# Evaluation of Fracture Toughness by Master Curve Approach Using Compact Tension (CT) Specimens

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Abstract

Fracture toughness is a property which describes the resistance of a material containing a crack to fracture initiation, and is one of the most important properties of any material for a number of engineering applications. In order to assess the fracture toughness behaviour in the transition region of a number of approaches have been developed. Master curve methodology is one of the most promising approaches. The Master curve method suggested by Wallin provides a description for the fracture toughness scatter about the median value with temperature for the transition region as well as the lower shelf. Compact tension (CT) specimens cut from the heterogeneous weld joint were tested in the transition region. All of these specimens have been tested for determining fracture toughness. The reference temperature was then obtained.

**Keywords:** Fracture toughness, Master curve, (CT) specimens, the reference temperature.

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## 1 Introduction

Mechanical testing is important for evaluating main service properties of engineering materials and for development of new materials. Evaluating material characteristics during application of a load help in finding out if the material is strong enough and rigid enough to resist the loads that it will experience in service. In this sense, a specific role belongs to evaluation of the material response to external load under presence of opening crack, defects and or sharp notches. A number of experimental techniques for mechanical testing of engineering materials have been developed such as fatigue testing, fracture toughness, hardness testing, impact and tensile testing.

In the frame of these mechanical tests a specific position belongs to fracture toughness determination. Fracture toughness is a very important material property of any material for many design applications, which describes as a stress intensity factor the amount of stress field required to force a preexisting flaw to propagate. The linear-elastic fracture toughness of a material is determined from the stress intensity factor $K_{Ic}$ at which a crack in the material begins to grow, whereas plastic-elastic fracture toughness includes a determination energy required for the crack propagation. This study focuses on the evaluation of the fracture behavior of welds carried out by fusion welding. This study aims to investigate the fracture behavior of the structure steels and welds with ferritic basic microstructure transition region.

## 2 Master curve

Master curve concept is an engineering approach enabling to quantify fracture toughness in transition region [1]. Master curve is a statistical model based on the engineering analysis of data and following quantification of the dependence, where the fracture toughness at a particular temperature in the transition region depends on three parameter Weibull distribution as it is shown by the following equation [2] [3]:

$$P_f = 1 - \exp\left[-\left(\frac{K_{Ic} - K_{min}}{K_0 - K_{min}}\right)^4\right] \qquad (1)$$

Where $P_f$ is a probability of brittle fracture for the arbitrarily selected specimen, where $K_0$ is the size-scale parameter, and $K_{min}$ is the minimum fracture toughness, is assumed to be equal to $20\ \mathrm{MP}\sqrt{\mathrm{m}}$.

For the median value of fracture toughness equal to $100\ \mathrm{MP}\sqrt{\mathrm{m}}$ reference temperature $T_0$ is defined. The relationship between the median of fracture toughness and temperature in the ductile-brittle transition temperature region of ferritic steels is given by the fracture toughness Master curve [4] [5].

$$K_{Jc(med)} = 30 + 70\exp[0.019(T - T_0)] \qquad (2)$$

There are two methods how to estimate the master curve transition temperature $T_0$. The first one is called the single temperature method where $T_0$ is calculated from size adjusted $K_0$ values by using Eq.2, as following [6] [5] [7]:

$$T_0 = T - \frac{1}{0.019}\ln\left[\frac{\left(K_{Jc(med)} - 30\right)}{70}\right], \qquad (3)$$

where $K_{Jc(med)}$ is determined by the following equation:

$$K_{Jc(med)} = 0.9124(K_0 - 20) + 20 \qquad (4)$$

And the second one is called the multi-temperature method. This is given by the following equation[2]:

$$\sum_{i=1}^{N} \delta_i \frac{\exp[0{,}019(T - T_0)]}{11 + 77\exp[0{,}019(T - T_0)]} = \sum_{i=1}^{N} \frac{\left(K_{Jc(i)} - 20\right)^4 \exp[0{,}019(T - T_0)]}{11 + 77\exp[0{,}019(T - T_0)]} \qquad (5)$$

At least six valid values of $K_{Jc(i)}$ must be available to establish the $T_0$ temperature, where the temperature is units of $C^0$, and $K_{Jc}$ in units of $MPa\sqrt{m}$. The ASTM standard E1921-02 includes the determination of a reference temperature $T_0$ for ferritic steels in the transition region, where the yield strengths are ranging from $275$ to $825MPa$. The temperature dependence of fracture toughness is given to conform to a standard shape known as the master curve see Eq.2. The temperature $T_0$ is obtained from the median ($50\%$ fracture probability) corresponding to$100\ MPa\sqrt{m}$ of the $K_{Jc}$ distribution from 1T size specimens.

## 3 Material and specimens Investigated material

Experimental material used were low carbon heterogeneous weld joint of low carbon ferritic steel and austenitic steel. The nominal chemical composition of low carbon steel 22K is shown in the table 1:

The chemical composition of austenitic heat resistance steel of type X8CrNiTi18-10 is shown in the table 2:

The origin material was cut from steam generator. Thermal ageing was detected for exposure at temperatures 450°C for 500, 700 and 1000 hours respectively.

**Table 1 The chemical composition of low carbon steel 22k in $[Wt\%]$**

| Material | **C** | **M n** | **S i** | **Cu** | **Ni** | **Cr** |
|---|---|---|---|---|---|---|
| **22K** | 0.21 | 0.60 | 0.34 | 0.20 | 0.23 | 0.25 |

**Table 2 The chemical composition of austenitic heat resistance steel has mark as X8CrNiTi18-10 in $[Wt\%]$**

| Material | **C** | **M n** | **S i** | **Cr** | **Ni** | **Ti** |
|---|---|---|---|---|---|---|
| **X8CrNiTi18-10** | max 0.10 | max 2.00 | max 1.00 | 17.0-19.0 | 9.00-12 | 0.80 |

### 3.1 Experimental determination of the fracture toughness $K_{IC}$ and $K_{JC}$:

For determining fracture toughness, standard testing condition and test specimens have been used in accordance with the ASTM E 399 [8]. The specimens compact test (CT) possessed the dimensions $25 \times 62.5 \times 60\ mm^3$. They were fabricated from base metal and welded joints. The specimen geometry of the (CT) specimens is shown in Fig 1. The specimens were fatigue precracked, after fatigue precracked the ratio of the crack length to specimen width is about $a/_W \approx 0.5$. Specimens were tested in the laboratory of the Institute of Physics of Materials of the Academy of Sciences of the Czech Republic, on hydro mechanical drive machine Z wick 200, this machine has a maximum load capacity of 200 k N. The fracture toughness tests were performed at different temperatures, where the specimens were cooled to a stable temperature in cryogenic using liquid nitrogen. Where the temperature was controlled using thermometers. The crack opening was tested with external displacement-measuring clip gage at the load line. The initial and final crack lengths of tested specimens were measured from the fracture surfaces using an optical microscope. The value of fracture toughness was obtained from plot of load vs. displacement. The stress intensity factor is obtained from the following relationship[11][8]:

$$K_Q = \left[\frac{F}{B.W^{1/2}}\right] \cdot g\left(\frac{a_0}{W}\right) , \qquad 6$$

where $g\left(\frac{a_0}{W}\right)$ is a geometrical function dimensionless crack length of $\frac{a_0}{W}$, and $B$ and $W$

are the thickness and the width of specimens respectively, $a_0$ is the initial crack length, and $g\left(\frac{a_0}{W}\right)$ is given by the following relationship[11]:

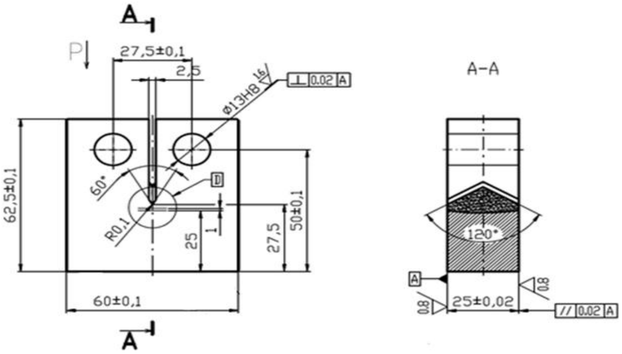

**Fig. 1: The (C T) specimens**

$$g\left(\frac{a_0}{W}\right) = \frac{\left(2+\frac{a_0}{W}\right)\left[\begin{array}{c}0.886 + 4.64\frac{a_0}{W} - 13.32\left(\frac{a_0}{W}\right)^2 \\ +14.72\left(\frac{a_0}{W}\right)^3 - 5.6\left(\frac{a_0}{W}\right)^4\end{array}\right]}{\left(1-\frac{a_0}{W}\right)^{1.5}} \qquad 7$$

In order to validate $K_Q$ as $K_{IC}$ $K_{JC}$ values, the following requirements according the standard ASTM E399 [8] have been checked:

$$B, a \geq 2.5\left(\frac{K_Q}{\sigma_{YS}}\right)^2 \qquad 8$$

$$0.45 \leq \frac{a}{W} \leq 0.55 \qquad 9$$

$$F_{max} \leq 1.10 F_Q \qquad 10$$

Where $\sigma_{YS}$ is the yield stress. Once this has not been the case, i.e. the crack tip plasticity has been too extensive (the samples have not kept the validity condition), the $J$ integral concept according to ISO 12135 [9] was used to evaluate the fracture behavior. For practical determination, the J-integral consists from elastic component and a plastic component as it follows from in the following equation [10]:

$$J = J_e + J_p \qquad 11$$

The elastic component was calculated using the value of linar elastic stress intensity factor as calculated from fracture load according to equation[11][8]:

$$J_e = \frac{K_e^2(1-v^2)}{E} \qquad 12$$

The plastic component is calculated from the following equation[11][8]:

$$J_p = \frac{{}_{p}U_p}{(B_N.b_0)} \qquad 13$$

Where $U_p$ is the plastic part of the area under curve of force versus load line displacement, $B_N$ is the specimen net thickness, $b_0$ is the uncracked ligament. $_p$ is a dimensionless constant which depends only on the geometry of the specimen [11]. The value of $K_{Jc}$ was then inferred for each individual specimen depending on a particular $J_c$ value from the following equation[11][8]:

$$K_{Jc} = \sqrt{\frac{J_c E}{(1-v^2)}} = \sqrt{J_c E'} \qquad 14$$

## 4 SELECTED RESULTS DESCRIPTION:

Fifteen sets of specimens cut from the heterogeneous weld joint were been tested in the transition region. All of these specimens has been tested for determining fracture toughness. The reference temperature was then obtained.

## 4.1 Material 22K – as received:

Only seven of these specimens were base material 22K without heat treatment. The first notice of these data is that this material behaved a very high scatter of fracture toughness data in transition region see Fig 2. The Master curve introduces a very good description of a large data base of RPV steel. Where the Master curve methodology has been developed for low alloy steels. For example at $-30°C$ measured fracture toughness value of base material 22K varied from about $72 MPa.m^{0.5}$ to $213 MPa.m^{0.5}$ at $0°C$ These data show that the upper bound of fracture toughness is increasing with temperature as a result of the transition region behavior.

Table 3. shows that only two specimens have liner elastic behavior, because the ratio Fc/ $F_Q$ is less than 1.1, according to the condition as refered in Eq. 10. The stress intensity factor is caculated directly as $K_Q$ in accordance with Eq. 6. The other specimens behaved in elastic-plastic behavior, where values of J-integral at cleavage instability, $J_c$, were converted to their equivalent values in terms of stress intensity factor $K_{Jc}$ as given in Eq. 14.

**Table 3 Base material 22K- non heat treatment**

| Specimen | t $[°C]$ | $a_0$ $[mm]$ | $F_Q$ $[kN]$ | Fc $[kN]$ | Fc/ $F_Q$ [-] | Upl $[J]$ | Uel $[J]$ | $K_Q$ $[MPa.m^{0.5}]$ | $K_{JC}$ $[MPa.m^{0.5}]$ | J $[MPa.m^{.5}]$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 22K-108 | 0 | 26.3 | 32.88 | 42.11 | 1.28 | 44.9 | 34.51 | 79.03 | 213.56 | 0.19 |
| 22K-405 | -30 | 26.44 | 33.33 | 38.42 | 1.15 | 5.11 | 12.63 | 72.77 | 99.01 | 0.04 |
| 22K-214 | -30 | 26.45 | 31.82 | 38.26 | 1.2 | 6.61 | 12.95 | 72.54 | 105.33 | 0.04 |
| 22K-101 | -20 | 26.43 | 33.29 | 39.85 | 1.2 | 15.93 | 19.06 | 75.45 | 140.51 | 0.08 |
| 22K-115 | -40 | 26.3 | 37.63 | 37.63 | 1 | 1.79 | 11.77 | 70.82 | 81.16 | 0.03 |
| 22K-401 | -40 | 26.49 | 36.51 | 36.51 | 1 | 1.92 | 10.56 | 69.38 | 80.69 | 0.02 |
| 22K-105 | -30 | 26.46 | 31.53 | 39.49 | 1.25 | 7.62 | 14.33 | 74.88 | 111.05 | 0.05 |

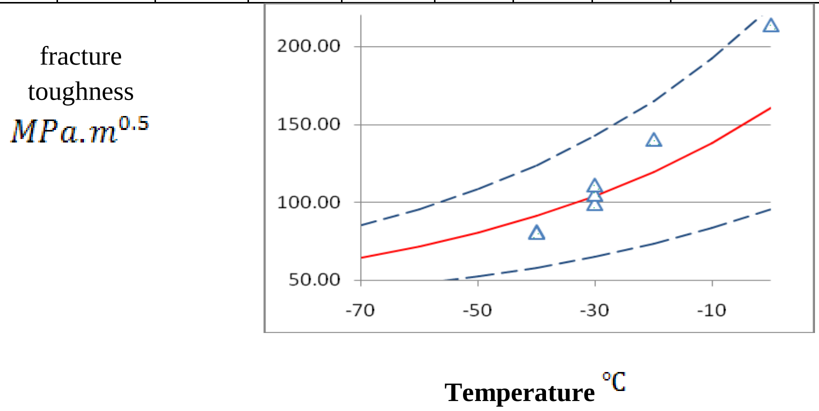

**Fig. 2: Experimental data and master curve obtainedusing as received 22K including the probability scatter band, where**

### 4.2 Weld joint after simulation heat treatment

The following figure 3 illustrates the temperature dependence of the transition fracture toughness data relative to its master curve with 5 and 95% tolerance bounds. While 5 and 95% tolerance bounds provide a reasonable description of the transition fracture toughness data, there are a noticeable three value of data points outside the bounds. Five values of these data were caculated directly to obtain the stress intensity factor is $K_Q$ using Eq.6. Other $J_c$ values were converted to their stress-intensity factor equivalent using Eq.14.

Table 3. shows that five specimens have liner elastic behavior, because the ratio Fc/ $F_Q$ is less than 1.1, the other specimens behaved in elastic-plastic behavior, where values of J-integral at cleavage instability, $J_c$, were converted to their equivalent values in terms of stress intensity factor $K_{Jc}$

**Table 4 Weld joint 22K- heat treatment 700h**

| Specimen | t [°C] | $a_0$ $[mm]$ | $F_Q$ $[kN]$ | Fc $[kN]$ | Fc/ $F_Q$ [-] | Upl $[J]$ | Uel $[J]$ | $K_Q$ $MPa.m^{0.5}]$ | $K_{JC}$ $[MPa.m^{0.5}]$ | J $[MPa.m^{\cdot 5}]$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Svar-111 | -30 | 26.91 | 38.78 | 42.36 | 1.09 | 3.1 | 15.28 | 82.79 | 98.21 | 0.04 |
| Svar-305 | -30 | 26.07 | 44.41 | 66.41 | 1.5 | 91.57 | 76.97 | 122.88 | 307.69 | 0.41 |
| Svar-207 | -30 | 26.15 | 26.09 | 26.09 | 1 | 0.18 | 4.57 | 48.51 | 50.07 | 0.01 |
| Svar-212 | -40 | 25.75 | 33.9 | 33.9 | 1 | 0.55 | 7.72 | 61.56 | 65.25 | 0.02 |
| Svar-307 | -30 | 25.95 | 37.8 | 37.8 | 1 | 1.02 | 10.55 | 69.5 | 75.58 | 0.02 |
| Svar-303 | -20 | 25.93 | 35.29 | 35.29 | 1 | 0.84 | 10.21 | 64.8 | 70.18 | 0.02 |
| Svar-105 | -30 | 26.6 | 44.49 | 53.34 | 1.2 | 19.05 | 33.13 | 102.35 | 165.61 | 0.12 |
| Svar-115 | -20 | 26.09 | 38.99 | 52.24 | 1.34 | 13.52 | 27.2 | 96.95 | 145.53 | 0.09 |

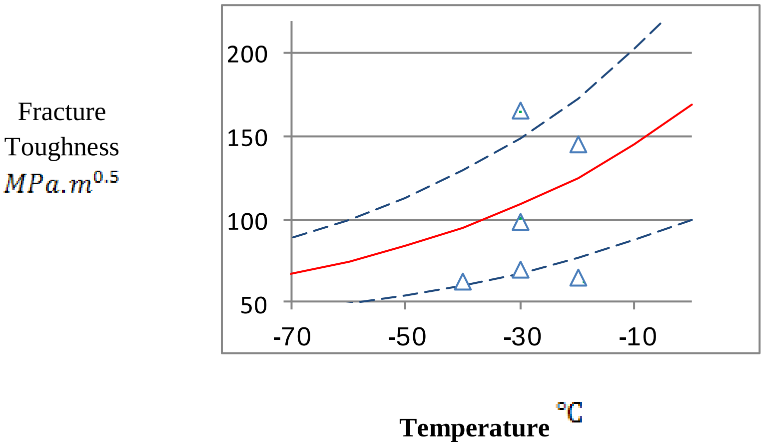

**Fig. 3: Experimental data and master curve results obtained using weld joint 22K- after thermal ageing 700h, where 03**

## 5 Conclusions:

This study shows that in brittle fracture resistance calculations it is necessary to use the fracture toughness temperature dependence. The development of the Master Curve testing procedure has provided a powerful new tool for performing this characterization. It was this observation that led Wallin to the definition of a

Master Curve that allows the fracture toughness for any ferritic steel to be characterized solely in terms of a reference temperature. To, corresponding to a fracture toughness of 100 MPa.

## REFERENCES[*]

[1] T. Yamamoto, D. Odette, H. Kurishita, H. Matsuib, W. Yang, M. Narui and M. Yamazaki, "Evaluation of Fracture Toughness Master Curve Shifts for JMTR Irradiated F82H Using Small Specimens," *Journal of Nuclear Materials,* Vols. 367-370, pp. 593-598, 2007.

[2] D. E. McCabe, J. G. Merkle and K. Wallin, An Introduction to the Development and Use of the Master Curve Method, Lancaster: ASTM International, 2005.

[3] M. A. Sokolov and H. Tanigawa, "Application of the Master Curve Methodology to Fracture Toughness Characterization of Ferritic-Martensitic Steel," pp. 83-95, 2005.

[4] D. E. McCabe, J. G. Merkle and K. Wallin, An Introduction to the Development and Use of the Master Curve Method, ASTM International, 2005, p. 66.

[5] K. Wallin, Master Curve Analysis of Ductile to Brittle Transition Region Fracture Toughness Round Robin Data: the " Euro " Fracture Toughness Curve, Technical Research Centre of Finland, 1998, p. 58.

[6] International Atomic Energy Agency, Guidelines for Application of the Master Curve Approach to Reactor Pressure Vessel Integrity in Nuclear Power Plants, Vienna: Technical reports series no. 429, 2005.

[7] H. Viehrig, J. Boehmert and J. Dzugan, "Some Issues by Using the Master Curve Concept," *Nuclear Engineering and Design 212,* vol. 212, no. 1–3, p. 115–124, 2002.

[8] ASTM E399, "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials," ASTM International, 1997.

[9] ISO 12135, "Metallic materials - Unified Method of Test for the Determination of Quasistatic Fracture Toughness," *American National Standards Institute,* p. 100 , 2007.

[10] T. L. Anderson, Fracture Mechanics Fundamentals and Applications, second edition, CRC Press, 1995, p. 688.

[11] ASTM E1820-99a, "Standard Test Method for Measurement of Fracture Toughness," ASTM International, West Conshohocken, 2003.

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