Periodicals of Engineering and Natural Sciences ISSN 2303-4521
Vol. 8, No. 3, September 2020, pp.1193-1201

Fitting curves and impact toughness transition temperature of quenched and tempered steel welds

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ABSTRACT

From the point of welding procedure evaluation, it is important to analyse welds for their impact toughness and transition temperature for three main zones: weld metal, heat-affected zone and base metal. This paper covers butt welds of two QT steel grades, 690 and 890, with thicknesses of 30 mm and 20 mm, respectively. They are interesting regarding yield strength and characteristic weld zones. Basic details of GMAW process used in experiment are provided, with temperatures for impact toughness tests of weld zones varied from +20 °C down to -60 °C. Based on acquired experimental results of impact toughness, fitting curves were developed by use of Oldfield model, i.e. hyperbolic tangent function. Acquired transition temperatures (T_T) from fitting curves show mostly allowable values for all three weld zones. As expected, lower strength grade 690 possess higher impact toughness, in comparison to higher strength grade 890. The standardized criteria of minimal absorbed energy of 30 J (KV) and 50% of shear fracture (SF) show different transition temperatures ($T_{T\text{-}30J}$ and $T_{T\text{-}50\%SF}$), while general dependence of impact toughness to shear fracture (KV vs. SF) shows a reasonable trend. Finally, used GMAW procedures may be considered as acceptable, since for both steel grades (690 and 890) all three weld zones show better $T_{T\text{-}30J}$ values than minimal required by standard ($T_{T\text{-}30J}$=-40 °C) for QT structural steels.

Keywords: Quenched and Tempered steel, Weld, Impact Toughness, Transition Temperature

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1. Introduction

1.1. Importance of impact toughness

For everyday products, it is important to avoid loads leading to fatal brittle fracture. Contrary to fully brittle fracture, the material can also behave in a fully ductile manner, which is by far more desirable. The most influential parameter for transition from ductile to brittle material behaviour is temperature. Thickness also plays an important role regarding stress state (2D or 3D), in a manner that the larger is thickness, the more complex 3D stress state is, hence the toughness is more impaired.

For any demanding welded product, toughness is required design property for base metal, heat-affected zone (HAZ), and weld metal (WM). Thus, necessary design toughness must be selected with consideration of minimum design temperature, stress state and material thickness. This approach is required by any welded product design code for steel structures (or, simply, product standard), such as Eurocode 3. Precisely, part of Eurocode 3 (EC3), EN 1993 1-10, defines material toughness and trough-thickness properties [1]. Eurocode 3 is applied for steel grades from 235 to 690 (numbers stand for standard yield stress in MPa). However, other product standards or client requirements may allow higher steel grades (up to 890), depending on other required material properties, such as ductility, or yield stress to tensile strength ratio.

For example, standard steel grade S690QL (or simply 690, where S stands for structural, Q for quenched and tempered delivery condition, and L for minimum required toughness) may have different maximum allowable thickness, depending on stress state (represented as percentage of yield stress, *Y*) and minimum design temperature. Specifically, if $0.75\times Y$ is allowable stress level, and minimum design temperature is -50 °C, the maximum allowable thickness is $t_{\text{max-all}}$=20 mm. Furthermore, if the allowable stress level is on $0.50\times Y$, for the same minimum design temperature, the maximum allowable thickness is $t_{\text{max-all}}$=35 mm [1].

The mentioned approach is not important only for design of new welded products, but also for existing ones in case when it is necessary to perform structural integrity assessment or residual life of product or component with detected defect(s). In general, material and weld strength and toughness at analysed minimum service temperature must be known. Besides general steel structures, this is particularly important for pressure equipment, such as vessels and pipelines. Example of such approach is described in the research of P. O. Maruschak et al. [2] on existing gas pipeline, where significant scatter of impact toughness data is observed on one normalized steel grade (originally designated as 17G1S and with yield stress in the range from 390 MPa to 440 MPa) and lower shelf of “cold brittleness” (fully brittle fracture) down to -90 °C.

A. A. Johnson et al. [3] has shown that carbon content has great effect to ductile-to-brittle transition for normalized structural steels. The higher is the carbon content, the more degraded are the impact toughness properties, the more unfavourable is the transition temperature, and the sharper is transition.

General overview of quasi-static and impact toughness, as well as mechanical properties (strength, ductility, hardness) of quenched and tempered steel grades and their weld zones is given in own research [4], but with the lack of proper use of fitting curves.

C. M. Mours et al. [5] has shown results of the evaluation of transition temperature on low carbon mild steel (assumed in “as rolled” condition), with the use of fitting curves in accordance to well-known Oldfield model.

C. S. Cubides-Herrera et al. [6] has shown results of transition temperature investigation of one ferrite-perlite, normalized steel, without consideration of any welded joints. Used fitting curve model is slightly modified Oldfield model, which was incorporated within supporting application software used for impact toughness testing.

Research from A. Ilic et al. [7] has shown results of evaluation of testing temperature influence on impact toughness for welded joints of 690 quenched and tempered steel grade (e.g. Weldox 700), but without provision of fitting curves.

Obviously, various standardized delivery conditions are available for structural steels and its welded products. Among them, quenched and tempered steels provide the highest level of strength, while maintaining sufficient levels of toughness, and therefore those steels may be favourable whenever there is a need for the light-weight product or structure. However, they are also interesting regarding welding and characteristic weld zones. Aim of this study is application of fitting curves to toughness data obtained for three weld zones, as well as estimation of toughness distribution through zones. In addition, transition temperature is assessed.

1.2. Fitting curve models for quenched and tempered steels

Comprehensive study with evaluation of existing models for the provision of fitting curves and estimation of transition temperatures is done by M. Todinov [8]. Various statistical models have been analysed, from most used one defined by the Oldfield [9], up to models of Moskovich et al. and Stephens et al. Models are mostly based on the research of welds made with carbon-manganese steels. According to M. Todinov, the main advantage of his proposed model is the reliability regarding problem of sparse data of impact toughness variation within the transition region. The proposed model is modified - normalised Oldfield model. However, in this paper, mentioned model is not used due to the fact that (1) there is no information regarding the range of evaluated steel strength grades or its delivery conditions, and (2) that own obtained experimental results show quite reasonable data variation.

S. Y. Shin et al. [10] have provided results of transition temperature evaluation on thermo-mechanically treated pipeline steels. They used Oldfield model for the provision of fitting curves. However, the major purpose of the presented study was determination of general fracture mechanics properties, such as fracture and impact toughness, but only for considered base metals (pipeline steels), without characterization of weld zones.
H. Liu et al. [11] have investigated the dependence of toughness on thickness of thermo-mechanically treated and then quenched and tempered steel (M+QT, strength grade 550-650). They have used hyperbolic-tangent model, similar or equal to Oldfield model, however, not precisely referenced. Results included both absorbed energies, and shear fracture(s).
Comprehensive study regarding quenched and tempered steels is provided by S. Pallaspuro et al. [12]. They have investigated high strength quenched and tempered steel grade 960. More specifically, the influence of steel microstructure on impact toughness properties and transition temperature has been investigated. Besides, this study is very descriptive since provides clear definition and reasons for the use of different transition temperature criteria. Used fitting curves model was based on hyperbolic-tangent function, i.e. Oldfield model.
Interesting study is presented by Y. Takashima et al. [13] regarding the analysis of statistical scatter of impact toughness using numerical analysis. Numerical analysis of impact Charpy toughness is quite rare, since they require the elastic-plastic material model and quite demanding nonlinear numerical analysis. Investigated steels were grades 400 and 800, without description of delivery condition. However, influence of testing temperature on impact toughness has not been investigated numerically, with research rather focused on the influence of stress filed in front of the initial notch.
Paper by B. Tanguy et al. [14] has shown results of numerical analysis and modelling of the ductile-to-brittle transition temperature of quenched and tempered steel. It contains detailed description of used elastic-plastic material model, particularly of dependence of material strength to loading rate and testing temperature. Results do not show clearly which model for fitting curves were used, while transition temperature criteria are designated as “TK_7” (temperature for absorbed energy of 70 J/cm^2, or for KV=56 J).
Study of Z. Yang et al. [15] has shown comprehensive results of the effect of microstructure on the impact toughness of one quenched an tempered pressure vessel steel (close to grade 600), and further ductile-to-brittle transition temperature, but without a clear distinction of used criterion. Provided fitting curves were obtained by use of Boltzmann function, which is basically quite like one presented in the Oldfield model, but with an exponential function instead of hyperbolic-tangent function.
Finally, for study presented in this paper, the most often used Oldfield model, one from 1975, for the fitting of impact toughness - transition curve is considered. There is a quite detailed description of terms and methods used for “Oldfield model”, which is based on hyperbolic tangent function (i.e. non-linear regression impact toughness - transition curve), within further research of R. A. Wullaert et al. including W. Oldfield [9].

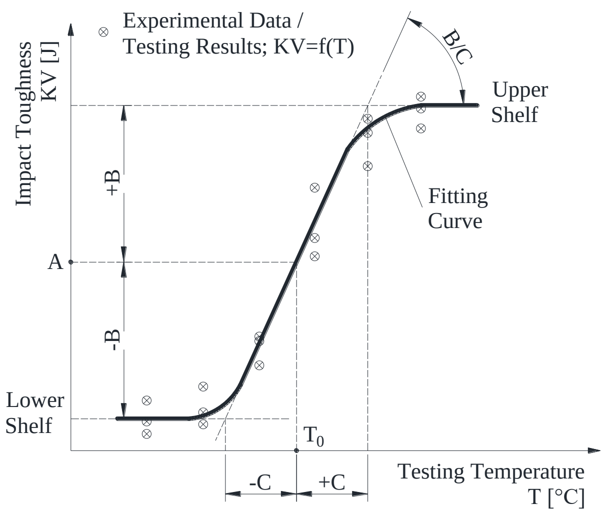


Figure 1. Non-linear Oldfield regression model for impact toughness transition curve [9]

Used Oldfield model (Fig. 1) for the non-linear regression fitting curve of impact toughness transition is:

$$\mathrm{KV} = A + B \cdot \tanh\left(\frac{T - T_0}{C}\right) \tag{1}$$

Here A (J) is mid-impact toughness value for mid-transition temperature T_0, A-B and A+B are a lower and upper shelf of impact toughness, and C (°C) is a span of the transition region.

Once the fitting curve is obtained based on acquired experimental data (impact toughness testing), one of the applicable transition temperatures criteria may apply.

Selection of transition criteria is quite important due to the previously described principles, such as those within Eurocode 3 [1]. However, most common criteria could be one defined for base metal, when considering welded joints. Here, for analysed QT steel grades criterion is that guaranteed impact energy of 30 J must be achieved at least at -40 °C, or that transition temperature ($T_{\text{T-30J}}$) must be at least -40 °C.

Another important criterion for transition temperature may apply whenever there is a need for so-called "ductile crack arrest", i.e. stoppage of crack growth due to the high ductility and toughness of the material. Regarding impact toughness evaluation, it is a fracture appearance transition temperature (FATT). Actually, for every pre-cracked specimen during impact toughness testing, besides total absorbed energy (with or without determination of KV_i and KV_p), it is possible to evaluate another impact toughness parameter – shear fracture percentage (the content of ductile fracture on the cross-section of cracked Charpy specimen), or simply shear fracture. FATT ($T_{\text{T-50\%SF}}$) is a temperature where 50% of shear (ductile) fracture is present, while rest of 50% is brittle or cleavage fracture). Such phenomena of crack arrest, as material resistance to crack growth, is important for pressure equipment, or whenever there is a need or requirement to avoid significant crack growth and further consequences of failures. Similarly, a fitting curve based on Oldfield model could be applied for shear fracture for evaluation of FATT (i.e. $T_{\text{T-50\%SF}}$). Loss of impact toughness with a decrease of temperature is always proportional, both for absorbed energy (KV) or shear fracture (SF). Lower shelf (Fig. 1), for all structural steels mostly correspond to 0% shear fracture, what is considered as Nil Ductility Temperature (NDT, $T_{\text{T-0\%SF}}$).

For the purpose of evaluation of two considered quenched and tempered steel welded joints in this paper, the following two criteria are considered:

1. guaranteed KV=30 J at T=-40°C, or minimum transition temperature $T_{\text{T-30J}}$=-40 °C, and
2. 50% shear fracture transition temperature, FATT or $T_{\text{T-50\%SF}}$, for evaluation only, since there are no values required by standard.

Note that the expression "minimum" for the first criterion is rather as it is required regarding impact toughness, while physically (for negative temperature) is maximally allowable. Also, it will be shown that $T_{\text{T-30J}}$ correspond to Nil Ductility Temperature.

2. Experimental procedure and overall results

Set of butt-welded joints (X-groove) were made using Gas Metal Arc Welding (GMAW) on two QT steel grades, 690 and 890. Filler metal is selected according to chemical composition and strength of base metal (BM), where achieved weld metal (WM) possess a slightly higher level of strength (i.e. minor overmatching). For both steel grades, preheating at 150-200 °C is used, while heat input was 1.4-1.8 kJ/mm. Both parameters were selected as a technological measure for avoidance of cold cracks. The thickness of grade 690 was 30 mm and for grade 890 was 20 mm. Achieved cooling time from 800 °C to 500 °C ($t_{8/5}$) for welded joints of both steels was in the range from 6 to 8 seconds [4].

V-notched specimens (10×10×55 mm in accordance with EN ISO 9016, Fig. 3) for impact toughness testing were sampled (in acc. to EN ISO 15614-1) from BM, WM and heat-affected zone (HAZ), as shown in Fig. 2. Length of joints (500 mm) was enough for sampling at least three specimens for testing at one temperature. Testing temperatures were +20 °C, -20 °C, -40 °C and -60 °C, with addition of -80 °C and -100 °C, depending on results with lowest KV and/or 0% of SF. Total of 4×3×3=36 specimens was sampled per welded joint.

Impact testing is performed on instrumented Charpy pendulum, and total absorbed energy KV was acquired, as well as its parts, KV_i and KV_p.

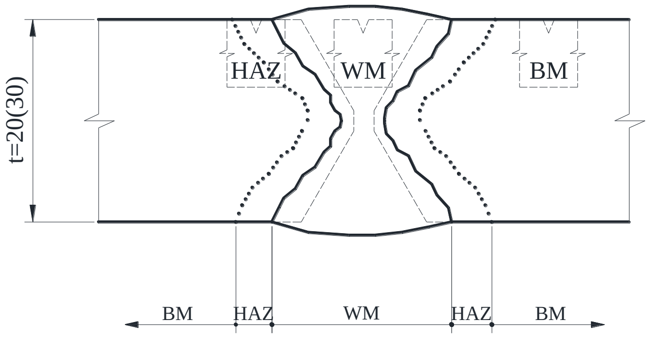


Figure 2. Position of V-notches within evaluated welded joint zones for Charpy specimens

After impact toughness testing, specimens were evaluated for fracture appearance and percentage of shear fracture (SF) and cleavage fracture (CF), as shown in Fig. 3.

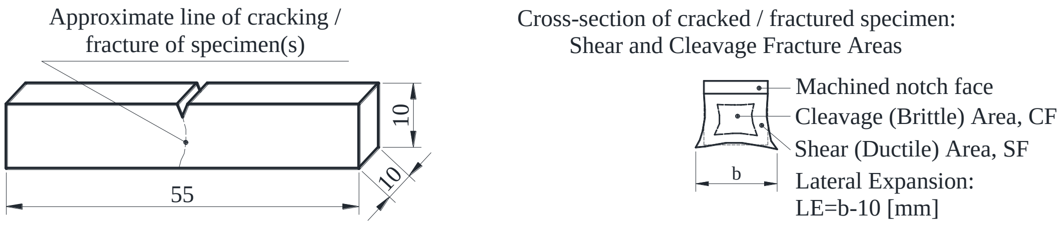


Figure 3. Charpy specimen according to EN ISO 9016 (left) and its fracture appearance (right)

Fig. 4 shows sample photos of fractured surfaces of specimens of grade 890.

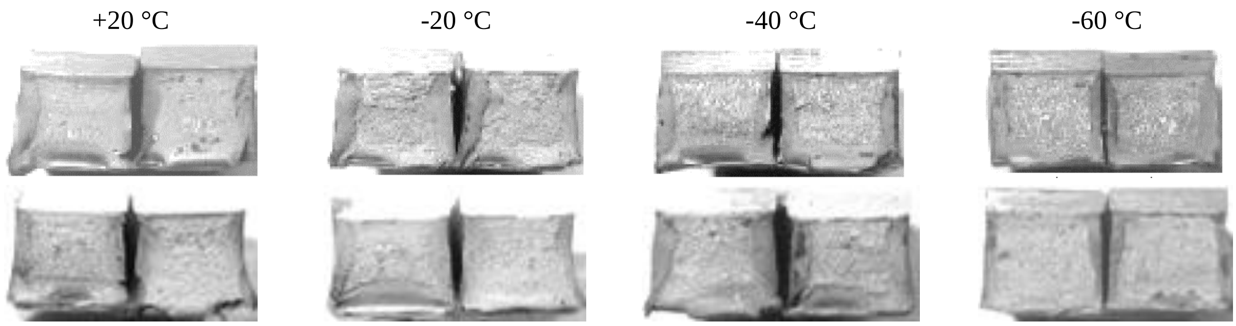


Figure 4. Samples of fracture surface of WM (up) and HAZ (down) for grade 890

Tab. 1 and Tab. 2 give results of impact toughness testing for three characteristic zones of welded joints of 690 and 890 steel grades, respectively.

Table 1. Overall impact toughness testing results for 690 steel welded joint zones

Testing temperature [°C]	Base metal (BM)		Heat-affected zone (HAZ)		Weld metal (WM)	
	KV [J]	SF [%]	KV [J]	SF [%]	KV [J]	SF [%]
+20	184-212	71-74	184-187	61-63	97-171	56-62
-20	143-173	50-66	139-162	53-58	71-75	42-54
-40 / -60*	50-94	27-41	69-107	32-43	54-64	21-30
-60** -80** -100**	 18-31	 0	26-30 	0-4 	 18-22 	 2-4

* -60 °C only for BM.
** Depending on the appearance of nil or close to zero ductility, i.e. 0% of SF.

Table 2. Overall impact toughness testing results for 890 steel welded joint zones

Testing temperature [°C]	Base metal (BM)		Heat-affected zone (HAZ)		Weld metal (WM)	
	KV [J]	SF [%]	KV [J]	SF [%]	KV [J]	SF [%]
+20	147-168	61-66	135-145	60-63	99-108	51-58
-20	76-117	44-58	130-136	55-59	72-107	43-57
-40	41-48	13-15	70-109	33-43	40-67	17-40
-60	32-44	0-6	40-60	6-10	28-43	0-10

3. Analysis of acquired fitting curves

The following general description of the acquisition of fitting curves is based on the average values (out of three specimens) of impact toughness results, both for absorbed energy and shear fracture. Provision of fitting curve and analysis of experimental data is performed by using Microsoft Excel. Based on the model shown in Fig. 1 and described with (1), the fitting curve parameters are calculated as follows:

- *A*: the sum of minimal value and parameter *B*,
- *B*: the halved value of max-min range, i.e. (max–min)/2,
- *C*: having value 15, 20 or 30, regarding visual appearance of transition width,
- T_0: adjusted manually, with the step of ±0.1, to achieve value of the coefficient of determination of 0.99, i.e. R^2=0.99 for averaged value on single temperature.

Tab. 3 and Tab. 4 show used fitting curve parameters. Single calculated R^2 was in the range from 0.82 to 0.94.

Table 3. Fitting curves parameters for grade 690 weld joint zones

Fitting curve parameter	Base metal (BM)		Weld metal (WM)		Heat-affected zone (HAZ)	
	for KV	for SF	for KV	for SF	for KV	for SF
A	108	36	74	31	107	32
B	86	36	54	28	79	30
C	30	30	30	30	30	30
T_0	-43.0	-52.0	-34.0	-42.0	-34.0	-52.0

Table 4. Fitting curves parameters for grade 890 weld joint zones

Fitting curve parameter	Base metal (BM)		Weld metal (WM)		Heat-affected zone (HAZ)	
	for KV	for SF	for KV	for SF	for KV	for SF
A	98	33	69	30	97	35
B	62	31	34	26	44	27
C	20	20	20	15	15	15
T_0	-29.0	-27.5	-28.3	-37.6	-39.0	-39.7

Interestingly, for grade 890 (Fig. 6), heat-affected zone shows a bit higher toughness in comparison to the base metal for testing temperatures lower than -20 °C for KV, and lower than 0 °C for SF. This phenomenon can be explained by the fact that crack front (from initial specimen notch) passes through several microstructural HAZ zones, including fine-grained HAZ with increased toughness, as well as base metal. This is schematically shown in Fig. 2. Depending on position of notch, crack can propagate through different zones in greater or lesser proportion. Detailed characterisation of mechanical properties (including toughness) of HAZ sub-zones should be a subject of further studies and research due to complexity of such investigation. The proof of this mismatching and variability of microstructural and mechanical properties of HAZ sub-zones can be found in Ref. [16] and [17].

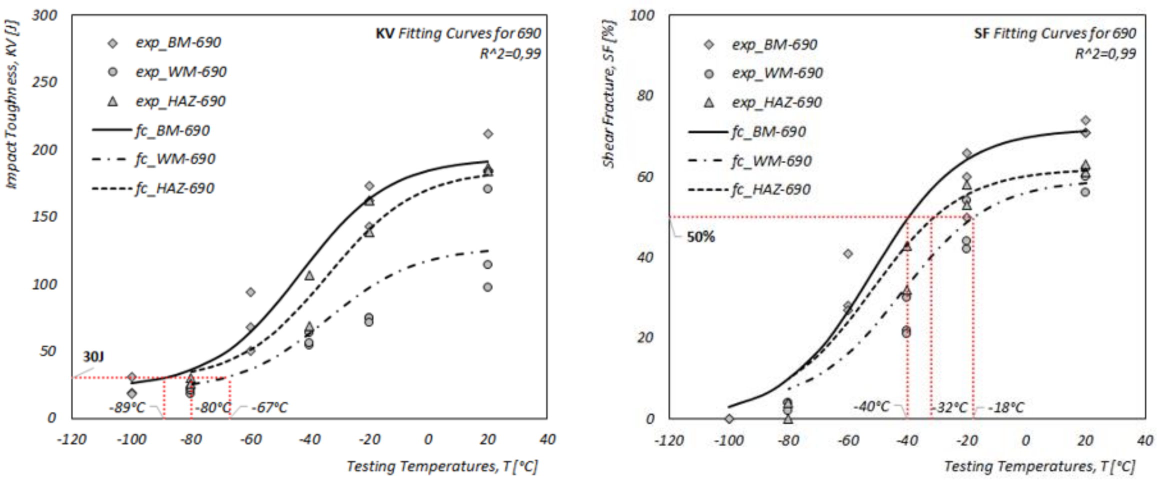
Fig. 5 and Fig. 6 shows acquired fitting curves for all three characteristic weld joint zones for steel grades 690 and 890, respectively. Analysis of absorbed energy (KV) vs. shear fracture (SF) is also performed, due to similarities of chemical composition and delivery condition of both steel grades. Results of this additional analysis are provided in Fig. 7, where the expected trend is shown with corresponding exponential regression function. From Fig. 7, the 0% shear fracture (i.e. Nil Ductility) corresponds to KV=30 J, which is guaranteed minimum impact toughness for analysed QT grades at -40 °C (i.e. guaranteed $T_{T\text{-}30J}$=-40°C). Thus, Nil Ductility Temperature corresponds to $T_{T\text{-}30J}$.

It can be seen that both steel welds satisfy set of criteria for transition temperatures, for both KV and SF. Regarding absorbed energy and guaranteed $T_{T\text{-}30J}$=-40°C, grade 690 shows $T_{T\text{-}30J}$ of -89 °C, -80 °C and -67 °C for BM, HAZ and WM, respectively (Fig. 5a). Values of $T_{T\text{-}30J}$ for grade 890 are limited to -60 °C, due to the limitation of experimental data (Fig. 6a). However, it is possible to give alternative interpretation of this transition temperature, considering achievable level of impact toughness (i.e. absorbed energy) at a guaranteed temperature of -40 °C, when KV_{min}=30 J is required. Therefore, achieved values of KV are 94 J, 65 J and 51 J for HAZ, BM and WM, respectively, for grade 890 (Fig. 6a). A similar decrease of impact toughness, which follows decrease of testing temperature, is shown for shear fracture for both steel grades (Fig. 5b and Fig. 6b).

The second criterion for transition temperature or $T_{T\text{-}50\%SF}$ shows the following values:

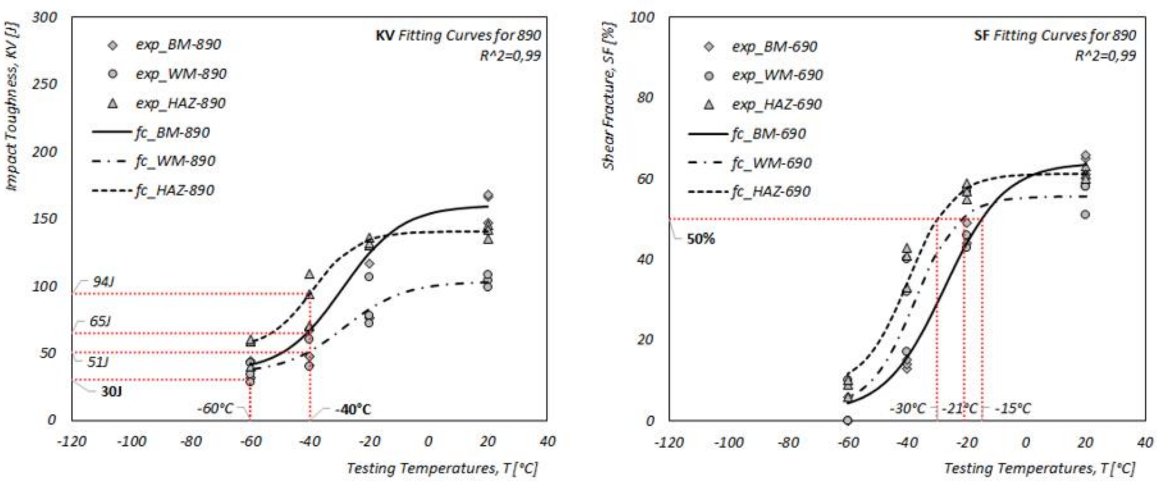
- -40 °C, -32 °C and -18 °C, for BM, HAZ and WM, respectively, for grade 690, and
- -30 °C, -21 °C and -15 °C, for HAZ, BM and WM, respectively, for grade 890.

Obviously, the $T_{T\text{-}50\%SF}$ criterion is more demanding (requires at least 50% of shear fracture), and therefore give higher values (less favourable) transition temperatures.



a) KV vs. *T* b) SF vs. *T*

Figure 5. Fitting curves of 690 steel grade welded joint zones



a) KV vs. *T* b) SF vs. *T*

Figure 6. Fitting curves of 890 steel grade welded joint zones

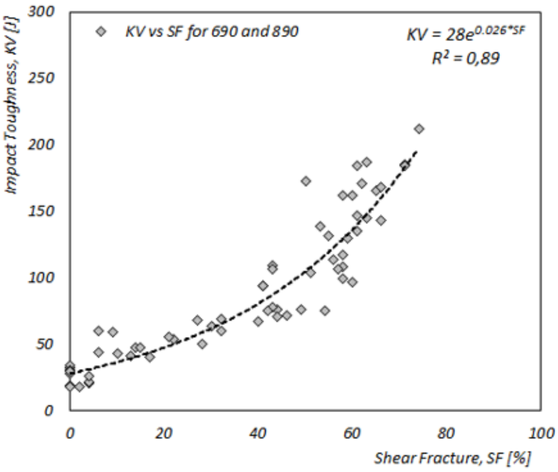


Figure 7. General dependence of absorbed energy on shear fracture for grades 690 and 890

4. Final remarks

This paper shows description of means and criteria for the acquisition of impact toughness and transition temperature. They are important material properties for design of various products and assessment of their structural integrity. That is particularly important for welded products and welded joints.

Welding procedures used for research presented in this paper and obtained welded joints can be considered as satisfactory. This is because criteria of transition temperature ($T_{T\text{-}30J}$) of welds joint zone (HAZ and WM) are better than those of base metal itself ($T_{T\text{-}30J}$=-40 °C, according to standard defining delivery condition).

In general, steel grade 690 exhibited more improved toughness properties in comparison to grade 890. However, selection of either steel grade should include consideration of important influential design parameters, such as thickness, minimum design temperature and stress state.

Acquired fitting curves for selected fitting parameters (A, B, C and T_0), in accordance to Oldfield hyperbolic tangent model, show good reliability (up to R^2=0.99 for averaged values) for determination of transition temperature, whatever criterion should be used.

Which criterion for transition temperature should be used, mainly depends on requirements of product standard or design code. Generally, it can be:

- need for minimum impact toughness (absorbed energy) with almost 0% shear fracture, or
- 50% shear fracture for avoidance of brittle fracture (for provision of ductile crack arrest).

The second criterion is obviously more demanding but provides more safety for the analysed product.

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