23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

ANALYSIS OF THE INFLUENCE OF TEST TEMPERATURE AND SPECIMEN SIZE IN THE DETERMINATION OF THE MASTER CURVE

Carlos Berejnoi
Alvaro I. Ruiz
Facultad de Ingeniería, Universidad Nacional de Salta / CIUNSa, Avda. Bolivia 5150, (4400) Salta, Argentina
berejnoi@unsa.edu.ar
ismaelair25@gmail.com

Juan E. Perez Ipiña
CONICET / Facultad de Ingeniería, Universidad Nacional del Comahue, Avda. Buenos Aires 1400, (8300) Neuquén, Argentina
juan.perezipina@fain.uncoma.edu.ar

Abstract. *This work presents an analysis of the effects of specimen size and test temperature in the determination of T_0, the reference temperature of the Master Curve for ferritic steels in the ductile-to-brittle transition region. The Master Curve procedure, for the determination of $K_{Jc(med)}$ as a function of temperature, assumes a Weibull distribution with K_{min}=20 MPa.m$^{0.5}$ and slope b=4 for 1T specimen size. It is allowed the use of different specimen sizes, but it is mandatory the conversion of K_{Jc} data to equivalent K_{Jc}(1T). ASTM E 1921-14 presents the methodology for the calculation of T_0, using datasets obtained at single and multiple temperatures. The standard imposes that the test temperature of the dataset used for T_0 calculation must be in the range T_0 +/- 50 ºC. Single and multi-temperature options were applied to the Euro Dataset. For the first case, it was observed that the upper restrictive limit of temperature may be relaxed, using data censored if corresponds. When the multi-temperature option was used, it was observed that the $K_{Jc(med)}$ rises as specimen size increases, being the most conservative the $K_{Jc(med)}$ obtained using 1/2T data. In these cases, the effect of specimen size resulted more important than the effect of the test temperature used for the calculation of T_0.*

Keywords: *Ductile-to-brittle transition, Scatter, Master Curve*

1. INTRODUCTION

ASTM E 1921standard (2013) has adopted the Master Curve (MC) method for the analysis of the fracture toughness of ferritic steels in the ductile-to-brittle transition region. The method derived from works beginning around 1980 (Landes and Shaffer, 1980; Landes and McCabe, 1982; Wallin, 1984, 1991,1993).

The MC gives the dependence of the 1T median fracture toughness with the temperature. It is based on an empirical equation calibrated at the T_0 temperature (McCabe *et al.*, 2005).

T_0 is determined assuming a Weibull distribution with K_{min}=20 MPa.m$^{0.5}$ and slope b_K=4 for the scatter treatment, and it is the temperature at which K_{med}=100 MPa.m$^{0.5}$ for this size.

Prior to the MC, ASME Boiler and Pressure Vessel Code (2001a; 2001b) already established the lower bound K_{IC} and K_{Ia} curves for the characterization of ferritic pressure vessel steels. The reference temperature was RT_{NDT} instead of T_0. Although the MC has represented a huge technological advance in the ductile-to-brittle transition region treatment, introducing fracture toughness measurements and the effects of size and scatter, there are still some aspects that need a deeper analysis.

MC considers as fixed the shape (b=4) and threshold (Kmin=20 MPa m$^{1/2}$) parameters, although other values of these parameters are obtained experimentally, even when the sample size could be considered big enough for parameter estimation, i.e. 30 or more specimens. Previous works (Larrainzar et al., 2010; Berejnoi and Perez Ipiña, 2010, 2014; Perez Ipiña and Berejnoi, 2013; Berejnoi *et al.*, 2015) suggested that neither the Weibull slope in terms of K is consistent with a fixed value equal to 4, nor the threshold parameter with a value of 20 MPa m$^{1/2}$. Consequently, the equation used in ASTM E1921 (2013) to model the specimen size effects could not work properly for toughness conversion from different specimen sizes other than 1 inch, and the determination of T_0 from these specimens could be not correct.

For the determination of T_0, ASTM E1921 (2013) specifies not only the procedure for thickness correction, but also the censoring of data and the range of temperatures where dataset is considered valid. The determination of this reference temperature may be performed with tests data obtained at only one temperature or from tests performed at various temperatures (multitemperature procedure).

This work presents an analysis of the effects of specimen size and test temperature in the determination of T_0, the reference temperature of the Master Curve for ferritic steels in the ductile-to-brittle transition region, using single and multitemperature procedures, converting data to 1" sizes and censoring data when necessary.

2. MATERIAL AND METHOD

Datasets taken from the Euro Fracture Toughness Dataset (Heerens and Hellmann, 2002) were used in the present work. They correspond to the Round Robin organized by the European Structural Integrity Society (ESIS) and all the information is available in ftp://ftp.gkss.de/pub/eurodataset.

The material tested in the project was a ferritic steel DIN 22NiMoCr37 forged, quenched and tempered. The analyzed datasets correspond to tests that were carried out at different temperatures (-154°C, -91°C, -60°C, -40°C, -20°C) and with different specimen thicknesses C(T) (½", 1", 2" and 4", identified as 1/2T, 1T, 2T and 4T respectively), with a thickness to width ratio B/W=0.5. Specimens were fatigue pre-cracked to be inside the range $0.52<a_0/W<0.6$. Side grooving was performed after pre-cracking in a few specimens. Tests were carried out in order to obtain the fracture toughness at the point of fracture, J_C.

2.1 T_0 determination using single test temperature

T_0 values were calculated according to ASTM E1921 (2013) for all the sets analyzed. The method includes the calculation of K_{Jc} values, derived from Jc using Eq. (1), their conversion to 1T equivalent size, as well as the procedure for data censoring when necessary. In this work E=210 GPa and μ=0.3 were used.

ASTM E1921 (2013) imposes two limits for K_{Jc} values: the first one is given by the condition of high crack-front constraint at fracture (Eq. (1)).

$$K_{J\max} = \sqrt{\frac{Eb_0\sigma_{YS}}{30\left(1-\nu^2\right)}} \tag{1}$$

The second limit states that K_{Jc} values also shall be regarded as invalid for tests that terminate in cleavage after more than $0.05(W-a_o)$ or 1 mm (0.040 in.), whichever is smaller, of slow-stable crack growth.

When high constraint conditions are violated, the K_{Jmax} value should be used as replacement for the K_{Jc} value. When censoring is due to an excessive crack growth, the highest ranked valid K_{Jc} should be used (denominated as $K_{Jc\_\Delta a}$) in place of K_{Jc}. When both conditions are violated, the minimum between K_{Jmax} and $K_{Jc\_\Delta a}$ must be used. Then, the K_{Jc} values for a B thickness specimen must be converted to 1T equivalent by means of Eq. (2), resulting K_{Jc-1T}.

$$K_{Jc-1T} = 20+\left[K_{Jc}-20\right].\left(\frac{B}{B_{1T}}\right)^{1/4} \tag{2}$$

Where B_{1T} refers to the thickness of prediction (1T specimen).

K_0 is calculated by means of Eq. (3).

$$K_0 = \left[\sum_{i=1}^{N}\frac{\left(K_{Jc(i)}-20\right)^4}{r}\right]^{1/4} + 20 \tag{3}$$

$K_{Jc(i)}$ corresponds to the individual K_{Jc} (originally 1T or converted to 1T equivalent), r is the quantity of non-censored tests, and N the total number of tests.

Then K_{med} is calculated by Eq. (4). For a dataset tested at temperature T, the value of T_0 is obtained by Eq. (5).

$$K_{med} = 20+\left(K_0-20\right)\left[\ln\left(2\right)\right]^{1/4} \tag{4}$$

$$T_0 = T-\left(\frac{1}{0.019}\right)\ln\left[\frac{K_{Jc(med)}-30}{70}\right] \tag{5}$$

K_0 and K_{med} were calculated for each size and temperature using Eqs. (3) and (4), respectively. Data censoring was applied when necessary. In addition, the values of K_0 and K_{med} were calculated at constant temperature using all equal temperature datasets as a unique dataset.

2.2 T_0 determination using multiple test temperature

Before T_0 calculation, data must be checked for validity, and then converted to equivalent 1T.

$$\sum_{i=1}^{N}\delta_i \frac{\exp\left[0.019\left(T_i - T_{0Q}\right)\right]}{11+77\exp\left[0.019\left(T_i - T_{0Q}\right)\right]} - \sum_{i=1}^{N}\frac{\left(K_{Jc(i)}-20\right)^4 \exp\left[0.019\left(T_i - T_{0Q}\right)\right]}{\left\{11+77\exp\left[0.019\left(T_i - T_{0Q}\right)\right]\right\}^5} = 0 \qquad (6)$$

The T_{0Q} value is the one that satisfies Eq. (6), that takes into account the number of specimens tested (N), the test temperature corresponding to $K_{Jc(i)}$ (T_i), and the $K_{Jc(i)}$ value (either a valid K_{Jc} datum or its substitute value). δ_i is equal to 1 when the datum is valid. This equation must be solved by iteration.

The validation of T_{0Q} as T_0 includes the verification of testing condition and minimum number of specimen tested.

When the multitemperature procedure was applied, only valid datasets were used for the first time (not further than +/-50 °C from the T_0 obtained using single temperature procedure), and later the datasets obtained at one temperature further than 50ºC of the first estimate of T_0 were incorporated, considering individual thicknesses and all thicknesses together.

3. RESULTS, ANALYSIS AND DISCUSSION

3.1 T_0 determination using single temperature datasets

Table 1 shows T_0, K_0 and K_{med}, while Fig. 1 shows the effect of thickness and test temperature on T_0, and Fig.2 shows the position of the different K_{med} in relation to the MC.

Table 1. T_0, K_0 and K_{med}.

T ^{0}C	Size	Total Tests	Cleavage tests	N_{NV}*	*K_0* MPa.m$^{1/2}$	*K_{med}* MPa.m$^{1/2}$	*T_0* ^{0}C	*T-T_0* ^{0}C
-154	1/2T	31	31	0	39.83	38.09	-40.42	-113.58
-154	1T	34	34	0	42.43	40.46	-53.97	-100.03
-154	2T	30	30	0	44.10	41.99	-61.13	-92.87
-154	All	95	95	0	42.30	40.35	-53.40	-100.6
-91	1/2T	31	31	0	106.41	98.84	-90.12	-0.88
-91	1T	34	34	0	116.11	107.7	-96.49	5.49
-91	2T	30	30	0	117.05	108.55	-97.07	6.07
-91	4T	15	15	0	117.25	108.73	-97.19	6.19
-91	All	110	110	0	114.12	105.88	-95.25	4.25
-60	1/2T	31	31	2	143.43	132.62	-80.13	20.13
-60	1T	34	34	0	158.63	146.5	-86.81	25.81
-60	2T	30	30	0	229.77	211.41	-110.12	50.12
-60	All	95	95	2	189.84	174.97	-98.32	38.32
-40**	1/2T	30	27	22	367.78	337.33	-117.86	77.86
-40	1T	32	32	1	232.15	213.58	-90.74	50.74
-40	2T	30	30	0	213.02	196.12	-85.48	45.48
-40	All	92	89	23	223.42	205.61	-88.41	-48.41
-20**	1/2T	31	10	29	465.22	426.24	-111.24	91.24
-20	1T	30	30	16	340.55	312.48	-93.43	73.43
-20	2T	30	30	0	304.24	279.35	-86.86	66.86
-20	4T	15	15	0	280.62	257.81	-82.11	62.11
-20	All	106	85	45	309.22	283.9	-87.81	67.81

(*) N_{NV}: Number of specimen with K_{Jc}>K_{Jmax} and/or violating Δa limitation

(**) Corresponds to datasets where K_0 was unable to be calculated because the minimum number of valid results stated in the ASTM standard was not reached.

Wallin (2002) presents the K_0 values calculated for different specimen sizes and temperatures, but considering datasets with no size corrections. For 1" specimens, the values in Table 1 are similar to those presented by Wallin (2002).

A band of $T_0 \pm 15$ ºC was incorporated in Fig. 1 as a limit for T_0 determination. From all T_0 values calculated, shown in Tab. I, the one to 1T specimens and T=-91ºC was selected as the T_0 value for this material. (T_0= -96.5°C).

Equation (7) was employed to obtain the Master Curve.

$$K_{med} = 30 + 70\exp\left[0.019\left(T - T_0\right)\right] \tag{7}$$

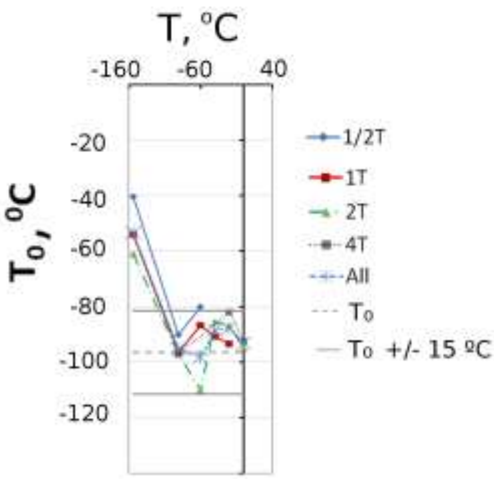

Figure 1. T_0 according to ASTM E1921, at different temperatures and specimen sizes

Most censored data corresponded to the K_{Jmax} limit. Almost all the data that had to be eliminated by the ductile crack growth (Δa) limit were previously eliminated by K_{Jmax}. As expected, censoring was larger for higher temperatures and smaller sizes. Only two data corresponding to 0ºC and *B*=4T were censored just for Δa limit. Non-valid K_{Jc} corresponded to -60°C and higher temperatures for 1/2T-CT specimens, while for 1T they began at -40°C. For 1/2T and -40°C most specimens were censored, although 8 valid results allowed a T_0 calculation. For higher temperatures, there were not enough 1/2T valid (non censored) results to calculate a T_0 value. For 1T at -20°C there were more than half non-valid results, although all of them presented cleavage.

Figure 1 shows the estimated T_0 values for the censored conditions. The standard states that the T_0 determination must be carried out with tests performed at temperatures close to T_0, with a span lower than 50°C. T_0 seems to be around -96 °C. Estimations shown in Fig. 1 exhibit a clear asymmetry: T_0 estimations from temperatures lower than T_0 and out of the admitted range, give very poor T_0 estimation (the standard does not allow testing at lower shelf regime), while for $T>T_0$, the limit imposed by the standard looks unnecessarily restrictive. Using the data censoring as the limit for high temperature seems to be more reasonable, although there will be more non-valid tests at higher temperatures and then more tests to be performed in order to reach the minimum number of valid results for T_0 calculation.

The general trend is that K_0 increases as T increases. For censored sets, K_0 appears not size dependent.

At high temperature and especially small sizes (1/2 T at and over -40°C, 1T at and over 0°C and all sizes for 20°C) there were not enough valid values to estimate K_0.

The K_{med} values should be size independent for each temperature, and they should also be located at the Master Curve. Figure 2 shows that this is almost verified for T=-154 ^{0}C and T = -91 ^{0}C, but it seems not to be valid for other cases. The Master Curve seems to slightly overestimate the K_{med} for -40°C and -20°C. The K_{med} values estimated for different sizes at equal temperature presented some scatter, especially for -60 °C and -20 °C, although no clear size tendency could be observed.

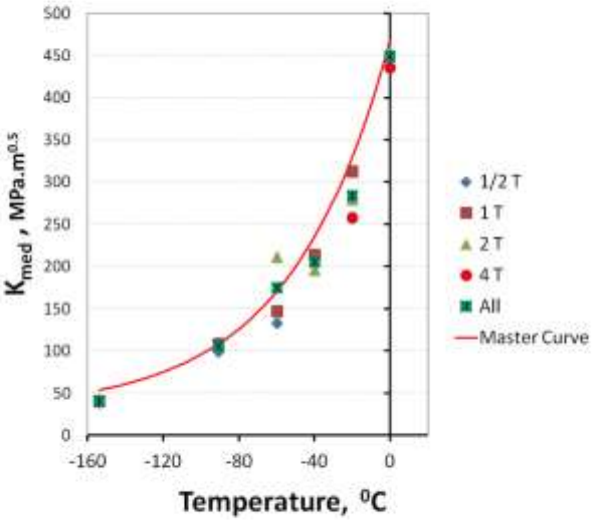

Figure 2. K_{med} vs. T for different sizes and Master Curve according to ASTM E1921

3.2 T_0 using multitemperature procedure

Table 2 shows the T_0 values obtained by the multitemperature procedure, using different temperature ranges and sample sizes. For instance, row [-91, -60] corresponds to the T_0 value calculated using specimens tested at -91 ºC and -60ºC, while [-91,-40] includes also the test results obtained at -60 ºC. The T_0 value for 4T size was not calculated as an individual size, because specimens of this thickness were tested at temperatures far from -96ºC, except -91ºC. However, the results for this size were used for T_0 estimation when all the results were taken as a unique dataset (column ALL).

Table 2. T_0 values calculated using different temperature ranges and specimen sizes.

Test Temperatures Range	Thickness			
	1/2 T	1 T	2 T	ALL
[-91,-60]	-85,65	-92,00	-105,10	-96,61
[-91.-40]	-86,95	-91,51	-100,85	-94,90
[-91,-20]	-87,22	-91,77	-98,27	-93,75
[-154,-60]	-81,60	-88,19	-101,03	-92,83
[-154,-40]	-83,36	-88,87	-98,13	-92,07
[-154,-20]	-83,72	-89,43	-96,26	-91,45
ALL	-83,88	-90,06	-96,65	-93,09

$K_{Jc(med)}$ rises as specimen size increases, being the most conservative those obtained using 1/2T data. In these cases, the effect of specimen size resulted more important than the effect of the test temperature used to calculate T_0.

When the number of results used in T_0 estimation is increased, the obtained MC using the multitemperature procedure approximates the one obtained by means of the single-temperature method for 1T size, even when the results correspond to temperatures far away from T_0. In part, this is because the MC for 1/2T specimens (conservative when compared with 1T specimens) compensates the MC for 2T specimens.

Figures 3 to 9 show the MC as function of original sample sizes. The MC obtained from 1T specimen at -91ºC using the single-temperature procedure and considered as reference in this paper is also plotted in these figures. The exponential form of the Master Curve makes that K_{Jmed} for different sizes are almost equal for temperatures close to the lower shelf region, while for temperatures higher than T_0, the K_{Jmed} predicted by MC for different sizes are clearly different.

When the temperatures used for the MC computation are within the range T_0+/- 50ºC, the curve obtained using all datasets almost coincides with MC from 1T single Temperature determination (Fig. 3 and Fig. 4). If the temperatures outside this range are incorporated, the MC from 1T single Temperature tends to be coincident with the MC obtained using only 2T specimens (Figs. 5, 6, 7, 8 and 9).

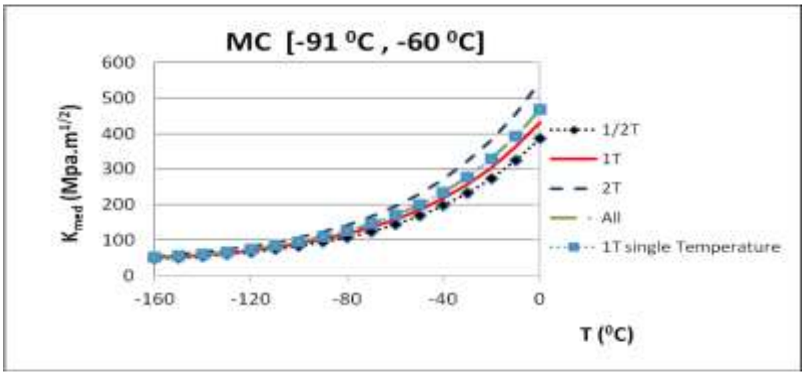

Figure 3. MC as function of original sample sizes for [-91ºC, -60ºC] range

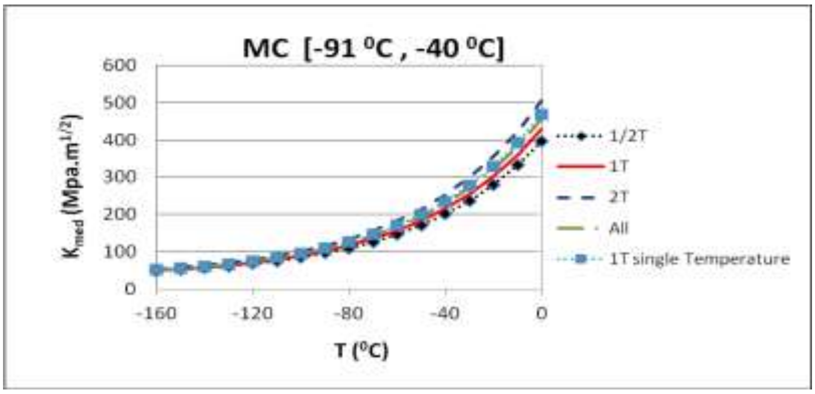

Figure 4. MC as function of original sample sizes for [-91ºC, -40ºC] range

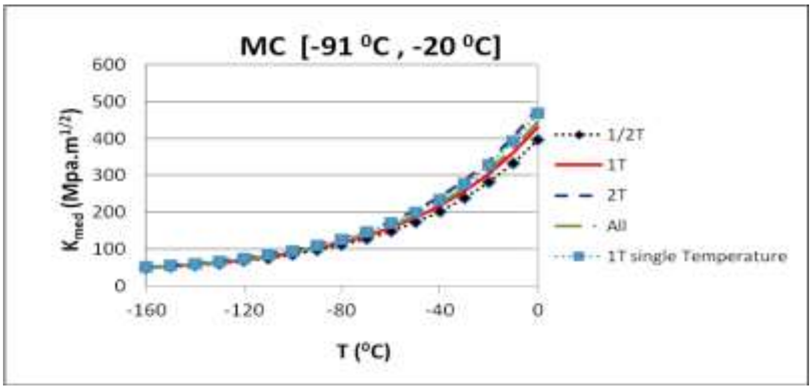

Figure 5. MC as function of original sample sizes for [-91ºC, -20ºC] range

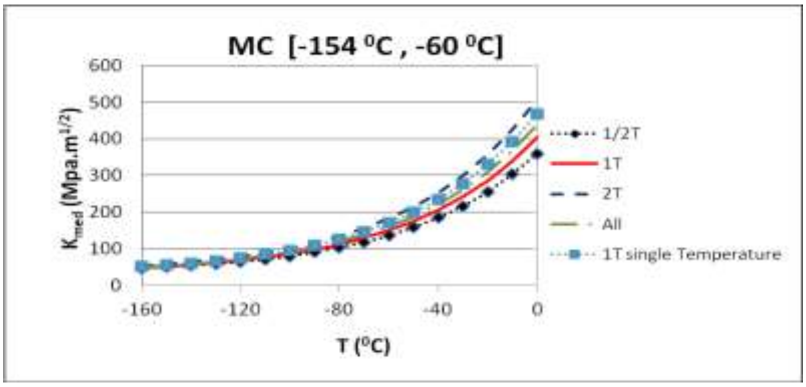

Figure 6. MC as function of original sample sizes for [-154ºC, -60ºC] range

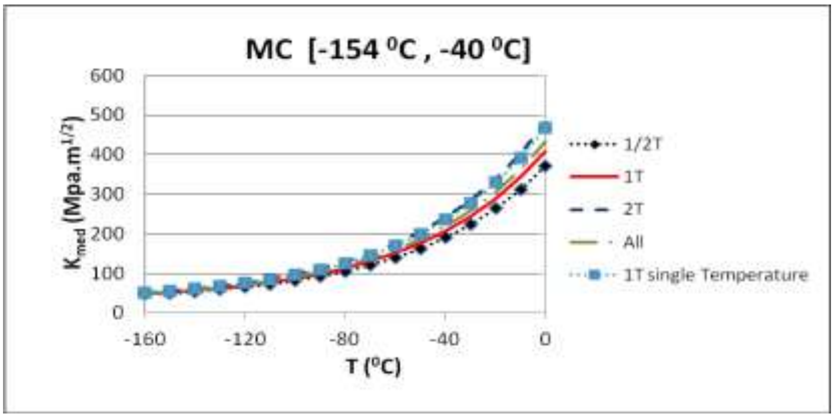

Figure 7. MC as function of original sample sizes for [-154ºC, -40ºC] range

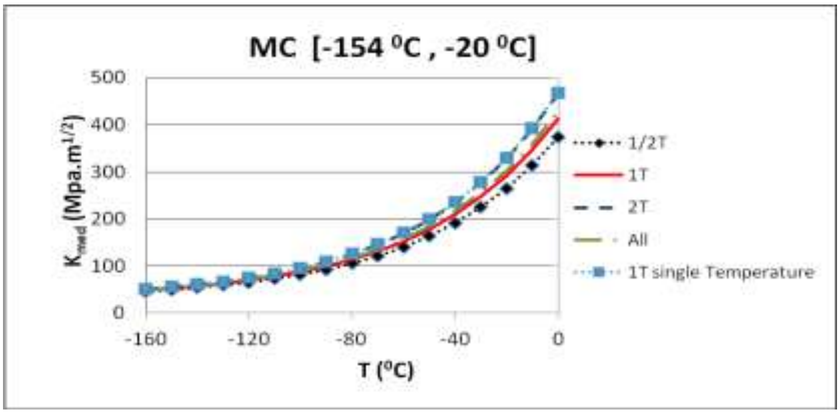

Figure 8. MC as function of original sample sizes for [-154ºC, -20ºC] range

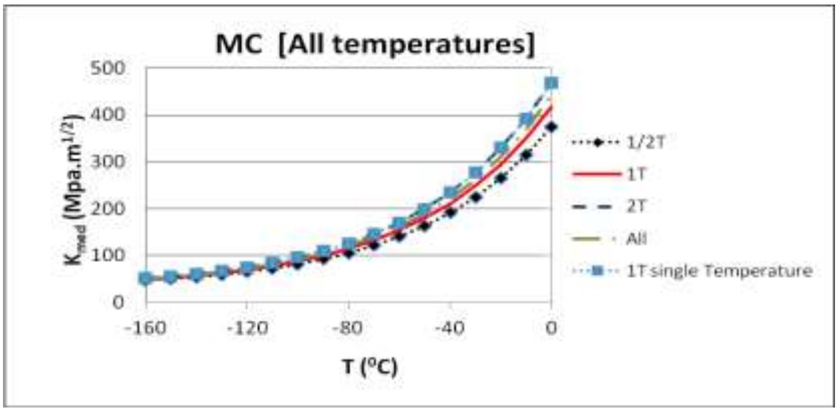

Figure 9. MC as function of original sample sizes including all test temperatures

4. CONCLUSIONS

When single-temperature method is used, the T_0 estimations from temperatures lower than T_0 and out of the admitted range, give very poor T_0 estimation. For $T>T_0$ using the data censoring as the limit for high temperature seems to be more reasonable than the T_0+50ºC limit.

$K_{Jc(med)}$ obtained by the multi-temperature method rises as specimen size increases, being the most conservative the $K_{Jc(med)}$ obtained using 1/2T data. In these cases, the effect of specimen size resulted more important than the effect of the test temperature used for the calculation of T_0. When the temperatures used for the MC computation are within the range T_0+/- 50ºC, the curve obtained using all datasets almost coincides with MC from 1T single-temperature determination. When temperatures outside this range are incorporated, the MC from 1T single-temperature tends to be coincident with the MC obtained using only 2T specimens.

K_{min}=20 is imposed in ASTM standard as the best threshold parameter when b_K=4, based on the fact that a large data set would be necessary for a good estimation of this parameter. But, in this work it is shown that when large datasets are employed, some differences arise in T_0 values obtained from different specimen sizes. Considering that this variation may be due to the size conversion formula, and the values of the fixed parameters used, it concludes that a deeper study considering b_K and K_{min} different from those stated in ASTM standard is necessary. This would help in decreasing the conservatism of the calculated $K_{Jc(med)}$ from small specimens.

5. ACKNOWLEDGEMENTS

To Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET) and to Consejo de Investigación de la Universidad Nacional de Salta by the support to this work.

6. REFERENCES

ASME Boiler and Pressure Vessel Code, 2001a. "Rules for Construction of Nuclear Power Plant Components". , *Section III*.

ASME Boiler and Pressure Vessel Code, 2001b. "Rules for In-Service Inspection of Nuclear Power Plant Components". *Section Xl*.

ASTM E 1921, 2013. "Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range". In: *Annual Book of ASTM Standards 2013, Vol. 03.01*.

Berejnoi, C. and Perez Ipina, J.E., 2012. "Análisis de los Parámetros de la Distribución de Weibull en la Descripción de los Resultados de Tenacidad a la Fractura de Aceros en la Transición Dúctil-Frágil". *Congreso Argentino de Ingeniería - CADI 2012, VII Congreso Argentino de Enseñanza de la Ingeniería – CAEDI.* Mar del Plata, Argentina.

Berejnoi, C. and Perez Ipina, J.E., 2014. "Análisis de los efectos del tamaño de probeta y la temperatura de ensayo en la determinación de la Curva Maestra". *II Congreso Argentino de Ingeniería - CADI 2014, VIII Congreso Argentino de Enseñanza de la Ingeniería - CAEDI 2014*. Tucumán, Argentina.

Berejnoi, C., Vacca, S., Galarza, C. and Perez Ipina, J.E., 2015. "Análisis del valor mínimo de la tenacidad a la fractura de un acero ADN420 a temperatura ambiente". *X Jornadas de Ciencia y Tecnología de Facultades de Ingeniería del NOA*. Salta, Argentina.

Heerens, J. and Hellmann, D., 2002. "Development of the fracture toughness Dataset". *Engineering Fracture Mechanics*, Vol. 69, p. 421-449.

Landes, J.D. and McCabe, D.E., 1982. "Effect of Section Size on Transition Behavior of Structural Steels". *Scientific Paper 81-1D7-Metal-P2*, Westinghouse R&D Centre.

Landes, J. D. and Shaffer, D. H., 1980. "Statistical Characterization of Fracture in the Transition Region". In *ASTM STP 700*, p. 368-382.

Larrainzar, C., Berejnoi, C. and Perez Ipina, J.E., 2010. "Comparison of 3p-Weibull parameters based on *Jc* and *KJc* values,"*Fatigue Fract. Eng. Mater. Struct.*, Vol. 34, p. 408-422.

McCabe, D.E., Merkle, J.G., and Wallin, K., 2005. "An Introduction to the Development and Use of the Master Curve Method". In: *ASTM manual series, MNL52, ASTM International*.

Perez Ipiña, J.E., Berejnoi C., 2013. "Experimental Validation of the Relationship between Parameters of 3P-Weibull Distributions Based in J_C or K_{JC}". *13th International Conference on Fracture*, Beijing, China.

Wallin, K., 1984. "The Scatter in K_{IC} – Results". *Engng. Fracture Mech.*, Vol. 19(6), p. 1085-1093.

Wallin, K., 1993. "Statistical Aspects of Constraint with Emphasis on Testing and Analysis of Laboratory Specimens in the Transition Region". In: *ASTM STP 1171*, p. 264-288.

Wallin, K., 1991. "Fracture Toughness Transition Curve Shape for Ferritic Structural Steels". In: *Proceedings of the Joint FEFGIICF International Conference on Fracture of Engineering Materials and Structures*, p. 83-88.

Wallin, K., 2002. "Master curve analysis of the ''Euro" fracture toughness dataset". *Engineering Fracture Mechanics*, Vol. 69, p. 451-481.

7. RESPONSIBILITY NOTICE