TECHNICAL
REPORT

ISO/TR
21704

First edition
2017-02

Toughness of round steel link chains — Test with sub-size specimens

Ténacité de la chaînes en acier rond — Essai avec les éprouvettes sous-dimensionnées

Reference number
ISO/TR 21704:2017(E)

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Foreword

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This document was prepared by Technical Committee ISO/TC 111, *Round steel link chains, chain slings, components and accessories*, Subcommittee SC 1, *Chains and chain slings*.

Introduction

This document provides the results of testing on the toughness of round steel chains.

In an initial study programme, the fundamental effects on the load bearing capacity of round steel chains were examined. The material strength and material toughness along with the temperature were incorporated in the tests. The tests were conducted on chains 16 x 48 and the specimens taken from these. To determine the toughness of sub-size round steel link chains, the required tests were performed with sub-size notch impact specimens that were taken from the unwelded legs of the chains.

The safety of round steel link chains was examined in detail in a load bearing concept and in a brittle fraction transition temperature concept, see Figure A.1. Temperatures and minimum notch impact energy values were determined using fracture mechanics methods, with the aim of ensuring sufficient load bearing capacity for a damaged chain at design temperature. These tests and their results are documented in ISO/TR 23602.

Toughness of round steel link chains — Test with sub-size specimens

1 Scope

This document contains investigations and investigation results on toughness of round steel link chains, tested with sub-size specimens.

It applies to round steel link chains for hand operated chain hoists of grade TH and VH and for sling chains used for chain slings of grade 8.

NOTE 1 Associated International Standards are ISO 16877, ISO 16872 and ISO 3076. In future it is intended to implement the results on toughness derived in this document in new standards.

Eleven steels, provided by four manufacturers, were tested to find a test regime on sub-size specimens and requirements on the notch impact toughness values at design temperature which resulted out of the tests. These requirements are adjusted to the toughness values of full size ISO-V specimens.

NOTE 2 The requirements are also valid for other cross sections of the chain than round.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

4 Abbreviated terms

$(Bb)_{full}$	width x height of the ligament of full size ISO-V specimens
$(Bb)_{sub}$	width x height of the ligament of sub-size specimens
C_1, C_2	correlation factors of the cross section of sub-size to full size specimens
$DBTT_{full\text{-}size}$	ductile-brittle transition temperature calculated for full size ISO-V specimens
$DBTT_{sub\text{-}size}$	ductile-brittle transition temperature tested with sub-size specimens
E_D	design energy at T_D (design notch impact energy at T_D)
E_{full}	calculated energy of full size ISO-V specimens
Ei	energy upon reaching the maximum force in the instrumented notch impact test
Ei_{sub}	Ei of sub-size specimens
Ep	energy component after exceeding the maximum force in the instrumented notch impact test
Ep_{sub}	Ep of sub-size specimens
E_{tot}	total energy: Ei + Ep

FATT	fracture appearance transition temperature; temperature at which the 50 % NCA occurs
NCA	non crystalline area of fracture surface; ductile fracture component of the fracture surface
SUS	sub-size notch impact specimen
SSUS	super sub-size notch impact specimen
T_D	design temperature
T_{NDT}	nil ductility transition temperature; brittle fracture transition temperature, reference value from Pellini tests, in the instrumented notch impact test determined with the crack arresting force (see ISO/TR 23602)
$T_{½ \text{ (USE)}}$	temperature at ½ (USE); temperature at half upper shelf notch impact energy
USE	upper shelf energy; upper shelf notch impact energy
α	slope of regression curve for the calculation of $\text{DBTT}_{\text{full-size}}$
β	calculated shift of temperatures associated with the energy values, sub-size to full size specimens (° C)

5 Target objective

The toughness characteristic values determined with sub-size notch impact specimens are very small in absolute terms (<5 J) and differ only to a minor extent. As a result, a transition function of the characteristic values determined at the sub-size specimens had to be derived to the values of standard ISO-V specimens. The aim was therefore to transfer the toughness requirements obtained for standard ISO-V specimens in ISO/TR 23602 at the lowest permissible application temperature of the corresponding chains to characteristic values of the sub-size specimens. Only in this way the aim of evaluating the chain safety can be attained with sub-size specimen characteristic values.

6 Chain manufacturers

Four chain manufacturers took part in the tests in respect to the toughness of round steel link chains. The results from three manufacturers were incorporated in this report. These are as follows:

Manufacturer 1:	Symbol R
Manufacturer 2:	Symbol K
Manufacturer 3:	Symbol M3
Manufacturer 4:	Symbol M4

7 Tested chain steels

The following different chain steels, provided by four manufacturers, were included in these toughness tests.

T (R)	NiCrMo-alloyed steel with high upper shelf energy and very low brittle fracture transition temperature, round steel link chains of grade 8
TH (R)	Manganese-boron steel (MnB), round steel link chains of grade 8
VH (R)	MnB-steel, model material, lower bound condition of upper shelf energy and high brittle fracture transition temperature, round steel link chains of grade 10

TH (K)	MnB-steel, standard round steel link chains of grade 8
VH (K)	MnB-steel, standard round steel link chains of grade 10
V* (R)	NiCrMo-alloyed chain steel with excellent low-temperature toughness, round steel link chains of a material with an ultimate tensile strength higher than 1500 MPa

The chain steels used by manufacturer M3 involve

Grade 8	NiCrMo-alloyed steel
Grade 10	NiCrMo-alloyed steel

The chain steels used by manufacturer M4 involve

Grade 8	MnB and NiCrMo-alloyed steel
Grade 10	NiCrMo-alloyed steel

The chains and chain steels T (R), TH (R), VH (R) were already incorporated in the fracture mechanics tests, ISO/TR 23602.

These steels comprise a wide range of toughness with different material strength, in particular in the transition area of the notch impact energy temperature curves.

8 Equipment, specimen geometry and sampling

The standard notch impact specimens (ISO-V) were tested in a pendulum impact testing machine with a maximum fall energy of 300 J, see Figure A.2. The peen of the hammer is instrumented with a strain gauge for determining the force-time curve, see Figure A.3. The integration yields the force-displacement curve whose integral is the fracture energy (notch impact energy) corresponding to the tested specimen. The test results (notch impact energy values) were read off directly at the drag pointer of the pendulum impact testing machine and in addition were determined by calculating the notch impact energy from the force-displacement curve. The measuring amplifier and the entire data logging system for recording the force-time progression were calibrated before each test series.

A pendulum impact testing machine with a maximum energy of 15 J was used for testing the sub-size notch impact specimen, see Figure A.4a). Here too, the hammer peen was instrumented with strain gauges, see Figure A.4b) and Figure A.4e). The anvil of the pendulum impact testing machine is shown in Figure A.4c). The amplifier and entire data logging system were calibrated before each test series, see Figure A.4d). During the tests on this pendulum impact testing machine, two energy values each were also determined: read off from the drag pointer and calculated from the force-displacement curve.

The specimens were either heated or cooled in liquid nitrogen in order to set different test temperatures. The required test temperature was monitored using thermocouples.

Another option for determining the notch impact energy of sub-size specimens is provided by the drop weight test, see Figure A.5. Here too, the measuring system and amplifier were calibrated before each test series. It is not possible to read off the impact energy from a drag pointer with this test method. The value calculated via integration can only be utilized.

The results of both test methods with sub-size specimens reveal a good correspondence, see Figures A.12 to A.14 and 9.2. To this end, the tests were conducted with the pendulum impact testing machine (R) and with the drop weight device (K).

The notch impact specimens were taken from the unwelded legs of round steel link chain links. The specimen location in a chain link of dimension 16 x 48 and the specimen dimensions in accordance with ISO 148-1 for the standard ISO-V specimens can be seen in Figure A.6. The same applies for the sub-size notch impact specimen in accordance with ISO 14556 in Figure A.7. The width of the ligament of the

ISO-V specimen is 8 mm, that of the sub-size specimen only 3 mm. The ligament areas therefore differ correspondingly from 80 mm^2 to 9 mm^2.

The small ligament area leads to extremely low energy values upon fracture of the sub-size specimen. A plane stress state at the notched tip of the sub-size specimen results from the width of only 3 mm, while the conditions of the plane strain state are essentially attained under bending load at the notched tip of the ISO-V specimen. Schematic notch impact energy temperature curves of standard ISO-V and sub-size notch impact specimens are illustrated in Figure A.8. The lower energy values of the sub-size specimen – ligament size – and the shift of the brittle fracture transition temperature ΔT to lower temperatures are characteristic. This predominantly results from the stress state.

An image comparison of all tested specimens from super sub-size notch impact specimens, sub-size notch impact specimens to standard ISO-V specimens is shown in Figure A.9. The super sub-size notch impact specimen is described in 10.3.

9 Results

9.1 Notch impact energy temperature of the tested steels

All notch impact energy temperature curves determined by manufacturer 1 (R) are shown in Figure A.10. They comprise a wide toughness range exhibited by the tested steels. VH (R) is a model material with extremely low toughness for the investigation of the lower limit behaviour. The notch impact energy upper shelf is 60 J and the T_{NDT} is 30° C. The materials TH (K), TH (R) and VH (K) are typical chain steels. The round steel link chains made from these steels fulfil the requirements of ISO 16872 and ISO 16877. The steel T (R) represents a notch impact energy temperature curve in the upper range of grade T with a brittle fracture transition temperature of –30° C. V* (R) is a steel with extreme low-temperature toughness (T_{NDT} = –75° C) and a tensile strength greater than 1 500 MPa.

The upper shelf notch impact energies of the tested steels are between 60 J and 110 J, the brittle fracture transition temperatures range from –75°C to +30° C.

The same characteristics and the same sequence of the steels are also exhibited by the notch impact energy temperature curves determined with sub-size notch impact specimens, see Figure A.11. The brittle fraction transition temperatures have shifted to lower values as is to be expected and the upper shelf impact notch energies attain values from 4 J to 5,5 J here.

9.2 Comparison of the test results and test equipment of manufacturer 1 and manufacturer 2

The two chain steels TH (K) and TH (R) were tested by manufacturer 1 with standard ISO-V specimens. The determined upper shelf impact energy of both steels is equal and the brittle fracture transition temperature of TH (K) is lower by 10 K to 15 K, see Figure A.12. The correspondence of the two steels during testing with sub-size notch impact specimens is excellent, see Figure A.13. The steel TH (K) was tested by manufacturer 2 in the drop weight test and the steel TH (R) by manufacturer 1 with the pendulum impact testing machine.

Furthermore, the sub-size specimens from the steels TH (R) and TH (K) were exchanged and hence a crossover test was conducted on the specimens in the drop weight test and on the pendulum impact testing machine. The results are only scattering to a minor extent, see Figure A.14. The comparability of both test methods is therefore validated. The basis for this is indispensably a specimen preparation corresponding to ISO 14556, the standard-compatible state of the test machines and a competent calibration of the measuring devices as well as a precise setting of the test temperature.

9.3 Conversion of the characteristic values determined at sub-size notch impact specimens

As the energy determined with sub-size notch impact specimens is very low, an attempt was made to convert these values to values ascertained with standard ISO-V specimens by means of calculation.

This is based on the force-displacement diagrams determined in the instrumented notch impact and drop weight test. The notch impact energy temperature curves that were determined with standard ISO-V specimens (CV) and sub-size specimens (SUS) are applied with the same scale for the notch impact energy in Figure A.15. Here the major difference in the notch impact energies is particularly clear owing to the different ligament.

A division of the area below the force-displacement curve in an energy component before reaching the maximum force (Ei) and an energy component after exceeding the maximum force (Ep), see Figure A.15, leads to partial energies, which, multiplied by the terms C1 and C2, see Figure A.17, and then added, yield the converted notch impact energy KV. The conversion of all notch impact energies of the sub-size specimens tested at different temperatures derives the notch impact temperature curve of converted SUS, see Figure A.15. The comparison with the CV curve (ISO-V specimens) explains the temperature shift ΔT to lower temperatures of the curve determined with sub-size specimens. This can be traced back to the plane stress state of the sub-size specimen. The temperature shift was equalised in Figure A.16 by means of a calculated value β, see Figure A.17. This shows that the progression of the CV and the converted SUS curve corresponds in theory.

Three different methods of energy conversion and the calculation of the temperature shift are shown in Figure A.17.

9.4 Validation of the conversion

The conversion, including the temperature shift, of the notch impact energy temperature curves of sub-size specimens to standard ISO-V specimens based on the described formulae, see 9.3, of the steels T (R), TH (R) and VH (R) with different methods is summarized in Figures A.18 to A.22. The materials TH and VH are shown without and with temperature shift, the material T (R) is shown only with shift. The conversion was realized in accordance with the "best fit" method.

The sub-size specimens of the steel T (R) yield an upper shelf energy too low by around 15 J after conversion (method 1). The calculated shift of the transition temperature is too high by around 30 K, see Figure A.18.

The notch impact energy values of the sub-size specimens made from steel TH (R) exhibit a good correspondence with the values of the ISO-V specimens after conversion (method 1), see Figure A.19. After the calculated temperature shift of around 60 K, both notch impact temperature curves correspond sufficiently, see Figure A.20. Comparable results were found by manufacturer 2 with specimens out of TH (K).

Steel VH (R) resulted in an acceptable correspondence of the converted (method 3) notch impact energy values, see Figure A.21. However, the calculated shift of the transition temperature led to a value excessive by 60 K, see Figure A.22.

The results discussed allow the conclusion that the energy conversion and the calculated shift of the transition temperature apply at best to the notch impact energy temperature curves of steels in the medium toughness range (TH). The curves based on the energy conversion and the temperature shift of very tough and extreme brittle steels can only be converted to an insufficient degree.

Correspondingly, the conversion of the notch impact energy values and the temperature shift are not suitable in all cases, according to the applied calculation basis, to compare the notch impact energy values determined with sub-size notch impact specimens with specific requirements on the impact energy values determined with standard ISO-V specimens. If there are no toughness values of standard ISO-V specimens available, then a verification of the by calculation converted SUS toughness values is not possible.

9.5 Scatter of the notch impact energy values determined with sub-size specimens

The definition of requirements in respect to the notch impact energy determined with sub-size notch impact specimens takes into account the scatter behaviour of the characteristic values ascertained with sub-size specimens. Ten specimens of the steels T (R), TH (R) and VH (R) were tested at –20° C and ambient temperature respectively for this. In the case of steel T (R), both temperatures are in the range of the notch impact energy upper shelf. Accordingly the scatter is low at ≤ 0,8 J, see Figure A.23. Due to the brittle fraction transition shifted to higher temperature ranges, the test temperature –20° C for the material TH (R) is only slightly above the temperature with half upper shelf energy, i.e. almost in the middle of the transition range. Here too the scatter is ≤ 0,9 J, see Figure A.24. In the case of the even more restricted low-temperature toughness of the model material VH (R), the test temperature –20° C is in the transition to the lower shelf and 20° C is clearly below the upper shelf, see Figure A.25. The scatter of the test results determined at ambient temperature is around 0,8 J. As is to be expected, the scatter in the lower range of the transition area increases, and reaches 1,2 J among the results for the specimens from material VH (R). As the scatter of the individual values provides important information on the homogeneity of the material from which the specimens were taken, tests for the scatter behaviour were incorporated in the implementation of the toughness test with sub-size specimens and in the requirements in respect to sub-size specimen characteristic values, see Clause 14.

Furthermore, the scatter in the results also provides information on the reproducibility of the specimen preparation, the test and the temperature setting.

9.6 Brittle fracture transition temperature

The safety of a round steel chain against brittle fracture or reduction in the fracture force is a function of the toughness (notch impact energy) and is evaluated according to the brittle fracture transition temperature concept. The relation of lowest permissible application temperature to brittle fracture transition temperature is crucial here, see ISO/TR 23602.

The brittle fracture transition temperature can be determined as T_{NDT}, FATT or ½ (USE). It is essential to know the brittle fracture transition temperature of the various steels and chains.

In ISO/TR 23602, the brittle fracture transition temperature of the chains T (R), TH (R) and VH (R) was determined by means of instrumented notch impact tests. With the help of the crack arrest criterion – force at crack stop (P4) is 4 kN – the nil ductility transition temperature (T_{NDT}) was determined from the force-displacement diagrams of the instrumented notch impact test at standard ISO-V specimens.

Another, less precise method for determining the brittle fraction transition temperature involves ascertaining the fracture appearance transition temperature (FATT); for derivation, see ISO/TR 23602. This temperature can be determined from the morphology of the fracture surface without complex measuring systems. Where the ductile fracture component (non crystalline area of the fracture surface, NCA) is 50 %, the test temperature corresponds to the brittle fracture transition temperature. The comparison between T_{NDT} and FATT for standard ISO-V specimens results in a good correlation for the chains from the steels T (R), TH (R), VH (R) and V* (R) over the temperature range of 140 K, see Figure A.26.

A further criterion allows the brittle fraction transition temperature to also be determined without instrumented tests. The temperature at which half of the notch impact upper shelf energy (½ USE) is present is incorporated here. The correlation $T_{½\ (USE)}$ with the T_{NDT} (determined at standard ISO-V specimens) also results in very good values for standard specimens, see Figure A.27. For standard specimens, the correlation between the temperatures $T_{½\ (USE)}$ and FATT is also very good, see Figure A.28.

The two criteria verified at standard specimens without instrumented notch impact test $T_{½\ (USE)}$ and FATT were also examined at sub-size notch impact specimens. The FATT of sub-size specimens of the chains T (R), TH (K), TH (R), VH (K), VH (R) and V* (R) yielded an excellent correlation to the $T_{½\ (USE)}$ values of these chains, see Figure A.29. These characteristic values are therefore applicable for sub-size notch impact specimens too.

A comparison of the $T_{½\ (USE)}$ values of standard and sub-size specimens results in an average temperature shift of 35 K, see Figure A.30.

Based on standard specimens, it was shown that the criteria FATT and $T_{½\ (USE)}$ correlate well with the T_{NDT} (reference brittle fracture transition temperature) determined in instrumented notch impact tests. This consequently established the basis for the transfer of FATT and $T_{½\ (USE)}$. A good correlation to the values of the standard specimens also resulted here. A shift by 35 K to lower temperatures of the brittle fracture transition temperature determined at standard specimens is necessary to be respected by the use of sub-size specimens.

10 Specimen extension

10.1 Laser welding

A specimen piece can be taken from the unwelded leg in the case of chain links with dimensions that do not enable the extraction of sub-size notch impact specimens. Figure A.31a) shows an example of this for a round steel link chain 13 x 39 and a 12 mm long section. The specimen piece and two 8 mm long welded-on pieces from steel with equal strength are machined to the cross-section dimensions 3 x 4,5 mm, see Figure A.31b). The pieces are clamped in the longitudinal direction and welded using laser technology. This is followed by machining of the specimen width to 4,0 mm, see Figure A.31c). The machining of the width and subsequent notching in accordance with ISO 14556 was performed on the bending tension side. Finally, the specimen length is machined at middle notch location to 27 mm.

To determine the effect of heat input resulting from laser welding, a hardness profile was determined in the longitudinal direction of the 12 mm long specimen piece from the chain where the two end pieces had been welded on, see Figure A.32. The heat affected zones of the two laser welds are very narrow with around 2,5 mm width, as is to be expected. The remaining length of the specimen piece extracted out of the chain of around 7 mm does not reveal any hardness effects, see Figure A.32. A minimum length of 9 mm results from the two-sided heat affected zones of around 2,5 mm for the specimen piece. This therefore ensures with precise positioning of the notch that the fracture starting from the notch tip progresses in a sufficiently wide zone with unaffected microstructure of the chain.

Sub-size notch impact specimens in the full and welded state from material V* (R) result in excellent corresponding notch impact energy temperature curves, see Figure A.33.

10.2 Friction welding

The application of friction welding for the two-sided extension of the specimens was examined by manufacturer K. However, the heat effects are extremely high in this process. The hardness profile over the length resulted in an extreme drop in the notch area. Consequently, a pronounced, impermissibly large change in the notch impact energy temperature curve was also apparent.

10.3 Extended super sub-size notch impact specimens

The toughness of chains from whose leg a 9 mm long specimen piece cannot be extracted is determined with super sub-size notch impact specimens. The dimensions of these specimens are 1,5 x 1,5 x 27 mm at a notch depth of 0,5 mm. The length of 27 mm is a consequence of the geometrical design of the test equipment. Owing to this length, the specimens are always extended with welded-on pieces. To achieve as low a heat input as possible, weld tests were conducted with a micro-laser and a pulsed energy of 6,4 J, see Figure A.34. The specimens are no longer machined after the welding. Hardness tests revealed that the extremely low applied welding energy did not lead to any change in the hardness. This also applies for the area directly next to the weld seams, see Figure A.34a).

The extremely small ligament area of 1,5 mm^2 only yields notch impact energy values < 1 J even in the upper shelf, see Figure A.35. A differentiation of these low energy values with incorporation of the test temperature is not possible owing to the flat profile of the energy temperature curve, see Figure A.35. The non-crystalline area of the fracture surfaces of specimens from TH (R) tested at various temperatures was therefore determined in the scanning electron microscope (SEM) evaluating the different NCA-values which are included in Figure A.35. An example of the analysis in the SEM with an NCA of 85 % is shown in Figure A.36. This involves the fracture surface of a specimen from material TH (R) tested at −50°C. The requirement derived from this result is NCA ≥ 80 %, see Clause 14. At a $T_{½ \text{ (USE)}}$ of −35° C of the sub-size specimens from steel TH (R), the fracture surface of the super sub-size specimen attains 50 % NCA at around 50 K lower test temperature, see Figure A.35. A shift of the brittle fracture transition temperature between sub-size and super sub-size notch impact specimens of around 50 K therefore becomes apparent.

11 Derivation of the toughness criteria for characteristic values determined with sub-size notch impact specimens

As a calculated conversion of the characteristic values of standard ISO-V specimens determined with sub-size specimens could not be verified in all tests, see 9.3 and 9.4, the requirements for sub-size specimens are now derived from the notch impact energy temperature curve of standard ISO-V specimens. ISO/TR 23602 requires 30 J for grade TH chains and 45 J for grade VH chains (load bearing concept), in order to prevent low load brittle fractures at the lowest permissible application temperature. In the ISO standards 16872 and 16877, a design temperature (T_D) of 0° C is required for the chain grades TH and VH. The toughness validation is realized at this temperature (30 J for TH and 45 J for VH). Based on the relation of the chain fracture forces at T_{NDT} and T_{NDT} – 10 K, the lowest permissible application temperature could be defined for both chain grades at −10° C.

Based on these requirements, the temperature (T_D) was now determined for all examined round steel link chains, at which a intersection with the respective notch impact energy temperature curve of ISO-V specimens yields 30 J or 45 J. If the notch impact energy temperature curves of standard ISO-V specimens and sub-size specimens are entered in a diagram with scales of the Y-axes adapted to the ligament areas of the specimens, the corresponding toughness value (E_D) of the sub-size specimen can be determined at T_D without temperature shift. These correlations were realized for all examined chains in Figures A.37 to A.42.

In the case of steel T (R), not 30 J but instead 40 J was incorporated as a requirement for the notch impact energy, as intended for grade TH (30 J). The notch impact temperature curve has attained the lower shelf in this low-temperature tough steel at a test temperature of −60° C. At lower test temperatures, the notch impact energy values would only change slightly and not fall below 30 J, see Figure A.37. This notch impact energy of 40 J (ISO specimen) at −60° C is in context with 3,7 J of the sub-size specimen. The same derivation led to the results for the other chains shown in Table 1.

Table 1

Round steel link chains	E_D		T_D	Figure
TH (R):	4,2 J	/	0° C,	Figure A.38
TH (K):	3,8 J	/	−10° C,	Figure A.39
VH (R):	4,0 J	/	+60° C,	Figure A.40
VH (K):	3,7 J	/	−10° C,	Figure A.41
V* (R):	3,8 J	/	−75° C,	Figure A.42

At this point, it should be pointed out again that VH (R) involves a chain made from low-toughness model material.

The temperature at which the 30 J or 45 J line intersects the notch impact energy temperature curve of the standard ISO-V specimens is the design temperature T_D. The characteristic value of the sub-size specimen resulting at T_D is the design notch impact energy E_D.

The value of the super sub-size specimen determined at −50°C for the steel TH (R) was entered with 0,55 J and 85 % NCA, as shown in Figure A.43. This value shifted by – 50 K to the T_D will be discussed later under the requirements in Clause 14.

12 Characteristic values of the round steel link chains from manufacturer M3 and M4

12.1 Manufacturer M3

Manufacturer M3 had extracted full size and sub-size specimens out of 16 mm chains of grade 8 and grade 10 and sub-size specimens out of a 8 mm chain of grade 8. The intersection of the notch impact energy temperature curve of the chain of grade 8 with a diameter of 16 mm with the 30 J line was found at −70° C for full size ISO-V specimens, see Figure A.44. This very low design temperature T_D resulted in a mean value of the design energy E_D of 4,1 J for sub-size specimens. At a design temperature of −40° C the E_D of the sub-size specimens of the 8 mm chain of grade 8 was determined to a mean value of > 3,5 J, see Figure A.45. The intersection of the notch impact energy temperature curve of full size ISO-V specimens out of the 16 mm chain of grade 10 with the 45 J line results in the T_D of −48° C. At that temperature the mean value of E_D determined from the energy-temperature curve of the sub-size specimens was 4,2 J, see Figure A.46.

These results are summarized in Table 2.

Table 2

Steel	E_D	T_D	Figure
M3 Ø 16, NiCrMo-alloyed, Grade 8	4,1 J	−70° C	Figure A.44
M3 Ø 8, NiCrMo-alloyed, Grade 8	3,5 J	−40° C	Figure A.45
M3 Ø 16, NiCrMo-alloyed, Grade 10	4,2 J	−48° C	Figure A.46

12.2 Manufacturer M4

The characteristic values of the specimens from the MnB-steel of the chains in grade 8 exhibits an exceptional scatter in the brittle fracture transition range for both standard and sub-size specimens, see the marked areas in Figure A.47, which also include the incipient upper shelf. The average E_D of the sub-size specimens of 5,0 J results in a T_D of −26° C. At −30° C the scatter of five individual values is 1,4 J. ½ (USE) is attained at −43° C (mean value of the two limit impact notch energy temperature curves). The scatter is 3,4 J at this temperature for five tested specimens, see Figure A.47. The characteristic values of the sub-size specimens from the other two chains do not reveal any conspicuous features in Figures A.48 and A.49. In summary, the results for chains of manufacturer M4 are shown in Table 3.

Table 3

Steel	E_D	T_D	Figure
M4, MnB-steel, Grade 8	5,0 J	−26° C	Figure A.47
M4, NiCrMo-alloyed, Grade 8	3,6 J	−50° C	Figure A.48
M4, NiCrMo-alloyed, Grade 10	4,0 J	−30° C	Figure A.49

13 Characteristic values of the sub-size notch impact specimens, temperature and notch impact energy

In order to derive the requirements to the characteristic values of sub-size notch impact specimens, the E_D derived in the diagrams, see Figures A.37 to A.42 and Figures A.44 to A.49, was applied over the T_D determined for the respective chain. This is shown in Figure A.50 for the chains T (R), TH (R) and TH (K). Furthermore, the notch impact energy at the brittle fracture transition temperature $T_{½\,(USE)}$ is also required for the safety consideration. These values were also entered accordingly in the diagram in Figure A.50. The notch impact energy values at $T_{½\,(USE)}$ were, for the sake of better clarity, placed in the area of the T_D. The arrows at the symbols indicate that the $T_{½\,(USE)}$ values are at lower temperatures.

It is clear that the notch impact energy values of the chains only differ slightly. However, they are shifted to lower temperatures for the chain T (R) with low T_{NDT} by around 50 K, see Figure A.50.

Corresponding to this procedure, Figure A.51 summarizes the characteristic values of the chains of grade 8 and Figure A.52 those of grade 10. In Figure A.52, the extreme tough chain V* (R) with T_D = –75° C and the low-toughness model material VH (R) with T_D = +60° C form the limits. Also the individual notch impact energy values differ only insignificantly in their height.

Owing to these minor differences, also with different grades, there was no need to define different requirements for grades 8 and 10. All examined materials are therefore entered in Figure A.53. The scatter ranges for the notch impact energy values E_D and ½ (USE) are entered; they are significantly separate from one another.

14 Requirements to the characteristic toughness values of the sub-size and the super sub-size notch impact specimens

In this document, the T_D for the individual round steel link chains with the requirements in ISO/TR 23602 for the notch impact energy (30 J for grade 8, 45 J for grade 10) was determined from the relevant notch impact energy temperature curve (standard ISO-V specimens).

However, T_D can also be specified in standards, see ISO 3076, ISO 16872 and ISO 16877. The lower limit for E_D of the chains examined with sub-size notch impact specimens is 3,7 J. As the corresponding chains did not reveal any conspicuous features in chain tensile tests and during testing with standard ISO-V specimens, the requirement for E_D was defined with

$$E_D \geq 3{,}5\ \text{J}$$

at the test temperature T_D.

To ensure a sufficient distance of the T_D to the $T_{½\,(USE)}$ – brittle fracture safety – it is required that E_D be significantly above ½ (USE). This energy interval ensures also an adequate temperature interval.

The requirement

$$E_D \geq ½\ (\text{USE}) + 1\ \text{J}$$

is fulfilled by all chains in Figure A.53.

In 9.5, the scatter of the characteristic values determined with sub-size notch impact tests was discussed and attention was drawn to their significance. The requirement in respect to the scatter range (R) of 10 individual values of the notch impact energy determined at the test temperature T_D is

$$R \leq 1{,}5\ \text{J}$$

In the case of sub-size and super sub-size notch impact tests with specimens extended by welding, it is important that the effects of heat input due to welding are excluded in a range of 2 mm left and right of the notch section. Super sub-size notch impact specimens were tested at a temperature T_D – 50 K. The fracture surface is required to exhibit a ductile fracture component ≥ 80 % during analysis in the SEM.

$$T_D - 50\ \text{K},\ \text{NCA} \geq 80\ \%$$

These requirements are summarized as follows:

T_D	a) determined on the basis of the C_V-toughness-temperature curve (C_V-specimens) and the required C_V-toughness value given in the appropriate standard. b) T_D is required in the standard.
E_D	≥ 3,5 J (sub-size specimens extracted out of the specific chain, tested at T_D).
E_D	≥ ½ (USE) + 1 J This requirement ensures that the distance of E_D to the brittle-tough-transition energy and temperature is sufficient.
E_D	is tested with 10 specimens, E_D is the mean value and the range of scattering is ≤ 1,5 J.

Additionally,

a) welding on of central pieces 3 × 4 x 12 mm on both sides to 3 × 4 x 27 mm without heat affect to the area of the notch is approved, and

b) SSUS out of a material with K_V = 30 J at 0 °C and E_D = 3,5 J at –20° C fails 85 % tough in the test at –50° C, the requirement is NCA ≥ 80 %.

15 Status of international standardization

The requirements derived in this document in respect to the notch impact energy of sub-size notch impact specimens and super sub-size notch impact specimens have been incorporated in ISO 3076:2012, ISO 16872:2015 and ISO 16877:2015.

Annex A
(informative)

Figures

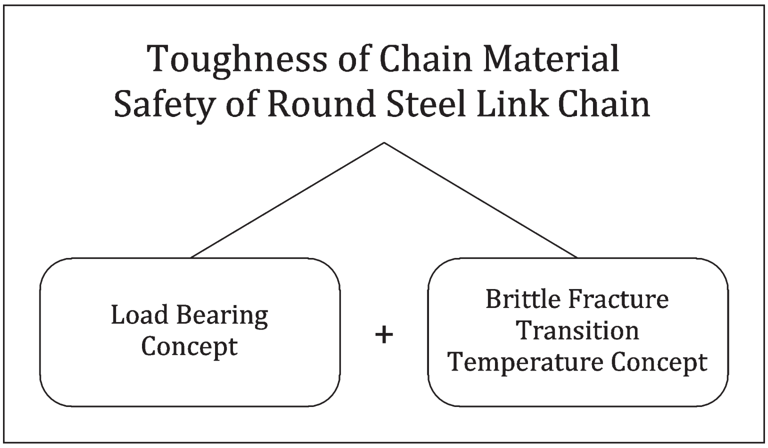


Figure A.1

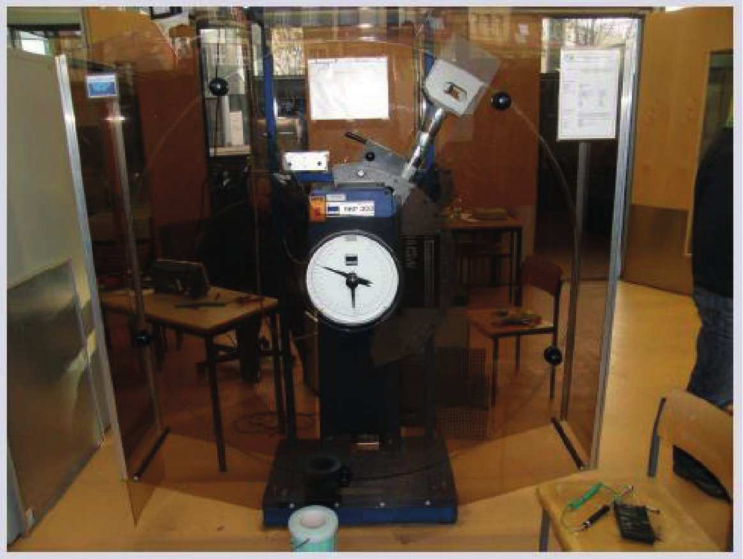


Figure A.2 — Testing equipment for ISO-V specimens — Instrumented pendulum — 300 J testing machine

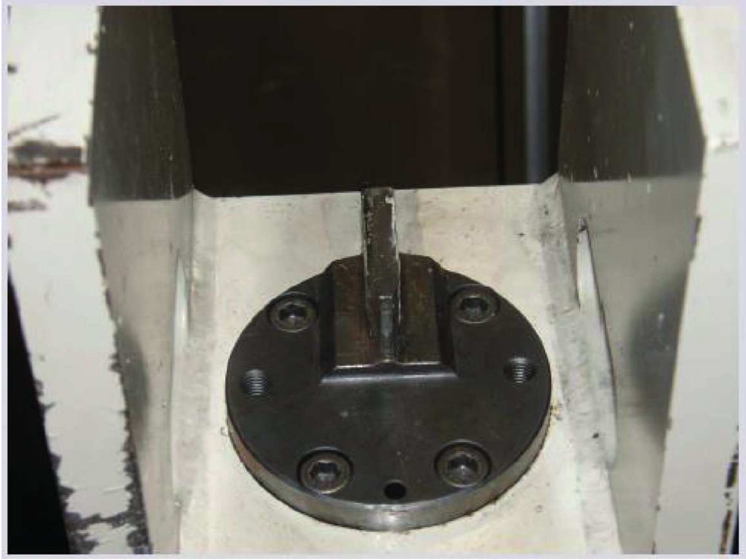
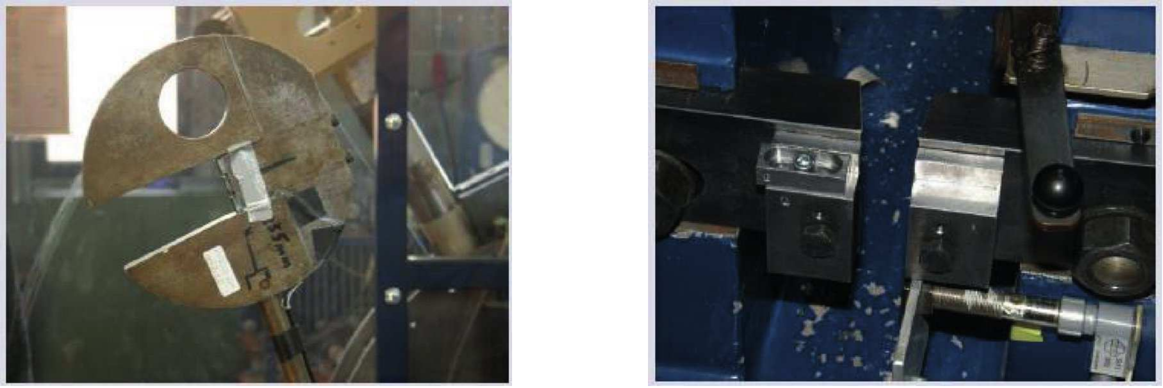


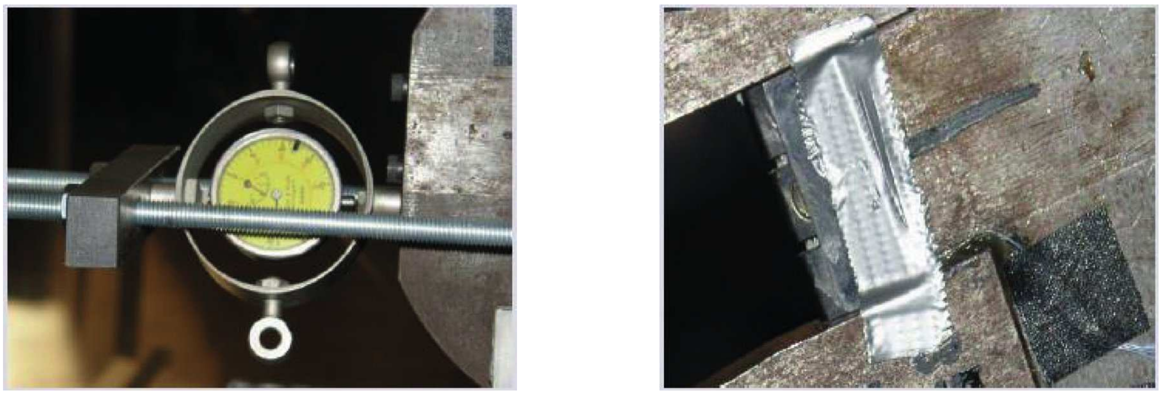
Figure A.3 — Testing equipment for ISO-V specimens — Instrumented peen

a) 15 J testing machine



b) Pendulum

c) Bearing for specimens



d) Calibration of the amplifier

e) Instrumented peen

Figure A.4 — Testing equipment for sub-size specimens — Instrumented pendulum

Test equipment		Instrumented compact drop weight impact test equipment
Maximum machine energy	J	25
Mass of drop weight	kg	0,73 to approximately 1,34
Falling height of drop weight	m	0,75
Impact speed	m/s	3,58 to approximately 3,65
Radius at tip of drop weight	mm	R1
Distance between anvils	mm	15
Low-pass filter	kHz	100

Key

1 strain gauge in this part of the drop weight

Figure A.5 — Instrumented compact drop weight impact test equipment — Manufacturer 2

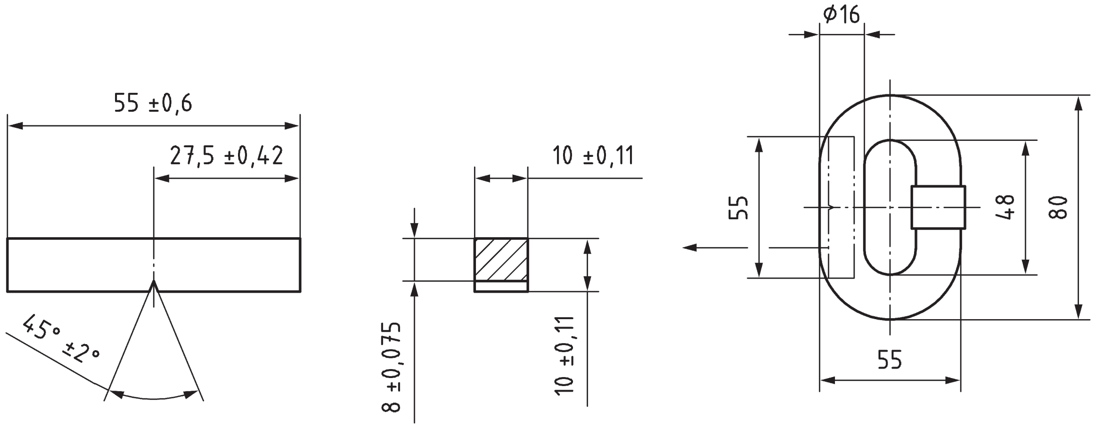


Figure A.6 — Notch impact specimens and their extraction — ISO-V-specimen in accordance with ISO 148-1

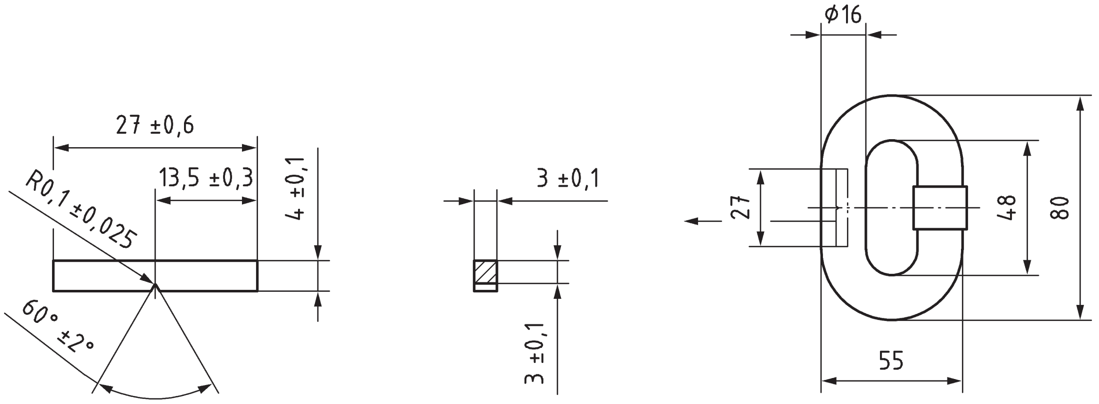


Figure A.7 — Notch impact specimens and their extraction — Sub-size specimen in accordance with ISO 14556

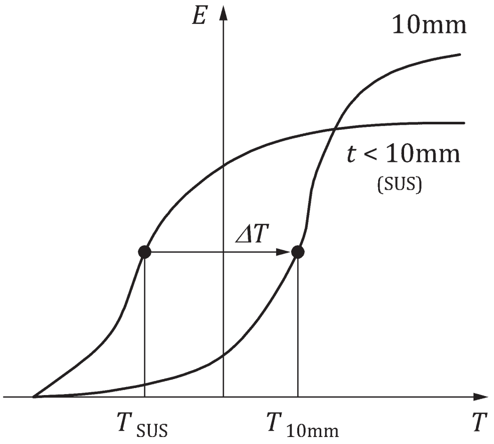
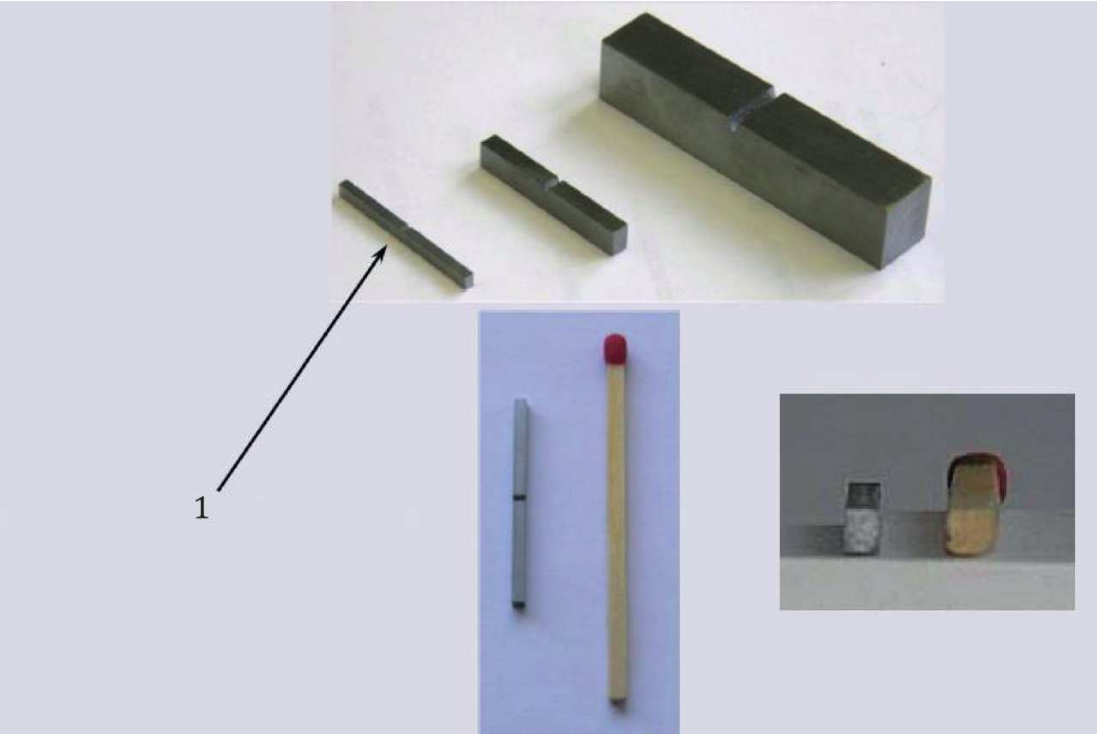


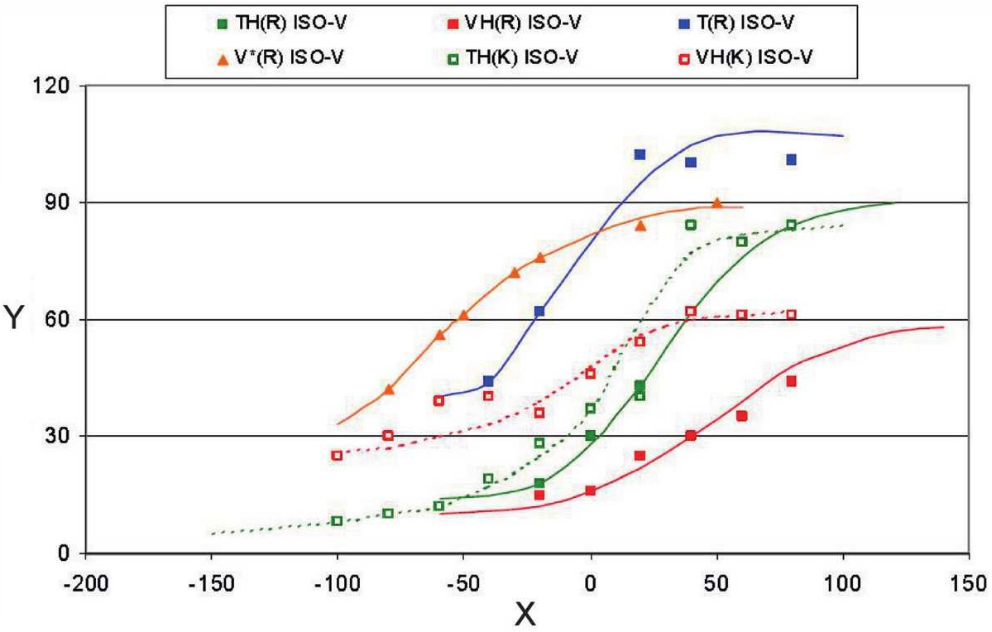
Figure A.8 — Notch impact specimens and their extraction — Schematic E-T-curves



Key

1 super sub-size specimen

Figure A.9 — Geometry of the specimens

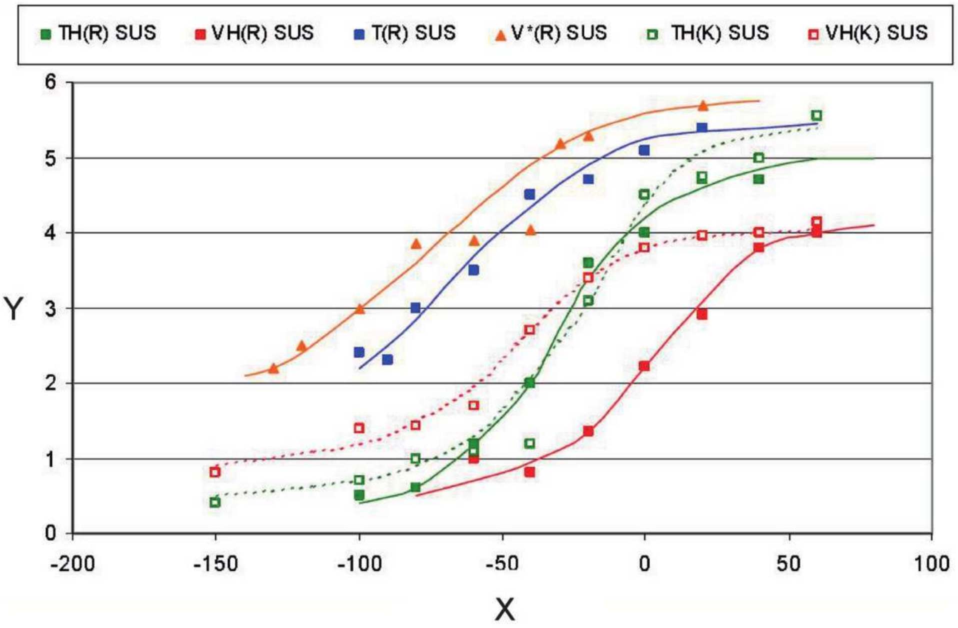


Key

X temperature in °C

Y impact energy in J, ISO-V

Figure A.10 — Comparison of ISO-V-T curves — Specimens tested by R

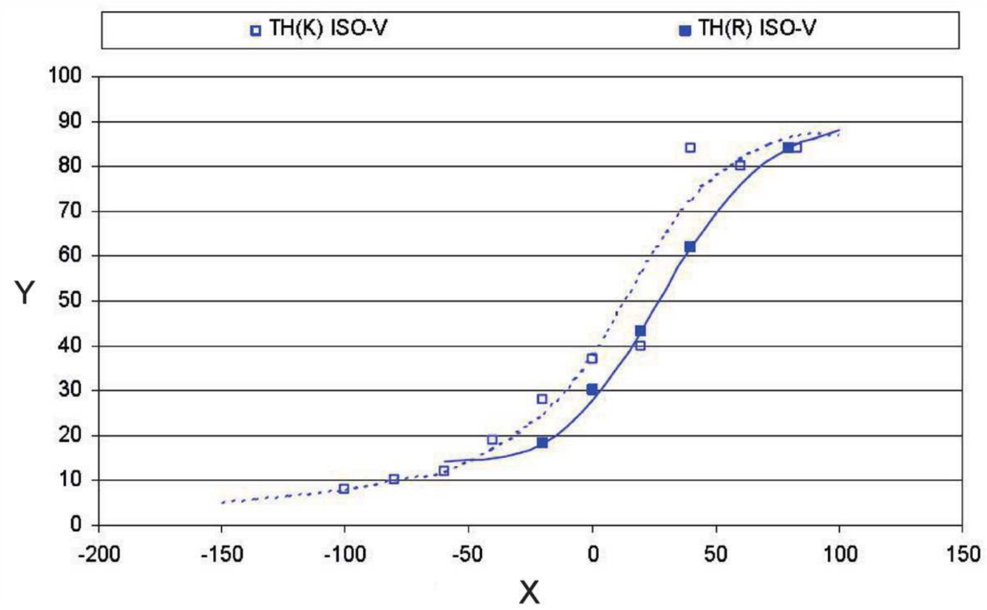


Key

X temperature in °C

Y impact energy in J, SUS

Figure A.11 — Comparison of SUS-T curves — Specimens tested by R

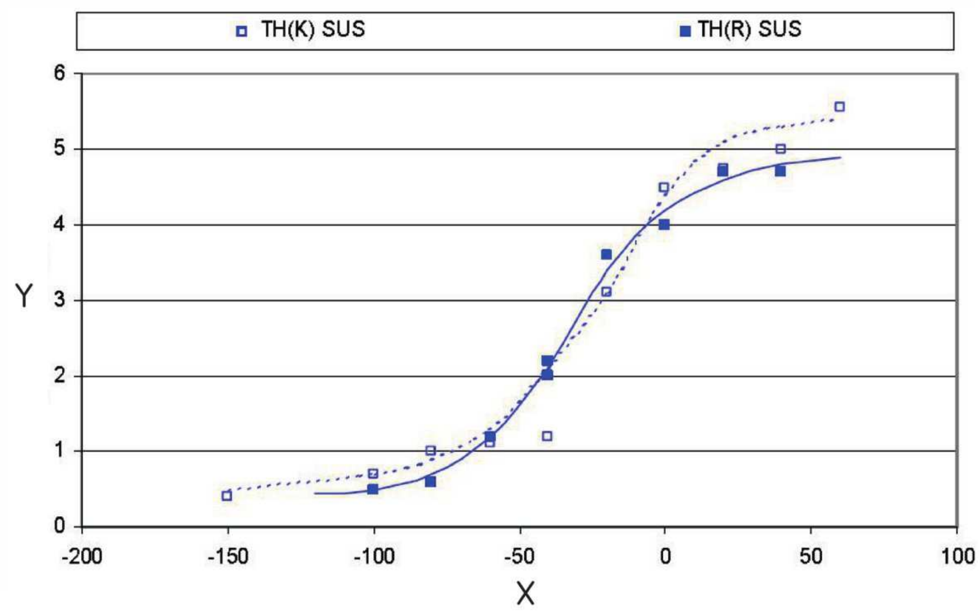


Key

X temperature in °C

Y impact energy in J, ISO-V

Figure A.12 — Comparison ISO-V; TH (R) to TH (K)

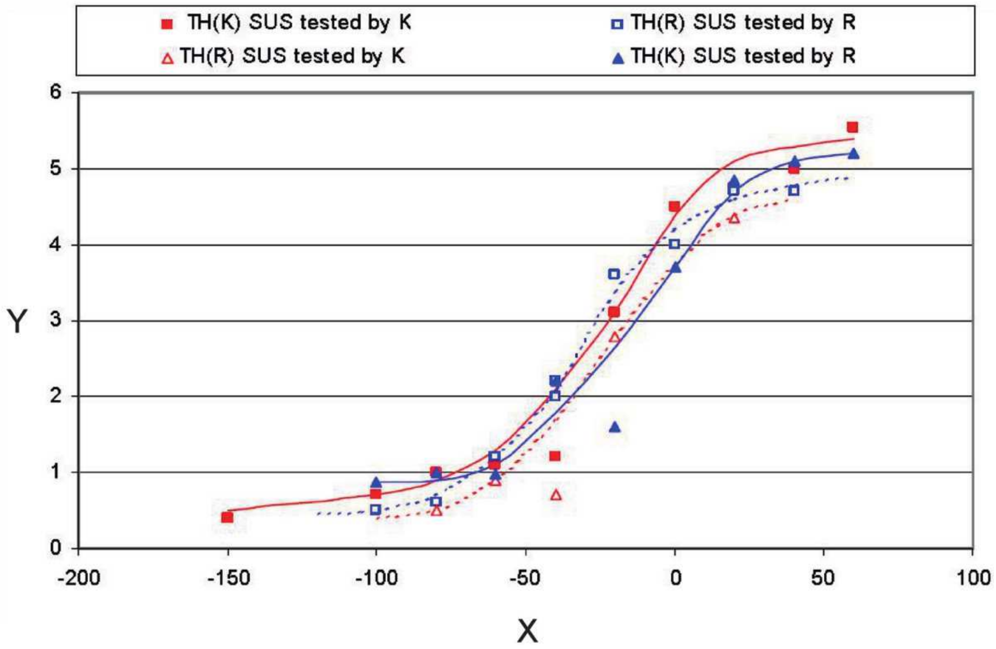


Key

X temperature in °C

Y impact energy in J, SUS

Figure A.13 — Comparison SUS - TH (R) to TH (K)

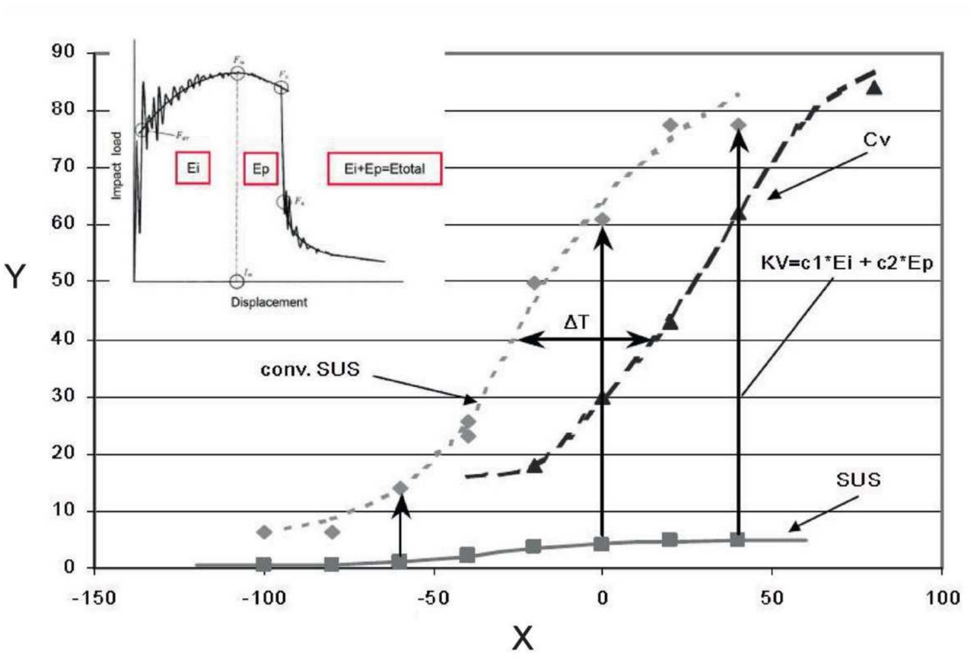


Key

X temperature in °C

Y impact energy in J, SUS

Figure A.14 — Comparison TH SUS — Tested by K and R

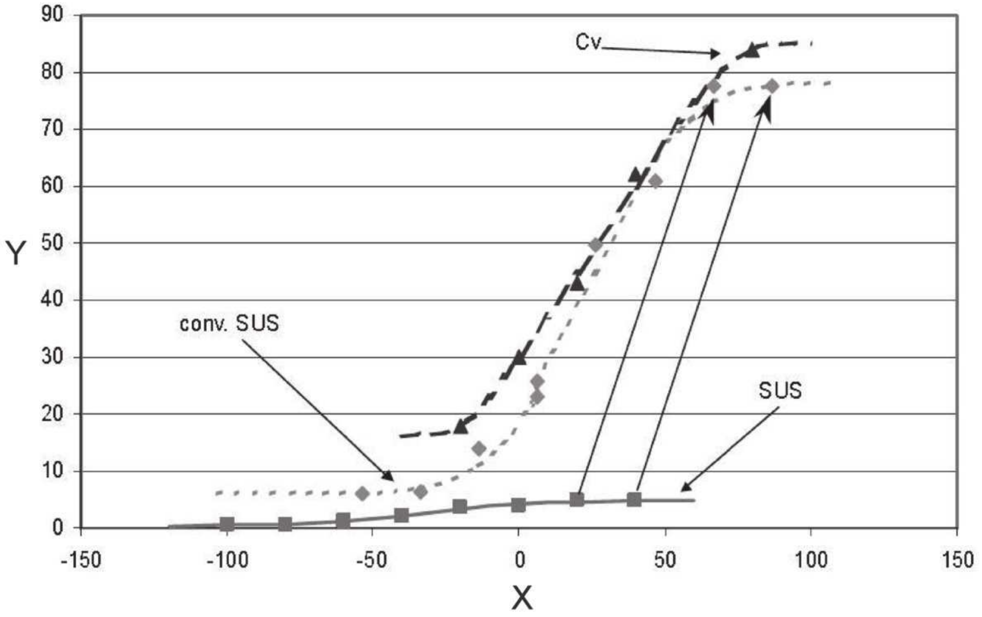


Key

X temperature in °C

Y impact energy in J

Figure A.15 — Schematic diagram of the conversion



Key

X temperature in °C

Y impact energy in J

Figure A.16 — Conversion — Energy with temperature shift method 1

$$E_{\text{full}} = \overset{\text{C1}}{\boxed{\frac{(Bb)_{\text{full}}}{(Bb)_{\text{sub}}}}} \cdot E_{\text{i, sub}} + \overset{\text{C2}}{\boxed{\frac{(Bb)^{2}_{\text{full}}}{(Bb)^{2}_{\text{sub}}}}} \cdot E_{\text{p,sub}} \qquad (1)$$

method 2

$$E_{\text{full}} = \boxed{\frac{(Bb)_{\text{full}}}{(Bb)_{\text{sub}}}} \cdot E_{\text{i, sub}} + \boxed{\frac{(Bb)^{3/2}_{\text{full}}}{(Bb)^{3/2}_{\text{sub}}}} \cdot E_{\text{p,sub}} \qquad (2)$$

method 3

$$E_{\text{full}} = \boxed{\frac{(Bb)_{\text{full}}}{(Bb)_{\text{sub}}}} \cdot E_{\text{i, sub}} + \boxed{\frac{(Bb)^{4/3}_{\text{full}}}{(Bb)^{4/3}_{\text{sub}}}} \cdot E_{\text{p,sub}} \qquad (3)$$

NOTE 1: The impact value is converted from the sub-size specimen to the standard specimen by using either Formula (1), (2) or (3). B indicates the height of specimen, and b indicates the ligament size.

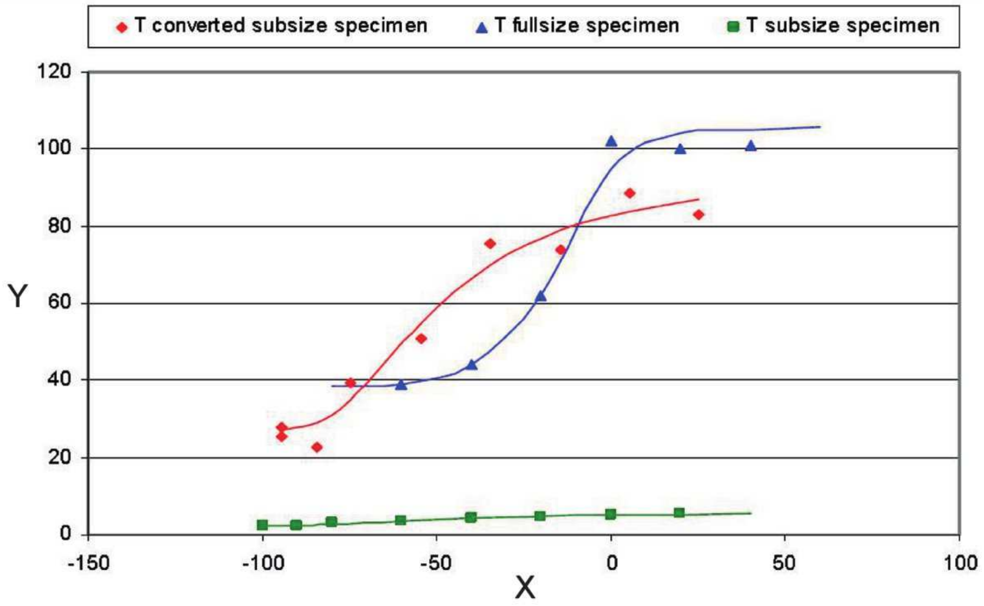
NOTE 2: The test temperature (= T_{21J}, T_{27J}, T_{30J}, T_{42J}, T_{45J}, $T_{1/2USE}$) is obtained for six different absorbed energy of 21J, 27J, 30J, 42J, 45J and the half of Upper Shelf Energy respectively from the converted sub-size specimen and standard specimen. As the result, Formula (4) is obtained by linear regression analysis.

$$DBTT_{\text{full-size}} = \alpha \times DBTT_{\text{subsize}} + \beta \left(^{\circ}\text{C} \right) \qquad (4)$$

β, the second term of the right side, in Formula (4) indicates the value that the energy transition temperature of sub-size specimen has been corrected from that of the standard specimen.

Then, shift the transition curve of the converted sub-size specimen in Formula (1), (2) or (3) for the correction made in respective temperatures (=β) to make the transition curve of the standard specimen.

Figure A.17 — Conversion from the sub-size specimen to the standard specimen (Ref. Manufacturer 2)

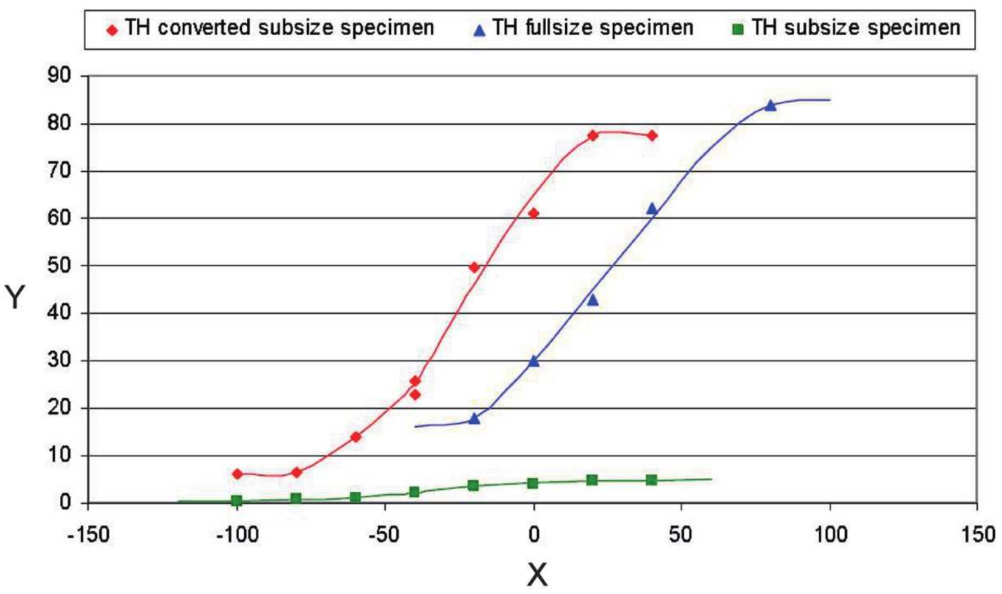


Key

X temperature in °C

Y impact energy in J

Figure A.18 — Energy conversion — T material with temperature shift (method 1)

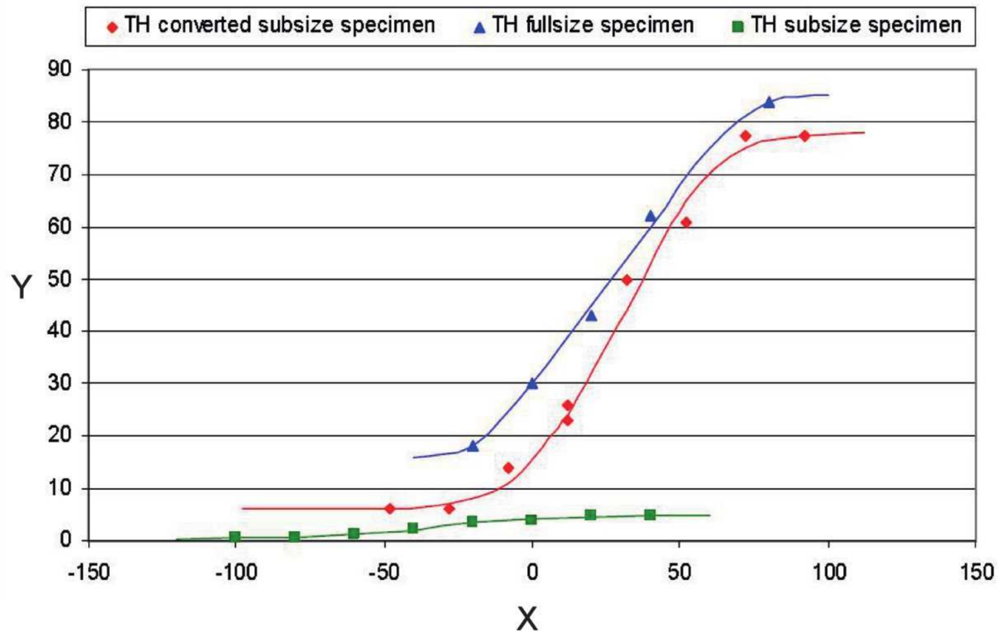


Key

X temperature in °C

Y impact energy in J

Figure A.19 — Energy conversion — TH material (method 1)

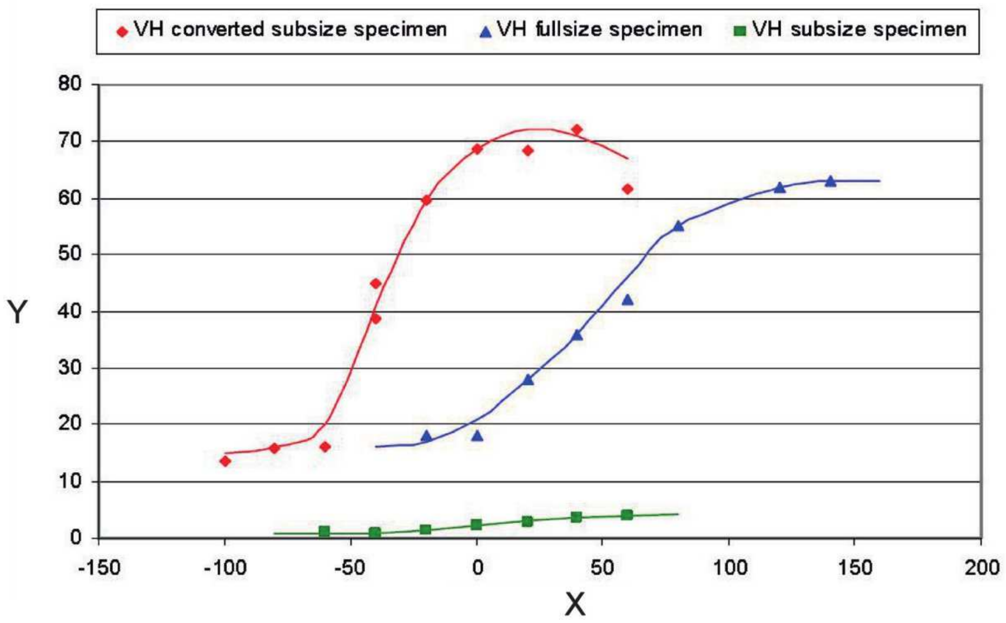


Key

X temperature in °C

Y impact energy in J

Figure A.20 — Energy conversion — TH material with temperature shift (method 1)

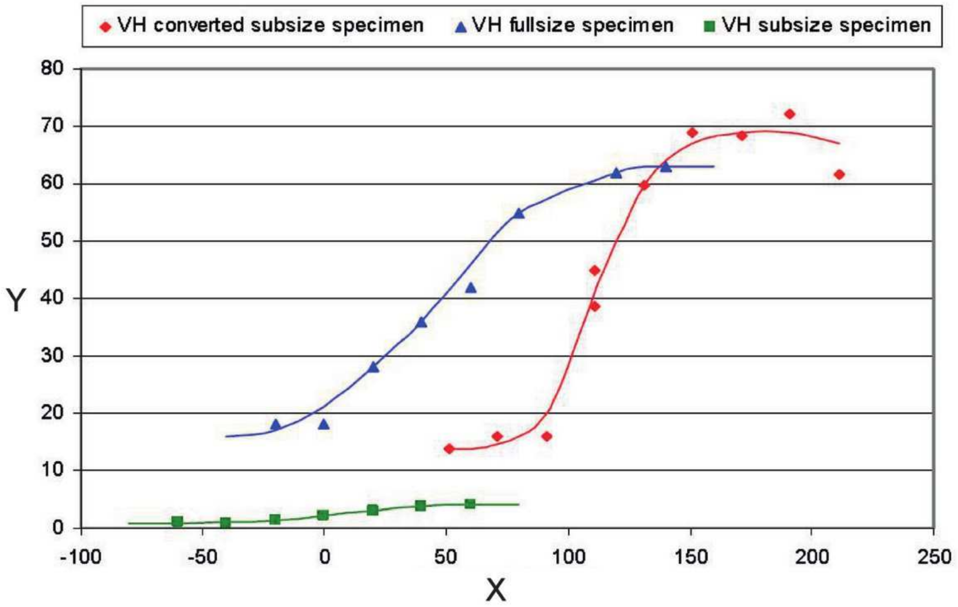


Key

X temperature in °C

Y impact energy in J

Figure A.21 — Energy conversion — VH material (method 3)

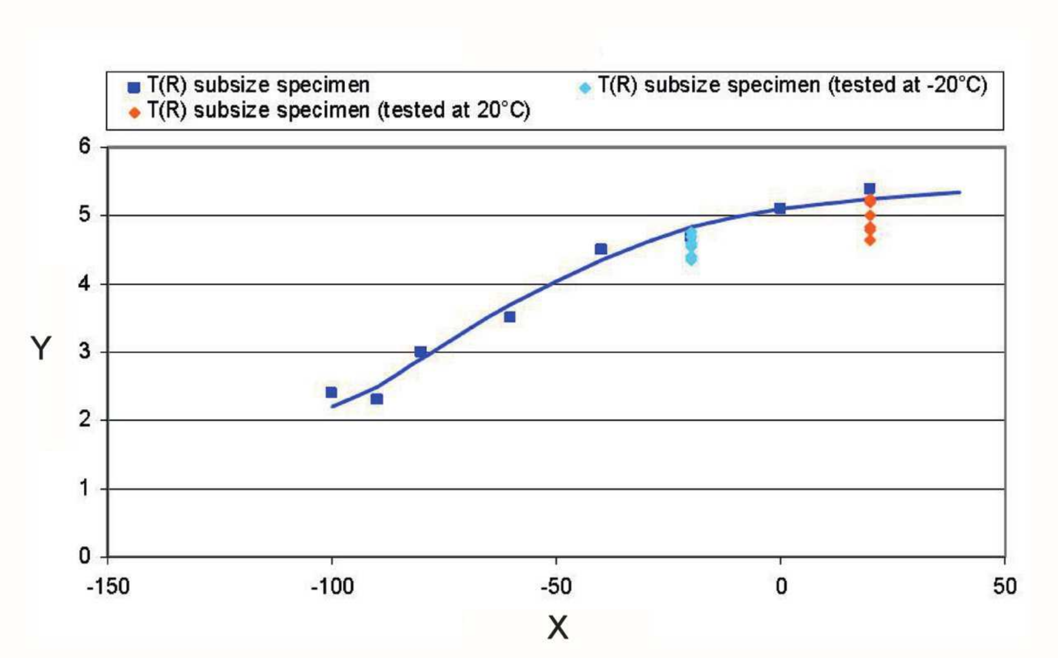


Key

X temperature in °C

Y impact energy in J

Figure A.22 — Energy conversion — VH material with temperature shift (method 3)

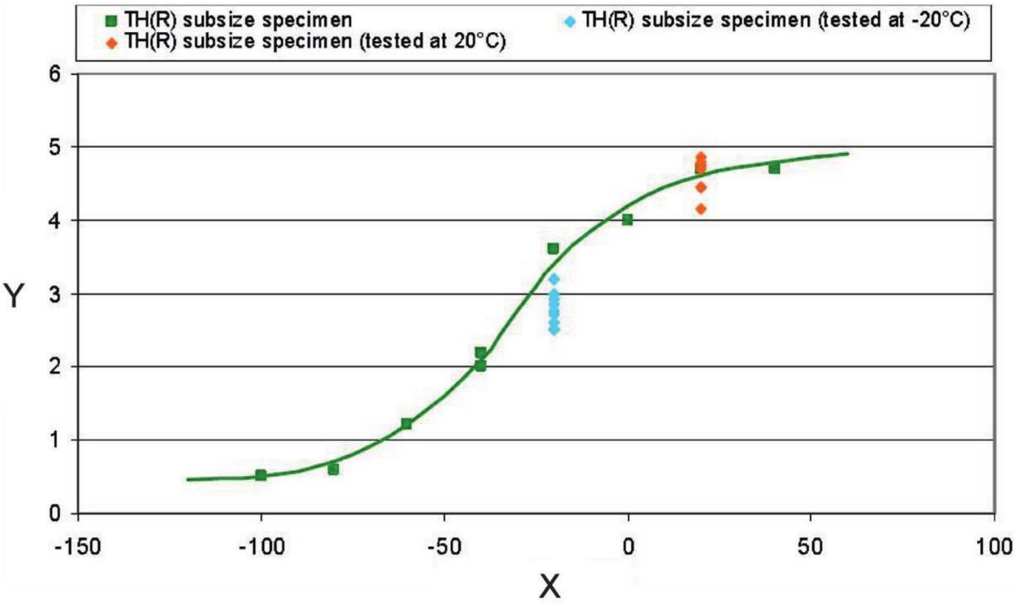


Key

X temperature in °C

Y impact energy in J

Figure A.23 — T (R) material

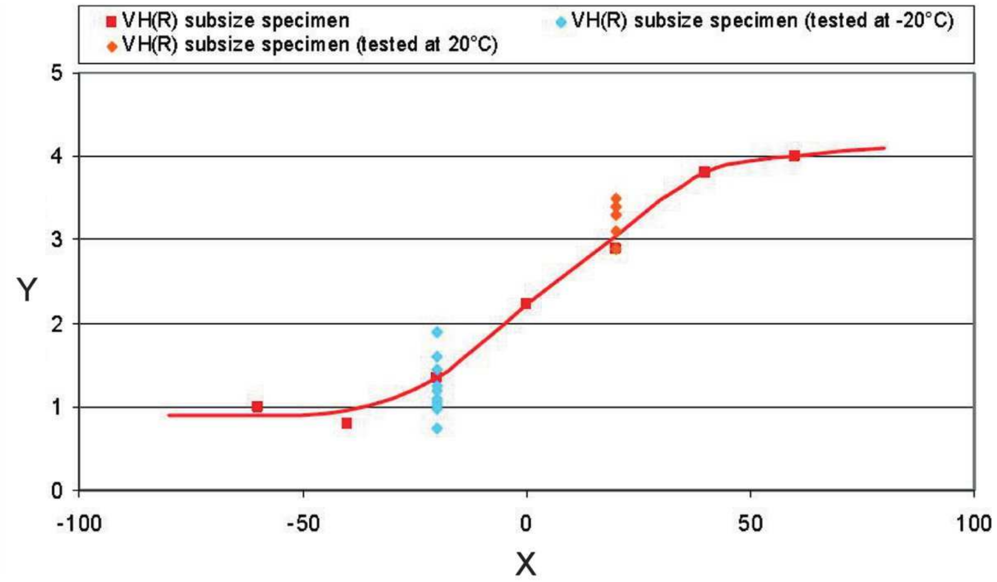


Key

X temperature in °C

Y impact energy in J

Figure A.24 — TH (R) material

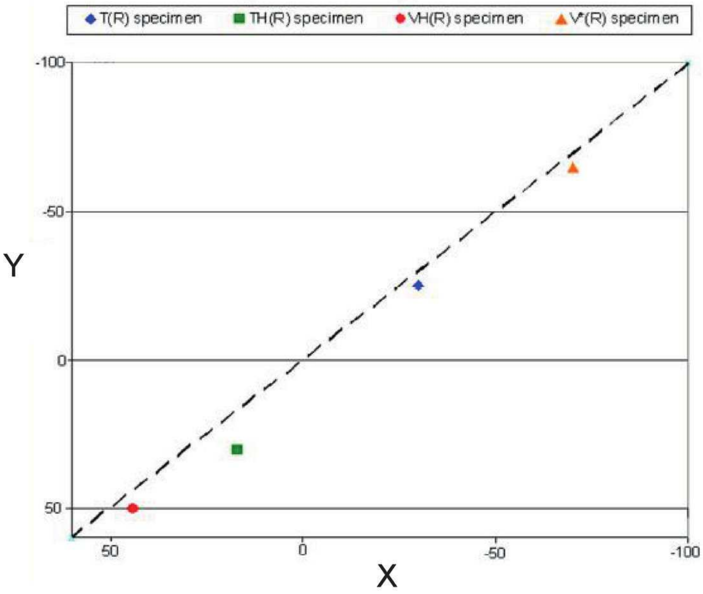


Key

X temperature in °C

Y impact energy in J

Figure A.25 — VH (R) material

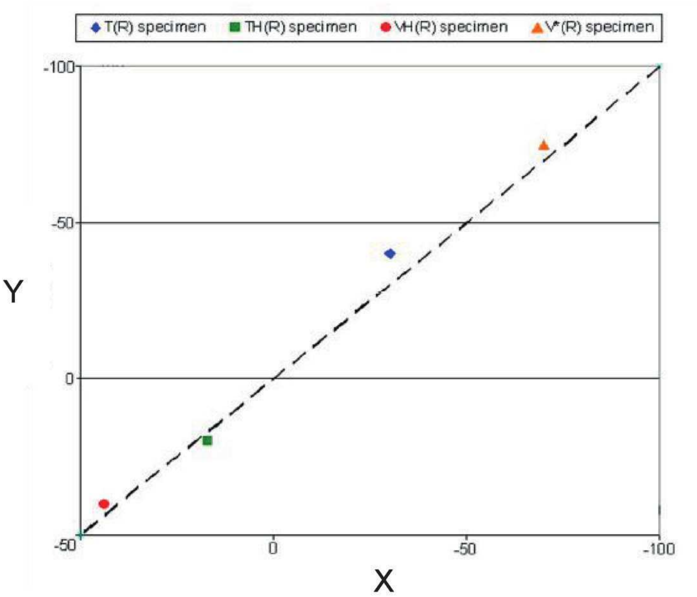


Key

X T_{NDT} in °C

Y FATT in °C

Figure A.26 — Ductile–Brittle–Temperature–Transition — Comparison of FATT to T_{NDT} of fullsize specimens (ISO-V)

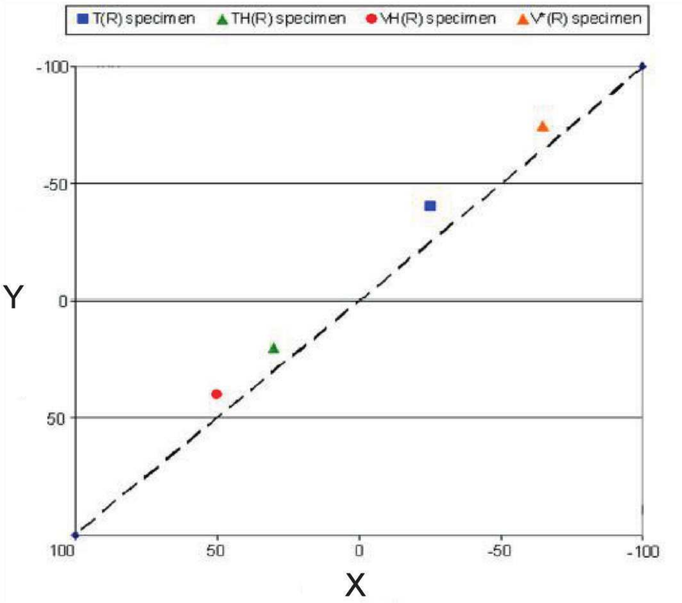


Key

X T_{NDT} in °C

Y $T_{½ (USE)}$ in °C

Figure A.27 — Ductile–Brittle–Temperature–Transition — Comparison of $T_{½ (USE)}$ to T_{NDT} of fullsize specimens (ISO-V)

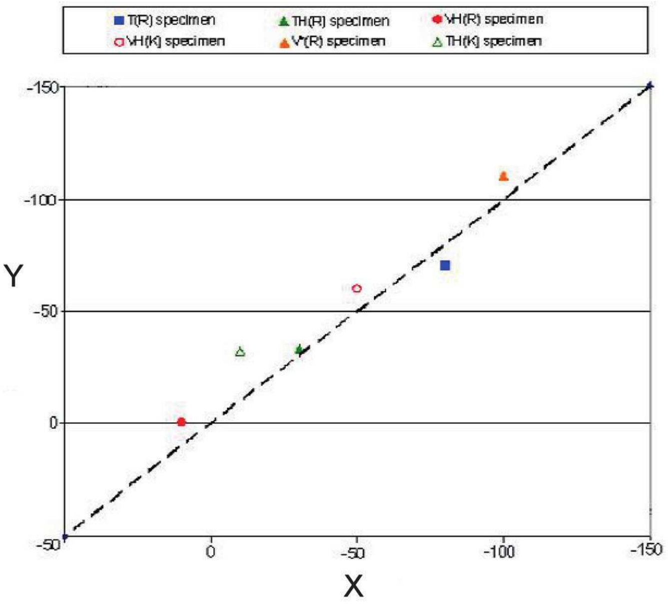


Key

X FATT in °C

Y $T_{½ (USE)}$ in °C, ISO-V

Figure A.28 — Ductile–Brittle–Temperature–Transition — Comparison of $T_{½ (USE)}$ to FATT of full-size specimens (ISO-V)

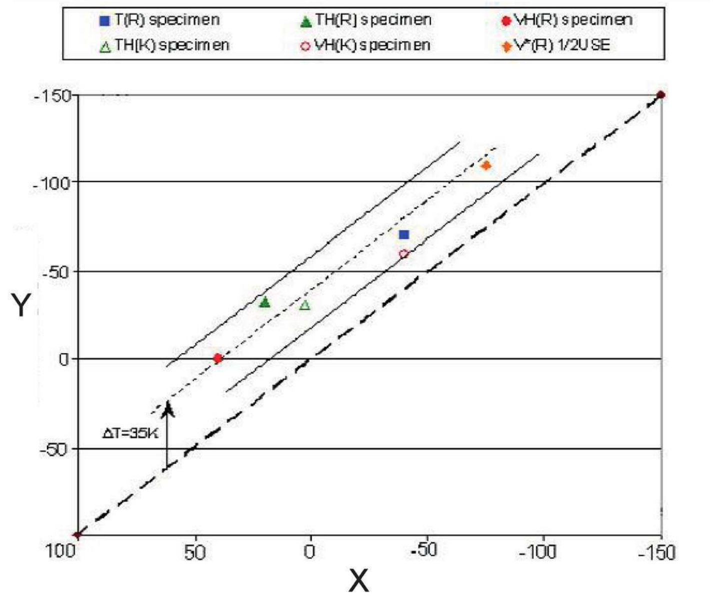


Key

X FATT in °C

Y $T_{½\ (USE)}$ in°C, SUS

Figure A.29 — Ductile–Brittle–Temperature–Transition — Comparison of $T_{½\ (USE)}$ to FATT of sub-size specimens (SUS)

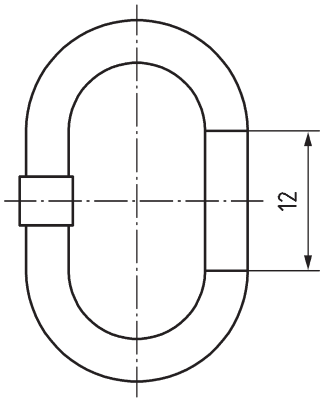


Key

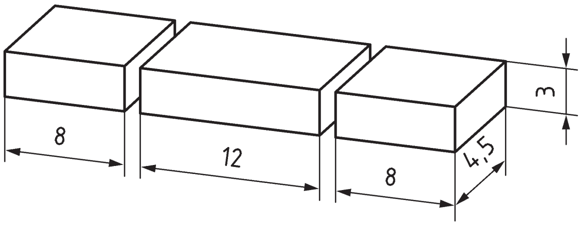
X $T_{½\ (USE)}$ in °C, ISO-V

Y $T_{½\ (USE)}$ in °C, SUS

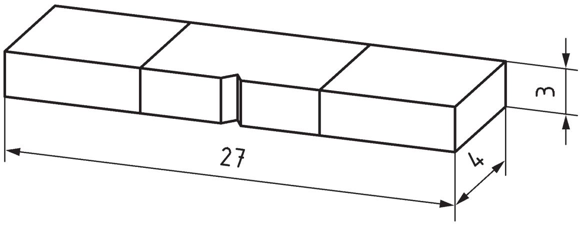
Figure A.30 — Ductile–Brittle–Temperature–Transition — Comparison of $T_{½\ (USE)}$ sub-size (SUS) and full-size (ISO-V) specimens dimensions in mm



a) Chain link 13 × 39 — Extraction

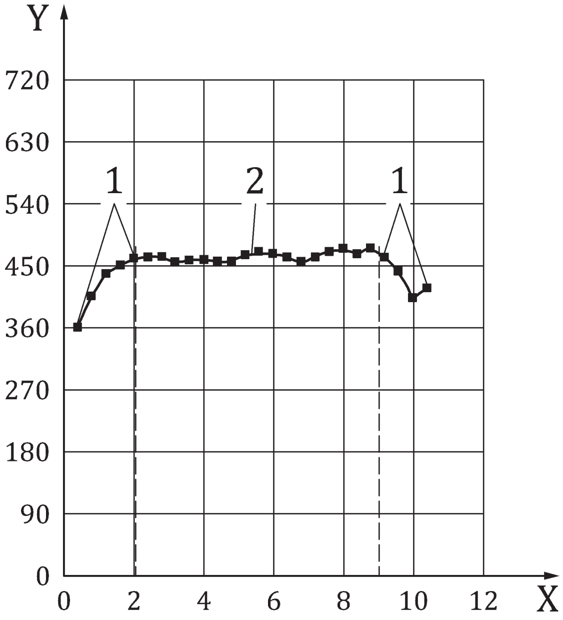


b) Geometry of the specimens before welding



c) Welded on specimen after machining

Figure A.31 — Laser welded-on — Extraction of specimen and geometry before welding and after machining

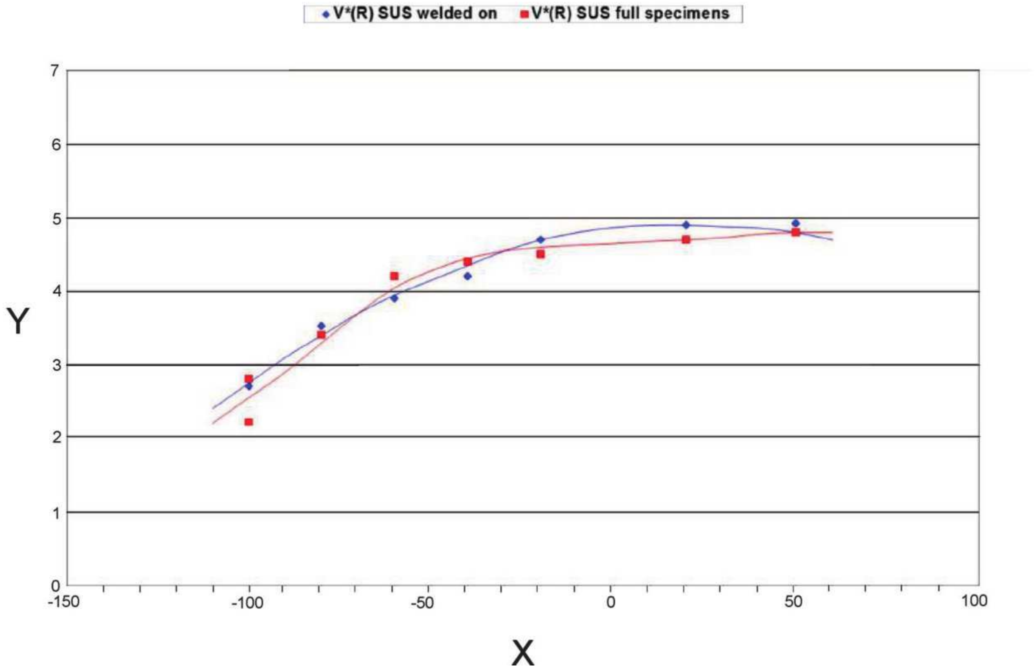


Key

1	HAZ	X	distance in mm
2	notch	Y	hardness, HV5

NOTE 7 mm unaffected zone; 2,5 mm each side affected zone.

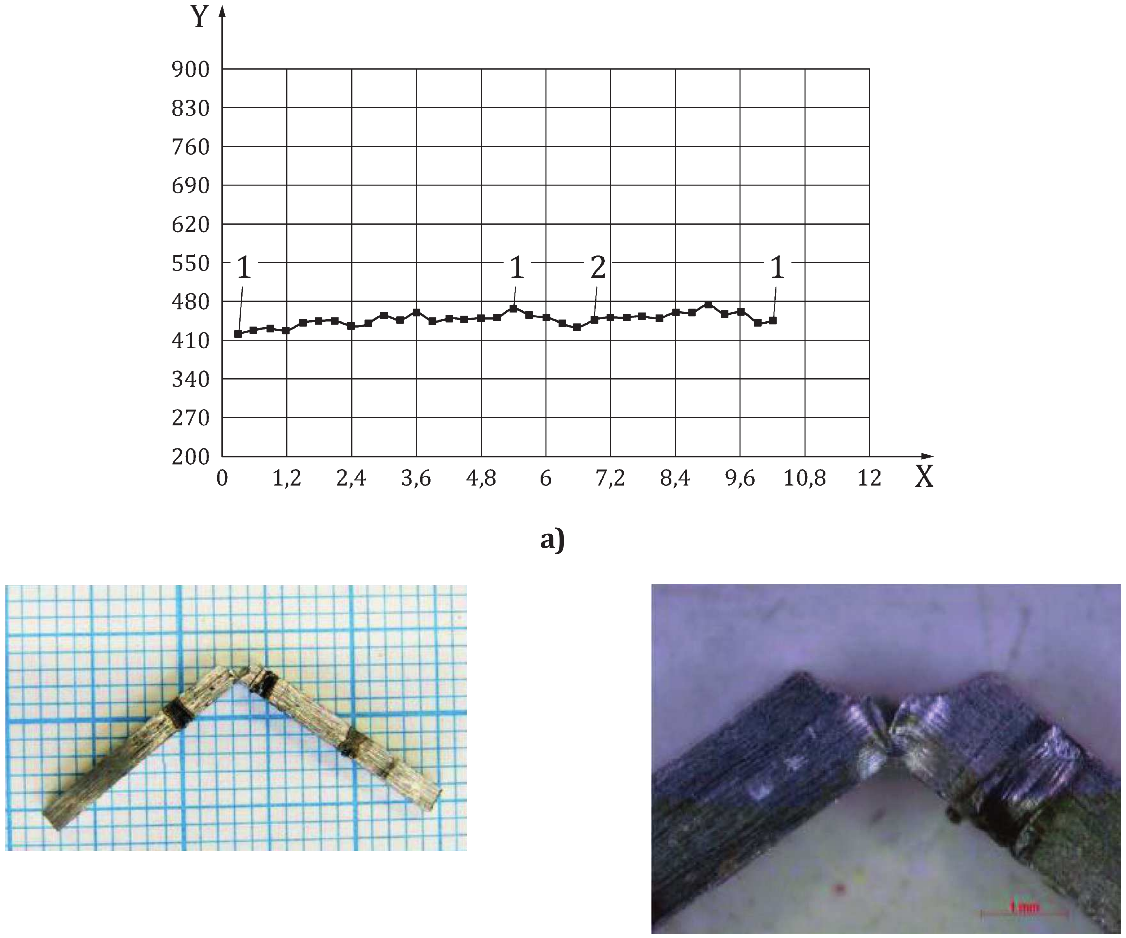
Figure A.32 — Laser welded-on — Hardness measurement



Key

X	temperature in °C
Y	impact energy in J, SUS

Figure A.33 — Comparison of V* full specimens to welded-on specimens



a)

b)

c)

NOTE 1 For b): Testing temperature −50°C; E = 0,6 J.

NOTE 2 For c): Complete tough.

Welding: Microlaser, pulsed energy 6,4 J. No heat influence on hardness by welding.

Specimen: 1,5 × 1,5 × 27 mm; notch depth 0,5 mm.

Key

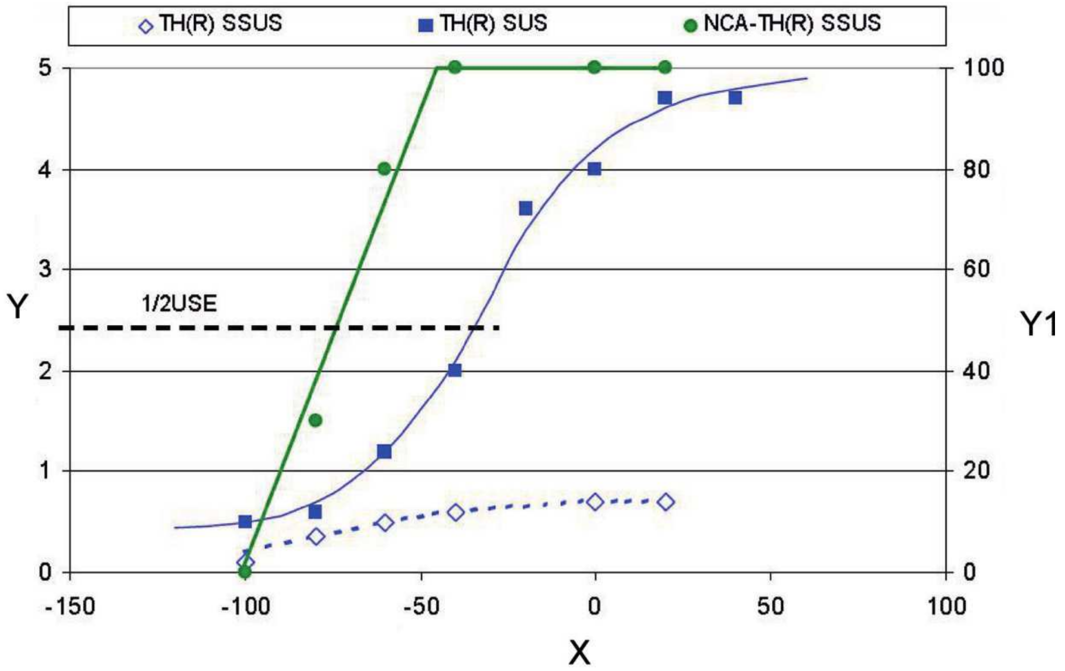
1 weldment

2 notch

X distance in mm

Y hardness, HV1

Figure A.34 — Super sub-size specimens



Key

X temperature in °C

Y impact energy in J

Y1 none crystalline area in %

Figure A.35 — Comparison SUS vs. SSUS – TH (R)

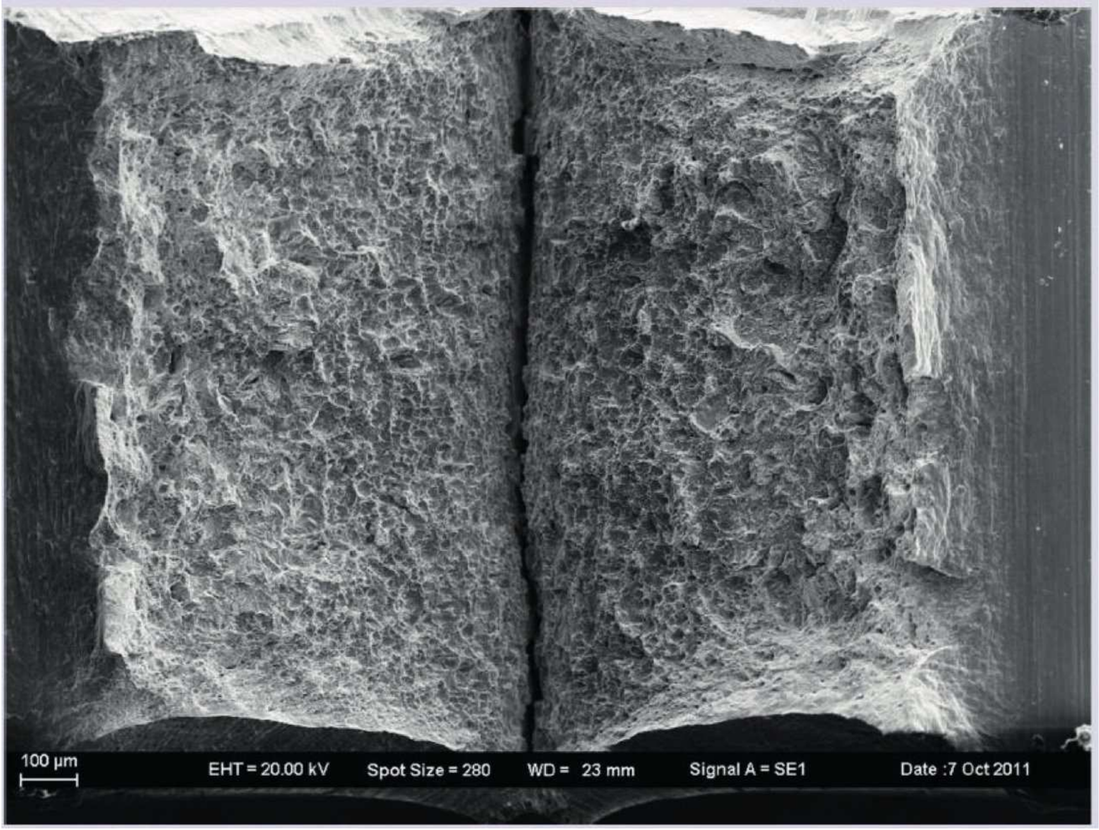
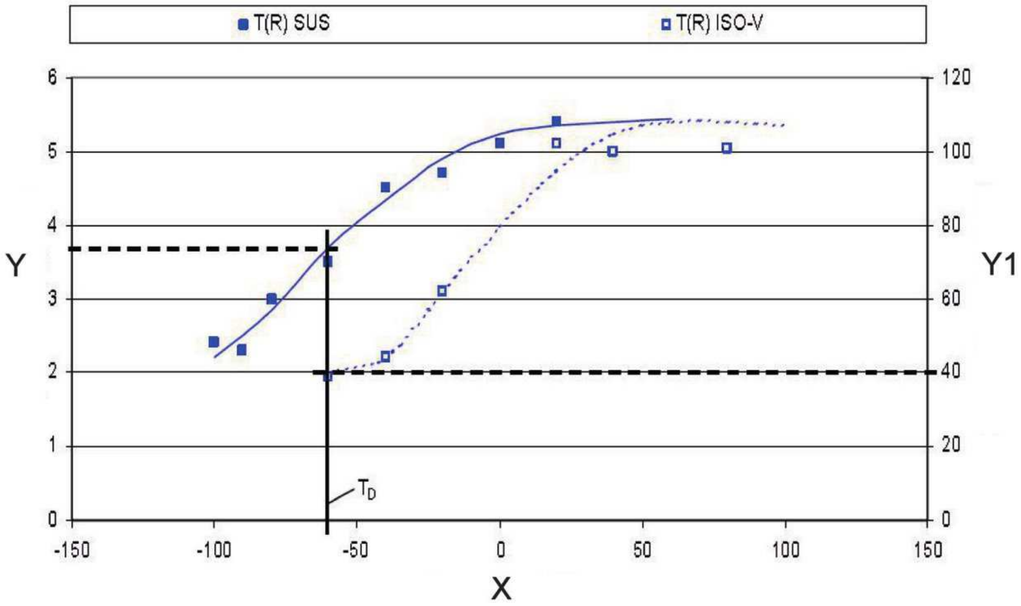


Figure A.36 — Fracture surface of SSUS, chain TH (R), tested at –50° C



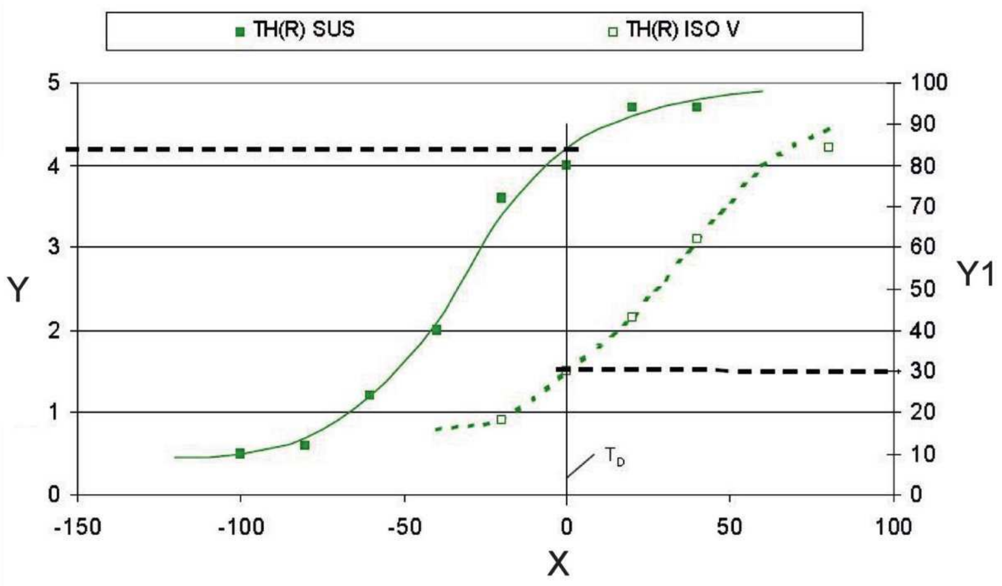
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.37 — Comparison T (R) – Sub-size to full-size



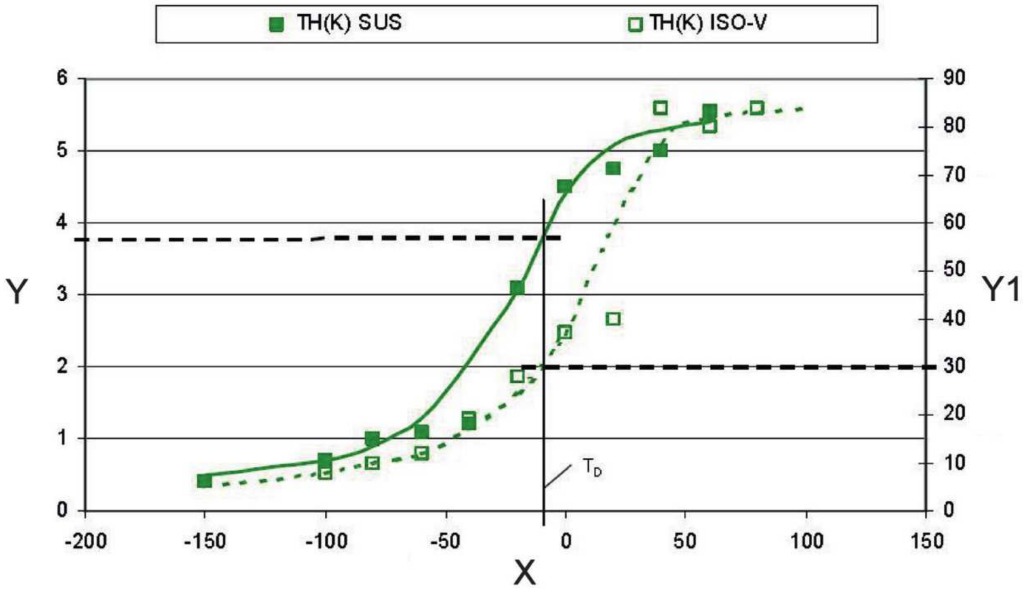
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.38 — Comparison TH (R) – Sub-size to full-size



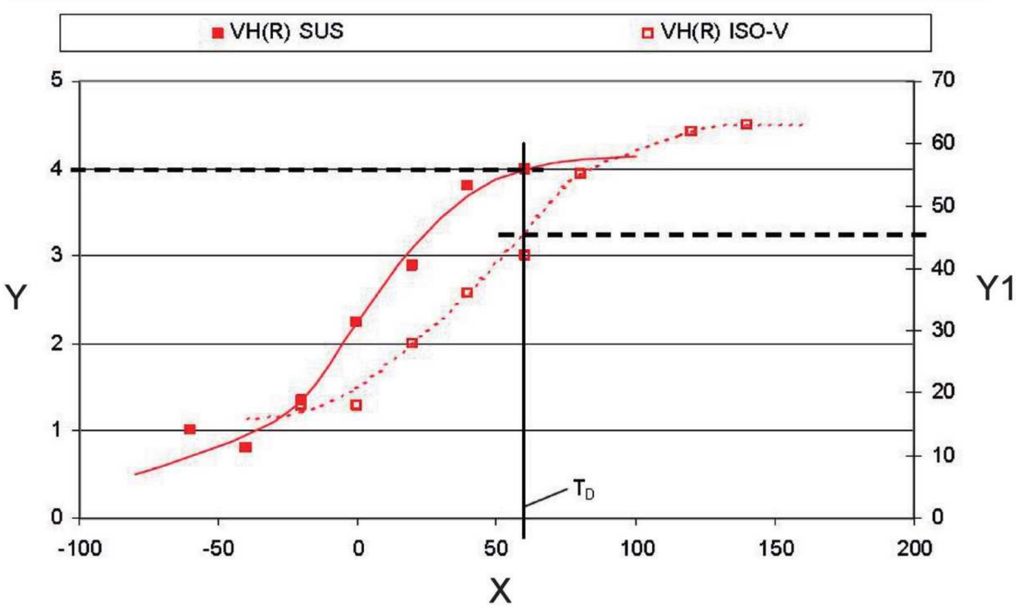
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

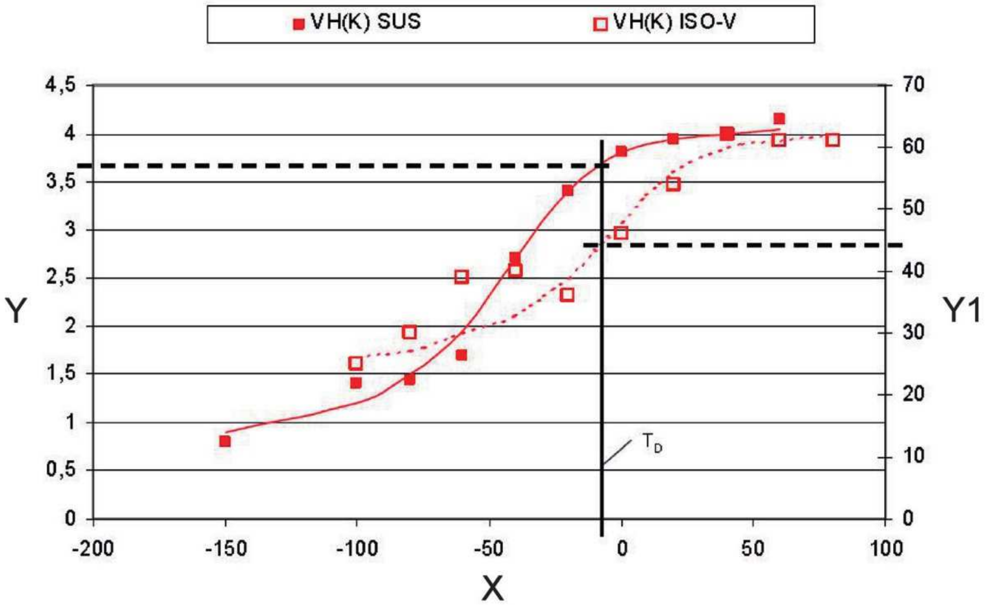
Figure A.39 — Comparison TH (K) – Sub-size to full-size



Key

X	temperature in °C
Y	impact energy in J, SUS
Y1	impact energy in J, ISO-V

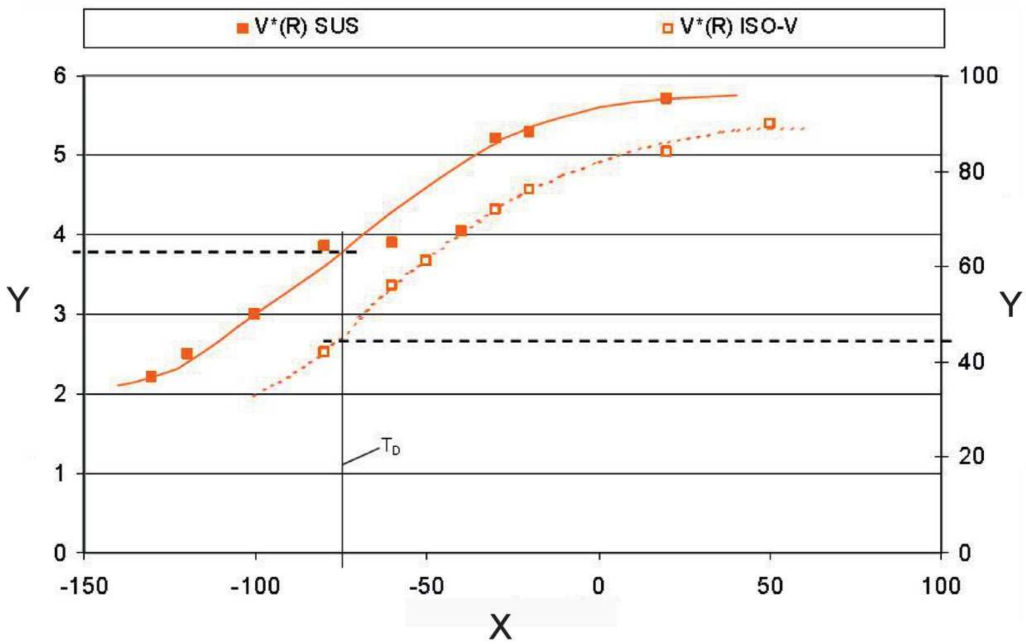
Figure A.40 — Comparison VH (R) – Sub-size to full-size



Key

X	temperature in °C
Y	impact energy in J, SUS
Y1	impact energy in J, ISO-V

Figure A.41 — Comparison VH (K) – Sub-size to full-size



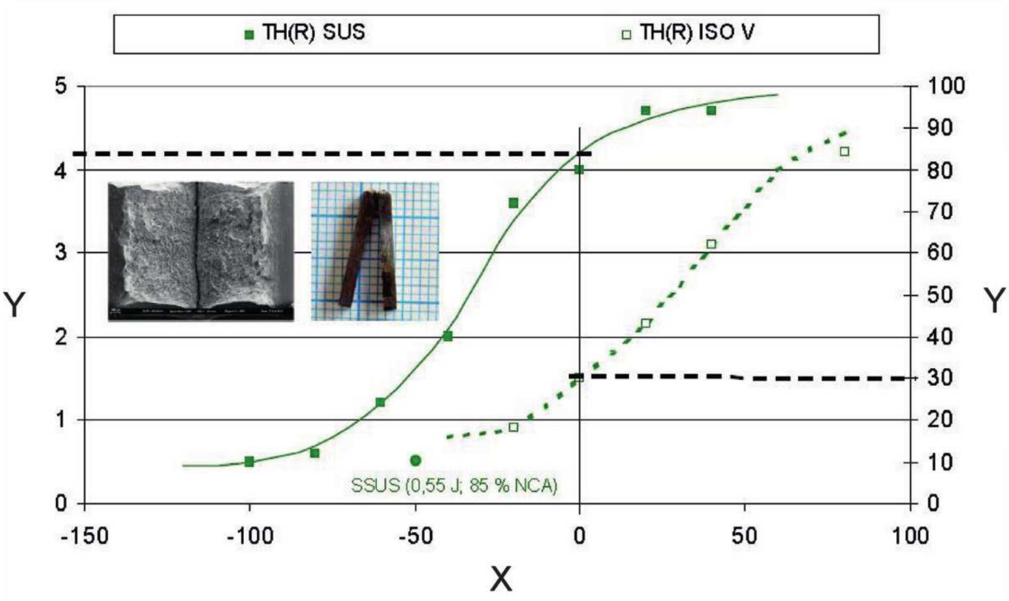
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.42 — Comparison V* (R) – Sub-size to full-size



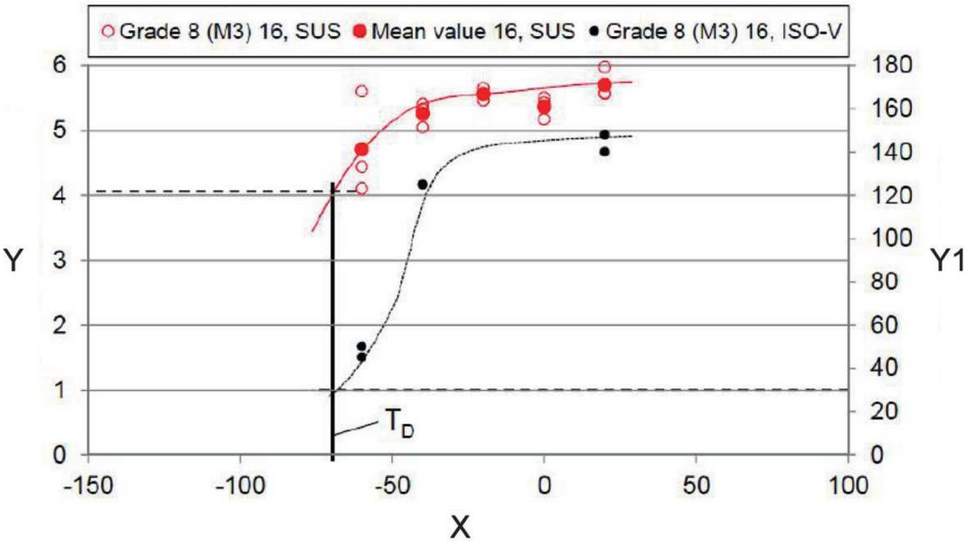
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.43 — Comparison TH (R) – Sub-size to full-size



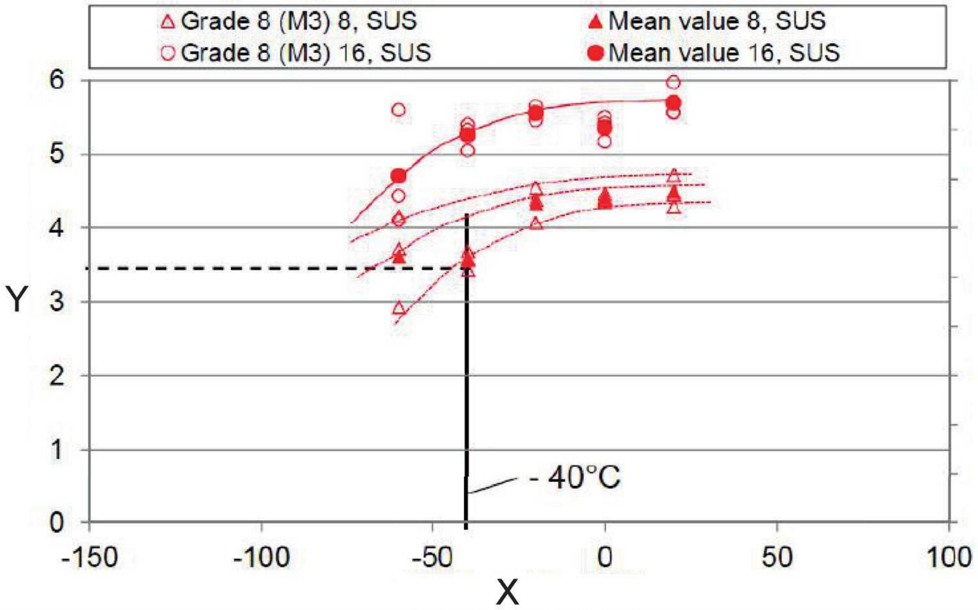
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.44 — M3, Grade 8, NiCrMo-alloyed sub-size to full-size specimens (Ø 16)

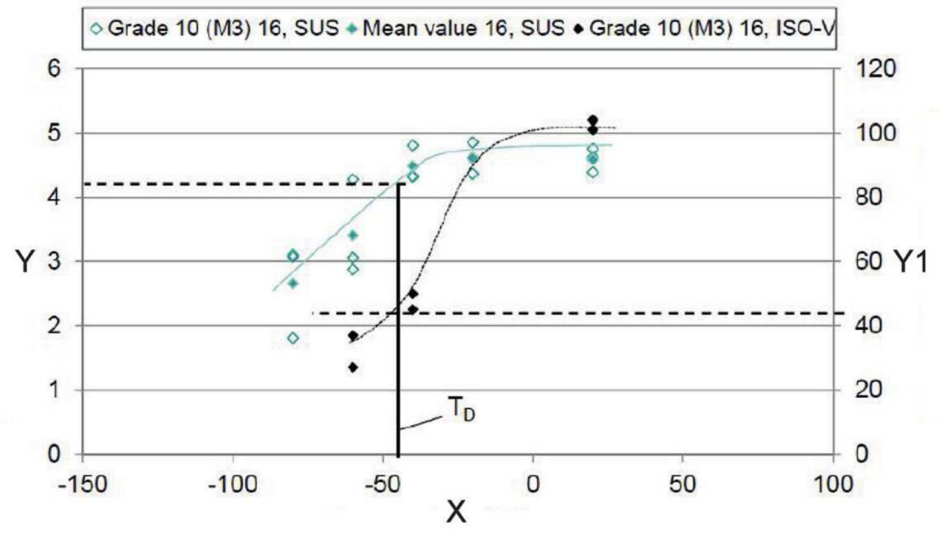


Key

X temperature in °C

Y impact energy in J, SUS

Figure A.45 — M3, Grade 8, NiCrMo-alloyed sub-size made from the chain size 16 and 8



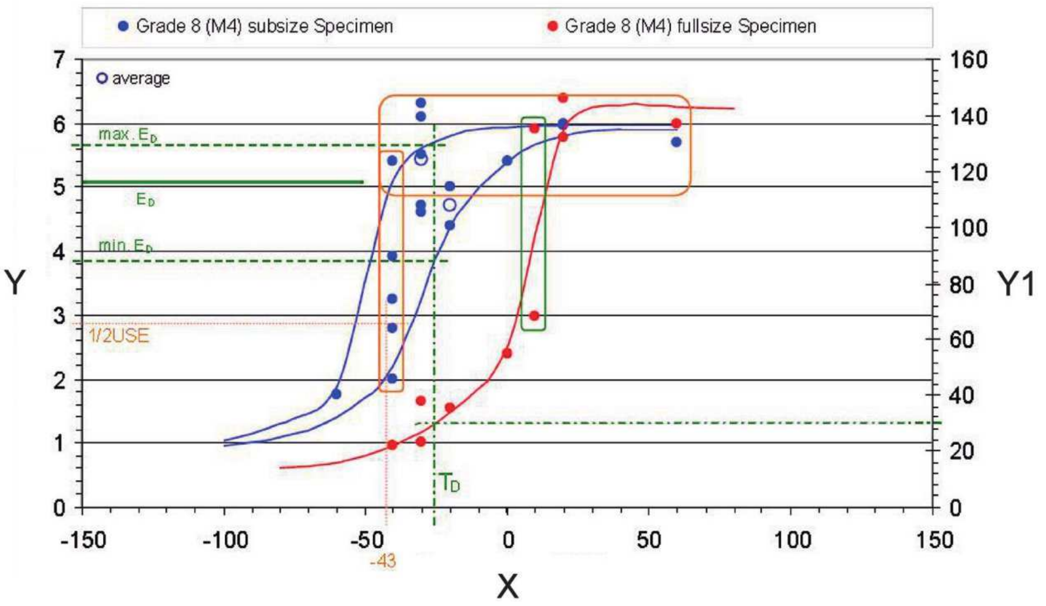
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.46 — M3, Grade 10, NiCrMo-alloyed sub-size to full-size specimens (Ø 16)



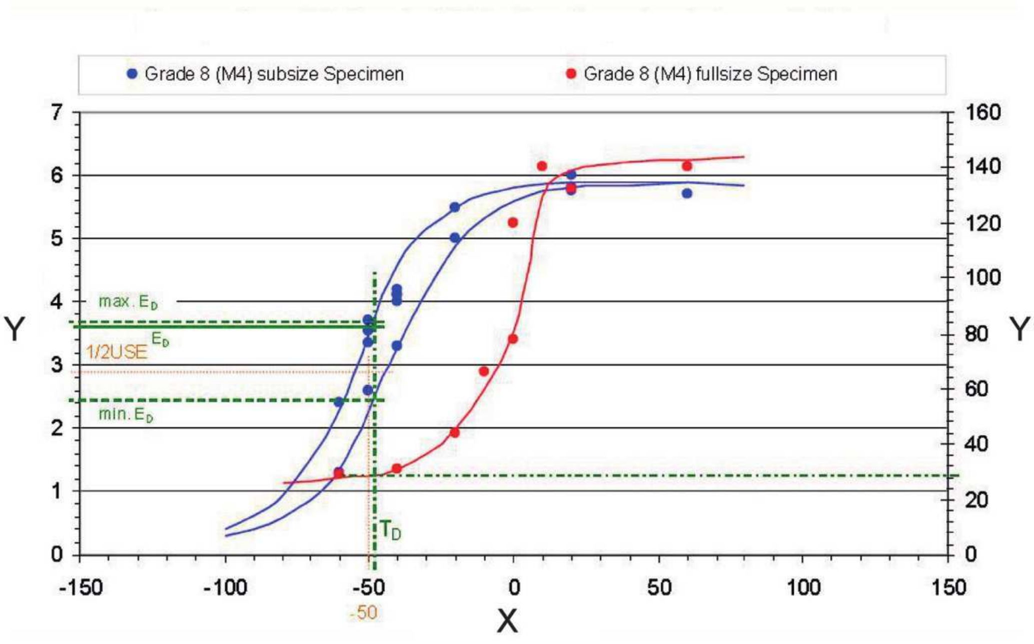
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.47 — Comparison of M4; Grade 8 MnB-steel sub-size to full-size specimens



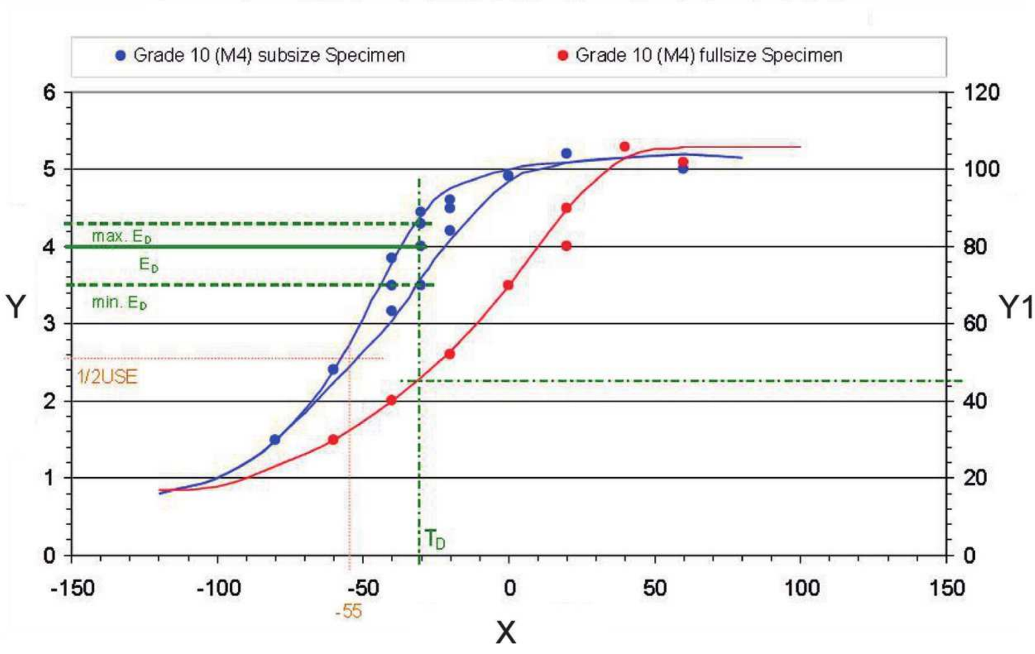
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.48 — Comparison of M4; Grade 8 NiCrMo-alloyed sub-size to full-size specimens



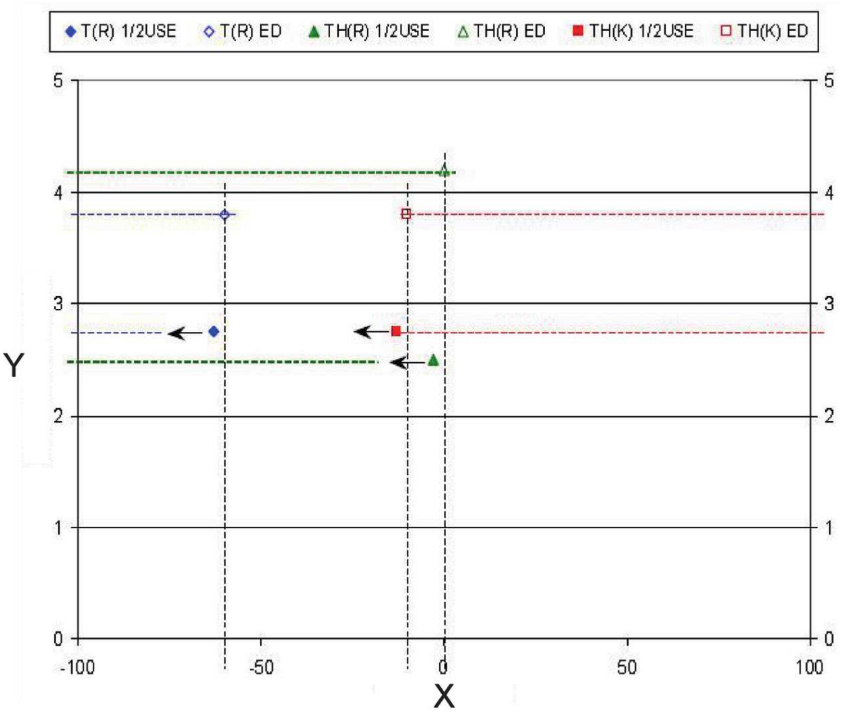
Key

X temperature in °C

Y impact energy in J, SUS

Y1 impact energy in J, ISO-V

Figure A.49 — Comparison of M4; Grade 10 NiCrMo-alloyed sub-size to full-size specimens

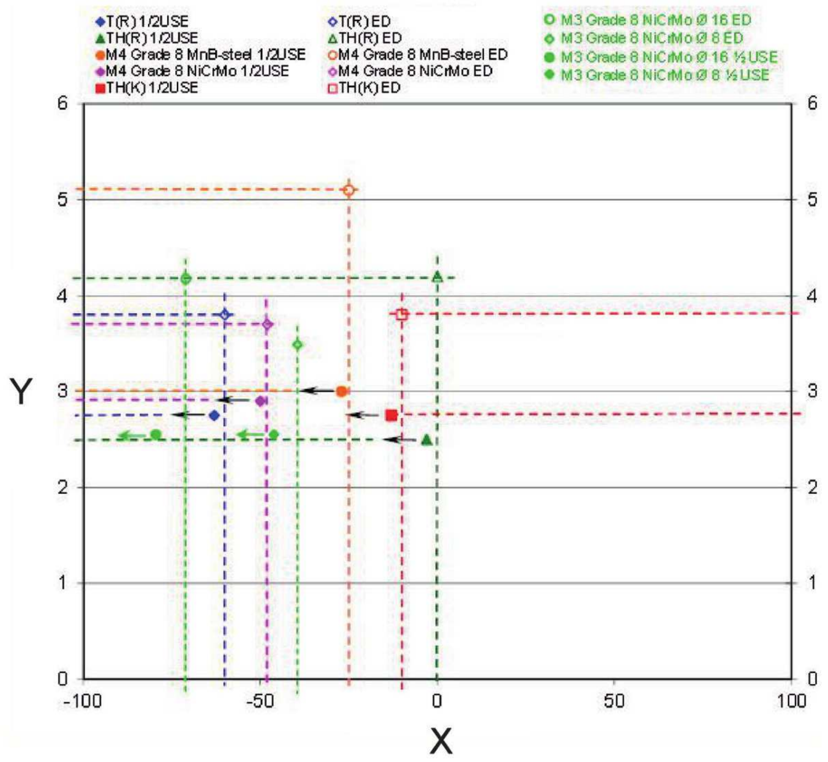


Key

X temperature in °C

Y impact energy in J, SUS

Figure A.50 — Comparison SUS T (R), TH (R), TH (K)

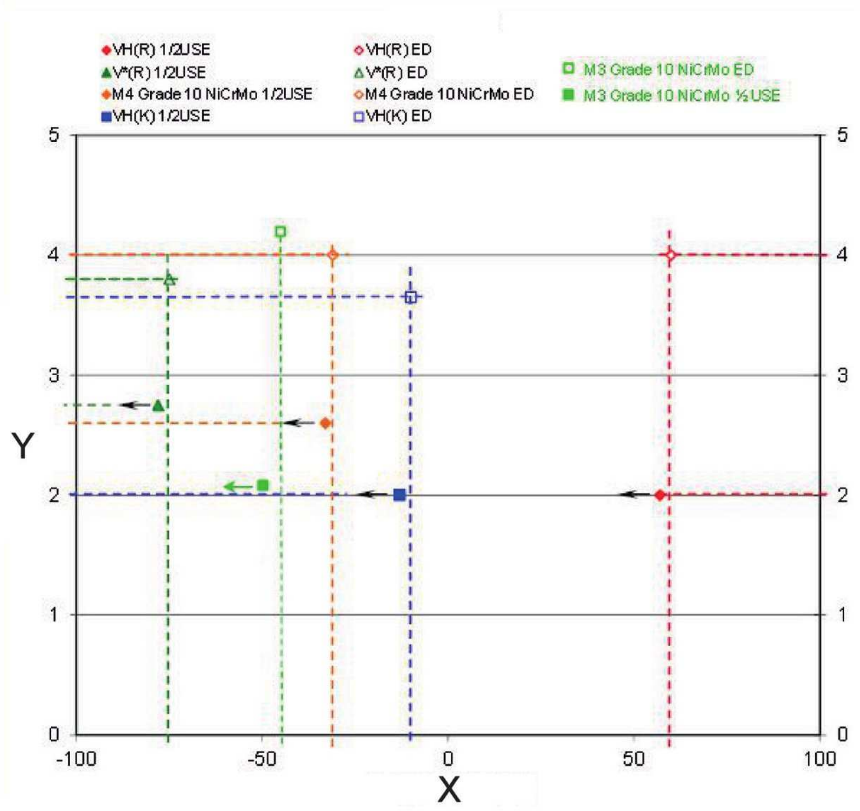


Key

X temperature in °C

Y impact energy in J, SUS

Figure A.51 — Comparison of SUS – Grade 8

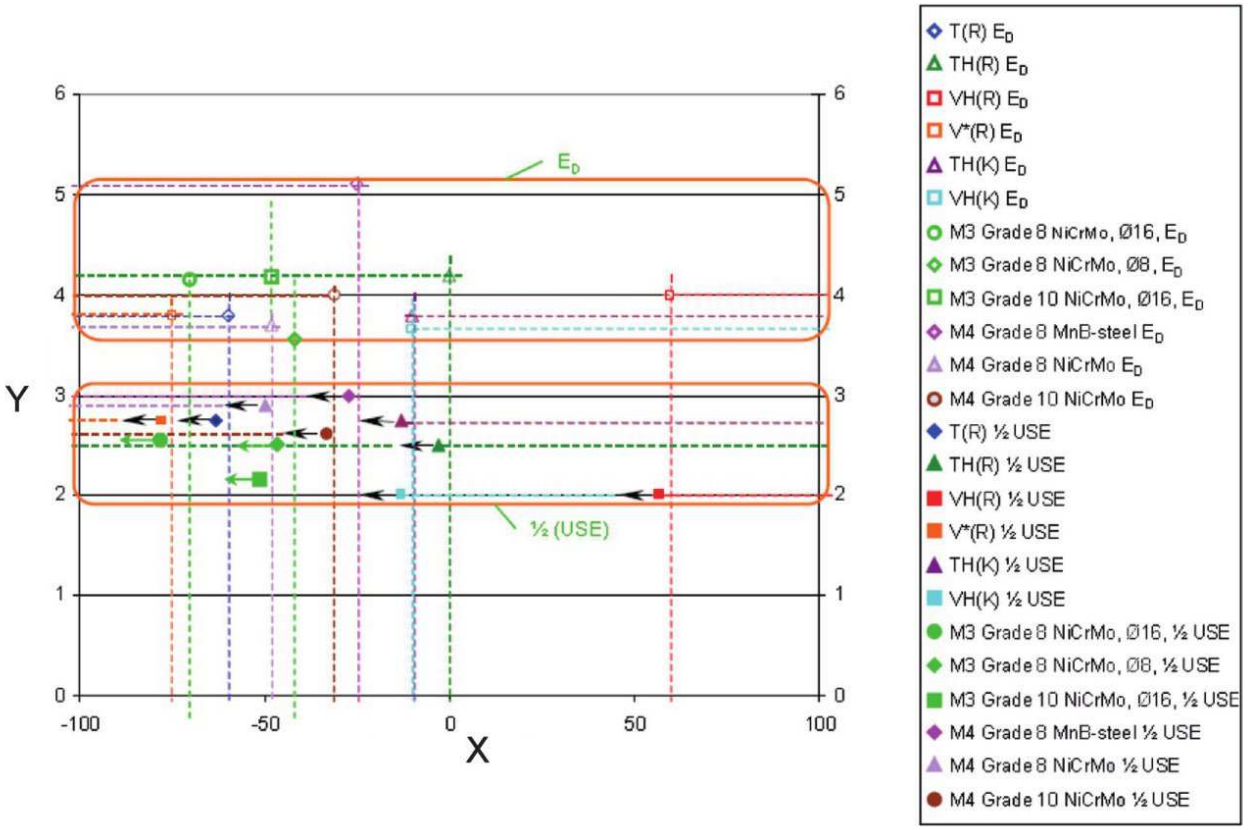


Key

X temperature in °C

Y impact energy in J, SUS

Figure A.52 — Comparison of SUS – Grade 10



Key

X temperature in °C

Y impact energy in J, SUS

Figure A.53 — Total comparison of SUS

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