STYRELSEN FÖR

VINTERSJÖFARTSFORSKNING

WINTER NAVIGATION RESEARCH BOARD

Research Report No 90

Kim Wallin

RELEVANCE OF CHARPY-V IMPACT CRITERIA FOR NODULAR CAST IRON

FOREWORD

In this report no 90, the Winter Navigation Research Board presents the outcome of research on the applicability of Charpy-V impact criteria for nodular cast iron. The Charpy-V criteria is in use in the Finnish-Swedish ice class rules for the determination of the fracture toughness of steel but it is not as such applicable to nodular cast iron due to the different transition behaviour and notching characteristics than steel, for which the criteria is originally developed.

However, the use of Charpy-V criteria can be more economic or practical than direct fracture toughness tests. In this research project, the relevance of the Charpy-V criteria for nodular cast iron was re-examined taking into account the different characteristics of steel and nodular cast iron and a new definition of equivalent energy criterion for nodular cast iron is proposed.

The Winter Navigation Research Board warmly thanks Dr. Kim Wallin for this report.

Helsinki and Norrköping

October 2016

Jorma Kämäräinen

Finnish Transport Safety Agency

Tomas Årnell

Swedish Maritime Administration
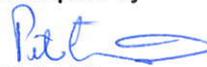
Markus Karjalainen

Finnish Transport Agency

Stefan Eriksson

Swedish Transport Agency

Relevance of Charpy-V impact criteria for nodular cast iron

Author: Kim Wallin

Confidentiality: Confidential

Report's title		
Relevance of Charpy-V impact criteria for nodular cast iron		
Customer, contact person, address		**Order reference**
Finnish Transport Safety Agency (Trafi), Jorma Kämäräinen, P.O.Box 320, FI-00101 Helsinki, Finland		TRAFI/7997/02.03.01/2013
Project name		**Project number/Short name**
Technical consultancy related to the ice class rules of propulsion machinery		82982-3.1 / ICERU2013
Author		**Pages**
Kim Wallin		11 p.
Keywords		**Report identification code**
Cast iron, Charpy-V, Fracture toughness		VTT-R-05567-13

Summary

Attempts to transfer the Charpy requirements developed for steels also to nodular cast irons have not been successful. The reason for this lies in the fact that nodular cast irons have different transition behaviour than steels and they experience notches differently. By accounting for these differences, the relevance of the Charpy-V test for nodular cast steels is re-examined here and as a result, a new definition of an equivalent energy criterion for nodular cast iron is proposed. The resulting equivalent impact energies are:

$C_{v\,GJS}$ [J]	$C_{v\,eq}$ [J]	$C_{v\,GJS}$ [J]	$C_{v\,eq}$ [J]	$C_{v\,GJS}$ [J]	$C_{v\,eq}$ [J]	$C_{v\,GJS}$ [J]	$C_{v\,eq}$ [J]
1	4	7	19	13	28	19	35
2	8	8	20	14	29	20	37
3	10	9	22	15	31	21	38
4	13	10	23	16	32	22	39
5	15	11	25	17	33	23	40
6	17	12	26	18	34	24	41

Specifically, the rules for ice class regulations require that "*Materials of components exposed to sea water, shall have an average impact energy value of 20 J taken from three tests obtained at minus 10 °C.*" This requirement is, in the case of nodular cast iron, equivalent to an average impact energy of 8 J.

Confidentiality	Confidential

Espoo, Finland, 15 August 2013

Written by	Reviewed by	Accepted by
Kim Wallin Research Professor	Päivi Karjalainen-Roikonen Principal Scientist	Petri Kinnunen Deputy Technology Manager

VTT's contact address

VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Finland
Tel. + 358 20 722 111 (exchange), firstname.lastname@vtt.fi

Distribution (customer and VTT)

Customer, 1 original,
VTT archives, 1 original

Contents

1. Introduction

On occasion, it may be impossible or impractical to perform actual fracture toughness tests on a material. There may be insufficient material available for testing, or the cost, in relation to the structure, may be too high. In these cases, the fracture toughness may sometimes be estimated indirectly from a simpler test. An example of such a test is the Charpy impact test. Today, the Charpy impact test is still the most commonly used standard test to evaluate a material's fracture properties. The test is quick and simple to perform and requires only comparatively small specimens. Nearly all materials and manufacturing standards apply requirements based on the Charpy impact test.

The development of the Charpy impact test was led by A. E. A. Charpy at the beginning of the 20th century. Thus, the test is more than 100 years old. The most common notch geometry today is the V-notch, but other geometries are sometimes used. The main parameter determined in the Charpy test is the energy required to fracture the specimen.

The use of notched impact specimens stems from the revelation that dynamic loading and stress concentrations promote cleavage fracture, i.e. such a loading was more severe from a structural integrity point of view than for a simple tension test. The choice of notch configuration is usually connected to material type. For structural ferritic steels, which show a ductile-to-brittle transition, the V-notch is commonly applied. Other geometries or even un-notched specimens are used for brittle materials like some cast irons, or tough materials like austenitic stainless steels.

The Charpy-V data is normally used in the context of some transition temperature concept. Transition temperature concepts are generally used with structural steels that undergo a ductile to brittle transition. However, Charpy-V tests may also be used to indirectly estimate the materials ductile tearing properties.

The Charpy tests were originally used mainly as quality control tests. After World War II, the analysis of the failures in welded merchant ships changed the nature of these tests to be more of a design tool. With 1289 out of the 4694 ships built during the war experiencing serious or potentially serious fractures, a large effort was put into understanding the reason for the failures. Ship plates where cracks had initiated, showed generally a lower toughness at the failure temperature, than plates where the fracture had arrested. This led to the introduction of the first transition temperature concepts.

Much of the early development work was performed at the Unites States Naval Research Laboratory (NRL) and their test methods and transition temperature definitions are still being used throughout different industries. The materials that were used in the NRL research were generally ship steel plates common for the time. This is an important detail that is often forgotten when the transition temperature definitions are used for other classes and types of metals.

Attempts to transfer the Charpy requirements developed for steels also to nodular cast irons have not been successful. Actually a resent conclusion [1] was that "*Charpy impact testing is neither an accurate nor acceptable way to measure impact toughness in cast irons. It is inappropriate to use it as a means of comparison between cast iron and steel*". The reason for this conclusion lies in the fact that nodular cast irons have different transition behaviour than steels and they experience notches differently. By accounting for these differences, the relevance of the Charpy-V test for nodular cast steels is re-examined here and as a result, a new definition of an equivalent energy criterion for nodular cast iron is proposed.

2. Fracture behaviour of nodular cast iron

The fracture process of nodular cast iron is either fully ductile (Figure 1a) or partly brittle (Figure 1b). The fracture process is controlled by factors like, temperature, strength, and perlite content. The fully ductile behaviour is similar to the upper shelf fracture behaviour of steels, but the partly brittle behaviour differs from the behaviour seen in steels in the transition region. In this region, the fracture energy for steels is controlled by the energy required for cleavage crack initiation. In the case of cast irons, the fracture energy is also controlled by the energy required for crack propagation as seen from Figure 1b. In terms of tearing resistance, the fully ductile case will lead to a classical full tearing resistance curve, whereas the partly brittle case will lead to a limited tearing resistance curve as schematically shown in Figure 2 [2]. The limited tearing resistance curve differs from cleavage fracture toughness in steel in that the limited tearing resistance curve requires a "constant" crack driving force to propagate the crack, whereas a cleavage crack propagates as long as the crack driving force is above the crack arrest toughness. This difference reflects on the Charpy-V fracture toughness correlation in the "transition region". Different to steels, nodular cast irons should have basically the same correlation between Charpy-V and fracture toughness both in the transition region and the upper shelf region. For this reason, transition temperature concepts are not descriptive for nodular cast irons.
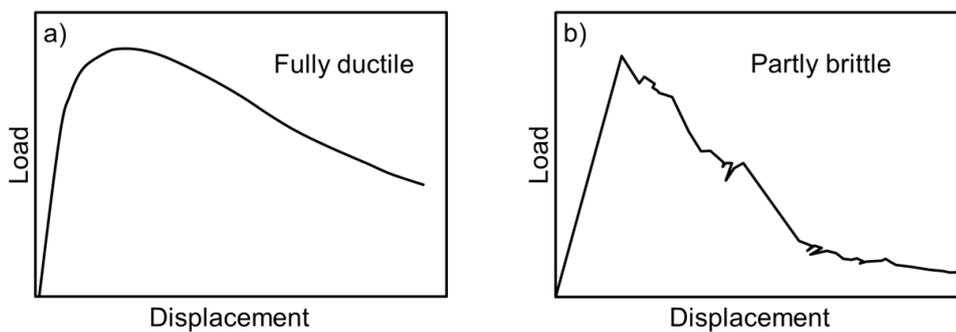
Figure 1. Fracture behaviour of nodular cast iron.
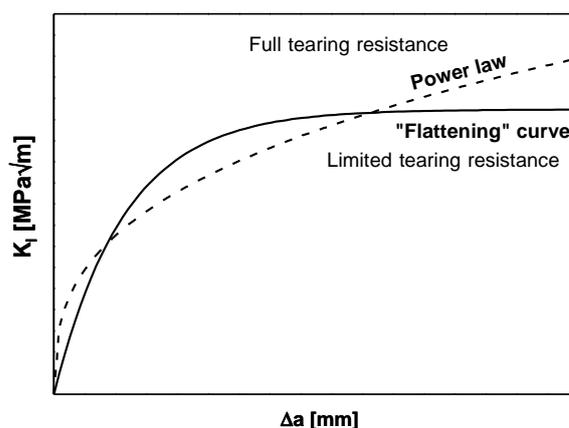
Figure 2. Schematic presentation of definitions for "limited tearing resistance" and "full tearing resistance [2].

The proper fracture toughness values describing nodular cast iron are the full tearing resistance curve, some defined point on the tearing resistance curve like J_{Ic} (K_{JIc}) or the instability value of the limited resistance curve (K_{inst}). To account for non-linearity in the tests it is advisable to assess the fracture toughness in terms of the J-integral that can be

presented in the form of K_{Jlc}. Nodular cast irons should preferably not be tested according to ASTM E399 or equivalent standards, nor should the fracture toughness be taken as the value corresponding to maximum load. Both of these values can lead to fully incorrect descriptions of the materials true fracture toughness. Only if $P_{max} = P_Q$ in a test, is the LEFM K_{IC} value descriptive of the critical fracture toughness.

The other factor being different for cast irons and steels is the response to a notch. Cast irons are traditionally known as notch insensitive materials, because their fracture energy is less affected by different notches than steels. The reason for this apparent insensitivity is however the opposite. Cast irons are very sensitive to notches. Even a moderate notch is sensed as if it were close to a sharp crack. This appears as an apparent insensitivity, since all notches are experienced as being close to cracks. The reason for this lies in the graphite nodules, which fail already at small strains. This results basically in a microcrack region in front of the notch. This microcrack region overwhelms the notch acuity effect, thus effectively making the notch sharper than what is normally experienced with steels. This causes the nodular cast iron to show a lower Charpy-V energy for the same fracture toughness compared to steels.

3. Ductile fracture toughness estimation

It is possible to derive a theoretical lower bound estimate of the C_{V-US} energy based on the J-R -curve information. The derivation is presented in [2]. It is based on the estimation of the total energy needed to fracture a CVN size ligament in half. It assumes a deep crack, quasi-static loading and J-controlled crack growth through the whole ligament. The tearing resistance curve is approximated as a simple power law, Eq. (1). The resulting theoretical estimate has the form of Eq. (2) [2].

$$J = J_{1mm} \cdot \Delta a^m \tag{1}$$

$$E_{TOT} = \frac{J_{1mm} \cdot 10 \text{ mm} \cdot (8 \text{ mm})^{m+1}}{(m+1) \cdot 1 \text{mm}^m} \tag{2}$$

The above energy estimate will be a theoretical lower bound estimate of the C_{V-US} energy. In a real Charpy-V-test the shallow notch and the dynamic loading combined with friction effects will increase the total absorbed energy. Furthermore, J-dominance will be lost in a real fracture of the ligament, also increasing the required energy. Thus, E_{TOT} should always be smaller than C_{V-US}. If Eq. (2) is used for materials with limited fracture toughness curves, J_{1mm} gets the value corresponding to instability and m becomes 0.

The ductile fracture toughness is usually not expressed in the form of the full tearing resistance curve, but in the form of a standard J_{IC} value. The mostly used ASTM definition of J_{IC} can be estimated from the J_{1mm} and m information and the flow stress (σ_f) by Eq. (3) [2].

$$\frac{J_{IC}}{2 \cdot \sigma_f} + 0.2 \text{ mm} - \left(\frac{J_{IC}}{J_{1mm}} \right)^{1/m} = 0 \tag{3}$$

3.1 General upper shelf correlation

An upper shelf correlation between the J-R-curve and C_{V-US}, for structural metals, has been developed using a total of 162 multi-specimen J-R -curve data sets [2]. The analysis was restricted to multi-specimen data to minimize possible experimental inaccuracies. The data sets corresponded to room temperature or temperatures below +100ºC. Thus, temperature was not a fitting parameter in the data sets. The materials yield strengths varied in the range 171 to 993 MPa and the Charpy-V-notch upper shelf energies in the range 20 to 300 J. The materials included mostly structural and pressure vessel steels and their welds, but also some Duplex, stainless and cast steels and even one aluminium alloy.

Figure 3 shows the resulting relation between C_{V-US} and the J-integral value at 1 mm crack growth. The dotted line in Figure 3 depicts the theoretical E_{TOT} estimate that would basically correspond to a pre-cracked specimen.

The exponent m can be expected to be controlled by the overall tearing resistance and the strain hardening properties of the material. The data are plotted as m against J_{1mm} in Figure 4. It is clear that m is related to J_{1mm} even though the scatter is considerable. A great deal of the scatter is however expected to be due to inadequate quality of many data sets. For engineering purposes, it is sufficient to use the mean estimate of m as given in Figure 4.
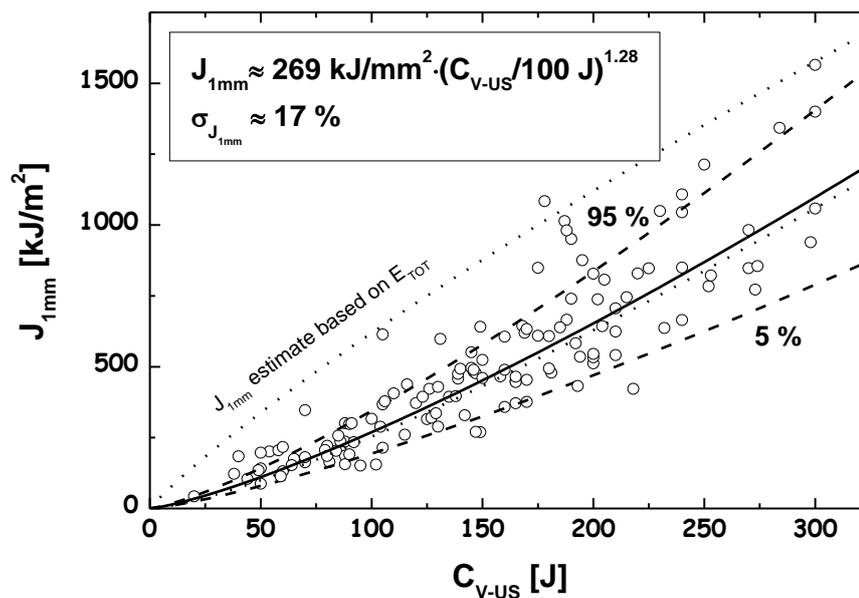

Figure 3. Relation between C_{V-US} and the J-integral value at 1 mm crack growth [2].
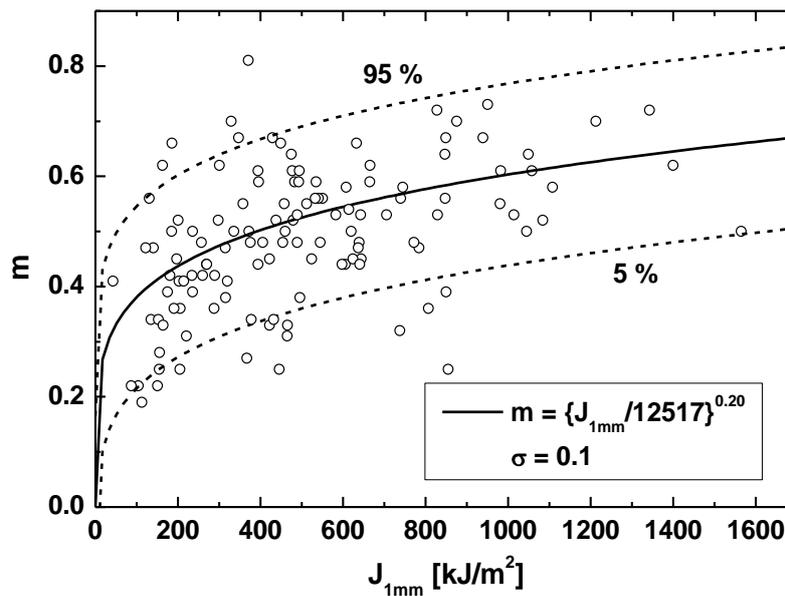
Figure 4.Shape of J-R –curve, described by exponent m, is dependent on J$_{1mm}$ [2].

4. The relation between Charpy-V and fracture toughness for nodular cast irons

Fracture toughness with accompanying Charpy-V data is somewhat scarce for nodular cast irons. However, there are a few good sources, where the fracture toughness has been estimated using a valid elastic-plastic procedure [3-5]. Figure 5 contains a compilation of ductile K_{JIC} values for a range of nodular cast irons. The data indicate a clear correlation between K_{JIC} and C_v, that is independent of iron grade. The proportional scatter in the correlation is similar as the scatter in the general correlation shown in Figure 3. The average relation between K_{JIC} and C_v for nodular cast iron can be expressed in the form of Eq. (4).

$$K_{JIC} \approx 180\,\text{MPa}\sqrt{\text{m}} \cdot \left(\frac{C_v}{100\,\text{J}} \right)^{0.4}$$
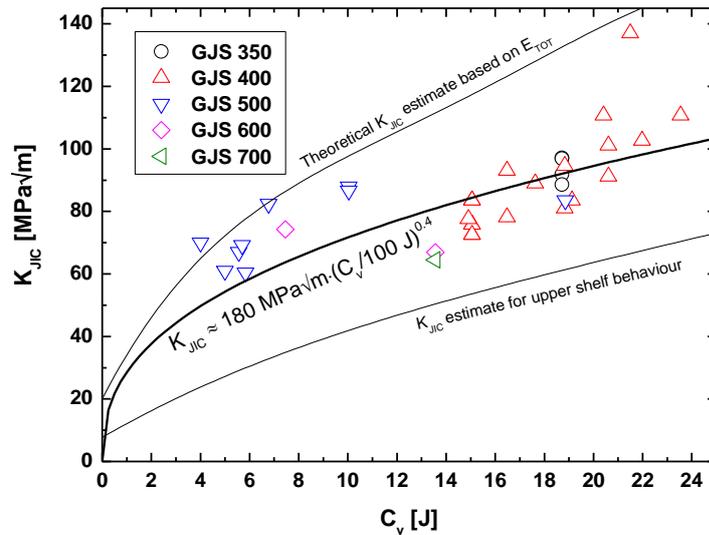
(4)

Figure 5. Relation between Charpy-V energy and ductile fracture toughness for nodular cast irons. Data taken from [3-5].

Included in Figure 5 is the K_{JIC} estimate corresponding to E_{TOT} and the K_{JIC} estimate corresponding to the general correlation given by Figures 3 and 4 and Eq. (3). As for the general correlation, E_{TOT} forms basically an absolute upper bound to the data, but the data is clearly closer to E_{TOT} than predicted based on the general correlation. This difference highlights the higher notch sensitivity of nodular cast iron, compared to bulk metals.

Figure 6 contains a compilation of partly brittle K_{IC} and K_{inst} values for a range of nodular cast irons. The K_{inst} estimate based on E_{TOT} is higher than the estimate for K_{JIC}, because K_{inst} and K_{IC} can correspond to a larger crack extension than K_{JIC}. Probably due to the flat tearing resistance curve for these materials, the partly brittle fracture toughness can be described with the same relation as found for K_{JIC}, Eq. (4). One single equation seems thus sufficient to describe the fracture toughness, Charpy-V correlation of nodular cast irons.
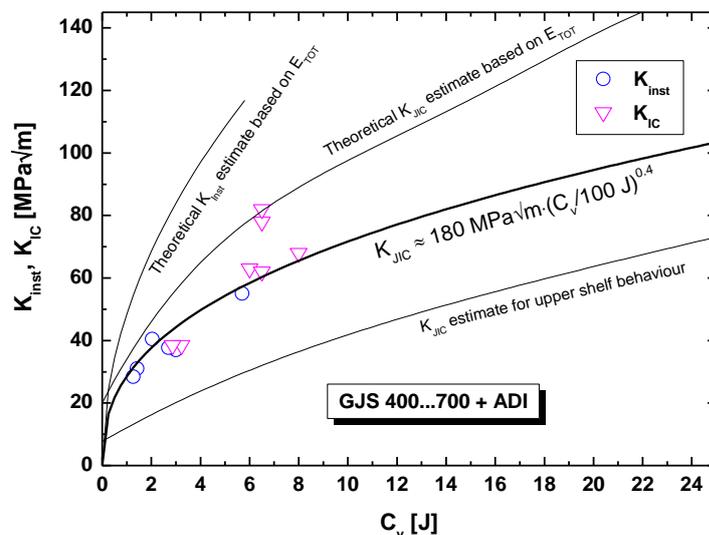

Figure 6. Relation between Charpy-V energy and fracture toughness for nodular cast irons. Data taken from [5-9].

The correlation between Charpy-V impact energy and fracture toughness is different for normal structural steels and nodular cast irons. Since the important parameter describing the materials resistance to cracks is the fracture toughness, it means that the Charpy-V requirements for nodular cast irons should be different from steels. With the help of the general correlation and the nodular cast iron specific correlation it is possible to estimate an equivalent impact energy, that gives for a steel the same fracture toughness as for nodular cast iron. The procedure to estimate the equivalent impact energy is described in Figure 7. This way it is possible to transform nodular cast iron impact toughness value to corresponding impact toughness for bulk metals. The resulting equivalent impact energies are given in Table 1 and Figure 8.

Table 1. Equivalent Charpy-V impact toughness for nodular cast irons.

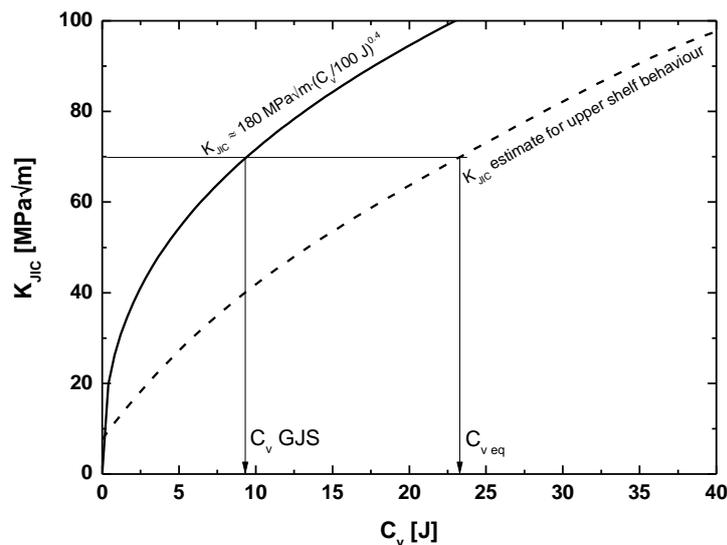| $C_{v\,GJS}$ [J]	$C_{v\,eq}$ [J]	$C_{v\,GJS}$ [J]	$C_{v\,eq}$ [J]	$C_{v\,GJS}$ [J]	$C_{v\,eq}$ [J]	$C_{v\,GJS}$ [J]	$C_{v\,eq}$ [J]
1	4	7	19	13	28	19	35
2	8	8	20	14	29	20	37
3	10	9	22	15	31	21	38
4	13	10	23	16	32	22	39
5	15	11	25	17	33	23	40
6	17	12	26	18	34	24	41

Figure 7. Principle of determining an equivalent impact energy for nodular cast iron.
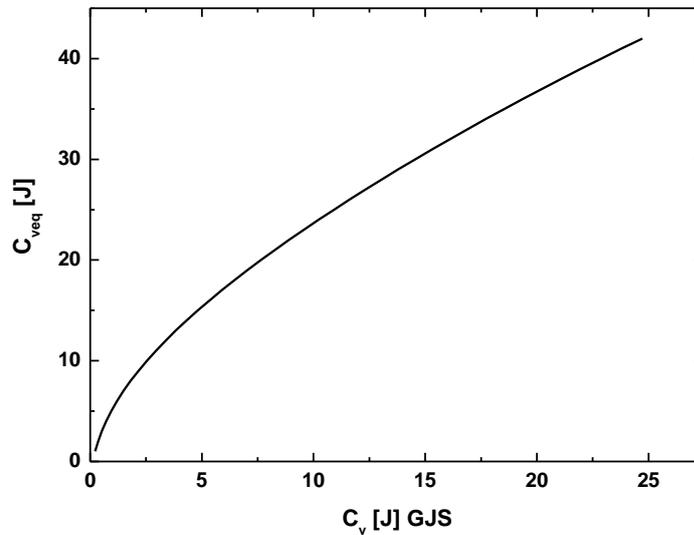
Figure 8. Equivalent Charpy-V impact toughness for nodular cast irons.

Table 1 can be used to define case specific Charpy-V requirements for nodular cast irons. If, e.g. the Charpy-V requirement for steel would be 28 J, the corresponding requirement for nodular cast iron should be 13 J. Specifically, the rules for ice class regulations [10] require that "*Materials of components exposed to sea water, such as propeller blades, propeller hubs, and thruster body, shall have an elongation of not less than 15% on a test specimen, the gauge length of which is five times the diameter. A Charpy V impact test shall be carried out for materials other than bronze and austenitic steel. An average impact energy value of 20 J taken from three tests is to be obtained at minus 10 ºC.*" This requirement is, in the case of nodular cast iron, equivalent to an average impact energy of 8 J.

It should be pointed out that the present work is not focussing on a direct estimation of the nodular cast iron fracture toughness from Charpy-V data. For this purpose, the available data base is not sufficiently large, to enable the definition of appropriate safety factors. Instead, the average behaviour of nodular cast iron, which has a larger confidence, is compared to the average general behaviour of metals. This provides a direct comparison of their Charpy-V impact energy relevance with respect to fracture toughness.

References

[1]   Oaks, M. Letting Mr. Charpy die: Evaluating the usefulness of Charpy impact testing on ductile iron. The Ductile Iron Society Spring 2012 Annual Meeting, Holiday Inn-Muskegon Harbor Ohio, June 6-8, 2012, 8 p.

[2]   Wallin, K. Fracture toughness of engineering materials - estimation and application. Warrington UK: EMAS Publishing; 2011, 543 p.

[3]   McConnell, P. & Lombrozo, P. Ductile iron data base - correlations between microstructure and fracture toughness. DE87006010, Sandia National Laboratories, 1986, 61 p.

[4]   Iwabuchi, Y., Narita, H. & Tsumura, O. Relationship between metallographic properties and fracture toughness of thick walled spheroidal graphite iron castings. Imono, 1988 ,60, pp. 215-220.

[5]   Iwabuchi, Y., Narita, H. & Tsumura, O. Toughness and ductility of heavy-walled ferritic spheroidal-graphite iron castings. Research Reports Kushiro National College, 2003, 37, pp. 1–9.

[6]   Gonzaga, R.A., Martínez Landa, P., Perez, A. & Villanueva, P. Mechanical properties dependency of the pearlite content of ductile irons. Journal of Achievements in Materials and Manufacturing Engineering, 2009, 33, pp. 150–158.

[7]   Gonzaga, R.A. & Carrasquilla, J.F. Influence of an appropriate balance of the alloying elements on microstructure and on mechanical properties of nodular cast iron. Journal of Materials Processing Technology, 2005, 162–163, pp. 293–297.

[8]   Martinez, R.A., Boeri, R.E. & Sikora, J.A. Impact and fracture properties of ADI compared with SAE 4140 steel. Transactions of the American Foundrymen's Society, 1998, 106, pp. 27-30.

[9]   Karjalainen-Roikonen, P. VTT proprietary data. VTT Technical Research Centre of Finland. Espoo 2012.

[10]   Ice class regulations and the application thereof. Maritime safety regulation: TRAFI/31298/03.04.01.00/2010. Transport Safety Agency TraFi. Helsinki 2010. 48 p.