

*Scaling laws of data obtained
from miniature Charpy tests and
their relation to fracture
toughness*

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Brno-Workshop



Contents

- Introduction, Statement of the underlying problem
- Scaling Laws of total fracture energy in bending
- Scaling Laws between Miniature Charpy (KLST – 3x4x22 mm specimens) and standard Charpy
- Correlation between Charpy Fracture Energy and J_{Ic} or K_{Jc}
- Examples
- Discussion and Conclusions

Objective

Estimation of fracture toughness of a ring-shaped structural part made of bronze in radial and tangential direction, the radial dimension being too small for standard specimens

Procedure:

1. Measurement of fracture energy of miniature (KLST-) specimens in radial and tangential direction
2. Scaling of fracture energy from miniature to standard size
3. Estimation of fracture toughness from standard Charpy fracture energy by analytical correlation formula.

Validation:

Comparison with Charpy-Data in tangential direction and J_{Ic} -measurements on similar material

Mechanical Properties of Bronze

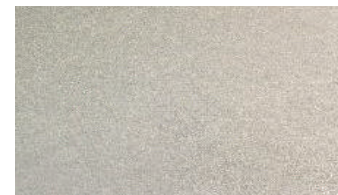
GZ-CuSn12Ni

Bronze-Typ	R_m [N/mm ²]	$R_{p0.2}$ [N/mm ²]	E [N/mm ²]	Z [-]	A_g [-]	KV
WDK	298.5	178	120000	0.155	0.11	5.9
Serie 290	289	217	119000	0.033	0.04	6.1
Serie 200	477	208	133000	0.43	0.5	32

Macrographs:

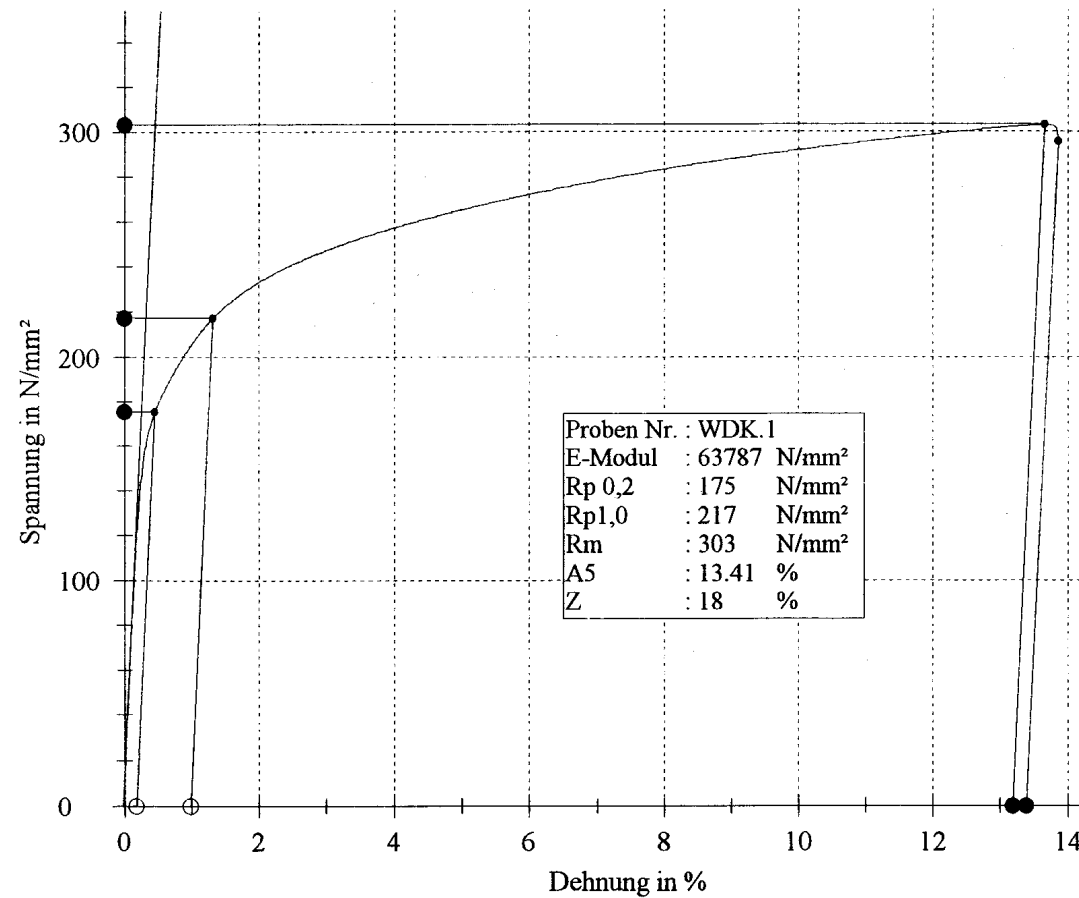


WDK



200

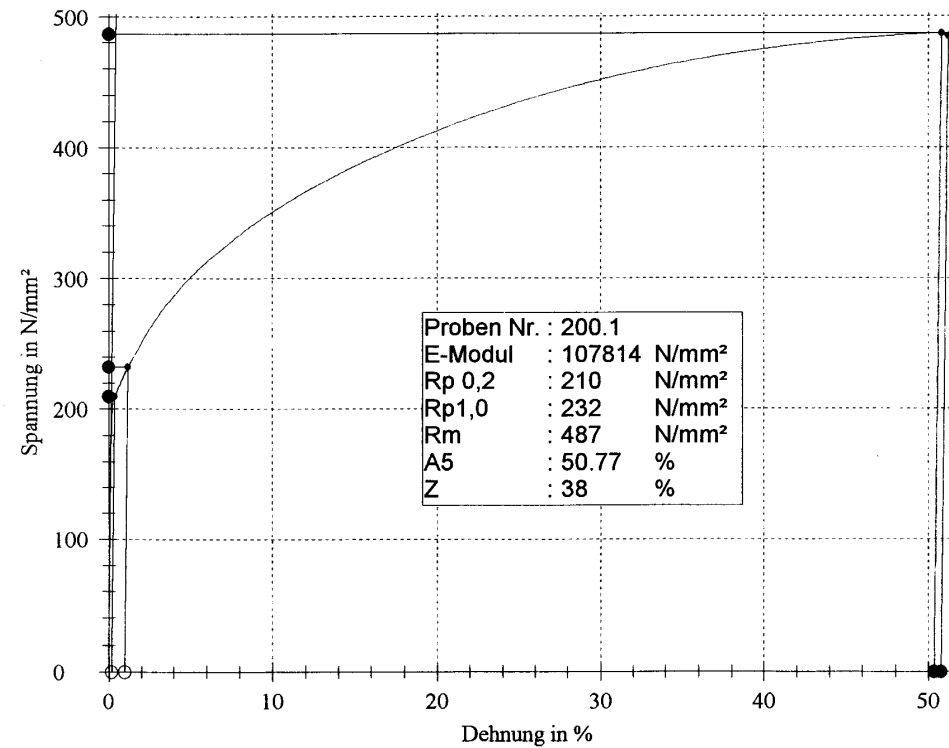
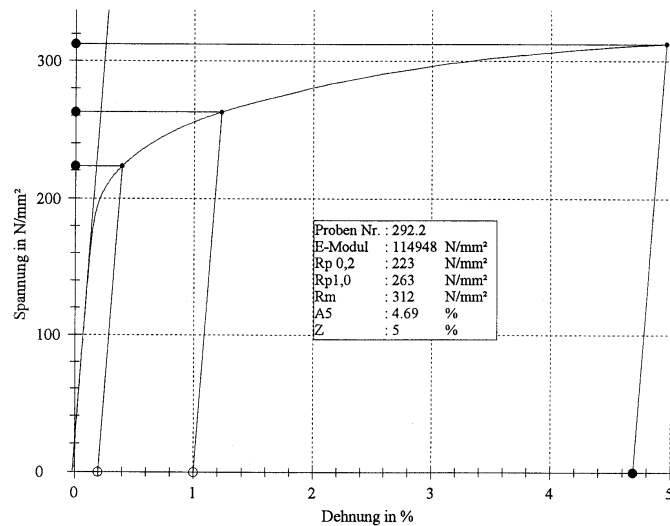
Stress-Strain Diagram of bronze WDK



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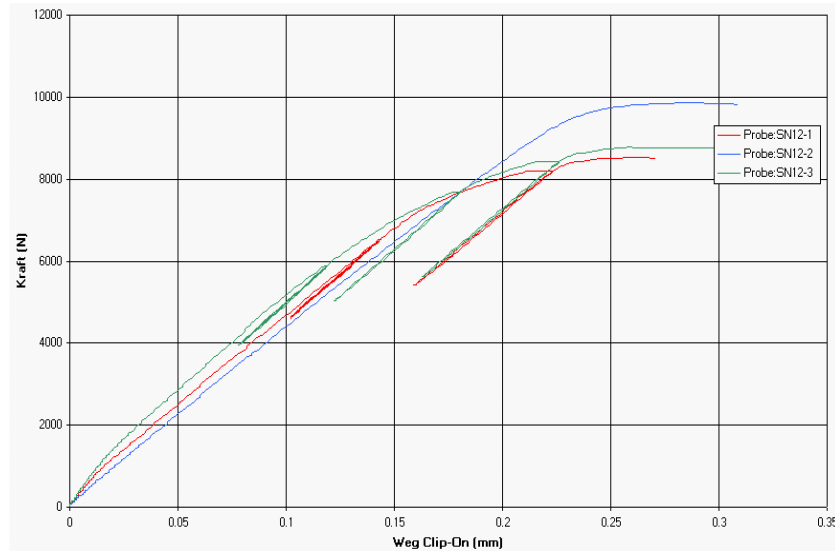
Stress-Strain Diagram of bronze type 2912 ans 200



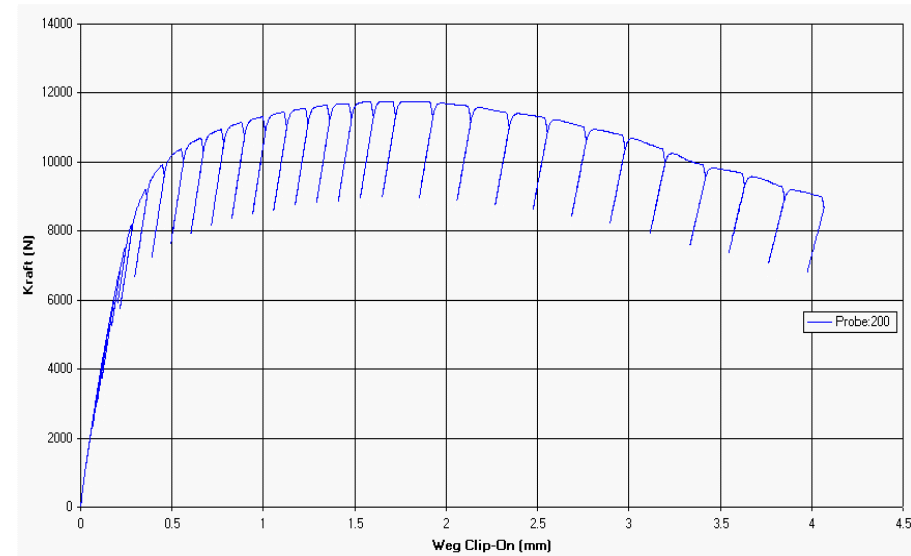
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Force-displacement diagrams of 0.8“-CT-Proben

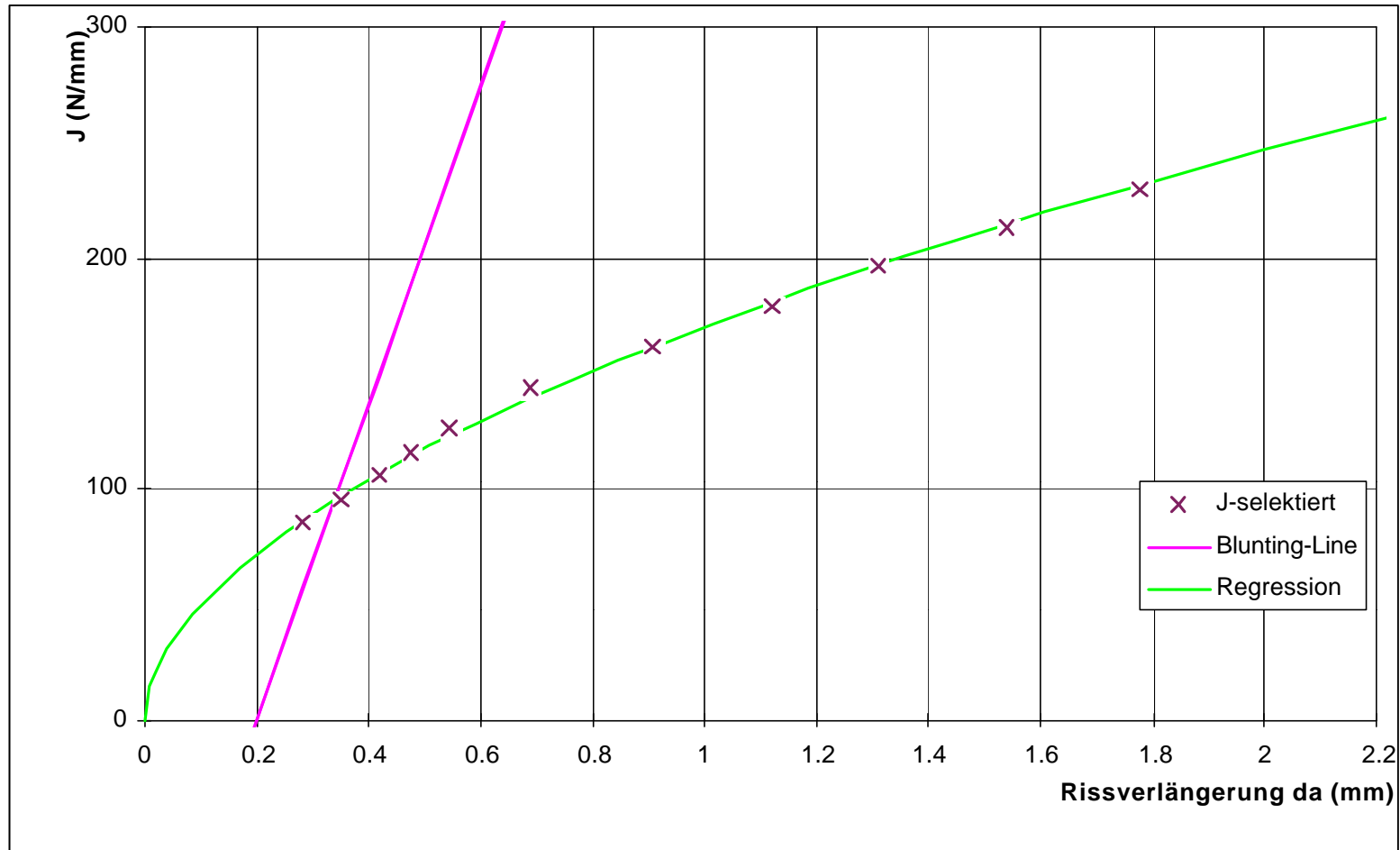


Bronze 292



Bronze 200

J-R-curve of 0.8''-CT-Probe Bronze 200



Scaling Law for Fracture Energy of Edge-Cracked bend Specimens

Schindler+Veidt , ASTM STP 1329,1997:

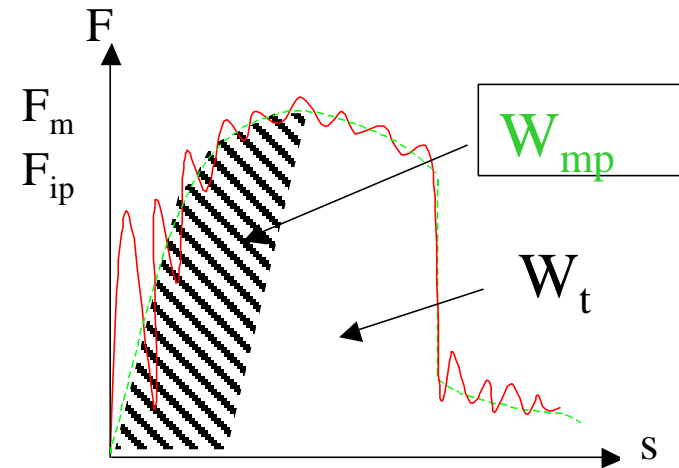
$$W_t' = \frac{B'}{B} \cdot \frac{h(a/W)}{h(a'/W')} \cdot \left[\left(\frac{b_0'}{b_0} \right)^{p+1} \cdot W_{mp} + \left(\frac{b_0'}{b_0} \right)^2 \cdot (W_t - W_{mp}) \right]$$

$$p = \left(1 + \frac{W_{mp}}{2 \cdot W_t} \right)^{-1}$$

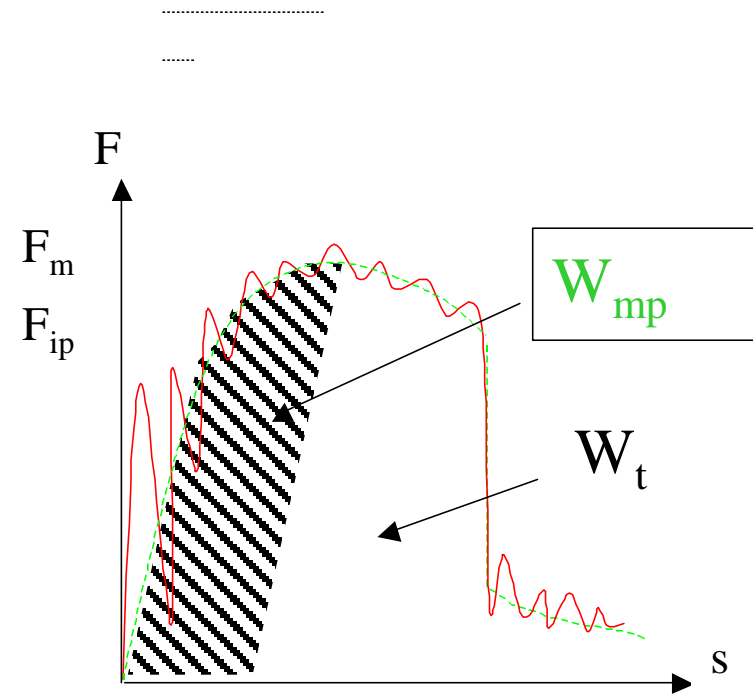
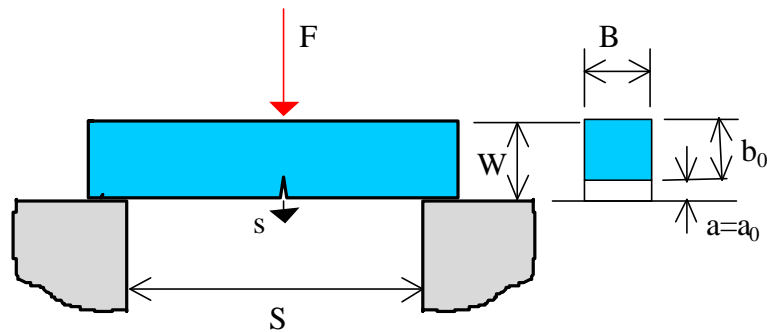
$$h(a/W) = \begin{cases} 13.818 \frac{a}{W} - 25.124 \left(\frac{a}{W} \right)^2 & \text{für } 0 < \frac{a}{W} < 0.275 \\ 1.90 + 0.138 \frac{a}{W} & \text{für } 0.275 < \frac{a}{W} < 1 \end{cases}$$

Für $W_{mp} = W_t/2$:

$$W_t' = \frac{B'}{B} \cdot \frac{h(a/W)}{h(a'/W')} \cdot \left[\left(\frac{b_0'}{b_0} \right)^{p+1} + \left(\frac{b_0'}{b_0} \right)^2 \right] \cdot W_t / 2$$



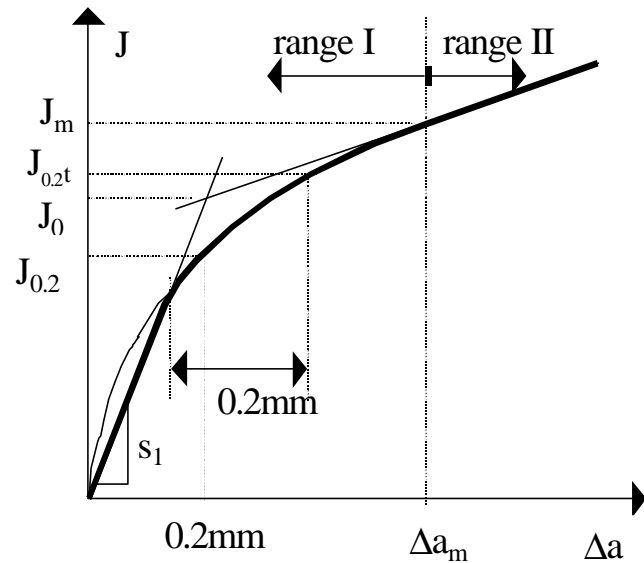
Theoretical Background: Evaluation of J-R-curve from instrumented impact bending test



(see Schindler, ESIS 20, 1996, or
Proc. ECF 12, 1998)

b_0

Analytical 3-parameter approach to evaluate J-R-curve



$$J(\Delta a) = \left(\frac{2}{p}\right)^p \cdot \frac{h(a_0)}{B (W - a_0)^{1+p}} \cdot W_t^p \cdot W_{mp}^{1-p} \cdot \Delta a^p$$

For range I ($\Delta a \leq \Delta a_m$)

where

$$p = \frac{3}{4} \cdot \left(1 + \frac{W_{mp}}{W_t}\right)^{-1} \quad \Delta a_m = \frac{W_m \cdot p \cdot b_0}{2W_t} \quad b_0 = W - a_0$$

(see Schindler, ESIS 20, 1996, or Proc. ECF 11, 1996)

Experimental Results of Bronze

specimen	KLST [J/cm^2]	W_t [J]	$W_t' (=KV')$ [J]
1T	3	0.27	5.89
2T	3.17	0.2853	6.23
3T	3.58	0.3222	7.033
4T	2.25	0.2025	4.423
5T	2.67	0.2403	5.25
Mean T-spec.	2.934	0.26406	5.765
Standard dev. T	0.50371619	0.04533446	0.99
1R	3.58	0.3222	7.03957
2R	3.5	0.315	6.88
3R	3.42	0.3078	6.72
4R	4.08	0.3672	8.02
5R	4	0.36	7.86
Mean R-specimens	3.716	0.33444	7.30
Standard dev. R-sp.	0.30245661	0.02722109	0.59

For comparison: KV measured on T-specimens: KV=5.9 J

Scaling Laws of KV from the literature

(see Lucon, ASTM 1380, 2000)

$$W_t = NF * W_t'$$

expressed in terms of a normalization factor (NF).

The most commonly used expressions for NF which can be found in the literature, are the following:

$$NF_1 = \frac{(Bb)_{fs}}{(Bb)_{ss}} \quad (4)$$

(Based on the ratio of fracture areas, with B = specimen thickness and b = specimen ligament depth - Corwin et al. [4,5].)

$$NF_2 = \frac{[(Bb)^{3/2}]_{fs}}{[(Bb)^{3/2}]_{ss}} \quad (5)$$

(Based on the ratio of nominal fracture volumes - Corwin et al. [4,5].)

$$NF_3 = \frac{(Bb^2)_{fs}}{(Bb^2)_{ss}} \quad (6)$$

(Based on a different expression for the ratio of nominal fracture volumes - Lucas et al. [6,7].)

$$NF_4 = \frac{\left(\frac{Bb^2}{LK_t}\right)_{fs}}{\left(\frac{Bb^2}{LK_t}\right)_{ss}} \quad (7)$$

(With L = span and K_t = elastic stress concentration factor - Loudon et al. [8].)

Scaling factors for Estimation of KV from miniature Charpy 3x4x22 mm

Considering the ratio of geometrical parameters between standard 10x10x55 and subsize DIN 50 115 Charpy-V specimens, one gets the following numerical values for NF:

$$\begin{aligned}NF_1 &= 8.9 \\NF_2 &= 23.7 \\NF_3 &= 26.5 \\NF_4 &= 13\end{aligned}$$

In addition, Sokolov and Alexander [14] have determined the following empirical value for NF by averaging the values of USE_{fs}/USE_{ss} obtained on 10 different materials (mostly pressure vessel steels with different heat treatments):

$$NF_5 = 21.3$$

Considering the nine materials (and 15 conditions) examined in the present work, the average value of the normalization factor is:

$$NF_6 = 21.56$$

According to present scaling Law: $NF=21.83$ (Upper Shelf: 23.6)

Experimentally for Bronze:

$$NF=22.34$$

Estimation of J_{Ic} from KV

General analytical correlation law :

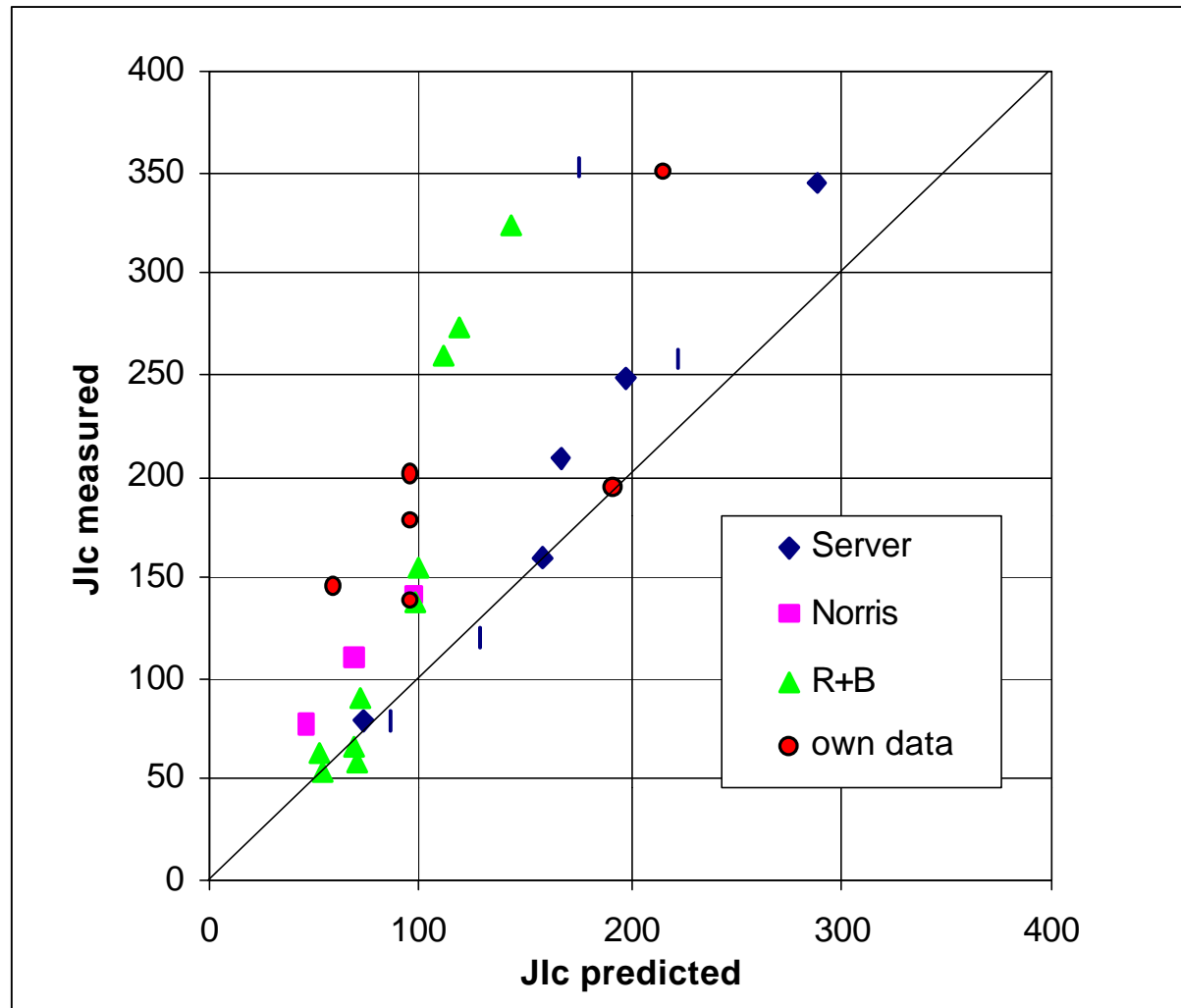
$$J_{0.2t} = C \cdot \left[\left(\frac{C}{3.75 \cdot R_m} \right)^{\frac{1}{1-p}} + 0.2mm \right]^p + \frac{7.15 \cdot s_f^2}{E}$$

$$C = \frac{0.0250}{8^p} \cdot \left(KV - \frac{7.97 \cdot s_f \cdot Z}{1-Z} \right) \cdot A_g^{1-p}$$

$$p = \frac{3}{4} \cdot (1 + A_g)^{-1}$$

(Schindler, Mat. Wissenschaft und Werkstofftechnik 32, No.6/2001)

Comparison of correlation for several steels



Results: fracture toughness of the considered bronze WDK estimated from KLST-specimens

specimen	KV' [J]	$J_{0.2t}$ [N/mm]	K_{Jc} [N/mm ^{1.5}]
1T	5.89	8.98	1088.19
2T	6.23	9.32	1108.45
3T	7.03	10.13	1155.86
4T	4.42	7.49	993.87
5T	5.25	8.32	1047.73
Mean value T-spec.	5.76	8.85	1078.82
Standard dev. T-sp.	0.99	1.00	61.41
1R	7.03	10.13	1155.86
2R	6.88	9.97	1146.76
3R	6.72	9.81	1137.59
4R	8.02	11.12	1211.17
5R	7.86	10.97	1202.49
Mean value R-spec.	7.30	10.40	1170.77
Standard dev. R-sp.	0.59	0.60	33.68

Comparison of fracture toughness as predicted from Charpy Energy to directly measured values

Bronze type	Charpy-energy KV	J_c or $J_{0.2BI}$ measured	$J_{0.2t}$ estimated analytically	K_{Jc} measured	K_{Jc} estimated analytically
	[J]	[N/mm]	[N/mm]	[N/mm ^{1.5}]	[N/mm ^{1.5}]
Serie 292	6.1	9.0	8.14	1084 ¹⁾	1031
Serie 200	32	101	92.25	3842 ¹⁾	3487

Summary and Conclusion

- Miniature Charpy specimens can serve well to characterise fracture toughness of small structural parts.
- Fracture energy of miniature specimens can be transformed to standard size values at a reasonable accuracy by means of the presented analytical scaling law. The correlation to full-size standard fracture toughness is better than expected even in non ferrous materials
- Good agreement between scaled fracture energy and directly measured KV on standard specimens even for non-ferrous materials
- From standard Charpy fracture energy fracture toughness can be estimated with reasonable accuracy by a semi-empirical relation
- The used analytical analytical scaling law as well as the relation between Charpy CVN and fracture toughness , which was developed for steel, seems to work rather generally for elastic-plastic materials.