

Toughness evaluation of EB welds

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Abstract For over a hundred years, Charpy impact testing has been performed. It is one of the most frequently used material tests. Due to a very simple test setup, a huge wealth of experience and an enormous database of results, it is still state of the art to evaluate toughness of materials and welds. Modern welding technologies like laser welding or electron beam welding (EBW) are characterized by a low heat input. The high energy density of these technologies results in very narrow welds. These kind of joints are difficult to analyse by means of a standard Charpy test. The combination of weld cross section and properties lead in most cases to a fracture path deviation (FPD). Although the crack starts from a notch, it deviates during propagation into the heat-affected zone or even in the base material. Therefore, the weld itself is not tested and cannot be characterized. FPD is a well-known issue but so far little attention in standards has been paid to this complex topic. Hence, establishing a valid welding procedure specification for beam welding procedures may imply difficulties. This work focuses on avoiding FPD in electron beam welds in soft-martensitic steel (1.4313) by using standard and side notched Charpy impact specimens.

Valid toughness result had to be found for 20- and 100-mm-thick welds at $-20\text{ }^{\circ}\text{C}$. Several test with three different kind of specimen in two different heat-treated conditions were carried out. It was found that beside the narrow seam a major reason for FPD is the significant overmatching of the weld. A post weld heat treatment to reduce overmatching facilitates testing but can decrease toughness. Adequate results for qualification were found and EB welds reached sufficient toughness at $-20\text{ }^{\circ}\text{C}$. Toughness of EB welds was compared to the toughness of conventional gas metal arc welds (GMAW). Finally, a recommendation for adapting the toughness characterization for narrow and overmatching seams is proposed.

Keywords (IIW Thesaurus) Ductility · EB welding · Fracture tests · Notches · Toughness

1 Introduction

In 1884, L. v. Tetmajer introduced an impact test on notched T-beams to qualify ingot steel (Flusseisen) instead of wrought iron (Schweisseisen) [1]. He measured the energy which was consumed by the specimen until breaking and described it as deformation energy. In 1901, Augustin Georges Albert Charpy reported this work on the *3rd traveling exhibition of the International Association for materials testing*. In 1906, the Brussels congress agreed on the importance of a testing procedure with notched bars and the science of fracture mechanics became an important approach in design [1, 2]. To date, the Charpy impact test is the most convenient procedure regarding ductility testing of materials. The Charpy impact test is the most frequently performed mechanical material test next to tensile and hardness

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testing. Compared to fracture mechanics tests (CT, CTOD), it is easy to carry out but the result cannot be used for dimensioning. The measured impact energy is a qualitative value used for comparison [3]. The execution and evaluation of the Charpy test is defined in the ISO standard 148-1:2010 and ISO 9016:2011 [4].

Due to the higher probability of flaws in welds, ductility is of significant importance. Unfortunately, proper toughness evaluation of welds is far more difficult than for a homogeneous material. Because of the very local heat input, a weld offers various zones with different microstructures and therefore different properties (metallurgical notch). In the work of Neves et al. [5] and Elliot [6], the influence of varying welding parameters on the microstructure and subsequently the toughness was investigated. They showed that a change of heat input results in different weld seam toughness values. Another problem in toughness evaluation of welds is the very local response of weld imperfections. Quintana et al. [7], Satho et al. [8] and Toyoda et al. [9] focus on local brittle zones which can affect crack initiation and growth in a drastic way. Cleavage can be initiated in an otherwise ductile material. This fact is supported by the statistical distribution of ductility values which do not follow a bell curve distribution [7] in contrast to other mechanical properties like the ultimate tensile strength.

In high energy density welding procedures, further problems occur in addition to those mentioned before:

- Narrow fusion zones
- High overmatching situations ($UTS_{FZ} \gg UTS_{BM}$)

Fracture path deviation (FPD) occurs as a result of these circumstances. FPD is a well-known problem in toughness testing of narrow welds. The crack deviates away from the notch plane in the fusion zone (FZ), into the heat affected zone (HAZ) and into the base material, providing very high toughness values and leaving the FZ untested (see Fig. 1). FPD occurs in Charpy testing as well as in fracture mechanic testing. So far, this problem has been addressed in several publications [6, 8, 10–17] and different solutions to overcome this problem have been presented. *Crack tip opening displacement tests* in different modes were performed in some of the previously mentioned publications [10, 11, 14–17]. Research on detecting the ductile-brittle transition temperature was done by Baryraktar et al. in [2, 18, 19]. They were carrying out *impact tensile testing* to eliminate the influence of specimen bending and investigate pure crack initiation. Goldak et al. [12] instead was using a standard notched specimen but specimens were taken in the longitudinal direction out of the weld with the notch transverse to the weld direction (*Cross weld Charpy test*). Another approach to overcome FPD is to produce a wider FZ by placing three welds next to each other

(*3-Weld method*) [15]. Other studies report testing *Side notched specimens*, where two additional notches are placed in the side planes of standard Charpy specimens [8, 13, 15].

Although a lot of research had been done over the last 30 years, little attention has been paid from standardisation institutes. In the standard ISO 15614-11:2004 “*Specification and qualification of welding procedures for metallic materials-Welding procedure test-Electron and laser beam welding*” [?], the toughness evaluation is left vague and can be defined by the customer. However, the author is aware of certain cases where an implementation of electron beam welding was rejected due to the absence of an appropriately accepted toughness qualification of EB seams.

The intention of this paper is to present a solution for a certain case where the toughness evaluation for EB welds was necessary and a standard Charpy test failed due to FPD (Fig. 1). In this work, toughness was investigated with standard Charpy samples and side notched Charpy samples. A key issue therefore is that side notched specimen are cheap to produce and can be tested with the same device as the standard samples. Moreover, earlier studies have shown [13, 15] that the absorbed energy of the side notched Charpy impact test can be related to the absorbed energy of the standard Charpy test.

2 Experiments

The present paper describes the toughness evaluation of electron beam welded soft martensitic steel (1.4313). The composition is listed in Table 1. The ultimate tensile strength of the base metal (UTS_{BM}) is 880 MPa, the hardness is around 285 HV and the impact energy at $-20\text{ }^{\circ}\text{C}$ was measured to be 131 J (arithmetic mean of nine samples). The minimum required toughness for the welded material at $-20\text{ }^{\circ}\text{C}$ is specified to be 27 J. For investigation, weld samples with thickness of 20 and 100 mm were used. Welding was carried out with a probeam universal chamber machine,



Fig. 1 Fracture path deviation

Table 1 Composition 1.4313

	C	Si	Mn	Cr	Mo	Ni	N
max.	0.029	0.40	0.85	13.00	0.55	4.20	0.04

equipped with a 45 kW EB-gun. The samples were welded in PA position, using a metal backing. Welding parameters are shown in Table 2.

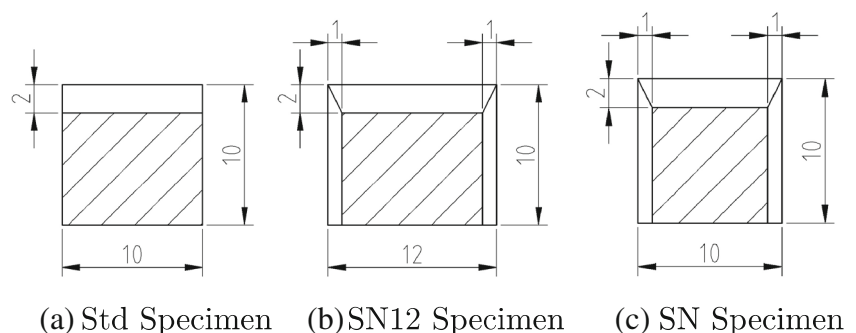
In a previous test, the seam area with the lowest toughness values was estimated by varying the notch position. The lowest toughness values were found in the weld centreline. Consequently, all samples tested in this work were notched in the seam centre. The Charpy samples were taken from the top and the middle of the weld. Prior testing showed that for these two positions, the toughness values are equal and the scattering was less compared to samples taken from the root of the weld. The impact tests were carried out with three different specimen geometries (see Fig. 2):

- Standard Charpy V-notch specimen (Std)
- Side notched specimen (SN12) with a 10 x 12 mm cross section
- Side notched specimen (SN) with a 10 x 10 mm cross section

Notches were machined with a standard Charpy notch milling tool. The main notches have a depth of 2 mm, whereas the side notches were machined with a depth of 1 mm. All notches were machined after etching the milled specimens to place the notch exactly in the seam centre. Charpy energy in all cases was measured at -20°C . A standard Charpy impact hammer with a maximum energy of

Table 2 Welding Parameters

Thickness (mm)	Power (kW)	Welding speed (mm/s)
20	9.0	12.0
100	37.5	2.1

Fig. 2 Specimen geometries, cross-section in the notch plane

300 J was used. Specimens were tested in the as welded (AW) and in post weld heat treated (PWHT) conditions. The post weld heat treatment was performed with a heating rate of 50°C/h to 580°C . After keeping the specimen 1 h at this temperature, they were cooled down to room temperature at 50°C/h . For every testing condition at least three samples were tested. According to the standard, the mean value of the tested samples gives the absorbed energy. Samples which did not break were excluded from calculation.

To compare toughness of EB welds with toughness of tungsten inert gas (TIG) and flux-cored metal active gas (FC-MAG) welds, side notched Charpy samples were machined out of TIG and FC-MAG welded plates. These welds were carried out in 25-mm-thick plates with double-V preparation. In Fig. 3, cross sections of these welds with inscribed Charpy specimen positions are shown. A post weld heat treatment was carried out for the FC-MAG welds to maximise toughness. TIG welds were not heat treated after welding. Charpy test conditions were the same as for the EBW welds.

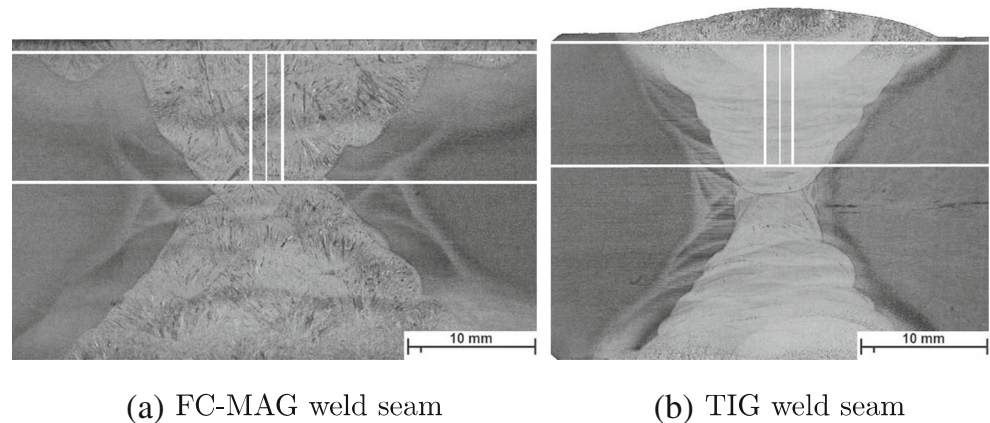
The full test matrix is shown in Table 3.

3 Results

The following section presents the results of the investigations. Outcomes are divided into three subsections. In addition to toughness testing, the microstructure and the hardness of the welds were also investigated. The results of the Charpy impact test for the 20-mm samples and the 100-mm samples are presented in separate subsections.

3.1 Microstructure

Prior to toughness testing the microstructure of the welds was investigated. In Fig. 4, half of the FZ and the HAZ is displayed. The seam width in the 20-mm weld sample is approximately 2 mm. A fine grained heat affected zone can be recognised next to the fusion line with a width of less than half a millimetre. The 100-mm sample shows a FZ with

Fig. 3 GMAW samples**Table 3** Charpy test matrix

	Std	SN12	SN
(a) 20 mm and 100 mm EB welds			
AW	✓	✓	✓
PWHT	✓	✓	✓
BM	✓	–	✓
(b) TIG and FC-MAG welds			
AW	TIG	TIG	TIG
PWHT	FC-MAG	FC-MAG	FC-MAG
BM	✓	–	✓

approximately 6-mm width. In this case, a fine grained heat affected zone of about 2 mm can be recognised. A coarse grained zone could not be identified. The dendritic grains in the FZ in the 20 mm seam are significantly smaller than the grains in the 100 mm seam. The average dendrite length in the 100 mm FZ is 630 μm , compared to 140 μm in the 20 mm FZ.

Since Charpy impact tests were carried out on the as welded and in post weld heat treated conditions, a Vickers hardness test was performed in both conditions. Hardness lines

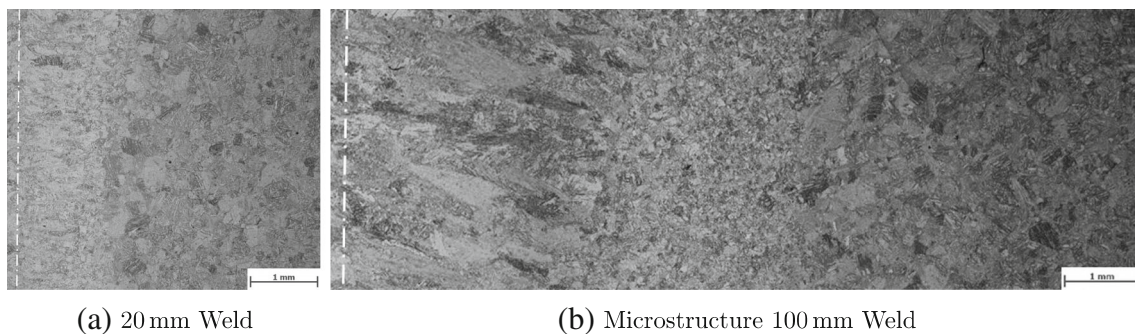
were measured across the FZ and the HAZ, at half seam depth. Spacing between the imprints was set to 0.7 mm. Figure 5 shows the impact of the PWHT. Hardness and consequently the overmatching, between base metal and weld seam, could be decreased. The seam hardness after the PWHT was below 350 HV, as required by ISO 15614-1:2004. The mismatch ratio M is calculated as $M = HV_{FZ}/HV_{BM}$. Average mismatch ratio between the base material and the FZ in the as welded condition was $M_{AW} = 1.31$ and for the PWHT condition $M_{PWHT} = 1.16$.

The microstructures of the TIG and FC-MAG welds did not show any irregularities and appear like typical multi-pass arc welded microstructures. The hardness of the FZ in the TIG welds was measured with 315 HV10 and with 308 HV10 in the FZ of the post weld heat treated FC-MAG welded cross sections.

3.2 Toughness of 20 mm welds

The average impact toughness of the 20 mm welds is displayed in Fig. 6. Values which are not valid according the standard (specimen is not fully broken; fracture deviates out of the FZ) are marked with an asterisk.

For specimens in AW conditions with standard notch (AW-Std), no regular values could be measured due to fracture path deviation (see Fig. 1). Toughness values are extraordinarily

**Fig. 4** Microstructure of FZ and HAZ

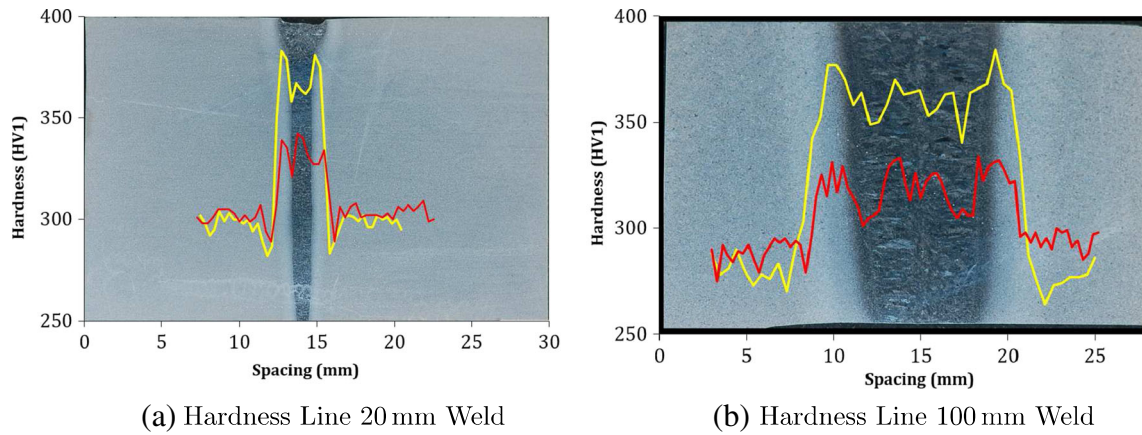


Fig. 5 Hardness lines, as welded (yellow) and PWHT (red)

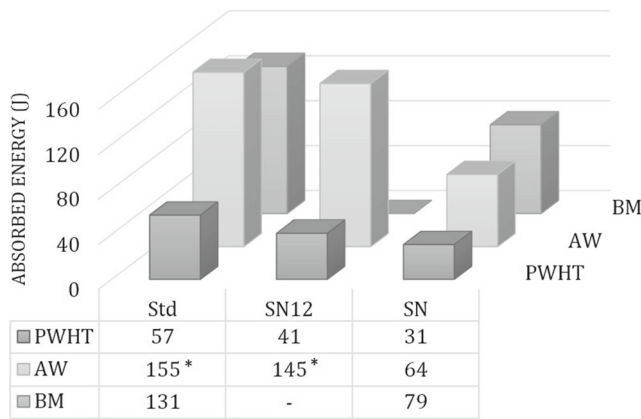


Fig. 6 Absorbed energy of the 20 mm specimen (asterisk-not valid values)

high and exceed the values of the base material. Lateral expansion exceeded 1.5 mm for all specimens in this group.

The SN12 specimen with the side notches (AW-SN12) did not return valid results either. Samples did not fully fracture and inner FPD (fracture plane is curved within the notches, see Fig. 7) occurred. The fracture path actually

crosses HAZ and base material. The value for the AW-SN12 group also exceed the value of the base material.

Specimen with standard 10 x 10 mm geometry and side notches (AW-SN) returned valid values. Some of the specimen also show this inner FPD but others broke with a flat brittle looking fracture. The absorbed energy reached 80 % of the side notched base metal specimens (BM-SN). Lateral expansion did not exceed 0.5 mm.

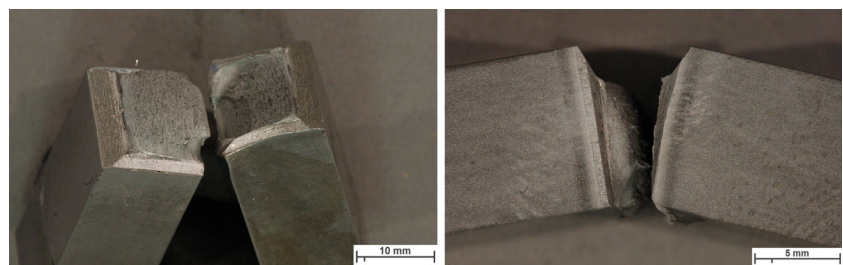
The situation for the post weld heat-treated specimen is more obvious. For all tested groups (Std, SN12 and SN), valid results could be measured. The PWHT-Std specimen fractured with a straight fracture plane with 100 % crystallinity; lateral expansion was 0.5 mm. Both side notched geometries (SN and SN12) fractured also in a brittle manner but with smaller lateral expansion (<0.5 mm).

3.3 Toughness of 100 mm welds

The average impact toughness of the 100 mm welds is displayed in Fig. 8. Values which are not valid according to the standard are marked with an asterisk.

The standard specimen in AW conditions offer no valid result since no sample broke fully. The fracture is clearly ductile with distinctive shear lips and the fracture path

Fig. 7 Inner fracture path deviation, AW_20_SN12 and AW_20_SN



(a) Fracture Surface

(b) Fracture Path

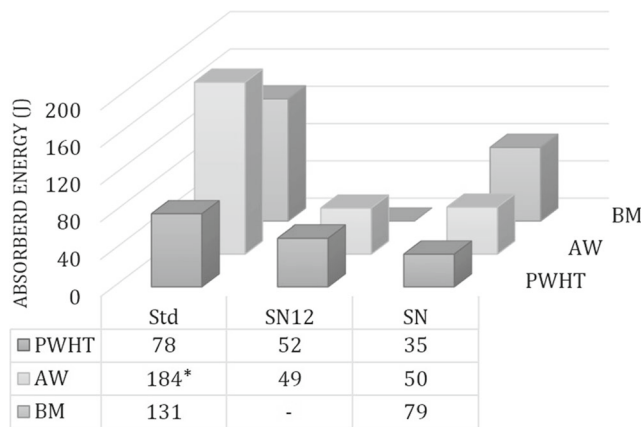


Fig. 8 Absorbed energy of the 100-mm specimen (*asterisk-not valid values*)

did not leave the FZ (see Fig. 9). Lateral expansion was measured with up to 2 mm.

The specimen with the side notches in AW conditions (AW-SN12 and AW-SN) returned valid results according the standard; all samples broke fully and no FPD occurred. The fracture planes are flat with a fully crystalline appearance and show a lateral expansion of approximately 0.2 mm.

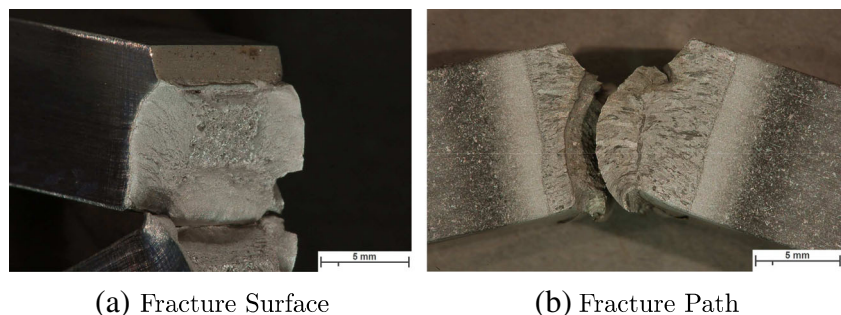
In the PWHT-Std group, two samples did not break fully (values around 180 J, lateral expansion >1.5 mm, noticeable shear lips). The other PWHT-Std specimen experienced fracture, with a rough crystalline surface. Small shear lips can be recognised. The lateral expansion was 0.9 mm.

All side notched specimen (SN12 and SN) in the 100 mm PWHT group behaved comparable to the PWHT side notched specimens in the 20 mm group. All specimen return valid values. The fracture surface appears brittle and flat with lateral expansion around 0.4 mm. No shear lips were found.

3.4 Comparison EBW to GMAW

For comparison, the results of the 100 mm EB welds were used, because in this tests the fracture path remained in the FZ (see Fig. 9b). To compare the maximum toughness values

Fig. 9 AW-Std 100 mm, Fracture surface and fracture path



of the different processes, the EB and TIG welds were tested in as welded conditions, whereas the FC-MAG welds were tested in PWHT conditions. Results are displayed in Fig. 10.

The TIG welds offer a superior toughness for all specimen geometries. Neither the Std nor the SN and SN12 specimens broke fully (values marked with an asterisk). All specimens showed fully ductile behaviour. Shear lips appeared only on the Std specimens. Lateral expansion was measured on all specimen with at least 0.7 mm.

The absorbed energy of the FC-MAG welds is lower compared to the EBW welds. The Std FC-MAG specimen broke fully, showing noticeable shear lips. Lateral expansion was below 0.5 mm. The fracture surface appeared dull (ductile) with some crystalline (brittle) areas. Charpy behaviour was as expected from former tests. The SN12 and SN specimen did not show shear lips or lateral expansion. The fracture surface appeared equal to the Std specimens. FC-MAG Charpy values do not show a high decrease of absorbed energy when using side notched specimens for testing.

4 Discussion

In several publications, the advantages of EBW, especially in thick-walled welding, is mentioned [20–27]. A low overall heat input and the high cooling rate of this process is a significant characteristic. These circumstances lead to a narrow FZ and a small HAZ with a fine-grained microstructure. A coarse-grained zone was not detectable (see Fig. 4). Generally, fine microstructures provide good toughness values. So in EBW in comparison to most other welding processes, the HAZ is not the critical area with regard to ductility [10]. Previous research by Bezensek et al. [10] demonstrated that the lowest ductility in beam welding is the weld centerline. The high cooling rates also lead to high hardness in the FZ and in the HAZ (see Fig. 5) which is not favourably regarding ductility. Other studies have shown

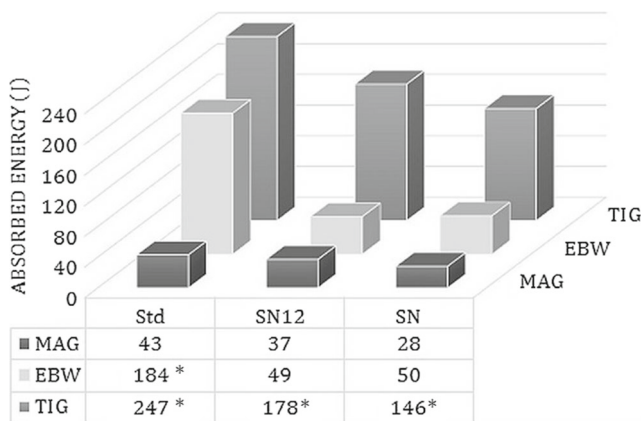


Fig. 10 Absorbed energy of the 100 mm EBW, TIG, and FC-MAG specimen

that a narrow area with high hardness does not generally lead to toughness problems (see [22]).

However, high hardness in the FZ causes a high mismatch ratio between base metal and FZ [28]. As our findings show, this overmatching is essential for FPD; for as welded specimens FPD was often observed, whereas in PWHT conditions, nearly no FPD occurred. In the literature [6, 11, 12, 14], this is explained with the so called *Plastic Hinge mechanism*. In narrow welds, the stress field in front of the crack tip extends to the base material. Due to lower strength of the BM, UTS in the base metal is reached before the weld metal reaches its UTS or even yield strength. This leads to a ductile collapse in the base material before a crack can be initiated in the FZ. In this case, the Charpy value does *not* represent the toughness of the weld, only the energy which is absorbed by the joint. The author of this paper interviewed several material testing institutes where FPD was interpreted as high ductility of the weld.

In 1977, Goldak et al. [12] introduced the cross weld Charpy test (CWCT) where the Charpy specimen is machined alongside the weld and the notch is perpendicular to the welding direction. In this test, the crack has to pass the FZ but also, depending on the width of the weld, the HAZ and the BM. Consequently, the measured Charpy value has no meaning, with respect to the toughness in the FZ, but the ductile brittle transition temperature can be estimated with a microscopic analyse of the fracture surface. Furthermore, because of the anisotropic microstructure of a weld, impact tests along and transverse to the welding direction are not directly comparable. Despite these limitations, some testing institutes are interpreting the CWCT measurements of absorbed energy as toughness values.

The notched Charpy specimen, applied in this work can suppress FPD in most cases. The side notches cause a

multi axial stress state and fracture is forced within the notched plane. Thus, absorbed energy becomes significantly lower compared to the standard specimen. Shear lips and lateral expansion are suppressed by the side notches and the specimen fractures in a brittle manner. These results are supported by Hagihara et al. and Satoh et al. [13, 29]. To conclude, the side notched Charpy impact test returns very conservative toughness results.

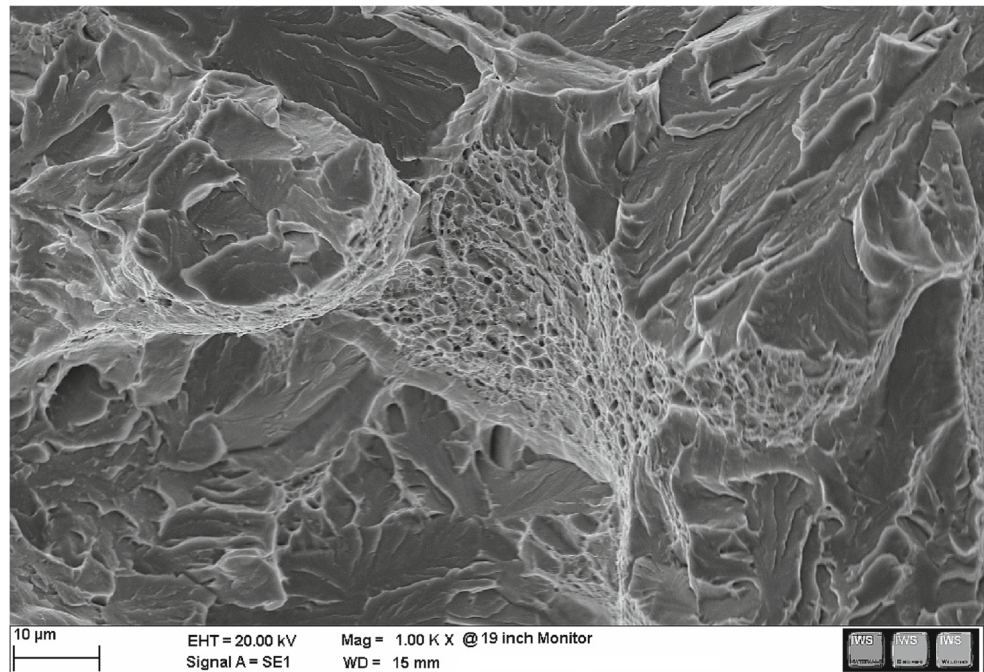
The quantitative influence of the side notches on the toughness can be seen from Figs. 6 and 8. The side notched base material BM-SN reached about 60 % of the BM-Std value. Taking into account that the SN specimen only has a cross-section of 64 mm², the specific toughness value of the SN-BM reaches 75 % of BM-Std. These findings correlate with values found by Hagihara et al. for a laser welded ultra-fine grained steel in the upper shelf area (see Fig. 5 in [13]). This correlation between SN and Std specimen was also found for the PWHT samples. As stated in [13], the absence of shear lips in the side notched specimen is the main reason for the lower toughness value.

Although, all side notched specimens, return a valid result and fractured in a brittle manner; low lateral expansion, flat fracture surface and crystalline appearance, the impact toughness, in this case, is above the required minimum of 27 J. Additionally, ductile fractured areas were found on the fracture surfaces of all tested EBW specimen. Even the macroscopic appearance of brittle fractures of the side notched samples turned out to be partial ductile (see Fig. 11).

Due to the multi axial stress state, the side notched specimens show lower toughness values compared to the standard specimens (cp. [13, 15]). For that reason, it can be assumed that a side notched value is a conservative toughness estimation and a reliable confirmation that the toughness exceeded the required 27 J at −20 °C.

The comparison of side notched EB, TIG and FC-MAG welds showed that in the case of EBW very conservative values are returned. This can be explained by the fact that in the FZ centre, the dendrites meet during solidification from both sides. Impurities and segregation will preferentially form in this area. In SN Charpy specimen, the fracture plane is forced to run along this area and therefore the toughness values are strongly decreased. In multi-pass GMAW welds, the fracture path crosses several solidification lines. Therefore, the difference of Std and SN specimens is lower compared to EB welds. Hence, the “in operation” toughness of EBW welds can be assumed higher than in this test. Our findings clearly show that in this case, EBW joints have sufficient toughness and are superior to FC-MAG joints. This comparison shows also that the fracture mode is independent of the specimen mode. The TIG fracture was ductile for

Fig. 11 Fracture surface of straight fractured specimen with valid values



all specimen geometries. Also, the FC-MAG fracture was a mixed brittle/ductile fracture in all tests.

A weakness of the side notched Charpy test may be identified when values around 27 J for EB welds are returned. Besides the assumption that this test is conservative, a comparison to SN specimens machined out of conventional welded joints can help to judge fitness for purpose. If this is not possible, fracture mechanics methods should be used.

5 Conclusion

The present work shows that toughness evaluation of narrow and overmatching weld seams is a challenge. In order to be able to obtain valid results, the standard test geometry has to be adapted. Therefore, the measured results cannot be compared directly with standard Charpy values. Nevertheless, a clear statement can be given about the utilisation of a seam according to the welding procedure qualification standard. When replacing conventional arc welding procedures with EBW, Charpy tests with side notched specimen for both procedures allow a cheap and easy to perform toughness comparison.

The results of this work may be summarised as follows:

- Toughness evaluation of 2-mm-wide welds with standard notched Charpy specimen is not possible due to fracture path deviation
- Also with side notched specimens fracture path deviation within the fracture plane is possible
- All kinds of FPD indicate considerably higher toughness value, than are actually present

- Side notched specimen without FPD show macroscopic brittle fracture but still return appropriate toughness values due to microscopic ductile fractured areas
- Decreasing the mismatch ratio of the joint applying a post weld heat treatment leads to a valid testing for standard Charpy specimen as well as for side notched specimens
- Side-notched specimens enable a suitable toughness comparison of high-energy-density welding processes to conventional welding processes
- Toughness of EB welds in 1.4313 steel is superior to FC-MAG welds

6 Outlook

This paper provides a recommendation for toughness evaluation if standard toughness testing fails. However, some question are still unanswered and will be investigated in ongoing work.

- Fracture surface investigation of side notched Charpy specimen by means of scanning electron microscope.
- More sophisticated methods (fracture mechanics test: CT, CTOD) are needed to verify and quantify toughness results.
- Future research might concentrate on finding a standard based toughness evaluation method for high energy welding procedures.

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References

- Blumenauer H (2001) 100 Jahre Kerbschlagbiegeversuch nach Charpy. *Materialwissenschaft und Werkstofftechnik* 32(6):506–513
- Bayraktar E, Kaplan D, Schmidt F, Paqueton H, Grumbach M (2008) State of art of impact tensile test (ITT): Its historical development as a simulated crash test of industrial materials and presentation of new ductile/brittle transition diagrams. *J Mater Process Technol* 204(1-3):313–326
- Macherauch E, Zoch H-W (2011) *Kerbschlagbiegeversuch*. Vieweg+Teubner Verlag, Wiesbaden, pp 281–288
- ISO. ISO 148-1 - Kerbschlagbiegeversuch nach Charpy (2010)
- Neves J, Loureiro A (2004) Fracture toughness of welds - effect of brittle zones and strength mismatch. *J Mater Process Technol* 153-154:537–543
- Elliott S (1984) Electron Beam Welding of C–Mn Steels–Toughness and Fatigue Properties. *Weld J*:8–16
- Quintana MA, Babu SS, Major J, Dallan C, James M (2010) Weld Metal Toughness: Sources of Variation. In: 8th ASME International Pipeline Conference 2010, Calgary, Canada, pp 559–608
- Satho K, Tozoda M (1985) Effect of mechanical heterogeneity on fracture toughness evaluation of steel welds, vol 74. *Transactions of the Japan Welding Society*
- Toyoda M, Praunseis Z (2000) The transferability of fracture-mechanics parameters to fracture performance evaluation of welds with mismatching. *MATERIALI IN TEHNOLOGIJE*. 34(6)
- Bezensek B, Hancock JW (2007) The toughness of laser welded joints in the ductile–brittle transition. *Eng Fract Mech*
- Cam G, Erim S, Yeni C, Kocak M (1999) Determination of mechanical and fracture properties of laser beam welded steel joints. *Welding Journal-New York*
- Goldak JA, Nguyen DS (1977) A fundamental difficulty in Charpy V-notch testing narrow zones in welds, pp 119–125. *Weld J*(Miami, FL, US)
- Hagihara Y, Tsukamoto S, Otani T (2005) An Evaluation Method for Laser Weld Metal Toughness by Side-Notched Charpy Test. *Welding in the World* 49(7-8):21–27
- Moltubakk T, Thaulow C, Zhang ZL (1999) Application of local approach to inhomogeneous welds. Influence of crack position and strength mismatch. *Eng Fract Mech* 62:445–462
- Takashima APY, Minami F (2009) Fracture Toughness Evaluation of Laser Beam-Welded Joints of 780 MPa-Strength Class Steel. *Welding in the World* 53(11-12):R304–R311
- Takashima Y, Nishi T, Shoji H, Ohata M, Minami F (2014) Evaluation method for Charpy impact toughness of laser welds based on lateral contraction analysis. *Welding in the World* 58(3):289–295
- Zhang H, Zhang Y, Li L, Ma X (2002) Influence of weld mis-matching on fatigue crack growth behaviors of electron beam welded joints. *Materials Science and Engineering: A* 334(1-2):141–146
- Bayraktar E, Hügele D, Jansen JP, Kaplan D (2004) Evaluation of pipeline laser girth weld properties by Charpy (V) toughness and impact tensile tests. *J Mater Process Technol* 147(2):155–162
- Bayraktar E, Kaplan D, Burette C, Grumbach M (2004) Application of impact tensile testing to welded thin sheets. *J Mater Process Technol* 145(1):27–39
- Various (2012) International Electron Beam Welding Conference - Lectures of the 2nd IEBW Conference Aachen March 26-30, 2012. In: DVS Berichte. Düsseldorf, Germany. DVS Media GmbH
- Kihara TH, Minehisa S, Sakabata N, Shibuya T (1984) High Power Electron Beam Welding of Thick Steel Plates–Method for Eliminating Beam Deflection Caused by Residual Magnetism. *Weld World* 22(5):126–134
- Wiednig C, Lochbichler C, Enzinger N, Beal C, Sommitsch C (2014) Dissimilar Electron Beam Welding of Nickel Base Alloy 625 and 9 % Cr Steel. *Procedia Engineering* 86:184–194
- Böhm S (2014) The electron beam as a welding tool: German study on the state of the art and future requirements. In: International Institute of Welding, Commission IV - Power Beam Processes Annual Assembly 2014. International Institute of Welding, Seoul, Korea
- Dilthey U, Dobner M (1996) Untersuchung des Werkzeugs Elektronenstrahl - Teil 3: Koordination von Strahlstrom und Fokussierung. *Schweissen und Schneiden* 48(10):770–785
- Sun Z, Karppi R (1996) The application of electron beam welding for the joining of dissimilar metals: an overview. *J Mater Process Technol* 59(3):257–267
- Dobeneck D (2007) *An International History of Electron Beam Welding*, 1edn. Pro-beam AG
- Schultz H (2004) *Elektron beam welding*. Woodhead Publishing Ltd, Cambridge
- Pavlina EJ, Van Tyne CJ (2008) Correlation of Yield Strength and Tensile Strength with Hardness for Steels. *Journal of Materials Engineering Performance* 17:888–893
- Satoh K, Toyoda M, Nohara K, Takeda S, Nayama M (1982) Notch Toughness Evaluation of HT80 Electron Beam Weld Metal by Charpy Test. *Journal of the Japan Welding Society* 51(8):679–686