STRUCTURAL APPLICATIONS OF FERRITIC STAINLESS STEELS (SAFSS)

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Summary

The impact toughness of five different ferritic stainless steel grades was studied by means of the Charpy-V impact test. The test matrix included the low-chromium grades 1.4003 and 1.4016 and the high-chromium grades 1.4509, 1.4521, and 1.4621. The thickness of the material varied from 1 to 6 mm, depending on the grade. Because of the thickness of the material, sub-sized specimens were used. Tests were performed both in the rolling and transversal directions. About 3000 impact tests were subcontracted to Kemi-Tornio University of Applied Sciences. About 500 tests were made at the Outokumpu Tornio Research Centre.

The data from the Charpy-V impact tests are fitted to form transition curves of the combinations of different thicknesses for each grade in two directions. The most commonly used hyperbolic tangent function was used in this study. Because of the use of sub-sized specimens, the results were size-corrected with Wallin's method to correspond to standard-sized specimens.

Generally, the transition temperatures that are determined are lower on the long side of the specimens in the rolling direction (the L-T direction). The transition temperature increases as a function of the thickness of the material. The size corrected temperatures are shown in parentheses. All of the materials tested have transition temperatures near -100 °C at a thickness of 1 mm. For the grade EN 1.4003 the temperature limit with a thickness of 1 mm is -100 °C (+13 °C) and with a thickness of 6 mm the limit is -15 °C (0 °C). For the grades EN 1.4016, 1.4509, and 1.4521 with a thickness of 2 mm the limit is -25 °C (29…39 °C).

Thin materials proved to be very difficult to test and in some cases the shear fracture mechanism was very significant. It is necessary to develop another testing method for thin materials. One possible test method is the Impact Tensile Test (ITT). It is recommended to study the fracture toughness testing of ferritic stainless steels on a larger scale.

Contents

1 Introduction

Ferritic stainless steel grades are widely used in the transport and domestic appliance sectors; structural applications in the construction industry are scarce. In the SAFSS project the target was to develop the necessary information which will enable comprehensive guidance on ferritic stainless steels to be included in the relevant parts of the Eurocode and other accompanying standards and guidance.

Ferritic stainless steels exhibit a reduction in their impact toughness when the temperature decreases and the fracture appearance changes from a ductile mode at mildly elevated temperatures to a brittle mode at low temperatures. This ductile-to-brittle transition temperature (DBTT) is characteristic of ferritic steels. DBTT is affected by heat treatment, such as by welding. Heat treatments that result in high hardness shift the transition temperature to higher temperatures. /1/

Because of their BCC[1] structure, ferritic stainless steels are sensitive to brittleness caused by interstitials. While high-purity metals may be ductile at very low temperatures, slightly less pure alloys have relatively high DBTT values. Interstitials cause embrittlement by locking dislocations. The solubility level of interstitials in BCC metals is relatively low and second-phase precipitates also cause brittleness. The precipitates are more important than the solute if the amount of interstitials significantly exceeds the solubility limit. If the amounts of carbon and nitrogen exceed the solubility limit, this increases the DBTT still further. Hence the toughness of ferritic stainless steels can be improved by reducing the combined carbon and nitrogen content. /2/

[1] BCC = Body-Centred Cubic

2 Objectives

The objective of Work Package One (WP1) was to determine the basic relevant mechanical property data for ferritic stainless steels which designers need in order to design the targeted structural applications. Task 1.4 consists of the Charpy notched impact testing of different ferritic stainless steel grades from steel producers in Europe.

Ferritic stainless steels have different mechanical properties from carbon steels and other families of stainless steels. In general, they have a higher yield strength and lower ductility than austenitic stainless grades. Like carbon steels, but unlike austenitics, they exhibit a reduction in their impact toughness when temperatures decrease and the fracture appearance changes from a ductile mode at mildly elevated temperatures to a brittle mode at low temperatures. Therefore it was necessary to carry out laboratory tests to measure toughness in order for the member behaviour under different loading conditions to be predicted. The data generated will enable suitable guidance to be included in the Eurocodes EN 1993-1-4 *Stainless steels* and EN 1993-1-10 Material toughness and through thickness properties.

In Task 1.4, Charpy notched impact tests, the objective was to determine Charpy V-notched impact tests at temperatures between -40 and +20 °C, in accordance with EN 10045 and ASTM E23, which will enable the Charpy V-notch shelf energy and the ductile transition curve to be determined. EN 10045 has not been valid since 13 December 2010. The new approved standard is EN ISO 148-1, and this was used. Another objective of this task was to determine the thickness limit for a given temperature to achieve adequate ductility, as in Table 2.1 in EN 1993-1-10.

For each grade, material from at least two steel producers was supposed to be tested. A total of 24 grade and thickness combinations from three steel producers were tested.

3 Experimental work

3.1 Test materials

The steels used in this study were the grades EN 1.4003, 1.4016, 1.4509, 1.4521, and 1.4621. The materials were supplied by Outokumpu, Acerinox, and Aperam. The materials in this study are listed below and their chemical compositions are given in Table 1. The chemical compositions are based on the material certificates and test results from the other work packages of SAFSS.

Table 1 Composition of the materials studied.

Grade	THK	Mfr.		Ident.	C	Si	Mn	Cr	Ni	Mo	Ti	Nb	Cu	Al	N	C+N ppm
1.4003	1.0	B	2B	85933	0.012	0.26	1.43	11.3	0.4	0	0	0	0.1	0	0.01	200
1.4003	2.0	B	2E	78700	0.015	0.26	1.45	11.4	0.4	0	0	0.01	0.1	0	0.013	300
1.4003	3.0	B	2E	91383	0.010	0.33	1.41	11.3	0.4	0	0	0	0	0.16	0.013	230
1.4003	4.0	B	1D	80023	0.009	0.28	1.41	11.3	0.4	0	0	0.01	0.1	0	0.014	250
1.4003	5.0	B	1D	91387	0.012	0.24	1.49	11.4	0.4	0	0	0	0	0	0.013	250
1.4003	6.0	B	1D	87983	0.01	0.27	1.45	11.1	0.4	0	0	0	0.2	0	0.009	200
1.4016	1.0	C	2B	01V5H4	0.039	0.37	0.39	16.2	0.2	0	0.01	0.01	0.1	0	0.029	700
1.4016	2.0	C	2B	03V3K7	0.023	0.36	0.46	16.3	0.2	0	0.01	0.01	0.1	0.01	0.028	500
1.4016	2.0	B	2B	79619	0.046	0.3	0.48	16.1	0.2	0.2	0	0.02	0.1	0	0.027	750
1.4016	3.0	C	1D	03V9D5	0.064	0.27	0.32	16.1	0.1	0	0.01	0.01	0.1	0.01	0.025	900
1.4016	4.0	C	1D	01V4J6	0.057	0.39	0.46	16.3								390
1.4509	1.0	C	2B	05T4B9	0.016	0.48	0.33	17.7	0.3	0	0.17	0.48	0.1	0.09	0.016	300
1.4509	1.0	B	2B	83795	0.014	0.52	0.45	17.9	0.2	0	0.11	0.41	0.1	0.01	0.016	300
1.4509	2.0	C	2B	01V2J6	0.017	0.55	0.45	17.8	0.2	0	0.14	0.49	0	0.05	0.018	350
1.4509	2.0	B	2B	75086	0.02	0.55	0.48	17.9	0.3	0	0.12	0.4	0.1	0.01	0.03	500
1.4509	3.0	B	2E	86951	0.018	0.45	0.46	18.1	0.1	0	0.11	0.39	0.0	0.13	0.019	370
1.4509	3.0	A	2B	22845	0.017	0.53	0.34	17.5	0.1	0	0.14	0.43	0.1	0.01	0.014	300
1.4509	3.5	C	1D	04V9M7	0.018	0.36	0.26	17.6	0.2	0	0.16	0.47	0.1	0.07	0.019	350
1.4509	4.0	B	2E	95299	0.027	0.51	0.44	18.3	0.2	0	0.12	0.42	0.2	0.01	0.017	450
1.4521	1.0	B	2B	89559	0.011	0.37	0.52	18	0.2	2.1	0.15	0.33	0.1	0.01	0.012	250
1.4521	2.0	C	2B	02X3M3	0.011	0.48	0.44	17.7	0.3	2	0.17	0.43	0.1	0	0.016	250
1.4521	2.0	B	2B	87805	0.015	0.52	0.49	18	0.1	2	0.13	0.4	0.2	0.01	0.019	350
1.4521	3.0	B	2B	89931	0.018	0.57	0.51	17.9	0.2	2.0	0.13	0.40	0.0	0.12	0.022	400
1.4621	1.5	A	2R	383719085	0.014	0.21	0.23	20.6	0.2	0	0.01	0.45	0.4	0	0.014	300

THK=thickness

Chemical compositions from analyses (wt%)

Mechanical properties are listed in Table 2. They are based on the material certificates and test results from the other work packages.

Table 2 Mechanical properties of the ferritic stainless steels that were studied.

Grade	THK	Mfr.	Surface finnish	Ident.	THK mm	Rp0.2 N/mm^2	Rm N/mm^2	A50/80
1.4003	1.0	B	2B	85933	1.0	343	481	30
1.4003	2.0	B	2E	78700	2.0	360	496	29
1.4003	3.0	B	2E	91383	2.9	346	492	
1.4003	4.0	B	1D	80023	4.0	426	575	21
1.4003	5.0	B	1D	91387	5.0	394	556	23
1.4003	6.0	B	1D	87983	6.0	354	495	29
1.4016	1.0	C	2B	01V5H4	1.0	332	492	27
1.4016	2.0	C	2B	03V3K7	2.0	342	494	29
1.4016	2.0	B	2B	79619	2.0	365	488	30
1.4016	3.0	C	1D	03V9D5	3.0	363	505	28
1.4016	4.0	C	1D	01V4J6	4.0	346	486	26
1.4509	1.0	C	2B	05T4B9	1.0	324	485	32
1.4509	1.0	B	2B	83795	1.0	381	477	31
1.4509	2.0	C	2B	01V2J6	2.0	360	494	36
1.4509	2.0	B	2B	75086	2.0	396	490	31
1.4509	3.0	B	2E	86951	2.9	401	478	
1.4509	3.0	A	2B	22845	3.0	322	501	
1.4509	3.5	C	1D	04V9M7	3.5	513	525	20
1.4509	4.0	B	2E	95299	3.9	401	495	29
1.4521	1.0	B	2B	89559	1.0	426	585	27
1.4521	2.0	C	2B	02X3M3	2.0	401	423	28
1.4521	2.0	B	2B	87805	2.0	434	571	26
1.4521	3.0	B	2B	89931	3.0	383	540	
1.4621	1.5	A	2R	383719085	1.5	395	479	29

THK=thickness

3.2 Specimen dimensions, orientation, and marking

The Charpy-V impact test is standardised to a 10x10x55-mm specimen. All the ferritic stainless steels that were tested were less than 10 mm in thickness. For that reason sub-sized specimens were used. A sub-sized Charpy-V specimen has the same dimensions as the standard specimen, except for its thickness. The dimensions of the specimens that were tested were Bx10x55 mm, where B is the thickness of the material. In the EN 10045 standard thicknesses of 7.5 or 5 mm are allowed for sub-sized specimens. In the EN ISO 148 and ASTM E 23 standards the recommended thicknesses were 2.5, 5, and 7.5 mm. The impact toughness test result of the sub-sized specimens requires extrapolation to correspond to the result from a standard-sized specimen. Precautions are mandatory when extrapolating these results to represent the actual standardised test specimen. /3, 4, 5, and 6/

The impact tests were carried out in two directions, L-T and T-L. The sample directions and the markings used are presented in Figure 1.

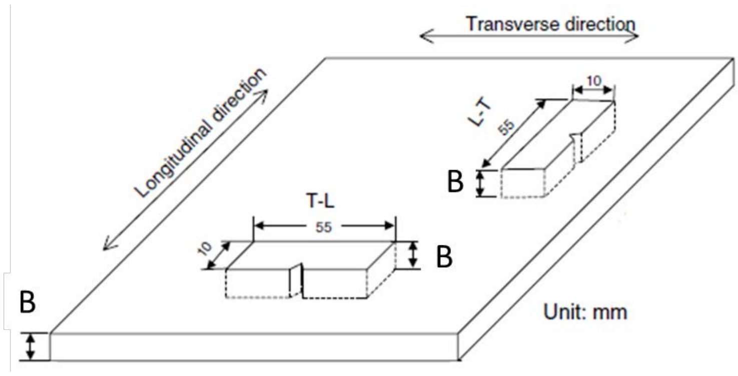


Figure 1 Direction and markings of specimens.

3.3 Testing machine

The impact tests were mainly performed at Kemi-Tornio University of Applied Sciences. An instrumented Zwick Roell PSW 750 pendulum impact tester with fully automatic tempering and an automatic feeding unit were used. A pendulum header of 300 J was used. The impact tests were performed according to the standard EN 10045. The tester used is presented in Figure 2 .

Figure 2 Instrumented Zwick Roell PSW 750 impact tester.

In the work package description the selected testing temperatures were between -40 and +20 °C, but this temperature range turned out to be too narrow in preliminary testing (at the Outokumpu TRC) to determine the ductile transition curves of all the grades. The final temperature range was -140 to +120 °C, depending on the steel grade being tested. Some grades were tested up to 240 °C. Temperatures of -160 and -180 °C were not possible because of problems with the cooling unit.

Some of the impact tests in the T-L direction were carried out and also reported in the report of WP5.2, Mechanical test and metallographic examination of welds.

3.4 Charpy-V impact toughness tests

A total of 24 steel grade and thickness combinations from the three steel producers were tested in two directions by means of the Charpy-V impact test. In total 5198 specimens were machined and 3025 impact toughness tests were performed on base materials with thicknesses from 1 to 6 mm for WP1 and WP5 at Kemi-Tornio University of Applied Sciences. At the Outokumpu Tornio Research Centre around 500 tests were performed with a manual Otto Wolpert PW 30/15 K impact tester.

Thin specimens, especially those that were 1 mm thick, caused challenges in the impact tests. The automatic feeding unit that was used is designed for specimens with a thickness of 10 mm. That led to feeding disruption at the beginning of the tests. The challenge was solved by using rubber or steel spacers to increase the height. Specimens with the rubber spacers are shown in Figure 3.

Figure 3 Specimens with rubber spacers.

Most of the 1-mm-thick specimens that were tested were twisted into a propeller shape in the impact tests. The problem is shown in Figure 4. The twisted specimens with thicknesses of 2 to 6 mm were cancelled and the tests were replaced.

Figure 4 Twisted specimens with a thickness of 1 mm.

3.5 Formation of the ductile transition curves

The data from the Charpy-V impact tests are fitted to form a transition curve. The most commonly used hyperbolic tangent function (tanh) was used in this study /7/. The equation used (1) is in the form:

$$\boldsymbol{C_v = \frac{C_{V-US}-C_{Vmin}}{2} \cdot \left(1 + \tanh\left(\frac{T-T_{50}}{C}\right)\right) + C_{Vmin}}, \tag{1}$$

where

C_v = Charpy-V impact energy,
$C_{V\text{-}US}$ = constant Charpy-V impact energy corresponding to the upper shelf energy,
C_{Vmin} = constant Charpy-V impact energy corresponding to the lower shelf energy,
T_{50} = a parameter to be fitted,
C = a parameter to be fitted.

The relation can also be presented in the form of exponentials as Equation (2).

$$C_V = \frac{(C_{V-US}-C_{Vmin})\cdot exp\left(\frac{2\cdot(T-T_{50})}{C}\right)}{1+exp\left(\frac{2\cdot(T-T_{50})}{C}\right)} + C_{Vmin} \tag{2}$$

The upper shelf energy $C_{V\text{-}US}$ and the lower shelf energy C_{Vmin} are assumed to be known in this function. The upper shelf energy ($C_{V\text{-}US}$) has been estimated for each grade, thickness, and test orientations from analysis of the impact energies when the values reached some constant value. The lower shelf energy (C_{Vmin}) is set at around 2 J, depending on the test results. /7/

The correspondence of the data points to the temperature region where the variation in terms of temperature is close to uniform is essential for the fitting. The region is defined as approximately $0{,}1 \cdot C_{V-US} \leq C_{Vi} \leq 0{,}85 \cdot C_{V-US}$. The limits may be changed if insufficient data exist in this region. /7/

One additional piece of data has to be added to ensure that the *tanh* function reaches the upper shelf in the right temperature region. This dummy piece of data is fixed at a toughness C_V = 0,97*$C_{V\text{-}US}$ and it corresponds to the lowest temperature at which the upper shelf data were obtained. /7,8/

The parameters T_{50} and C can be calculated from Equations (3) and (4).

$$C = \frac{n\cdot\sum_{i=1}^{n} T_i\cdot ln\left(\frac{C_{V-\overline{US}}-C_{Vmin}}{C_{Vi}-C_{Vmin}}-1\right) - \sum_{i=1}^{n} T_i\cdot \sum_{i=1}^{n} ln\left(\frac{C_{V-\overline{US}}-C_{Vmin}}{C_{Vi}-C_{Vmin}}-1\right)}{\left(\sum_{i=1}^{n} ln\left(\frac{C_{V-\overline{US}}-C_{Vmin}}{C_{Vi}-C_{Vmin}}-1\right)\right)^2 - n\cdot\sum_{i=1}^{n} ln\left(\frac{C_{V-\overline{US}}-C_{Vmin}}{C_{Vi}-C_{Vmin}}-1\right)^2} \tag{3}$$

$$T_{50} = \frac{\sum_{i=1}^{n} T_i + \frac{C}{2}\cdot\sum_{i=1}^{n} ln\left(\frac{C_{V-\overline{US}}-C_{Vmin}}{C_{Vi}-C_{Vmin}}-1\right)}{n}. \tag{4}$$

In the equations, n is the number of data values between $0{,}1 \cdot C_{V-US} \leq C_{Vi} \leq 0{,}85 \cdot C_{V-US}$ plus the dummy data.

3.6 Determination of the transition temperature

The transition curves of the materials that were studied were determined from the Charpy-V impact test results. Generally, the temperature at which the steel achieves an impact value of 28 J (or 27 J) was used for the Charpy-V impact test transition temperature. For a standard-sized specimen 28 J corresponds to 28J/(1.0 cm * 0.8 cm)=35J/cm^2. The symbol that is typically used for this temperature is T_{28J} or $T_{35J/cm}{}^2$. A criterion of 35J/cm^2 for the transition temperature was also used in the study. The absorption energy criteria [J] for different thicknesses are shown in Table 3.

Table 3 Charpy-V energy of different size specimens at the transition temperature $T_{35J/cm}{}^2$

Specimen type	Dimensions	Value of Charpy-V test in transition	
	[mm]	[J]	[J/cm2]
Standard	10 x 10 x 55	**28**	35
Sub size	1 x 10 x 55	**2.8**	35
Sub size	2 x 10 x 55	**5.6**	35
Sub size	3 x 10 x 55	**8.4**	35
Sub size	4 x 10 x 55	**11.2**	35
Sub size	5 x 10 x 55	**14**	35
Sub size	6 x 10 x 55	**16.8**	35

When the transition temperatures of the sub-sized specimens are compared to those of the standard specimen, it is necessary to extrapolate the transition temperatures. Kim Wallin has developed a relation between 35 J/cm^2 transition temperatures of the standard and sub-sized specimens for ferritic structural steels (carbon steels, yield stress > 500 MPa). The Wallin correlation for sub-sized specimens is material independent and therefore applies to ferritic stainless steels /14/. The temperature correction for the sub-sized specimens can be calculated by Equation (5) /7/

$$\Delta TC_{V35J/cm^2} = 51.4°\mathrm{C} \cdot ln\left\{2 \cdot \left(\frac{B}{10mm}\right)^{0.25} - 1\right\} \quad (5)$$

where B = specimen thickness in mm.

The effect of the specimen thickness on the 35 J/cm^2 transition temperatures for high-strength steels is presented in Figure 5. The effect of the thickness on the transition temperature is substantial when the specimen thickness is less than 3 mm. That means a major temperature correction for the results of specimens thinner than 3 mm. For 1-mm specimens the correction is -107 °C. Equation (5) was developed for use for sub-sized specimens with thicknesses between 1.25 and 10 mm. The temperature correction was not used for the 1-mm material in this study. /7/

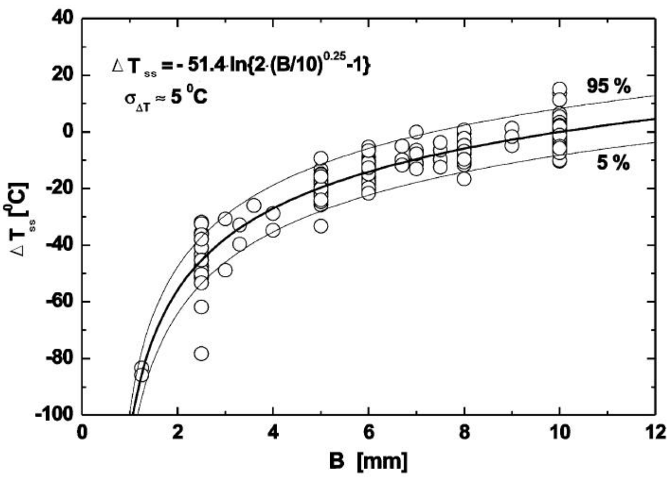


Figure 5 Effect of specimen thickness on shift of $T_{35J/cm}{}^2$ transition temperature. /7/

4 Results and observations

The fitted impact toughness ductile-brittle transition temperature curves are presented in Appendices 1 to 5. Equations 2, 3, and 4 were used for the definitions. The ductile-to-brittle transition temperatures were determined for the sub-sized specimens, and the results were size-corrected with Wallin's method to correspond to standard-sized specimens. The thickness correction was calculated by means of Equation (5). All the determined and size-corrected transition temperatures are presented in Table 4. A 95% confidence interval is taken into account in the presentation of the transition temperatures. There was not enough impact toughness testing data on some materials for realistic transition curves to be formed. These materials are marked in yellow in Table 4. The impact toughness test data are listed in Appendix 6.

Table 4 Determined and size-corrected transition temperatures of the materials that were tested.

				Test direction				
				T-L		L-T		
Grade	**Producer**	**B = THK [mm]**	**Transition criterion [J]***	T_{xJ}	T_{28J}	T_{xJ}	T_{28J}	$\Delta T_{CV35J/cm^2}$ f(B) (equation 5)
1.4003	B	1.00	2.8	-130 ± 30	-	-	-	(-107)**
1.4003	B	1.97	5.5	-	-	-	-	-57
1.4003	B	2.83	7.9	-75 ± 26	-35	-102 ± 21	-62	-40
1.4003	B	3.95	11.1	-	-	-105 ± 17	-77	-28
1.4003	B	4.91	13.8	-49 ± 22	-29	-67 ± 12	-47	-20
1.4003	B	5.97	16.7	-34 ± 19	-20	-53 ± 12	-39	-14
1.4016	C	1.02	2.9	-112 ± 44	-	-132 ± 35	-	(-105)**
1.4016	B	2.00	5.6	-42 ± 18	14	-110 ± 23	-54	-56
1.4016	C	2.01	5.6			-84 ± 25	-28	-56
1.4016	C	2.97	8.3	-25 ± 11	13	-36 ± 22	2	-38
1.4016	C	3.99	11.2	7 ± 21	34	-7 ± 20	20	-27
1.4509	B	1.02	2.8	-94 ± 26	-	-107 ± 24	-	(-105)**
1.4509	C	0.99	2.8	-97 ± 26	-	-108 ± 25	-	(-108)**
1.4509	B	1.98	5.5	-30 ± 13	26	-59 ± 26	-3	-56
1.4509	C	1.98	5.5	-29 ± 19	27	-74 ± 37	-18	-56
1.4509	B	2.95	8.3	-5 ± 20	33	-7 ± 14	31	-38
1.4509	A	2.95	8.3	-12 ± 22	26	-32 ± 34	6	-38
1.4509	C	3.52	9.9	-	-	25 ± 32	57	-32
1.4509	B	3.91	10.9	-11 ± 23	17	-4 ± 20	24	-28
1.4521	B	0.99	2.8	-104 ± 25	-	-114 ± 37	-	(-107)**
1.4521	B	1.99	5.6	-44 ± 17	12	-43 ± 33	7	-56
1.4521	C	1.97	5.5	-29 ± 29	28	-59 ± 25	-2	-57
1.4521	B	3.02	8.5	23 ± 17	60	21 ± 17	58	-37
1.4621	A	1.49	4.2	-84 ± 31	-15	-100 ± 26	-27	-73

* Based on 35 J/cm^2 transition criterion, reference Table 3

** Thickness correction only for thicknesses from 1.25 mm to 10 mm

More data is required

4.1 Grade EN 1.4003

Figures 6 and 7 illustrate the impact toughness ductile-brittle transition temperature curves for EN 1.4003 produced by producer B with a thickness of 3 mm in the T-L and L-T directions. The red squares in the transition curve figures are data between 0.1*$C_{V\text{-}US}$ and 0.85*$C_{V\text{-}US}$ used for fitting the transition curve, equations 3 and 4. The curves for the other thicknesses are presented in Appendix 1.

The estimated upper shelf energies were 48 J in the T-L direction and 59 J in the L-T direction. The upper shelf energy ($C_{V\text{-}US}$) was about 10 J higher in the L-T direction than the T-L direction. The trend was the same with the other thicknesses that were tested. The transition temperatures $T_{7.9J}$ for EN 1.4003 with a thickness of 3 mm were -102 °C and -75 °C. The lower value was estimated in the L-T direction. The size-corrected transition temperatures T_{28J} were -62 °C and -35 °C.

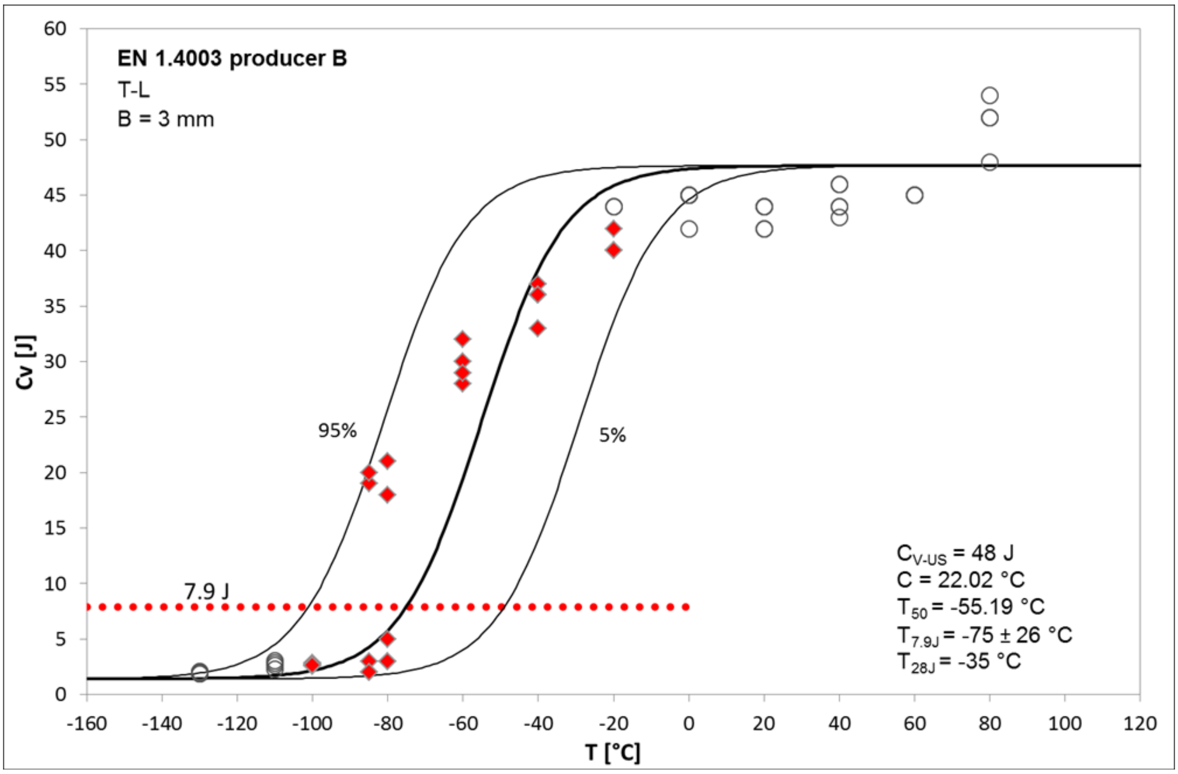


Figure 6 Transition curve determined for 3-mm-thick EN 1.4003 produced by producer B. Testing direction T-L.

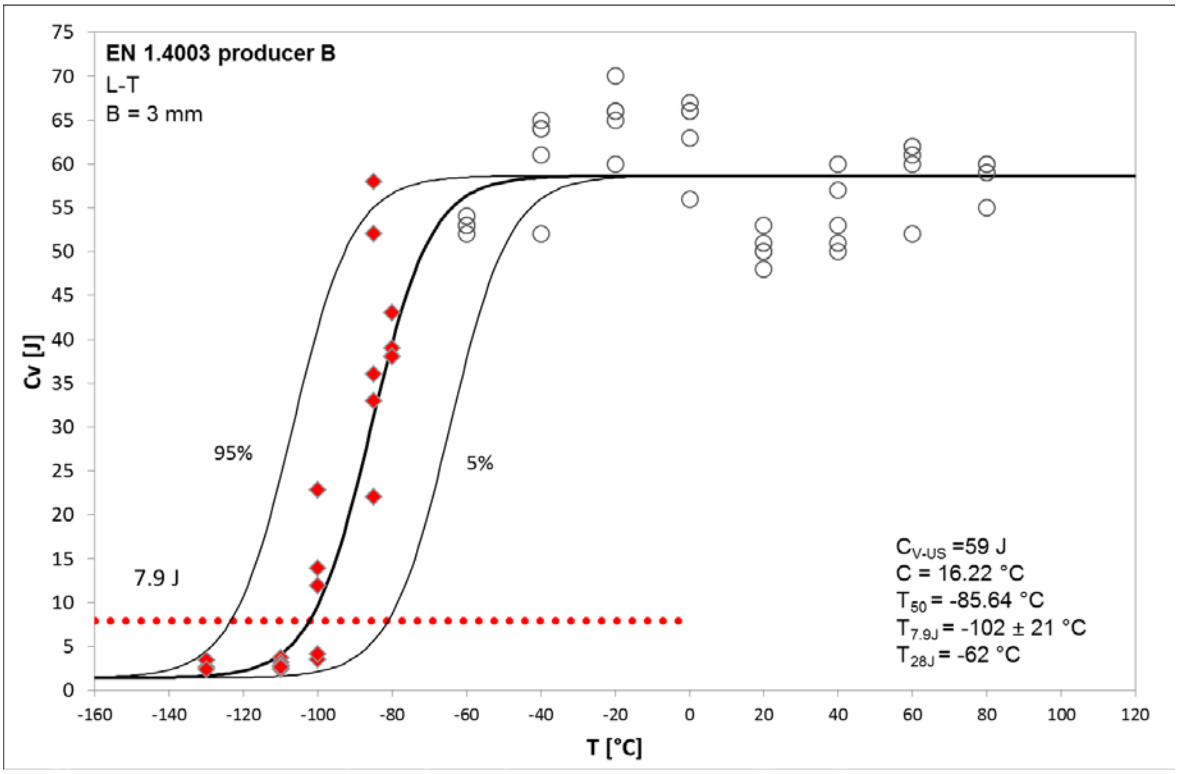


Figure 7 Transition curve determined for 3-mm-thick EN 1.4003 produced by producer B. Testing direction L-T.

4.2 Grade EN 1.4016

Figures 8 and 9 illustrate the impact toughness ductile-brittle transition temperature curves for EN 1.4016 produced by producer C with a thickness of 3 mm in the T-L and L-T directions. The curves for the other thicknesses are presented in Appendix 2.

The estimated upper shelf energies were 25 J in the T-L direction and 38 J in the L-T direction. The upper shelf energy ($C_{V\text{-}US}$) was about 13 J higher in the L-T direction than the T-L direction. The trend was the same with the thickness of 4 mm. Thinner materials 1 and 2 mm thick have similar upper shelf energy in both directions. The transition temperatures $T_{8.3J}$ for EN 1.4016 with a thickness of 3 mm were -36 °C and -25 °C. The lower value was estimated in the L-T direction. The size-corrected transition temperatures T_{28J} were +2 °C and +13 °C.

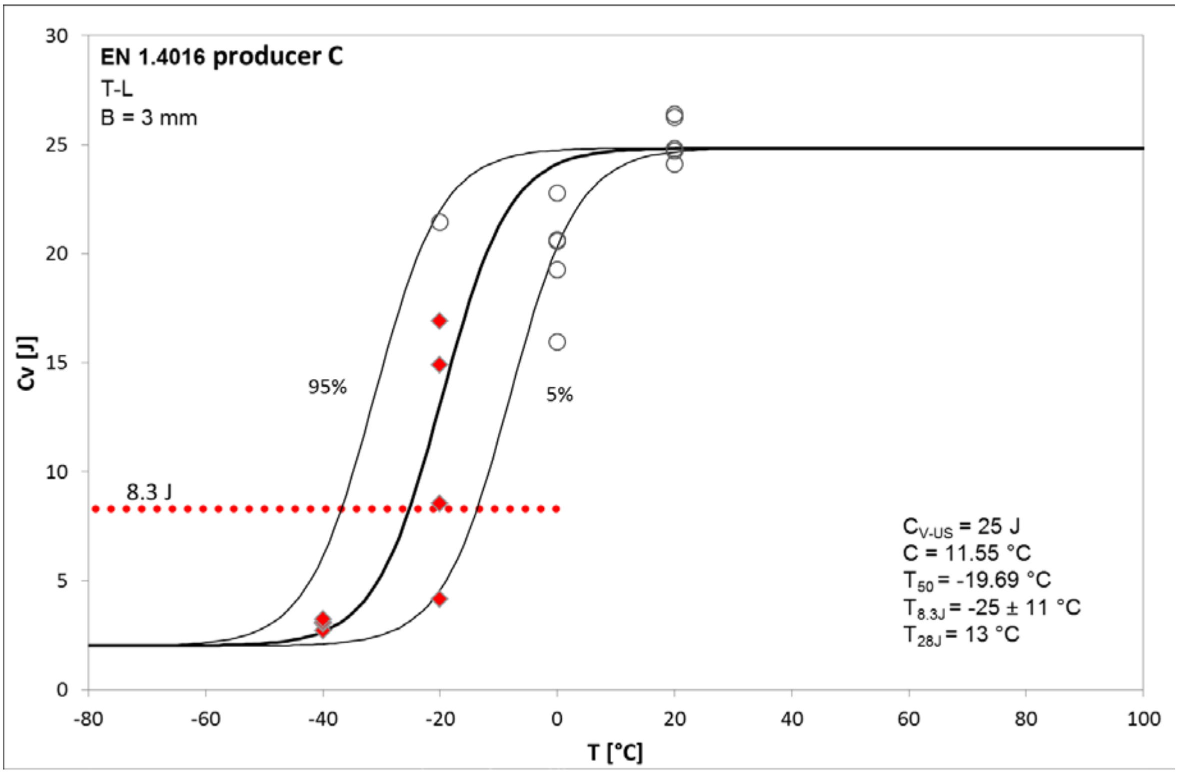


Figure 8 Transition curve determined for 3-mm-thick EN 1.4016 produced by producer C. Direction T-L.

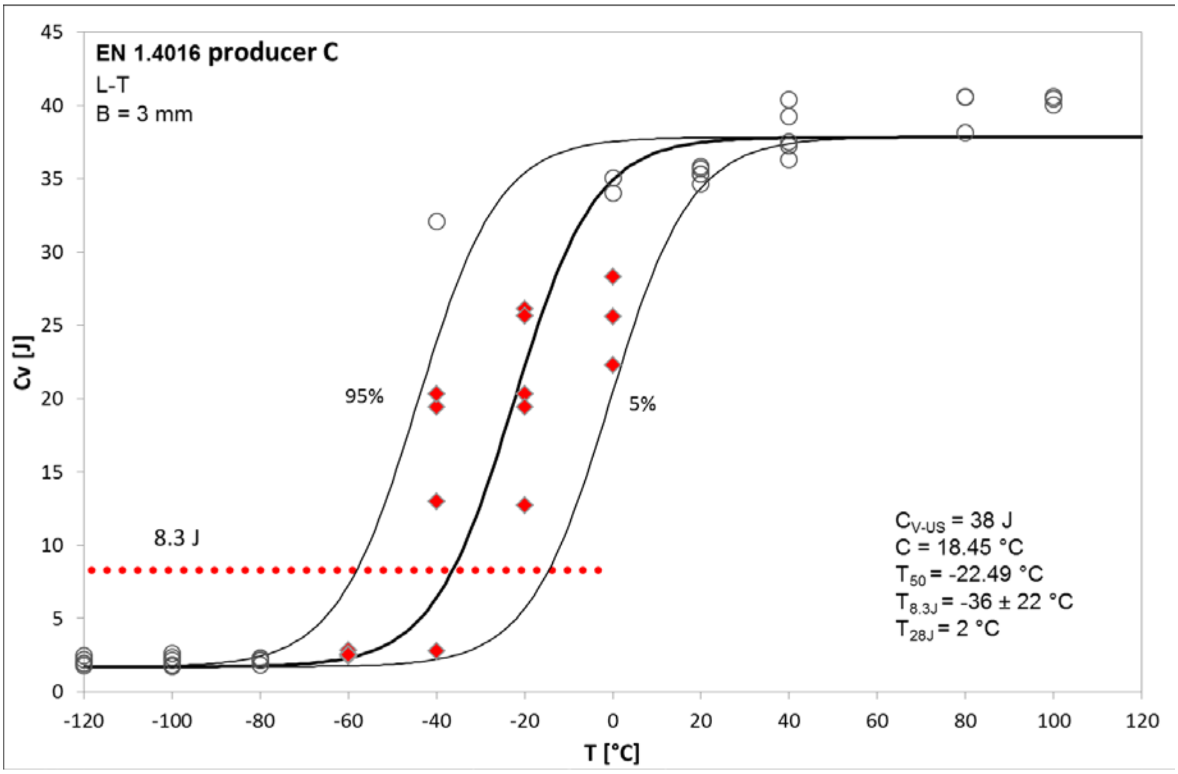


Figure 9 Ductile transition curve determined for 3-mm-thick EN 1.4016 produced by producer C. Direction L-T.

4.3 Grade EN 1.4509

Figures 10-13 illustrate the impact toughness ductile-brittle transition temperature curves for the stabilised grade EN 1.4509 with a thickness of 3 mm produced by producers B and A in the T-L and L-T directions. The curves for the other thicknesses are presented in Appendix 3.

The estimated upper shelf energies were 34 and 38 J in the T-L direction and 38 and 44 J in the L-T direction. The transition temperatures $T_{8.3J}$ for the EN 1.4509 produced by producer B with a thickness of 3 mm were -5 °C and -7 °C. The size corrected transition temperatures T_{28J} were +31 °C and +33 °C. For the material produced by producer A the temperatures $T_{8.3J}$ were -12 °C and -32 °C. The size-corrected transition temperatures T_{28J} were +26 °C and +6 °C.

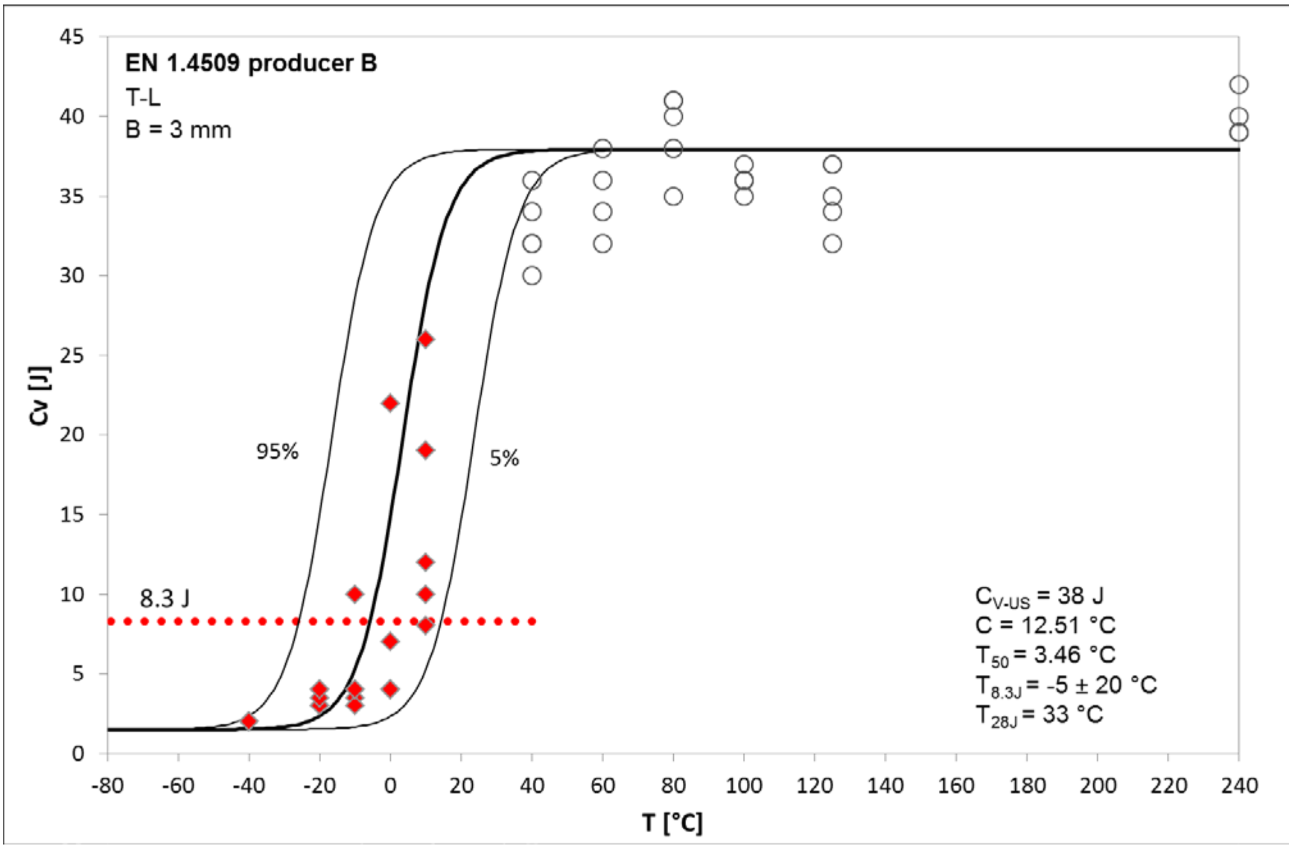


Figure 10 Transition curve determined for 3-mm-thick EN 1.4509 produced by producer B. Testing direction T-L.

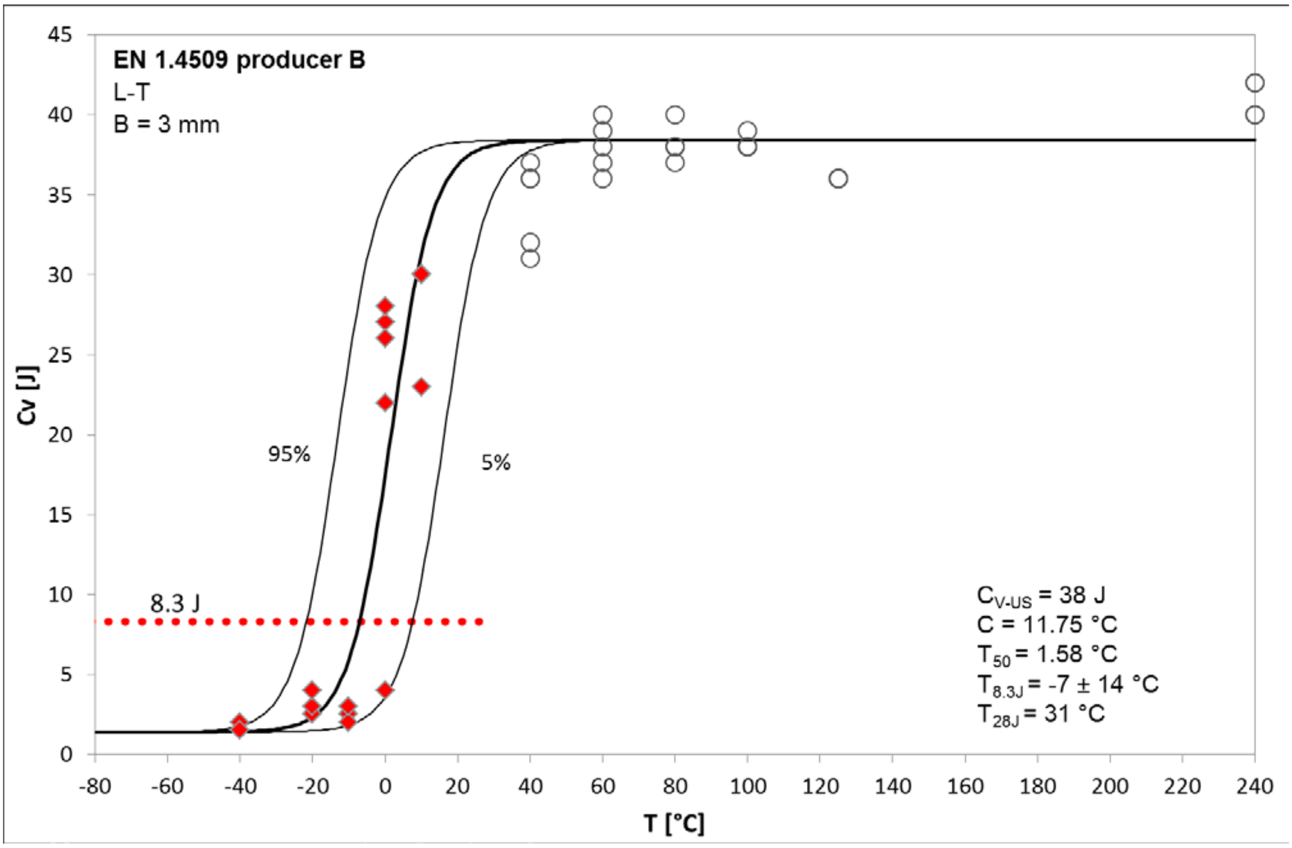


Figure 11 Transition curve determined for 1-mm-thick EN 1.4509 produced by producer B. Testing direction L-T.

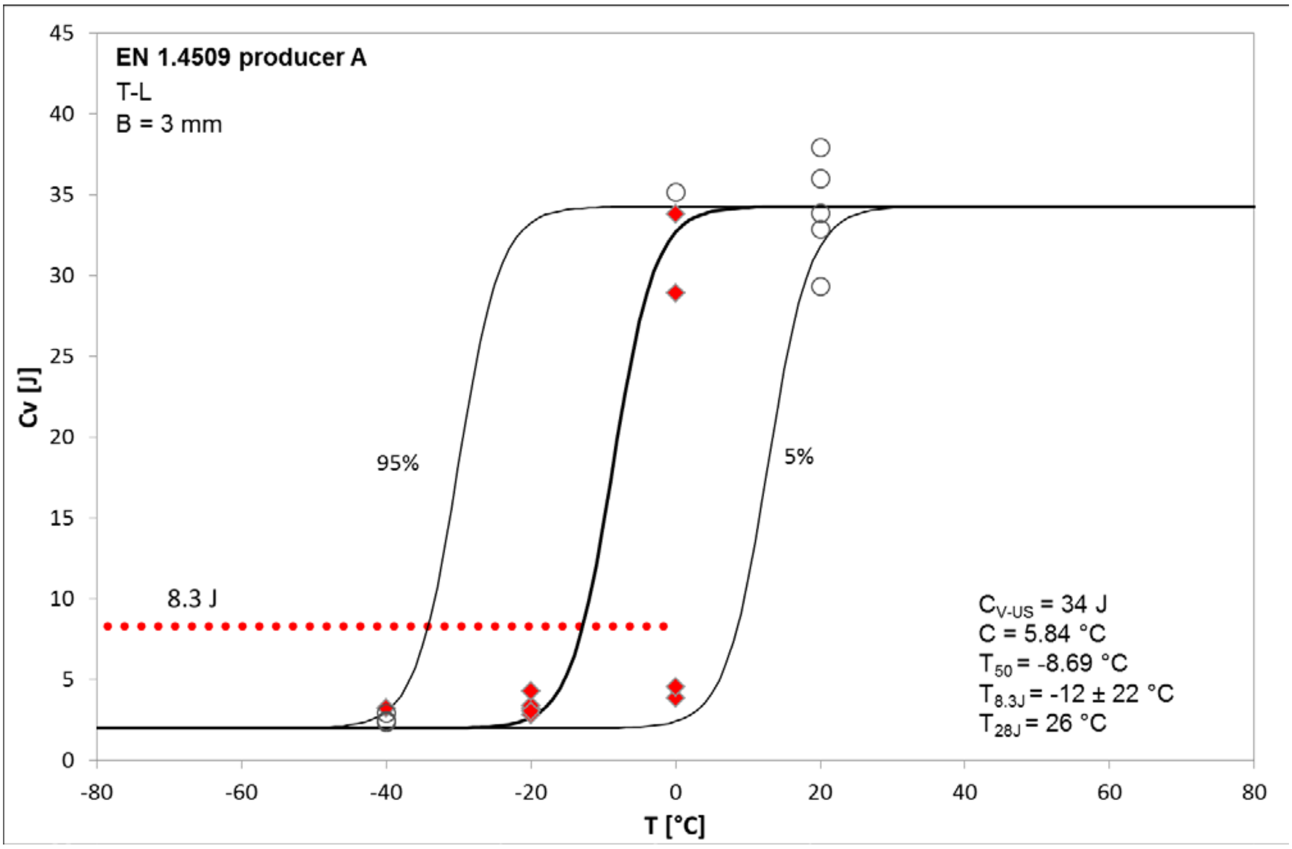


Figure 12 Ductile transition curve determined for 3-mm-thick EN 1.4509 produced by producer A. Direction T-L.

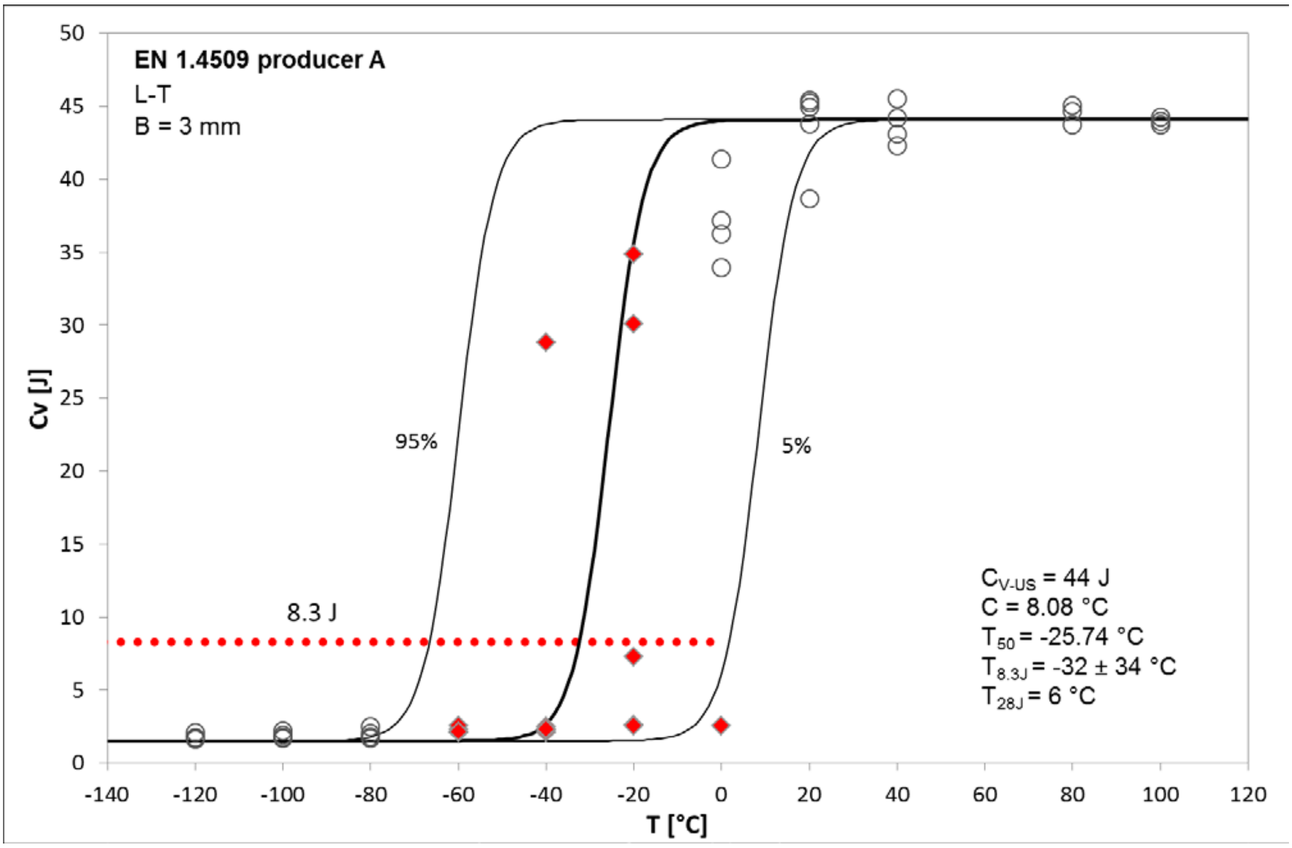


Figure 13 Ductile transition curve determined for 3-mm-thick EN 1.4509 produced by producer A. Testing direction L-T.

4.4 Grade EN 1.4521

The transition curves for the stabilised and molybdenum alloyed grade EN 1.4521 with a thickness of 2 mm produced by producer C and producer B are shown in Figures 14-17. The curves for the other thicknesses are presented in Appendix 3.

It is shown that both producers' materials have about the same upper shelf energies (26 and 29 J) in the L-T direction. In the T-L direction the producer C material has same upper shelf energy than in the L-T direction and the producer B material one that is slightly lower, 21 J. The differences are minor. It is not possible to compare the transition temperatures in the T-L direction because of the lack of testing data on the producer B material. In the results for other directions it can be seen that the producer C material has a better transition temperature. The producer C material had a transition temperature $T_{5.5J}$ of -59 °C, while the producer B material had a transition temperature of -43 °C. The size-corrected transition temperatures are around zero for both materials. A possible explanation for this difference is the material compositions. The compositions are shown in Table 1. The producer C material had lower interstitial level (C+N 250 ppm) than the producer B material (350 C+N). Another difference is in the mechanical properties, where the ultimate tensile strength of the producer C material is 423 N/mm^2 and that of the producer B material are 571 N/mm^2. The grain sizes of the material were not measured.

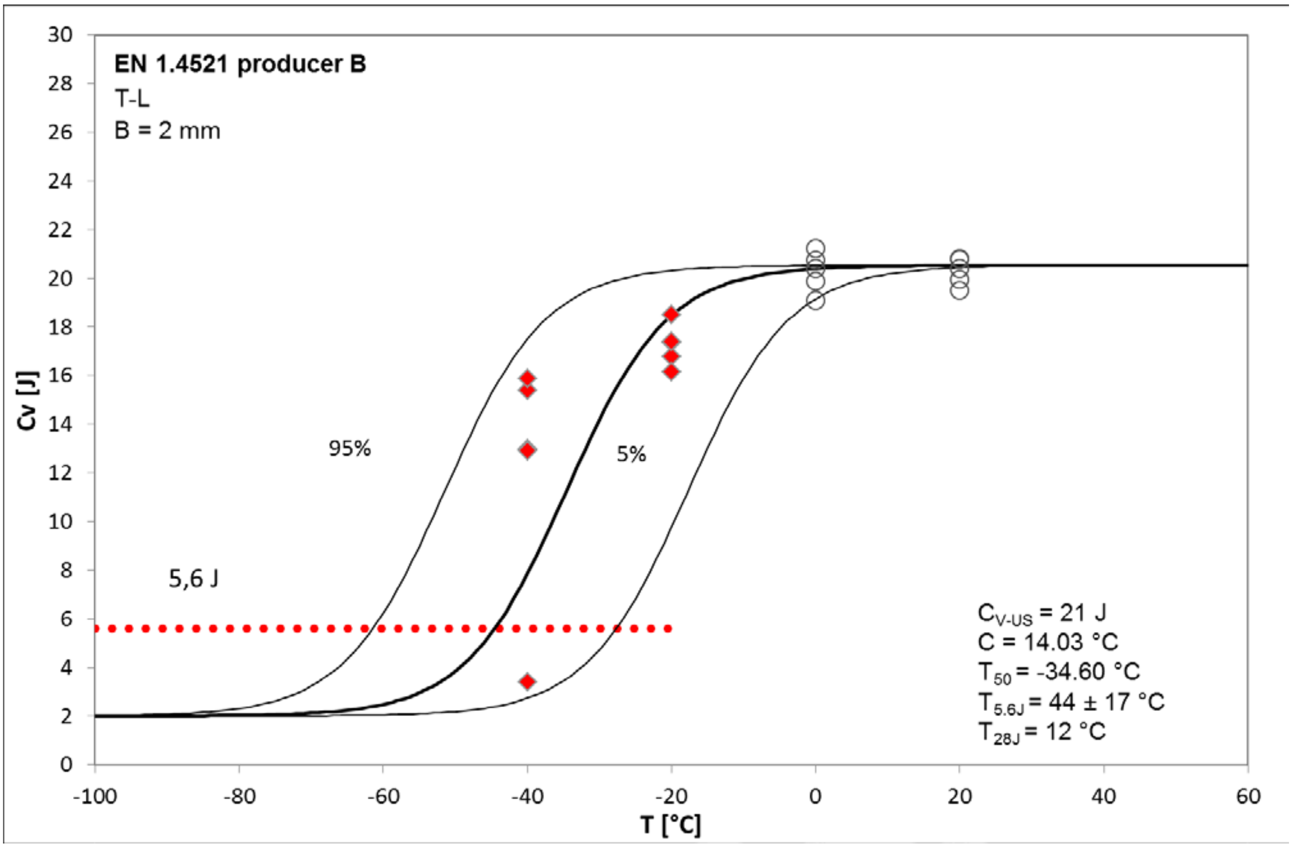


Figure 14 Transition curve determined for 2-mm-thick EN 1.4521 produced by producer B. Direction T-L.

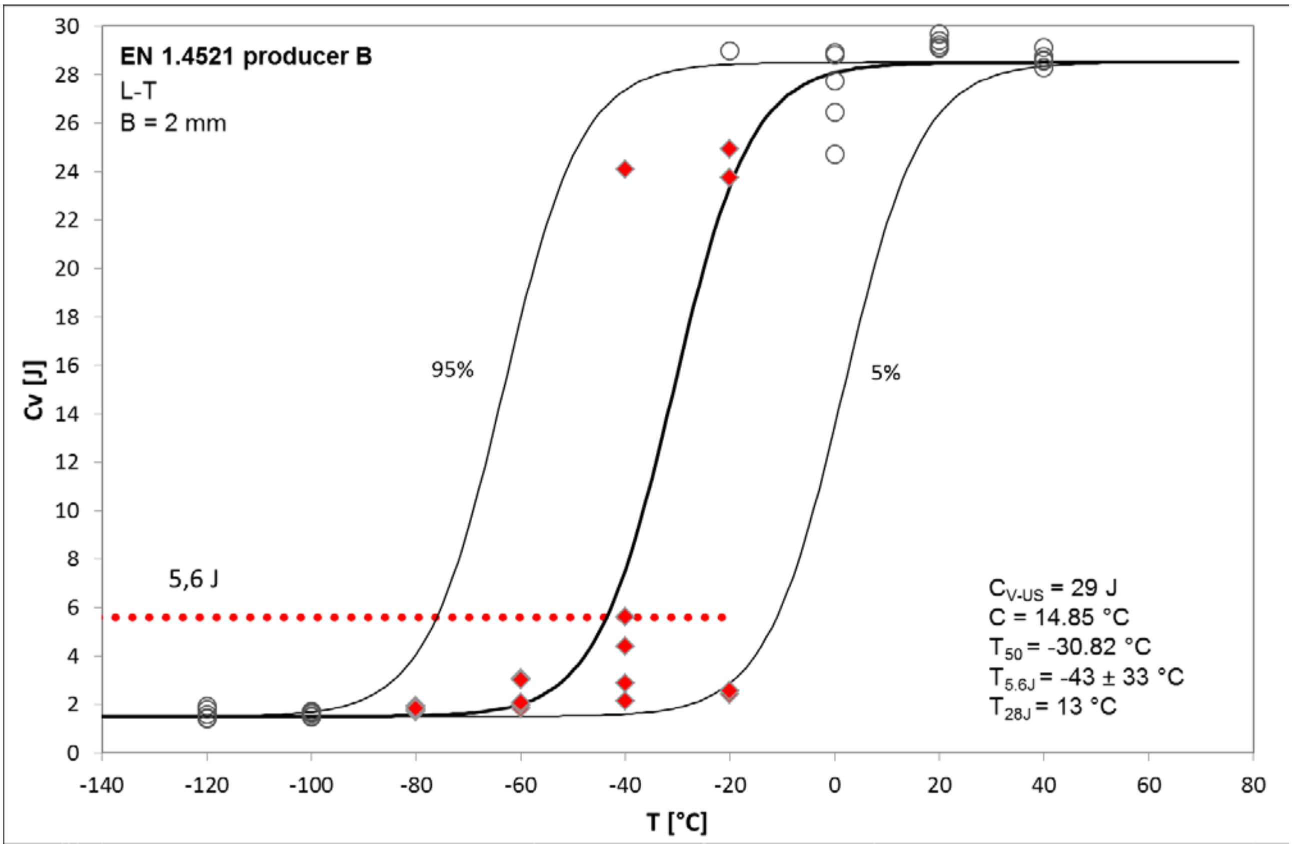


Figure 15 Transition curve determined for 3-mm-thick EN 1.4521 produced by producer B. Direction T-L.

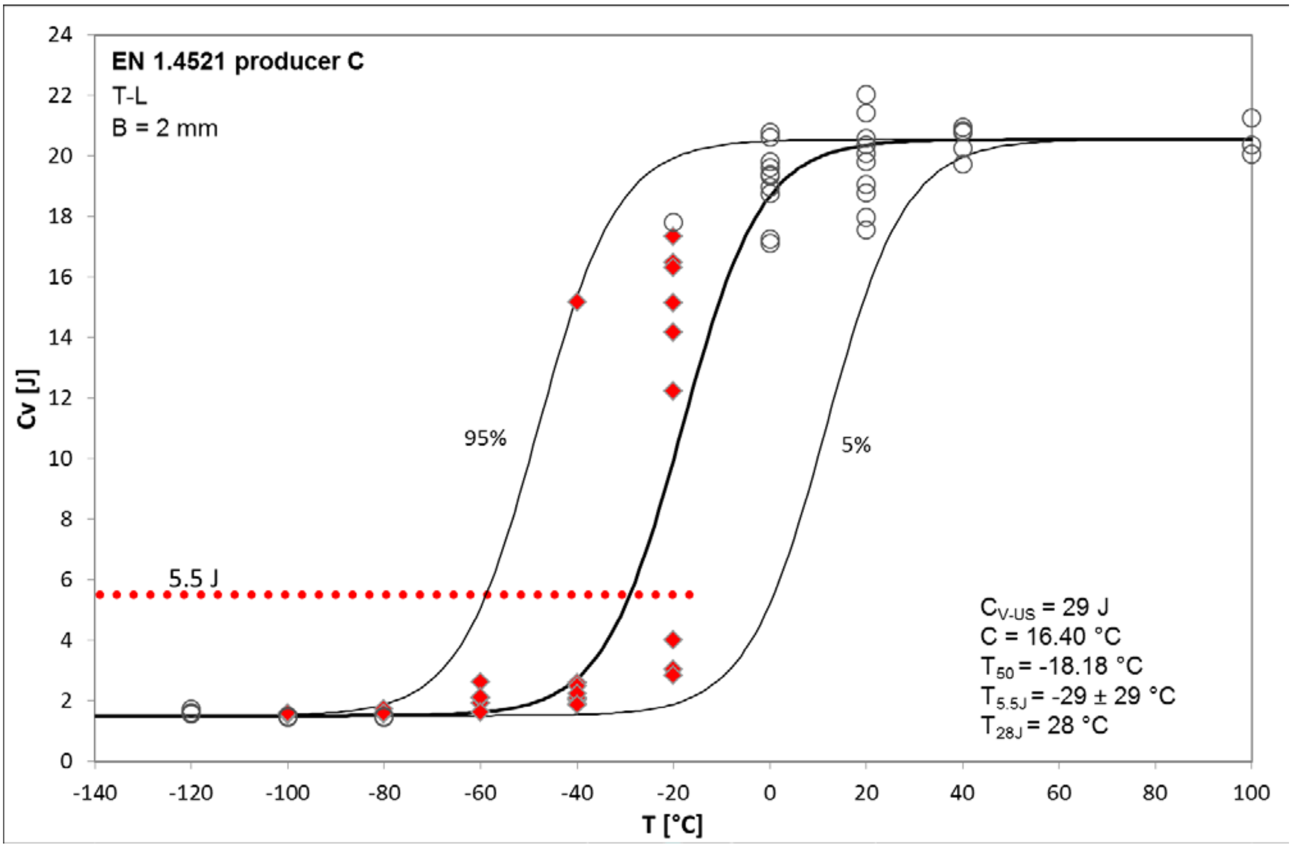


Figure 16 Ductile transition curve determined for 2-mm-thick EN 1.4521 produced by producer C. Direction T-L.

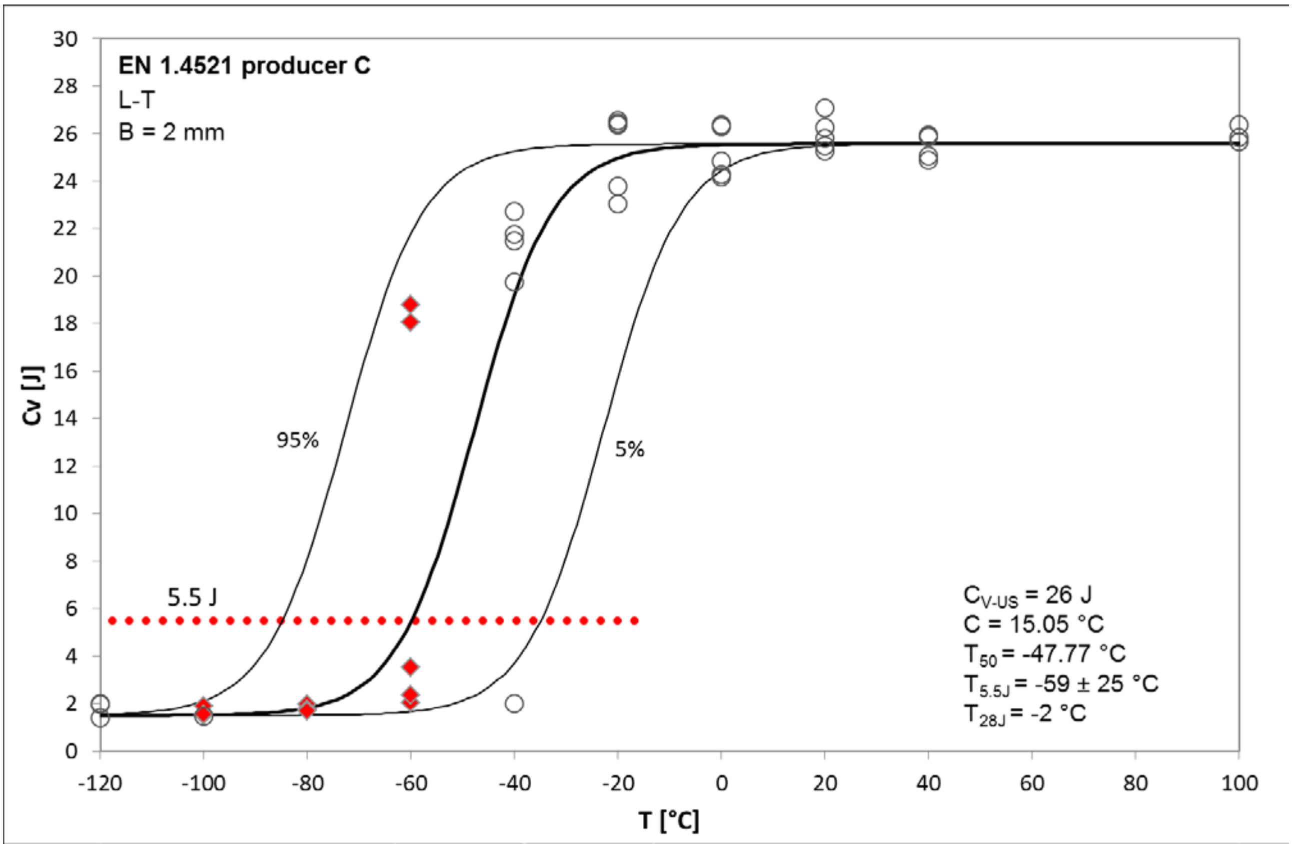
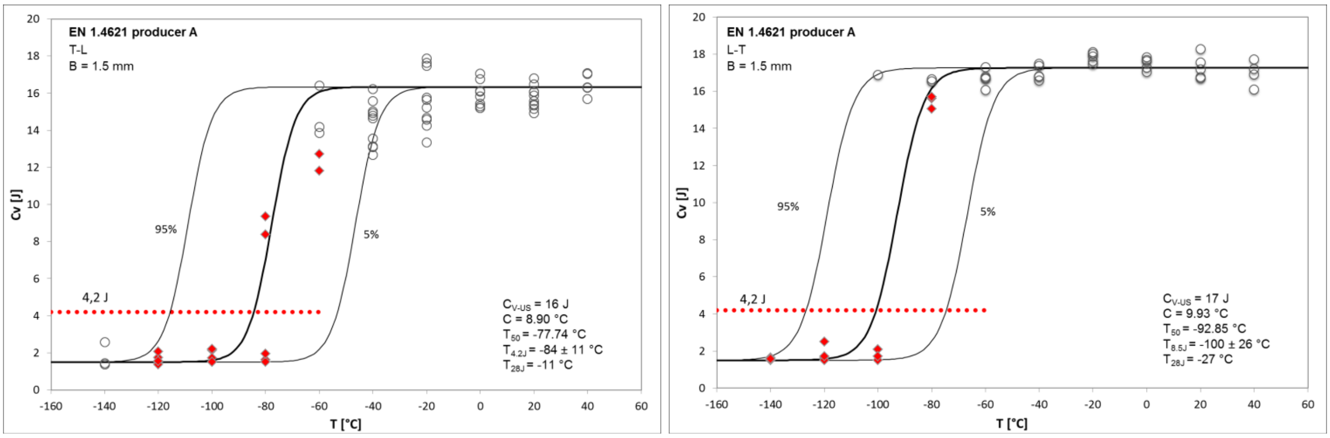


Figure 17 Ductile transition curve determined for 2-mm-thick EN 1.4521 produced by producer C. Direction L-T.

4.5 Grade EN 1.4621

Only one thickness of the grade EN 1.4621 from one producer was tested. The transition temperature curves that were determined are presented in Figures 18. The curves are presented with a higher resolution in Appendix 5. The upper shelf energies in both directions were similar, 16 and 17 J. The transition temperatures $T_{4.2J}$ were -84 °C and -100 °C. The thickness correction for 1.5-mm material is quite major, -73 °C. The correction raises the transition temperature T_{28J} to -11 °C and -27 °C.



Figures 18 Transition curves determined for 1.5-mm-thick EN 1.4621 produced by producer A.

4.6 Summary

One of the objectives of Task 1.4 was to develop a table giving thickness limits for a given temperature to achieve adequate ductility. A proposal for the temperature limits for the ferritic stainless steels that were tested is presented in Table 5. The proposed temperature limits are based on the test results and the transition curves that were determined. A confidence interval of 95% is taken into account in the determination of the temperature limits.

Table 5 Summary of DBTT transition temperatures for each of the ferritic stainless steel grades that were tested.

Grade	Thickness [mm]	Min Temp [°C]
1.4003	1	-100
	3	-50
	5	-30
	6	-15

Grade	Thickness [mm]	Min Temp [°C]
1.4509	1	-70
	2	-20
	3	0
	4	0

Grade	Thickness [mm]	Min Temp [°C]
1.4016	1	-70
	2	-25
	3	-15
	4	RT

Grade	Thickness [mm]	Min Temp [°C]
1.4521	1	-75
	2	-30
	3	RT

Grade	Thickness [mm]	Min Temp [°C]
1.4621	1.5	-50

5 Conclusions

The determination of the impact toughness of materials thinner than 3 mm materials proved difficult. The automatic impact toughness tester that was used is designed to use only standard-sized specimens (B = 10 mm). Thinner and lighter specimens require modification to avoid feeding problems. The corrections used were glued spacers. Both rubber and metallic spacers were used.

Generally, the transition temperatures that were defined are lower in the L-T directional specimens in this study. The materials that were tested have very different transition temperatures. The lowest transition temperatures were defined for the grades EN 1.4003 and 1.4016 with a thickness of 1 mm as -130 and -132 °C. With a thickness of 3 mm the lowest transition temperature is -100 °C for the grade EN 1.4003. The grades EN 1.4509 and 1.4521 have higher transition temperatures. All the grades have transition temperatures near -100 °C at a thickness of 1 mm. The transition temperatures that were determined shifted to higher temperatures with increased specimen thickness, which correlated with earlier studies /9/.

According to the study, the grade EN 1.4003 has adequate toughness down to -30 °C up to a thickness of 6 mm. The grade 1.4016 has slightly higher transition temperatures than 1.4003. EN 1.4016 has a transition temperature below -20 °C up to a thickness of 3 mm. The stabilised grades 1.4509 and 1.4521 have transition temperatures below -20 °C up to a thickness of 2 mm. When a 95% confidence interval is taken into account, the temperature limits for the material studied here shifted to higher temperatures, as shown in Table 5.

Similar impact toughness results were reported in WP5. A summary of the impact toughness tests of the base materials of WP5 is presented in Figure 19. In the WP5 testing the temperature range was too narrow to get a general view of the temperature behaviour of impact toughness in the Charpy V test. /12, 13/

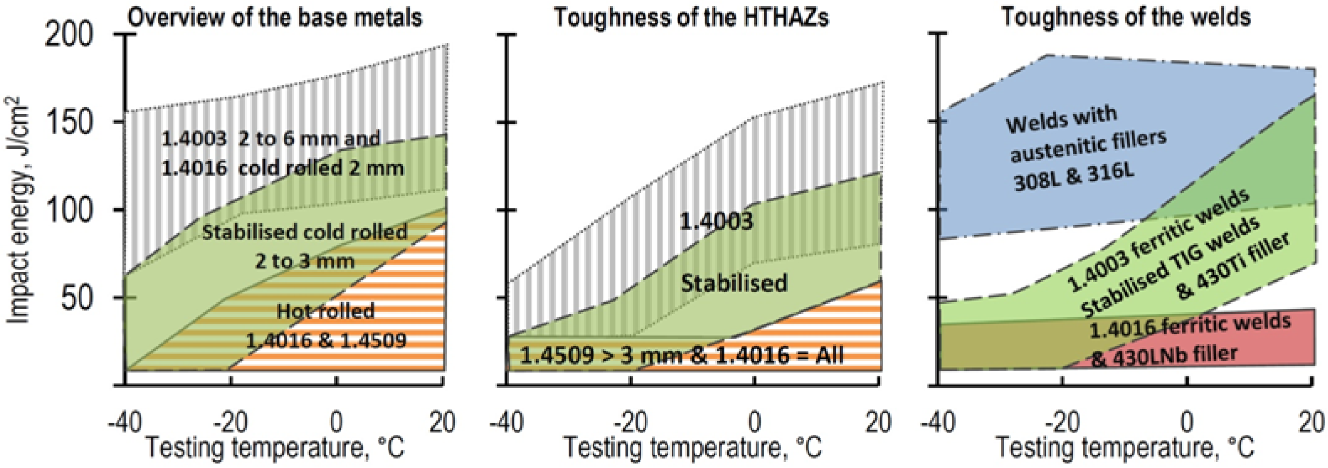


Figure 19 Representative graph from the impact toughness tests for base materials in WP5 /13/.

It is notable that only one heat of the each manufacturer of each grade was studied. That is not enough to get reliable data on the impact toughness behaviour of each of the steel grades. The composition of ferritic stainless steel, especially the interstitial elements, carbon and nitrogen, has a strong effect on the impact toughness behavior, as does the grain size, which varies in steel processing /9, 10/.

On the basis of the test results, the grade EN 1.4003 has the lowest transition temperature. The proposed temperature limit for 6-mm material is -15 °C and with a thickness of 1 mm it is -100 °C. The temperature limit is linear between these temperatures for this grade. For the other grades, the temperature limit with a thickness of 1 mm is around -70 °C and the limit with a thickness of 2 mm is about -25 °C.

Thin materials proved to be very difficult to test and in some cases the shear fracture mechanism played a very significant role. It is necessary to develop another testing method for thin materials. A possible test method is the Impact Tensile Test (ITT). A replacement for the Charpy V impact toughness testing of thin materials may be similar to the impact tensile test (ITT). This test method is presented in the standard ISO 8256: *Determination of tensile-impact strength*. A similar impact test was developed at VTT in the RFCS project *Stainless steels in bus constructions* /11/. In addition, based on findings from literature and discussions during the project it is recommended to study the fracture toughness testing of ferritic stainless steels.

6 References

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11. Kyröläinen A. et al, European Commission, Stainless steels in bus constructions, Final report, EUR 20884, 2003.
12. Anttila, S., Heikkinen H-P., Study of weldability, SAFSS WP5.1 final report, July 2011.
13. Anttila, S., Mechanical tests and metallographic examination of welds, SAFSS WP5.2 final report, July 2012.
14. Discussions between prof. Kim Wallin (VTT) and Dr. Katherine Cashell (SCI), in May 2012.

7 Appendices

1. Ductile transition curves determined for EN 1.4003
2. Ductile transition curves determined for EN 1.4016
3. Ductile transition curves determined for EN 1.4509
4. Ductile transition curves determined for EN 1.4521
5. Ductile transition curves determined for EN 1.4621
6. Impact toughness test data

Ductile transition curves determined for the grade EN 1.4003 with a thickness from 1 to 6 mm.

$C_{V\text{-}US}$ = Upper shelf energy [J]
C = fitted parameter from Equation (3), [°C]
T_{50} = fitted parameter from Equation (4), [°C]
$T_{x.xJ}$ = determined transition temperature. Criterion (x.x) is depending on thickness of the sub-sized specimen. [°C]
T_{28J} = size-corrected transition temperature [°C]
The red squares in the transition curve figures are data between $0.1*C_{V\text{-}US}$ and $0.85*C_{V\text{-}US}$ used for fitting the transition curve, equations 3 and 4.

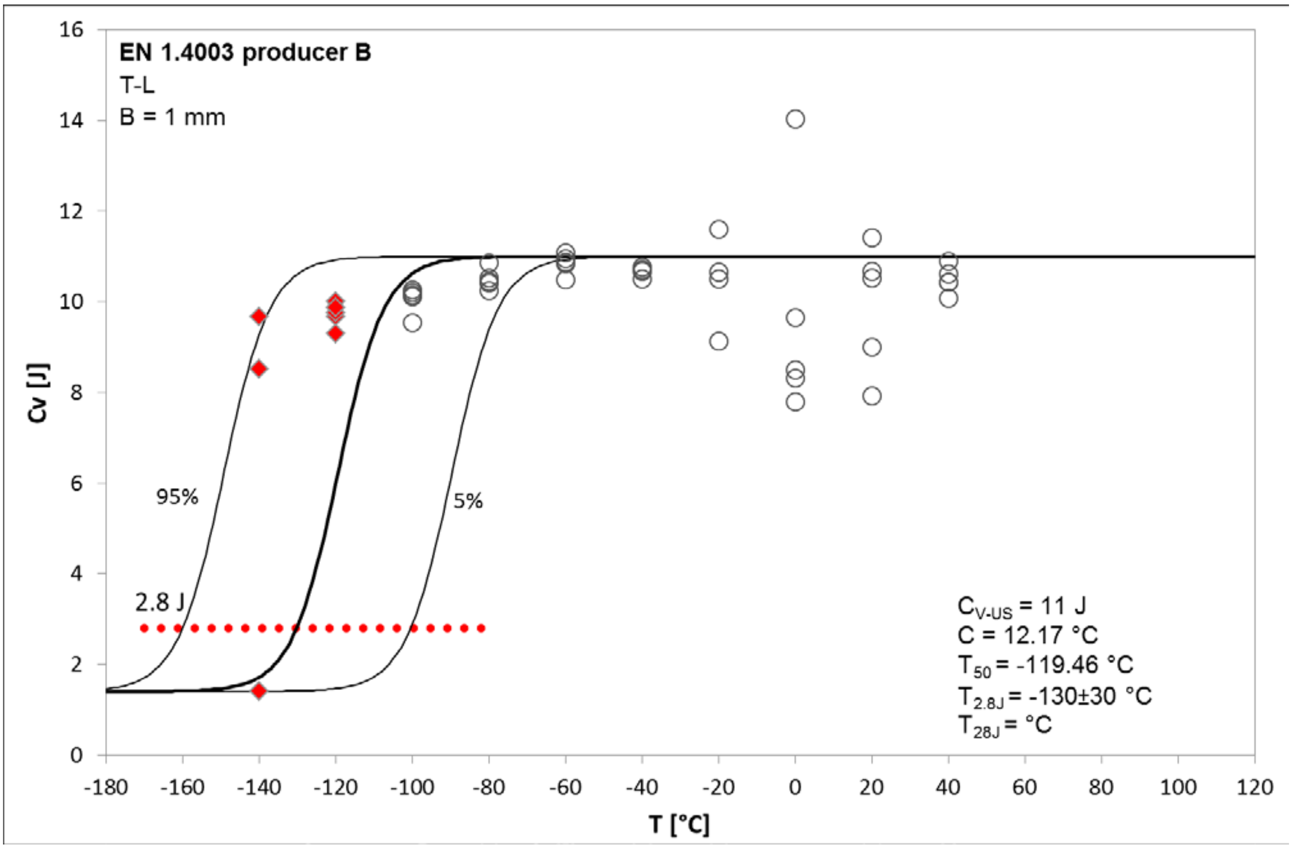

Figure 1 Transition curve determined for 1-mm-thick EN 1.4003 produced by producer B. Testing direction T-L.

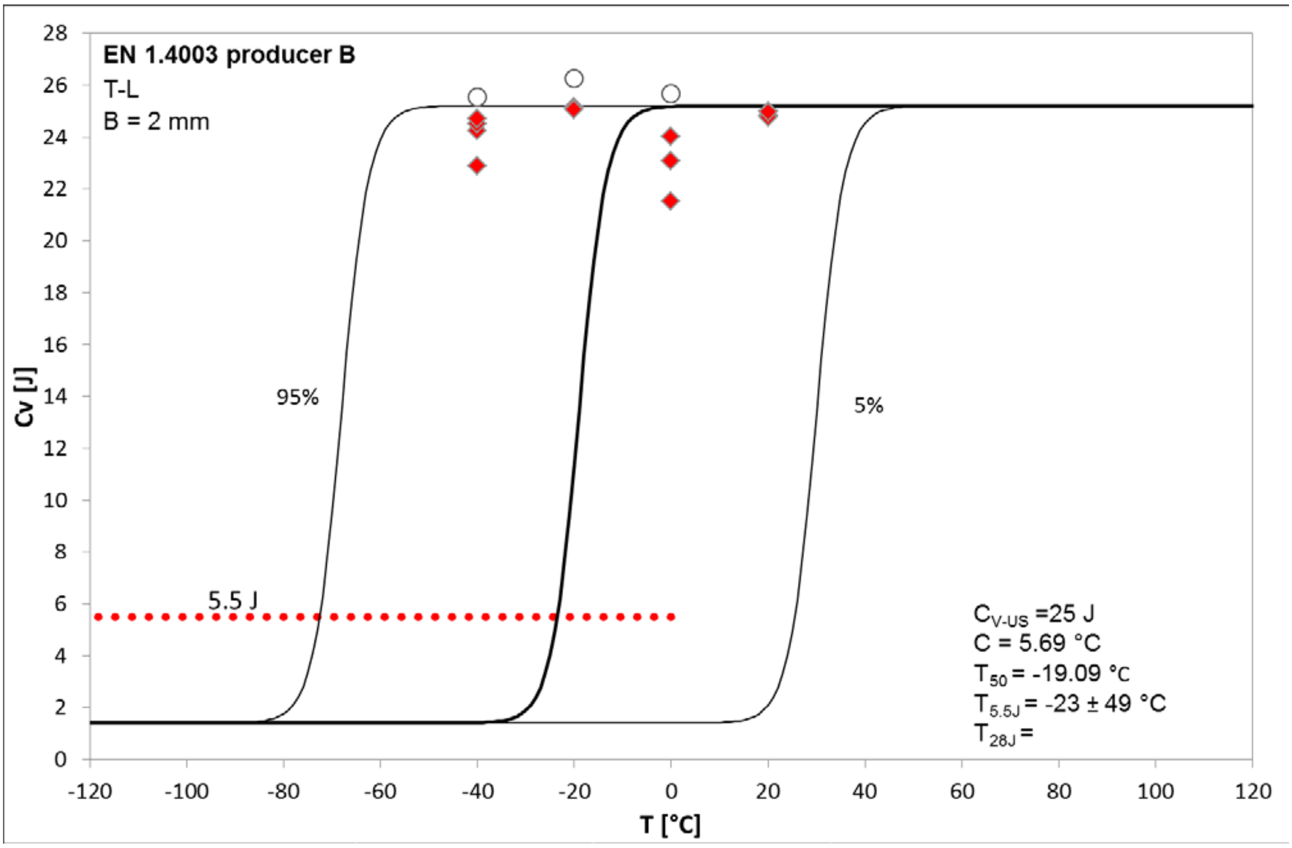

Figure 2 Transition curve determined for 2-mm-thick EN 1.4003 produced by producer B. Testing direction T-L.

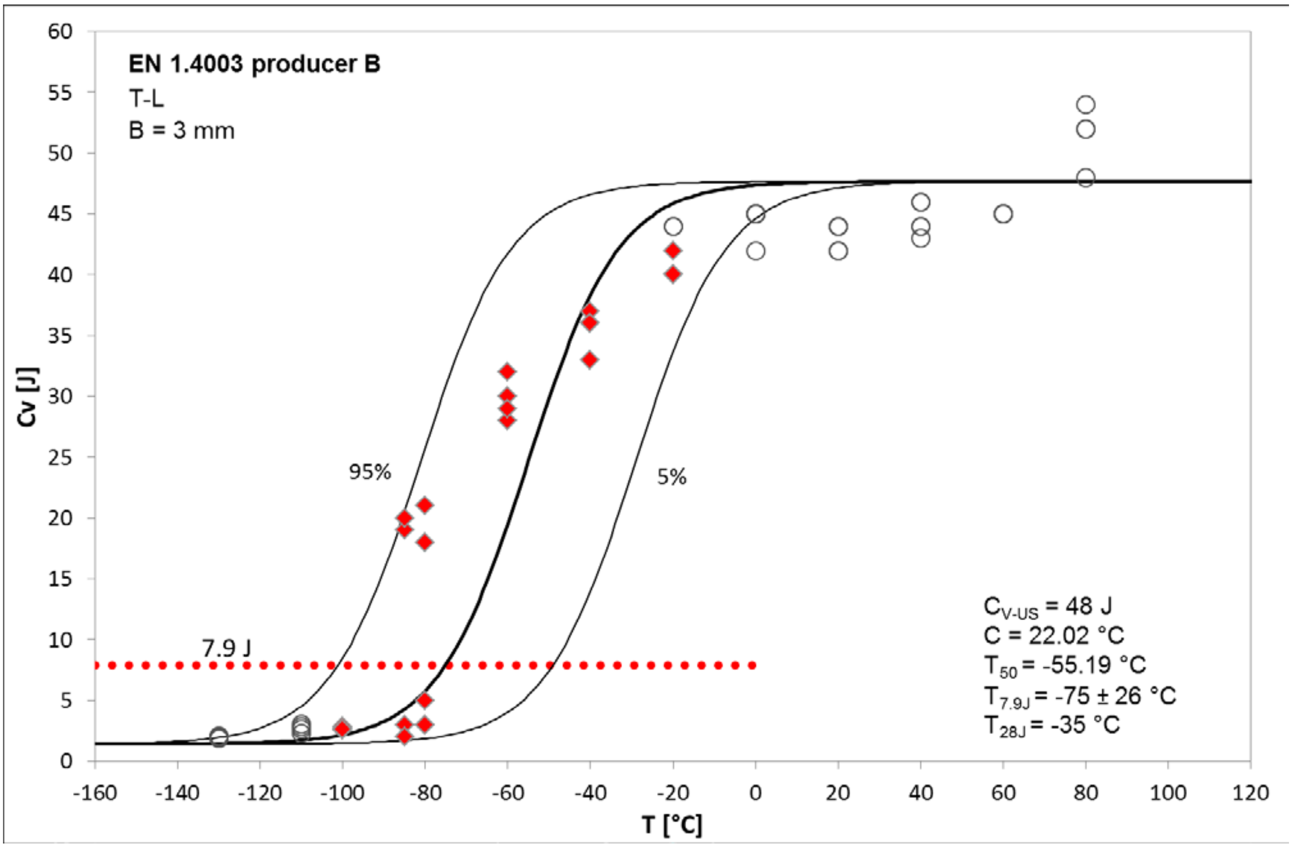

Figure 3 Transition curve determined for 3-mm-thick EN 1.4003 produced by producer B. Testing direction T-L.

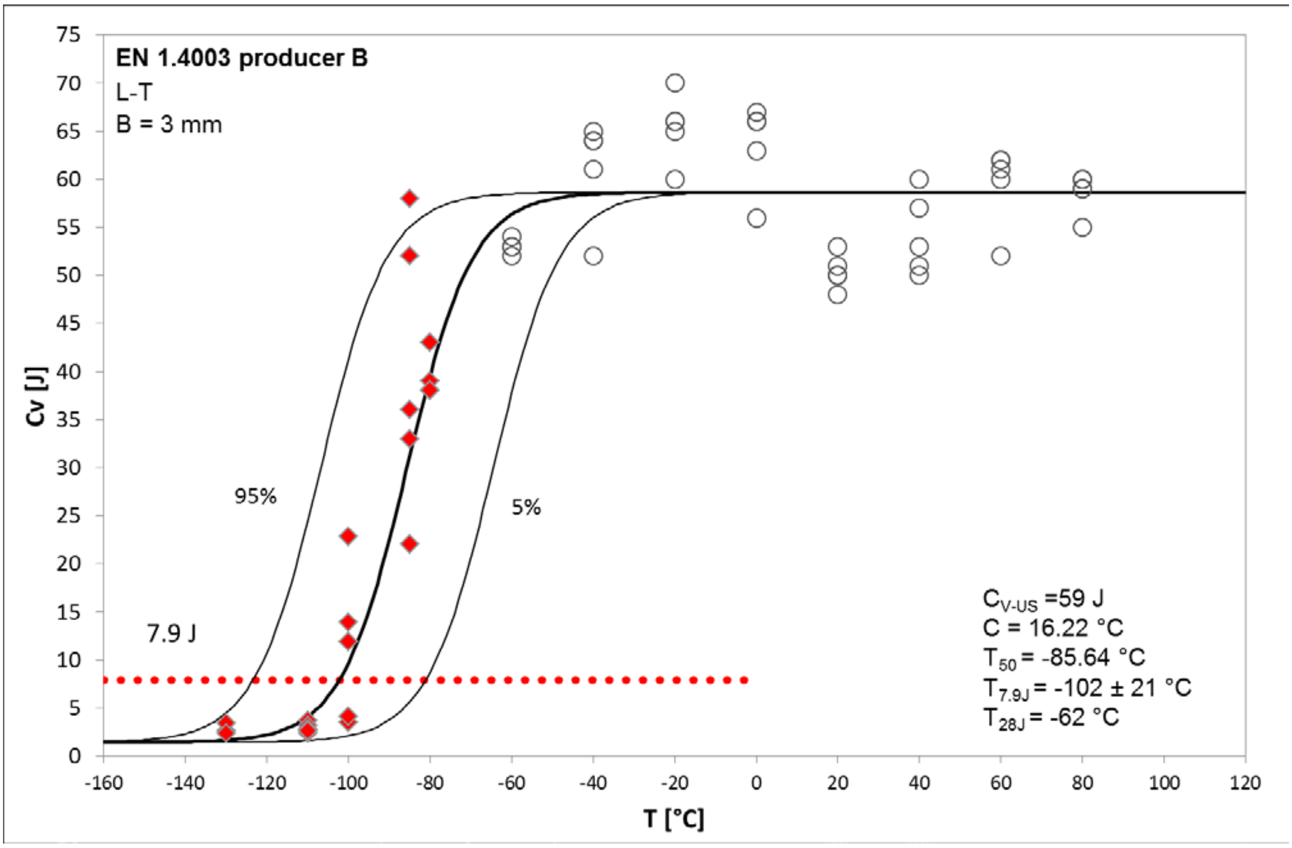

Figure 4 Transition curve determined for 3-mm-thick EN 1.4003 produced by producer B. Testing direction L-T.

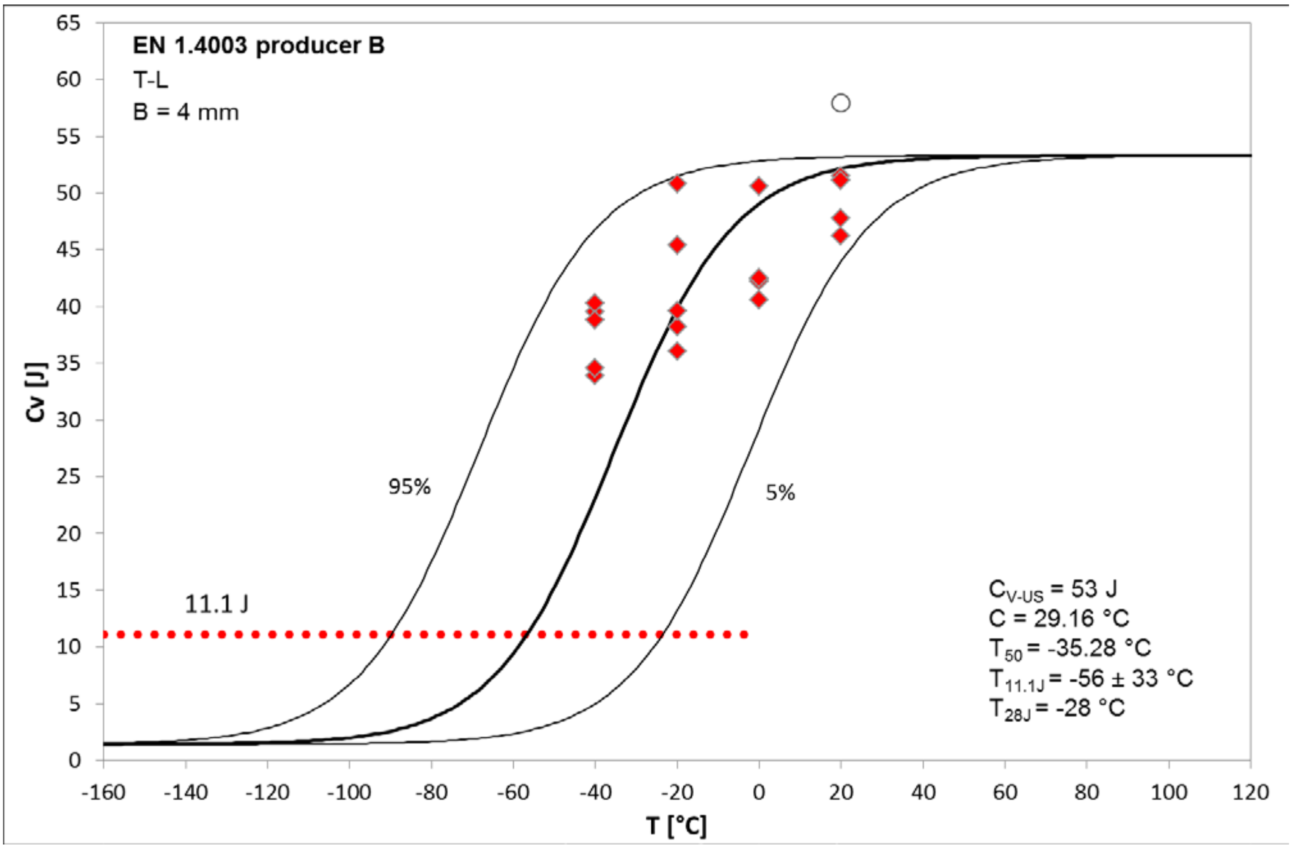

Figure 5 Transition curve determined for 4-mm-thick EN 1.4003 produced by producer B. Testing direction T-L.

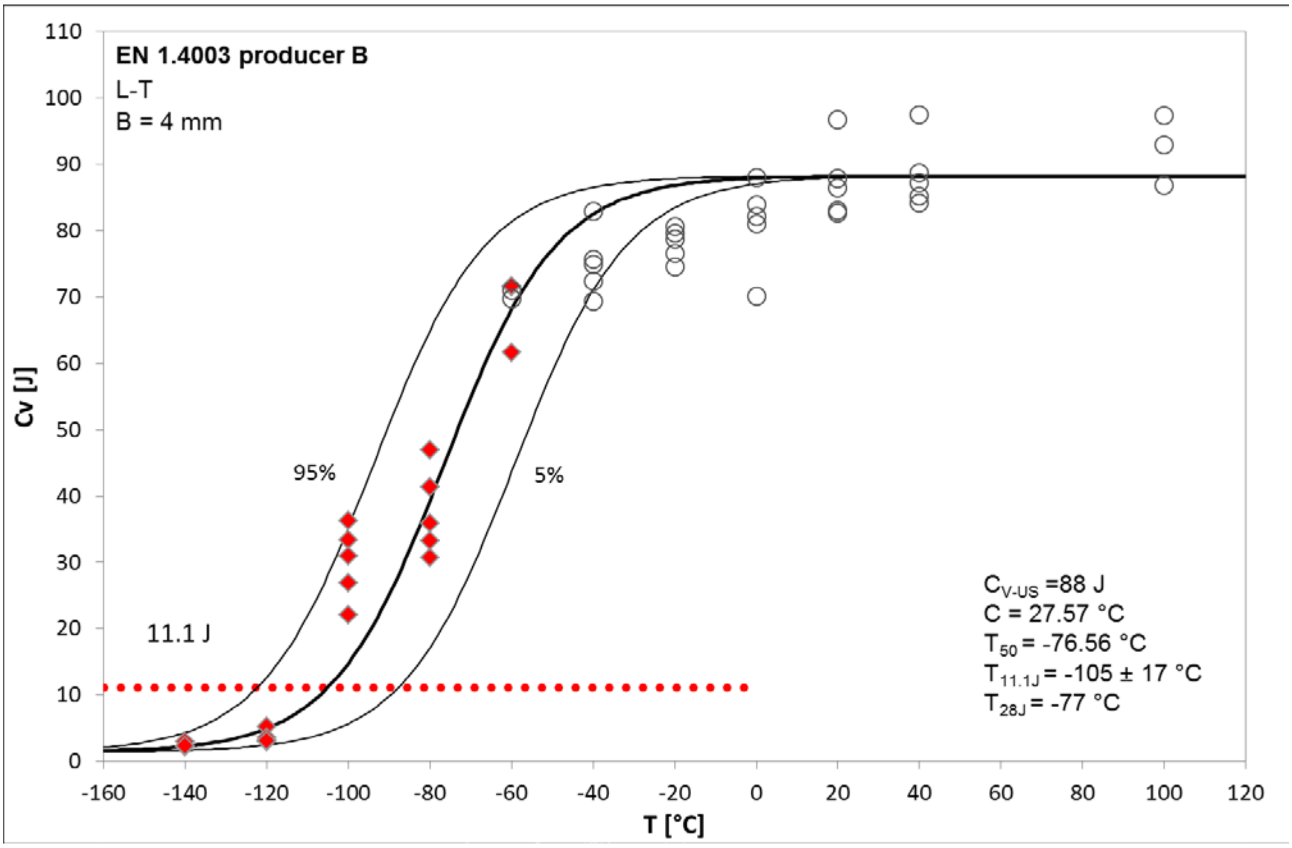

Figure 6 Transition curve determined for 4-mm-thick EN 1.4003 produced by producer B. Testing direction L-T.

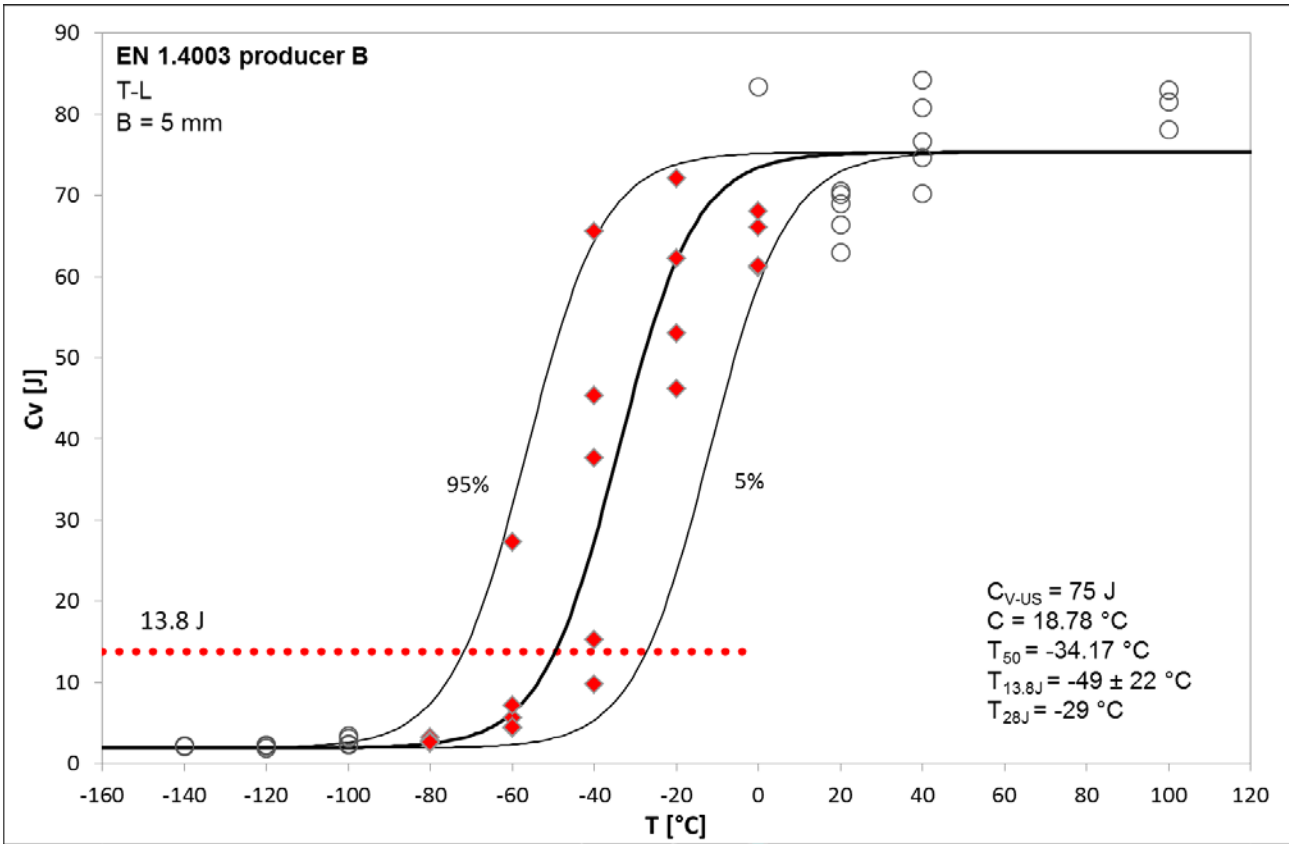

Figure 7 Transition curve determined for 5-mm-thick EN 1.4003 produced by producer B. Testing direction T-L.

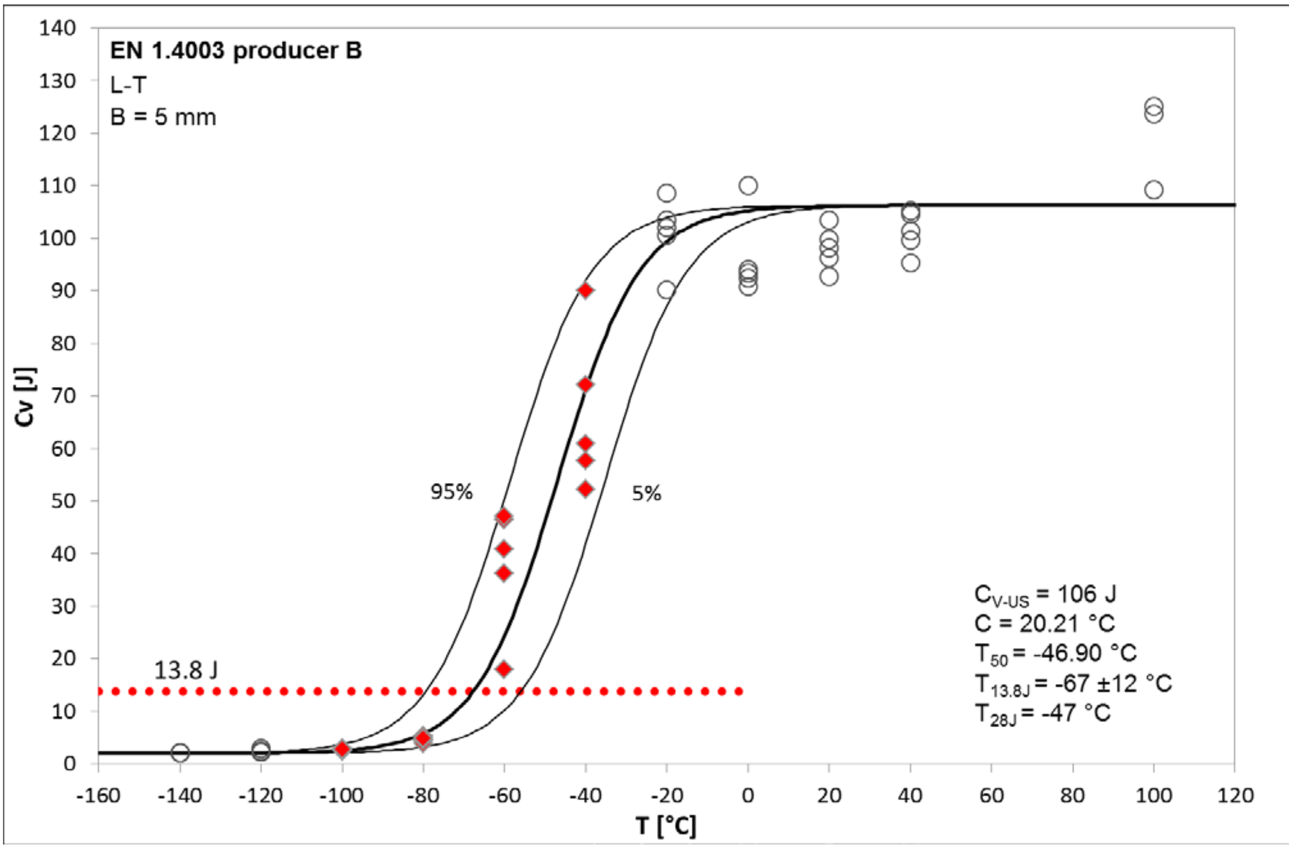

Figure 8 Transition curve determined for 5-mm-thick EN 1.4003 produced by producer B. Testing direction L-T.

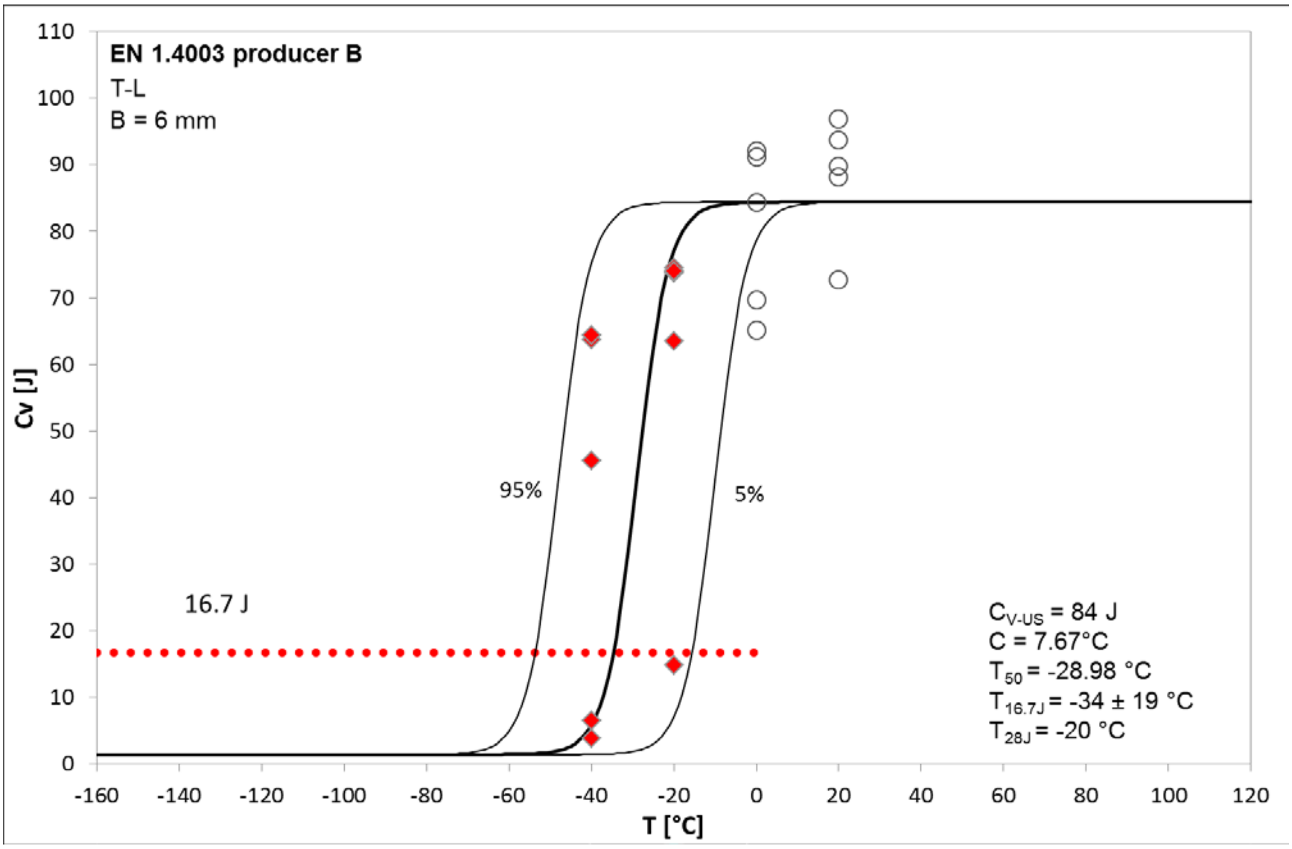

Figure 9 Transition curve determined for 6-mm-thick EN 1.4003 produced by producer B. Testing direction T-L.

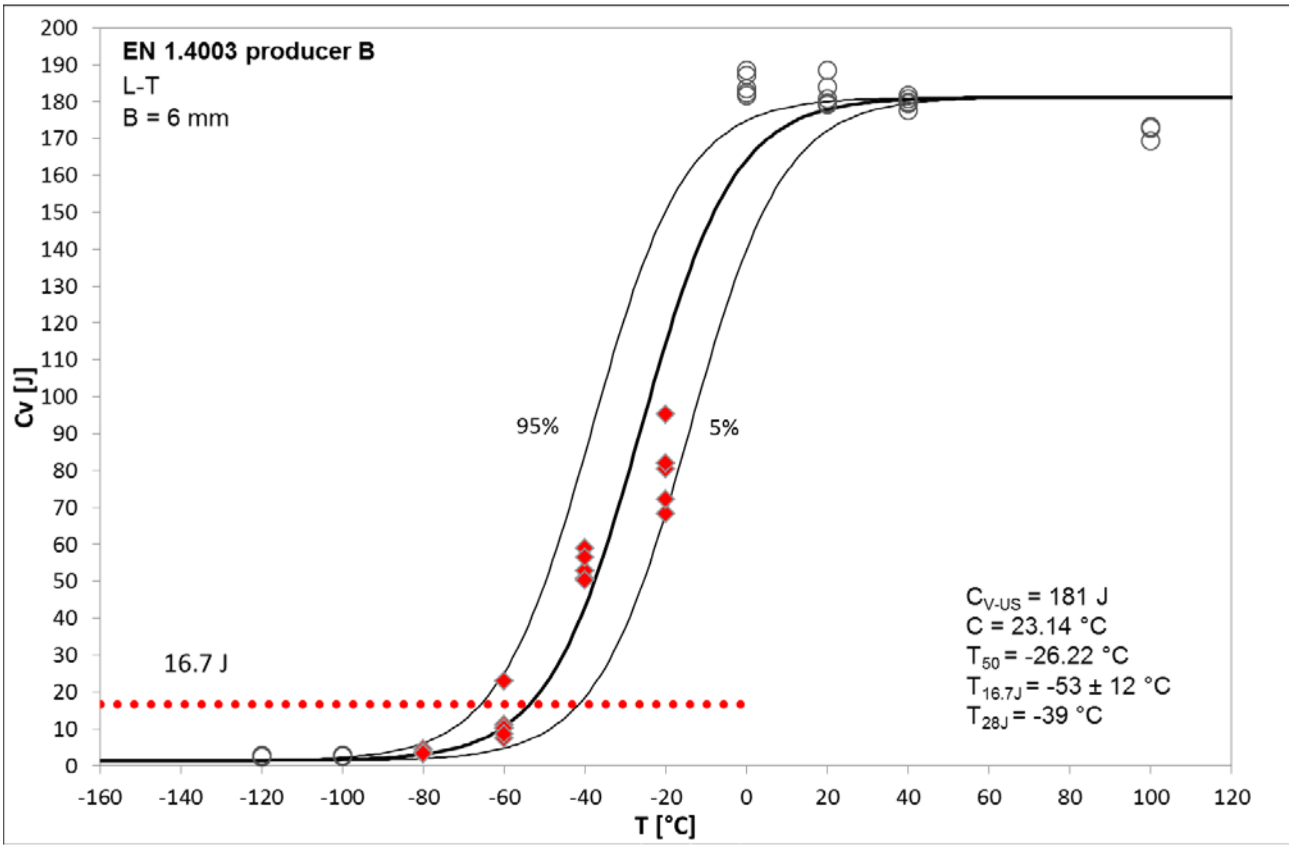

Figure 10 Transition curve determined for 6-mm-thick EN 1.4003 produced by producer B. Testing direction L-T.

Ductile transition curves determined for the grade EN 1.4016 with a thickness from 1 to 4 mm.

$C_{V\text{-}US}$ = Upper shelf energy [J]
C = fitted parameter from Equation (3), [°C]
T_{50} = fitted parameter from Equation (4), [°C]
$T_{x.xJ}$ = determined transition temperature. Criterion (x.x) is depending on thickness of the sub-sized specimen. [°C]
T_{28J} = size-corrected transition temperature [°C]
The red squares in the transition curve figures are data between $0.1{*}C_{V\text{-}US}$ and $0.85{*}C_{V\text{-}US}$ used for fitting the transition curve, equations 3 and 4.

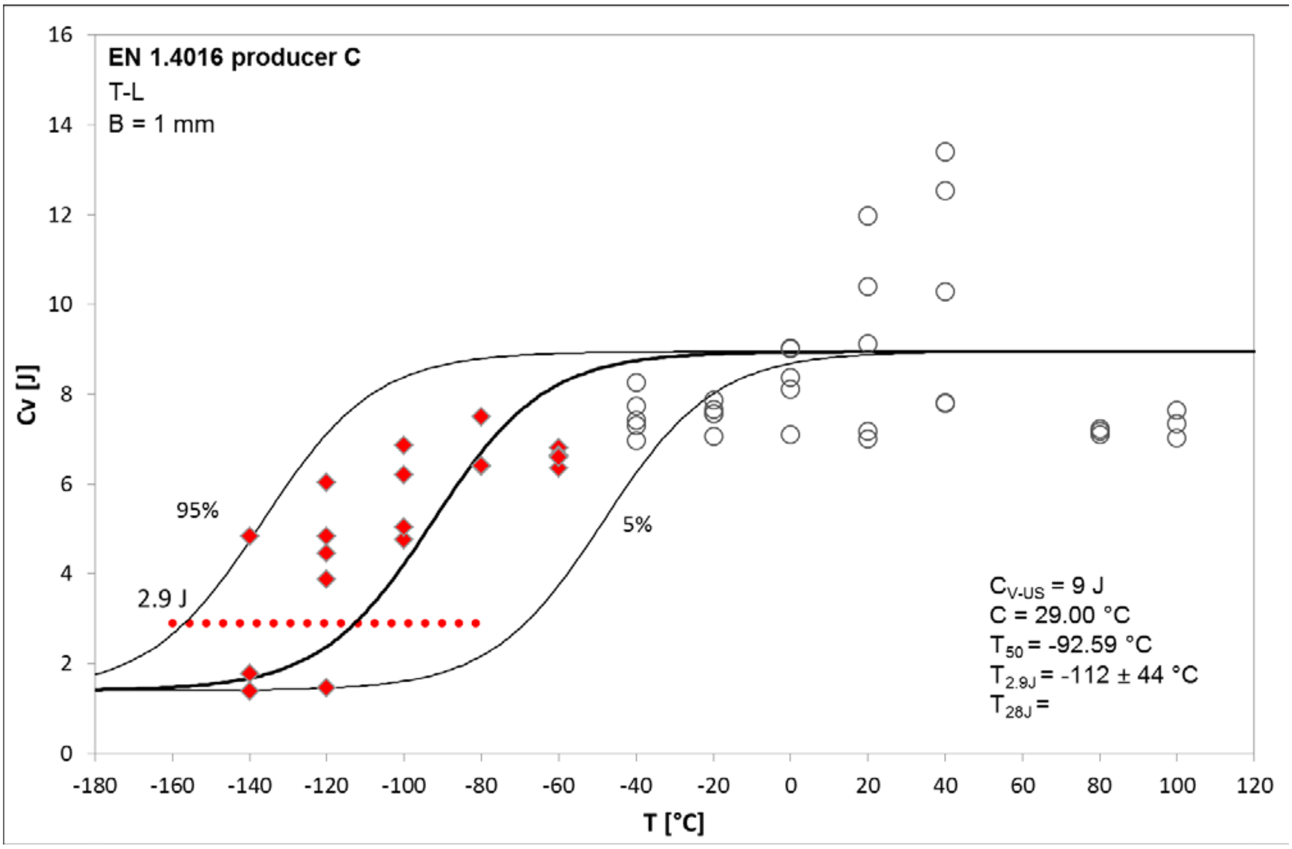

Figure 1 Transition curve determined for 1-mm-thick EN 1.4016 produced by producer C. Testing direction T-L.

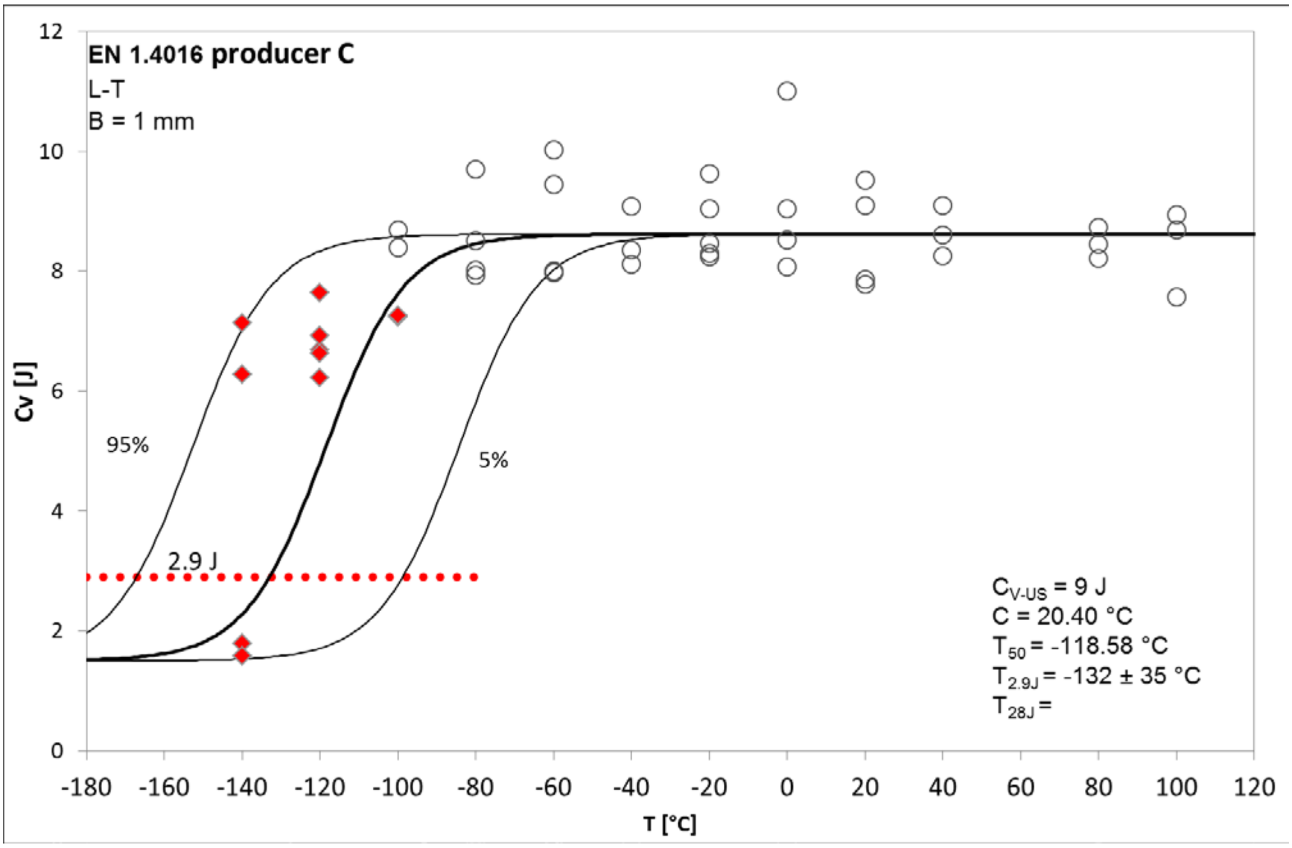

Figure 2 Transition curve determined for 1-mm-thick EN 1.4016 produced by producer C. Testing direction L-T.

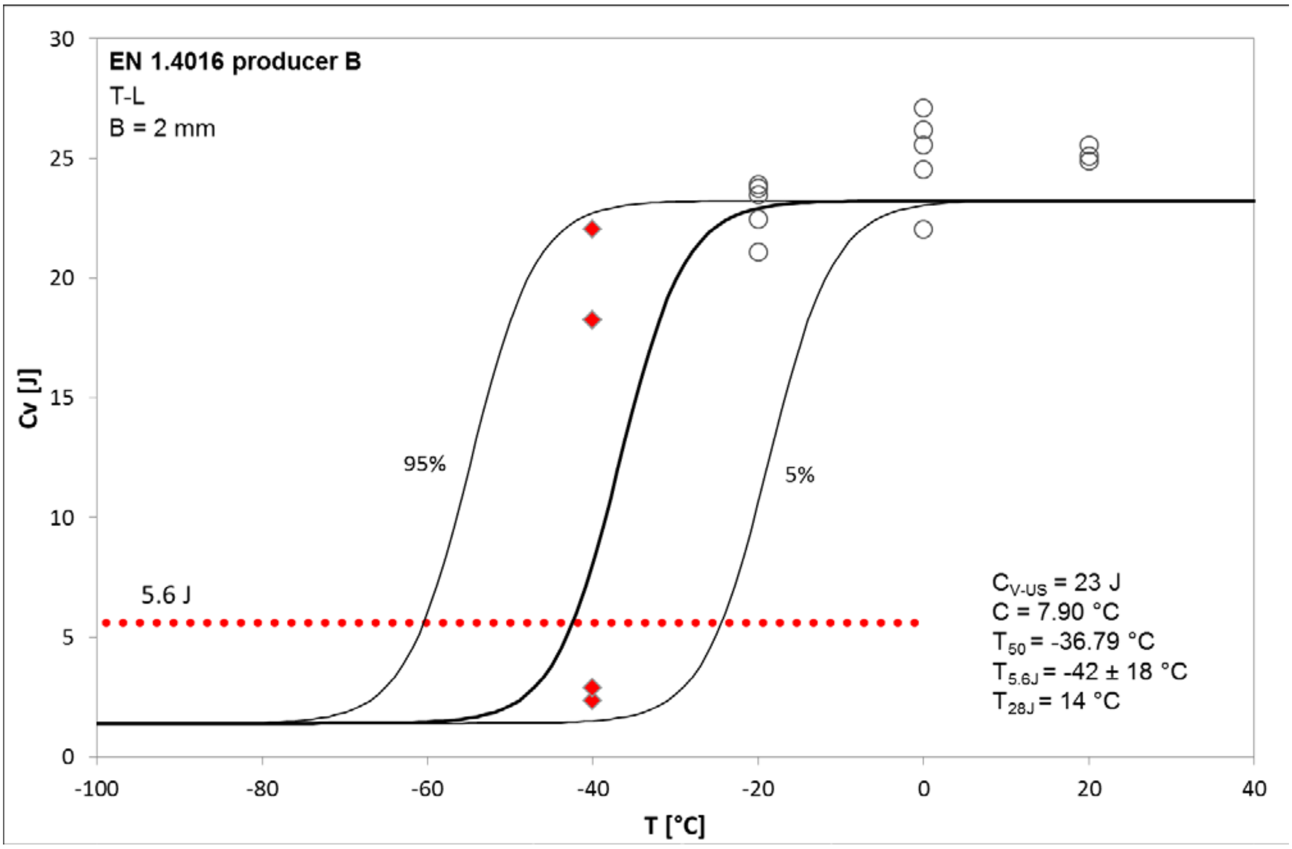

Figure 3 Transition curve determined for 2-mm-thick EN 1.4016 produced by producer B. Testing direction T-L.

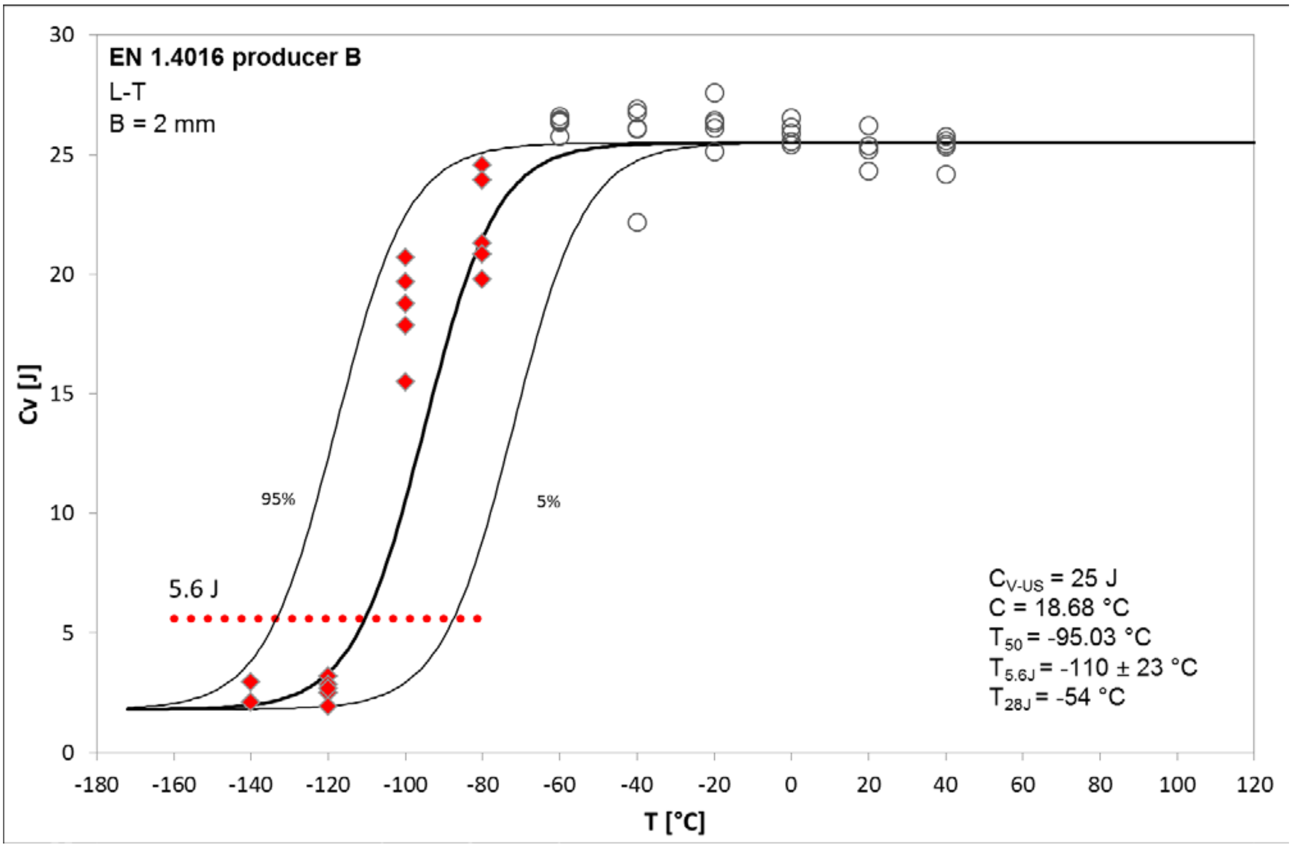

Figure 4 Transition curve determined for 2-mm-thick EN 1.4016 produced by producer B. Testing direction L-T.

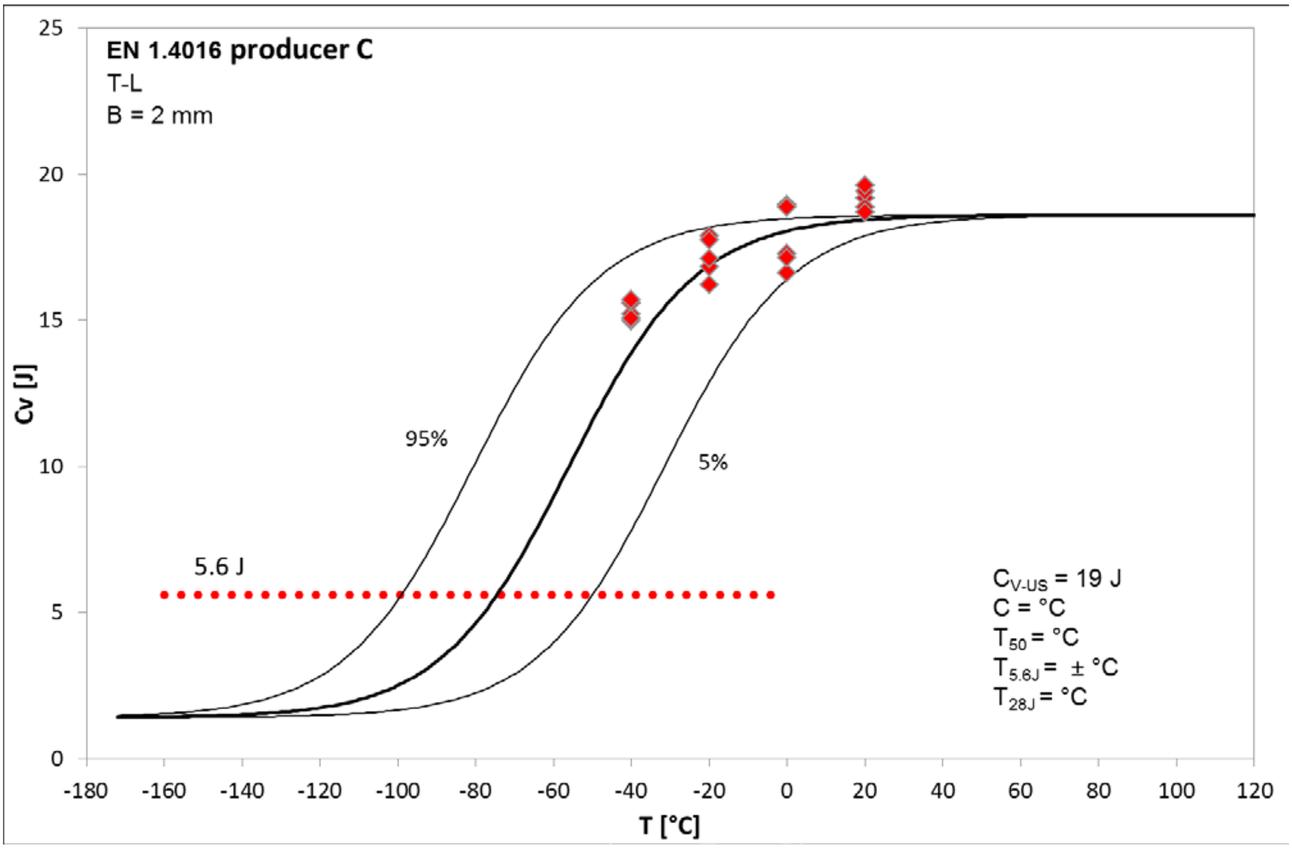

Figure 5 Transition curve determined for 2-mm-thick EN 1.4016 produced by producer C. Testing direction T-L.

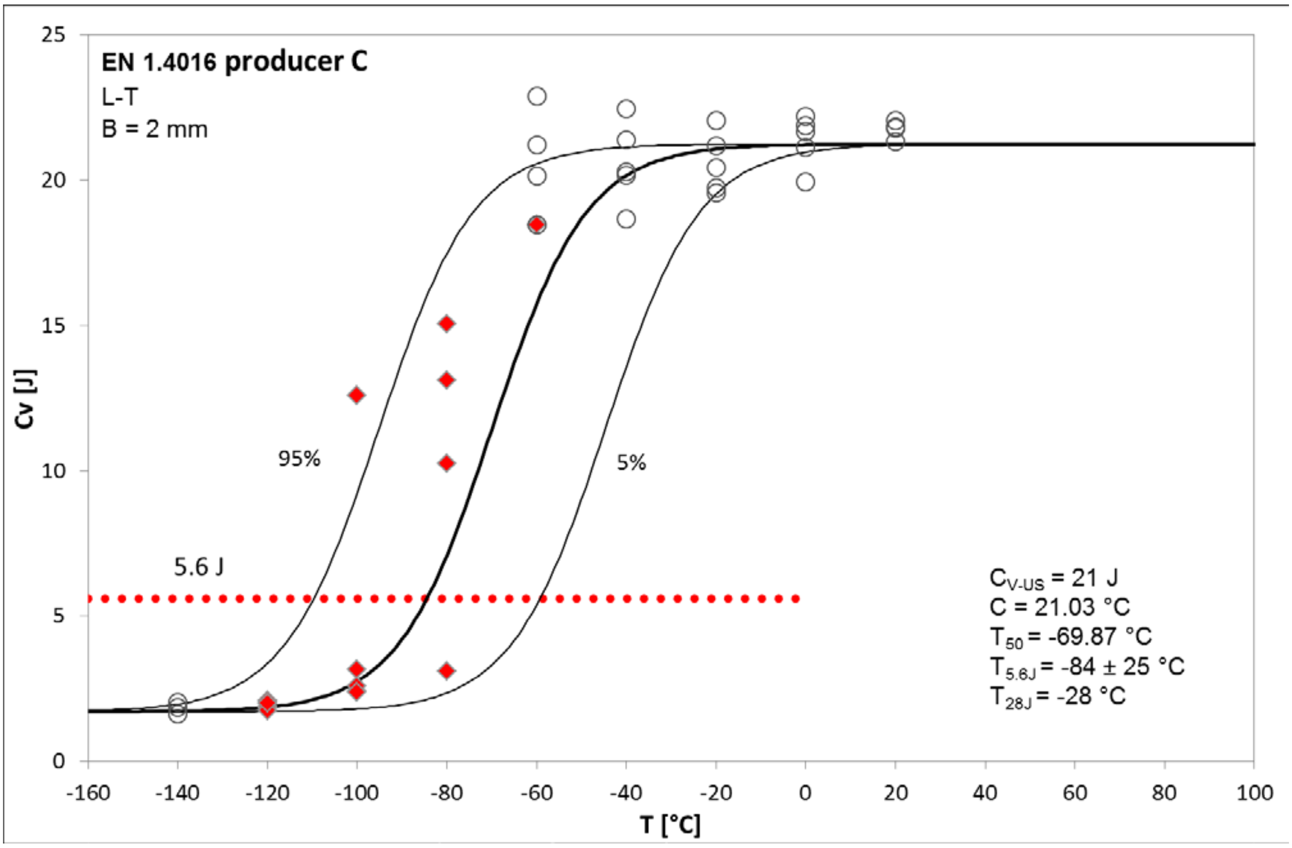

Figure 6 Transition curve determined for 2-mm-thick EN 1.4016 produced by producer C. Testing direction L-T.

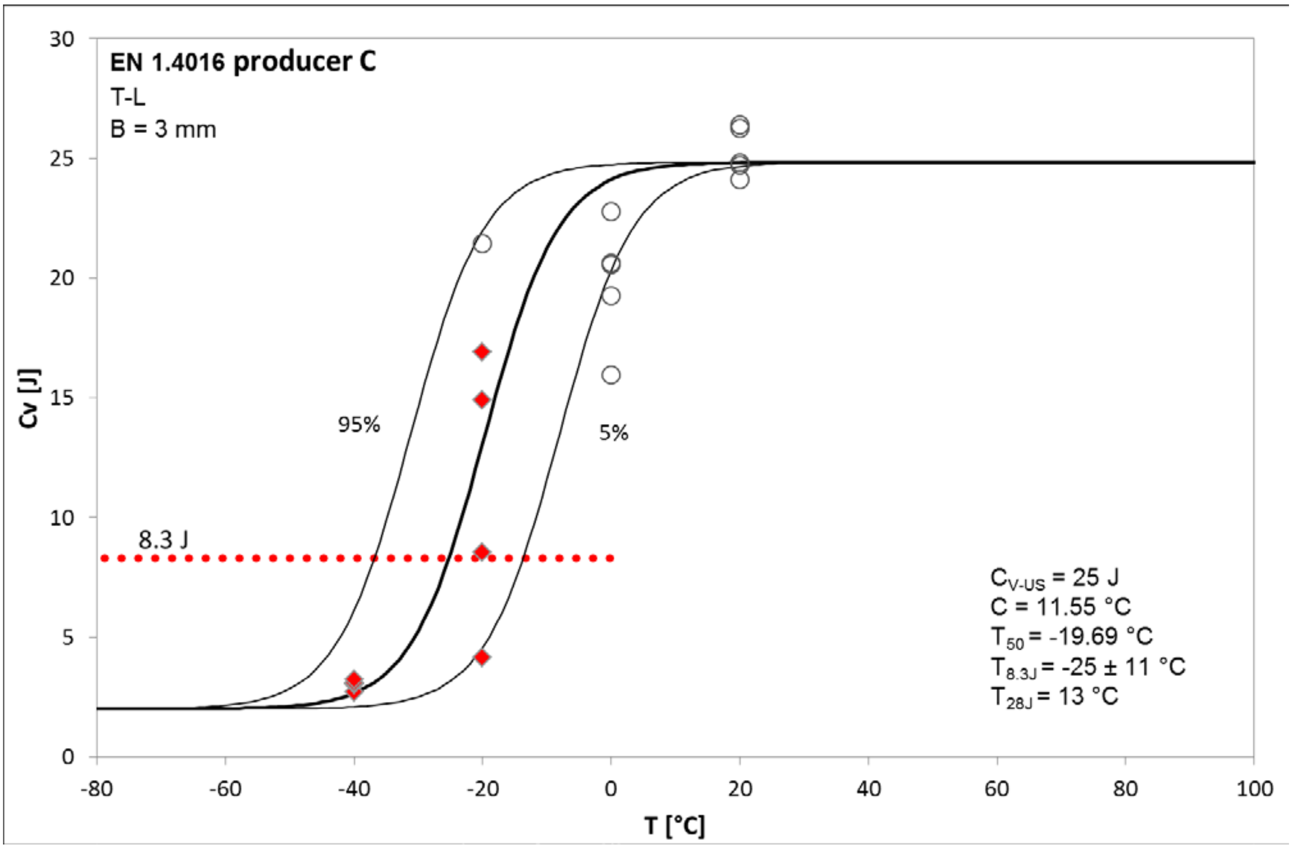

Figure 7 Transition curve determined for 3-mm-thick EN 1.4016 produced by producer C. Testing direction T-L.

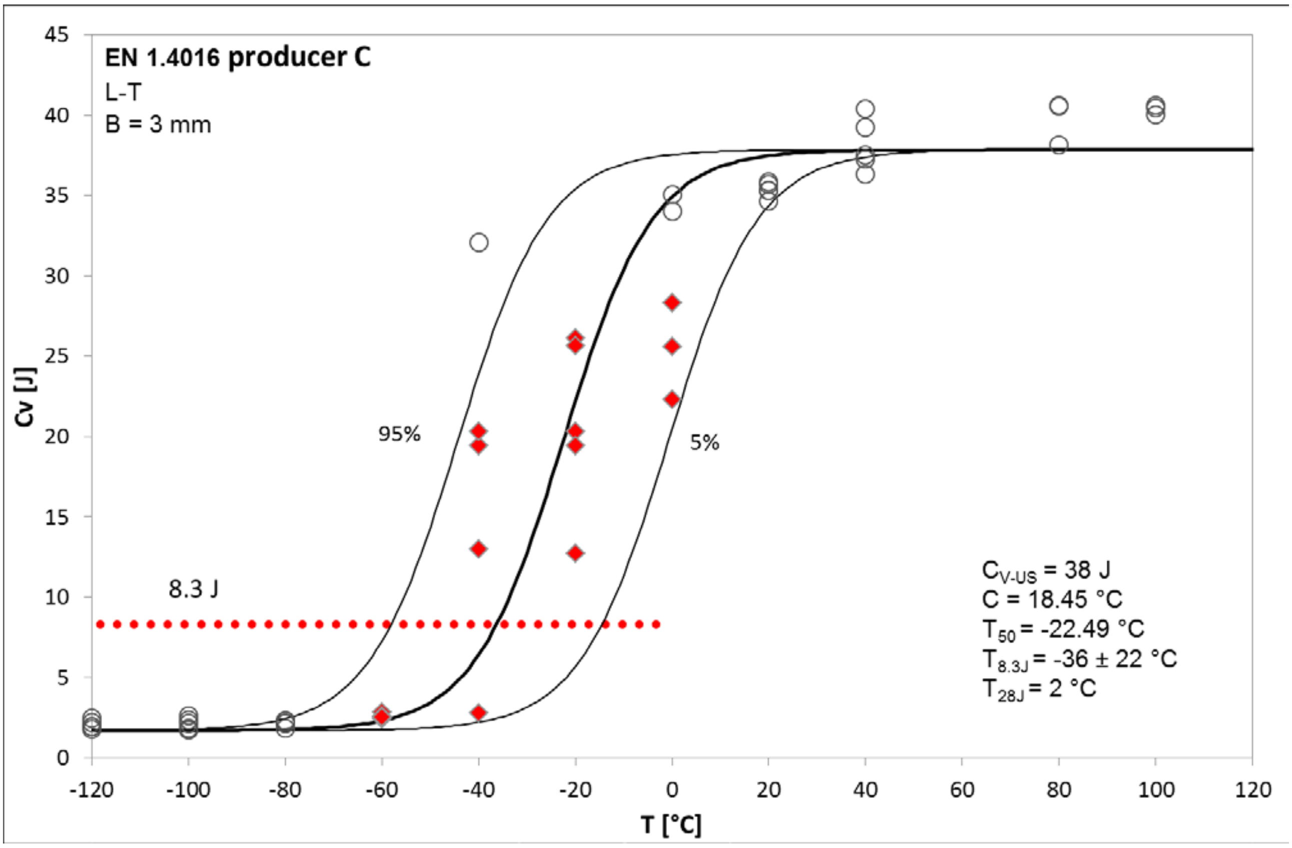

Figure 8 Transition curve determined for 3-mm-thick EN 1.4016 produced by producer C. Testing direction L-T.

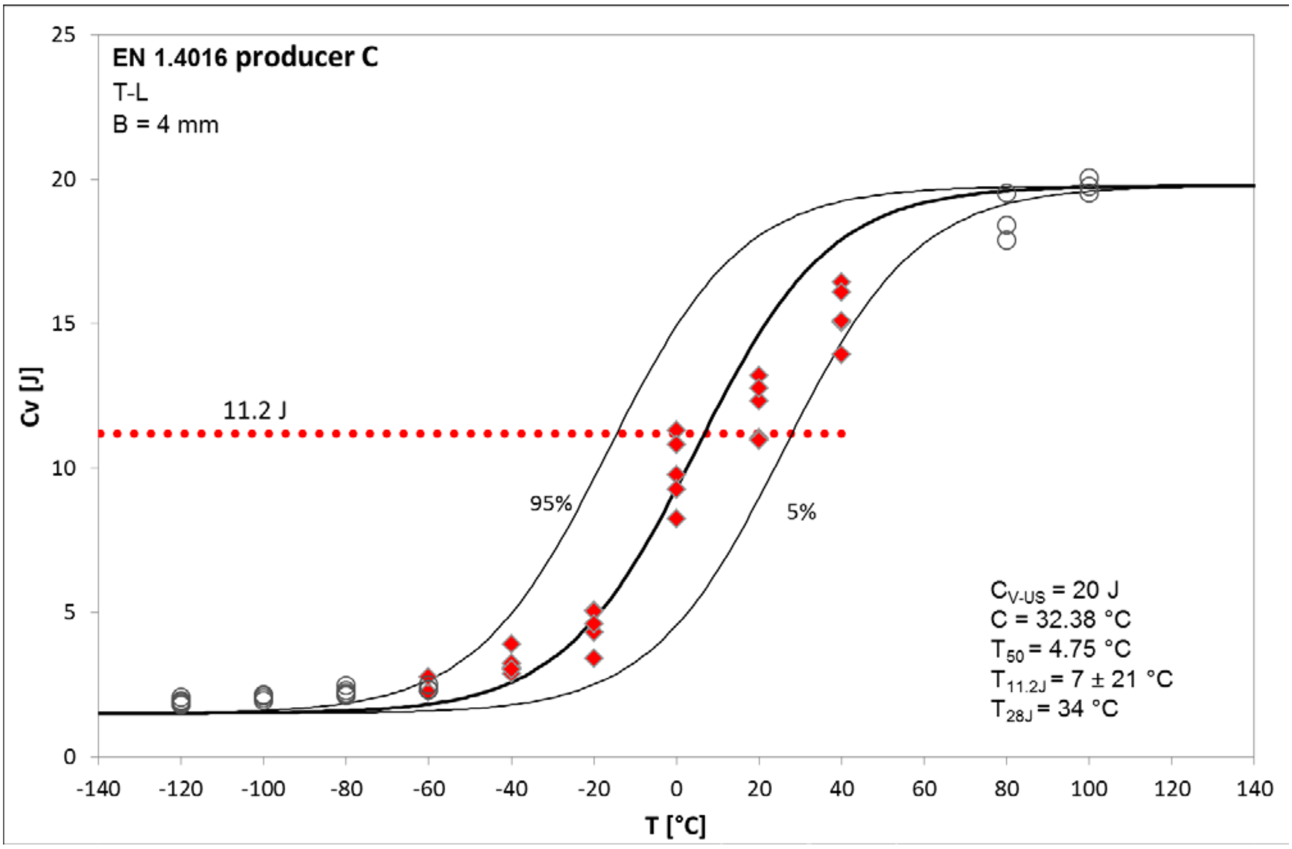

Figure 9 Transition curve determined for 4-mm-thick EN 1.4016 produced by producer C. Testing direction T-L.

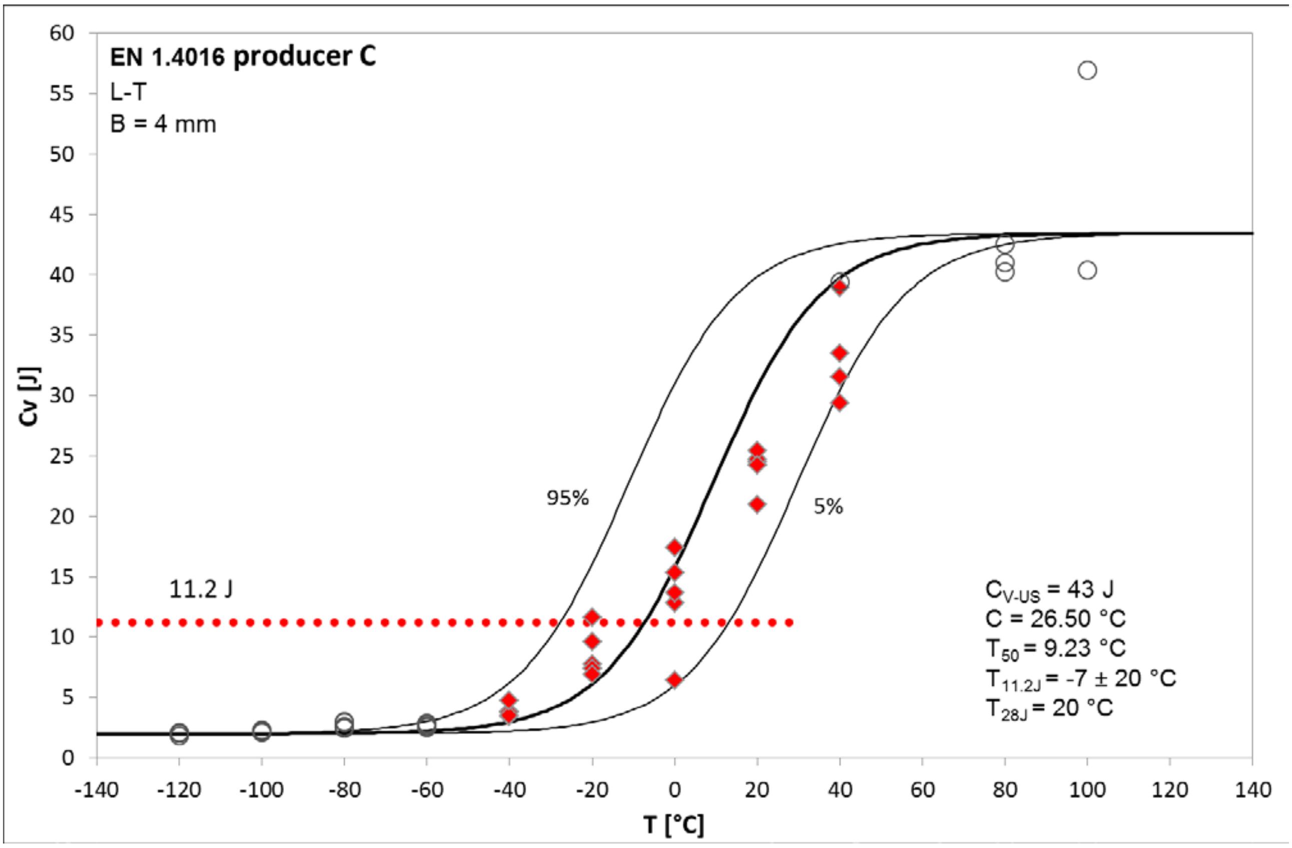

Figure 10 Transition curve determined for 4-mm-thick EN 1.4016 produced by producer C. Testing direction L-T.

Ductile transition curves determined for the grade EN 1.4509 with a thickness from 1 to 4 mm.

$C_{V\text{-}US}$ = Upper shelf energy [J]
C = fitted parameter from Equation (3), [°C]
T_{50} = fitted parameter from Equation (4), [°C]
$T_{x.xJ}$ = determined transition temperature. Criterion (x.x) is depending on thickness of the sub-sized specimen. [°C]
T_{28J} = size-corrected transition temperature [°C]
The red squares in the transition curve figures are data between 0.1*$C_{V\text{-}US}$ and 0.85*$C_{V\text{-}US}$ used for fitting the transition curve, equations 3 and 4.

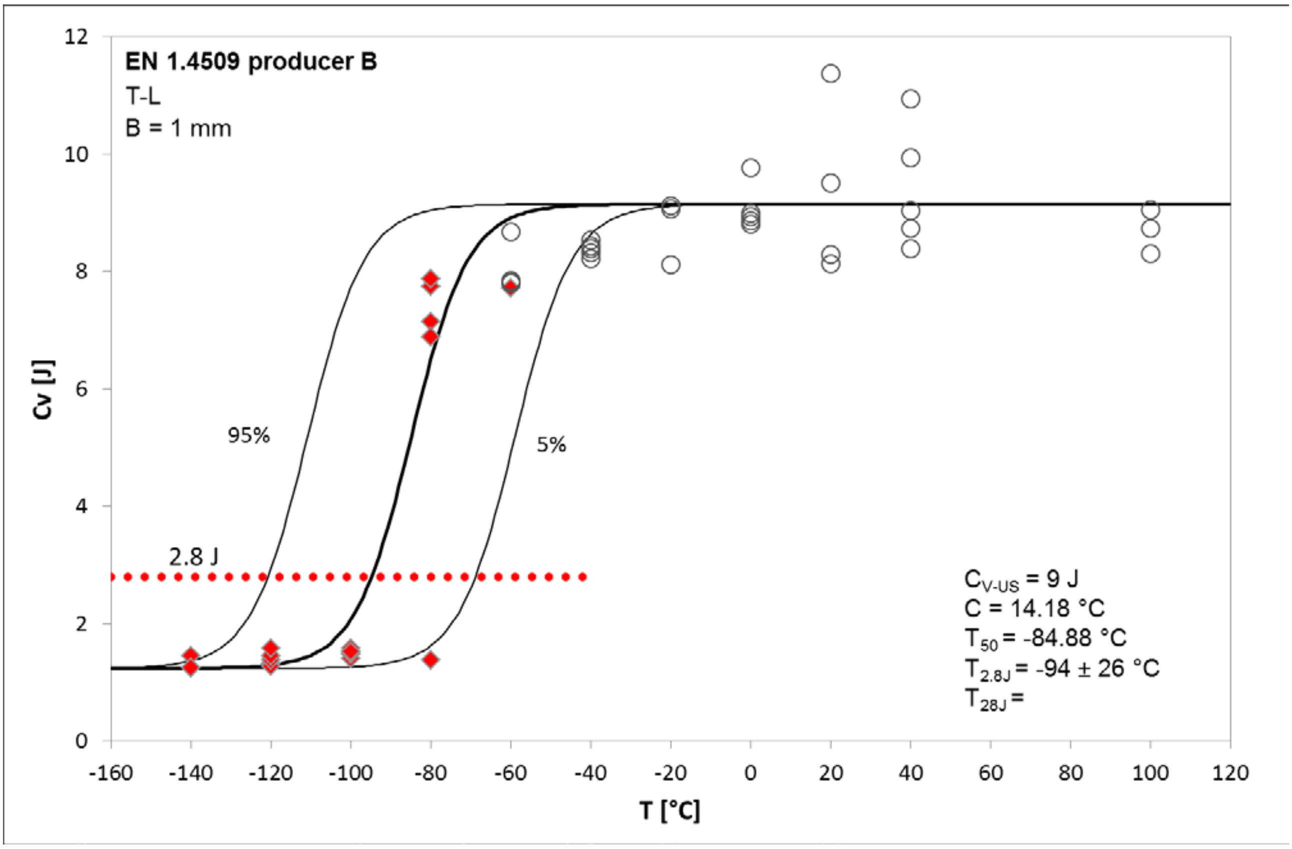

Figure 1 Transition curve determined for 1-mm-thick EN 1.4509 produced by producer B. Testing direction T-L.

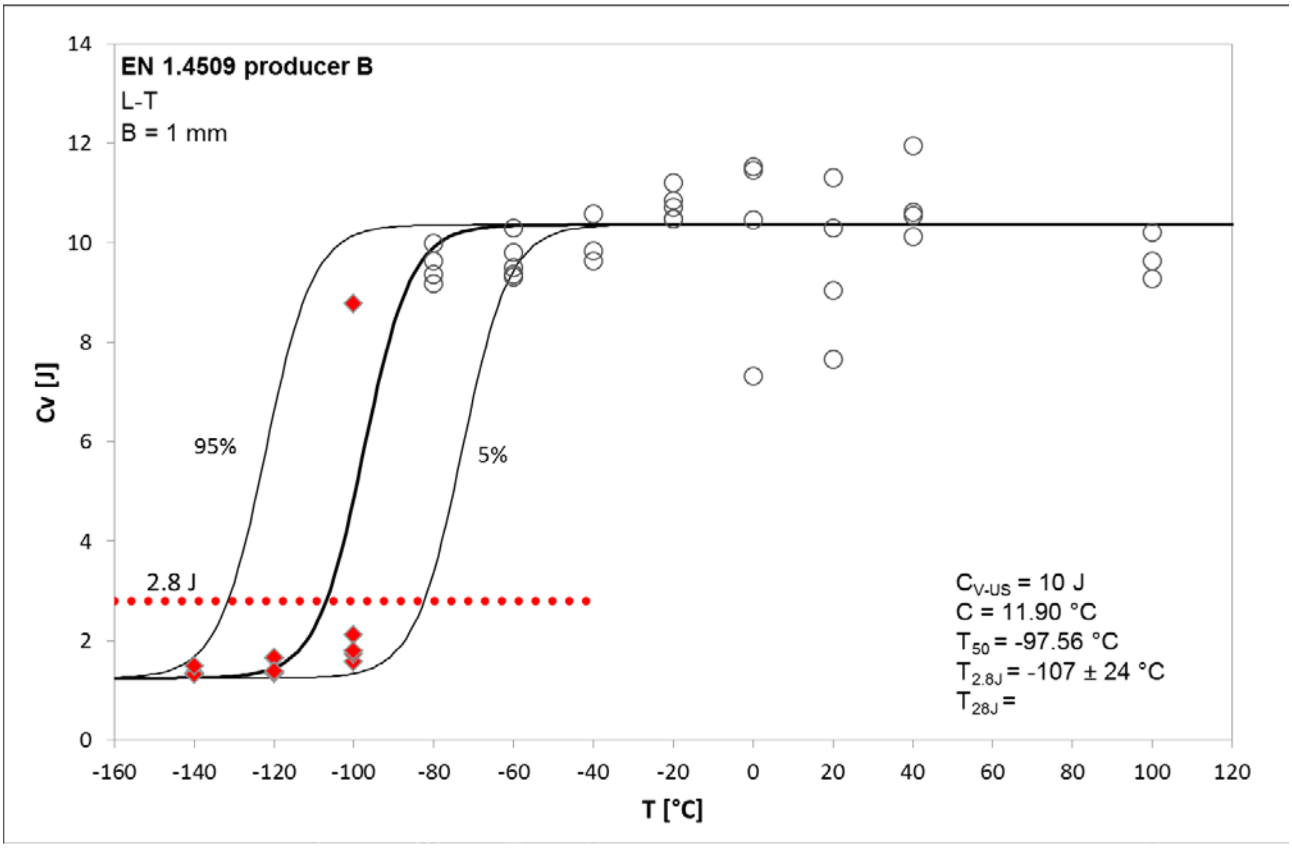

Figure 2 Transition curve determined for 1-mm-thick EN 1.4509 produced by producer B. Testing direction L-T

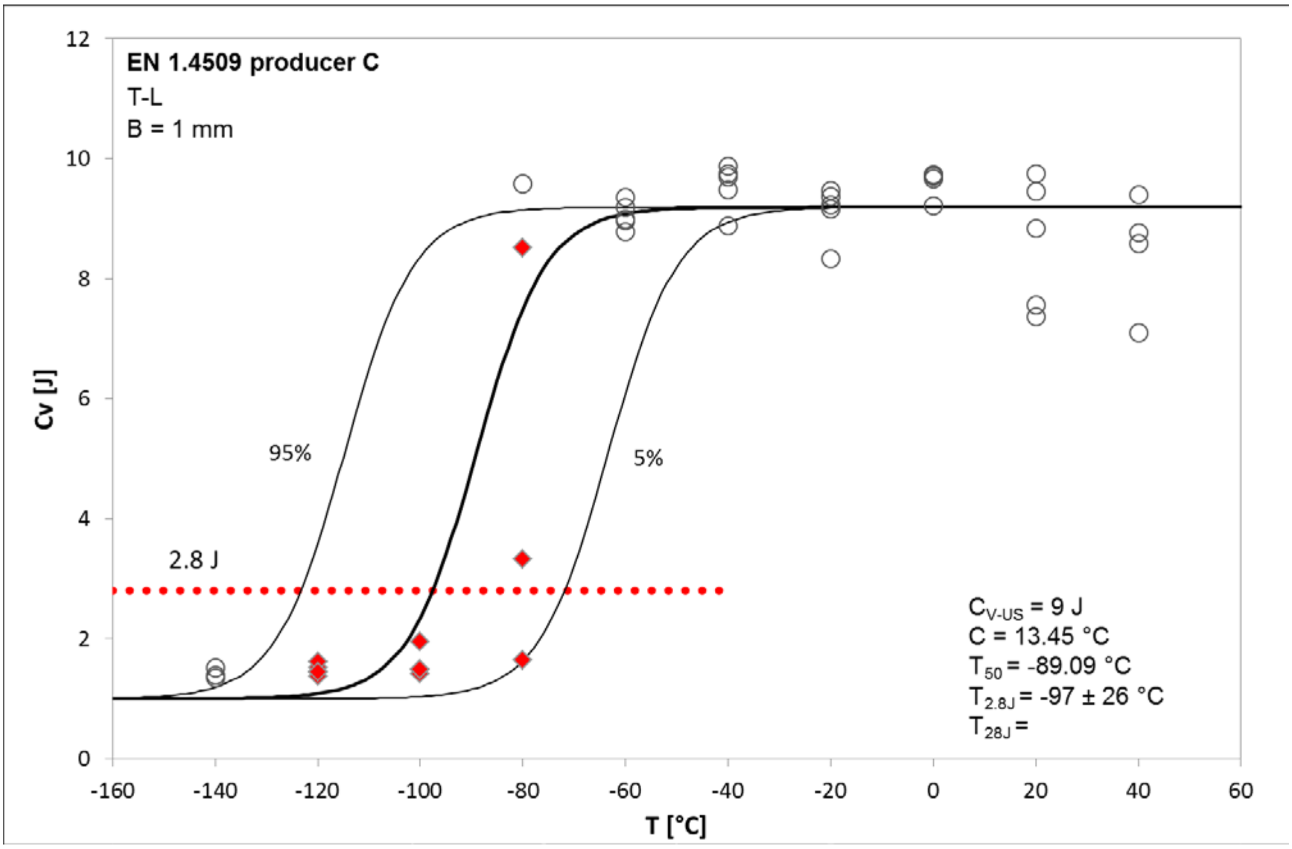

Figure 3 Transition curve determined for 1-mm-thick EN 1.4509 produced by producer C. Testing direction T-L

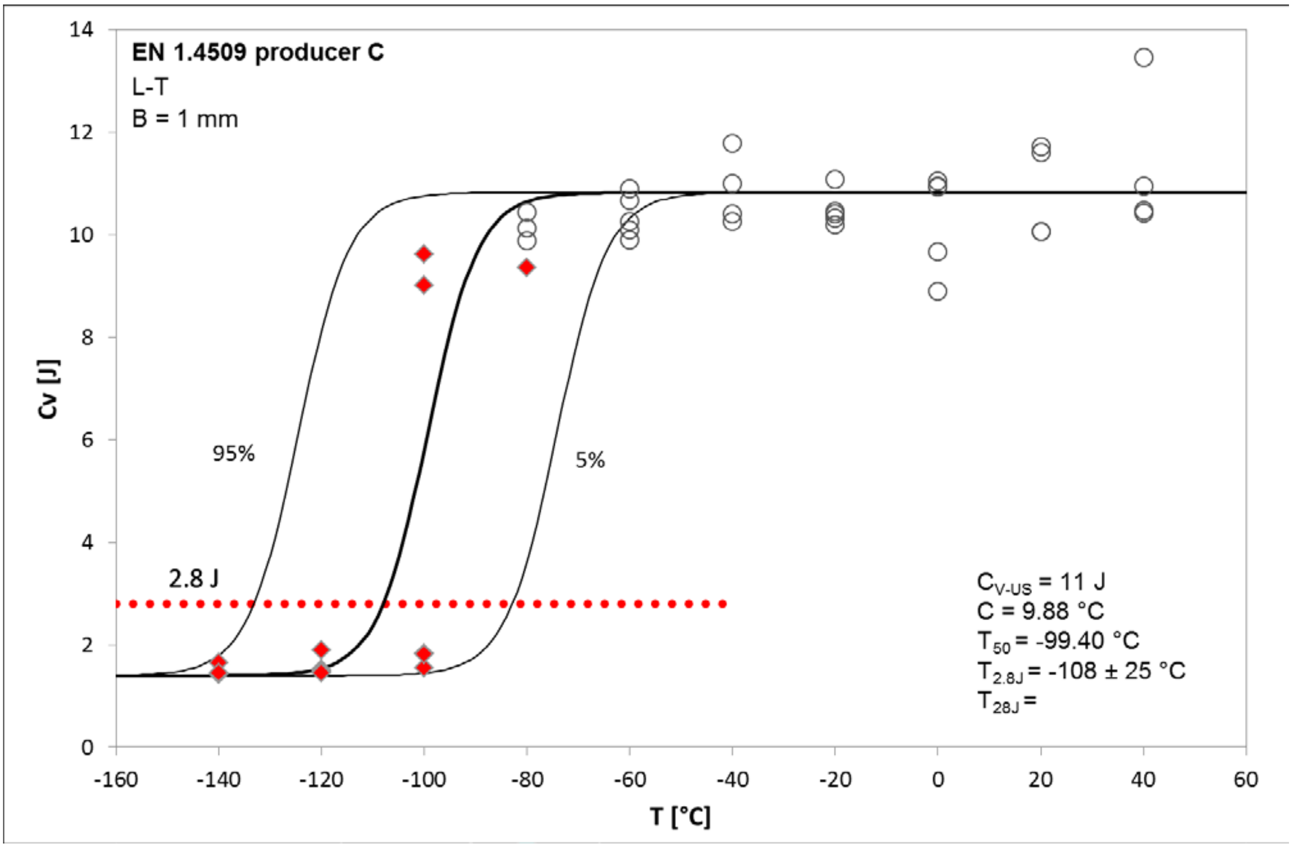

Figure 4 Transition curve determined for 1-mm-thick EN 1.4509 produced by producer C. Testing direction L-T.

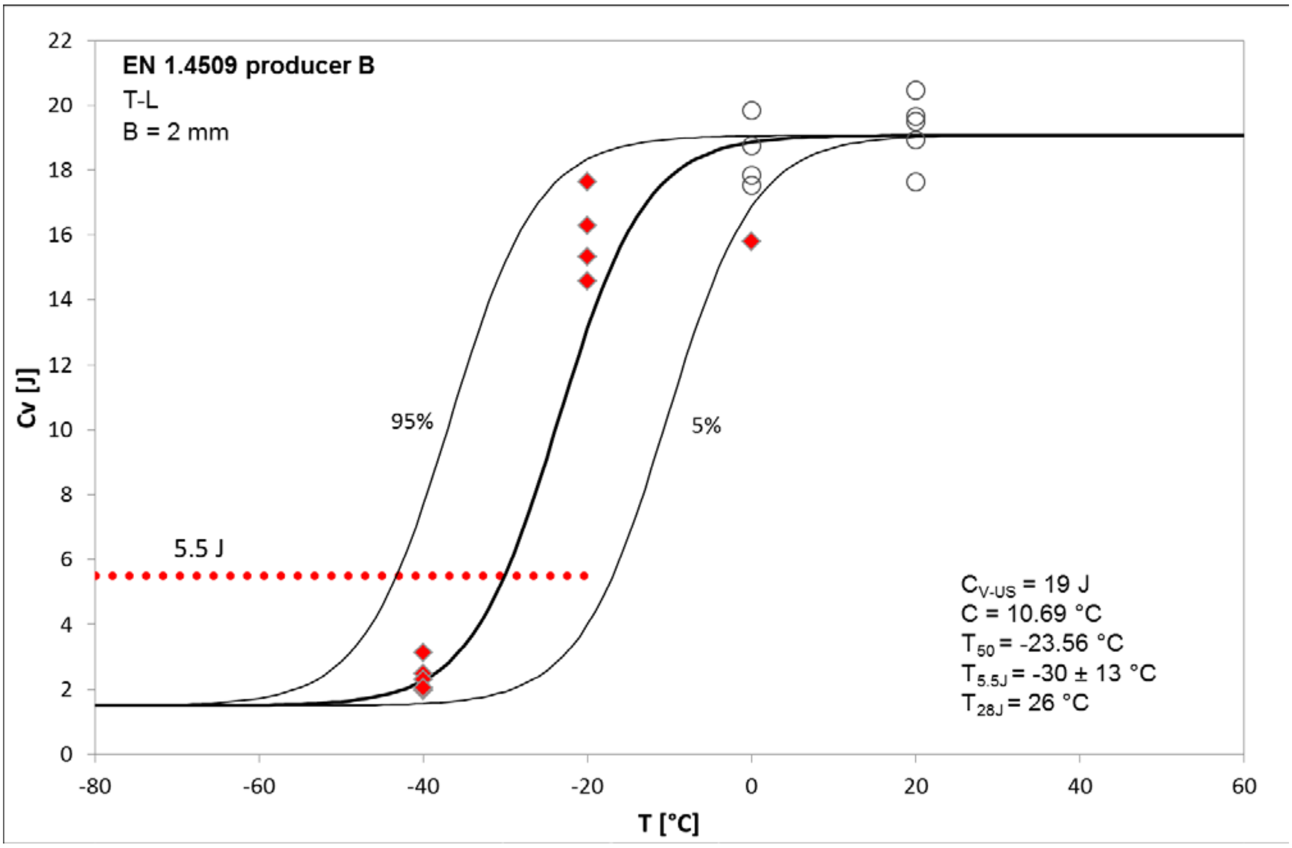

Figure 5 Transition curve determined for 2-mm-thick EN 1.4509 produced by producer B. Testing direction T-L.

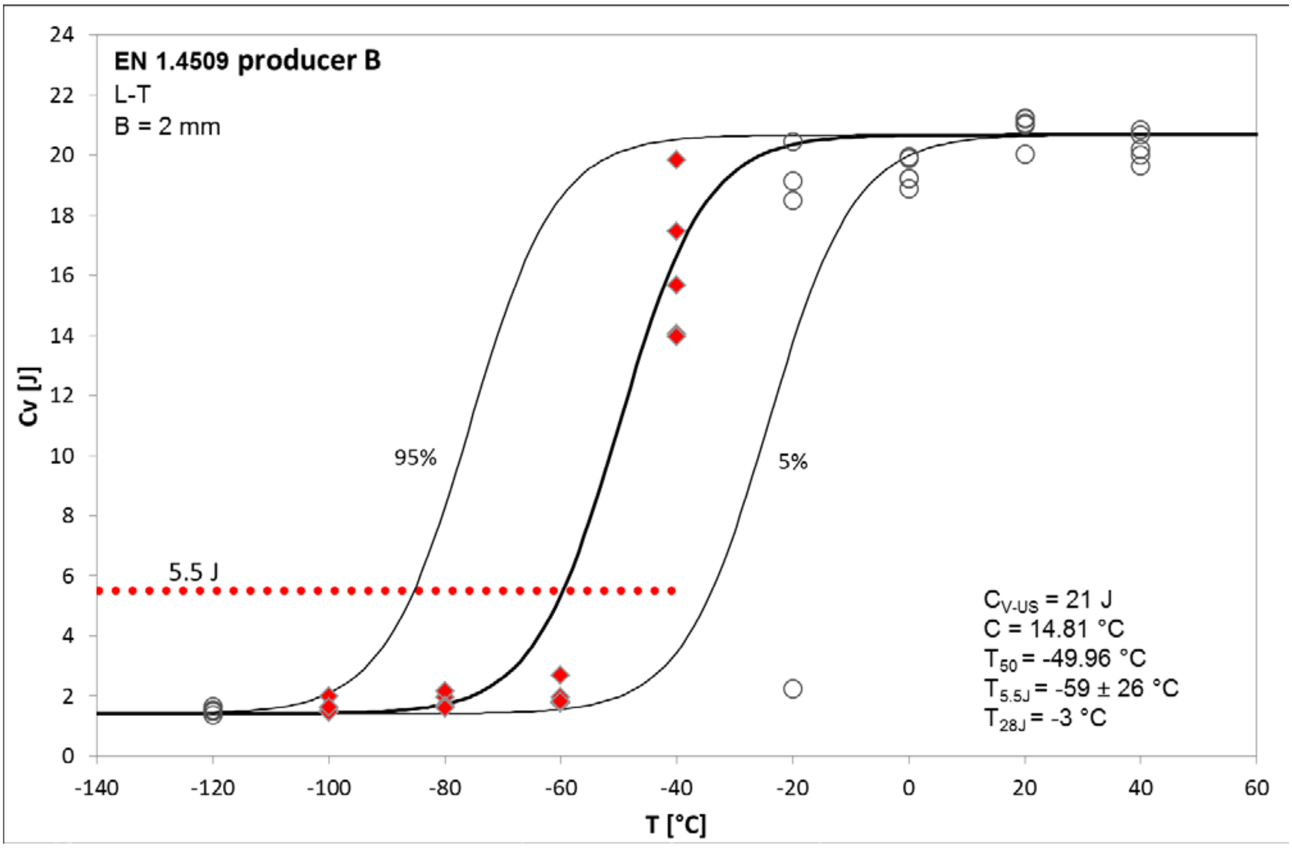

Figure 6 Transition curve determined for 2-mm-thick EN 1.4509 produced by producer B. Testing direction L-T.

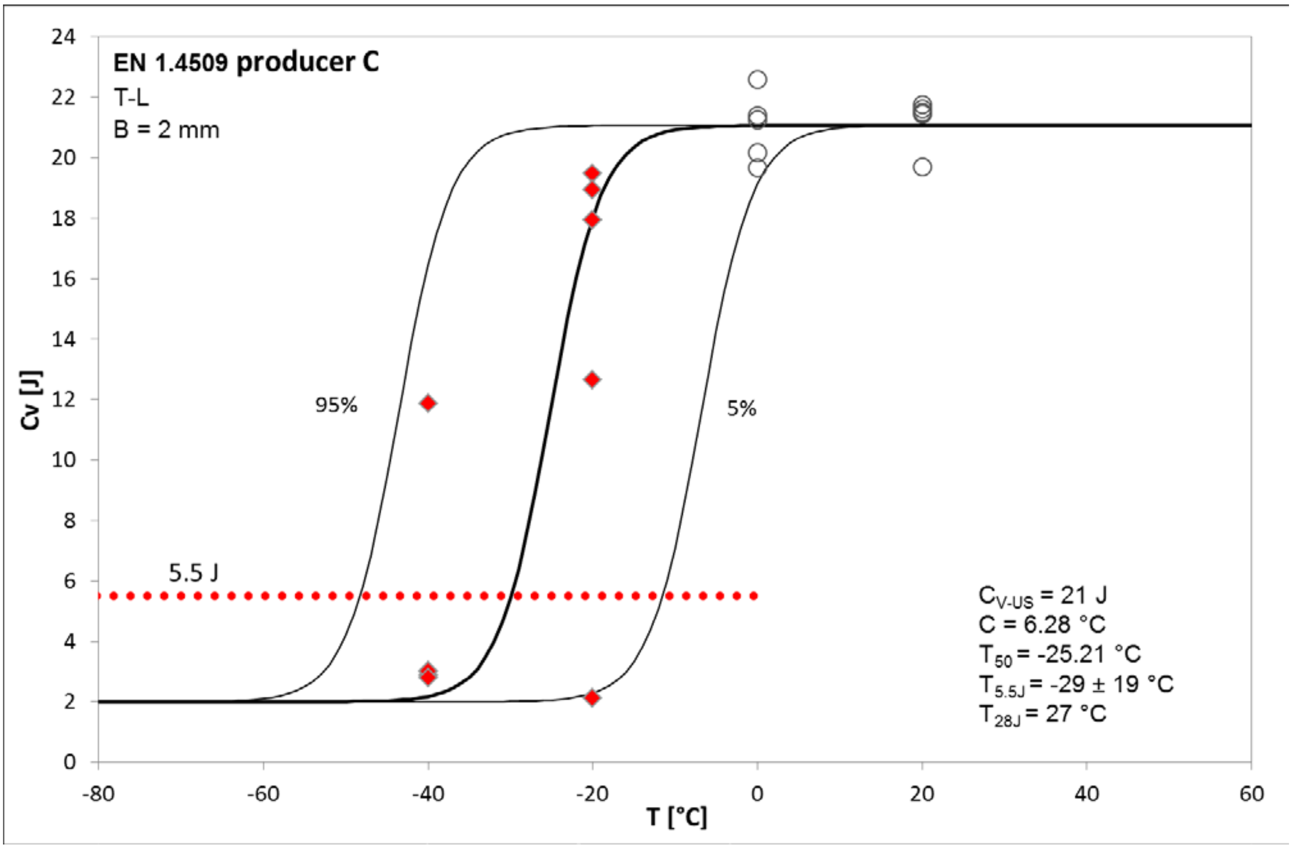

Figure 7 Transition curve determined for 2-mm-thick EN 1.4509 produced by producer C. Testing direction T-L.

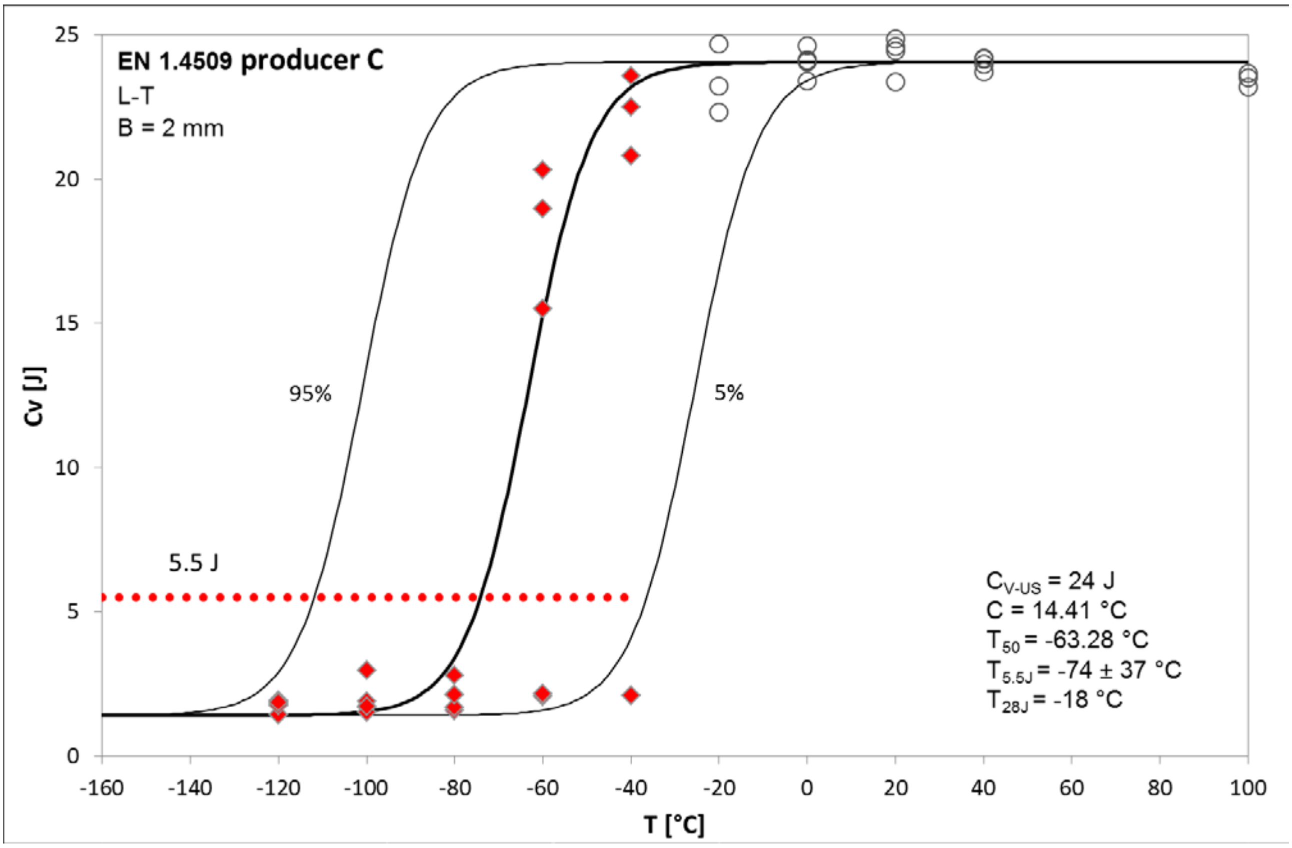

Figure 8 Transition curve determined for 2-mm-thick EN 1.4509 produced by producer C. Testing direction L-T.

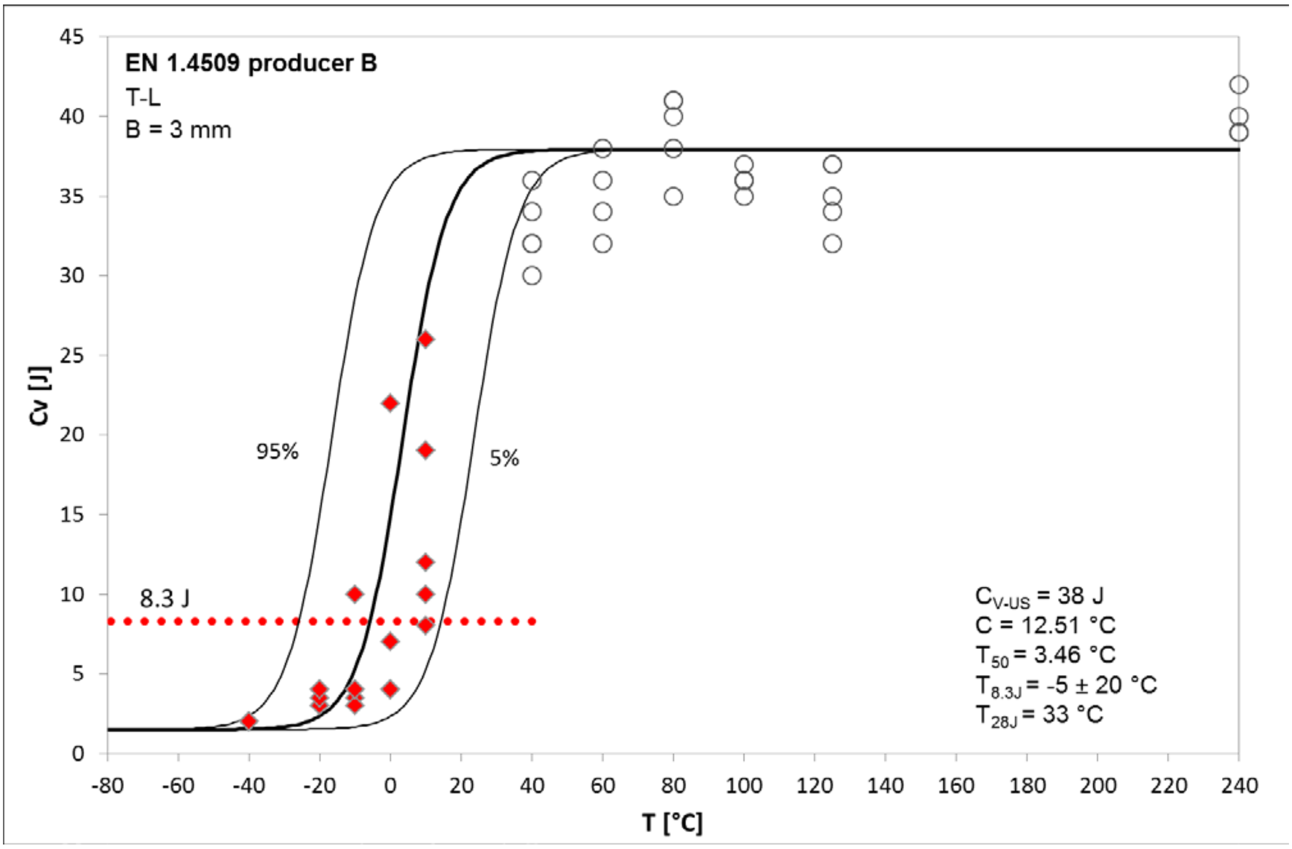

Figure 9 Transition curve determined for 3-mm-thick EN 1.4509 produced by producer B. Testing direction T-L.

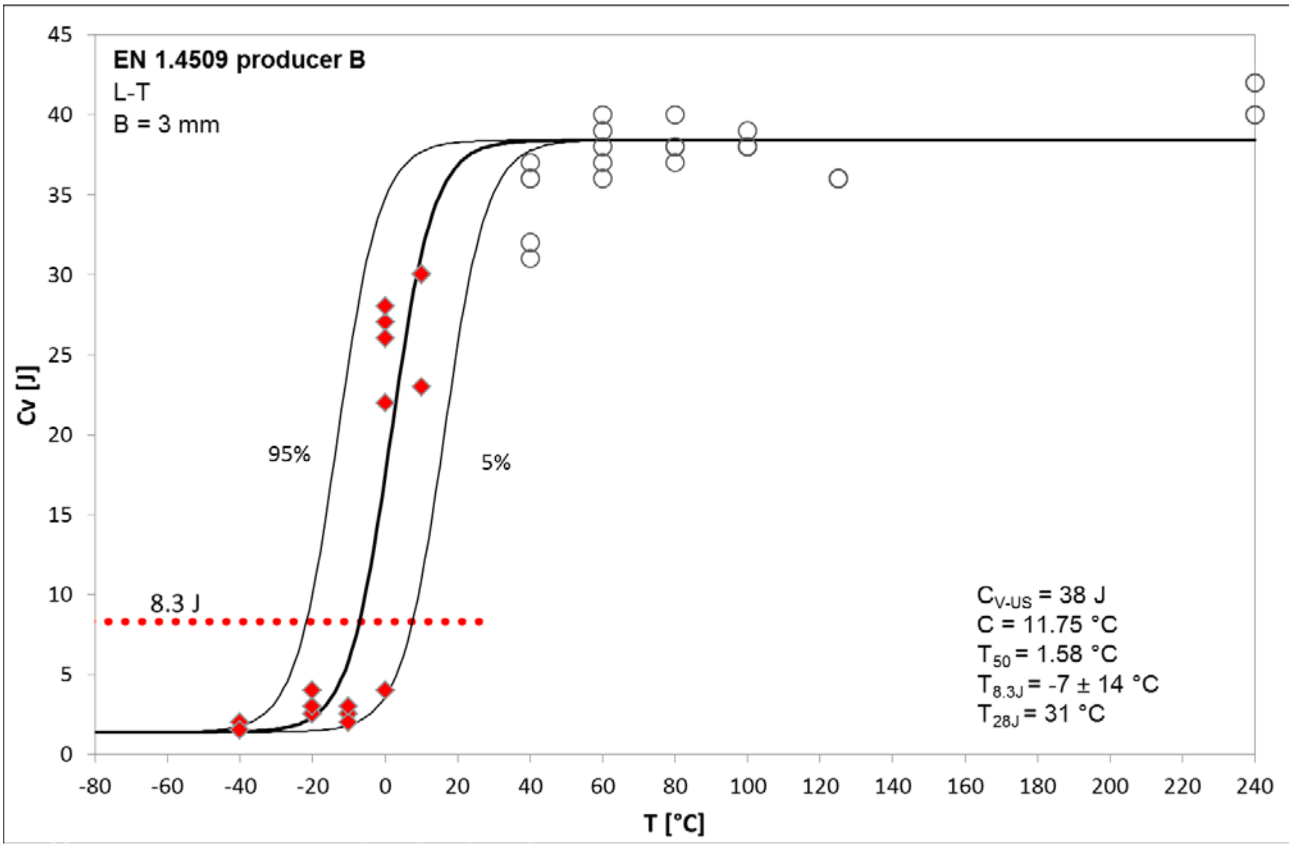

Figure 10 Transition curve determined for 3-mm-thick EN 1.4509 produced by producer B. Testing direction L-T.

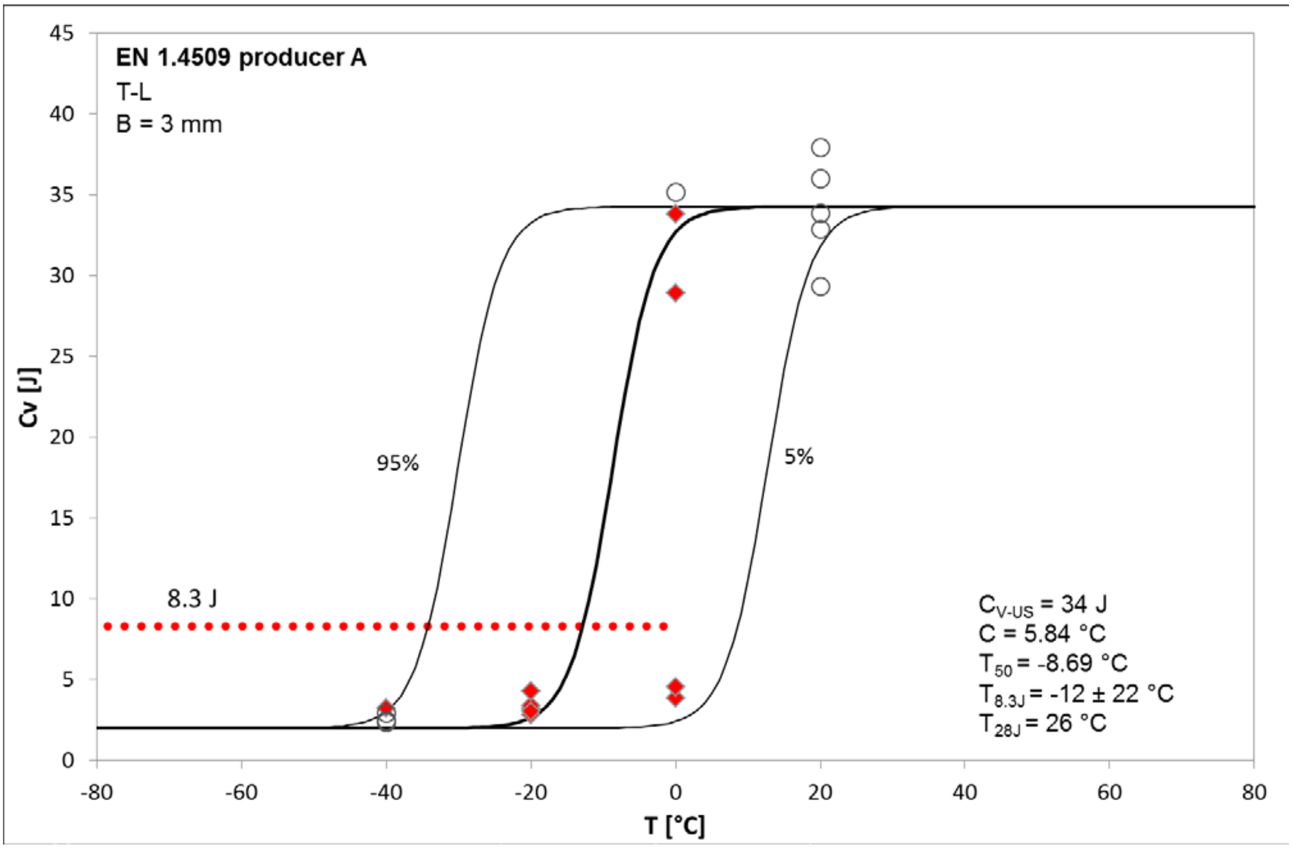

Figure 11 Transition curve determined for 3-mm-thick EN 1.4509 produced by producer A. Testing direction T-L.

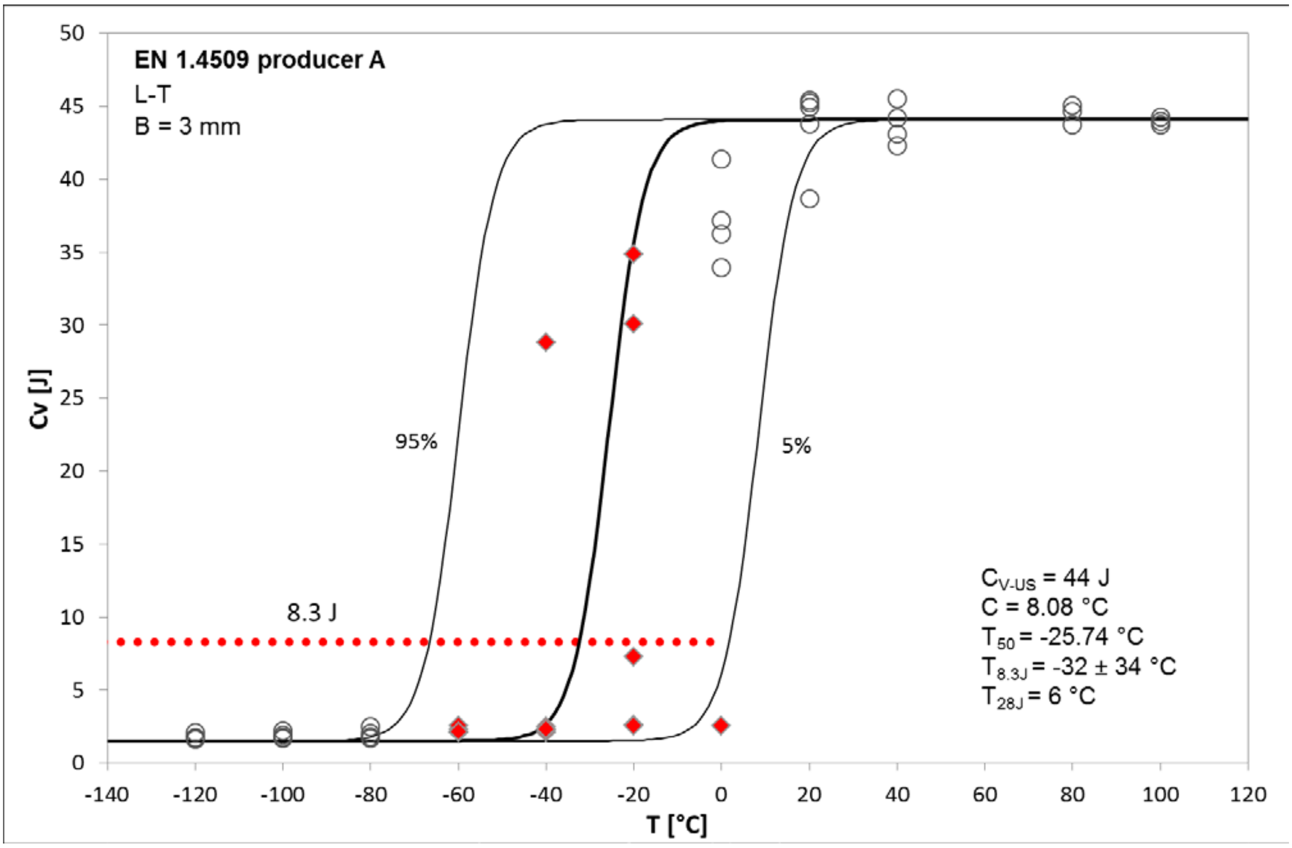

Figure 12 Transition curve determined for 3-mm-thick EN 1.4509 produced by producer A. Testing direction L-T.

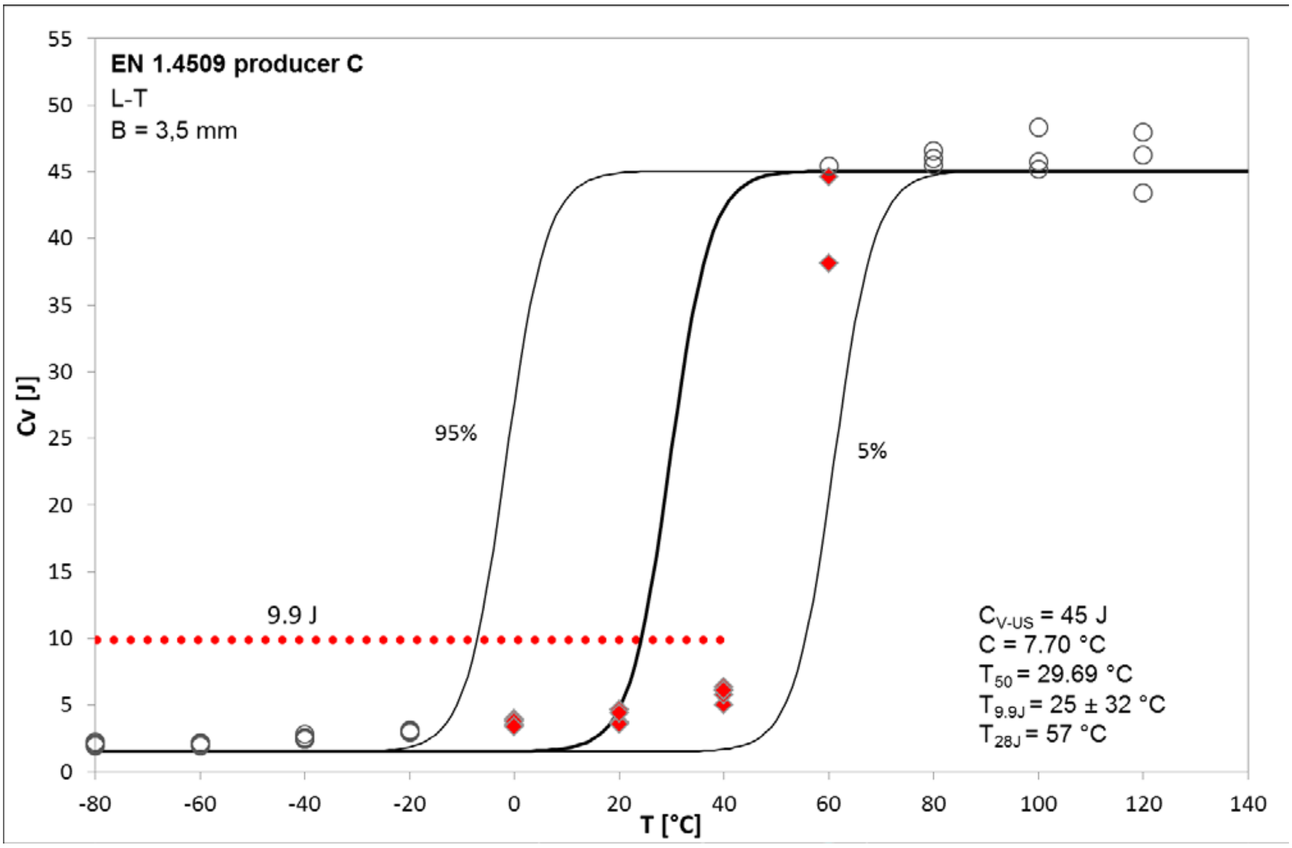

Figure 13 Transition curve determined for 3.5-mm-thick EN 1.4509 produced by producer C. Testing direction L-T.

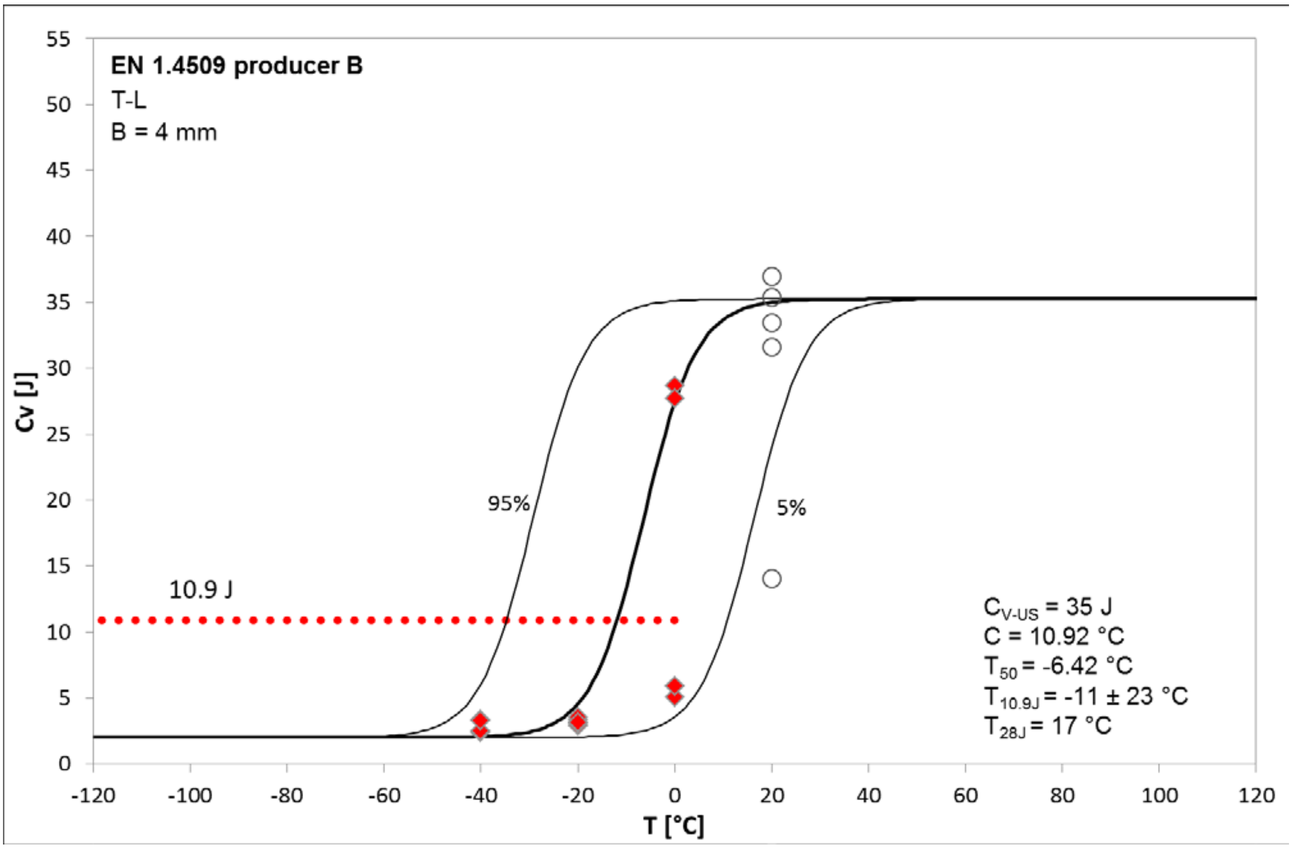

Figure 14 Transition curve determined for 4-mm-thick EN 1.4509 produced by producer B. Testing direction T-L.

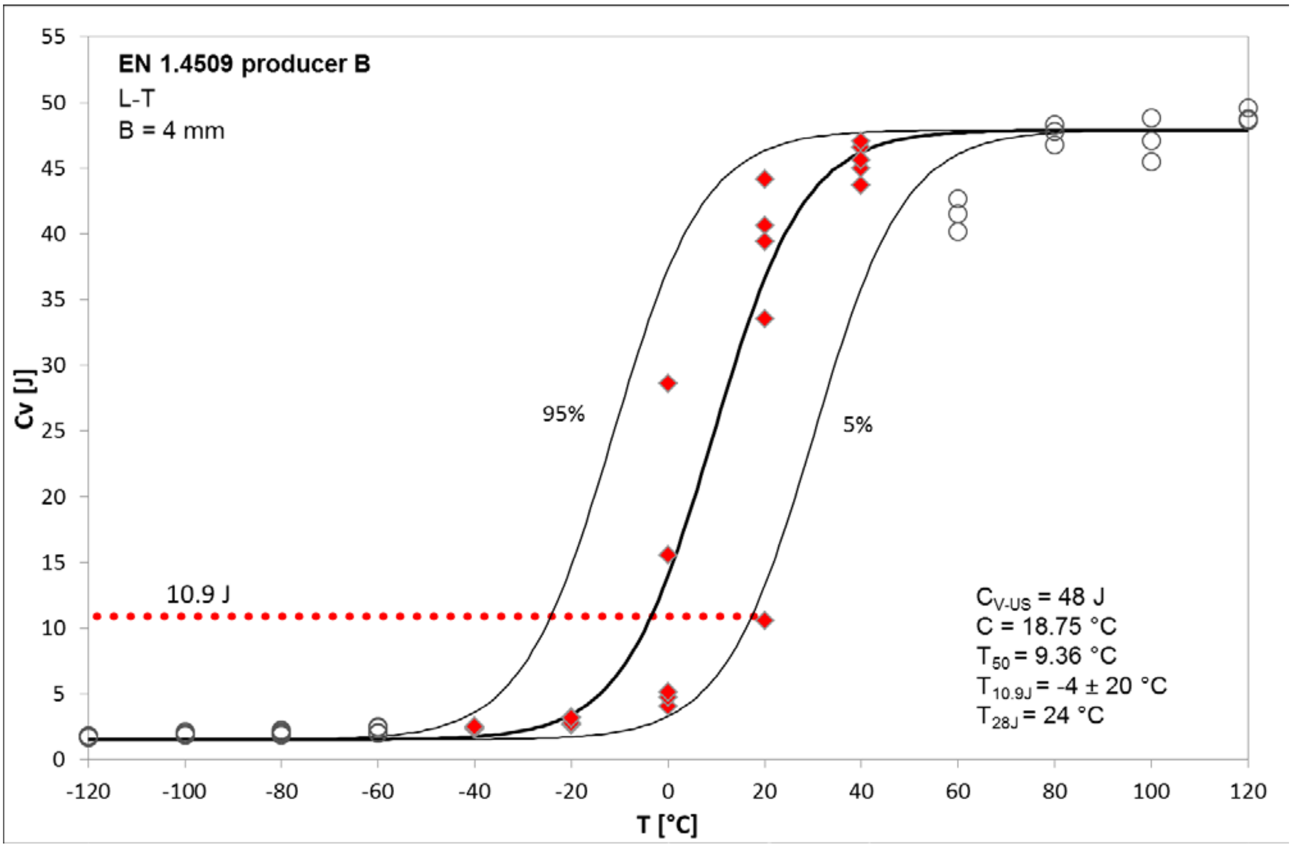

Figure 15 Transition curve determined for 4-mm-thick EN 1.4509 produced by producer B. Testing direction L-T.

Ductile transition curves determined for the grade EN 1.4521 with a thickness from 1 to 3 mm.

$C_{V\text{-}US}$ = Upper shelf energy [J]
C = fitted parameter from Equation (3), [°C]
T_{50} = fitted parameter from Equation (4), [°C]
$T_{x.xJ}$ = determined transition temperature. Criterion (x.x) is depending on thickness of the sub-sized specimen. [°C]
T_{28J} = size-corrected transition temperature [°C]
The red squares in the transition curve figures are data between $0.1{*}C_{V\text{-}US}$ and $0.85{*}C_{V\text{-}US}$ used for fitting the transition curve, equations 3 and 4.

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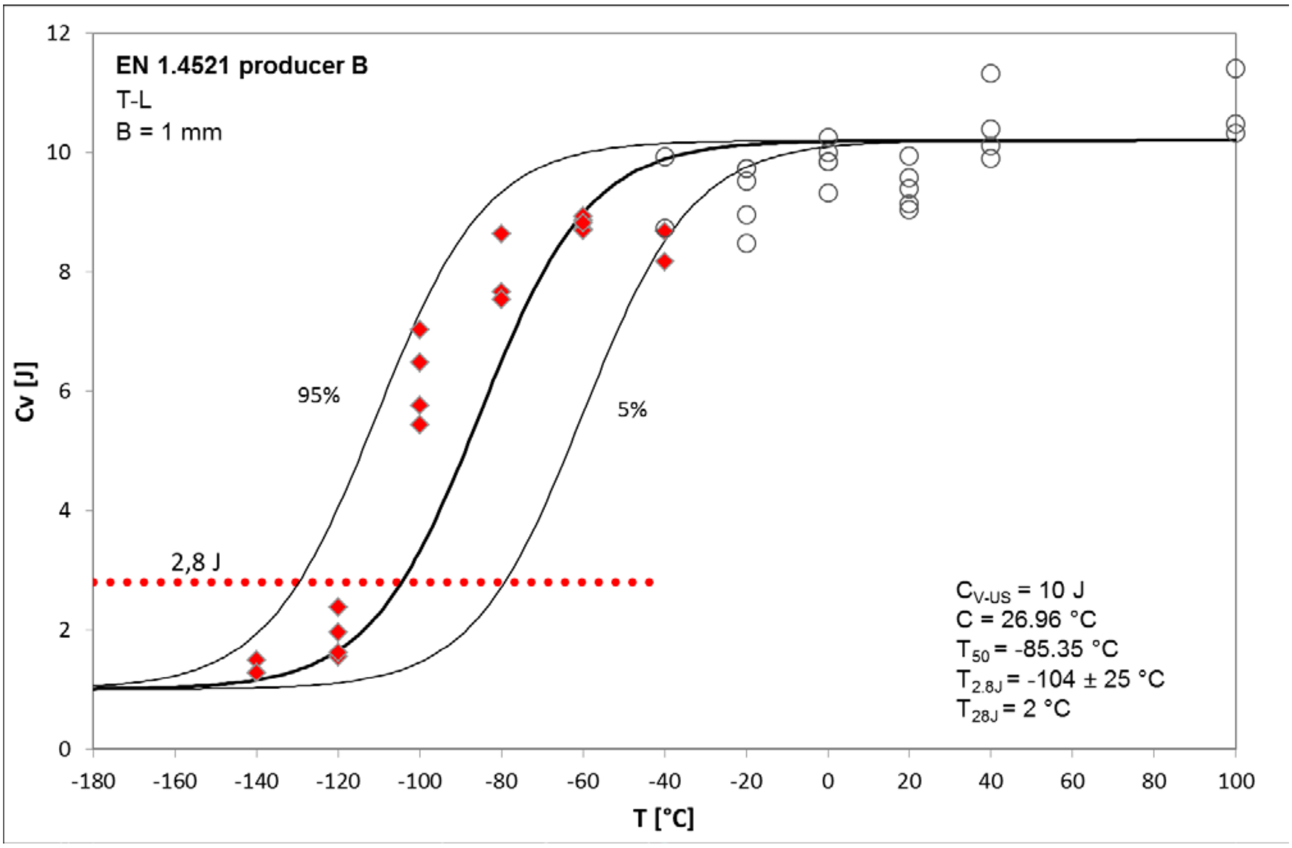

Figure 1 Transition curve determined for 1-mm-thick EN 1.4521 produced by producer B. Testing direction T-L.

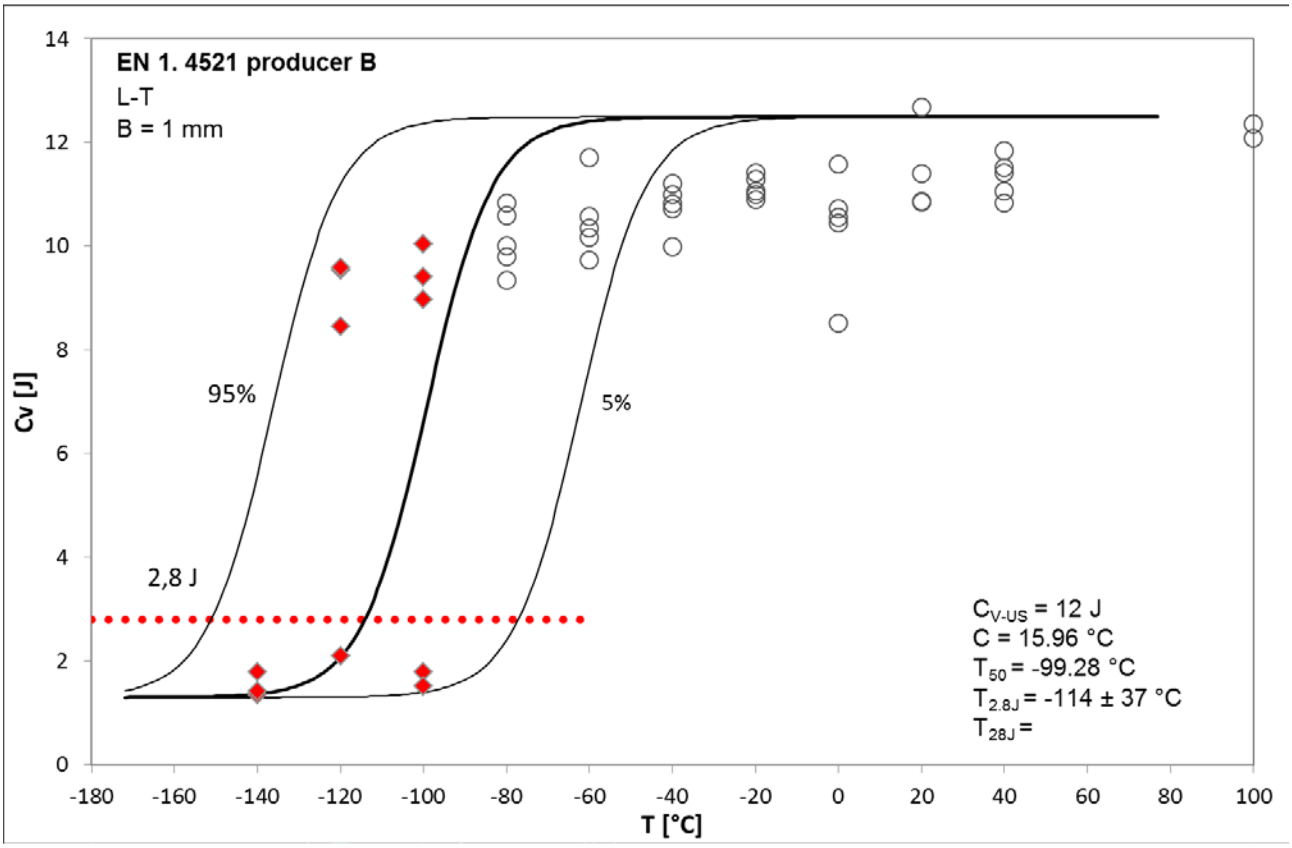

Figure 2 Transition curve determined for 1-mm-thick EN 1.4521 produced by producer B. Testing direction L-T.

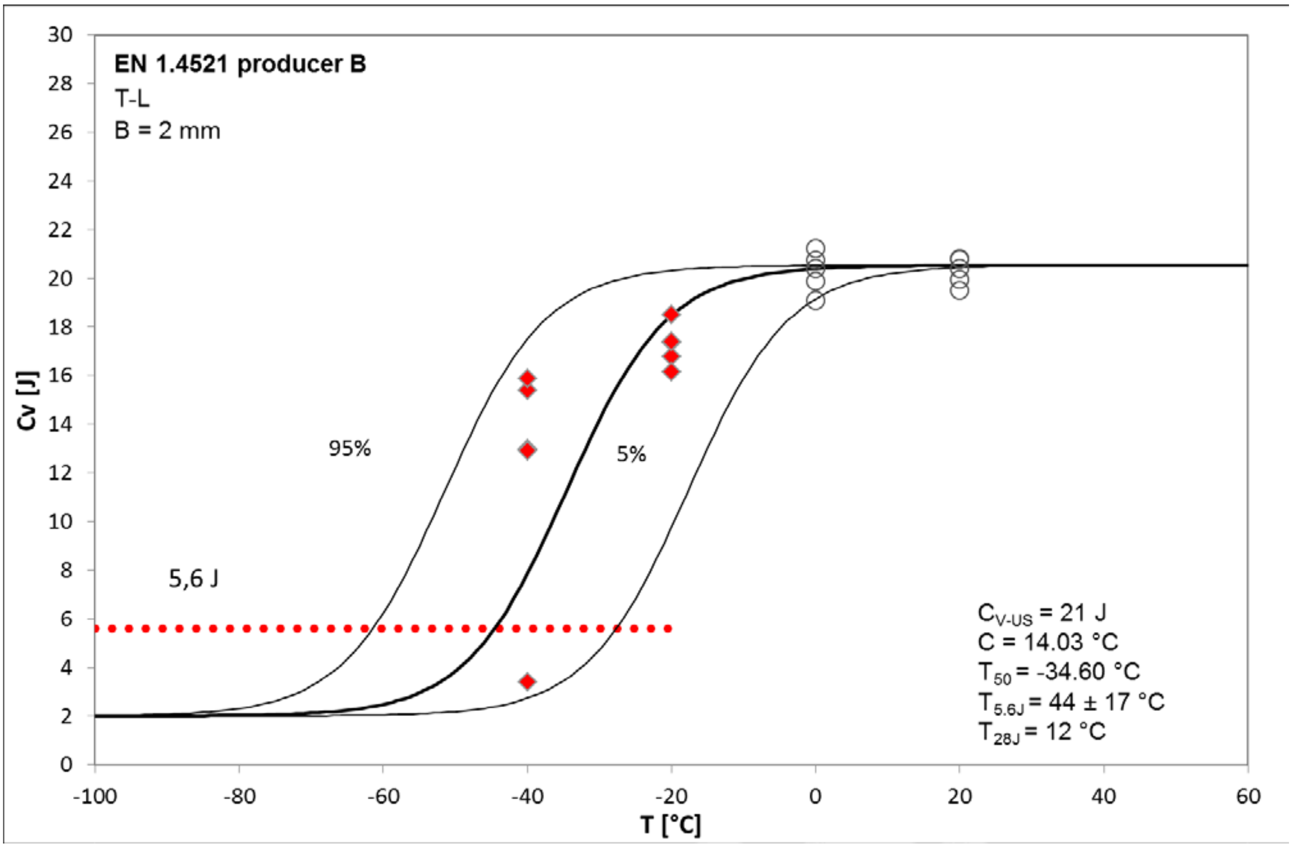

Figure 3 Transition curve determined for 2-mm-thick EN 1.4521 produced by producer B. Testing direction T-L.

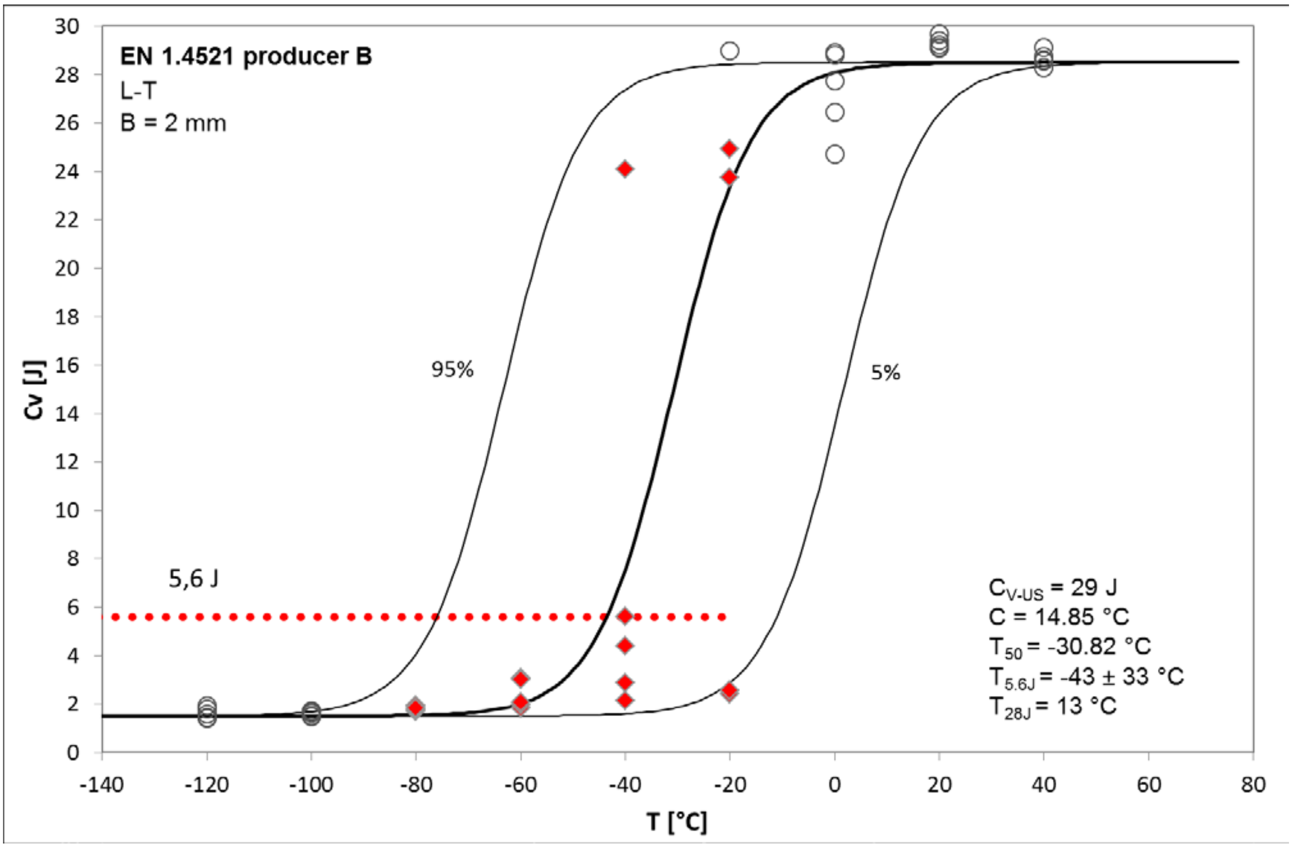

Figure 4 Transition curve determined for 2-mm-thick EN 1.4521 produced by producer B. Testing direction L-T.

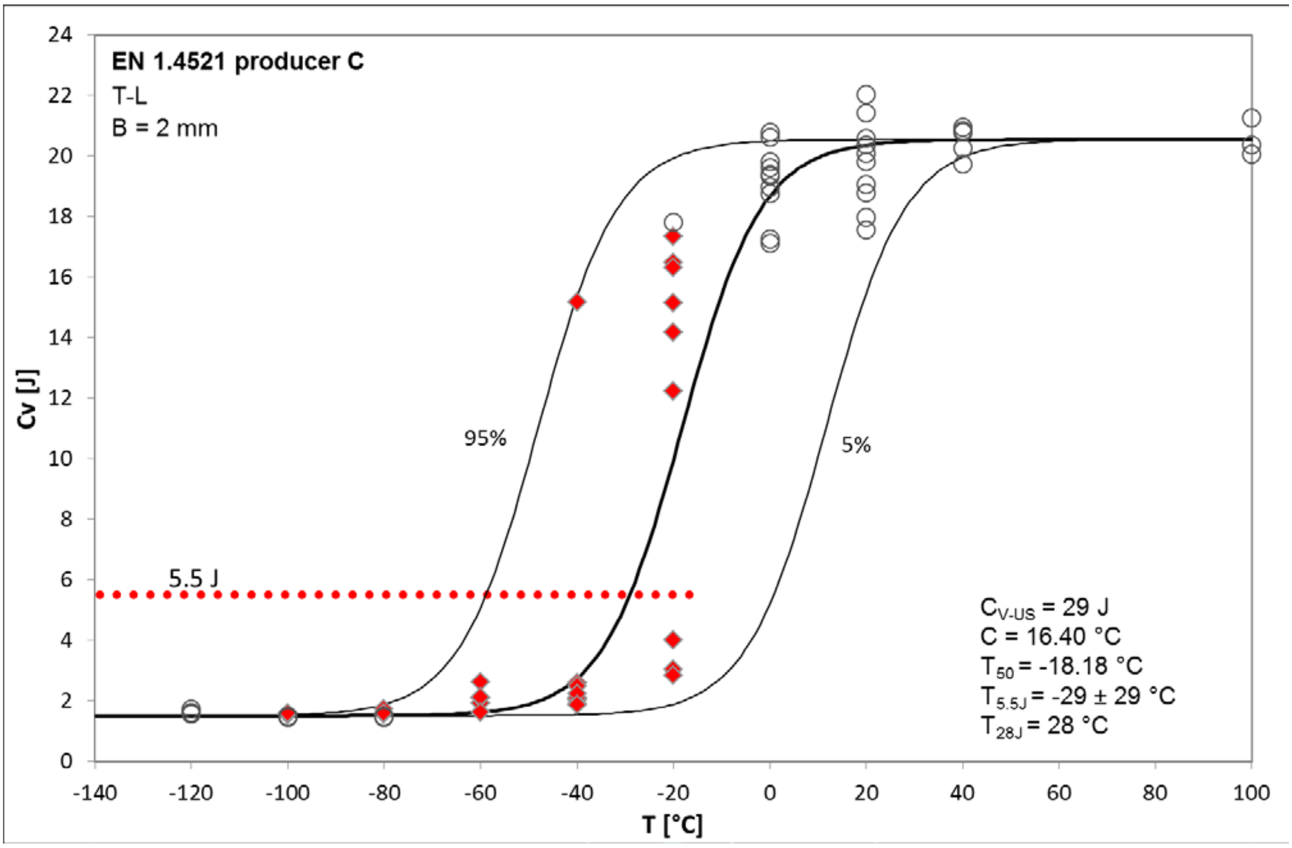

Figure 5 Transition curve determined for 2-mm-thick EN 1.4521 produced by producer C. Testing direction T-L.

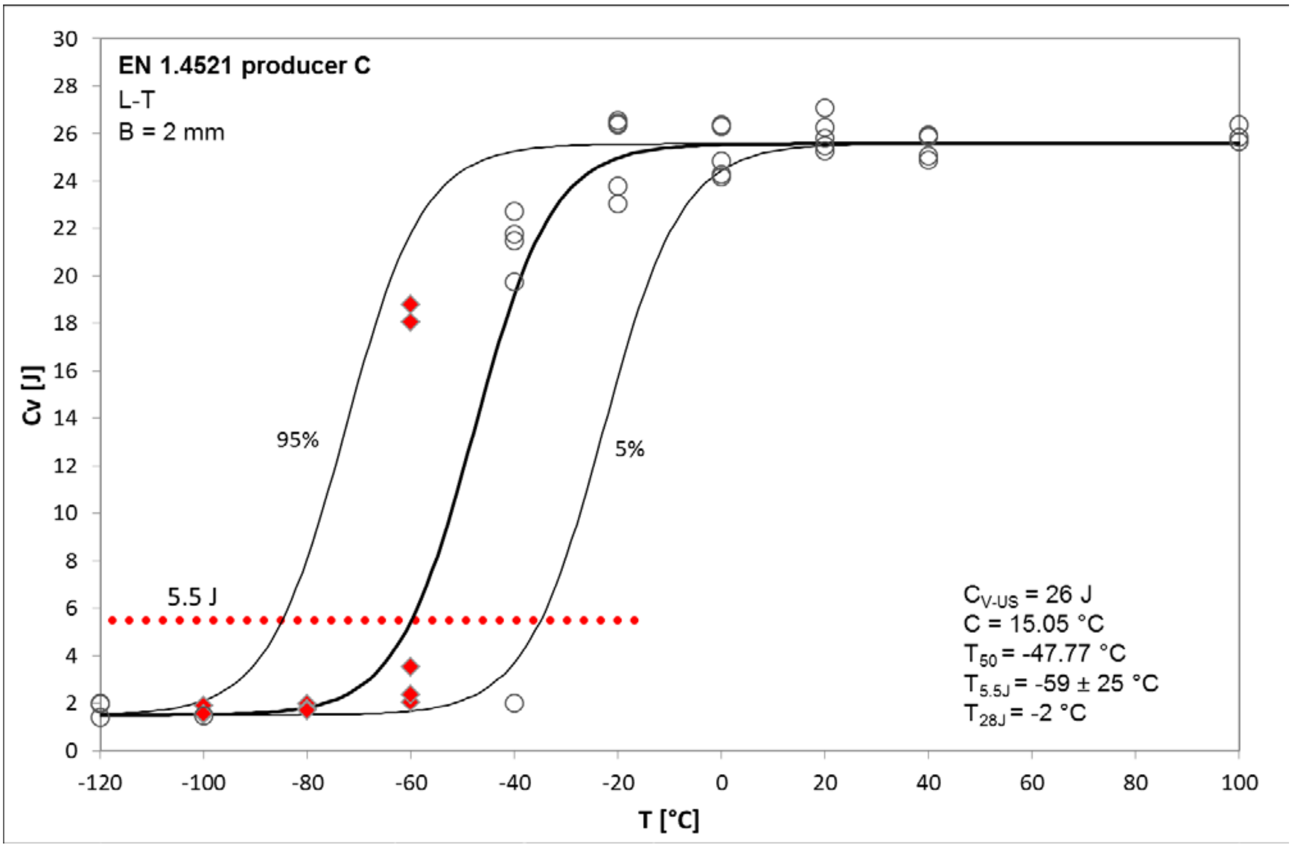

Figure 6 Transition curve determined for 2-mm-thick EN 1.4521 produced by producer C. Testing direction L-T.

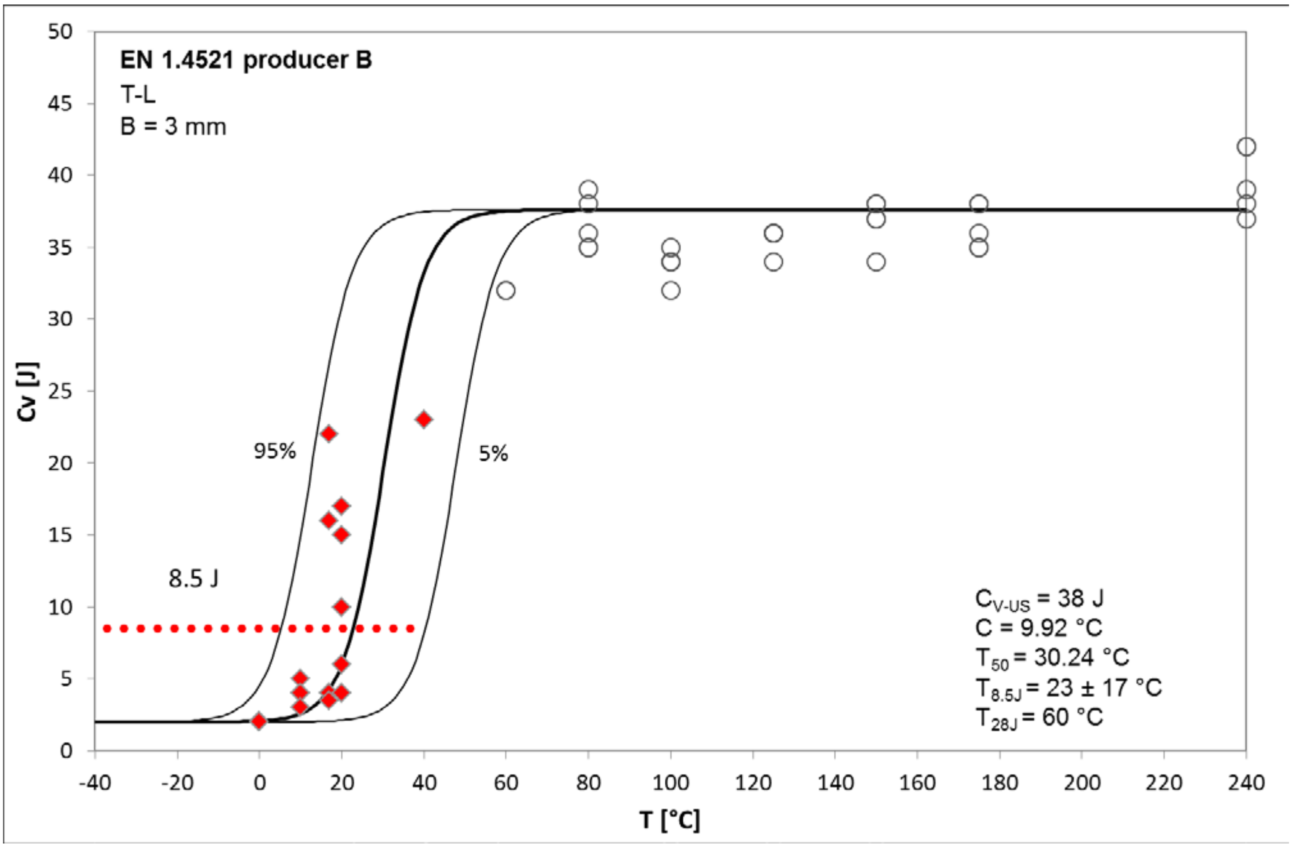

Figure 7 Transition curve determined for 3-mm-thick EN 1.4521 produced by producer B. Testing direction T-L.

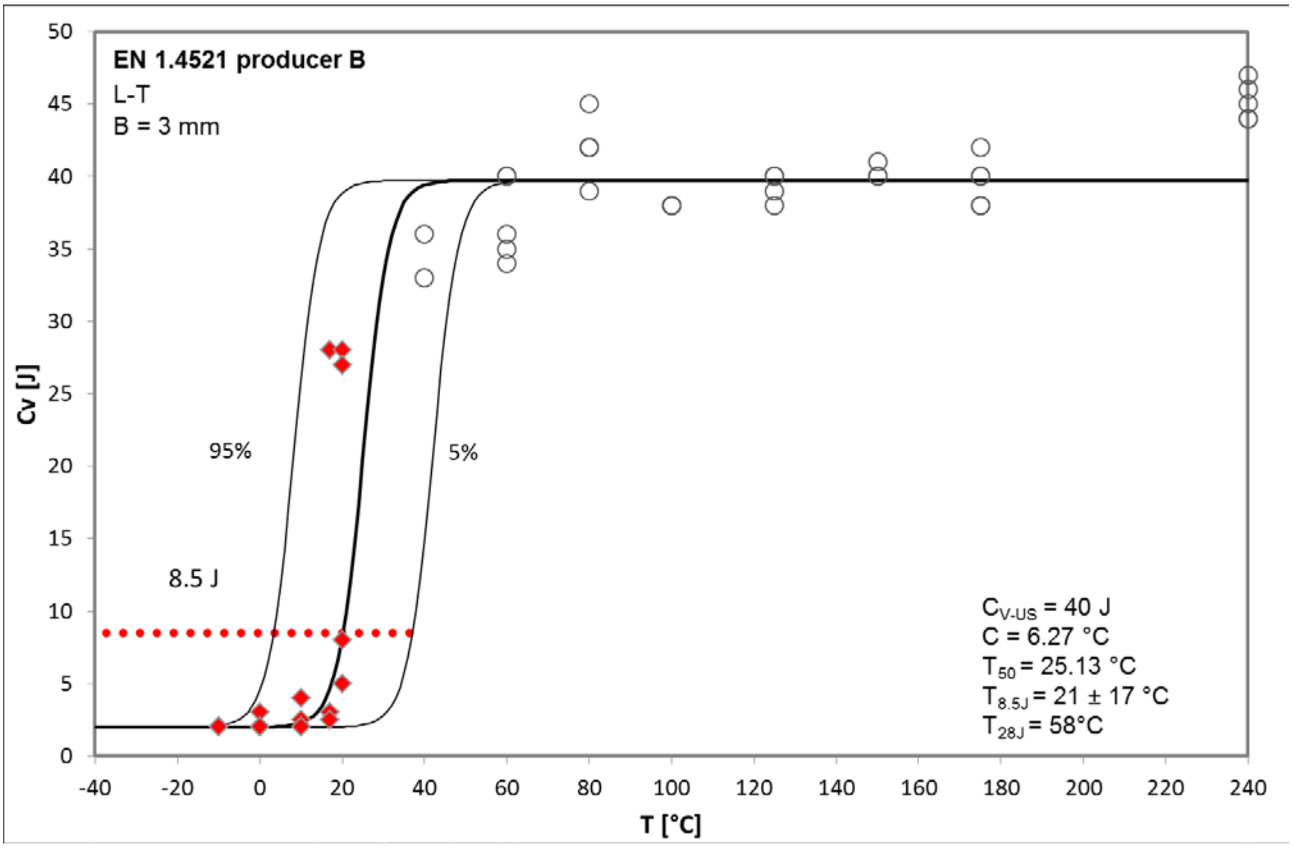

Figure 8 Transition curve determined for 3-mm-thick EN 1.4521 produced by producer B. Testing direction L-T.

Ductile transition curves determined for the grade EN 1.4621 with a thickness of 1.5 mm.

$C_{V\text{-}US}$ = Upper shelf energy [J]
C = fitted parameter from Equation (3), [°C]
T_{50} = fitted parameter from Equation (4), [°C]
$T_{x.xJ}$ = determined transition temperature. Criterion (x.x) is depending on thickness of the sub-sized specimen. [°C]
T_{28J} = size-corrected transition temperature [°C]
The red squares in the transition curve figures are data between 0.1*$C_{V\text{-}US}$ and 0.85*$C_{V\text{-}US}$ used for fitting the transition curve, equations 3 and 4.

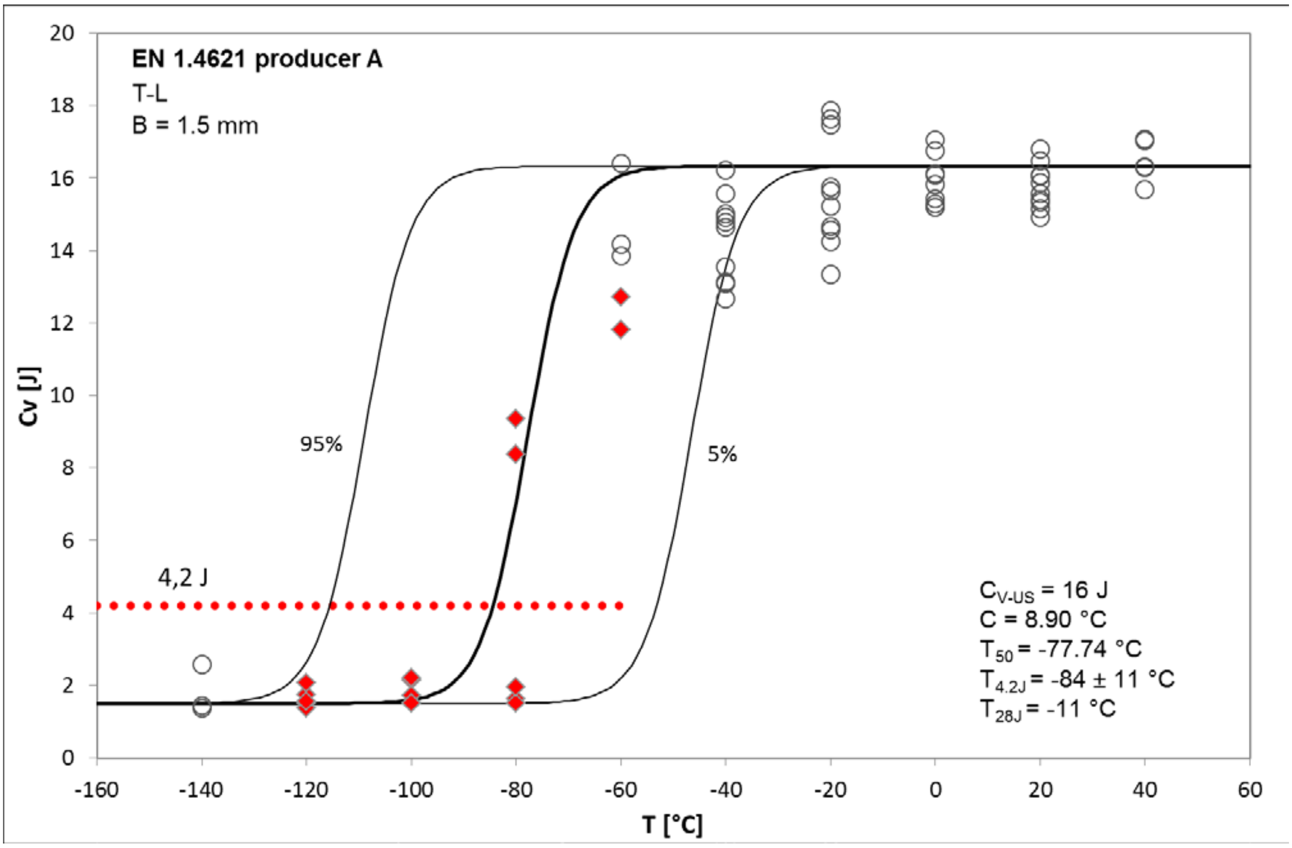

Figure 1 Transition curves determined for 1.5-mm-thick EN 1.4621 produced by producer A. Testing direction T-L.

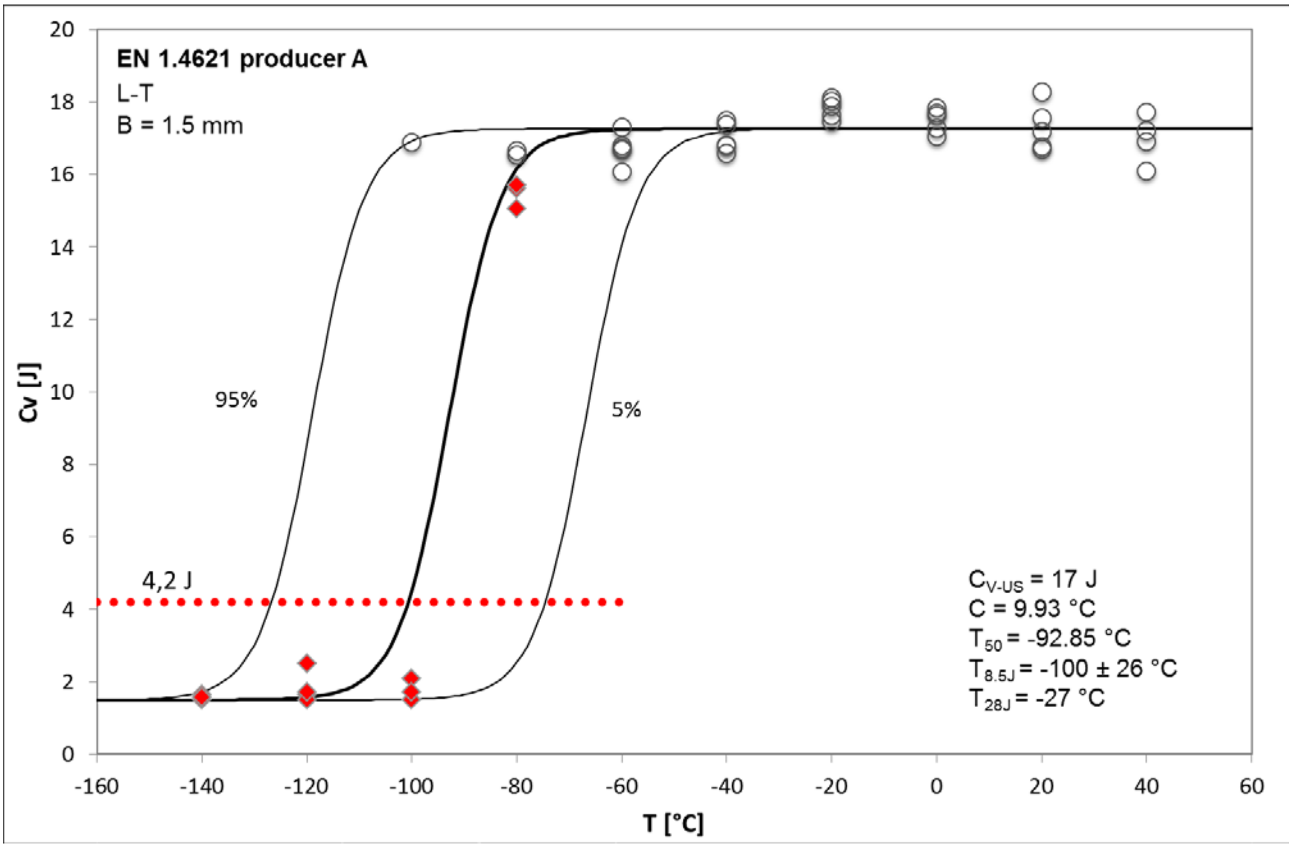

Figure 2 Transition curves determined for 1.5-mm-thick EN 1.4621 produced by producer A. Testing direction L-T.

Charpy V impact test results

Mrf.x = manufacturer / producer

	Temperature [°C]	1.4003 T-L 1 mm Mfr. B	1.4003 L-T 1 mm Mfr. B	1.4003 T-L 2 mm Mfr. B	1.4003 T-L 3mm Mfr. B	1.4003 L-T 3mm Mfr. B	1.4003 T-L 4 mm Mfr. B	1.4003 L-T 4 mm Mfr. B	1.4003 T-L 5 mm Mfr. B	1.4003 L-T 5 mm Mfr. B	1.4003 T-L 6 mm Mfr. B	1.4003 L-T 6 mm Mfr. B
KV [J]	-140	9	10					3	2	2		
	-140	1	10					2	2	2		
	-140	10	10					2	2	2		
	-130				2	3						
	-130				2	3						
	-130				2	2						
	-130				2							
	-130				2							
	-120	9	10					3	2	2		3
	-120	10	10					5	2	3		3
	-120	10	10					3	2	2		3
	-120	10	10					4	2	2		2
	-120	10	10					3	2	2		3
	-110				3	2						
	-110				3	4						
	-110					3						
	-110				2	3						
	-110				3	3						
	-100	10	11		3	14		22	3	3		3
	-100	10	11		3	3		33	3	3		3
	-100	10	10		3	23		36	2	3		3
	-100	10	10			4		31	2	3		3
	-100	10	10		3	12		27	2	3		3
	-85				3	36						
	-85				2	33						
	-85				19	58						
	-85				20	52						
	-85				2	22						
	-80	11	11		3	38		47	2	5		3
	-80	10	11		21	43		31	3	4		3
	-80	10			18	39		36	3	4		4
	-80	11	11		3	38		41	3	5		3
	-80	10	11		5	38		33	3	5		3
	-60	11	11		32	52		62	6	41		11
	-60	10	12		28	54		72	4	46		7
	-60	11	11		30			72	27	47		10
	-60	11	11		29	53		70	7	18		9
	-60	11	12			53		71	5	36		23
	-40	10	11	26	37	52	34	83	38	61	6	51
	-40	11	11	23	36	61	40	76	66	72	64	59
	-40	11	11	24	36	64	35	69	10	58	46	53
	-40	11	11	25	36	64	40	72	45	52	64	50
	-40			25	33	65	39	75	15	90	4	57
	-20	9	12	26	42	66	36	80	62	90	74	68
	-20		10	25	40	60	51	77	72	102	74	80
	-20	11	11		40	66	45	81	53	101	74	95
	-20	11	11	25	44	70	38	74	62	109	63	72
	-20	12	11		44	65	40	79	46	103	15	82

KV [J]

Temperature [°C]	1.4003 T-L 1 mm Mfr. B	1.4003 L-T 1 mm Mfr. B	1.4003 T-L 2 mm Mfr. B	1.4003 T-L 3mm Mfr. B	1.4003 L-T 3mm Mfr. B	1.4003 T-L 4 mm Mfr. B	1.4003 L-T 4 mm Mfr. B	1.4003 T-L 5 mm Mfr. B	1.4003 L-T 5 mm Mfr. B	1.4003 T-L 6 mm Mfr. B	1.4003 L-T 6 mm Mfr. B
0	8	8	22	45	56	41	88	83	91	84	182
0	8	11	23	45	66	42	81	61	93	92	189
0	8	9	26	45	63	42	82	61	94	70	187
0	10	11	24	42	66	42	70	66	110	91	182
0	14	9		45	67	51	84	68	92	65	183
20	9	11		44	48	46	83	63	96	90	181
20	11	10	25	42	50	48	83	66	93	97	180
20	11	12	25	44	51	51	88	70	103	73	179
20	11	12	25	44	50	58	97	69	98	94	184
20	8	13	25	42	53	51	86	70	100	88	189
40	11	10		44	50		89	75	101		179
40	10	10		43	51		87	84	95		181
40	10	11		44	53		97	77	105		178
40	11	11		46	60		85	70	105		180
40	10	10		46	57		84	81	100		182
60				45	52						
60					62						
60					60						
60				45	62						
60				45	61						
80				52	55						
80				52	59						
80					60						
80				54	60						
80				48	59						
100							87	83	109		173
100							93	82	124		169
100							97	78	125		173
120											
120											
120											

	Temperature [°C]	1.4016 T-L 1 mm Mfr. C	1.4016 L-T 1 mm Mfr. C	1.4016 T-L 2 mm Mfr. B	1.4016 L-T 2 mm Mfr. B	1.4016 T-L 2 mm Mfr. C	1.4016 L-T 2 mm Mfr. C	1.4016 T-L 3 mm Mfr. C	1.4016 L-T 3 mm Mfr. C	1.4016 T-L 4 mm Mfr. C	1.4016 L-T 4 mm Mfr. C
KV [J]	-140	1	2		3		2				
	-140	2	6		2		2				
	-140	5	7		2		2				
	-140										
	-140		2								
	-120	4	7		3		2		2	2	2
	-120	4	8		3		2		2	2	2
	-120	1	7		2		2		2	2	2
	-120	5	7		3		2		2	2	2
	-120	6	6		2		2		2	2	2
	-100	7	7		21		2		2	2	2
	-100		7		18		3		2	2	2
	-100	5	9		20		3		2	2	2
	-100	6			19		13		3	2	2
	-100	5	8		15		2		2	2	2
	-80	6	10		25		15		2	2	3
	-80	6			21		10		2	2	3
	-80		8		24				2	2	2
	-80	6	8		21		3		2	2	3
	-80	7	9		20		13		2	2	3
	-60	7	10		26		21		2	2	3
	-60	7	8		26		18		3	2	3
	-60	6	9		27		20		3	3	3
	-60	7	8		26				3	2	3
	-60	7	8		26		23		3	3	3
	-40	7	8	2	26	15	22	3	13	3	3
	-40	7		22	26	15	19	3	19	3	4
	-40	8		3	22	16	20	3	32	3	4
	-40	8	8	18	27	15	20	3	20	4	3
	-40	7	9	18	27	16	21	3	3	3	5
	-20	8	8	24	25	18	20	4	26	5	8
	-20	8	8	24	28	16	22	9	13	5	7
	-20	7	9	21	26	17	20	17	20	3	7
	-20	8	10	22	26	17	20	15	19	4	10
	-20	8	8	23	26	18	21	21	26	5	12
	0	9		26	27	17	22	19	22	8	13
	0	8	8	27	26	19	21	21	35	11	17
	0	8	9	25	26	17	22	16	28	10	15
	0	7	11	26	26	17	20	21	34	9	14
	0	9	9	22	25	19	22	23	26	11	6
	20	7	8	26	25	19	22	26	36	11	24
	20	10	10	25	25	19	22	25	35	13	25
	20	7	8		25	19	22	24	35	11	21
	20	9		25	26	20	22	26	35	12	25
	20	12	9		24	19	21	25	36	13	24
	40	13	9		26				36	15	29
	40	10			25				37	15	39
	40	13			26				40	14	34
	40	8	9		25				38	16	32
	40	8	8		24				39	16	39

	Temperature [°C]	1.4016 T-L 1 mm Mfr. C	1.4016 L-T 1 mm Mfr. C	1.4016 T-L 2 mm Mfr. B	1.4016 L-T 2 mm Mfr. B	1.4016 T-L 2 mm Mfr. C	1.4016 L-T 2 mm Mfr. C	1.4016 T-L 3 mm Mfr. C	1.4016 L-T 3 mm Mfr. C	1.4016 T-L 4 mm Mfr. C	1.4016 L-T 4 mm Mfr. C
KV [J]	60										
	60										
	60										
	80	7	9						41	18	41
	80	7	8						38	18	40
	80	7	8						41	20	43
	100	7	8						41	20	40
	100	7	9						40	20	57
	100	8	9						40	20	60
	120										
	120										
	120										

	Temperature [°C]	1.4509 T-L 1 mm Mfr. B	1.4509 L-T 1 mm Mfr. B	1.4509 T-L 1 mm Mfr. C	1.4509 L-T 1 mm Mfr. C	1.4509 T-L 2 mm Mfr. B	1.4509 L-T 2 mm Mfr. B	1.4509 T-L 2 mm Mfr. C	1.4509 L-T 2 mm Mfr. C	1.4509 T-L 3 mm Mfr. B	1.4509 L-T 3 mm Mfr. B	1.4509 T-L 3 mm Mfr. A	1.4509 L-T 3 mm Mfr. A	1.4509 T-L 3,5 mm Mfr. C	1.4509 L-T 3,5 mm Mfr. C	1.4509 T-L 4 mm Mfr. B	1.4509 L-T 4 mm Mfr. B
KV [J]	-140	1	1	1	2												
	-140	1		1	1												
	-140	1	1	2	1												
	-140																
	-140		1														
	-120	1	1	2	2		2		2				2		2		2
	-120	1	2	1	1		1		1				2				2
	-120	1	2	1	2		1		2				2				2
	-120	1	1	2			2		2				2		2		2
	-120	2	1	1	1		2		2				2		2		2
	-100	2	2	2	2		2		3				2		2		2
	-100		9	1	2		2		2				2		2		2
	-100	1	2		9		2		2				2		2		2
	-100	1	2	1	10		1		2				2		2		
	-100	2	2	1	2		2		2				2		2		2
	-80	7	10		9				3				2		2		2
	-80	7	9	10	10		2		2						2		2
	-80	1	9	9	10		2		2				2		2		2
	-80	8	10	3	10		2		2				2		2		2
	-80	8		2			2		2				2		2		2
	-60	8	10	9	10		3		16				2		2		2
	-60	8	10	9	10		2		19				3		2		2
	-60	8	9	9	11		2		2				2		2		2
	-60	8	9	9	10		2		2				2		2		2
	-60	9	9	9	11		2		20				2		2		2
	-40	8		10		2	20	3	24	2	2	2	2	3	3	2	3
	-40	8		10	10	3	17	3	21	2	2	3	2	3	2	2	2
	-40	8	10	9	10	2	14	12	25	2	2	2	2	3	3	3	2
	-40	9	11	10	11	2	16	3	23			2	2	3	2	3	2
	-40	8	10	9	12	2	14	3	2			3	29	3	3	3	3
	-20	9	11	9	10	16	19	13	26	3	3	3	3	3	3	3	3
	-20		11	9	11	15	20	19	22	3	3	3	35	4	3	3	3
	-20		10	9	10		2	18	23	4	3	4	3	3	3	3	3
	-20	8	11	9	10	18	19	19	27	4	3	3	7	3	3	4	3
	-20	9	10	8	10	15		2	25	4	4	3	30	3	3	3	3
	-10									4	3						
	-10									4	3						
	-10									3	3						
	-10									10	2						
	-10									4	3						
	0	9	12	10	11	16	19	21	24	4	27	4	3	8	4	6	4
	0	9		10	10	19	20	20	25	4	22	29	41	6	4	29	16
	0	9	7	10	11	20	19	20	23	22	4	5	34	4	4	5	29
	0	10	10	9	9	18	20	23	24	7	28	34	36	5	4	28	5
	0	9	11	10	11	18	19	21	24	4	26	35	37	4	3	6	5
	10									10	23						
	10									12	30						
	10									19	30						
	10									26	30						
	10									8	30						
	20	8	10	8		20	21	22	25			36	45	7	5	37	34
	20	11	9	9	10	18	21	22	25			34	39	5	4	33	44
	20	10	8	9	10	19	21	20	24			29	44	6	4	32	41
	20	8	11	10	12	20	21	21	25			38	45	6	5	35	39
	20			7	12	20	20	22	23			33	45	6	4	14	11

	Temperature [°C]	1.4509 T-L 1 mm Mfr. B	1.4509 L-T 1 mm Mfr. B	1.4509 T-L 1 mm Mfr. C	1.4509 L-T 1 mm Mfr. C	1.4509 T-L 2 mm Mfr. B	1.4509 L-T 2 mm Mfr. B	1.4509 T-L 2 mm Mfr. C	1.4509 L-T 2 mm Mfr. C	1.4509 T-L 3 mm Mfr. B	1.4509 L-T 3 mm Mfr. B	1.4509 T-L 3 mm Mfr. A	1.4509 L-T 3 mm Mfr. A	1.4509 T-L 3,5 mm Mfr. C	1.4509 L-T 3,5 mm Mfr. C	1.4509 T-L 4 mm Mfr. B	1.4509 L-T 4 mm Mfr. B
KV [J]	40	9	12	13	10		21		24	36	31		43		6		47
	40	11	16	9			20		24	32	36		44		5		44
	40	8	10	9	10		20		24	34	37		46		6		47
	40	9	11	7	11		21		24	30	32		42		6		45
	40	10	11	9	13		20		25	32	36				6		46
	60									34	40				45		40
	60									38	36				45		42
	60										39				38		43
	60									36	38						
	60									32	37						
	80									41	38		45		45		47
	80									38	40		44		46		48
	80									35	37		45		47		48
	80									41	38						
	80									40	38						
	100	8	9				21		24	36	38		44		46		45
	100	9	10				20		23	36	39		44		45		49
	100	9	10				21		24	35	38		44		48		47
	100									37	38						
	100									36	38						
	120														43		49
	120														48		49
	120														46		50
	125									32	36						
	125									35	36						
	125									34	36						
	125									37							
	125									37							
	240									42	40						
	240									39	40						
	240									39	42						
	240									40	42						
	240									39							

	Temperature [°C]	1.4521 T-L 1 mm Mfr. B	1.4521 L-T 1 mm Mfr. B	1.4521 T-L 2 mm Mfr. B	1.4521 L-T 2 mm Mfr. B	1.4521 T-L 2 mm Mfr. C	1.4521 L-T 2 mm Mfr. C	1.4521 T-L 3 mm Mfr. B	1.4521 L-T 3 mm Mfr. B
KV [J]	-140	1	2						
	-140	1	1						
	-140	1	1						
	-140								
	-140								
	-120	2	2		2	2	2		
	-120	2			1	2	2		
	-120		10		1	2			
	-120	2	8		2	2	1		
	-120	2	10		2	2			
	-100	5	9		2	1	2		
	-100	6	2		2	2	1		
	-100	6	10		2	1	2		
	-100		9		1	2	2		
	-100	7	2		2	1			
	-80	8	10		2	2	2		
	-80		10		2	2	2		
	-80	9	11		2	1	2		
	-80	0	11		2	2			
	-80	8	9		2	1			
	-60	9	10		2	2	4		
	-60	9	11		2	3	2		
	-60	9	12		3	2	2		
	-60	9	10		2	2	18		
	-60	9	10		3	2	19		
	-40	9	11		3	2	2		
	-40	10	11		24	2	23		
	-40		11		6	2	21		
	-40	9	10		2	2	22		
	-40	8	11		4	15	20		
	-40			13		3			
	-40			13		2			
	-40			3		2			
	-40			15		2			
	-40			16		2			
	-20	10	11		25	16	23		
	-20	9	11		29	18	24		
	-20	10	11		24	14	26		
	-20	8	11		2	3	27		
	-20	10	11		3	12	26		
	-20			17		3			
	-20			17		17			
	-20			17		4			
	-20			16		15			
	-20			19		16			
	-10							2	2
	-10							2	2
	-10							2	2
	-10								
	-10								
	0	10	12		26	20	26	2	2
	0	10	10		29	19	25	2	3
	0	10	11		29	19	24	2	2
	0	9	11		25	20	24	2	2
	0	10	9		28	21	26	2	2
	0			20		19			
	0			21		17			
	0			20		21			
	0			19		19			
	0			21		17			

	Temperature [°C]	1.4521 T-L 1 mm Mfr. B	1.4521 L-T 1 mm Mfr. B	1.4521 T-L 2 mm Mfr. B	1.4521 L-T 2 mm Mfr. B	1.4521 T-L 2 mm Mfr. C	1.4521 L-T 2 mm Mfr. C	1.4521 T-L 3 mm Mfr. B	1.4521 L-T 3 mm Mfr. B
KV [J]	10							4	3
	10							5	2
	10							3	
	10							4	4
	10							3	2
	17							16	28
	17							4	3
	17							22	28
	17							4	3
	17							4	3
	20	9	11		29	20	25	10	8
	20	9	11		30	21	25	6	28
	20	10			29	21	26	4	27
	20	10	11		29	22	27	17	5
	20	9	13		29	20	26	15	3
	20			21		19			
	20			21		18			
	20			20		19			
	20			20		20			
	20			20		18			
	40	10	11		28	20	25	23	8
	40	11	11		29	21	26	26	32
	40	10	12		29	21	26	27	32
	40	10	11		29	21	26	26	33
	40	0	12		29	20	25	13	36
	60							30	34
	60							36	36
	60							32	40
	60							28	35
	60							32	40
	80							35	39
	80							38	42
	80							36	42
	80							35	42
	80							39	45
	100	10	12		28	20	26	32	38
	100	10	20		28	20	26	34	38
	100	11	12		27	21	26	35	38
	100							34	
	100							34	
	120								
	120								
	120								
	125							36	38
	125							36	39
	125							36	40
	125							34	40
	125							36	
	150							34	40
	150							37	40
	150							37	41
	150							38	
	150							38	
	175							38	38
	175							35	40
	175							36	42
	175							35	38
	175							38	40
	240							37	44
	240							38	45
	240							39	44
	240							42	46
	240							42	47

	Temperature [°C]	1.4621 T-L 1,5 mm Mfr. A	1.4621 L-T 1,5 mm Mfr. A
KV [J]	40	16	18
	40	16	17
	40	17	16
	40	17	17
	40	16	
	20	16	17
	20	16	17
	20	16	18
	20	16	18
	20	17	17
	20	16	
	20	15	
	20	15	
	20	15	
	20	15	
	0	16	18
	0	17	18
	0	16	17
	0	17	17
	0	16	18
	0		
	0	15	
	0	15	
	0	15	
	0	15	
	-20	16	17
	-20	17	18
	-20	16	18
	-20	18	18
	-20	18	18
	-20	15	
	-20	15	
	-20	14	
	-20	15	
	-20	13	
	-40	15	17
	-40	16	17
	-40	15	17
	-40	15	17
	-40	13	18
	-40	14	
	-40	16	
	-40	13	
	-40	15	
	-40	13	
	-60	12	16
	-60	16	17
	-60	13	17
	-60	14	17
	-60	14	17

	Temperature [°C]	1.4621 T-L 1,5 mm Mfr. A	1.4621 L-T 1,5 mm Mfr. A
KV [J]	-80	9	17
	-80	2	16
	-80	8	16
	-80	2	17
	-80	2	15
	-100	2	2
	-100	2	2
	-100	2	17
	-100	2	2
	-100	2	2
	-120	2	2
	-120	2	3
	-120	2	2
	-120	1	2
	-120	2	2
	-140	3	2
	-140	1	2
	-140	1	2