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Toughness of old mild steels

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Abstract

For the rehabilitation of steel structures from the 19th and the early 20th century the brittle fracture behaviour is essential for the structural safety. The methods of the assessment used in EN 1993-1-10 were predominantly developed for welded structures made of current steel grades with more or less high toughness. The check by limitation of the plate thickness (Table 2.1 in [1]) is not suitable for old mild steel structures with riveted and bolted connections. Notch effects and residual stresses are quite different to those ones of welded structures. The material properties of old mild steels are characterised by larger scatters, particularly due to the inhomogeneous distribution of tramp elements and higher contents of non-metallic inclusions. In this paper, experimental and analytical studies of the brittle fracture behaviour of mild steels as well as aging effects of structural elements with holes for riveted and bolted connections are presented (see also [2-4], [20]).

Keywords: *Brittle fracture; old mild steel; riveted structures; fracture toughness; Master-Curve; Sanz-correlation.*

1. Introduction

Lots of steel structures dating from the 19th and early 20th century are still in use today even if their expected lifetime has been significantly exceeded. Steel structures constitute a large proportion of the existing buildings. Storey buildings, railway stations and industrial plants from the 20th century play a particular role. Due to heritage preservation aspects and also for economic reasons, it is of significant importance to ensure the safe usage of these buildings.

The analysis of the different reasons for damages and collapses of old steel structures shows, that besides the safety of the structural elements and connections against stability and strength failure, the risk of brittle fracture plays an important role (e. g. [5]). The procedure for choosing steel grades to avoid brittle fracture according to EN 1993-1-10 [1] is developed for structures out of current steel grades in welded structures. The particular properties of old mild steels made by the Thomas-, Bessemer- or Siemens-Martin-procedure were not reflected. In addition, notch effects from holes for rivets and bolts in structures are significantly lower.

Nevertheless, in practice the limits for the Charpy-energy according to EN 1993-1-10 are often used to assess old steel structures. This can lead to miscalculations of toughness requirements and unnecessary reinforcement measures or the preventive dismantling of the structures.

It is already known from previous tests even at low temperatures, that old mild steels may have sufficient toughness to withstand brittle component failure. The assessment of the safety against brittle fracture by using the results of fracture-mechanical tests (C(T)-tests) for the material toughness and the principals of fracture mechanics to determine the stress intensity at crack tips is not widespread. Up to now, it is limited to selected structures, in particular railway and road bridges with cyclic traffic loads.

2. Steel grade selection in EN 1993-1-10

To evaluate the safety of steel structures against brittle fracture, different complex and meaningful methods have been developed, which are more or less closely related to the phenomenon of brittle fracture. The procedure

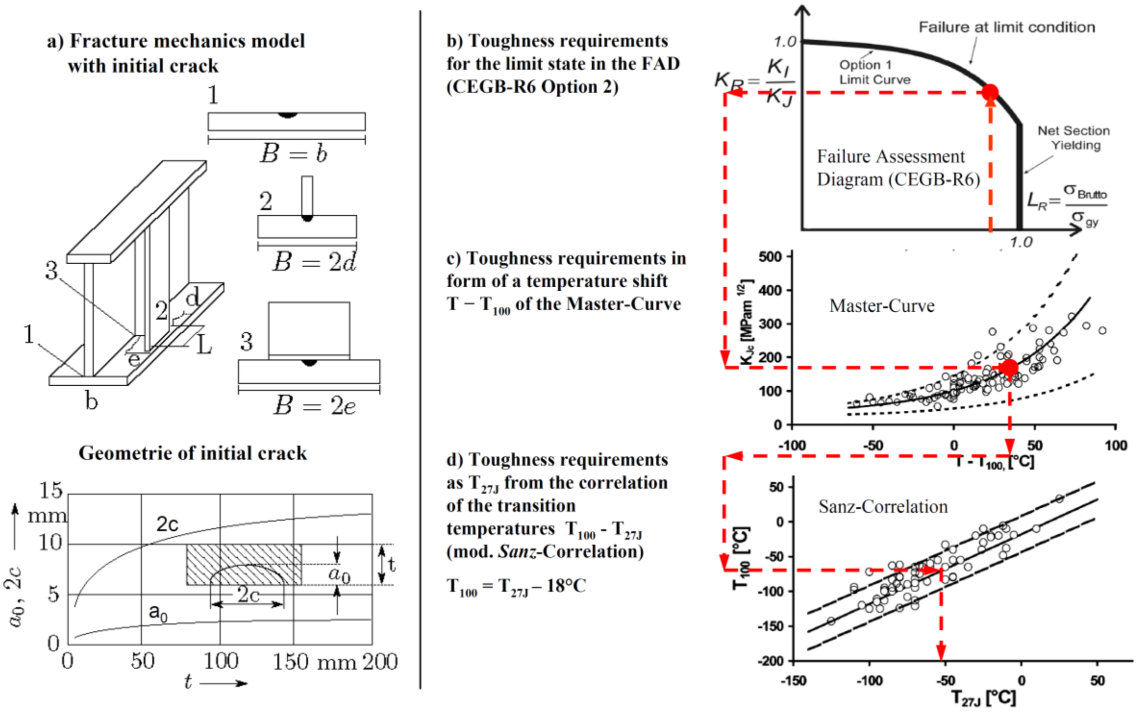

Fig. 1. Fracture mechanical basics for the safety assessment of brittle failure by EN 1993-1-10 [1, 6]

and background for the choice of steel grades according to EN 1993-1-10 are briefly described as follows (see [6] and Fig. 1).

Based on a plate thickness-dependent initial crack a_0 (semi-elliptical surface crack from the production, Fig. 1a), the design value of the crack depth a_d will be determined after 500,000 load cycles. This value is associated with the period, in which a damaged component with an increasing crack can be safely used, even at extreme low temperatures (return period 50 years). Typical intervals for the fundamental renewal of corrosion protection at bridges are about one quarter of the life time, for which a calculated lump sum of two million load cycles was assumed. Based on the maximum crack depth at the end of the observation period, the stress at the crack tip in form of the linear elastic stress intensity factor K_I in the component will be determined as the reference for the impact. The increase of the stress at the crack tip due to plastic zones can be considered by the k_{R6} correction factor in the Failure Assessment Diagram (FAD) of the R6 routine (Fig. 1b).

The technical delivery conditions for structural steels do not specify fracture toughnesses K_{Jc}, but minimum values of the Charpy-energy from notch impact tests at a given temperature (e. g. T_{27J}). This requires a suitable transformation, which takes place in two steps. On the one hand, the relationship between the fracture toughness K_{Jc} and the component temperature will be described by the Wallin's "Master-Curve" (Fig. 1c). In a second step, the ratio between the transition temperature T_{27J} at the Charpy-test and the reference temperature T_{100}, at which the median value of the fracture toughness corresponds to 100 MPa√m (also called T_0), will be determined by using the modified Sanz-correlation (Fig. 1d). With this procedure it is possible to replace the complex determination of the fracture toughness K_{Jc} by simple notch impact tests.

To simplify the assessment EN 1993-1-10 provides Table 2.1 [1]. It enables the determination of the maximum permissible product thicknesses of the intended steel grades depending on the reference temperature and the applied stress for a defined exceptional combination of actions [1]. The table was developed for welded structures made out of steel grades according to EN 10025 under defined boundary conditions.

3. Investigations of old mild steels

3.1. Specimens and their chemical content

Table 1. Results of the chemical analysis

sample / section	**chemical content [%]**						
	C	**Mn**	**Si**	**P**	**S**	**N**	**O**
DT200 (I200)	0.03	0.27	0.001	0.049	0.029	0.0135	0.0110
DT260 (I260)	0.10	0.72	0.001	0.095	0.102	0.0250	0.0155
M31 (L120x13)	0.07	0.48	0.001	0.024	0.043	0.0115	0.0385
M56 (L110x12)	0.15	0.36	0.001	0.018	0.091	0.0080	0.0100
SGM21 (L80x8)	0.09	0.23	0.001	0.087	0.089	0.0210	0.0160
PA2 (L60x8)	0.07	0.67	0.001	0.103	0.079	0.0225	0.0150
DB_G1 (L100x65x11)	0.03	0.32	0.002	0.053	0.085	0.0250	0.0710
DB_G3 (L100x65x11)	0.04	0.41	0.001	0.060	0.084	0.0190	0.0570
Thomas-steel	0.05	0.46	0.009	0.051	0.044	0.0140	-
Siemens-Martin-steel	0.09	0.48	0.008	0.035	0.038	0.0050	-

It is already known from the investigation in [7, 8] that the chemical, metallurgical and mechanical characteristics of old structural steels may differ considerably. In order to capture a large range of mild steels, material samples from different structures and years of construction were chosen for these investigations. To get more conservative results only material samples from buildings were analysed, because the steel quality of bridges was usually higher. The results of the chemical analysis are concluded and compared with the average concentrations of mild steels from typical production procedures [7] in Table 1. The specimens include Thomas-steels with high contents of nitrogen (e. g. PA2) as well as Siemens-Martin-steels (e. g. M3). For each analysed material sample, the following test specimens were produced:

- 6 cylindrical tensile specimens B5 (see DIN 50125:2009),
- 12 Charpy-impact-test specimens (see EN ISO 148-1:2011),
- 10 fracture mechanic specimens (compact tension specimens, see ASTM E1820-13).

Before starting sample preparation sulphur prints were made to make core segregations visible. The specimens were positioned in the areas of segregations. Due to the increased amount of impurity the lowest material toughness could be expected in these parts of the cross sections. All test specimens of one type were positioned behind each other in longitudinal direction of the sections to make sure, that the tested series have approximately the same material properties. Furthermore, the notches of the Charpy-specimens and the fatigue cracks of the C(T)-specimens were located in areas of the cross sections, where rivet holes are usually positioned and cracks are expected. Fig. 2 shows the sulphur print of an angle section and the location of the test specimens.

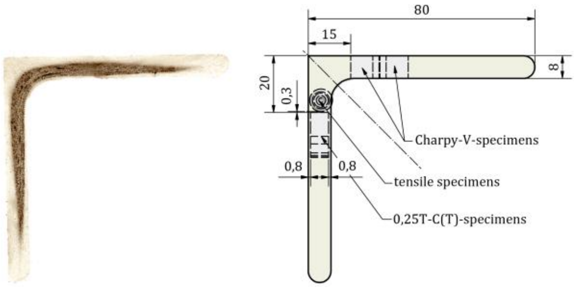

Fig. 2. Sulphur print and positioning of test specimens at sample SGM21 [19]

3.2. Fracture toughness

The fracture behaviour of structural steels corresponds to a temperature-dependent transition of material toughness from the ductile (upper shelf) to the brittle state (lower shelf). The transition region is characterised by significantly larger scatter than the upper and the lower shelf. The wide range of fracture toughness can be explained with the weakest-link-model [9]. The weakness of a ligament at the crack front (weakest link of a chain) is decisive for the toughness of a sample. At these weak points micro-cracks will form, which extend in an unstable manner and thus initiate failure. The reason for the wide scatter range is the stochastic distribution of the weaknesses of the microstructure in the ligament. The closer there is the weak point to the crack front, the lower is the fracture toughness. The probability increases with the width of the crack. For that reason, the toughness against brittle fracture of a thicker sample is lower than that of a thinner one. At the same time, the scatter of the material toughness is lower. This will be captured with the Weibull distribution of the Master-Curve-concept ([10, 11]) in the brittle-ductile transition region. For the probability of failure P_f a three-parametric distribution is common in which two parameters are predefined. The shape parameter m is 4, the threshold parameter K_{min} restricts the lower bound of the fractural toughness of ferritic steels to 20 MPa√m.

$$P_f = 1 - exp\left(-\left(\frac{K_{Jc} - K_{min}}{K_0 - K_{min}}\right)^m\right) \quad (1)$$

The scale parameter K_0 will be determined from the values of fracture toughness K_{Jc} for unstable failure. The values K_{Jc} are assigned to a normalised toughness-temperature-curve. The Master-Curve describes the dependency of the median fracture toughness of 1T-samples from the temperature.

$$K_{Jc(med)} = 30 + 70 \cdot exp[0.019 \cdot (T - T_0)] \quad (2)$$

The test standard ASTM E1921 is valid for macroscopic homogenous material. The multimodal Master-Curve-approach by [12] allows the analysis of data sets which consist of several subsets, e. g. records of different batches or non-homogeneous material. Hence this method is suitable for the evaluation of different mild steel samples. However, it is much more complex than the standard method according to ASTM E1921 [13]. The results from the analysis of the old mild steels related to the standard Master-Curve of ASTM E1921 are also shown in Fig. 3.

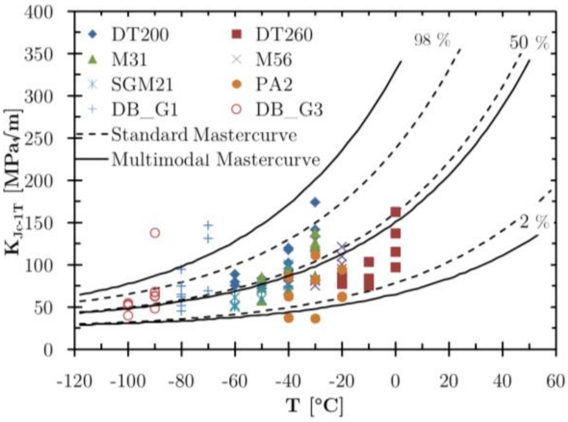

Fig. 3. Assessment of all test series according to ASTM E1921 and the multimodal approach

As expected, the fracture toughness of the inhomogeneous samples are better represented by the multimodal Master-curve. Only two (2,4 %) of the totally determined 83 $K_{Jc\text{-}1T}$-values are below the curve for 2 % failure probability. However, it can be seen that (except the sample PA2) the fracture toughness of the mild steels is also described sufficiently precise by the standard Master-Curve according to ASTM E1921. Based on experimental data and the multimodal evaluation the reference temperature T_0 of -30 °C as well as a characteristic value of the fracture toughness (5 %-fractile) are obtained with

$$K^{MM}_{Jc-1T,5\%} = 25.9 + 29.7 \cdot exp[0.0186 \cdot (T + 30)] \quad (3)$$

3.3. Previous investigations

Since the 1980th, fracture mechanical investigations of old structural steels have been performed in order to evaluate the brittle fracture safety of bridge structures. The results were published e. g. in [14–16] and were used in various concepts to determine the brittle fracture resistance of riveted structures. Some of the research results have also been published on an international level (e. g. [17, 18]). While the origin of the steels was mostly given, the test procedure and standards, the dimensions of the specimens and also partly the test temperatures were only insufficiently recorded.

The fracture toughnesses and the conditions for their determination are only stated in [15]. While the sample thickness varies between 7 and 12.5 mm, the tests were carried out according to ASTM E813-89 [19] on 0.5T-C(T)-samples. The data of the analysed structural bridge steels are well described with a few exceptions with the multimodal Master-curve (Fig. 4). However, it is remarkable that with increasing temperature the fracture toughness K_{Jc} seems to drop in the average. Reasons for this may be given in the way of evaluation and interpretation of the test results. Depending on the fracture behaviour of the specimen, a distinction between brittle failure and initiation of ductile crack growth was made.

If the specimen completely failed brittle without macroscopic visible cracks on the fracture surface, the determined fracture toughness was named J_c (Index c means “critical”). The equivalent K_{Jc}-values are shown in Fig. 4. If the cleavage fracture was initiated by a ductile and on the fracture surface visible crack, the fracture toughness was named with J_i (toughness when initiating ductile crack growth). The applied experimental procedure during the current investigations at TU Dresden also quantifies the fracture toughness due to brittle failure according to ASTM E1921. However, the code permits a low level of ductile crack growth up to a crack elongation of

$$0.05 \cdot (W - a_0) \leq 1mm \qquad (4)$$

were W is the width of the specimen and a_0 the length of the initial crack. The fracture toughness is limited to the maximum measurement capacity $K_{Jc(limit)}$ depending on the specimen and the yield strength of the material [13]. Since the degree of ductile crack growth is not documented in [15], Fig. 4 does not contain J_i-values in this comparison.

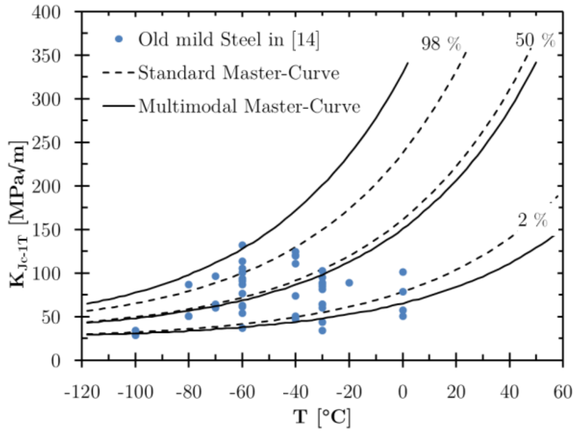

Fig. 4. Comparison of the fracture toughness values from [15] with results of the Master-Curve analysis in [20]

3.4. Dependency from the production process

To compare the fracture toughness of mainly Thomas-steels described in 3.1. and 3.2. with those once of higher quality, further investigations were carried out (see [20]). Additional material samples of welded structures from 1937 were considered. The results of the chemical analyses are shown in Table 2. All four samples are identified as Siemens-Martin-steels. Since specimen B3 contains a silicon ratio of 0.2 % it is a killed steel.

Similar to the investigations described before, extensive tests for analysing the material toughness according the Master-Curve-concept were carried out. As expected, the transition temperature T_{27J} of the Charpy-energy as well as the reference temperature T_0 of the C(T)-tests are significantly lower for the killed steel than for the other plate samples. In general, the analysed Siemens-Martin-steels have significantly lower reference temperatures than the Thomas-steels.

Table 2. Results of the chemical analysis from specimens out of Siemens-Martin-steels

Sample / Section	**Chemical content [%]**					
	C	**Mn**	**Si**	**P**	**S**	**N**
B1 (L80x8)	0.07	0.35	0.000	0.029	0.028	0.0047
B2 (Pl 13)	0.14	0.42	0.007	0.038	0.044	0.0057
B3 (Pl 13)	0.09	0.42	0.202	0.018	0.027	0.0053
B4 (Pl 11)	0.19	0.41	0.011	0.065	0.030	0.0074
Thomas-St.	0.05	0.46	0.009	0.051	0.044	0.0140
S-M-Steel	0.09	0.48	0.008	0.035	0.038	0.0050

Two material samples in Table 1 and Fig. 3, which are designated as M31 and M56, may also be identified as Siemens-Martin-steels. The evaluation of the fracture toughness together with the three rimming mild steels B1, B2 and B4 according to ASTM E1921 leads to a reference temperature T_0 of -45 °C (Fig. 5). This is about 15 K lower than the value of the mild steels according chapter 3.2. The characteristic value of the fracture toughness is obtained for the Siemens-Martin-steels as

$$K_{Jc-1T,5\%} = 25.2 + 36.6 \cdot exp[0.019 \cdot (T + 45)] \qquad (5)$$

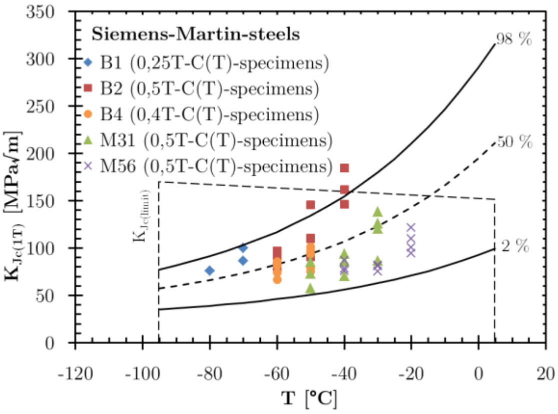

Fig. 5. Evaluation of all test series of Siemens-Martin-steels acc. to ASTM E1921 [3, 20].

3.5. Correlation of the material toughness

Since the dermination of the fracture toughness is sometimes not possible or too expensive, many research projects were carried out to derive correlations to other material properties. Most of the research was focused on the estimation of K_{Jc} from the Charpy-impact-energy KV_2. Some of the correlations are explained, evaluated and critically discussed in [21, 22]. In general these relationships are based on empirical data and only valid for certain types and states of materials.

For the mild steels of Table 1, the recommended estimation of the fracture toughness from the results of the Charpy-test according to the SINTAP-guidelines [23] was checked. The lower threshold value of the fracture toughness K_{mat} in a brittle material state was determined by Eq. (6).

$$K_{mat} = \left(12 \cdot \sqrt{KV_2} - 20\right) \cdot \left(\frac{25}{B}\right)^{0.25} + 20 \qquad (6)$$

B is the given thickness of the specimen related to 25 mm.

The minimum Charpy-impact energy of the mild steel specimens from Table 1 is 4.5 J, the related fracture toughness K_{mat} according Eq. (6) is 25.5 MPa√m. This lower threshold value is below all crack toughnesses $K_{Jc\text{-}1T}$ of the analysed mild steels and thereby provides a conservative estimation. The fracture toughness in the lower transition region of the toughness-temperature-curve can be estimated for a certain failure probability P_f as a function of the temperature T and the transition temperature T_{27J} by Eq. (7).

$$K_{mat} = 20 + \left[11 + 77 \cdot exp\left(0.019 \cdot \left(T - T_{27J} + 3\right)\right)\right] \cdot \left(\frac{25}{B}\right)^{0.25} \cdot \left(ln\frac{1}{1-P_f}\right)^{0.25} \qquad (7)$$

This approach is also applicable for old mild steels but leads to very conservative values of the toughness for the steels of Table 1.

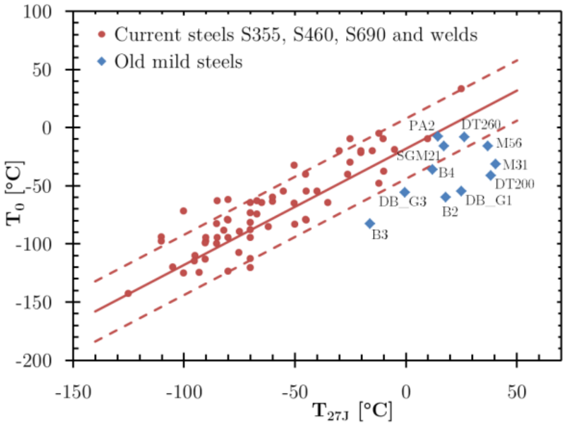

Fig. 6. Toughness of the examined mild steels and modern structural steels compared to the modified SANZ-correlation [3, 20].

The relationship between Charpy-impact energy and fracture toughness, which is very often used in steel engineering, is the correlation of transition temperatures T_{27J} and T_0 [24]. The modified type in Eq. (8) is part of the steel grade selection by EN 1993-1-10. The comparison of the analysed mild steels with current steel grades shows that the correlation

$$T_0 = T_{27J} - 18°C \quad \left(\pm 2 \cdot \sigma\right) \text{ with } \sigma = 13°C \qquad (8)$$

is not correct for old mild steels (Fig. 6). For comparable reference temperatures T_0 of the fracture toughness, the transition region of the Charpy-impact test is at significant higher temperatures.

4. Structures with punched holes

The risk of brittle fracture of riveted and bolted steel structures is affected by influences from the material, construction and production methods of the structural elements. The high nitrogen concentration of converter steels (Bessemer and Thomas procedure) in combination with plastic deformation leads to ageing and brittleness.

The risk of brittle fracture increases significantly due to strain ageing, particularly in the region of plastic deformations. Such strain ageing effects can occur due to cold deformations, e. g. in the peripheral areas of punched holes. At the beginning of the 20th century punched holes at cyclic loaded steel structures were only allowed in secondary structural components. In contrast, the rivet holes for joints in steel structures of the 19th century were always punched.

The notch effect of holes causes stress concentrations, which have to be compensated by local plastifications. If local yielding due to embrittlement is only insufficiently possible, brittle fracture, starting from cracks at the punched holes, may occur (see e. g. [5]).

To examine the influence of punching on the brittleness in the region of the holes, metallographic investigations and measurements of Vickers hardnesses were carried out in [4]. In the microsections (Fig. 7) there are visible the typical areas of penetration and plastic deformations in moving direction of the punching tool. The direction of the stretched ferrite grains is pronounced in the middle and the exit part of the hole. Similar texture conditions were documented at all punched edges. The micrographs illustrated that the visually deformed zones of the grain texture have a maximum width of 1.5 mm. In the examinations in [25] the strain hardening effect at the punched holes was alredy quantified by Vickers hardness measurements. However, the research was done with current steel grades without any significant tendency of strain ageing.

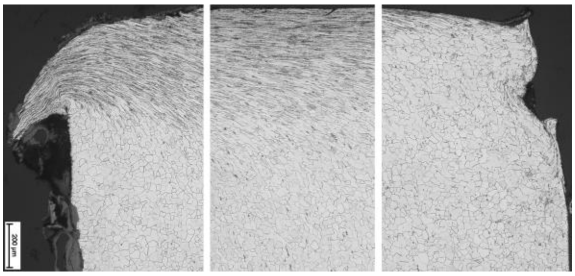

Fig. 7. Micrographs at the punched edge of a hole after micro etching in alcoholic HNO_3-solution [20].

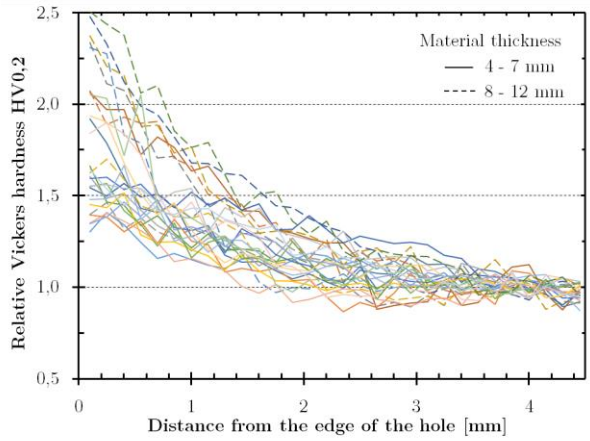

Fig. 8. Hardness of all examined samples, hardness values in relation to the unaffected base material [20]

Analogous to [25], hardness measurements by Vickers (HV0,2 according to EN ISO 6507) on sections of old mild steels with punched holes were carried out in [4]. The results are shown in Fig. 8. The measured values refer to the hardness of the unaffected base materials (HV_{BM}), which is in the range between 130 and 180 HV0.2. In the peripheral zone of the holes the hardness values increases up to 2.5-times. These values already point out an increasing tendency of cold cracking, but they are still below the permissible hardness value 380 HV 10 according to EN 1090-2. As already shown in the investigations in [11], the influence of punching is noticeable within an edge distance of about 3 mm. The hardened zone is wider than the area, in which deformed grain texture occurs.

5. Summary and Outlook

This paper presents examinations of the fracture toughness of old mild steels, the correlation between the results of Charpy- and C(T)-tests as well as effects of strain ageing at punched holes of riveted structures. An essentiel part is the extensive material analysis carried out to identify the fracture toughness in the brittle-ductile transition zone using the Master-Curve concept. The evaluation confirms that different material grades can be defined depending on the manufacturing process. To assess the influence of punching holes in combination with high contents of nitrogen, microstructure examinations and hardness measurements were carried out.

Based on the analysed material toughness of old mild steels a procedure for the assessment of brittle fracture of riveted structural elements was derived for typical structural details within a fracture mechanical safety analysis in [20, 26]. Related to the width of the hardened zone from punched holes, a crack with a straight front and a depth of 3 mm may be assumed at the most stressed hole edges of predominantly statically loaded structures. Equations for stress intensity factor approaches from the relevant literature can be used to determine the toughness requirements for components with rivet holes. Based on fracture mechanical finite-element-calculations a modification of these approaches was carried out for the joints of angle profiles in [20, 26]. The assessment procedure was transferred to a semi-probabilistic verification concept by using statistic methods to consider the variation of strength and toughness values of old mild steels after verification by component tests.

Acknowledgements

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