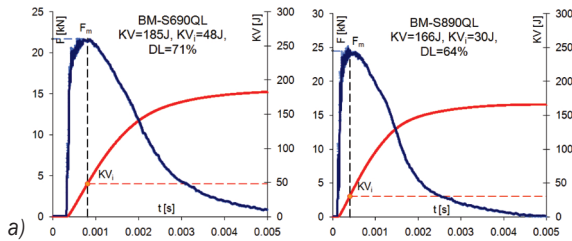


Fig. 5. Typical results of impact toughness at room temperature with initial notch in a) BM, b) HAZ and c) WM

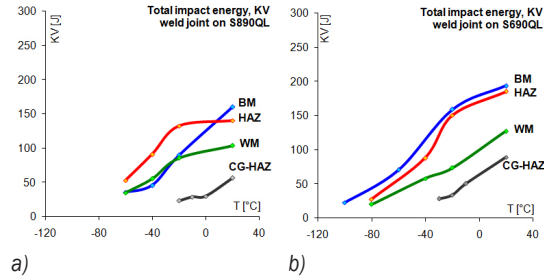


Fig. 6. Total impact energy vs. testing temperature for specimens with initial notch in BM, HAZ and WM; a) welded joint on S690QL, b) welded joint on S890QL

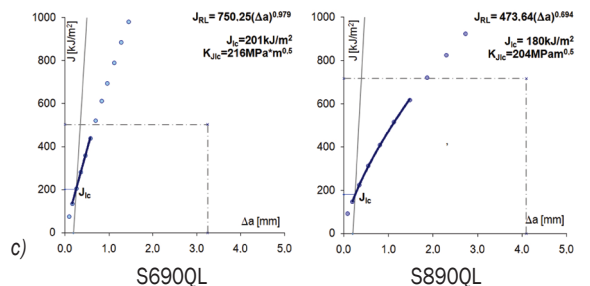
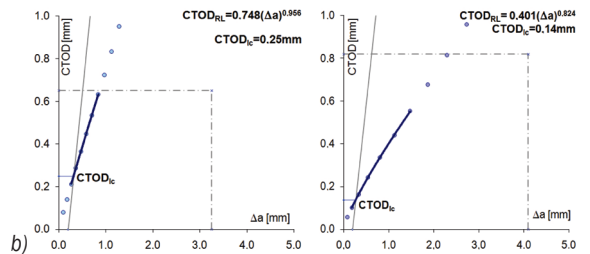
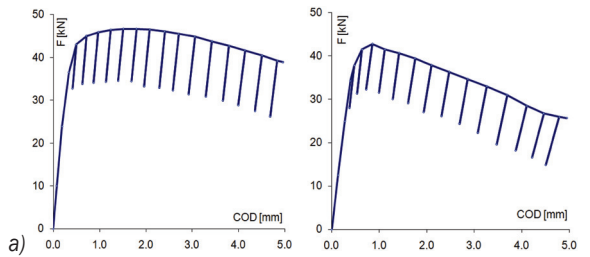


Fig. 7. Typical EPFM resistance curves for BM: a) F-COD, b) CTOD- Δa , c) J- Δa

appropriate results for KV , KV_i , KV_p and DL . The impact toughness dependence on testing temperature, from -100 to $+20$ °C (Fig. 6) shows that BM has the highest, while CG-HAZ has the weakest impact toughness. Without neglecting the lowest impact toughness found in CG-HAZ, the specimens from real welds, e.g. BM, WM and HAZ, have sufficient toughness as guaranteed for BM in acc. to the standard for delivery condition, e.g. EN 10025-6, or $KV > 27$ J at -40 °C [2]. Also, $KV_i = 10$ to 45 J presents a minor part of the total absorbed energy, KV , and a slight

decrease with a temperature decrease, while KV_p values follows the general trend of KV . Typical results of EPFM parameters testing, and the corresponding resistance curves, are shown in Figs. 7 and 8.

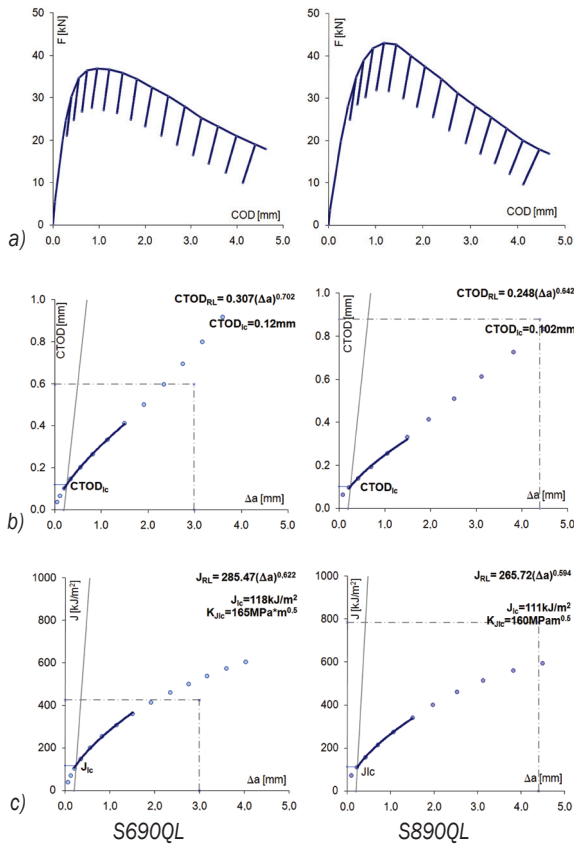


Fig. 8. Typical EPFM resistance curves for WM; a) F-COD, b) CTOD- Δa , c) J- Δa

Summarized range of critical materials EPFM and LEFM parameters testing are shown in Table 2.

Table 2. Critical material's EPFM and LEFM parameters

Specimen	J_{Ic} [kJ/m ²]	$CTOD_{Ic}$ [mm]	$K_{J_{Ic}}$ [MPa·m ^{0.5}]
S690QL-BM	201 to 238	0.25 to 0.27	202 to 227
S690QL-WM	117 to 133	0.12 to 0.13	164 to 175
S890QL-BM	173 to 188	0.14 to 0.15	200 to 204
S890QL-WM	111 to 126	0.10 to 0.11	160 to 170

3 RELATIONSHIP TERMS

If we consider experimentally obtained results of general toughness characteristics testing, both impact toughness, KV , and quasi-static toughness (critical fracture mechanics parameters), J_{Ic} , $CTOD_{Ic}$, $K_{J_{Ic}}$, it is possible to provide approximation terms. The same

is possible for corresponding results of hardness and tensile testing. These approximation terms may be particularly helpful for a further assessment of costly fracture mechanics parameters testing. The terms definition is based on similar approaches founded in novel integrity assessment procedures, such as FITNET, as well in respective scientific research works [8] and [9].

The obtained Eqs. (1) to (3), also presented in Fig. 9. were used for the calculation (prediction) of critical fracture mechanics parameters for HAZ and CG-HAZ, where the corresponding impact toughness, KV , was experimentally determined.

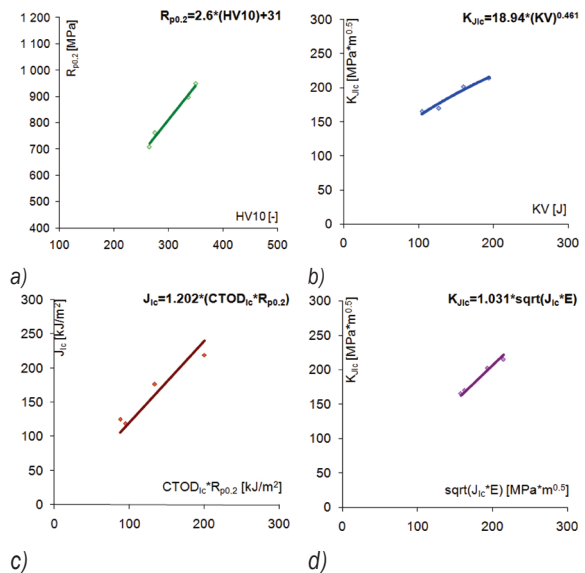


Fig. 9. Relationship terms between investigated mechanical properties of HSS welds; a) $R_{p0.2} = f(HV)$, b) $K_{J_{Ic}} = f(KV)$, c) $J_{Ic} = f(CTOD_{Ic}, R_{p0.2})$, d) $K_{J_{Ic}} = f(J_{Ic}, E)$

Finally, both experimentally obtained and by calculation approximated fracture resistance parameters are used to found the distribution of fracture resistance along welded joints, for both steels respectively, which is presented in Tables 3 to 6.

The following are obtained relationship terms Fig. 9, where E [GPa] stand for Young's modulus:

$$K_{Ic} = 18.94 \cdot KV^{0.461}, \quad (1)$$

$$J_{Ic} = 1.202 \cdot (CTOD_{Ic} \cdot R_{p0.2}), \quad (2)$$

$$K_{Ic} = 1.031 \cdot \sqrt{J_{Ic} \cdot E}. \quad (3)$$

4 CONCLUSION

The summarized preview of average toughness distribution, and corresponding undermatching, UM, for investigated welded joints are shown in Tables 3 to 6.

Table 3. Distribution of average impact toughness, KV [J], at room temperature (20 °C)

Welded joint on	BM	HAZ	CG-HAZ	WM
S690QL	194	186	89	127
UMtoBM	-	0.96	0.46	0.65
S890QL	160	141	56	104
UMtoBM	-	0.88	0.35	0.65

Table 4. Distribution of average critical EPFM parameter, J_{Ic} [kJ/m²], at room temperature (20 °C)

Welded joint on	BM	HAZ	CG-HAZ	WM
S690QL	222	201	90	122
UMtoBM	-	0.91	0.41	0.55
S890QL	176	148	54	119
UMtoBM	-	0.85	0.31	0.68

Table 5. Distribution of average critical EPFM parameter, CTOD_{Ic} [mm], at room temperature (20 °C)

Welded joint on	BM	HAZ	CG-HAZ	WM
S690QL	0.26	0.26	0.12	0.13
UMtoBM	-	1.00	0.46	0.50
S890QL	0.22	0.19	0.07	0.12
UMtoBM	-	0.86	0.32	0.55

Table 6. Distribution of average critical LEFM parameter, K_{Ic} [MPa·m^{0.5}], at room temperature (20 °C)

Welded joint on	BM	HAZ	CG-HAZ	WM
S690QL	227	205	137	168
UMtoBM	-	0.90	0.60	0.74
S890QL	202	177	107	166
UMtoBM	-	0.88	0.53	0.82

Eqs. (1) to (3) presented in Fig. 9 for the approximation of fracture mechanics parameters, K_{Ic} , J_{Ic} , CTOD_{Ic}, based on the known impact toughness, KV, are valid only for welded joints executed with GMAW process, on high strength structural steels S690QL and S890QL respectively, in the thickness range of 20 to 30 mm. However, future research may include effects of specimens thickness and testing temperatures to adjust more precisely provided approximation terms. Also, a similar approach may be applied to other type of materials and their welded joints.

From the point of applied welding technology, it should be noted that welded joints on the subject HSS, e.g. S690QL and S890QL, are obtained by the use of preheating, but without post-weld heat-treatment, PWHT. This was possible in one way, by producing the slightly strength undermatching joints ($UM = 0.89$ to 0.96). Also, this strength undermatching is followed with generally acceptable toughness undermatching (Tables 3 to 6) which should be particularly included in any design or structural assessment, for such kind of materials and joints.

Therefore, evaluated complete welded joints resistance (particularly represented in strength and toughness) should provide more than a satisfactory confidence, with minimum conservatism.

The complete toughness undermatching, UM, of welded joint characteristic zone's properties (in comparison to base metal, BM) are found to be on the following lowest limits (from Tables 3 to 6):

- 0.85, for real HAZ,
- 0.31, for simulated CG-HAZ,
- 0.50, for real WM.

Finally, the presented investigation and characterization approach, as well as the obtained results, could be helpful for a future setting of new acceptance criteria based on fracture mechanics parameters, or general toughness.

5 ACKNOWLEDGMENT

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