The Liquidus Temperatures of Steels

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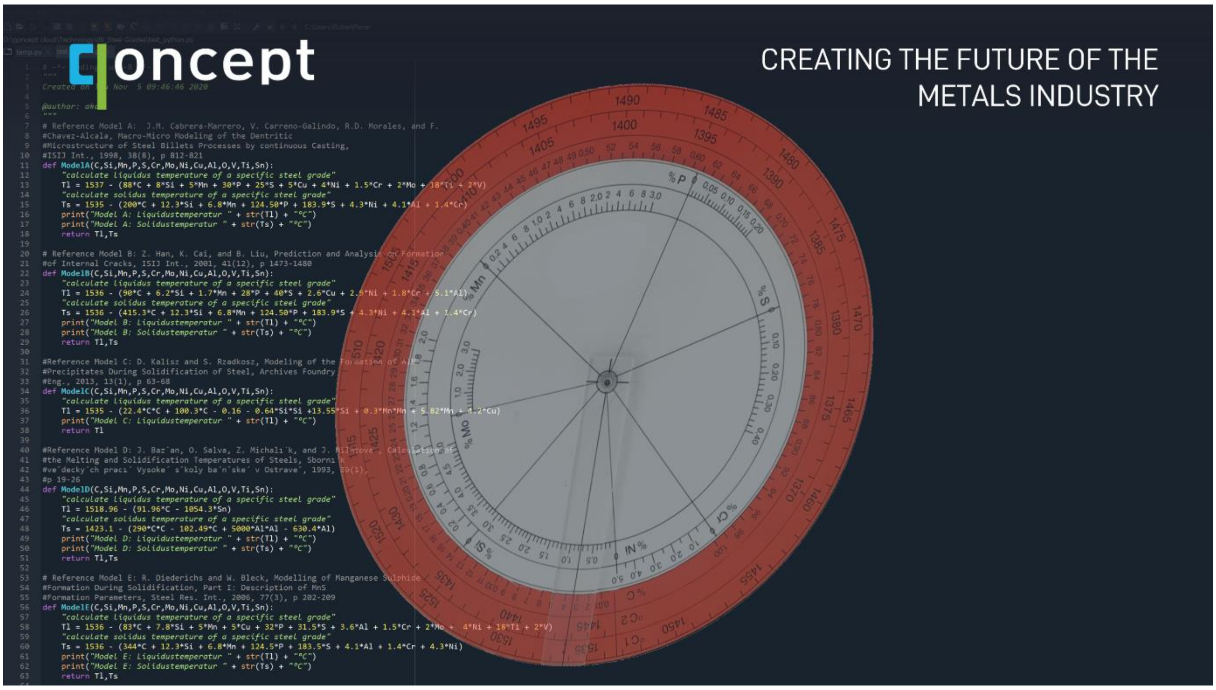
How do you calculate liquidus temperatures for a large number of different steels? Why should you choose the formula for calculating liquidus temperatures carefully?

We checked the results of 32 empirical equations for calculating the liquidus temperature on typical low alloyed and stainless steels. In addition, the voestalpine slide rule was used to determine the liquidus temperature and compared with the results of the formulas from the relevant literature.



1 INTRODUCTION

In a survey here on LinkedIn we ask the following question in context of the picture illustrated on top of this article:

Does anyone have any idea what to do with this thing in the picture?

For all those who do not know what it is, it is a slide rule to determine the liquidus temperatures of steel. Precise knowledge of the liquidus temperatures (sometimes referred to as melting temperature) is necessary to determine the optimal casting temperatures in various casting processes. The idea of such a slide rule follows the approach to reduce the melting point of pure iron by the element concentrations times a factor. This should make it possible for the operators in the steel mill to quickly and easily calculate the liquidus temperature. Curious as we are, we wanted to verify the results of this slide rule and compare them with the many empirical formulas available in the relevant literature. For this we have selected typical steels (A to G) and stainless steels (H to L), which are summarized in **Table 1.**

(Low) Alloyed Steels

	DIN	afnor	BSi	UNI	SIS	SAE	JIS	cen	ISO	GOST-R	GB	ASTM	UNS	American Iron and Steel Institute
A	DIN 1.0402 DIN C22 DIN C 22 UNE F.112	AFNOR CC20	BS 050A20	UNI C21	SS 1450	SAE 1020	JIS S20C JIS S22C	EN C22 EN 1.0402	ISO C22	GOST 20				AISI 1020
B	DIN 1.1121 DIN Ck10	AFNOR CC10 AFNOR XC 10	BS 040A10	UNI C10	SS 1264	SAE 1010	JIS S10C	EN C10E EN 1.11.21		GOST 10	GB 10	ASTM 1010	UNS G10100	AISI 1010
C	DIN 1.7218 DIN 25CrMo4 UNE 55Cr3	AFNOR 25CD4	BS 1717CDS110 BS 708A25	UNI 25CrMo4(KB)	SS 2225	SAE 4130	JIS SM420 JIS SCM430	EN 25CrMo4 EN 1.7218					UNS G41300 UNS H41300	AISI 4130
D	DIN 1.6563 DIN 1.6582 DIN 35CrNiMo6	AFNOR 35NCD6 AFNOR 34CrNiMo8	BS S 149 BS 817M40 BS 816M40 BS EN24	UNI 35NiCrMo6(KB)	SS 2541	SAE 4340 SAR 4337	JIS SNCM447	EN 41NiCrMo7-3-2 EN 1.6563 EN 34CrNiMo6 EN 1.6582		GOST 38Ch2N2MA			UNS G43400	AISI 4337
E	DIN 1.6523 DIN 21NiCrMo2 DIN 1.7321 UNE 20NiCrMo2	AFNOR 20NCD2	BS 805M20	UNI 20NiCrMo2	SS 2506	SAE 8620	JIS SNCM220(H)	EN 20NiCrMo2-2 EN 1.6523 EN 20MoCr4 EN 1.7321						AISI 8620
F	DIN 1.7176 DIN 55Cr3	AFNOR 55C3	BS 527A60 BS 525A58			SAE 5155 SAE 5155H SAE 5160 SAE 5160H	JIS SUP9(A) JIS SUP9	EN 55Cr3 EN 1.7176		GOST 50ChGA				AISI 5155 AISI 5155H AISI 5160H
G	DIN 1.2067 DIN 100Cr6 DIN 1.3505 DIN 100Cr6 UNE 100Cr6	AFNOR Y100C6 AFNOR 100C6	BS BL3 BS 534A99	UNI 100Cr6	SS 2258	SAE L3 SAE 52100	JIS SUJ2	EN 102Cr6 EN 99Cr6 EN 1.2067 EN 1.3505		GOST 9Ch	GB Cr2			AISI L3

Stainless Steels

	DIN	afnor	BSi	UNI	SIS	SAE	JIS	cen	ISO	GOST-R	GB	ASTM	UNS	American Iron and Steel Institute
H	DIN 1.4301 DIN X5CrNi189 DIN 1.4350 UNE F.3551	AFNOR Z6CN18-09 AFNOR Z7CN18-09 AFNOR Z6CN18.09	BS 302S15 BS 304S31	UNI X5CrNi1810	SS 2332 SS 2333	SAE 304	JIS SUS304	EN X5CrNi18-10 EN 1.4301 EN 1.4350	ISO 4301-303-00-I	GOST 08Ch18N10	GB 0Cr18Ni9	ASTM TP304 ASTM S30400 ASTM Grade 8 ASTM F304 ASTM 304 ASTM FP304 ASTM MT304	UNS S30400	AISI 304
I	DIN 1.4401 DIN X5CrNiMo17122 DIN 1.4436 DIN X5CrNiMo17133 UNE F.3543	AFNOR Z7CND17-11-02 AFNOR Z7CND18-12-03	BS 316S16 BS 316S13	UNI X5CrNiMo1712 UNI X8CrNiMo1713	SS 2347 SS 2343/2347	SAE 316	JIS SUS316 JIS SUS316TKA	EN X5CrNiMo17-12-2 EN 1.4401 EN X3CrNiMo17-13-3 EN 1.4436		GOST 0Cr17Ni12Mo2	GB 08Ch27N13M2	ASTM TP316 ASTM 316 ASTM S31600 ASTM F316 ASTM Grade 8M ASTM FP316 ASTM MT316	UNS S31600	AISI 316
J	DIN 1.4016 DIN X8Cr17 DIN UNE F.3113	AFNOR Z8C17	BS 430S15	UNI X8Cr17	SS 2320	SAE 430	JIS SUS430	EN X6C17 EN 1.4016		GOST 12Ch17	GB 1Cr17	ASTM MT430 ASTM 430	UNS S43000	AISI 430
K	DIN 1.4113 DIN X6CrMo17	AFNOR Z8CD17-01	BS 434S17	UNI X8CrMo17	SS 2325	SAE 434	JIS SUS434	EN X6CrMo17-1 EN 1.4113					UNS S43400	AISI 434
L	DIN 1.2083 DIN X40Cr14 DIN 1.4021 DIN X20Cr13 DIN 1.4031 DIN 1.4034 DIN X46Cr13 UNE F.3405	AFNOR Z40C14 AFNOR Z20C13 AFNOR Z44C14	BS 420S37 BS 420S29 BS 420S45	UNI X20Cr13 UNI X40Cr14	SS 2303 SS 2304	SAE 420	JIS SUS420J1	EN X40Cr14 EN 1.2083 EN X20Cr13 EN 1.4021 EN X39Cr13 EN 1.4031 EN X46Cr13 EN 1.4034	ISO X40Cr14	GOST 20Ch13 GOST 40Ch13	GB 2Cr13			AISI 420

Table 1: The (low) alloyed and stainless steels used for the calculation of the liquidus and solidus temperatures based on empirical equations from literature.

The sources (references) of the empirical equations used are listed in Chapter 6, whereby the determination of such empirical equations is mainly based on regression analysis. Based on these empirical equations and the above illustrated (low) alloyed and stainless steel we calculated the liquidus temperature.

Before discussing the results, the following must be pointed out according to J. Miettinen and A. A. Howe (*J. Miettinen and A. A. Howe: Estimation of liquidus temperatures for steels using thermodynamic approach, Ironmaking and Steelmaking, (2000), Vol. 27, No. 3, pp. 212-227*):

+ The various equations can only be compared to a limited extent, as they are closely related to the alloys examined.
+ The compositions of the alloys under consideration are often not shown in detail
+ A specific equation usually only provides good results for the alloys examined. The calculation results are insufficient for other alloys that are not included in the analysis.

The main weakness of these empirical equations is that linear equations cannot describe the numerous chemical interactions between different solutes. In order to eliminate these weaknesses, J. Miettinen and A. A. Howe take into account thermodynamic equations for the calculation of the liquidus temperatures. The main advantage of such equations is that the primary solid phase is also determined. Consequently, different liquidus surfaces can be treated, taking into account the change in surface area resulting from the change in composition.

Due to all above mentioned reasons and the fact that the determined equations from J. Miettinen and A. A. Howe were tested against a great number of experimental data, the present article strongly recommends to calculate the liquidus temperature based on the equations of these authors. **Figure 1** shows the results of the work of Miettinen and A. A. Howe, which is supplemented by the range of +/- 5 °C (light blue area in the diagrams). In addition, we tried to determine the share (number) of the calculations that show a deviation of less than +/- 5 ° C. These values (denoted by R) are also indicated in the figures and is in all cases greater than 80 %.

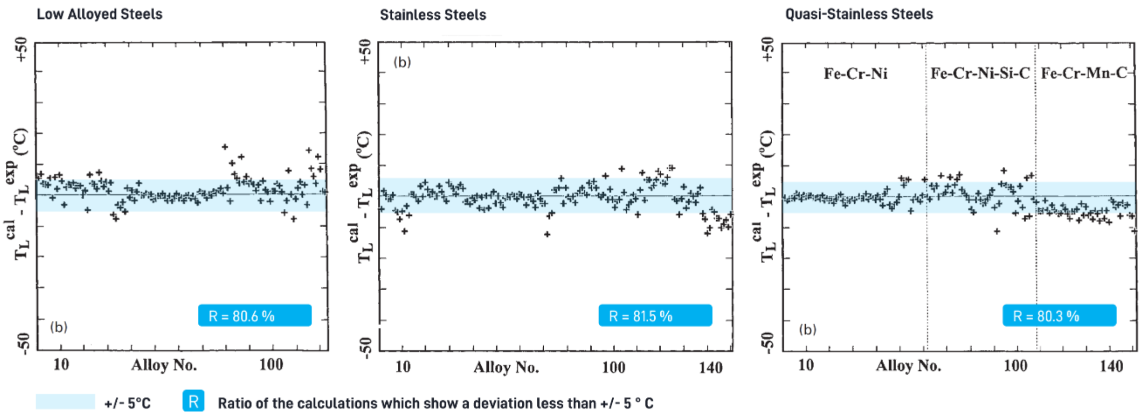


Figure 1: Difference between calculated and measured liquidus temperatures for low alloyed and stainless steels according to the equations determined J. Miettinen and A. A. Howe

In the following two chapters, 32 empirical equations to calculate the liquidus temperature of steels are considered and compared with the well validated equations determined by Miettinen and A. A. Howe based on a thermodynamic approach.

2 LOW ALLOYED STEELS

The chemical composition of the considered (low) alloyed steel grades are summarized in **Table 2**. The carbon content of the (low) alloyed steels ranges from 0.07 - 1.05 wt.-%, the Si content is in all cases < 0.4 wt.-%, Mn ranges from 0.25 - 1.00 wt-% and the P and S content is between 0.05 and 0.045 wt.-%. In addition, the steels are alloyed with Cr, Ni and Mo as indicated in detail in the table.

	C / %	Si / %	Mn / %	P / %	S / %	Cr / %	Mo / %	Ni / %	Cu / %	Al / %	O / %	
A	0.17 – 0.24	≤ 0.40	0.40 – 0.70	≤ 0.045	≤ 0.045	≤ 0.40	≤ 0.10	≤ 0.40				(Cr + Mo + Ni) ≤ 0.63
B	0.07 – 0.13	≤ 0.40	0.30 – 0.60	≤ 0.035	≤ 0.035	(≤ 0.40)						
C	0.22 – 0.29	≤ 0.40	0.60 - 0.90	≤ 0.035	≤ 0.035	0.90 – 1.20	0.15 – 0.30					
D	0.38 – 0.44	≤ 0.30	0.60 – 0.90	≤ 0.025	≤ 0.025	0.70 – 0.90	0.15 - 0.30	1.65 – 2.00	≤ 0.25			
E	0.17 – 0.23	≤ 0.40	0.65 – 0.95	≤ 0.035	≤ 0.035	0.35 – 0.70	0.15 – 0.25	0.40 – 0.70				
F	0.52 – 0.59	≤ 0.40	0.70 – 1.00	≤ 0.025	≤ 0.025	0.70 – 1.00						
G	0.93 – 1.05	0.15 – 0.35	0.25 – 0.45	≤ 0.025	≤ 0.015	1.35 – 1.60	≤ 0.10		≤ 0.30	≤ 0.05	≤ 0.0015	

Table 2: Chemical composition of the steel grades considered in the present article

For the calculation of the liquidus temperature, all elements were taken into account by with *(Min + Max) / 2*. All equations were integrated into a Python code to make the calculations easy and quick. Figure 2 shows the results of our calculations. The dark bar represents the smallest, the lighter bar the highest calculated liquidus temperature. The white line indicates the values calculated with the equations of J. Miettinen and A. A. Howe, whereas the green area marks the above mentioned +/- 5 °C range. The numbers within the green area indicates how many equations out of 32 are within the +/- 5 °C range. As can be seen, many equations for steel grades A, B, C and E are in the range of +/- 5 ° C. Steel grades D and F already show less agreement and steel grades G show the worst results.

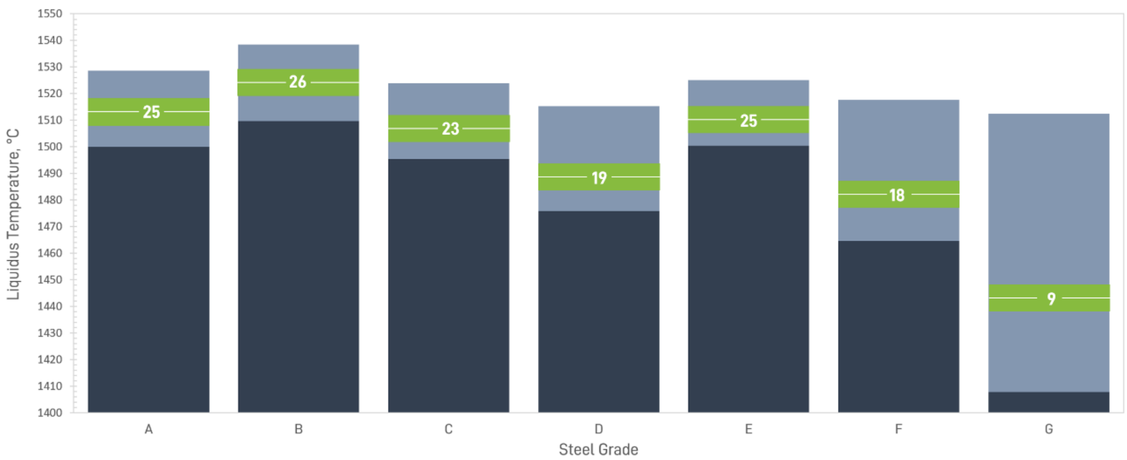


Figure 2: The results of the 32 used equations to calculate the liquidus temperatures of the steel grades A to G

3 STAINLESS STEEL

The chemical composition of the stainless steels considered in the present article are summarized in **Table 3**. Grade H and I represent typical austenitic stainless steels, grade J and K are ferritic stainless steels and grade L represents a martensitic stainless steel.

	C / %	Si / %	Mn / %	P / %	S / %	Cr / %	Mo / %	Ni / %	Cu / %	Al / %	N / %
H	≤ 0.07	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.015	17.00 -19.50		8.00 – 10.50			≤ 0.11
I	≤ 0.07	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.015	16.50 -18.50	2.00 -2.50	10.00 -13.00			≤ 0.11
J	≤ 0.08	≤ 1.00	≤ 1.00	≤ 0.040	≤ 0.015	16.00 – 18.00					
K	≤ 0.08	≤ 1.00	≤ 1.00	≤ 0.040	≤ 0.015	16.00 – 18.00	0.90 – 1.40				
L	0.36 – 0.42	≤ 1.00	≤ 1.00	≤ 0.030	≤ 0.030	12.50 – 14.50					

Table 3: Chemical composition of the stainless steel grades considered in the present article

Figure 3 shows the comparison of the liquidus temperatures for the stainless steels and can be summarized as follows: In the case of stainless steel grades, the number of equations that calculate the liquidus temperature in the range of +/- 5 ° C is significantly lower than in the case of (low) alloyed steel grades. The best results were found with the ferritic stainless steel without Mo (Grade J → 17 equations). However, the Mo-alloyed ferritic stainless steel showed the fewest equations (Grade K → 5 equations) which determine the liquidus temperature within the +/- 5 ° C range. The Cr, Ni, and Mo alloyed austenitic stainless steel showed the greatest range of results (1388 to 1525 °C).

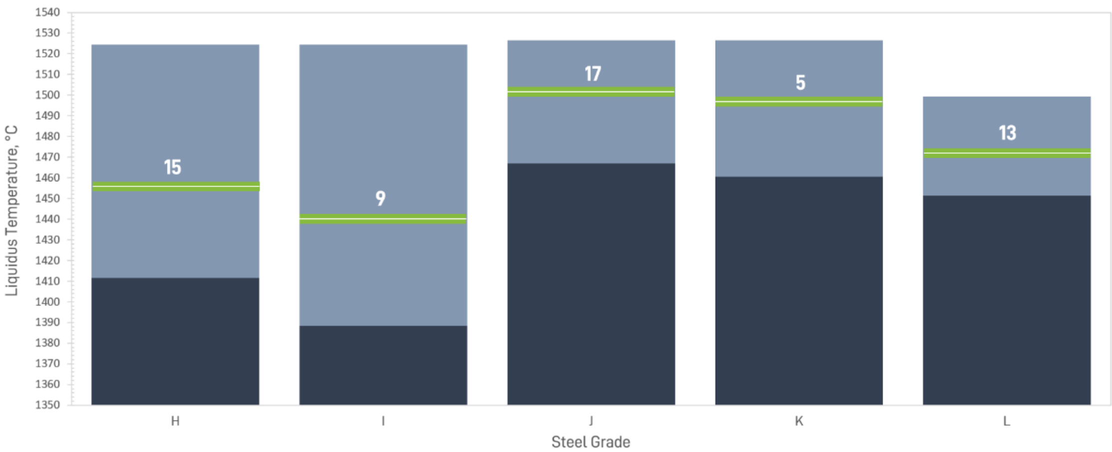


Figure 3: The results of the 32 used equations to calculate the liquidus temperatures of the stainless steel grades H to L

4 THE RESULTS OF THE SLIDE RULE

How good are the results now determined using the slide rule mentioned at the beginning of this article? These results are illustrated in Figure 4. Surprisingly (or perhaps not surprisingly) the determined liquidus temperatures are very close to the results of the equations by J. Miettinen and A. A. Howe. In all cases (both low-alloy and stainless steels) the temperatures determined are in the range of +/- 5 ° C. No other equation could calculate the liquidus temperatures in such a way that they are in the range of +/- 5 ° C for all the qualities considered.

In the case of the low-alloy steels, a total of 5 equations calculated all 7 steels with sufficient accuracy (values within the +/- 5 ° C range). With three equations, the mean error was less than +/- 1 ° C, i.e. better than the slide rule. In the case of stainless steels, only one equation was able to determine the liquidus temperature of all 5 steels within the +/- 5 ° C deviation, with an average error of +/- 2.84 °C.

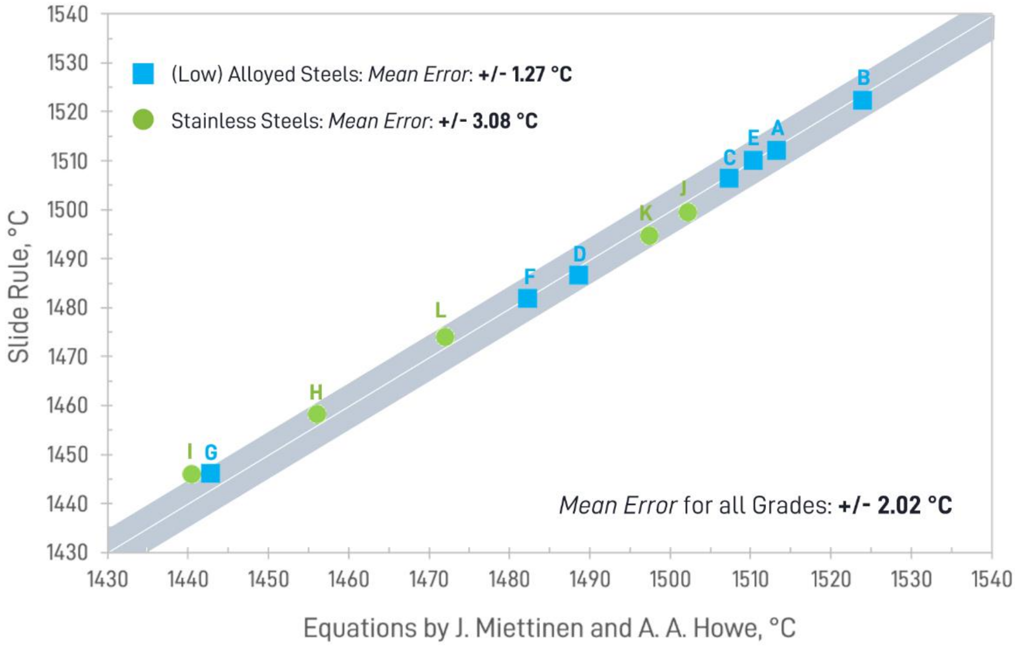


Figure 4: The results determined by the slide rule in comparison to the results using the equations according to J. Miettinen and A. A. Howe for all low alloyed and stainless steels.

If the mean error for all 12 steels is considered, one equation is better than the slide rule. This one equation only has a deviation of -7.4 ° C for Grade I (compared to the slide rule: 5.6 °C), but overall a mean error of 1.96 °C (compared to the slide rule: 5.6 °C).

5 SUMMARY

Although precise knowledge of the liquidus temperatures is required to determine the optimal casting temperatures in various casting processes, empirical equations are very often used to estimate the liquidus temperature. With this in mind, it is always important to check the area of validity of the formula. The present article tested 32 equations from the relevant literature and compared the results with the well validated equations determined by J. Miettinen and A. A. Howe (J. Miettinen and A. A. Howe: Estimation of liquidus temperatures for steels using thermodynamic approach, Ironmaking and Steelmaking, (2000), Vol. 27, No. 3, pp. 212-227). Seven typical low alloyed and five typical stainless steels were used for this comparison. The voestalpine slide rule was also used to calculate the liquidus temperature and the results were illustrated. For the types of steel considered, the choice of slide rule is, very surprisingly, a very good one. For all types of steel, the temperatures determined agree very well with the liquidus temperatures that were calculated using the equations by J. Miettinen and A. A. Howe. Only one equation had a smaller mean error than the slide rule but showed a deviation greater than +/- 5 ° C for one type of steel.

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